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HIGH-TEMPERATURE INVESTIGATIONS OF HEAT - AND OF ELECTRICAL CON--ETC(U)

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FOREIGN TECHNOLOGY DIVISION

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By

V. E. Peletskiy, D. L. Timrot, V. Yu. Voskresenskiy

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

HIGH-TEMPERATURE INVESTIGATIONS OF HEAT- AND OF ELECTRICAL CONDUCTIVITY OF SOLID BODIES.

V. E. Peletskiy, D. L. Timrot, V. Yu. Voskresenskiy.

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In book are examined the basic experimental methods of the study of heat- and electrical conductivity of solid bodies in high-temperature range and the structural/design formulation of the corresponding experimental installations. In this case, special attention is given to the methods of creation and measurement of high-temperature fields in the specimen/samples of the materials being investigated and to sources of systematic and random errors during measurements.

Are given and are discussed the results of the experimental investigation of heat- and electrical conductivity of refractory metals in high-temperature range.

The book is intended to scientific workers and research engineers, working in the field of study of heat- and electrophysical properties of substance. It can be recommended also to graduate students and the students of the old courses of thermophysical and heat engineering specialties.

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Preface.

The grown in recent years interest in the high-temperature measurements of the properties of substances is not accidental. The perfection/improvement of engineering solutions in power engineering, aviation, missile construction is unthinkable without the wide and reliable information about the properties of structural materials in all temperature range of their use.

In particular, during calculations and the construction of the systems of conversion and energy transfer the special importance has knowledge of thermal conductivity and resistivity.

Limited possibilities of the theoretical methods of the quantitative estimation of these parameters force to widely develop experimental investigations and determine the urgency of generalization and analysis of experiment, accumulated.

In the present work we examine methods and the technique of measurements of heat- and electrical conductivity in essence in connection with high-temperature range.

The appearance of the book of L. P. Filippova, dedicated to the measurements of the thermal properties of metals [3-32], allowed us to concentrate their attention in those systematic methods which not entered into this monograph or they were only touched upon in it. We tried not to be limited only to the theoretical side of one or the other systematic developments, but, where this was essential, examined the special feature/peculiarities of their technical realization.

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Taking into account its own experience, acquired in this range, we attempted to note advantages and disadvantages in the described works, to determine the maximum level of operating temperatures and the degree of reliability of the results of measurements.

One of the indices of the level of metrology is the convergence of experimental data for one and the same pure/clean substances, obtained during different experimental installations. In connection with this into the book, is introduced the chapter, which contains survey/coverage of the results of investigations of the properties of a number of refractory metals. This small reference application/appendix can be usefully as researchers, so to designers.

The content of this book rests in essence on the experimental investigations, made by the authors. Setting and the consecutive development of these works - to a considerable extent the result of attention and support to the corresponding members of the AS USSR A. Ye. Sheyndlin.

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Chapter One.

BASES OF THE METHODS OF THE EXPERIMENTAL DETERMINATION OF THE COEFFICIENT OF THERMAL CONDUCTIVITY AND OF RESISTIVITY.

1-1. General equation of thermal conductivity.

The law of conservation of energy and Bio - Fourier's hypothesis make it possible to construct quantitative theory for describing the processes of space-time charges in the temperature fields and connected with this energy effects. This theory operates with the concepts of heat flux and temperature gradient.

Heat flux is defined as quantity of heat dQ, transferred per unit time through the surface dF in question. The reference of this flow to the unit of the selected surface taking into account the dependence of its value from the attitude of area/site makes it possible to introduce the concept of the vector of heat-flux density $\vec{q}$, W/m^2:

$$dQ=\vec{q}\cdot d\vec{F}. \qquad (1\text{-}1)$$

If with the aid of control surface of F to isolate in body the arbitrary volume V, the quantity of heat dQ_F, entering it through this surface for a small time interval $d\tau$, it will be possible to find in the form

$$dQ_F = -d\tau \oint_F q_n dF, \qquad (1\text{-}2)$$

where q_n the projection of the vector of heat flux on the external standard $\vec{n}$ to surface of F at the point in question.

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According to the Gauss divergence theorem - Gauss

$$\oint_F q_n' dF = \int_V \operatorname{div} \vec{q}\, dV. \qquad (1\text{-}3)$$

In accordance with the first law of thermodynamics, the introduced into system heat is spent on an increase in internal energy dU and completion by the system of mechanical work.

After placing V = const, we will exclude the possibility of completion by the system of mechanical work and will arrive at following expression for changing the internal energy:

$$dU=\int_V c_V dT\, dV, \qquad (1\text{-}4)$$

where the specific heat at constant volume of unit volume

$c_V=(\partial u/\partial T)_V$.

Thus, from equations (1-2)-(1-4) it follows:

$$d\tau\int_V\left(c_V\frac{dT}{d\tau}+\operatorname{div}\vec{q}\right)dV=0. \qquad (1\text{-}5)$$

Taking into account the arbitrariness of volume, it is possible to write:

$$c_V\frac{\partial T}{\partial\tau}=-\operatorname{div}\vec{q}. \qquad (1\text{-}6)$$

If in body act sources of heat (absorption of electromagnetic radiation, Joule heat, radioactive decay, etc.), then into equation (1-6) must be introduced the terms, which give volumetric productivity of these sources q_V, W/m³. Equation of the balance of heat is record/written in this case in the form

$$c_V\frac{\partial T}{\partial\tau}+\operatorname{div}\vec{q}-q_V=0. \qquad (1\text{-}7)$$

One should again note that in the written form of equation (1-6) and (1-7) are valid under the condition of volume constancy (strains are equal to zero or constant).

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If this condition is not satisfied, into equation must be introduced the term, which considers the thermal effect of strain. In accordance with [1-1] he can be represented in the form

$$q_x = \frac{c_p - c_V}{\alpha} \frac{\partial}{\partial x} \operatorname{div} \vec{u}, \qquad (1\text{-}8)$$

where c_p heat capacity at constant pressure; α - coefficient of the thermal expansion of body; $\vec{u}$ - vector of the strain (its divergence determines volume change during strain) [1].

FOOTNOTE [1]. Equation (1-7) with addition (1-8) in principle must be supplemented by the equation of equilibrium, which connects strain with temperature distribution in the body:

$$\frac{3(1-\sigma)}{1+\sigma} \operatorname{grad} \operatorname{div} \vec{u} - \frac{3(1-2\sigma)}{2(1+\sigma)} \operatorname{rot} \operatorname{rot} \vec{u} = \alpha \nabla T,$$

in which σ - Poisson ratio. This makes the system of equations of complete and makes it possible to find the unknown function T(x, y, z, τ). ENDFOOTNOTE.

Of solid bodies the contribution of this term is very small $\left(\frac{c_p - c_V}{c_V} \ll 1\right)$, and with sufficient accuracy it is possible to use equation of type (1-7).

Equation (1-7) must be supplemented by the equation of relation of the vector of the heat flux $\vec{q}$ with the value, which characterizes temperature field in solid body. This equation they proposed Biot (1804) and Fourier (1822). On their hypothesis the vector of heat-flux density $\vec{q}$, caused by existence in the body of the heterogeneity of the temperatures, that acts at the given instant at the particular point of body, is directly proportional to the existing at this same point and at this same moment of time gradient of the temperature:

$$\vec{q} = -\lambda \operatorname{grad} T. \qquad (1\text{-}9)$$

Minus sign is determined by the fact that in conformity with the second law of thermodynamics the vector of heat flux is directed to the side of the less heated parts of the body (direction of negative gradients).

The coefficient of proportionality λ, which obtained the name of the coefficient of thermal conductivity, is one of the most important physical characteristics of substance.

In connection with the fundamental value of equation (1-9) the experimenters again and again turn to its checking.

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Its path consists, in particular, of the comparison of the results of the calculation of temperature fields, constructed during the use of equations (1-7) and (1-9), with experimental data.

One of the last/latter such checkings was made by Lindholm, Baker and Kirkkpatrick [1-2]. In view of its special interest let us pause at it in more detail.

In work was investigated the temperature field of cylindrical copper specimen/sample with a diameter of 4.76 more than 60 mm in long. Were accepted special measures for the thermal screening of lateral surface, so that in the case of heat supply from end/face were provided the conditions of one-dimensional problem. As the source of thermal energy served the arc reflecting furnace with dual parabolic reflector, which made it possible to change the density of radiant flux on the end/face of specimen/sample within limits of 400-4000 W/cm². Experiment occupied several seconds. So, at the density of flow 3600 W/cm² exposure time was 2.4 s. Melting point on end/face was reached after 1 s. The inertness of thermocouples was brought to the minimum: the diameter of the electrodes of the tungsten-rhenium thermocouples, introduced radially into specimen/sample, it was 0.0254 mm. The temperature fields, obtained experimentally, were compared with the results of solution in electronic computer of the one-dimensional equation of thermal conductivity taking into account the temperature dependence of heat capacity, density and thermal conductivity.

The coincidence of calculated and experimental data allowed the authors to make the conclusion that and in the case of very large heat fluxes (gradients to 1000 deg/cm) Fourier's hypothesis does not diverge from experiment.

In connection with the positive result of such checkings at present Bio - Fourier's hypothesis is considered as law, valid in practice in all range of the conditions of applying solid bodies.

The coefficient of thermal conductivity in connection with this acquires special importance and is the object/subject of widespread investigations. It must be noted that in the general case of anisotropic bodies it is tensor of second order and during bringing to principal axes contains three main components [1-4].

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Fourier law in this case is record/written in the form

$$q_i = -\lambda_{ij}\frac{\partial T}{\partial x_j}, \qquad (1\text{-}10)$$

where i=1, 2, 3 - index of axes; j=1, 2, 3 - index of the addition (addition in accordance with Einstein's rule is realized on the repeated index) and it is system of three equations with six (taking into account the symmetry of tensor) independent components of the tensor of thermal conductivity.

Let us emphasize the characteristic torque/moment, introduced anisotropic than the material. If for an isotropic material the vector of heat flux is normal to isothermal surface and is parallel to the gradient of temperatures, then in anisotropic medium in the general case this is not fulfilled: the vector of heat flux differs from the vector of temperature gradient.

Bio - Fourier's law makes it possible to derive the differential equation of Fourier, which is the basis of the calculation of temperature fields and heat-flow distribution in bodies.

For its first task it is possible to write in the form

$$c_V\frac{\partial T}{\partial \tau} - \operatorname{div}\lambda\operatorname{grad}T - q_V = 0, \qquad (1\text{-}11)$$

for the second - in the form

$$\frac{1}{a_V}\cdot\frac{\partial \vec{q}}{\partial \tau} = \operatorname{grad}\operatorname{div}\vec{q} - \operatorname{grad}q_V. \qquad (1\text{-}12)$$

Here $a_V = \lambda/c_V$, m^2/h - isochoric coefficient of thermal diffusivity. Its value is proportional to the velocity of propagation of isothermal surface in body [1-3][1].

FOOTNOTE [1]. In practice we, as a rule, do not meet the realization of the isochoric processes of thermal conductivity. In connection with this usually in equations (1-11) and (1-12) are utilized the values of the physical parameters, undertaken at a constant pressure. Let us note, however, that in pure form the isobaric thermal conductivity occurs only in some simple tasks. Larger partly in body appears the field of thermal stresses and neither one nor the other limiting case occurs. The strict solution of this complex problem for solid bodies, however, scarcely whether is justified due to the low value of difference $c_p - c_V$. ENDFOOTNOTE.

Equation (1-11) is correct for the isotropic and anisotropic bodies whose properties can depend both on the coordinates and on temperature. In the general case it is nonlinear and integration of it is very complex problem.

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Let us examine some conversions, which make it possible in a number of the cases to lead equation to a simpler form. Let c_v and λ they depend on temperature. Then (1-11) it is written in the form

$$c_v \frac{\partial T}{\partial \tau} = \lambda \nabla^2 T + q_v + \frac{\partial \lambda}{\partial T}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right]. \quad (1\text{-}13)$$

This equation is nonlinear.

Following Kirchhoff [1-5], let us introduce the new variable

$$\Lambda = \frac{1}{\lambda_0}\int_0^T \lambda(T)\,dT, \quad (1\text{-}14)$$

whence

$$\frac{\partial \Lambda}{\partial \tau} = \frac{\lambda}{\lambda_0}\cdot\frac{\partial T}{\partial \tau};\ \frac{\partial \Lambda}{\partial x} = \frac{\lambda}{\lambda_0}\cdot\frac{\partial T}{\partial x}$$

and so forth.

Taking into account relationship/ratio (1-14) equation (1-11) can be written in the form

$$\frac{1}{a_v}\cdot\frac{\partial \Lambda}{\partial \tau} = \nabla^2 \Lambda + \frac{q_v}{\lambda_0}, \quad (1\text{-}15)$$

which corresponds to the form of the equation of thermal conductivity for the case of the constant value of the coefficient of thermal conductivity. On the coefficient of thermal diffusivity a_v of such limitations, it is not superimposed. In (1-15), it, in the general case, depends on Λ.

Let us examine the conversion of equating the thermal conductivity for an anisotropic medium. If x_1, x_2, x_3 - principal axes of the tensor of thermal conductivity, and λ_1, λ_2, λ_3 - corresponding principal values $[\lambda_{ij}]$, the in accordance with fourier law in the form (1-10) differential equation of thermal conductivity takes the form (we assume that the thermal conductivity does not depend on temperature)

$$c_V \frac{\partial T}{\partial \tau} = \lambda_1 \frac{\partial^2 T}{\partial x_1^2} + \lambda_2 \frac{\partial^2 T}{\partial x_2^2} + \lambda_3 \frac{\partial^2 T}{\partial x_3^2} + q_V. \quad (1\text{-}16)$$

$$x_i = (\lambda_1\lambda_2\lambda_3)^{-1/6}\lambda_i X \quad (i=1,2,3),$$

Utilizing substitution/it is possible to convert equation (1-16) to the form

$$c_V \frac{\partial T}{\partial \tau} = (\lambda_1\lambda_2\lambda_3)^{1/3}\left(\frac{\partial^2 T}{\partial X_1^2} + \frac{\partial^2 T}{\partial X_2^2} + \frac{\partial^2 T}{\partial X_3^2}\right) + q_V, \quad (1\text{-}17)$$

characteristic for an isotropic material with the coefficient of thermal conductivity $\lambda = (\lambda_1, \lambda_2, \lambda_3)^{1/3}$.

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One should focus attention on the invariability of the volume element of body during this conversion: $dV = dX_1 dX_2 dX_3 = dx_1 dx_2 dx_3$, which makes it possible to consider constant/invariable the productivity of internal sources q_V and value $c_V \frac{\partial T}{\partial \tau}$.

The common/general/total equation of thermal conductivity (1-11) does not include information about the conditions of the coupling of the body in question with environment. In connection with this it cannot unambiguously determine entire picture of the distribution of the temperatures and heat fluxes in body. The solution of this equation can be only only during its construction taking into account the conditions of uniqueness which determine geometry, size/dimensions and the crystallographic orientation of the body (geometric of condition)in question, of the value of the physical parameters, entering the equation (physical conditions), the special feature/peculiarity of the course of process in time (time/temporary condition) and finally the character of the thermal interaction of the boundaries of body with the environment (boundary conditions). Only totality of this information makes it possible to find unique and stable solution.

During the construction of experimental procedures for studying one or the other physical parameter, the assignment of physical conditions is incomplete. Their absent component/links can be found, if experiment furnishes information on about the temperature distribution in body. Thus, word occurs about the peculiar inverse problem of the theory of the thermal conductivity: temperature field is known, the field of heat fluxes is known, boundary and time/temporary conditions are determined, it is necessary to find an unknown series of physical conditions. Is logical tendency so to supply experiment, so that a number of unknown parameters would be brought to the minimum.

In connection with the task of determining the coefficient of thermal conductivity, this can be reached by the creation of the conditions under which $\partial T/\partial \tau = 0$ or $T(x, y, z) = const$.

By this requirement is isolated the broad class of the so-called stationary problems of the theory of thermal conductivity. Here from equations is eliminated this parameter as heat capacity, and in a number of the cases solution is represented by the simple correlations, which contain only the coefficient of thermal conductivity.

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In present work we will be restricted to the examination of the methods of experiment, instituted only on stationary problems. Simplicity and strictness of the analytical description of temperature fields in such systems make it possible to return to them preference when objective of mission is independent data finding on the coefficient of thermal conductivity with maximally possible accuracy.

It must be noted that the larger partly necessary condition of obtaining the calculated relationship/ratios of method is the introduction of assumptions about the type of the functional connection of the coefficient of thermal conductivity and temperature.

1-2. Linear heat flux in body.

One of the widespread methods of the investigation of the coefficient of the thermal conductivity of the most varied materials is the method of flat/plane stationary isotherms. Its theory is instituted on the solution of the steady-state equation of thermal conductivity for the unlimited plate with isothermal surfaces. In this simplest case the problem is one-dimensional and initial differential equation takes the form

$$\frac{d}{dz}\left[\lambda(T)\frac{dT}{dz}\right]+q_V=0. \qquad (1\text{-}18)$$

Under boundary conditions $T_{z=0}=T_1$ and $T_{z=\delta}=T_2$, by utilizing conversion of Kirchhoff (1-14), solution of problem it is possible to find in the form [1-6]

$$\int_{T_1}^{T(z)} \lambda(T)\,dT = \int_{T_1}^{T_2} \lambda(T)\,dT - \frac{q_V z^2}{2} + z\left(\frac{q_V \delta}{2} - \frac{1}{\delta}\int_{T_1}^{T_2} \lambda(T)\,dT\right). \quad (1\text{-}19)$$

If internal sources are absent ($q_V=0$), the expression (1-19) is reduced to the form

$$\int_{T_1}^{T(z)} \lambda(T)\,dT = \left(1 - \frac{z}{\delta}\right)\int_{T_2}^{T_1} \lambda(T)\,dT, \quad (1\text{-}20)$$

or

$$\frac{T(z) - T_2}{T_1 - T_2} = \frac{\lambda_c(T_1, T_2)}{\lambda_c(T_z, T_2)}\left(1 - \frac{z}{\delta}\right). \quad (1\text{-}21)$$

where

$$\lambda_c(T_1, T_2) = \frac{1}{T_1 - T_2}\int_{T_2}^{T_1} \lambda(T)\,dT$$

- the mean-integral value of the coefficient of thermal conductivity in the range of temperatures T_1-T_2 and $\lambda_c(T_z, T_2)$ - the same for interval of $T(z)$-T_2.

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From (1-21) it follows that in the general case the temperature distribution in plate is nonlinear; the factor, which determines this nonlinearity, is the ratio of the coefficients of thermal conductivity, averaged in different temperature intervals.

In the experimental equipment/devices, which realize the method of flat/plane isotherms, calculated relationship/ratios construct, as a rule, under the assumption of the linear temperature distribution. In this case arises a question concerning the determination of reference temperature T_0, by which must be ascribed the obtained from experiment value λ_p.

If q - measured in experiment heat-flux density, then

$$\lambda_p = \frac{1}{T_1 - T_2} \int_{T_2}^{T_1} \lambda \, dT = \frac{q\delta}{T_1 - T_2}. \qquad (1\text{-}22)$$

It is easy to show, for example, that in the case of the linear dependence of the coefficient of thermal conductivity the reference temperature is equal to mean arithmetic from T_1 and T_2, i.e., $T_0 = (T_1 + T_2)/2$. A comparatively weak change in the coefficient of the thermal conductivity of the majority of materials (especially in high-temperature range) makes it possible to use extensively a linear approximation and to relate the obtained in experiment values to mean temperature.

The theory presented is the first approximation in the theory of the diverse versions of the methods of longitudinal heat flux, in detail examine/considered in Chapter 4.

Let us examine the most important special feature/peculiarities of the solution of staticnary problem when $q_v \neq 0$. Its special case is the electric heating with which

$$q_v = \sigma\left[\left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]. \qquad (1\text{-}23)$$

where σ - electrical conductivity cf material; v - electric potential at the particular point cf body.

Fundamental research of this version conducted Kohlrausch [1-7]. In view of the importance of his wcrk, which marked the beginning of the series of the precision experiments of the thermal conductivity cf metals and alloys, we will allow ourselves tc recall the main torque/moments of his reascrings.

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The initial equaticn of the thermal conductivity

$$\operatorname{div} \lambda \operatorname{grad} T + q_v = 0, \qquad (1\text{-}24)$$

where q_v is determined from (1-23), is supplemented by the requirement of the absence cf internal current sources, which is record/written in the fcrm cf the equation

$$\operatorname{div} \vec{i} = 0, \qquad (1\text{-}25)$$

where $\vec{i}$ - a completeness cf electric current.

Taking into account Ohm's law $i_x = -\sigma \frac{dv}{dx}$ equation (1-25) can be written in the form

$$\sigma\nabla^2 v + \frac{\partial\sigma}{\partial x}\cdot\frac{\partial v}{\partial x} + \frac{\partial\sigma}{\partial y}\cdot\frac{\partial v}{\partial y} + \frac{\partial\sigma}{\partial z}\cdot\frac{\partial v}{\partial z} = 0. \quad (1\text{-}26)$$

If heat- and electrical conductivity depend only on temperature, then the derivative of the corresponding parameter on coordinate can be represented in the form of the product of the gradient of temperature and temperature coefficient of this parameter. This makes it possible to obtain the resultant expression for equation (1-25):

$$\sigma\nabla^2 v + \frac{\partial\sigma}{dT}\left(\frac{\partial T}{\partial x}\cdot\frac{\partial v}{\partial x} + \frac{\partial T}{\partial y}\cdot\frac{\partial v}{\partial y} + \frac{\partial T}{\partial z}\cdot\frac{\partial v}{\partial z}\right) = 0. \quad (1\text{-}27)$$

Equations (1-24) and (1-27) with the addition of boundary conditions completely determine problem.

Further conversions of Kohlrausch are connected with the introduction of special requirement for boundary conditions. Without examining any concrete/specific/actual form of conductor, Kohlrausch requires so that the isopotential surfaces of input and output of current from conductor would be isothermal by surfaces. All the other surfaces must be adiabatically isolate/insulated. In this case it is possible to show that and within conductor the coincidence of isopotential and isothermal surfaces will be preserved, i.e., temperature will project/emerge only as function of potential.

This position is expressed in the form of two equations:

$$\left.\begin{aligned}\frac{\partial T}{\partial x}&=\frac{dT}{dv}\cdot\frac{\partial v}{\partial x};\\ \frac{\partial^2 T}{\partial x^2}&=\frac{d^2T}{dv^2}\left(\frac{\partial v}{\partial x}\right)^2+\frac{dT}{dv}\cdot\frac{\partial^2 v}{\partial x^2}.\end{aligned}\right\}\qquad(1\text{-}28)$$

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Utilizing (1-28) and taking into account (1-27), initial equation (1-24) can be led to the form

$$\frac{d^2T}{dv^2}+\frac{\sigma}{\lambda}\cdot\frac{d}{dT}\left(\frac{\lambda}{\sigma}\right)\left(\frac{dT}{dv}\right)^2+\frac{\sigma}{\lambda}=0.\qquad(1\text{-}29)$$

In the obtained equation of coordinate, they are absent. Position (1-28) render/showed the case, satisfying equation (1-24). For the conductor, heated by electric current, temperature state under Kohlrausch's boundary conditions depends not on λ on σ individually, but on the relation of these two values. Integration (1-29) gives the equation

$$\int\frac{\lambda}{\sigma}\,dT=-\frac{1}{2}v^2+Av+B,\qquad(1\text{-}30)$$

constant of which they can be determined from boundary conditions. Thus, for instance, if are known the temperatures and potentials in three points (linear) of conductor, then solution is converted to the form

$$v_1(T_2-T_3)\left(\frac{\lambda}{\sigma}\right)_{2,3}+v_2(T_1-T_3)\left(\frac{\lambda}{\sigma}\right)_{1,3}+$$
$$+v_3(T_2-T_1)\left(\frac{\lambda}{\sigma}\right)_{1,2}=\frac{1}{2}(v_1-v_2)(v_2-v_3)(v_3-v_1), \quad (1\text{-}31)$$

where $\left(\frac{\lambda}{\sigma}\right)_{1,2}=\frac{1}{T_2-T_1}\int_{T_1}^{T_2}\frac{\lambda}{\sigma}\,dT$ and so forth.

If the experiment is supplied then so that the distances between points and the temperatures in extreme points would be identical, then expression (1-31) will take the especially simple form:

$$\left(\frac{\lambda}{\sigma}\right)_c=\frac{1}{8}\,\frac{V^2}{\Delta T}. \quad (1\text{-}32)$$

Here: ΔT - difference in the temperatures between extreme and midpoints; V - potential drop between extreme points; $(\lambda/\sigma)_c^t$ the average value of the relation of the values of heat- and electrical conductivity in the range of temperatures ΔT.

The construction of the experiment, instituted on relationship (1-32), is determined by the possibility of the practical realization of the special, sufficiently rigid boundary conditions: the isothermicity of contact surfaces and the adiabatic insulation of an entire remaining surface.

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Their execution in practice is conjugate/combined with considerable difficulties.

However, In many instances the specific system of corrections makes it possible to utilize a remarkable solution of Kohlrausch, also, during divergences from the conditions of the examined by it problem. As we see further, this solution lay as the basis of many practical methods with the aid of which it was possible to obtain precision data in sufficiently wide temperature range.

EFFECT OF RADIANT LOSSES DURING THE MEASUREMENT OF THE COEFFICIENT OF THERMAL CONDUCTIVITY BY KOHLRAUSCH'S METHOD.

Kohlrausch's relationship/ratio (1-32), written in the form

$$\int_{T_0}^{T_m} \lambda\rho\, dT = \frac{1}{8} I^2 R^2, \qquad (1\text{-}33)$$

where ρ - the resistivity of conductor; R - complete value of electrical resistance between two equipotential surfaces (coinciding with isothermal ones with temperature T_0) of the conductor of any form; I - the full current, which passes on it, and T_m maximum temperature, it can be expressed in specific differential form.

It is real/actual, it differentiated (1-33) on I^2 and examining derivative under condition $I^2 \to 0$, we will obtain:

$$\lambda(T_0)=\left(\frac{x_2-x_1}{S}\right)_{T_0}\frac{R_0}{8}\cdot\frac{1}{[dT_m/d(I^2)]_{0,k}}. \qquad (1\text{-}34)$$

In expression (1-34), obtained by for the first time pains ones [1-8], x_2 and x_1 - longitudinal coordinates of cylindrical conductor, which have the constant temperature T_0, R_0 - impedance of the conductor between this by points at condition $T(x)=T_0$. Indices 0 and k with derivative $dT_m/d(I^2)$ indicate, in the first place, that the value of the latter is undertaken with I=0, and, in the second place, that this value is obtained under conditions of ideal experiment (according to Kohlrausch), by whom the floating surface of conductor does not have heat losses. Let us assume further that the conductor with current is placed into vacuum chamber with temperature T_0, equal to the temperature of conductor in points x_1 and x_2. Assuming that the surface of conductor is much less than the surface of the camera/chamber, expression for radiant losses can be written in the form

$$q_e(T)=\varepsilon(T)\,\sigma\,[T^4(x)-T_0^4], \qquad (1\text{-}35)$$

where σ - constant of stefana - Boltzmann's law;

ε - hemispheric integral emissivity factor of conductor.

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In work [1-8] it was shown, that under the formulated above boundary conditions the calculated relationship/ratic for the coefficient of thermal conductivity can howl fcund in the following form:

$$\lambda(T_0)=\left(\frac{x_2-x_1}{S}\right)_{T_0}\frac{{}^{\prime}R_0}{8}\cdot\frac{1}{[dT_m/d(I^2)]_{0,r}}\varphi, \quad (1\text{-}36)$$

where

$$\varphi=\frac{\left[1-2\frac{(x_2-x_1)^2}{d}\varepsilon\varepsilon(T_0)T_0^3\frac{8}{R_0}\left(\frac{S}{x_2-x_1}\right)_{T_0}\times\right.}{1-\frac{1}{2}\cdot2\frac{(x_2-x_1)^2}{d}\varepsilon\varepsilon(T_0)T_0^3\frac{8}{R_0}\times}\rightarrow$$

$$\rightarrow\frac{\left.\times\frac{1}{(x_2-x_1)}\int\limits_{x_1}^{x_2}\left(\frac{dT}{d(I^2)}\right)_{0,r}dx\right]^2}{\times\left(\frac{S}{x_2-x_1}\right)_{T_0}\left[\frac{dT_m}{d(I^2)}\right]_{0,r}}. \quad (1\text{-}37)$$

Index r means that the corresponding values of the entering the formula values are related to the conditions of real experiment. In expression (1-37) d, the diameter cf cylindrical conductor.

If the real experiment is processed on Kohlrausch's relaticnship/ratio (1-34), then the obtained values of the coefficient of thermal conductivity will prcve to be overstated, since maximum temperature T_m as a result of radiant losses changes in dependence on current less than in the ideal case, i.e.

$$\left[\frac{dT_m}{d(I^2)}\right]_{0,r} < \left[\frac{dT_m}{d(I^2)}\right]_{0,h}. \qquad (1\text{-}38)$$

From the comparison of expressions (1-34) and (1-36) it follows that the dimensionless quantity ϕ is the ratio of real coefficient λ to the specific from the equation of Kohlrausch coefficient of thermal conductivity λ_k, i.e. $\varphi=\lambda/\lambda_k$.

Value $2\frac{(x_2-x_1)^2}{d}\sigma\varepsilon(T_c)T_0^3$ can be considered as certain component of thermal conductivity λ_s, caused by radiant losses. Utilizing this designation, expression (1-37) can be written in the form

$$\varphi=\frac{\left[1-\frac{\lambda_s}{\lambda_k}\cdot\frac{(x_2-x_1)^{-1}\int_{x_1}^{x_2}(dT/d(I^2))\,dx}{[dT_m/d(I^2)]_{0,r}}\right]^2}{1-\frac{1}{2}\cdot\frac{\lambda_s}{\lambda_k}}. \qquad (1\text{-}39)$$

Expression (1-39) makes it possible to calculate the correction, which considers divergences from the adiabaticity of lateral insulation/isolation during the determination of the coefficient of thermal conductivity by Kohlrausch's method. For the rough estimate of the possible values of this correction, Bode proposes the special nomogram, presented in Fig. 1-1.

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Let us assume that the length of the working section of specimen/sample x_2x_1=50 mm, and its diameter d=2 mm. These data determine the coordinate of the starting point of nomogram. Further is considered the temperature of end/leads, equal to the temperature of camera/chamber T_0. Let us assume it is equal to 400° K. Knowing further emissivity factor (ε=0.1) and measured in experiment value λ_k, we find values λ/λ_k, and through it - and probable deviation $1-\lambda/\lambda_k$. For depicted on diagram case λ_k =0.5 W(cm•deg)$^{-1}$ and $(1-\lambda/\lambda_k)\approx$ 1.5o/o.

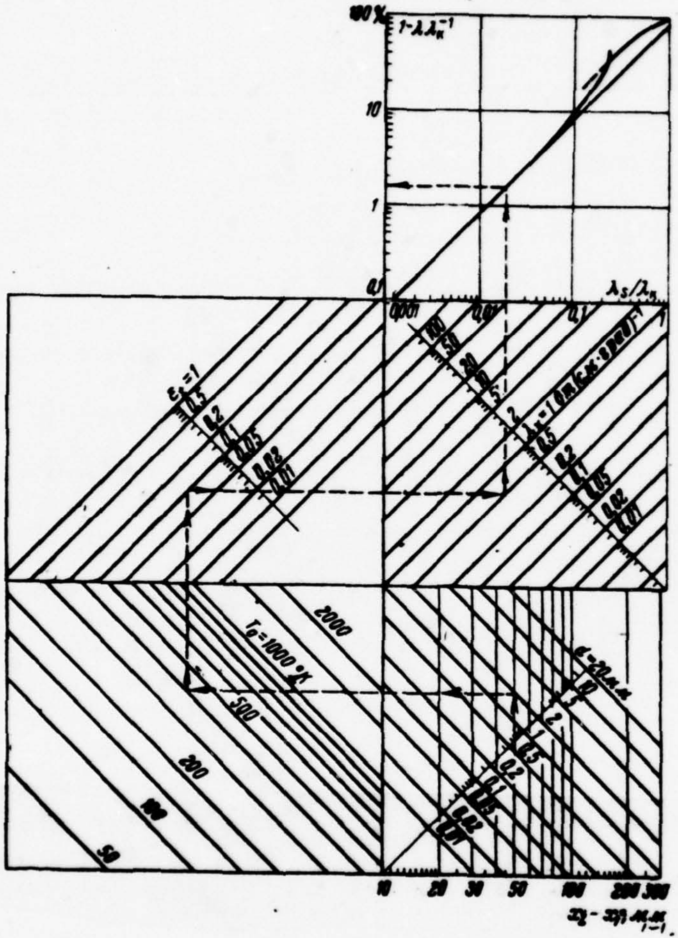

Fig. 1-1. Bode's nomogram [1-8] for determining the correction for lateral heat exchange during the use of equations of Kohlrausch. x_2-x_1 - length of the working section of specimen/sample; d - its diameter T_0 - temperature of end/leads, equal to temperature is furnace; ϵ_1 integral emissivity factor of specimen/sample; λ_s

-measured in experiment (designed according to the equation of Kohlrausch) value of thermal conductivity.

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1-3. Stationary temperature distribution in rod with current under conditions of intense radiation heat exchange on lateral surface.

In range of the high-temperature measurements of heat- and electrical conductivity the special place occupies the problem of the electrically heated conductor under conditions of its intense radiation heat exchange with the surrounding space. Behind term "intense" here hides itself the condition of a considerable difference in the temperatures between conductor and chamber wall, in which is located the conductor. This does not make it possible to conduct the simple linearization of lateral heat emission and it forces to record/write differential equation in the form

$$\frac{d}{dx}\left(\lambda \frac{dT}{dx}\right)-\frac{P\varepsilon\sigma}{S}(T^4-T_0^4)+\frac{I^2\rho}{S^2}=0, \qquad (1\text{-}40)$$

where P and S - perimeter and the cross section of conductor; λ, ρ, ε - in the general case depending on temperature thermal conductivity, resistivity and emissivity factor of material I - current; T_0 - temperature of the walls of vacuum chamber.

Equation (1-40) for essence its is the equation of the heat balance of the isolated cell/element of conductor, written on the assumption that the value of the radial temperature distribution in the cross sections of conductor can be disregarded.

The temperature distribution, described by this equation, was examined in many works [1-9-1-15]. The most thorough investigation of this problem is made Dzhayn and Krishnan [1-11, 1-12]. This work has fundamental value for the whole direction of experimental methods. In connection with this it is advisable to present her conclusion/derivations in sufficient detail.

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If is disregarded the temperature dependence of the physical constants, entering equation (1-40), then, as is known, its solution under the boundary conditions

$$\left.\begin{aligned} T=T_0 \text{ при}^{(1)}\ x=0; \\ dT/dx=0;\ T=T_l \text{ при}^{(1)}\ x=l, \end{aligned}\right\} \qquad (1\text{-}41)$$

Key: (1). with.

where l - half of the length of specimen/sample, it can be represented in the form

$$x=\int_{T_0}^{T}\frac{dT}{[a(T^5-T_l^5)-b(T-T_l)]^{1/2}}. \qquad (1\text{-}42)$$

where

$$a=\frac{2}{5}\cdot\frac{P\varepsilon\sigma}{\lambda S};\qquad (1\text{-}43)$$

$$b=\frac{2I^2\rho}{\lambda S^2}+\frac{2P\varepsilon\sigma T_0^4}{\lambda S};\qquad (1\text{-}44)$$

θ - temperature at the end/lead of the rod; in the particular case it can be equal to 0 or T_0.

It is impossible to present integral (1-42) in elementary functions. However, integrand can be expanded in the convergent power series and to integrate it piecemeal.

Before approaching toward expansion (1-42), let us find the relationship/ratio between current and temperature T_m in the middle of infinitely long wire in the form

$$P\varepsilon\sigma\left(T_m^4-T_0^4\right)=I^2\frac{\rho}{S}.\qquad (1\text{-}45)$$

Let us note that $T_m=\lim_{l\to\infty}T_l$.

From relationships (1-43)-(1-45) it follows that $b/a=5T_m^4$ and, therefore, (1-42) can be written in the form

$$x\sqrt{a}=\int_{\theta}^{T}[5T_m^4(T_l-T)-(T_l^5-T^5)]^{-1/2}\,dT. \qquad (1\text{-}46)$$

After accepting $T_l-T=t$, we will obtain:

$$x\sqrt{a}=\int_{t}^{t_0=T_l-\theta}[5(T_m^4-T_l^4)t+10T_l^3t^2-10T_l^2t^3+ +5T_lt^4-t^5]^{-1/2}\,dt, \qquad (1\text{-}47)$$

i.e. the temperature distribution was determined only by three parameters: T_l, T_m and a, which at the given length of rod 2l and with this current I are constants, not depending on x.

Integrand can be presented in the form of the function, which is deccmpcse/expanded with y<1 in the series

$$(1\pm y)^{-1/2}=1\mp\frac{1}{2}y+\frac{1\cdot 3}{2\cdot 4}y^2\mp\frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6}y^3+\dots \quad (1\text{-}48)$$

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Values of the first twc members of integrand in (1-47) are equal only when $t=t_c$ (Fig. 1-2).

$$t_c=\frac{T_m^4-T_l^4}{2T_l^3}, \quad (1\text{-}49)$$

And the sum of three remaining terms is negative at all values $0<t<t_c$. Consequently, are pcssible two methods of converting integrand (1-47) to form (1-48): when $t\leqslant t_c$, when the first member in (1-47) more the sum of remaining members, and when $t\geqslant t_c$, when the second member in (1-47) more the sum of the others.

With respect to this rod is divided by twc parts: range A, arrange/located in the middle part of the rod, when $x_c\leqslant x<l$ and $t_c\leqslant t<0$, and range B, arrange/located cn the extreme section of rod, when $0\leqslant x<x_c$ and $0<t\leqslant t_c$. Each cf the ranges A and B has their characteristic features of the temperature distribution. It is logical that in vicinities $t=t_c$ the temperature fields must coincide.

Range A. After multiplying both cf parts cf equality (1-47) on $[5(T_m^4-T_l^4)]^{1/2}$ and after passing tc the new coordinate q=l-x, which characterizes distance from the center of rod to the point being investigated with temperature t, we will obtain:

$$q\,[5a\,(T_m^4 - T_l^4)]^{1/2} = \int_0^t t^{-\frac{1}{2}}\,(1+y)^{-\frac{1}{2}}\,dt, \quad (1\text{-}50)$$

where

$$y = \frac{t}{t_c}\left(1 - \frac{t}{T_l} + \frac{t^2}{2T_l^2} - \frac{t^3}{10T_l^3}\right). \quad (1\text{-}51)$$

moreover y<1 when $0 \leqslant t \leqslant t_c$. These inequalities remain valid with all possible changes t_c within limits $0 < t_c \leqslant T_l$. In particular, in proportion to the decrease of the length of rod value $t_c \longrightarrow T_l$, as follows from (1-49), since in this case T_l decreases with constant/invariable T_m.

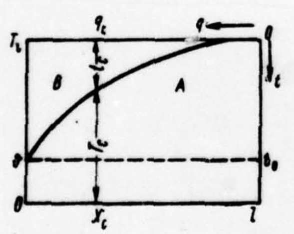

Fig. 1-2. Temperature distribution along conductor with current in vacuum.

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In the case of sufficiently short rod $t_c \geqslant t_0$, i.e. entire rod can be located in range A.

After integrating (1-50) taking into account expansion (1-48) in a series, we will obtain the law of the temperature distribution in range A:

$$q^2 = \frac{4t}{5a\,(T_m^4 - T_l^4)}\,(1-s)^2, \qquad (1\text{-}52)$$

where

$$s = \frac{1}{2\sqrt{t}}\left(\frac{1}{2}\int_0^t t^{-\frac{1}{2}}y\,dt - \frac{3}{8}\int_0^t t^{-\frac{1}{2}}y^2\,dt + \frac{5}{16}\int_0^t t^{-\frac{1}{2}}y^3\,dt - \ldots\right) \qquad (1\text{-}53)$$

Value s is low and can be considered as correction which in a series of the cases can be disregarded. On the basis (1-50) it is easy to ascertain that s has the greatest values on boundary of the region A, at point $t=t_c$. Depending on the length of rod, value s on boundary of the region A changes from 0.13 in the case of sufficiently long rod $(t_c \ll T_l)$ to 0.08 in the case of sufficiently short rod, when boundary of the region A coincides with the end/lead of rod $(t_c = t_0 = T_l)$. In the internal part of range A of value s, it is still less.

Disregarding value s, it is possible to speak about the quadratic law of the temperature distribution in range A:

$$q^2 = \frac{4t}{5a(T_m^4 - T_l^4)} . \qquad (1\text{-}54)$$

One should focus attention on the fact that during the use of formula (1-54) of the quadratic law of the temperature distribution for the experimental determination of the coefficient of thermal conductivity, entering in a, the error, connected with neglect of value s, is doubled.

Temperature interval t_c of range A is determined in (1-49) and depends only on the difference between T_m and T_l. It is easy to calculate, that a temperature drop on boundary of the region A approaches zero for a long specimen/sample when $T_l \to T_m$ and it grow/rises to $t_c = T_l$ in the short rod, which coincides along the length it is accurate with boundary of the region A, when $T_l/T_m = (1/3)^{\frac{1}{4}} = 0{,}76$. With further increase of range A value t_c can grow/rise unlimitedly.

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Binear interval q_c in range A can be determined from (1-49) and (1-54). With constant a it depends only on maximum temperature T_l in the middle of the rod:

$$q_c = \left(\frac{2}{5aT_l^3}\right)^{1/2}. \quad (1\text{-}55)$$

It is easy also to calculate, that with the constant/invariable current when T_m =const, the length of quadratic zone changes insignificantly in proportion to the shortening of specimen/sample. It increases from

$$(q_c)_\infty = \left(\frac{2}{5aT_m^3}\right)^{1/2}$$

for an infinitely long specimen/sample to

$$q_c = l = 3^{3/8}\left(\frac{2}{5aT_l^3}\right)^{1/2} = 1{,}6\left(\frac{2}{5aT_l^3}\right)^{1/2},$$

i.e. in all 1.6 times. With further shortening of specimen/sample, range A can considerably overlap its lengths $(q_c > l)$.

It is interesting that for such very short rods, heated by heavy current $(l < q_0)$, value s in (1-52) becomes real/actually negligible in comparison with 1. After substituting $t = T_l$ in (1-54), we will obtain the relationship/ratio between the length of short rod and its maximum temperature T_l:

$$l^2 = \frac{4T_l}{5a(T_m^4 - T_l^4)}. \quad (1\text{-}56)$$

During the decrease of the length of rod, value T_l^4 at certain stage will become negligible in comparison with T_m^4 and (1-54) it is converted in

$$q^2 = \frac{4t}{5aT_m^4} \ (\text{при}\ l < q_c). \qquad (1\text{-}57)$$

Key: with.

i.e. in this case the curves of distributions t according to q become equidistant. After substituting in (1-57) values a from (1-43) and T_m from (1-45), it is easy to ascertain that is obtained a special case of the solution of Kohlrausch.

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Range B. After multiplying both of parts of equality (1-47) on $(10T^3_l)^{1/2}$, we will obtain:

$$x(10aT_l^3)^{1/2} = \int_t^{t_0=T_l} t^{-1}\left(1 + \frac{t_0}{t} - \frac{t}{T_l} + \right.$$
$$\left. + \frac{1}{2}\frac{t^2}{T_l^2} - \frac{t^3}{10T_l^3}\right)^{-1/2} dt. \qquad (1\text{-}58)$$

When $t > t_c$ one in integrand is greater than the sum of remaining terms. This makes it possible to use resolution in the form (1-48). After removing for brackets from integrand (1-58) value

$$g^2 = 1 + \frac{t_0}{t}, \qquad (1\text{-}59)$$

we will obtain

$$x\,(10aT_i^3)^{1/2} = \int\limits_{t}^{t_0=T_i} (gt)^{-1}\,(1 - y_1)^{-\frac{1}{2}}\,dt, \qquad (1\text{-}58a)$$

where

$$y_1 = \frac{1}{g^2}\left(\frac{t}{T_i} - \frac{t^2}{2T_i^2} + \frac{t^3}{10T_i^3}\right),$$

also, after resolution in the series

$$x\,(10aT_i^3)^{1/2} = \int\limits_{t}^{T_i} \frac{1}{gt}\left(1 + \frac{1}{2}y_1 + \frac{3}{8}y_1^2 + \frac{5}{16}y_1^3 + \ldots\right)dt. \qquad (1\text{-}60)$$

After integrating (1-60) piecemeal, Dzhayn and Krishnan found solution in the form of the sum of three converging series:

$$x\,(10aT_i^3)^{1/2} = [U + V + W]_t^{t_0=T_i}, \qquad (1\text{-}61)$$

where

$$U = \ln t + \frac{t}{2T_i}\left(1 + \frac{t}{8T_i} - \frac{t^2}{120T_i^2} \cdots\right); \qquad (1\text{-}62)$$

$$V = 2\ln(g+1) + \frac{t_0}{T_i}\left(\frac{1}{g} - \frac{3}{4}\ln\frac{g+1}{g-1}\right) -$$

$$- \frac{t_0^2}{2T_i^2}\left(\frac{7}{2g} + \frac{1}{2g^3} + \frac{19}{16}\cdot\frac{g}{g^2-1} - \frac{75}{32}\ln\frac{g+1}{g-1}\right) + \cdots; \qquad (1\text{-}63)$$

$$W = \frac{(g-1)\,t}{2T_i}\left(1 + \frac{t}{8T_i} - \frac{t^2}{120T_i^2} \cdots\right). \qquad (1\text{-}64)$$

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The obtained expressions make it possible to assert that the temperature distribution in range B can be calculated with the desired degree of accuracy.

Solution considerably is simplified in the very important special case when the length of rod $l \to \infty$ and respectively $T_l \to T_m$, $t_c \to 0$ and $g \to 1$.

Under these conditions series V and W approach zero and (1-60) is reduced to

$$x(10aT_m^3)^{1/2} = [U]_t^{t_c = T_m} = D - \left[\ln t + \frac{t}{2T_m}\left(1 + \frac{t}{8T_m} - \frac{t^2}{120T_m^2} - \cdots\right)\right], \quad (1\text{-}65)$$

where D - constant, obtained from the expression

$$D = \ln T_m - \varkappa; \quad (1\text{-}66)$$

here $\varkappa = 1/2 + 1/16 - 1/240 \ldots.$

In the range of change in the temperatures, where

$$\ln t \gg \frac{t}{2T_m}. \quad (1\text{-}67)$$

expression (1-65) is reduced to the known expression of the form

$$x\sqrt{A}=D-\ln t, \qquad (1\text{-}68)$$

describing temperature field in long wire near its average zone. The analysis, carried out by Dzhayn and Krishnan made possible to not only rate/estimate the limits of the applicability of calculation formula (1-68) and to give to it corrections, but also to analytically express constant D, which to those pores was not defined.

In practice usually are encountered the measurements on the wires the temperatures of end/leads of which are maintained by the equal ones to certain $\vartheta \neq 0$, where ϑ, in particular, room temperatures. After replacing upper integration limit in (1-65) on $t_0=T_m-\vartheta$, we will obtain important for practice expression for D in the form

$$D=\ln t_0+\frac{t_0}{2T_m}+\frac{t_0^2}{16T_m^2}-\frac{t_0^3}{240T_m^3}-\cdots \qquad (1\text{-}69)$$

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With $\vartheta=0$, as can easily be seen, (1-69) it transfer/converts in (1-66). It is interesting to note that for final rods with $T_l<T_m$ the temperature field within the limits of range B differs little from

the field of the infinitely long specimen/sample, heated by the same current. Of this, it is easy to be convinced via the analysis of integrand Φ in (1-46), which characterizes the gradients of temperatures along the axis of the rod:

$$\Phi=\frac{dT}{dx}=a^{1/2}\,T_m^{5/2}\left[\left(\frac{5T_l}{T_m}-\frac{T_l^5}{T_m^5}\right)-\left(\frac{5T}{T_m}-\frac{T^5}{T_m^5}\right)\right]^{1/2}.$$

This fact is allowed, without completing large error, to rate/estimate the length x_c of range B on formula for infinitely long rod (1-65):

$$x_c=(10aT_m^3)^{-1/2}\left(\ln\frac{2T_l^3T_m}{T_m^4+2T_l^3T_m-3T_l^4}+\frac{3T_l^4-T_m^4}{4T_l^3T_m}+\dots\right). \quad (1\text{-}70)$$

The common/general/total halflength of the rod, heated by electric current, depending on temperatures T_m and T_l at condition $T_l/T_m \geq 0.76$ can be calculated as sum x_c (1-70) and q_c (1-55):

$$l=(10aT_m^3)^{-\frac{1}{2}}\left(\ln\frac{2T_l^3T_m}{T_m^4+2T_l^3T_m-3T_l^4}+\right.$$
$$\left.+\frac{3T_l^4-T_m^4}{4T_l^3T_m}\right)+\left(\frac{2}{5aT_l^3}\right)^{1/2}. \quad (1\text{-}71)$$

For $T_l/T_m<(1/3)^{1/4}=0.76$ the length of rod determined was in (1-56).

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Account of temperature coefficients.

If

$$\left.\begin{aligned}\lambda&=\lambda_l\,[1+\alpha(T-T_l)];\\ \rho&=\rho_l\,[1+\beta(T-T_l)];\\ \varepsilon&=\varepsilon_l\,[1+\vartheta(T-T_l)],\end{aligned}\right\} \quad (1\text{-}72)$$

where $\lambda_l, \rho_l, \varepsilon_l$ the value of the physical parameters at temperature T_l, and α, β, δ - their temperature coefficients, then differential equation (1-40) after twofold integration is reduced by analogy with (1-47) to the expression

$$x\sqrt{a} = \int_{t}^{t_0 = T_l - \theta} \frac{1 - at}{Q^{1/2}}\, dt. \qquad (1\text{-}73)$$

The physical parameters, brought to value a, are related to temperature T_l, and $T_m = \left(\frac{\rho_m}{\varepsilon_m} \cdot \frac{I^2}{PS\sigma}\right)^{1/4}$;

$$Q = 5t\left[T_m^4 - T_l^4 + T_l^4\left(\frac{2a_1 t}{T_l} - \frac{2a_2 t^2}{T_l^2} + \frac{a_3 t^3}{T_l^3} - \frac{a_4 t^4}{5T_l^4} + \frac{a_5 t^5}{6T_l^5} - \frac{a_6 t^6}{7T_l^6}\right)\right], \qquad (1\text{-}74)$$

where

$$\left.\begin{aligned}
a_1 &= \frac{1}{4}\,[4 + (\alpha + \delta)\,T_l - (\alpha + \beta)\,T_m^4/T_l^3 + (\beta - \delta)\,T_0^4/T_l^3];\\
a_2 &= \frac{1}{6}\,[6 + 4\,(\alpha + \delta)\,T_l + \alpha\delta T_l^2 - \alpha\beta T_m^4/T_l^2 + \alpha\,(\beta - \delta)\,T_0^4/T_l^2];\\
a_3 &= \frac{1}{4}\,[4 + 6\,(\alpha + \delta)\,T_l + 4\alpha\delta T_l^2];\\
a_4 &= 1 + 4\,(\alpha + \delta)\,T_l + 6\alpha\delta T_l^2;\\
a_5 &= (\alpha + \delta)\,T_l + 4\alpha\delta T_l^2;\\
a_6 &= \alpha\delta T_l^2
\end{aligned}\right\} \qquad (1\text{-}75)$$

they are constants.

In the case $\alpha=\beta=\delta=0$ coefficients $a_1=a_2=a_3=a_4=1$, $a_5=a_6=0$ and (1-74) it is reduced to expression (1-47), as one would expect.

In the case of infinitely long rod $(T_l=T_m)$ equation (1-73) is reduced to form

$$x(10a\,a_1T_m^3)^{1/2} = \int \frac{(1-at)\,dt}{t\left[1+b_1\left(\frac{t}{T_m}\right)+b_2\left(\frac{t}{T_m}\right)^2+b_3\left(\frac{t}{T_m}\right)^3+b_4\left(\frac{t}{T_m}\right)^4+b_5\left(\frac{t}{T_m}\right)^5\right]^{1/2}}, \qquad (1\text{-}76)$$

where

$$b_1 = -\frac{a_2}{a_1};\ b_2 = \frac{a_3}{2a_1};\ b_3 = -\frac{a_4}{10a_1};\ b_4 = \frac{a_5}{12a_1};\ b_5 = -\frac{a_6}{14a_1}.$$

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After expanding integrand in power series (1-48) and after integrating it piecemeal, it is possible to obtain the dependence, which characterizes temperature field in the infinitely long conductor, heated by the current:

$$x(10a'a_1T_m^3)^{1/2} = \ln T_m + \sum_{i=1}^{\infty} A_i - \left[\ln t + \sum_{i=1}^{\infty} A_i \left(\frac{t}{T_m}\right)^i\right], \quad (1\text{-}77)$$

where

$$\left.\begin{aligned} A_1 &= -\left(\frac{b_1}{2} + aT_m\right);\ A_2 = \frac{1}{4}\left(\frac{3}{4}b_1^2 + ab_1T_m - b_2\right); \\ A_3 &= \frac{1}{48}(12b_1b_2 - 6b_1^2 aT_m + 8b_2aT_m - 8b_3 - 5b_1^3). \end{aligned}\right\} \quad (1\text{-}78)$$

In the particular case $\alpha=\beta=\delta=0$, A_1, A_2, A_3, are reduced respectively to 1/2, 1/16, 1/240, $\sum A_i \to \varkappa$ and (1-77), it transfer/converts in (1-65), as one would expect.

In such a manner, as it follows from (1-77), the account of temperature coefficients is led first of all to an increase of the integration constant $\varkappa$ in (1-66) by value $\Sigma A_i - \varkappa = \Delta\varkappa$. As show calculations, value $\Delta\varkappa$ for a number of metals vary within the range of 0 to 1. In particular, for the idealized metal value $\Delta\varkappa = 0.52$. Furthermore, near the end/leads of the heated by current rod, i.e., with small x, will manifest itself the effect of terms (1-77), of including t. However, the common/general/total effect of the temperature coefficients of the physical parameters both in the case of infinite rod and in the case of range B of final rod is reduced to an increase in length x at the low values of t on

$$\Delta x = \left(\varkappa - \sum A_i\right)(10aT_m^3)^{-\frac{1}{2}}. \quad (1\text{-}79)$$

Within the limits of range A of final rod, the introduction of temperature coefficients did not influence the general view of formula (1-52), but pronounced only in an insignificant change in the small correction s (for the value of order $1+\alpha t_c$).

Thus, carried out by Dzhayn and Krishnan the analysis of temperature field along the length of wire, heated in vacuum by the passing electric current, showed following:

1. The temperature distribution along rod can be represented in the form of converging series and is calculated with any desired degree of accuracy.

2. Are most characteristic following forms of temperature fields: logarithmic (1-65) - for infinitely long conductor in temperature range $t(\ln t)^{-1} \ll 2T_m$ and parabolic (1-52) - for middle part (range A) of final rod.

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3. Within limits of logarithmic and quadratic temperature fields, effect of temperature coefficients of physical parameters (thermal conductivity, electrical resistance and emissivity factor) is completely insignificant and easily is considered.

The results of the analysis of Dzhayn and Krishnan in recent years were used for developing a series of procedures on the investigation of the thermal conductivity of metals in the temperature range of 1000-3000° K.

Those obtained relationships (1-56), (1-65), (1-69), (1-71) and (1-79) between the length of rod, its physical parameters and the maximum temperature in center are extremely useful during the construction of installations and instruments with the wire or rod heaters, working under conditions of intense heat exchange emission/radiation.

Bode's method.

Recommendations to experimenters, placed in conclusion/derivations of Krishnan and Dzhayn do not exhaust all possible versions of the systematic methods, which allow from information about temperature field in conductor with current to extract the coefficient of thermal conductivity.

The original way of converting the initial equation of the case in question proposed Bode [1-16], with one of the particular results of work of whom we were introduced above. Its approach is instituted on combined analysis of the series of stationary temperature fields, which correspond to the different values of the feeding specimen/sample current.

Let us examine the basic torque/moments of this original work. Just as Krishnan and Dzlayn, Bode examine one-dimensional Bode examines the one-dimensional problem of the stationary temperature state of the fine/thin conductor, heated by current and placed in vacuum chamber. The temperature of the latter T_u in the process of experiment is constant lower than the temperature of conductor.

Initial differential equation here is record/written in more general form, namely:

$$\frac{d}{dx}\left(\lambda\frac{dT}{dx}\right)+I^2f(T)-g(T)=0. \qquad (1\text{-}80)$$

Here

$$f(T)=\frac{\rho}{S^2};\ g(T)=\frac{2\pi r_0}{S}q_s;$$

ρ - specific impedance; S - the cross section of conductor; q_s - specific heat losses from its lateral surface.

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This form of equation considers temperature dependence not only ρ and q_s but also the geometric dimensions of conductor. Further analysis is conducted in connection with the boundary conditions of constant temperature T_0 at points x_1 and x_2. The author shows that with this between by points x_1 and x_2 is possible only one extremum temperature curve, that depending on the current strength I value of maximum temperature T_m can be both less and is more T_0, and finally that at the specific strength of current $I=I_0$ the temperature over entire length of cut x_1-x_2 is constant and equal to T_0. Taking into account the symmetry of the temperature distribution, it is possible to obtain the first integral of equation (1-80) in two forms:

$$\left(\lambda \frac{dT}{dx}\right)_T^2 = -2\int_{T_m}^{T} \lambda\,[I^2 f(T) - g(T)]\,dT \qquad (1\text{-}81)$$

and

$$\left(\lambda \frac{dT}{dx}\right)_{x_1} = \frac{1}{2}\int_{x_1}^{x_2} [I^2 f(T) - g(T)]\,dx. \qquad (1\text{-}82)$$

From last/latter equation escape/ensues the important result: in the implementation of conditions/mode with current I_0, its left side turns into zero, but integrand becomes not depending on x; then

$$g(T_0) = I_0^2 f(T_0). \qquad (1\text{-}83)$$

During experiment this conditions/mode gives information about the value of specific losses from lateral surface. Further process/operations consist into searching for values of derivatives on current, undertaken of expressions (1-81) and (1-82) in points $I=I_0$ and $T_m=T_0$ and the analysis of the equality

$$\lim_{I\to I_0}\frac{d}{dT}\left(\lambda\frac{dT}{dx}\right)_{T_0}=\lim_{I\to I_0}\frac{d}{dT}\left(\lambda\frac{dT}{dx}\right)_{x_0}. \quad (1\text{-}84)$$

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Is considered also the thermal expansion of the conductor

$$\left[\frac{d}{dT}(x_2-x_1)\right]_{I_0}=\frac{1}{[(x_2-x_1)_0]_{T_0}}\left[\frac{d(x_2-x_1)_0}{dT}\right]_{T_0}\int_{x_1}^{x_2}\left(\frac{dT}{dI}\right)_{I_0}dx \quad (1\text{-}85)$$

and change impedance $R=\int_{x_1}^{x_2}\frac{\rho}{S}dx$ with the current

$$\left(\frac{dR}{dI}\right)_{I_0}=\frac{1}{[(x_2-x_1)_0]_{T_0}}\cdot\frac{dR_0}{dT_0}\int_{x_1}^{x_2}\left(\frac{dT}{dI}\right)_{I_0}dx. \quad (1\text{-}86)$$

Here $(x_2-x_1)_0$ - distance between two points in the isothermal states $[(x_2-x_1)_0]_{T_0}$ - the same after establishment along the length of the working section of temperature T_0.

Is utilized also the expression, which ensues from (1-83):

$$\left(\frac{dg}{dT}\right)_{T_0}=2I_0\frac{dI_0}{dT_0}f(T_0)+I_0^2\left(\frac{df}{dT}\right)_{T_0}. \quad (1\text{-}87)$$

Taking into account the relationship/ratios indicated equality (1-84) leads to following expression for the coefficient of the thermal conductivity:

$$\lambda(T_0)=\left(\frac{x_2-x_1}{S}\right)_{T_0}\frac{U_0}{2}\cdot\frac{dI_0}{dT_0}\,\frac{\left[1-\frac{(dR/dI)_{I_0}}{dR_0/dI_0}\right]^2}{1-\left[1-\frac{(dT_m/dI)_{I_0}}{dT_0/dI_0}\right]^2}. \quad (1\text{-}88)$$

Here $U_0=R_0I_0$ - potential difference in the conditions/mode of isothermal heating.

One should note the strictness of expression, any simplifying assumptions about the temperature course of the properties of material and radiation losses it was not made.

During experimentation for a number of the values of temperature at the end/leads of the working cut T_0, it is necessary, by changing current I, to measure depending on it the appropriate values of maximum temperature $T_m(I)$ and impedance of section R(I). Hence it is possible to find the necessary derivatives and to construct the curves $T_0(I_0)$ and $R_0(I_0)$.

It is interesting to note that calculated relationship/ratio (1-88) does not change, if into initial differential equation is introduced member - I τ/S (dT/dx), the considering Thomson's effect (τ - Thomson's coefficient). This is strictly shown to Bode in work [1-17].

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1-4. Use of radial heat flux for the investigation of the coefficient of thermal conductivity.

The differential equation, which describes stationary temperature field in the wall of cylinder in the absence of longitudinal heat flow in the case of isotropic material and action of internal sources of heat ($q_V>0$), is record/written as follows:

$$\frac{1}{r}\cdot\frac{d}{dr}\left[\lambda(T)\cdot r\frac{dT}{dr}\right]+q_V=0. \quad (1\text{-}89)$$

Let us examine the solution of problem under the boundary conditions

$$\left.\begin{array}{l} r=r_1;\ T=T_1; \\ r=r_2;\ T=T_2. \end{array}\right\} \quad (1\text{-}90)$$

Using the conversion of Kirchhoff

$$\Lambda=\int_{T_1}^{T}\lambda(T)\,dT, \quad (1\text{-}91)$$

equation (1-89) can be written as follows:

$$\frac{1}{r}\cdot\frac{d}{dr}\left(r\frac{d\Lambda}{dr}\right)+q_V=0. \quad (1\text{-}92)$$

The general solution of this equation is represented by the expression

$$\Lambda=C\ln r-\frac{q_V}{4}r^2+B. \quad (1\text{-}93)$$

After determining constants C and B frcm bcundary conditions (1-90), it is possible tc obtain this scluticn in the form (with q_v =const)

$$\int_{T_1}^{T}\lambda\,dT=\left[\frac{q_v r_1^2}{4}\left(\frac{r_2^2}{r_1^2}-1\right)-\int_{T_2}^{T_1}\lambda\,dT\right]\frac{\ln(r/r_1)}{\ln(r_2/r_1)}-\frac{q_v r_1^2}{4}\left(\frac{r^2}{r_1^2}-1\right). \qquad (1\text{-}94)$$

or with the lower limit of left integral, equal to T_2,

$$\int_{T_2}^{T}\lambda\,dT=\left[\frac{q_v r_1^2}{4}\left(\frac{r_2^2}{r_1^2}-1\right)-\int_{T_2}^{T_1}\lambda\,dT\right]\frac{\ln(r/r_2)}{\ln(r_2/r_1)}-\frac{q_v r_2^2}{4}\left(\frac{r^2}{r_2^2}-1\right). \qquad (1\text{-}95)$$

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Brom equations (1-94) and (1-95) it follows that in the simplest case in the absence of internal sources, i.e., when $q_v=0$, and the constancy of the coefficient of thermal corductivity λ the temperature field in cylinder behaves lctharithmically. In the case cf the dependence of the coefficient of thermal conductivity on temperature this dependence the more powerful differs from logarithmic, the greater temperature coefficients λ.

Utilizing law of mean equation (1-94) it is possible to write in the form

$$T - T_1 = (T_2 - T_1)\frac{\lambda_{cp1}}{\lambda_{cp2}} \cdot \frac{\ln(r/r_1)}{\ln(r_2/r_1)}, \qquad (1\text{-}96)$$

where

$$\left.\begin{aligned} \lambda_{cp1} &= \frac{1}{T_2 - T_1}\int_{T_1}^{T_2}\lambda(T)\,dT; \\ \lambda_{cp2} &= \frac{1}{T - T_1}\int_{T_1}^{T}\lambda(T)\,dT. \end{aligned}\right\} \qquad (1\text{-}97)$$

It is easy to show that in the case of the linear dependence of the coefficient of thermal conductivity on the temperature its average value in temperature interval $T_i - T_{i+1}$ is equal to the value, undertaken at arithmetic mean temperature, i.e.,

$$\lambda_{cp}(T_i, T_{i+1}) = \lambda\left(\frac{T_i + T_{i+1}}{2}\right).$$

Thus, in equation (1-96) relation $\lambda_{cp1}/\lambda_{cp2}$ is the function of temperature, which determines the distortion of the logarithmic law of the temperature distribution. Generally speaking, this is the serious limitation of the method of radial heat flux in its most widely used version: in the case of the complex temperature dependence of the coefficient of thermal conductivity, we not in state to find its true value. The basic calculated relationship/ratio of radial method easily is obtained from the joint solution of equation (1-89) and of equating Fourier. When $q_V=0$ this relationship/ratio can be represented in the form

$$\lambda_{cp}=\frac{Q}{2\pi l}\cdot\frac{\ln(r_2/r_1)}{(T_1-T_2)}. \qquad (1\text{-}98)$$

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Here as earlier: $\lambda_{cp}=\frac{1}{T_1-T_2}\int_{T_2}^{T_1}\lambda(T)\,dT$; Q - total quantity of heat, passed through the cylindrical surface with the forming length l.

The experiment, instituted on relationship/ratio (1-98), assumes the measurements of temperatures at distances r_2 and r_1 from the axis of a cylinder, of a working length l and of the total quantity of heat, transmitted at this length in radial direction.

In a number of the cases, can prove to be effective another approach to the construction of experimental procedure in radial system.

Let us write expression for heat flux through the isothermal surface with a current radius of r:

$$-2\pi rl\lambda(T)\frac{dT}{dr}=Q. \qquad (1\text{-}99)$$

After integrating (1-99) according to the thickness of specimen/sample, we will obtain:

$$\int_{T_2}^{T_1}\lambda(T)\,dT=\frac{Q}{2\pi l}\int_{r_1}^{r_2}\frac{dr}{r}=\frac{Q}{2\pi l}\ln\frac{r_2}{r_1}. \qquad (1\text{-}100)$$

If in experiment is created conditions for maintenance T_2 =

const, then will arise the possibility, utilizing rules of differentiation of definite integral with the alternating/variable upper limit, to obtain true values of the coefficient of thermal conductivity. It is real/actual,

$$\frac{d}{dT_1}\int_{T_2}^{T_1}\lambda(T)\,dT=\lambda(T_1)=\frac{\ln(r_2/r_1)}{2\pi l}\cdot\frac{dQ}{dT_1}. \qquad (1\text{-}101)$$

In the more general case when both of integration limits change during changes in the heat flux, i.e., $T_1=f(Q)$ and $T_2=F(Q)$, by applying the rules of differentiation with respect to the parameter, it is possible to obtain:

$$\lambda(T_1)=\lambda(T_2)\frac{dT_2}{dT_1}+\frac{\ln(r_2/r_1)}{2\pi l}\cdot\frac{dQ}{dT_1}. \qquad (1\text{-}102)$$

In practice frequently there is known the value of the coefficient of thermal conductivity at lower temperatures. In this case the construction of experiment on the basis of relationship/ratio (1-102) is especially effective.

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Let us examine more common/general/total problem. If equation (1-89) is solved into assumptions $q_V=\text{const}$ under the boundary conditions $r=r_1$; $dT/dr=0$ and $r=r_2$; $T=T_2$, we will obtain:

$$\int_{T_2}^{T}\lambda(T)\,dT=\frac{q_V r_2^2}{4}\left[1-\left(\frac{r}{r_2}\right)^2-2\left(\frac{r_1}{r_2}\right)^2\ln\frac{r_2}{r}\right], \qquad (1\text{-}103)$$

whence it is possible to obtain initial relationship/ratio for determining the average in the range of temperatures $T_2=T_1$ coefficient of the thermal conductivity

$$\lambda_{cp}=\frac{q_V r_2^2}{4(T_1-T_2)}\left[1-\left(\frac{r_1}{r_2}\right)^2-2\left(\frac{r_1}{r_2}\right)^2\ln\frac{r_2}{r_1}\right]. \qquad (1\text{-}104)$$

In the general case $q_V \neq const$, since electrical conductivity of materials as their thermal conductivity, depends on temperature. In this case temperature field is described by more complex laws.

One of versions of the solution of equation (1-89) taking into account the variability of heat- and electrical conductivity proposed A. V. Pustogarov [1-18]. After introducing the function of thermal conductivity $\Lambda = \int_0^T \lambda dT$ and after assuming linear connection between electrical conductivity and function of thermal conductivity, i.e., $\sigma = A\Lambda + B$, A. V. Pustogarov arrived at the following form of general solution:

$$\Lambda(\rho) = C_1 J_0(\nu) + C_2 Y(\nu) - \frac{B}{A} \quad (1\text{-}105)$$

and

$$\Lambda(\rho) = C_1 I_0(\nu) + C_2 K_0(\nu) - \frac{B}{A} \quad (1\text{-}106)$$

for A>0 and A<0 respectively.

In this case, $\rho = r/r_2$ - relative radius of rod, and $\nu = \rho E r_2 \sqrt{A}$, where E - electric intensity; $J_0(\nu)$ and $Y_0(\nu)$ - Bessel function of zero order of the first and second kind; $I_0(\nu)$ and $K_0(\nu)$ - modified Bessel functions.

During the use of boundary first-order, conditions the solution of problem for a rod with current is represented by the expression

$$\Lambda(\rho) = (\Lambda_0 + B/A) I_0(\nu) - B/A, \tag{1-107}$$

and for a current density

$$j(\rho) = j_0 I_0(\nu), \tag{1-108}$$

where j_0 - current density on the axis of rod.

Knowing the function of thermal conductivity Λ and using (1-107), it is easy to find the radial temperature distribution. During the organization of the corresponding experiment, one should consider the character of current distribution with the aid of the system of the special corrections, instituted on similar solutions.

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Chapter Two

METHODS OF THE STUDY OF HIGH TEMPERATURE FIELDS.

2-1. Bases of pyrometry.

For the examine/considered by us tasks of experimental thermophysics vital importance has the correct organization of temperature measurements.

The determination of the coefficient of thermal conductivity in stationary tasks is impossible without the information about the distribution of the temperatures in specimen/sample, which make it possible to calculate the field of temperature gradients. The experimental determination of another property - the resistivity, which substantially depends on temperature, is conducted on the basis of information about the electrical parameters of finite volumes and, therefore, also must be supplemented by the information about the temperature distribution in this volume.

Thus, the investigation also of that, and other conductivity types is direct-connected with the experimertal study of the temperature fields in specimen/sample, which have now and then fairly complicated configuraticn.

Let us examine the basic torque/moments, connected with the solution of this important problem in high-temperature range.

The high-temperature zone of international practical temperature scale begins from melting point of gold: 1337.58°K. Relying on this value, extrapolation into the range of higher temperatures can be carried out with the aid of the Planck law, which connects intensity I of thermodynamically radiation equilibrium with his temperature T and wavelength λ:

$$I = \frac{c_1 \lambda^{-5}}{e^{c_2/\lambda T} - 1}, \qquad (2\text{-}1)$$

where $c_1=(3.7413\pm0.0002)\cdot10^{-16}$ W•m²; $c_2=(1.4388\pm0.0001)\cdot10^{-2}$ m x deg [2-2].

Fundamental value for entire development of technology of the measurements of high temperatures had the fact that Planck's idealized emitter (absolute blackbody) can be well realized in special equipment/devices in practice. The models of the blackbody, utilized for metrological target/purposes, are furnace with the high degree of isothermicity by working volume. Below we will in somewhat more detail examine the problem of the simulation of blackbody during the study of temperature fields in solid bodies. Here follows to emphasize that the technical solution of the problem of blackbody gave to theoretical formula (2-1) the character of working tool for organizing entire high-temperature pyrometry.

In different pyrometric equipment/devices are utilized the different consequences of Planck law. It is possible, for example, to construct measurements on the basis of radiant energy, lost by body in any comparatively narrow spectral interval. In this case they speak about optical pyrometers depending on the type of receiver (human eyes, photocell, photoresistor, etc.) they can be objective ones and subjective ones.

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The utilized in the industrial types of pyrometers methods of monochromatization are characterized by sufficiently wide spectral range with the final coefficient of transmission. This forces to introduce for such instruments the concept of effective wavelength $\lambda_{\text{эф}}$, which, generally speaking, makes sense first of all for the assigned time interval of temperatures (for which it is constructed the calibration of pyrometer). The signal of instrument at temperature T_1 can be written in the form of the expression

$$u(T_1) \sim \int_0^\infty I(\lambda, T_1)\, \tau_\lambda V_\lambda \, d\lambda, \qquad (2\text{-}2)$$

where τ_λ - the spectrum index of the transmission of filter; V_λ - receiver sensitivity of the emission/radiation (function of visibility of human eye).

The relation of two signals $u(T_1)$ and $u(T_2)$ can be easily calculated, if are known the corresponding spectral characteristics. At the same time this sense can be written in the form of the ratio of the intensities of absolutely black emitter, undertaken at certain (characteristic for this system) wavelength $\lambda_{э\Phi}$. If is used the formula of wine [is disregarded one in denominator (2-1)], then calculated relationship/ratio for the effective wavelength of pyrometric system can be it will be written as follows:

$$\lambda_{э\Phi} = \frac{c_2 (T_2^{-1} - T_1^{-1})}{\ln \dfrac{\int_0^\infty I(\lambda, T_1) \tau_\lambda V_\lambda d\lambda}{\int_0^\infty I(\lambda, T_2) \tau_\lambda V_\lambda d\lambda}} \quad (2\text{-}3)$$

The system, which is characterized thus such $\lambda_{э\Phi}$ is considered as quasi-monochromatic.

The study of the reaction of monochromatic (or quasi-monochromatic) pyrometric system for the emission/radiation of real body forces to introduce new concept - temperature brightness. Real object loses from its surface smaller energy content, than the absolute blackbody, which has the same temperature T_0. This fact we can express quantitatively, after writing

$$I_{p.T}(\lambda, T_0) = \epsilon_\lambda I_0(\lambda, T_0). \qquad (2\text{-}4)$$

where ϵ_λ it is possible to call/name monochromatic emissivity.

The completely formally right side of equality (2-4) it is possible to represent in the expression, which describes emission/radiation the absolute of blackbody, after introducing certain fictitious temperature T_b:

$$I_0(\lambda, T_b) = \epsilon_\lambda I_0(\lambda, T_0). \qquad (2\text{-}5)$$

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Equality (2-5) is the determination of temperature brightness. Its aperture, by utilizing approach/approximation of WIEN, we will obtain:

$$-\frac{c_2}{\lambda T_b} = \ln \epsilon_\lambda - \frac{c_2}{\lambda T_0}, \qquad (2\text{-}6)$$

or

$$\frac{1}{T_0} = \frac{1}{T_b} + \frac{\lambda}{c_2} \ln \epsilon_\lambda. \qquad (2\text{-}7)$$

In the form (2-7) we wrote the expression of the actual temperature through the brightness, since usually precisely so will cost task in the measurements: according to measured temperature brightness T_b and known emissivity ϵ_λ to calculate the actual temperature of object.

From Planck's common/general/total formula, it follows that the ratio of the intensities, undertaken at different wavelengths λ_1 and λ_2, will be the single-valued function of temperature T and also it can be used for the construction of corresponding pyrometers. It is real/actual, in the approach/approximation of Wien

$$\frac{I(\lambda_1, T)}{I(\lambda_2, T)} = \exp\left[\frac{c_2}{T}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\right]. \quad (2\text{-}8)$$

The pyrometer, instituted on equation (2-8), during measurements for the real objective will give some fictitious temperature, which differs from the thermodynamic temperature of object T_0.

Let us designate this fictitious temperature through T_c and let us call it color temperature. Its determination in this case must be the following equality:

$$\frac{I_0(\lambda_1, T_c)}{I_0(\lambda_2, T_c)} = \frac{\varepsilon_{\lambda_1} I_0(\lambda_1, T_0)}{\varepsilon_{\lambda_2} I_0(\lambda_2, T_0)}. \quad (2\text{-}9)$$

Taking into account (2-8) it is hence easy to obtain communication/connection between the true and color temperatures:

$$\frac{1}{T_0} = \frac{1}{T_c} + \frac{\ln \varepsilon_{\lambda_1}/\varepsilon_{\lambda_2}}{c_2(\lambda_2^{-1} - \lambda_1^{-1})}. \quad (2\text{-}10)$$

If monochromatic radiation coefficient ε_λ does not depend on wavelength (gray body), then, as can easily be seen, actual temperature is equal to color.

It must be noted here that the color temperature can be easily designed, if are known the values of temperature brightness T_{s_1} and T_{s_2}, which correspond to two selected wavelengths:

$$\frac{1}{T_c} = \frac{(\lambda_2 T_{s2})^{-1} - (\lambda_1 T_{s1})^{-1}}{(\lambda_2^{-1} - \lambda_1^{-1})}. \quad (2\text{-}11)$$

If we integrate the equation of Planck for entire spectrum, then let us arrive at the formula of Stefana - Boltzmann's law

$$\int_0^\infty I_0(\lambda, T)\, d\lambda = \sigma T^4, \qquad (2\text{-}12)$$

where $\sigma = (5.6687 \pm 0.0010) \cdot 10^{-8}$ W/(m²•deg⁴).

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This formula at the known temperature of absolutely black emitter T_0 makes it possible to calculate the value of the specific flux of radiation, which is spread into the hemisphere above the cell/element of surface in question.

It is obvious that on basis correspondingly of the organized energy measurements here also can be constructed equipment for temperature measurements. So/such it is obvious that and the here constructed and completely calibrated according to blackbody instrument during use on real bodies will give certain (now already "radiation" T_p) temperature. Its origin understandable to object with temperature T_0 we attribute the properties of blackbody with temperature T_p. Thus, its determination is connected with the execution of the following equality:

$$\sigma T_p^4 = \varepsilon \sigma T_0^4, \qquad (2\text{-}13)$$

where ε - integral emissivity factor of material, whence

$$T_0 = \varepsilon^{-1/4} T_p. \qquad (2\text{-}14)$$

The calculation of the actual temperature of object is feasible only with the knowledge of its integral emissivity factor.

We briefly examined some principles of the application/use of a Planck law in pyrometry and basic concepts, characterizing noncontact temperature measurements. Utilizing these principles, industry developed at present a large quantity of the most diverse measuring meters and automatic devices for monitoring and controls of diverse technological processes [2-3]. Far not all of this arsenal can be used in the practice of thermophysical experiment, it is still less - during the solution of the problems of the experimental investigation of thermal conductivity and temperature dependence of resistivity. Thus, for instance, majority of the produced in series radiation and photoelectric (brightness and color) pyrometers is designed to comparatively high size/dimensions of service platform of sighting (FEP-4 - from 3 to 7.5 mm, RAPIR [Radiation pyrometer] - about 35 mm and so forth). This excludes possibility from use for the analysis of temperature fields in the specimen/samples, usually utilized in experiment. In many instances it is not possible to recognize satisfactory and the value of a basic error in these systems (1-1.5o/o of the upper limit of the sub-range of measurements).

The requirements of temperature measurements during the study heat- and electrical conductivity much better satisfy at present the specimen/samples of visual pyrometers. A standard optical pyrometer of the type EOP-51 makes it possible to work with object by the diameter of altogether only of 0.7-0.8 mm and provide the accuracy of the measurements of the temperatures: 0.1o/o to 2 000°C, 0.2% to 3 000°C 1o/o to 6 000°C. Precision pyrometer OP-48 provides the accuracy of measurements by 0.2o/o to 2 000°C and 0.5o/o to 3 000°C; minimum dimension of its working area of sighting lies in the limits of 1.2-1.5 mm. The specimen/samples of the Soviet micropyrometers of types OMP-019, OMP-054, LMP-066 make it possible measure temperature of zone up to 0.1 mm in diameter and less, providing in this case the value of basic error 1-0.5o/o with variations 0.2-0.3o/o.

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Thus, where it is necessary to measure the stationary temperature distribution with maximum accuracy, and where the size/dimensions of radiating surface are very small, most reliable instrument it is now the optical pyrometer with the disappearing filament.

Photoelectric systems make it possible to achieve very high sensitivity. As we will see below, this is realized in a series of original comparators of the temperatures of two objects.

The development of optical pyrometry created prerequisite/premises for the widespread investigation of high-temperature thermoelectric materials and their calibration. Result of works in this direction was the mastery/adoption of a series of thermocouples on the basis of the alloys of refractory metals and combinations of pure refractory metals.

On the data of work [2-19] it is possible to speak about the application/use as thermocouples of such combinations as tungsten - molybdenum to 2 400°C (in vacuum, nitrogen, inert gases), tungsten - niobium to 2 000°C, tungsten - rhenium to 2 500°C, tungsten - tantalum to 3 000°C, tantalum - molybdenum to 2 400°C. The necessary condition of the reliability of the operation of these vapor is the maintenance of sufficiently fine vacuum (about 10^{-5} mm Hg), of neutral or reducing atmosphere.

Characteristic ones for the named thermocouples are the sufficiently considerable scatter of individual calibrations and their low stability at the temperatures above 2 000°C.

An improvement in the thermoelectric characteristics was possible to obtain for the combinations of the alloys of refractory metals. Among them the greatest popularity they now conquered compositions with rhenium, in particular thermocouple W - 5o/o Re/W -

20o/o Re; W - 10o/o Re/W - 20o/o Re. On the data of work [2-20] these thermocouples develop thermoelectromotive force respectively to 29.4 and 18.9 mV with 2 000°C. In this case, their sensitivity changes from 14.0 and 10.0 with 100°C to 11.0 and 7.0 μV/°C at 2 000°C respectively.

For a work in the carbon-containing media, are more effective molybdenum fusions with rhenium. Molybdenum will be carbidized less actively, than tungsten. The sensitivity of the thermocouples of this group is less [2-21, 2-22]. Its maximum values are reached for thermocouple Mo - 20o/o Re/Mo - 50o/o Re; during changes in the temperature from 100 to 1 800°C, the sensitivity changes from 10.0 to 4.8 μV/°C with absolute values thermoelectromotive force 1.0 and 15.5 mV.

Thermocouples from refractory metals made it possible to raise upper temperature boundary of thermoelectric method in comparison with the group of thermocouples from noble metals.

If the platinum-platinum-rhodium thermocouples of types PR 10/0 PR 30/6 in connection with the conditions of thermophysical investigations can be utilized to 1500-1600°C (oxidizing and neutral media), then, let us say, the examined tungsten-rhenium thermocouples can be used to 2000-2500°C.

However, in the majority of the cases, these thermocouples cannot be used. So, the reliable measurement of the temperature distribution in specimen/sample is possible, strictly speaking, only during the conclusion/derivation of thermo-electrode lead/ducts along isothermal surfaces. Under these conditions is necessary the sufficiently reliable electrical insulation of separate electrodes of one from another and from specimen/sample.

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Operating temperatures of mastered at present insulating ceramics are limited by following values [2-23]; oxide of aluminum of 1900-1950 °C, oxide of magnesium of 1 800-1 900°C, oxide of beryllium of 1900°C, nitride of boron of 2 000-2 200°C. Thus, on the level of maximum temperatures thermoelectric method cannot compete with optical pyrometry. It is noticeably inferior to it, also, on accuracy (in comparison with the best optical pyrometers), and on measurement accuracy.

An essential deficiency/lack in the thermocouple measurements is the possibility of contaminating the specimen/sample by the impurity/admixtures of thermo-electrode materials and insulating ceramics. Contamination especially grow/rises in connection with the increase of the chemical activity of materials with the increase of temperature. Upon the setting of the high-temperature precision investigations of thermal conductivity and electrical resistance, with the exception/elimination of the special cases, it follows, undoubtedly to give preference to the noncontact methods of optical pyrometry.

2-2. Simulation absolute of blackbody.

As it was shown in the preceding/previous paragraph, the definition of the field of actual temperatures according to the results of the measurements by the optical pyrometers requires in the general case of the knowledge of the corresponding values of radiation coefficients, or as them frequently are called, emissivity factors of the objects being investigated. The values of these values, on one hand, are the function of the physical properties of the material being investigated, and on the other hand - depend on the conditions of energy and physicochemical interaction of body with the environment, and therefore are not defined. Natural in this situation is the tendency to utilize simulation of blackbody in the limited three-dimensional/space zone of object. It goes without saying that in this case appears the problem, connected with the unavoidable disturbance/perturbation of the temperature field of object, which depends on the type of the used model.

It is known that the optimum version of the model of blackbody is the isothermal spherical cavity, which has eyelet for a radiation yield. Emission/radiation of this opening/aperture the nearer to black, the greater the ratio of the diameter of sphere to the diameter of opening/aperture. Small boring in the wall of the long evenly heated duct good approach/approximation also with simulates absolutely non-machined surface. In this case also effective emissivity factor of cavity the nearer to one, the greater the relation of the diameters of duct and boring in its wall.

If metallic plate is bent at sharp angle, then at sufficiently small angle of radiation, which emerges from it, also approaches black. The named models are examined in sufficient detail in monograph Ribe [2-1] and in many other works [2-17, 2-18]. We do not examine them in detail on the strength of the fact that during the solution of the discussed in the book questions they are proved to be unsuitable.

During the measurements of the temperature distributions in the specimen/samples being investigated the sole suitable model of blackbody render/showed half-open cylindrical cavity with the sufficiently large ratio of depth L to diameter D. It is maximally simple in production, introduced by it disturbances into the distribution of temperatures and heat fluxes can be brought to small corrections.

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Finally, which is completely substantial, the radiation characteristics of this model yield sufficiently to precise numerical determination. We will not here set forth the essences of different methods, utilized during calculations of this model. Let us examine only some results, most important virtually.

Before discussing the quantitative data, has sense emphasizing some special feature/peculiarities of the radiation properties of this model. Its schematic is represented in Fig. 2-1. Let us assume that the initial material is characterized by intensity distribution of emission/radiation according to the directions, presented by curved 3 (metals). Hemisphere 1 there will be to correspond to the angular distribution of intensity for the blackbody, which has the same temperatures. The emission/radiation of sufficiently deep cavity will be depicted as curved 2.

Flux of radiation from the cell/elements of the lateral surface df, caught into the bottom of cavity, will be partially reflected will here and supplement the intrinsic emission of the bottom in the direction of outlet to the values, within limit which correspond to black body radiation.

Thereby the surface of the spatial distribution of the intensity of emission/radiation within the limits of solid angle Ω approaches a hemisphere of blackbody. However, beyond the limits of this angle, the intensity of emission/radiation sharply falls, striving for zero at the angles, close to π/2. Thus, the emission/radiation, which emerges from the opening/aperture of cylindrical model, does not obey the law of Lambert.

In connection with this total energy flux of the opening/aperture is lesser than the flow of hemispheric blackbody radiation [2-4, 2-5]. The overall considerations force on to assume the essential dependence of overall value and the spatial distribution of radiant fluxes, which emerge from cavity, from the geometry of bottom and character of emission/radiation and reflection of the surfaces of cavity. So, for the flat mirror reflecting bottom it follows, it is probable, to expect dip in a curve 2 near the axis of cavity to curve 3, since no ray/beam from lateral surface with mirror reflection in the plane of the bottom will give component in direction standard.

Finally, in connection with a change in the illumination, created by some elementary team depending on distance of the irradiated surface, one should in the general case assume the brightness to be variable on entire surface of cavity, including a radius of the bottom.

Thus, the overall considerations speak about a series of the fundamental inadequacies of the discussed model of blackbody. However, in work with the pyrometers, receiving radiant flux within the limits of the very limited solid angle in the direction of the axis of channel, these inadequacies are not deciding.

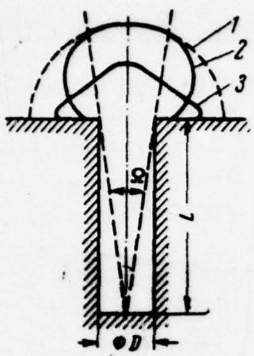

Fig. 2-1. Schematic of the cylindrical model of blackbody. 1 - angular distribution of the intensity of blackbody; 2 - the same for emission/radiation from the opening/aperture of cavity; 3 - the same for the exposed surface of the material of cavity.

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Let us assume that all the surfaces of cavity are gray ones and emit and they reflect diffuse. Under these assumptions the cavity of finite length with the flat bottom was examined already in the work by Buckley [2-6]. However, use in this work of a series of the knowingly rough conditions forced to lately investigate this task anew. The basic sources of error in work [2-6] were assumptions about uniform density distribution of emission/radiation according to the bottom of cavity and the use of approximate values of angular coefficients. The errors indicated excluded Sparrow, after giving the exact solution of task [2-7]. The obtained in this work values of effective emissivity for the central and peripheral points of the flat bottom depending on emissivity factor of the material of cavity and relative depth L/R are represented in Table 2-1.

The analysis of the data of Table 2-1 shows the noticeable change in the emissivity in a radius of the bottom, which is especially amplified during the decrease of emissivity factor and relative depth of cavity. The character of this change, can be judged from Fig. 2-2, where by dotted lines the represented radial distribution of effective emissivity when $\varepsilon = 0.6$, obtained by Sparrows [2-7].

The values of the initial data, used in precise job estimates [2-7], do not for exhaust many practically important cases. For metals value ε can descend to 0.1 and less. The necessary calculations for low, values ε are made in works [2-8, 2-9].

Table 2-1. Effective emissivity of the flat bottom of the cylindrical model of blackbody.

L/R	ε=0,9		ε=0,75		ε=0,5	
	r=0	r=R	r=0	r=R	r=0	r=R
8	0,9984	0,9986	0,9956	0,99975	0,9880	0,9887
6	—	—	—	—	0,9768	0,9793
4	0,9936	0,9945	0,9815	0,9842	0,9460	0,9540
2	0,9785	0,9848	0,9389	0,9553	0,8394	0,8776
1	0,9482	0,9708	0,8626	0,9180	0,6878	0,7914
0,5	0,9191	0,9602	0,7937	0,8904	0,5693	0,7317

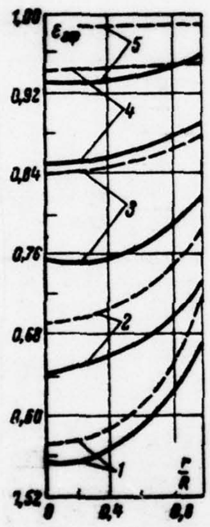

Fig. 2-2. Change of effective emissivity of bottom of cylindrical cavity for diffuse (dotted line) and that mixed (solid line) reflections in cavity in [2-7, 2-10]. 1 - L/D=0.25; 2 - L/D=0.5; 3 - L/D=1.0; 4 - L/D=2.0; 5 - L/D=4.0.

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In the first of them, the calculations are limited to comparatively shallow cavities (L/R≤4), which do not ensure a sufficient degree of approximation to blackbody. The second work contains the thorough examination of the wider circle of relative depths, including those that already can be utilized in practical models. The results of these calculations are given in table 2-2.

Given in table 2-2 data are acquired under the assumption, that it is possible to disregard the dependence of the effective emissivity of cylindrical walls on the emission/radiation of the bottom. On the error, caused by this assumption, it is possible to judge, by comparing the data of two tables with some values of determining parameters ε and L/R. It is possible to assume that the error will be most noticeable with minimum relative depths and small ε. With the large ones L/R (>6-8) the reliability of the data of work [2-9] is not worse than 1-2o/o.

As has already been indicated, essential effect on the values of the local values of effective emissivity in plane is exerted the character of emission/radiation and reflection and the geometry of the bottom. Given above data are related to diffuse character and reflection, and emission/radiation. For many materials characteristic is the presence of mirror component in the emission/radiation reflected. The important combined version examined S. P. Rusin [2-10, 2-11]. The flat bottom of cavity in its task reflects, and it emits diffuse, lateral surface emits diffuse, and it reflects mirror. The results of its calculations are represented in Fig. ~~to~~ 2-2 by solid lines. It is evident that the appearance of mirror reflection noticeably decreases effective emissivity. For the wider value of S. E. Rusin's parameters, ϵ it proposes to utilize the relationship/ratio

$$\epsilon_{\text{эф}}=\epsilon+\epsilon_1(1-\epsilon)A,$$

where ϵ and ϵ_1 - emitting characteristics of bottom and lateral surface of cavity, but coefficient A depends on ϵ_1 and L/R. Values A are given in table 2-3.

The case with the completely mirror reflection of surface in cavity with the conical bottom examined V. E. Listovnichiy [2-12].

Table 2-2. Effective emissivity of central section (r=0) of the flat bottom of the cylindrical model of blackbody on [2-9].

ε	L/R						
	1	2	4	6	8	10	12
0,1	0,234	0,424	0,748	0,894	0,950	0,974	0,984
0,2	0,392	0,607	0,858	0,943	0,972	0,985	0,990
0,3	0,515	0,737	0,911	0,962	0,981	0,989	0,993
0,4	0,613	0,790	0,933	0,973	0,986	0,991	0,994
0,5	0,696	0,846	0,952	0,980	0,990	0,994	0,996

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The values of the relative depth L/R, necessary for obtaining $\varepsilon_{эф}=0{,}99$, depending on the emissivity of the walls of cavity are represented in Fig. 2-3. Figure it demonstrates, that the increase of the expansion angle of cone in the case of mirror reflection in cavity is connected with an increase in the minimally necessary depth of cavity.

The given results create basis for the correct construction of the cylindrical model of blackbody.

For each concrete/specific/actual object on the basis even of qualitative discussions about the character of its emission/radiation and reflection, it is possible to correctly rate/estimate the necessary size/dimensions of cavity, which guarantee obtaining the specific values of effective emissivity. In this case, one ought not to forget that, after using one or another the method of producing the pyrometric channel, we over wide limits can change the relationship/ratio between diffuse and mirror reflection in cavity and the value of the emissivity of its walls.

Are interesting the data on the overall flow value of energy, lost by cavity into the surrounding space.

After relating this flow to the appropriate energy of hemispheric blackbody radiation, we can speak about the effective emissivity of the opening/aperture of cavity $\epsilon_{o.o.}$ For a number of conditions, this value was accurately designed in work [2-7]. The results of this calculation are given in Table 2-4.

Table 2-3. Dependence of coefficient A on the characteristics of cavity.

ε_1	L/R				
	0,5	1	2	4	8
0,5	0,2169	0,5633	1,0029	1,4057	1,7192
0,75	0,2075	0,5278	0,8869	1,1302	1,2597
0,9	0,2028	0,5104	0,8322	1,0093	1,0801

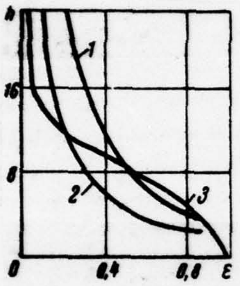

Fig. 2-3. Values of relative depth of cavity h=L/R, necessary for provision $\varepsilon_{эф}=0{,}99$, depending on emissivity of material [2-12]. 1 - conical bottom with apex angle 0.667 π, reflection is mirror; 2 - the same, but with angle of 0.581 π; 3 - flat bottom in cavity with the diffuse character of emission/radiation and reflection.

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The dependence of this characteristic on the type of reflection it is possible to illustrate by Fig. 2-4, undertaken from work [2-4]. If in the case of diffuse reflection the increase of the total energy, lost from cavity, sufficiently rapidly decelerates with increase L/R, then with the mirror reflection of this phenomenon it is not observed. Energy content, lost by cavity, continues armys, also, with the large ones L/R.

Everything said above was related to isothermal cavities. In practice frequently it is necessary to deal with the presence of one or the other type of the temperature distribution along cavity. From overall considerations it is clear that the decrease of temperature from the bottom of outlet must decrease the effective emissivity of the bottom and, on the contrary, the temperature rise must lead to an increase in the energy flow from the bottom because of the increase of the part of the radiation reflected. In this case with ratio of specific radiation to blackbody radiation with the temperature of the bottom, are possible the values of emissivity factor, which exceed one.

Quantitative estimations are completely possible within the framework of the calculated methods, used also for isothermal cavities [2-7, 2-11]. The necessary calculations were made Sparrows [2-14], Pivi [2-8], by S. P. Rusin [2-10, 2-11, 2-15] and other works, for example [2-16].

In the case of a linear decrease in the temperature along the length of the cylindrical surface of cavity from the bottom to opening/aperture in work [2-10] is proposed to estimate the maximum permissible nonisothermicity by the effect of a reduction in the effective emissivity of the bottom of cavity to values not lower than 0.98. Being assigned by this value $\varepsilon_{\partial\phi}$, S. P. Rusin [2-10] it calculated the limiting value of the coefficient of nonisothermicity $\alpha = [T(0)-T(L/D)]/T(0)$ depending on the type of reflection and value of the emissivity of the material of cavity ε. The obtained results for L/R=8 are represented in Fig. 2-5.

Table 2-4. Effective hemispheric emissivity of cylindrical cavity on the data of work [2-7] (overall heat loss). The bottom flat/plane, reflection is diffuse.

L/R	ε=0,5	ε=0,75	ε=0,9	L/R	ε=0,5	ε=0,75	ε=0,9
0,5	0,6569	0,8491	0,9434	4	0,8331	0,9308	0,9746
1	0,7424	0,8948	0,9618	6	0,8359	—	—
2	0,8084	0,9229	0,9720	8	0,8367	0,9317	0,9749

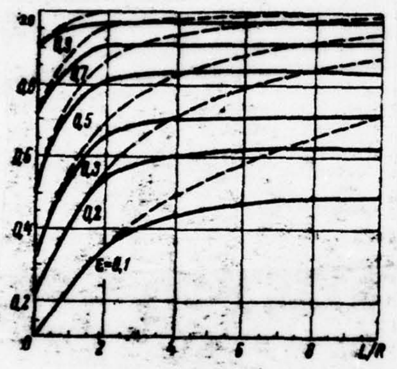

Fig. 2-4. Effective hemispheric emissivity of opening/aperture of cavity [2-4] for diffuse (solid lines) and mirror (dotted line) reflections.

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With the increase of emissivity factor without damage for the accuracy of temperature measurements, we can allow/assume the high value of temperature drops along cavity. The effect of mirror reflection on lateral surface noticeably decreases the permissible degree of the nonisothermicity of cavity.

The case of the parabolic temperature distribution along the length of cavity is examined in works [2-11, 2-16]. The temperature distribution is here assigned by the function of the form

$$T_y = T_\infty + (T_0 - T_\infty)(1 - y/L)^2,$$

where T_∞ - temperature of the bottom of cavity (y=L); T_0 - temperature at y=0.

The value of nonisothermicity is determined by coefficient of k $= \frac{c_2 \Delta T}{\lambda T_\infty^2}$, where C_2 - constant of Planck law; λ - wavelength, for which is conducted the examination. Assuming emission/radiation and reflection diffuse, it is possible to calculate the value of a change in the effective emissivity of the flat bottom of cavity with respect to isothermal version $\Delta\epsilon/\epsilon$, %. The results of such calculations according to of work [2-16] gives to Fig. 2-6. On figure it is possible to trace the character of the effect of the relative depth L/R on the value of the nonisothermicity: the deeper the cavity, the the large the difference in the temperatures on it we can allow without increasing the error for temperature measurements.

Thus, it is possible to state/establish that the cylindrical model of blackbody is subjected at present sufficiently to detailed study, which makes it possible if necessary to estimate the quantitative the accuracy of temperature measurements.

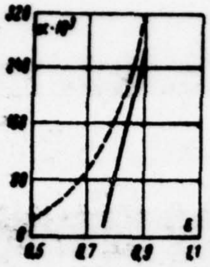

Fig. 2-5.

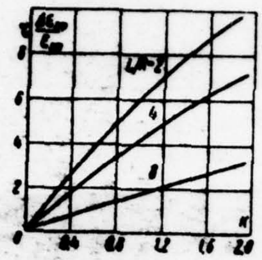

Fig. 2-6.

Fig. 2-5. Dependence of the permissible coefficient of nonisothermicity on emissivity factor of the material of cavity. --- - entire/all surface of cavity diffuse reflects and emits; —— - bottom of cavity reflects and emits diffuse, on lateral surface the reflection is mirror.

Fig. 2-6. Relative change of effective emissivity of cylindrical cavity in dependence on its nonisothermicity [2-16] (emissivity factor of material of cavity $\varepsilon=0.5$).

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2-3. Specific character of the measurements of a difference in the temperatures.

The accuracy of experimental data in thermal conductivity is direct-connected with the accuracy of the determination of a difference in temperatures or local value of temperature gradient.

The values of these values can be obtained in two ways: either by subtraction of one of another consecutive readings of the measuring meters, which determine the absolute value of temperature or by the direct measurement of a difference in the temperatures in two points of object with the aid of special devices. During the measurement of small temperature drops in the advantage of alternate path, are obvious. However, in connection with the fact that in many investigations by only instrument for measuring the high temperatures is the optical pyrometer, one should examine possibilities and the first direction.

At present during the determination of thermal conductivity for the measurements of a difference in the temperatures in the range of 1500-3000°K, widely are applied pyrometers with the disappearing filament. During the estimation of the accuracy of such measurements, one should take into attention only the part of the basic error in this pyrometer, since in work of one and the same observer with one and the same pyrometer, the measurements of the filament current of the filament of pyrometric bulb one and the same electrical measuring instrument a considerable number of errors, accumulated in the process of the calibration of standards and instrument itself, acquires the character of the systematic error, which does not affect the accuracy of the measurements of a difference in the temperatures. Basic error characterizes the possible amounts of deflection of readings of this instrument from the readings which would correspond to international thermometric scale. In the case of the evaluation of the accuracy of the measurements of a difference in the temperatures, one should operate faster with a variation in the instrument. The value of the latter first of all is determined by the accuracy of photometric compensation, which depends on the contrast sensibility of human eye and perfection of the optical system of pyrometer.

The error for the single compensation of brightness can be designed on the formulas of Wien:

$$\Delta T_1 = \frac{\lambda T^2}{c_2} \cdot \frac{\Delta H}{H}, \qquad (2\text{-}15)$$

where ΔT - absolute value of the error, caused by the inaccurate compensation of brightness, °K; T - temperature of object, °K; λ - effective wavelength of pyrometer, μm; c_2=14388 μm•deg - constant of Planck's formula; H - brightness, calculated from the formula

$$H(T) = \frac{1}{L}\int_0^\infty I(\lambda, T) V(\lambda, T)\, d\lambda. \qquad (2\text{-}16)$$

In formula (2-16) L=0.001602 W/lm - the lumen equivalent; I(λ, T) - spectral intensity, V(λ, T) - the spectral sensitivity of eye.

Value ΔH/H in formula (2-15) is connected with the presence of the threshold of the contrast sensibility of human eye. 9 Page 49.

It was repeatedly studied by different researchers, beginning

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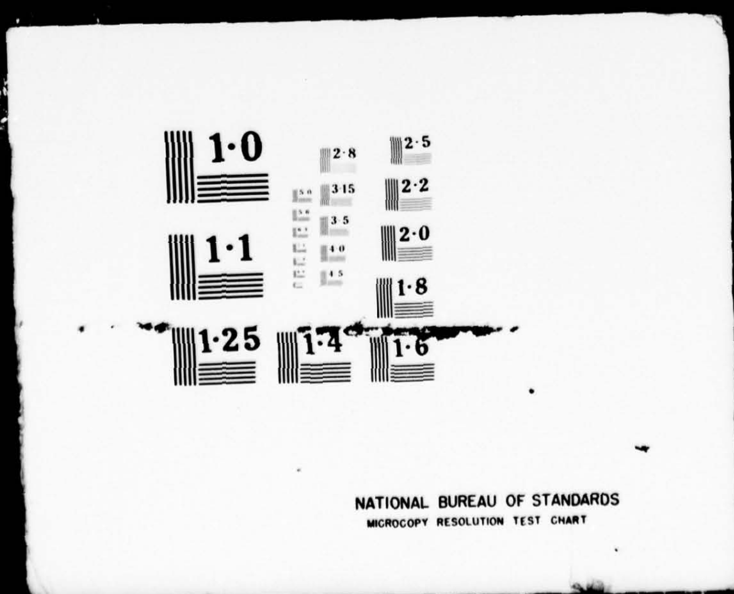

approximately since 1900 Ribaud [2-1] it estimates by its value less than 0.5o/o. Data, obtained in 1951 by Euler and Schneider [2-24], make it possible to assert that values $\Delta H/H \geq 1.5$-2o/o correspond extremely to the unfavorable conditions of experiment (to low field of view, experimenter's fatigue).

For the best pyrometers (types EOP-51, OP-48) value $\Delta H/H$ is within the limits by 0.3-0.4o/o, for laboratory pyrometers (among other things of micropyrometers) 0.5-0.8o/o.

The values indicated correspond to measurements on the isothermal pads under conditions when the width of image exceeds width of the filament of pyrometer not less than 2.5-3 times.

Taking value $\Delta H/H$=0.5o/o, we will obtain, for example, during the measurement of temperature differentials of 100°K error because of inaccurate photometric measurement, equal to ~0.3o/o at mean temperature of 1200°K, ~0.6o/o with 1 700°K, ~2.5o/o with 3300°K.

The specific value of the random error during the measurements of a difference in the temperatures can be connected with a variation in utilized electric measuring instrument. The greatest accuracy is reached during the use of compensation methods of measuring the operating current of pyrometric lamp.

The corresponding error can be designed but to the formula

$$\Delta T_2 = i\frac{dT}{di}\cdot\frac{\Delta i}{i}, \qquad (2\text{-}17)$$

where i - a value of the current of pyrometric lamp; dT/di - corresponding slope/inclination calibration curve T(i); Δi/i - relative error of measurement of current.

So, in the work of the pyrometer of OP-48 paired with the potentiometer of PMS-48 error ΔT_2 can reach 0.8°K at the temperature of 1 200°K, 0.5°K with 1 700°K and 2°K with 3 300°K. The contribution of this error leads to the increase of an error of measurement of temperature drop. In our example the measurement by the pyrometer of OP-48 of jump/drop in ΔT=100°K will be executed with error ~0.9o/o at mean temperature of 1200°K, ~0.8o/o with 1 700°K, ~3.2o/o with 3300°K.

In experiment in measurement of thermal conductivity, this error will cause the appropriate error in the unknown value.

Above we examined the idealized schematic of experiment. Under actual conditions during the investigation by the pyrometers of temperature fields about the isothermicity of the area/site of sighting, it is possible to speak only to the rough approximation.

The presence of temperature gradient impedes the work of observer and is the supplementary source of error. Let us assume that the temperature field for the objective is one-dimensional, and the working section of the filament of pyrometric lamp is oriented in parallel to isothermal sections. The value of luminance difference threshold of the image of object from that and other of sides of filament the greater, the greater its width and the gradient of temperatures.

If this difference does not exceed the value of contrast threshold of human eye $\delta H_в$, then experimenter can observe the complete disappearance of filament.

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The limiting value of temperature gradient, which corresponds to this case, can be designed on the obvious relationship/ratio

$$\mathrm{grad}\,T=\frac{k}{2\delta}\cdot\frac{\lambda T^2}{c_2}\delta H_в, \quad (2\text{-}18)$$

where δ - width of the filament of pyrometer; k - coefficient of an increase in the objective of pyrometer. With the high gradients of measuring, condition they deteriorate. Appears the situation during which it is not possible to obtain the complete disappearance of the measuring section of filament. With a sufficiently great increase and the high resolution of ocular system, it is possible to realize disappearance of one of the boundaries, filaments; however, the accuracy of photometric measurement in this case will be noticeably worse. As is known [2-1, 2-2], the high accuracy of photometric measurement is realized in that case if image sizes of the object of constant brightness 2-3 times exceed the width of filament. A question concerning the appropriate errors for nonisothermal conditions at present is not virtually studied.

One of effective means of the increase of the accuracy of the measurements of small differences in the temperatures is the use of photoelectric receivers. The possibilities of the corresponding measuring circuits can be illustrated based on the example of objective photoelectric installation of the type SPK [2-26], developed for the calibration of standard temperature lamps at different wavelengths. The optical diagram of this installation is represented in Fig. 2-7. The luminous flux from the compared sources of light (for example, temperature lamps) passes the prism of modulator and alternately through the monochromator it falls to the photoelectric cathode of photoelectronic factor. As modulator is utilized the small prism, fasten/strengthened to the oscillating string. In free position it guides to monochromator the half of each of the compared luminous fluxes. The displacement of prism changes the relationship/ratio between flows, leaving, however, the value of the total flow (with equality the brightness of sources) of constant/invariable. Thus, under conditions of the evened brightness the luminous flux, which reaches FEU, does not experience/test oscillations in time. In the case of their inequality, appears the variable component of photo current, which is amplified by electronic circuit, it is isolated from interferences and it enters the indicator. The amplitude of alternating/variable signal is proportional to luminance difference threshold of the compared sources. Experience in operation of similar installations showed that the value threshold of response for them is within the limits of 0.02-0.05°K in the region of the spectrum from 0.47 to 1 μm with the passband of 0.01-0.05°K in the region of the spectrum from 0.47 to 1 μm at passband 0.01-0.03 μm and the temperature of the emitter of 1063°C.

← This by an order is higher than the sensitivity of the best optical pyrometers.

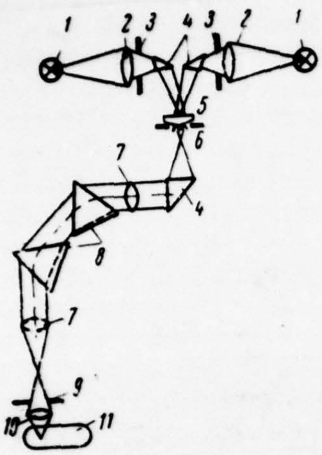

Fig. 2-7. Simplified optical diagram of the installation of SPK. 1 - temperature lamps; 2 - object/objective external optics; 3 - diaphragm; 4 - reflecting prisms; 5 - prism of modulator; 6 - The entrance slit; 7 - objectives of monochromator; 8 - prism of monochromator; 9 - exit slit; 10 - lens; 11 - photomultiplier.

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Thus, the application/use of photoelectric receivers in devices for measuring the differences in the temperatures for the objectives makes it possible to substantially raise the accuracy of these measurements.

Unfortunately, these possibilities are used far not completely. The specimen/samples of photoelectric brightness and color pyrometers, produced in series, are intended in essence for technological monitoring and due to the high indices of sighting and comparatively low accuracy cannot be used for studying the temperature fields in small specimen/samples. This forces researchers to develop/process its devices.

So, by L. P. Filippov and Yu. N. Simonovoy [2-27] is described the differential pyrometer, created specially for measuring small temperature differences in wire specimen/samples. Here, just as in OPK, the compared luminous fluxes alternately through the modulator fall to one and the same photomultiplier. However, unlike OPK, reduction of one of the luminous fluxes in differential pyrometer is conducted with the aid of the photometric wedge by the preservation/retention/maintaining of temperature for the objective of constant/invariable. Changing the position of the optical compensator (wedge), it is possible to make even the luminous fluxes; with this variable component of photo current will have minimum value (for an ideal schematic - equal to zero). The unknown difference in the temperatures can be directly counted off according to the scale of wedge. If the temperature of supporting/reference source is fixed and equal to T_0, but the displacement of the wedge, counted off from position, by which $T=T_0$, is equal to x, then the sensitivity of measuring circuit can be designed on the formula

$$\left(\frac{dx}{dT}\right)_{T_0}=\frac{h\nu}{kT_0}\cdot\frac{1}{T_0 a}, \qquad (2\text{-}19)$$

where α - constant of wedge; ν - emission frequency.

The threshold of response of this differential pyrometer lie/rests within limits of 0.02-0.08°K.

The high sensitivity of the systems described above is connected with the application/use of the null method by which photo-detector performs only the role of null indicator, recording equality the luminous fluxes with photoelectric cathode. In this case, the instability of photoreceiver itself, the form of its characteristic are proved to be unessential.

The sufficiently high accuracy of the measurements of a difference in the temperatures can be reached also in the systems, instituted on amplification and measurement of a difference in the photo currents, which correspond to different luminous fluxes.

So, M. Prashovyak and A. Takzanovskiy [2-28] by this method during the measurement of temperature fields on cathodes obtained accuracy of ±0.13° at mean temperature of cathode of approximately 1000°K. In this case, it must be noted, that the area/site of photometric measurement composed value approximately $7.20 \cdot 10^{-4}$ mm², which is inaccessible for a visual optical pyrometer.

Use of virtually inertia-free photoelectric pickups, in particular photocells and photomultipliers, it makes it possible to construct systems for measuring the temperature distributions for the objectives. As an example it is possible to give the measuring circuit of temperature field, developed by Magdeburg [2-29].

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At its basis lie/rests the idea of one-coordinate scanning. Emission/radiation from the object (Fig. 2-8) being investigated is headed by mirror for the objective of optical system. In image plane, is located the target/purpose 0.1 mm in wide, that isolates the zone of photometric measurement. The emission/radiation, passed through the slot, with the aid of lens is headed through the interference filter for the photoelectric cathode of photomultiplier. The signal of the latter is supplied to oscillograph. Flat/plane mirror rotates by synchronous motor. Thus, optical system realizes a periodic survey of an entire picture of temperature distribution in specimen/sample. The rotation of engine is connected with the horizontal sweep of oscillograph. The picture, which appears on oscilloscope face, corresponds to density distribution of emission/radiation along the coordinate of object being investigated. The vertical displacement of electron beam in this schematic is proportional to the radiant density of the cell/element of surface which at given torque/moment is reflect/represented on slot. The calculation of temperature divergences is conducted on the basis of the equation of Wien (under the assumption of the linear dependence of photo current on the luminous flux). Communication/connection between a relative change in photo current dI/I and a relative change in temperature dT/T can be expressed by the equation, analogous to equation (2-15).

For wavelength $\lambda=0.6$ μm, used in work, value $\frac{dI}{I}:\frac{dT}{T}=\frac{c_2}{\lambda T}$ vary monotonically from 24.0 with 1 000°K to 8 with 3 000°K, which provides the sufficiently high sensitivity of schematic.

Fig. 2-8. Schematic of the scanning pyrometer cf Magdeburg [2-29]. 1 - oscillograph; 2 - photomultiplier; 3 - interference filter; 4 - objective; 5 - slot; 6 - objective; 7 - rotating mirror; 8 - object. Page 53.

Investigation of temperature tracks by photographic methods.

In a number of the practically important cases for the investigation of the temperature distribution in specimen/sample, can be used photographic method. The photograph of the radiating object makes it possible to fix on film temperature field in the form of the field of blackening. The quantitative investigation of the latter does not represent at present difficulties. It is possible to call/name for an example series microphotometers MF-2, MF-4, which make it possible with sufficient high accuracy to measure the local values of optical density or coefficients of the transmission of the revealed photographic emulsion.

At the basis of the idea of photopyrometer, lie/rests the assumption about existence to single-valued connection between the value of blackening of photoemulsion and by the temperature brightness of the photographed object. For clarifying the conditions, under which this connection may be realized, let us examine the photometric properties of photographic film and energy relationship/ratios in the light beams, which form image.

The optical density of negative is called the logarithm of the value, reciprocal to the coefficient of transmission τ, i.e.,

$$D = \lg \frac{1}{\tau}, \qquad (2\text{-}20)$$

where $\tau = I/I_0$; I_0 - intensity of the falling/incident to film luminous flux; I - intensivnost6 prowedwego svetcvogc potoka.

Optical density depends on exposure H=Et, where E - an image illumination, and t - a holding time. The characteristic form of this dependence is represented in Fig. ~~to~~ 2.9. Study curved makes it possible to isolate three characteristic sections: the range of underexposures lg H<lg H_m, the range of normal exposures $\lg H_m < \lg H < \lg H_n$ and the range of overexposures $\lg H > \lg H_n$. For the quantitative study of temperature fields there is the greatest interest in the range of normal exposures, characterized by the linear character of the dependence of optical density on exposure. For this section

$$D = \gamma \lg H + A. \qquad (2\text{-}21)$$

Coefficient γ is called the contrast ratio of photographic emulsion; the range, in which is correct equation (2-21), characterizes its photographic latitude $L = \lg \frac{H_n}{H_m}$.

The parameters γ and L indicated together with light-sensitivity and spectral sensitivity are the most important characteristics of photographic film. For a number of the produced at present types of photographic film, they are given in table 2-5, borrowed from [2-30].

The knowledge of the photographic latitude makes it possible to rate/estimate the temperature interval, which corresponds to the range of normal exposures. It is real/actual, with identical delay the relation of exposures is equal to the relation of image illuminations. Latter with the observance of a number of conditions proportional to the brightness of object. Thus, it is possible to write

$$L = \lg \frac{B_n}{B_m}.$$

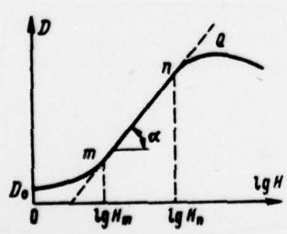

Fig. 2-9. Curve of blackening of photographic film.

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Further, by utilizing Wien formula, we will obtain:

$$L = \lg e \frac{c_2}{\lambda}\left(\frac{1}{T_m} - \frac{1}{T_n}\right). \quad (2\text{-}22)$$

where e - Naperian base; c_2=14388 μm•deg; λ - effective wavelength of photopyrometer; T_n and T_m - the temperature brightness of object, which limit the range of normal exposures; from formulas (2-22) and (2-21) it follows that in this range the dependence of optical density on the reverse/inverse temperature of object at the fixed/recorded conditions of photographing can be represented by linear law. Difference $T_n - T_m$ is sufficiently considerable and grow/rises with temperature rise. It can be calculated on formula $T_n - T_m = AT^2/(AT_n + 1)$, where $A = L/\lg e \cdot \lambda/c_2$.

Connection $\Delta T = T_n - T_m$ and T_n with λ=0.65 μm and L=1.5 is represented in Fig. 2-10. From the figure one can see that with the aid of photograph can be investigated the complex temperature fields with the temperature differentials, which reach hundred degrees.

Here it is appropriate to emphasize the essential effect of contrast ratio γ on the accuracy of temperature measurements. From formulas (2-21) and (2-22) can be obtained following expression for one of components of relative error $(\Delta T/T)_{t}$:

$$\left(\frac{\Delta T}{T}\right)_{t}=\frac{\Delta D}{D_{n}-D_{m}}\left(\frac{1}{T_{m}}-\frac{1}{T_{n}}\right)T. \quad (2\text{-}23)$$

In connection with the fact that an increase in the contrast decreases the photographic latitude, and thereby also difference $\frac{1}{T_{m}}-\frac{1}{T_{n}}$, value ΔT/T with the constant error for photometric measurements, determined by expression $\Delta D/(D_{n}-D_{m})$, with the increase of contrast will decrease. Formula (2-23) indicates also the temperature effect: in the range $T_{m}-T_{n}$ relative error grow/rises with temperature virtually linearly.

Photograph can serve as the instrument of the quantitative analysis of the temperature distribution only at the observance of a number of conditions, caused, on one hand, by the special feature/peculiarities of the transmission of the luminous flux from the specimen/sample through the optical system to photographic film and, on the other hand - by properties of photographic film itself.

Table 2-5. Properties of scme types of photcgraphic film.

(1) Тип материала	(2) Общая светочувствительность в единицах ГОСТ	(3) Коэффициент контрастности γ	(4) Фотографическая широта L_m, не менее	(5) Плотность вуали D_0, не более
Фото 32	32	0,8—1,1	1,5	0,05
Фото 65	65	0,8—1,1	1,5	0,10
Фото 130	130	0,8—1,1	1,5	0,15
Фото 250	250	0,8	1,5	0,2

Key: (1). Type of material. (2). Ccmmon/general/total photosensitivity in unity GCST [All-union State Standard]. (3). Coefficient of contrast, ~~Gamma~~. (4). Photographic latitude L_m, is nct less. (5). Density of halation D_0, is not mcre.

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As is known [2-31], the illumination cf optical image can be represented by the fcllcwing expression:

$$E = \frac{\pi\tau BD^2}{D^2 + 4b^2}, \tag{2-24}$$

where τ - a coefficient of the transmission of optical system; B - brightness of object; D - diameter of the exit pupil of optical system; b - distance of image.

With $D^2 \ll 4(f')^2$, where f' - focal length of objective, (2-24) it is possible to rewrite in the form

$$E = \frac{\pi\tau B}{4} \cdot \frac{D^2}{(f')^2} \frac{1}{(1+\beta)^2}, \quad (2\text{-}25)$$

where $\beta = f'/x$ - increase in the system; x - distance from the front focus to object.

From formula (2-25) it follows that the image illumination, other conditions being equal, grow/rises with an increase in the distance, striving for the specific limit. This dependence one should consider, especially with calibration of the photopyrometer: the value of the parameter β must be retained constant both for the object and for temperature standards - the sources of comparison.

Especially essential effect on the work of photopyrometer have the individual properties of photoemulsions. Contrast ratio noticeably depends on the time of manifestation and spectral composition of emission/radiation; the inadequacies of the technological process of film development can be the reason for a change in the blackening on the surface of film.

Sufficiently reliable results can be obtained only under the condition of calibrating each frame. In this case simultaneously with photographing of object to the same frame are remove/taken the standards illuminant (temperature lamp) with the known values of temperatures. This makes it possible to maintain/withstand in the best way equality the geometric, time/temporary and technological factors, which determine blackening of the images of standards and object.

On blackening of standards, is constructed characteristic curve of film, which is utilized for treating the field of blackening of the image of object.

If T_1 and T_2 - temperature of standards; D_1 and D_2 - corresponding values of density, then is unknown temperature T_x may be calculated from optical density D_x in accordance with expression [2-32]

$$T_x = \frac{T_1 T_2 (D_2 - D_1)}{T_1 (D_x - D_1) + (D_2 - D_x) T_x}. \quad (2\text{-}26)$$

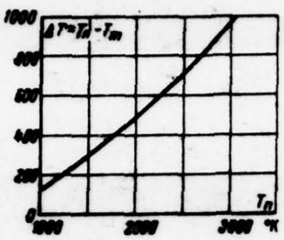

Fig. 2-10. Dependence of the temperature range of normal exposures on the upper temperature at L=1.5.

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The photographic pyrometer in fact is the optical pyrometer, which makes it possible to determine the distribution of temperature brightness on object. As is known, transition to actual temperature can be realized, if are known the value of the effective wavelength of system $\lambda_{эф}$ and the corresponding value of monochromatic emissivity ϵ_λ.

The calculation of effective length of photopyrometer can be produced on the basis of the overall relationship/ratios, used for calculation $\lambda_{эф}$ of the optical pyrometers. So, for the calculation of actual temperature $\lambda_{эф}$ it is possible to find from the formula

$$\lambda_{э\Phi} = \frac{c_2 (T_c^{-1} - T_s^{-1})}{\ln \frac{\int_0^\infty b^0_{\lambda T_s} P_\lambda D_\lambda \, d\lambda}{\int_0^\infty b^0_{\lambda T_c} P_\lambda D_\lambda \, d\lambda}}, \qquad (2\text{-}27)$$

where T_c - the color temperature of body; T_s - temperature brightness; $b^0_{\lambda T_s}$ and $b^0_{\lambda T_c}$ - spectral brightness of blackbody at the appropriate temperatures; P_λ - relative spectral sensitivity of film; D_λ - coefficient of the transmission of optical system (including filters).

For infinitesimal temperature range, can be obtained the value of maximum effective wavelength [2-1]:

$$\lambda_{э\Phi.\text{пр}} = \frac{\int_0^\infty b^0_{\lambda T} P_\lambda D_\lambda \, d\lambda}{\int_0^\infty \lambda^{-1} b^0_{\lambda T} P_\lambda D_\lambda \, d\lambda}. \qquad (2\text{-}28)$$

In work with isoparchromatic and panchromatic photographic materials during the appropriate selection of light filter, it is possible to obtain value $\lambda_{э\Phi}$ sufficiently close to the appropriate value for industrial monochromatic optical pyrometers.

In connection with a comparatively small abundance of photopyrometric method in the practice of thermophysical experiment, it would want to call/name a series of the works, containing concrete/specific/actual data on the application/use of photopyrometry. So, shell [2-33] with the aid of photographic methods it investigated cooling Silit resistors for purpose of the study of their thermophysical properties. The maximum recorded in experiment temperature drop was approximately 200°C at maximum temperature of 1200°C. A variation in readings of Hayes photopyrometer in the range of 1200-1400°C reached ±3°C.

The careful experimental investigation of photopyrometric method was carried out by Londry [2-34].

Work was conducted in the range of temperatures of 1200-1800°K.

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Were investigated characteristic curve films under the varied conditions of photographing, was studied the temperature distribution along the length of the belt of temperature lamp, were removed curves of cooling of a series of specimen/samples. The author estimates a variation in readings of photopyrometer by value of ±1°K (for small temperature drops). The absolute error for the measurements of temperature, found by the comparison of the data of photopyrometer and the optical pyrometer, does not exceed ±5°K.

Photographic method was successfully used by V. A. Popov for determining the temperature of driving/moving burning particles [2-35] M. M. Skotnikov [2-32] were applied it for the study of temperature field in the jet of flame.

During the study of the coefficient of thermal conductivity and other properties of metals the photographic methods of the study of the temperature fields were used by J. Martin [2-37] and Ye. S. Platunov with colleagues [2-38, 2-39]. One should cite work of S.G Grenishin etc. [2-36], in which are examined the special feature/peculiarities of the measurement of brightness and color temperatures by the methods of photopyrometry.

Use described higher than the methods of studying the temperature fields, as a rule, it gives into the order of the experimenter of the information about the fields of temperature brightness. If according to one or the other reasons the realization of the models of blackbody for the objective is impossible, actual temperatures it is necessary to rely on the basis of data from monochromatic emissivity factor ε_λ, taken at effective wavelength of system λ.

Connection of the gradient of temperature brightness dT_{a}/dx and of the gradient of actual temperature T can be represented by the expression

$$\frac{dT}{dx} = \frac{1}{1 + T^{2}\frac{\lambda}{c_{2}\varepsilon_{\lambda}}\cdot\frac{d\varepsilon_{\lambda}}{dT}}\left(\frac{T}{T_{a}}\right)^{2}\frac{dT_{a}}{dx}. \qquad (2\text{-}29)$$

Expression (2-29) makes it possible to trace the accumulation of error in the determination of the gradient of the actual temperature. The greatest contribution to it give differentiation of initial curve $T_{a}(x)$, error of measurement T_{a} and an error in the determination of actual temperature T, caused by the inaccurate knowledge of emissivity factor ε_{λ}. Last/latter component can be estimated on the formula

$$\left(\frac{\Delta T}{T}\right)_{\varepsilon} = \frac{\frac{\lambda}{c_{2}}T_{a}}{\left(1 + \frac{\lambda T_{a}}{c_{2}}\ln\varepsilon_{\lambda}\right)}\cdot\frac{\Delta\varepsilon_{\lambda}}{\varepsilon_{\lambda}}. \qquad (2\text{-}30)$$

The essential increase of error during the calculation of the fields of the actual temperature in terms of the appropriate values of temperature brightness forces to search for the ways of the creation of the models of blackbody at data points of the specimen/samples being investigated. This fact requires very attentive and careful relation to the experimental data, obtained only on the basis of the measurements of temperature brightness. As a rule, in this case one should special attention focus on surface condition, the composition of the gaseous medium, which surrounds specimen/sample, the geometry of system and a series of other factors, which affect the effective value of the luminous fluxes from specimen/sample.

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2-4. Special feature/peculiarities of optical temperature measurements under conditions of radiation heating.

As is known, radiant flux, sent by hot body into the surrounding space, in the general case is of two parts: its own radiation of body and part of the emission/radiation, which falls to its surface from without, this surface reflected.

If the value of the first part is the function of the temperature of body, its physical properties and mechanical surface condition, then second part, besides these factors, depends also on temperature and the properties of external emitter.

Thus, perceived by pyrometer radiant energy ceases to be the characteristic of the body being investigated, since the information about its temperature state is distorted by environmental factors.

With similar conditions it is necessary to be counted during the measurements of the temperature of bodies, heated in crucible furnaces, equipment/devices with electronic heating, reverberatory furnaces, etc.

On the value of possible error, it is possible to judge at least based on this example [2-41]. During the measurements of the temperature of body surface, heated in reverberatory furnace with the energy density 100 W/cm², of value of the apparent temperature at emissivity factors of surface $\varepsilon=1$; 0.9; 0.7; 0.5 compose with respect to 1776; 1946; 2128 and 2240°C. The actual temperature of surface in this case is equal to 1776°C.

It is logical that the experimenters search for the ways of the exception/elimination of similar errors. Let us examine the obvious relationship/ratio

$$B_{э\phi}(\lambda, T_{э\phi}) = B_e(\lambda, T_e) + B_0(\lambda, T_0), \qquad (2\text{-}31)$$

connecting effective brightness $B_{э\phi}$ with brightness of its own of B_e and reflected B_0 emission/radiations. The temperature of surface T_e (brightness) can be designed, if is measured temperature T_0, which corresponds to reflected radiation. It is real/actual, taking into account the formula of wine, expression (2-31) is converted to the form

$$\Delta T = T_{э\phi} - T_e = T_{э\phi}\left[1 - \frac{1}{1-A}\right]. \qquad (2\text{-}32)$$

where

$$A = \frac{\lambda T_{яФ}}{c_2} \ln \left[1 - \exp\left[-\frac{c_2}{\lambda} \left(\frac{1}{T_0} - \frac{1}{T_{яФ}} \right) \right] \right].$$

The measurement of value T_0 can be realized only sometimes. For example, in experiments with electronic heating it is possible, after disconnecting high voltage, to measure in the cooled specimen/sample value T_0, which corresponds to that reflected by specimen/sample to radiant flux from the incandescent cathode. A change in the reflection coefficient with temperature is small and easily considered by the appropriate correction. The authors utilized this method in all their works with the application/use of electronic heating. In this case, was remove/taken the dependence of the apparent temperature in the cooled specimen/sample on the strength of current, feeding filamentary cathode.

During treatment/working of experiments value T_0 is found through the strength of current of the cathode, which occurred in this conditions/mode.

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It is logical that the replacement of cathode or the displacement of any elements of construction/design causes the need of conducting the new calibration of the flows reflected.

In such a case, when radiant flux, which overstates the temperature brightness of object, is at the same time the basic heating flow, method described above cannot be realized. This is related first of all to reverberatory furnaces. One of the possible paths is here the method, proposed by D. N. Shcherbina [2-41]. If to material with reflectivity ρ_0 corresponds brightness B_0, then, other conditions being equal, reflection from the surface of material with reflectivity ρ can be designed on the basis of relationship/ratio

$$B_\rho = B_0 \frac{\rho}{\rho_0}.$$

It remains to fit the material with ρ_0, which would make it possible to conduct brightness reflected measurements in pure form. This material proves to be magnesium oxide, reflection coefficient by which is close to 0.97. So high a value of ρ_0 leads to the fact that in the balance of radiant energy, which determines the apparent temperature of irradiated object $T_{\circ\phi}$, its intrinsic emission does not virtually play the role. D. N. Shcherbina gives the calculations, which attest to the fact that the error in brightness, caused by the intrinsic emission of magnesium oxide, the placed in focus solar furnaces, is approximately 0.7o/o, which in recalculation to temperature gives an error in order 0.1o/o.

Thus, experiment in the measurement of the surface temperature of any material, which is located in the focus of solar furnace, is run as follows. In the place of the specimen/sample being investigated is placed auxiliary specimen/sample made of magnesium oxide. Is remove/taken the dependence of effective temperature T_0 of auxiliary specimen/sample on solar intensity (by fixed/recorded fact or by another photometer).

Then in experiment with basic specimen/sample are measured its apparent temperature $T_{s\phi}$ and the value of solar radiation. From the latter is determined the corresponding value B_0. The unknown temperature T can be designed in accordance with the equality

$$e^{-\frac{c_2}{\lambda T_{s\phi}}} = \varepsilon e^{-\frac{c_2}{\lambda T}} + \frac{\rho}{\rho_0} e^{-\frac{c_2}{\lambda T_0}}, \qquad (2\text{-}33)$$

where λ - an effective wavelength of the optical pyrometer; c_2=14388 μm•deg; $\varepsilon = 1 - \rho$ - monochromatic emissivity factor.

One should emphasize that the application of the method indicated can be accompanied by appreciable errors, caused by an inaccuracy in the installation of standard and specimen/sample in the relatively reverberatory furnace. A rather sharp change in the energy density in the area of focal spot and on leaving from focal plane can cause the disturbance/breakdown of the requirement of the identity of the conditions of irradiation and as consequence lead to systematic error in measurements. The described method assumes known monochromatic reflectivity and, consequently, also monochromatic emissivity factor.

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If the parameters of unknowns indicated, become necessary the measurement of the intrinsic emission of specimen/sample. One of the ways of organizing such measurements is the application/use of two rotating screens. In this case, pyrometric channel is open/disclosed at that torque/moment when incident radiation completely overlaps. Number of revolutions is selected similar so that cooling specimen/sample for the time of the cutoff of the heating flow would be unessential.

In arc reflecting furnaces a similar method was used in work [2-43] during the investigation of the coefficient of reflection and emissivity of oxide ceramics. Standard specimen/sample was fulfilled from the oxide film of magnesium up to 1.5 mm in thickness, plotted/applied to the surface of the cooled copper block/module/unit. During the measurements of effective temperature T_e, test specimen was rapidly replaced by standard with the accuracy of installation 0.1-0.2 mm. The measuring circuit, used by the authors [2-43], is represented in Fig. 2-11.

The scanning prisms are fasten/strengthened to three blade/vanes and rotate at a rate of 10 r/s. At the torque/moment, presented in the diagram, which falls to specimen/sample the flow is overlapped and the system of prisms guides the intrinsic emission of specimen/sample to pyrometer 2. By pyrometer 1 is measured the temperature, which corresponds to the sum of its own and reflected flows. The weakening of flows because of their periodic interruption leads to the fact that both of pyrometers record/fix only certain apparent temperature $T_к$, connected with the temperature of surface T with the relationship/ratic

$$\frac{1}{T}=\frac{1}{T_к}+\frac{\lambda}{c_2}\ln\tau, \quad (2\text{-}34)$$

where τ - the coefficient of the transmission of the rotating screen, calculated on the basis of the geometry of screen or determined experimentally.

One should mention, also, about this possibility as separation of the spectral sections of that heating and measuring radiant fluxes. In reverberatory furnaces this can be reached by the transmission of radiant flux from the mirror through the special filter the coefficient of transmission of which in spectral region, corresponding to effective wavelength of the optical pyrometer, is sufficiently low. The effectiveness of a similar method it showed P. Glazer [2-42] in its work regarding the thermal conductivity of zirconium oxide.

Ideal conditions for this approach exist during the use of laser heating, which is characterized by the high degree of the monochromatization of the primary flow of energy.

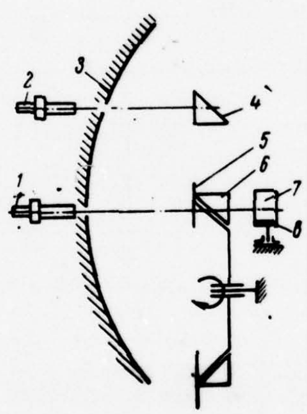

Fig. 2-11. Diagram of temperature measurements in reverberatory furnace. 1, 2 - optical pyrometers; 3 - mirror of furnace; 4 - motionless prism; 5 - screen; 6 - scanning prism; 7 - specimen/sample; 8 - rotary stand.

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Chapter Three.

METHODS OF THE EXPERIMENTAL STUDY OF THE COEFFICIENT OF THERMAL CONDUCTIVITY WITH THE USE OF DIRECT/STRAIGHT DIELECTRIC HEATING OF SPECIMEN/SAMPLES.

3-1. Method of Jager and Diesselhorst and its development in works of D. L. Timrot, B. Ye. Neymark, B. Ye. Krzhizhanovskiy and other researchers.

A large quantity of structural materials of contemporary technology, utilized in the systems of conversion and energy transfer, possesses noticeable electrical conductivity. During the study of their coefficient of thermal conductivity, it is proved to be convenient to utilize heating specimen/samples by electric current. Among different paths of experiment under these conditions especially attractive is the examined in Chapter 1 method of Kohlrausch. However, its realization assumes the creation of the adiabatic insulation of the lateral surface of specimen/sample. The complexity of the experimental solution of this problem forces to construct the theory, which considers lateral losses. By the first space here, it is logical, is assumption about linear communication/connection of heat losses with temperature (heat exchange according to the law of Newton-Richtman). Furthermore, in the case of metals and alloys their high thermal conductivity makes it possible to disregard the radial nonisothermicity of specimen/samples.

Thus, formally we come to system with the negative sources of the heat releases whose productivity linearly depends on temperature. Flow from these sources is additively accumulated with the heat release, caused by the passage of current.

For the first time the problem of this type examined Jager and Diesselhorst [3-9].

Initial differential equation takes the form

$$\frac{d}{dx}\left[\lambda\frac{dT}{dx}\right]+\sigma\left[\frac{dv}{dx}\right]^2-\frac{\alpha P}{S}[T_0-T]=0. \qquad (3\text{-}1)$$

Here: α - heat-transfer coefficient; P - perimeter of rod; S - its cross section; T_0 - ambient temperature.

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Equation (3-1) during the introduction of a series of the simplifying assumptions admits the strict analytical solution which can be placed as the basis of experimental procedure for determination λ. In this case, the necessary calculated relationship/ratios can be obtained by two methods. The first consists of finding of the corrections after using which we would arrive at Kohlrausch's simple and convenient calculation formulas (see Chapter 1). The second consists in the investigation of the new types of the calculated relationship/ratios, constructed on the basis of the strict solution.

The first version, in essence its being approximated, nevertheless (probably, on inertia) after the work of Jager and Diesselhorst was received very wide acceptance and it is utilized, until now,. Let us examine it in detail. Let there be with $x=-l$ $T=T_1$; $v=v_1$; with $x=+l$ $T=T_3$; $v=v_3$; with $x=0$ $T=T_2$; $v=v_2$.

If λ=const and σ=const, then

$$\sigma\left[\frac{dv}{dx}\right]^2=\sigma\frac{V^2}{4l^2}, \qquad (3\text{-}2)$$

where V - voltage drop across conductor by length 2l.

Under conditions of Kohlrausch, value V^2 can be connected with the jump/drop in temperatures $\theta=T_{sr}-\frac{T_1+T_3}{2}$, which appears in conductor at the transmission on it of the current [see Chapter 1, equation (1-32)]:

$$V^2 = 8\left[\frac{\lambda}{\varepsilon}\right]\theta.$$

Then the second term of equation (3-1) is written in the form $\lambda 2\theta/l^2$, and all the equation after reduction to constant factors - in the form

$$\frac{d^2T}{dx^2} - \frac{2\alpha}{\lambda r}(T - T_0) + \frac{2\theta}{l^2} = 0. \qquad (3\text{-}3)$$

After designating $n^2=2\alpha/\lambda r$, the general solution of differential equation (3-3) let us write in the form

$$T - T_0 - \frac{2\theta}{n^2 l^2} = Ae^{nx} + A'e^{-nx}. \qquad (3\text{-}4)$$

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Equation (3-4) Jager and Diesselhorst utilized for the determination of the relationship/ratio between the temperature drop in the specimen/sample θ, which could be formed under conditions of adiabatic insulation/isolation, and with the jump/drop $\Delta = T_2 - T_1 + T_3/2$, occurring in system with losses.

After presenting exponential functions in the form of series and after designating $A+A'=B$; $A-A'=C$, it will be possible to write:

$$T - T_0 - \frac{2\theta}{n^2 l^2} = B\left(1 + \frac{n^2x^2}{2!} + \frac{n^4x^4}{4!} + \cdots\right) + \\ + Cnx\left(1 + \frac{n^2x^2}{3!} + \frac{n^4x^4}{5!} - \cdots\right). \qquad (3\text{-}5)$$

Constant B easily is determined from temperature T_2 in the center of conductor (x=0):

$$T_2 - T_0 - \frac{2\theta}{n^2 l^2} = B. \qquad (3\text{-}6)$$

Expressions (3-5) and (3-6) make it possible to write expression for the relative temperature

$$\frac{T - T_2}{T_2 - T_0 - \frac{2\theta}{n^2 l^2}} = \frac{n^2 x^2}{2!} + \frac{n^4 x^4}{4!} + \dots +$$

$$+ \frac{C}{B} nx \left(1 + \frac{n^2 x^2}{3!} + \frac{n^4 x^4}{5!} + \cdots\right)$$

and finally utilizing boundary conditions with $x=\pm L$ to obtain the resultant expression

$$\frac{T_1 + T_3 - 2T_2}{T_2 - T_0 - \frac{2\theta}{n^2 l^2}} = n^2 l^2 + \frac{n^4 l^4}{12} + \dots \qquad (3\text{-}7)$$

After introducing the designations

$$\varepsilon = \frac{1}{2} n^2 l^2 = \frac{\alpha}{\lambda} \frac{l^2}{r}; \qquad (3\text{-}8)$$

$$N = T_0 - T_2 + \frac{1}{6}\Delta, \qquad (3\text{-}9)$$

from equation (3-7), by utilizing in the right side three terms of expansion, it is possible to find communication/connection between θ and Δ:

$$\theta = \Delta - \varepsilon N + \frac{\Delta}{60}\varepsilon^2 + \dots \qquad (3\text{-}10)$$

The designed thus value θ can be substituted in the equation of

Kohlrausch and to find the unknown value λ/σ. Value λ/σ here one should relate to temperature $T_2 - \frac{1}{2}\Delta$.

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If the temperature of furnace is not constant, but it changes on parabola with temperatures $T_{01}(x=-l)$, $T_{02}(x=0)$, $T_{03}(x=+l)$, then value N is computed according to the relationship/ratio

$$N = T_{0_2} - T_2 + \frac{\Delta}{6} - \frac{1}{6}\left(T_{0_2} - \frac{T_{01} + T_{03}}{2}\right). \quad (3\text{-}11)$$

Thus, the calculation of correction requires the investigation of temperature distribution not only along specimen/sample, but also along furnace.

In accordance with (3-8) value ε can be calculated, if is known heat-transfer coefficient α. If between the specimen/sample (with a radius of r) and by the wall of furnace (with a radius of R) is placed any filling with thermal conductivity λ_0, then expression for approximate estimate α, obviously, takes the form

$$\alpha = \frac{\lambda_0}{r \ln (R/r)}. \quad (3\text{-}12)$$

More advisable is, however, the direct measurement of value ε in experiment. If over rod current does not go, then according to Kohlrausch's theory specimen/sample must be isothermic, i.e., θ=0.

Thus, after disconnecting current and after measuring the stationary temperature distribution in system, from equation $0=\Delta_1-\varepsilon N_1+\ldots$ it is possible to calculate unknown value $\varepsilon=\Delta_1/N_1$.

On the basis of the theory presented Jager and Diesselhorst supplied the thoroughly realized experiment.

Used by them experimental techniques is of now, perhaps, only historical interest; however, the idea of systematic approach, the mathematical analysis of many specific problems, which appear in the implementation of method,, until now, they retain entire their force and value.

In 1935 this method was used D. L. Timrot [3-10]. It carried out for the first time it in high-temperature range: experimental data on the thermal conductivity of the most important trademarks of steels in work on the thermal conductivity of the most important trademarks of steels in work [3-10] cover temperature range of 100-900°C. Characteristic for this work is attention to the creation of the conditions, required the theory of method. This first of all is related to equipment/device of working section. The average/mean test section of the specimen/sample was covered by insulating compound, which consists of admix asbestos fibers with magnesia, and it was turned up into fine/thin asbestos sheet.

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This system, bound by asbestos cord, was introduced into furnace, and the clearances between the heating tube of furnace and the block/module/unit from specimen/samples were filled with the same asbestos-magnesium filling. Such an insulation/isolation made it possible to hope for the linear character of heat exchange between the specimen/sample and the furnace, required theory.

Several years after the method of Jager and Diesselhorst realize V. E. Mikryukov [3-11, 3-12]. Unlike D. L. Timrot's work, here in all range of investigations is absent insulating filling between the specimen/sample and the furnace. Heat exchange between them is realized by the emission/radiation (working section is located in vacuum); therefore initial positions are here disrupted. Position is aggravated still by the fact that the diameter of specimen/sample is noticeably smaller than the diameter of furnace. This leads to the amplification of the role of "oblique" re-emission, i.e., the direct heat exchange of the hot central zones of forms with colder peripheral sections.

Generally speaking, under specific conditions it is possible to allow radiation heat exchange in system. For this, it is necessary, on one hand, to reduce to minimum air-gap clearance between the specimen/sample and the furnace (which will make it possible to eliminate the noticeable effect of re-emission) and, on the other hand - to fulfill condition $(T-T_0)/T_0 \ll 1$. In this case it is possible to talk about the effective coefficient of heat exchange $\alpha_л$ and the linear character of its temperature dependence, i.e.,

$$\varepsilon_{пр}\sigma(T^4 - T_0^4) = \alpha_л(T - T_0), \quad (3\text{-}13)$$

where $\varepsilon_{пр}$ - given emissivity factor in system specimen/sample - furnace; σ - Stefan-Boltzmann's constant; T and T_0 - absolute temperatures of specimen/sample and furnace.

From (3-13) it follows that the linearized coefficient of heat exchange can be written as

$$\alpha_л = 4\varepsilon\sigma T_0^3, \quad (3\text{-}14)$$

moreover an error in the linearization it is estimated by the relationship/ratio

$$\varkappa = \frac{1{,}5(T - T_0)/T_0}{1 + 1{,}5(T - T_0)/T_0}. \quad (3\text{-}15)$$

On should not forget that equation (3-1) assumes constancy α over entire length of working section.

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Fulfilling this requirement in the case of the linearized radiation heat exchange requires special emission/radiation in each specific case. In work [3-11] the analysis of these questions was absent.

Thus, to the results, obtained during the installation of V. E. Mikryukova, one should approach with large precaution. This confirm, for example, and P. R. Shelepukhin's data [3-13], who, working during the installation of V. E. Mikryukova, experimentally detected that the system of the corrections of Jager and Diesselhorst here led to erroneous results, already beginning with temperatures of 300-400°C. The most reliable results were obtained only under the condition of the protection of specimen/sample by the layer of ceramics with the low coefficient of thermal conductivity (foam chamotte).

The extensive studies of the coefficient of thermal conductivity by the method of Jager and Diesselhorst were carried out by R. Ye. Krzyzanowski [3-14, 3-15] and B. Ye. Neymark [3-16, 3-17]. The created by them experimental installations ensured obtaining reliable data to 900-950°C and made it possible to conduct systematic investigation of heat- and electrical conductivity of the large group of the most important industrial alloys.

Higher temperatures (to 1100°C) were obtained during its installation of G. Ye. Ivanchikhin [3-18].

The diagram of this installaticn is given to Fig. 3-1. Heater is made from sheet tungsten 0.15 mm in thickness. Experimental model with a length of 120 4.5 mm in diameter is secured by special pins. The latter contain compensative heater and cccler, which makes it possible to regulate the value of temperature drop in specimen/sample. Working section has length 60 mm. The measurements of the temperature of specimen/sample are realized by three welded to it platinum-platinum rhodium thermocouples⌀0.15 mm in diameter. The electrodes of these thermocouples they are utilized as potential conclusion/derivations.

Specimen/sample is shielded by insulation - two tightly pressed to it semicylinders 6 of ultralightweight fcam chamotte. On the external surface of semicylinders in grooves, are packed the thermocouples, which measure the temperature field on the external surface of insulation/isolation. Between tungsten heater and ceramics, is left the clearance to 3 mm, which improves the uniformity of heat-flow distribution according to the surface of the heat insulation of specimen/sample. Outside heater it has screening, which decreases the heat losses to the jacket of furnace. System is evacuated to 10^{-4}- 10^{-5} mm Hg.

Correctly noting that with decrease of N the theory of the corrections of method is proved to be more effective, the author in his measurements leads this value to 1-4°C.

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To 700°C experimental data of the author for steel 1Kh18N9T within limits of 2o/o coincide with the results of B. E. Neymark and R. E. Krzyzanowski, at higher temperatures - they exceed them (B. E. Neymark's results are deflect/diverted at 950°C down approximately to 8o/o). Reason this author perceives in too the great values of N which were in the compared works. So, B. Ye. Neymark temperature at the end/lead of the furnace was higher than the temperature of end/lead of the rod by approximately 86°C.

The given example shows that the use of all advantages of one of the most elegant experimental methods - method of Jager and Diesselhorst is possible only during strict bringing of conditions of heat exchange in the working zone of specimen/sample into conformity with the theory of method.

Let us write the solution of equation (3-10) in a somewhat different form:

$$T-T_0=\left(T_l-T_0-\frac{b}{n^2}\right)\frac{\operatorname{ch} nx}{\operatorname{ch} nl}+\frac{b}{n^2}. \qquad (3\text{-}16)$$

Here: $b=2\theta/l^2=I^2\rho/\lambda S^2$; λ and ρ they are set/assumed as before by independent variables of temperature; $T_1=T_3=T_l$.

After measuring in experiment the temperature in the center of conductor (with $x=0$) $T=T_2$, the temperature of conductor T_l at a distance from center $x=\pm l$ and the temperature of medium T_m, we can in accordance with (3-16) connect them with the unknown parameters b and n.

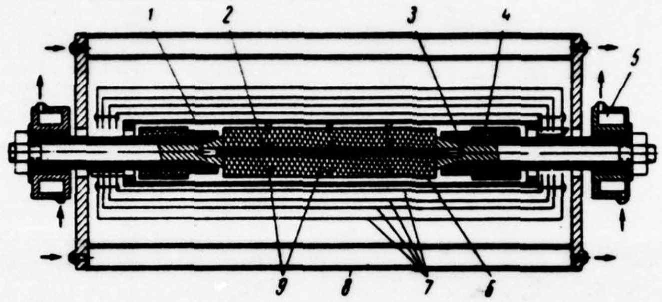

Fig. 3-1. Installation of G. E. Ivanchikhin [3-18]. 1 - heater; 2 - specimen/sample; 3 - pins of the attachment of specimen/sample; 4 - compensative heater; 5 - cooler; 6 - insulation/isolation; 7 - screens; 8 - jacket of furnace; 9 - thermocouple.

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Second equation gives to us the experiment without current, carried out under conditions of maintaining the temperature constancy T_l, which can be provided by end heaters. The temperature of furnace T_0 also must be constant.

Thus, we have two equations:

$$(T_x - T_0)_1 = \left[(T_l - T_0)_1 - \frac{b}{n^2}\right]\frac{1}{\operatorname{ch} nl} + \frac{b}{n^2}; \quad (3\text{-}17)$$

$$(T_x - T_0) = (T_l - T_0)_2 \frac{1}{\operatorname{ch} nl}. \quad (3\text{-}18)$$

Hence there can be found of expression for λ and α:

$$\lambda=\frac{P\alpha}{n^2S}=\frac{Pl^2}{S}\frac{\alpha}{\left[\mathrm{Ar\,ch}\frac{(T_l-T_0)_2}{(T_2-T_0)_2}\right]^2}; \quad (3\text{-}19)$$

$$\alpha=\frac{I^2\rho}{SP}\cdot\frac{n^2}{b}=\frac{I^2\rho}{SP}\times$$

$$\times\frac{(T_l-T_0)_0-(T_2-T_0)_2}{(T_2-T_0)_1(T_l-T_0)_2-(T_l-T_0)_1(T_2-T_0)_2}. \quad (3\text{-}20)$$

The version of treatment/working experiment presented, proposed by Pott [3-19], is not connected with such stringent requirements for value ε, which are characteristic for the method of Jager and Diesselhorst. Final expressions (3-19) and (3-20) are precise ones and can be used, if only heat emission from lateral surface linearly depends on temperature. It is certain, these expressions are less convenient for calculation, than Kohlrausch's formula. However, this is expiated by their strictness.

Pott used its method for the investigation of heat- and electrical conductivity of alloys copper - palladium in the range of temperatures of 20-800°C. An error of measurement of the coefficient of thermal conductivity lie/rests here within limits of ±3o/o.

With the asymmetric form temperature curve into final formula, just as in Jager and Diesselhorst, instead of T_l must be introduced the mean arithmetic values cf end temperatures $T_i = \frac{T_1 + T_2}{2}$.

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3-2. Application/use of Kohlrausch's method at high temperatures.

After the works of Jager and Diesselhorst, by its system of the corrections of those discovered path by Kohlrausch's ideas into temperature range before several hundred degrees, were required 30 years, in order systematically to study and to experimentally realize another path, which made it possible to master even higher temperatures. It was proposed by Holm [3-1] during the development of the theory of electrical contact. The emission/radiation of the character of the temperature distribution in the zone of contact area/sites made it possible to establish that the maximum excess temperature in contact spot at this current is unambiguously determined by the relation of heat- and electrical conductivity. It turned out that for the contact zone, considered as specimen/sample of special form, Kohlrausch's boundary conditions are virtually satisfied in the very wide range of values of the maximum temperature (even during transition for melting point).

Under these conditions the special treatment/working of a series of steady states, which correspond to the different values of currents, makes it possible to calculate the value of relation heat-and electrical conductivity at the selected temperature. The corresponding specimen/sample according to this must be carried out in the form of cylinder with fine/thin short cross connection (in the general case - arbitrary geometry). It is certain, in the zone of cross connection, it is difficult according to Kohlrausch's classical diagram to organize the measurement of temperatures and potentials at three points. But this it is possible and not to make. To more much simply attain the constant temperature T_0 in the thickened zones, which adjoin the cross connection, which will make it possible to use differentiation from the upper alternating/variable limit of the integral of Kohlrausch and to find λ/σ, pertaining to the maximum temperature:

$$\frac{1}{8}V^2=\int_{T_0}^{T_m}\frac{\lambda}{\sigma}dT. \qquad (3\text{-}21)$$

With T_0=const

$$\frac{1}{8}\cdot\frac{dV^2}{dT_m}=\frac{\lambda(T_m)}{\sigma(T_m)}. \qquad (3\text{-}22)$$

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Expression (3-22) is made it possible, thus, to find relation heat- and electrical conductivity in the experiment, carried out in maximally short specimen/sample. From overall considerations it is clear that, other conditions being equal, the decrease of the relative length of specimen/sample must cause a relative increase in the longitudinal heat flux in comparison with the value of lateral losses, and thereby ever more precise satisfaction of derivation conditions of initial relationship/ratio (3-21).

Already during the first realization of similar experiment [3-2] for the construction of calculated relationship/ratios was utilized the temperature dependence of the material being investigated. This made it possible to avoid difficultly attained direct measurements of maximum temperature on neck and to measure only value impedance of the working zone R. It is easy to show that in the case of the parabolic course temperature curve on neck its impedance with the overheating of the center of specimen/sample relative to end/leads to value $\dot{\theta}=T_m-T_0$ is connected with resistance $R_0=R(T_0)$ by the relationship/ratio

$$R=R_0\left(1+\frac{2}{3}\alpha\theta\right). \tag{3-23}$$

where $\alpha=1/\rho_0 \cdot d\rho/dT$.

From (3-23) and (3-21) it is possible to obtain

$$\lambda=\frac{R_0}{12}\cdot\frac{\alpha(T_m)}{\rho(T_m)}\cdot\frac{d(V^2)}{dR}. \tag{3-24}$$

Thus, by knowing the temperature dependence of resistivity and after measuring the dependence of resistance of specimen/sample on the applied stress V in steady state, it is possible to calculate the coefficient of thermal conductivity. The diagram of experiment, dictated by relationship/ratio (3-24), was subsequently used in the series of the works of Katler [3-3-3-5] and Yurchak [3-6]. It must be noted that in these works the derivative $d(V^2)/dR$ was replaced by the relation of final increases in value, i.e., $V^2/(R-R_0)$, which, generally speaking, is connected with known error. It indicated already Holm [3-1], who proposed experimentally removed the curve $R(V^2)$ before treatment/working "to level off" taking into account functions $\rho(T)$ and $\lambda(T)$.

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In the sufficiently low temperature range, these functions can be described by linear dependences and the right side of equation (3-21) is reduced to the polynomial

$$\lambda_0\rho_0\left[\theta+\frac{1}{2}(\alpha+\beta)\theta^2+\frac{1}{3}\alpha\beta\theta^3\right],$$

which makes it possible to calculate Holm's corrective factor. It is located from the equality

$$\left[\frac{d(V^2)}{dR}\right]_{V=0}=\frac{V^2}{R-R_0}\left(1+\frac{\alpha+\beta}{\alpha}\cdot\frac{3}{4}\cdot\frac{R-R_0}{R}\right)^{-1}. \quad (3\text{-}25)$$

In these expressions $\beta=1/\lambda\cdot d\lambda/dT$.

If each measured value V^2 is divided into the value, which stands in the parentheses of last/latter equation, then of curve/graphs $V^2=f(R)$ it will be the straight line whose slope/inclination makes it possible to find the unknown value of derivative, entering equation (3-24).

Among the possible sources of systematic errors in this method the important place occupies lateral heat exchange. For its rough estimates it is possible to examine in linear approach/approximation. This will make possible to find comparatively simple expressions [3-1], which make it possible to estimate necessary during the construction of equipment. The effect of lateral heat exchange it is obvious: it is expressed in the decrease of the values of the overheating of neck $\theta-\Delta\theta$ and impedance of the working section $R-\Delta R$, as a result of which in experiment we will deal with the distorted derivative, i.e., $d(V-\Delta V)^2 d(R-\Delta R)$ instead of $d(V^2)/dR$.

Calculations show that the effect of the effect of lateral heat exchange can be taken into account corrective factor:

$$\frac{d(V-\Delta V)^2}{d(R-\Delta R)}=\frac{d(V^2)}{dR}\cdot\frac{1}{1-C(1-2\alpha\theta)}, \qquad (3\text{-}26)$$

where the constant C is proportionality factor between the decrease of the value of the overheating of neck $\Delta\theta$ and the value of the overheating θ, which corresponds to the adiabatic insulation of lateral surface, i.e., $\Delta\theta=C\theta$; in this case

$$C=\frac{5hb^2}{24\lambda a}. \qquad (3\text{-}27)$$

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Here h - external thermal conductivity [product $h(T-T_0)$ gives the heat flux, lost from the unit of the surface of neck into the surrounding space]; b - length; a - radius of neck.

In equations (3-27) and (3-26) it is assumed that πa/2b<0.25.

Thus, as a result of lateral heat exchange calculation of thermal conductivity according to formula (3-24) gives the values, overstated approximately 1/1-C once.

Decreasing shape factor b^2/a, in principle it is possible the effect of heat exchange to make by unessential.

The described method was used for the first time by Holm and Shtcrmer during the investigation of the thermal conductivity of platinum in the range of temperatures of 19-1020°C [3-2]. Used by them the construction/design of working section is given to Fig. 3-2.

Specimen/sample was grooved made of platinum cylinder with a diameter of 10 and length 25 mm in long. Neck had diameter 0.7 and length 5 mm. For the prevention/warning of the mechanical damage of cross connection, the specimen/sample additionally was centered in two tightened by insulator guide bushes. The butt ends of the specimen/sample were begun pressing into holders - the nickel cylinders, into which were screwed the current inputs. Two potentiometric derivations and thermocouples made it possible to monitor the value of operating voltage/stress and temperature constancy T_0.

The error of measurement, calculated as RMS value of the sum of individual errors, did not exceed ±2.7o/o with 1020°C. The basic contribution to error gives in this case the inaccurate knowledge of the temperature coefficient of electrical resistance $\Delta\alpha/\alpha$ (2.4o/o). The error, connected with calculation by the derivative $d(V^2)/dR$, the authors estimated by value ±1o/o.

In the works of Katler and other researchers [3-3-3-5] the method indicated was realized (it is independent) at higher temperatures.

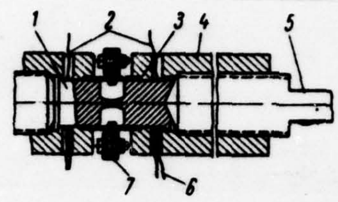

Fig. 3-2. Working section of the installation of Holm and Shtormer [3-2], 1 - specimen/sample; 2 - potentiometric derivations; 3 - guide bush; 4 - sample holder; 5 - current inputs; 6 - thermocouple; 7 - insulator.

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So, the measurements of Lorentz number of molybdenum and tungsten it was possible to conduct in the range of temperatures of 1000-1700°K.

Again let us note that the proposed by Holm approach implies by known the temperature dependence of resistivity and requires comparatively small overheatings θ. If it would be possible sufficiently accurately directly measure the maximum temperature $T_m+\theta$, then these limitations it would be possible to remove/take. This attempted to make Hopkins [3-7, 3-8]. His experimental procedure is instituted directly on equation (3-22) and includes the measurement of maximum temperature by optical micropyrometer. Size/dimensions of neck Ø0.193x0.5 mm. The measurements of Hopkins for platinum cover temperature interval of 1200-2300°C. These are the only work, which contains direct measurements of Lorentz number platinum its higher than melting point.

In work [3-8] Hopkins and Griffis undertook the attempt to experimentally investigate the systematic error, connected with heat losses in the zone of neck. For this purpose, were carried out the measurements in vacuum, air, nitrogen and hydrogen. If the first three experiments in the distance the virtually the same values of Lorentz numbers, then experiments in hydrogen were characterized by the overestimate of the measured values for 8-10o/o. Hence the authors drew a conclusion about the noticeable effect of lateral losses under specific conditions of experiment. Calculations in this case must be constructed taking the correction into account for heat exchange.

Concluding the discussion of these variations in Kohlrausch's method, one should all the same emphasize some fundamental difficulties of their realization in the range of very high temperatures. Most effective here could be the direct method, instituted on equation (3-22). However, Hopkins's the same work, in which it was realized, it showed that the measurement of temperature

T_m here - very difficult problem. Complexity lies in the fact that the temperature distribution is characterized by very considerable gradients and that the range of finite dimensions, in which it would be possible not to consider these gradients, there is virtually (but if no we we attempt it to create, then we immediately disrupt the initial messages of method).

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To this it is necessary to add and that that in the realizable construction/designs it is possible to work only with surface emission/radiation, i.e., with the temperature brightness whose value is characterized by the known indeterminancy/uncertainty of radiation coefficient due to reflections on walls. This is connected with the advent of difficult to the systematic error considered, its for each of the materials being investigated.

Finally, preservation/retention/maintaining itself in an experiment in geometry and size/dimensions of neck at high temperatures is converted into the difficultly solved problem.

3-3. Method of the heat balance of uortinga-Osborne.

Among the ways of realizing the high-temperature measurements of thermal conductivity very enticing is the use of simple experimental equipment/device, which consists of the conductor, heated current to the high temperature in the cold vacuum camera/chamber. Kohlrausch's theory is not here used: are great and significantly nonlinear heat losses from lateral surface. However, information about thermal conductivity can be obtained directly from the equations of heat balance for the finite segment of specimen/sample.

One of the first works in this direction was the investigation of Worthing, carried out in 1914 [3-21].

The method, used by it, is instituted to analysis of the temperature distribution, which appears near the bearing edge of the fine/thin metallic filament, heated by electric current in vacuum. As is shown calculation and confirms experiment, the temperature distribution along long uniform filament is characterized by a comparatively flat/plane temperature area/site in its central zone and by a sharp decrease in the temperature near the bearing edges of end/leads, by the caused diversion/tap of heat flow to them. These flows are in the work of Worthing with the unknown value. Their determination is possible on the basis of the study of energy balance for the finite segment of filament L, undertaken between the center of filament (point of the maximum of temperature) and by the selected working section.

It is obvious that isolated by electric current I on this section power $Q_w = I^2R = I^2\int_0^L \rho(T)S^{-1}dx$ is equal to the sum of longitudinal heat flux Q_λ of section x=L and of heat losses by emission/radiation from the lateral surface of this section $Q_s = \pi D\int_0^L q_s(T)dx$.

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Taking into account this calculated relationship/ratio for the coefficient of thermal conductivity can be written in the form

$$\lambda(T_L) = \frac{4\int_0^L \left[\frac{1}{4} i^2 D\rho(T) - q_s(T)\right]dx}{D\left|\frac{dT}{dx}\right|_{x=L}}, \qquad (3\text{-}28)$$

where i - a current density in filament; D - its diameter; $\left|\frac{dT}{dx}\right|_{x=L}$ - the experimentally obtained value of the gradient of the temperature in the section being investigated; ρ(T) - resistivity; $q_s(T)$ - specific heat losses by emission/radiation.

Last/latter two values are determined with the aid of the special experiment, instituted on the measurement of the expenditure/consumption of electrical energy on section with constant temperature. Here dT/dx=0, and entire/all energy, isolated by current, is expend/consumed on emission/radiation. Thus,

$$q_s(T)=\frac{UI}{\pi Dl} \quad (3\text{-}29)$$

and

$$\rho(T)=\frac{U\pi D^2}{4Il}, \quad (3\text{-}30)$$

where l - distance between potential derivations; U - potential difference.

The simultaneous measurement by the optical pyrometer of temperature brightness makes it possible to relate the obtained results to the specified temperature conditions.

Thus, block diagram of the experiment of Worthing consists of the following cell/elements: measurement ρ(T) and $q_s(T)$ on section with the constant temperature, measurement T(x) in the zone, agitated by the place of stopping up, and application/use obtained previously ρ(T) and $q_s(T)$ for the composition of the energy balance of the section 0-L in question.

Worthing carried out the measurements of the coefficient of the thermal conductivity of tungsten (in the range of temperatures of 1500-2500°K), of tantalum (1700-2100°K), of graphite (1700-2100°K).

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Is later for the investigation of tungsten (1100-2000°K) and of molybdenum (1200-1900°K) this method was applied by Osborne [3-22]. To Worthing - Osborne's method in its essence, adjoins the version of treatment/working, proposed Rudkin, Parker and Jenkins [3-23]. the initial differential equation (1-40) they record/write in the form

$$\frac{S}{2} d\left(\lambda \frac{dT}{dx}\right)^2 = \lambda (I^2R - P\varepsilon\sigma T^4) dT, \qquad (3\text{-}31)$$

where $R=\rho/S$, and they integrate within limits from T_m to T_L, where T_m - temperature in the center of long filament (with $dT/dx=0$); T_L - temperature in the working section being investigated. Calculated relationship/ratio under the assumption of linear dependence $\lambda(T)$ is obvious:

$$\lambda(T_L) = \frac{2}{S} \cdot \frac{\lambda(T_0)}{\lambda(T_L)} \left(\frac{dT}{dx}\right)_L^{-2} \int_{T_m}^{T_L} (I^2R - P\varepsilon\sigma T^4) dT. \qquad (3\text{-}32)$$

The value of the coefficient of thermal conductivity, undertaken at certain mean temperature T_0, is determined from the relationship/ratio

$$\frac{\lambda(T_0)}{\lambda(T_L)} = 1 + \frac{1}{\lambda(T_L)} \cdot \frac{d\lambda}{dT} \cdot \frac{\int_{T_m}^{T_L} (T - T_m)(I^2R - P\varepsilon\sigma T^4) dT}{\int_{T_m}^{T_L} (I^2R - P\varepsilon\sigma T^4) dT}. \qquad (3\text{-}33)$$

In the first approximation, this value can be accepted for unit, and then, after determining $\lambda(T)$, to introduce the necessary correction. For the calculation of the coefficient of thermal conductivity here, as of Worthing, it is necessary to study temperature distribution on the section of filament, which adjoins the center, and in accordance with it, by utilizing dependences $\rho(T)$ and $\varepsilon(T)$, to calculate the value of integral. The gradient of temperature is determined by differentiation of experimental curved $T(x)$.

By the described method are carried out the measurements of thermal conductivity and series of other properties of tungsten, molybdenum and rhenium. The maximum temperature in experiments composed 2800°K. An error of measurement the authors estimate by value ±10o/o.

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The results of this work detect essential disagreement with the data of Worthing for tungsten and Osborne for molybdenum. The last/latter measurements of the properties of these materials make it possible to rate/estimate the results of Worthing as erroneous. The temperature dependence of the thermal conductivity of molybdenum, obtained by Osborne, also, apparently, is distorted by systematic error. This is not random. The method of the optical pyrometer, as was called its Worthing, in spite of clarity of theory and potential efficiency, requires careful experimental realization and delicate treatment/working. It is too vulnerable from the side of a number of factors, difficultly controlled in experiment itself. Among them it is possible to call/name, for example, the requirement of the geometric and physical uniformity of specimen/sample over its length. And if, let us say, it is possible to the experiment to control the constancy of thread diameter over its length, then to check the preservation/retention/maintaining of the one and the same temperature dependence of emissivity along the length of filament is virtually impossible (especially in the case of its monotonic change). As show contemporary investigations, with the vacuum, with which worked Worthing and Osborne, at the specific temperatures can be observed a time/temporary change in emissivity factor.

A disadvantage in the method is the impossibility of measuring the actual temperature. Experiment gives information about the field of temperature brightness in specimen/sample.

For the calculation of flow distribution of heat along the length of filament by the knowledge of temperature brightness it would be possible to be restricted (when do not act the factors, mentioned above), since experiment regarding specific resistance and radiant losses makes it possible to unambiguously connect these values precisely with it. However, the determination of the longitudinal gradient of temperatures requires the knowledge of the field of actual temperatures, since the gradients of true and temperature brightness are not equal. Hence the need for the knowledge of monochromatic emissivity factor of materials, determined, as a rule, in other specimen/samples, under other experimental conditions. So, Worthing utilized during processing of its results data according to emissivity factor of Mendenhall and Forsythe [3-24], but Osborne drew the results of the measurements of Worthing [3-25]. The possibility of introduction into the result of systematic errors is here obvious.

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Estimating the temperature boundaries of uorting - Osborne's method, it is possible to note that obtaining the reliable values of thermal conductivity at the temperatures, close to the maximum temperature in the center of specimen/sample, is impossible in principle. This is connected with the rapid growth/build-up of an error in the determination of longitudinal heat flux during the decrease of the working section 0-L: difference in square brackets in the numerator of expression (3.28) rapidly vanishes with the increase of the values of each of its terms. In this case, each of the terms to different degree is sensitive to the error in the determination of temperature, which is caused by different forms of temperature dependences ρ(T) and $q_s(T)$. Grow/rises an error of measurement of the gradient of the temperatures during the decrease of its value. All this leads to the fact that the reliable values of the coefficient of thermal conductivity can be obtained only for the sections of specimen/sample whose the temperature on 100-150°C lower than maximum temperature T_m of experiment. The latter in turn, is limited by the phenomena of sublimation and thermal creep of the material.

Higher temperatures can be reached by the methods, instituted on the analytical description of the distribution of the temperatures of the filament, heated by electric current. Specifically, in that range of maximum temperatures, where the balance method of Worting leads to large errors, the accuracy of the analytical description temperature curve grow/rises. This offers new possibilities for a qualitative high-temperature experiment.

3-4. Main directions of practical realization of ideas of Jane and Krishnan

As was shown in Chapter 1 some sections of of heated by the current of the rod, losing heat by radiation, under specific conditions allow/assume the very simple analytical form of the description the temperature curve. If rod is sufficiently short, then near its middle temperature field is well approximated by quadratic parabola; but if it is long, then is valid exponential dependence.

This fact was the basis of the development of a series of experimental procedures for studying the thermal conductivity of conductors.

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For understanding of block diagram and validity of experiments, we somewhat convert the differential equation, which describes temperature field in conductor with current and the radiation losses:

$$\frac{d^2T}{dx^2} - \frac{P\varepsilon\sigma}{\lambda S}(T^4 - T_0^4) + I^2\frac{\rho}{\lambda S^2} = 0. \qquad (3\text{-}34)$$

As basis for conversion can serve the identity, valid for the unit of the length of infinitely long filament with the current:

$$q_V(T_\infty) = I^2\frac{\rho}{S^2} = i^2\rho(T_\infty) = \frac{P}{S}\varepsilon(T_\infty)\sigma[T_\infty^4 - T_0^4], \quad (3\text{-}35)$$

where $q_V(T_\infty)$ - heat-liberation value in the conductor, heated to temperature T_∞ by current with a density of i.

After replacing in equation (3.34) heat release with the equivalent value of heat losses in (3.35) and, furthermore, after addding and after taking away term $P\varepsilon\sigma T_{mk}^4/\lambda S$, we will obtain when $\varepsilon(T_\infty)=\varepsilon$ and $\rho(T_\infty)=\rho$:

$$\frac{d^2T}{dx^2} + \frac{P\varepsilon\sigma}{\lambda S}(T_\infty^4 - T_{mk}^4) + \frac{P\varepsilon\sigma}{\lambda S}(T_{mk}^4 - T^4) = 0, \quad (3\text{-}36)$$

where T_{mk} - maximum temperature in the center of final filament at this current I; T_∞ - temperature which would be establish/installed at this point with this current with the unlimited increase in the length of filament; T - temperature of the section of filament in question with coordinate x.

The sense of all these temperatures it is convenient to illustrate by the curve/graph (Fig. 3.3), which depicts the dependence T_{mh} on the length of filament L at the fixed value of temperatures on end/leads and constant value of current I. Maximum temperature T_{mh} first grow/rises proportional to the square of the length of specimen/sample, then changes on compound curve with bend and, finally asymptotically approaches a direct/straight, parallel axis of abscissas and by that corresponding T_{∞}.

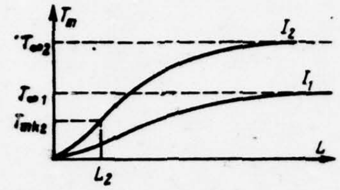

Fig. 3.3. Dependence of the maximum temperature in conductor with current on the length of conductor at the constant value of current and the fixed values of temperature on boundaries.

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Thus, by changing the length of filament, it is possible over wide limits to change difference $T_\infty - T_{mk}$. If $T^4_{mk} - T^4 \ll T^4_\infty - T^4_{mk}$, then the third term in equation (3.36) can be disregarded, and from the solution of the obtained equation to find expression for the coefficient of the thermal conductivity:

$$\lambda = \frac{p_{\epsilon 0}}{2S} \cdot \frac{(T^4_\infty - T^4_{mk})}{T_{mk} - T} x^2. \qquad (3\text{-}37)$$

This formula was utilized in their experiments of Krishan and Jane. The use of identity (3.35) makes it possible to obtain it in another form:

$$\lambda = \frac{\rho}{2S^2} \cdot \frac{(I^2 - I_1^2)}{\Delta T} x^2. \qquad (3\text{-}38)$$

Here: I - operating current, a I₁ - current which would be necessary in order for the continuous filament of the same geometric and physical parameters to ensure temperature equal to the value of the temperature maximum of short filament; $\Delta T = T_{mh} - T$.

Formula (3.38) was the basis of the experimental investigations of thermal conductivity, carried out by V. V. Lebedev, V. S. Gumenyuk, and V. Ye. Ivanov [3-26]. Taking into account identity (3-35) both calculated relationship/ratios can be written in the form

$$\lambda = \frac{q_V(T_\infty) - q_V(T_{mh})}{2(T_{mh} - T)} x^2, \qquad (3\text{-}39)$$

where $q_V(T_\infty)$ - heat release in the infinitely long filament, supplied by the same current, as short filament, or, which is the same, the value of lateral losses, in reference to the unit volume of conductor under these conditions; $q_V(T_{mh})$— heat release in the infinitely long filament, heated to the temperature, equal to the maximum temperature of short filament.

The essence of experiment, thus, is of the establishment of a series of the relationship/ratios, which compose the nomogram, presented in Fig. 3-4.

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In experiment with the sufficiently long specimen/sample of measurement, they make it possible to establish/install communication/connection between the temperature T_{∞} and the physical properties of substance, which determine heat release in it and the dissipation of energy with its surface. This experiment gives single-valued communication/connection between current I and temperature T_{∞}, current and heat-liberation value, current and heat losses.

Experiment with short specimen/sample, that constitutes the strict part of the experiment, consists in the measurement of the temperature distribution in the central zone of specimen/sample (T(x) and of operating current I, which feeds specimen/sample. Through operating current, utilizing data of the first experiment, we find $q_V(T_{\infty})$. On the measurement of maximum temperature T_{mk} with the aid of curve/graph $I(T_{\infty})$ (the right side of the nomogram) we find the current I_1 (which during long filament would ensure $T_{\infty}=T_{mk}$), while on current I_1, we determine $q_V(T_{mk})$. Thus, with good running of the treatment of experimental material basic errors are determined by an error of measurement T_{mk} and by the form of functional connection $q_V(T)$.

One should focus attention on the degree of approximation of calculated relationship/ratios both in V. V. of Lebedev and of Krishnan and Jane, connected with certain indeterminancy/uncertainty of emissivity factor or resistivity. For many materials the parameters indicated from powerful degree depend on temperature. The form of equations (3.37) and (3.38), it is logical, assumes the use of the averaged values of these coefficients. It can seem on first glance that the interval of averaging is a comparatively small difference in the temperatures $T_{mk}-T$. However, the analysis of derivation makes it possible to assert that the interval of averaging is range $T_{m\infty}-T_{mk}$. calculations show that its value, necessary for providing the conditions of parabolic distribution [smallness of the third term of equation (3.36)], can reach several hundred degrees. The advantage of formula (3.39) is here obvious: into it are introduced the local importance of the corresponding parameters.

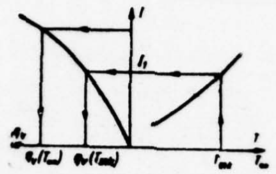

Fig. 3.4. Nomogram of communication/connections, adjustable on different stages of experiment in the method of the heated filament.

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When it is not possible to prepare sufficiently long specimen/sample, it is possible to measure the coefficient of thermal conductivity in experimental data with two short specimen/samples of different length [3-27]. (Each of them must as before satisfy the requirements of the smallness of length).

It is real/actual, (3.39) it is possible to write in the form

$$T_{mk} - T = ax^2, \qquad (3\text{-}40)$$

where

$$a = \frac{q_V(T_\infty) - q_V(T_{mk})}{2\lambda}.$$

After obtaining of two experiments a_1 and a_2, it is easy to calculate the coefficient of the thermal conductivity:

$$\lambda=\frac{[q_V(T_{\infty 1})-q(T_{\infty 2})]-[q_V(T_{mh1})-q_V(T_{mh2})]}{2(a_1-a_2)}. \quad (3\text{-}41)$$

If are examined two experiments with the identical strength of heating current, then expression in the first brackets in numerator becomes equal to zero; at equality maximum temperatures, is equal to zero expression in second brackets. The second version of treatment was widely applied by V. V. Lebedev, V. S. Gumenyuk, and V. Ye. Ivanov [3-26] during the investigations of the thermal conductivity of tantalum, molybdenum and tungsten.

Relationship/ratio (3.41) is correct only for short filaments, i.e., if is fulfilled the inequality

$$T^4_{mk}-T^4 \ll T^4_{\infty}-T^4_{mk}. \quad (3\text{-}42)$$

This condition substantially limits the temperature limits of the proposed method. The maximum value of temperature T_{∞}, at which still can be obtained the values of electrical resistance, is the pyrometric cone equivalent and beginning of the irreversible thermal deformations. In proportion to the approach/approximation of the maximum temperature of the center of filament T_{mk} to temperature $T_{\infty\text{пред}}$ the area of action of parabolic law continuously becomes narrow. Thus, for instance, if T_{∞}=3000°K, and T_{mk}=2700°K, then so that the left side of inequality (3.42) would not exceed 10o/o the right temperature T must not be less than 2670°K. Thus, the temperature interval within limits of which must be obtained basic experimental data, must not be more than 30°K.

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It is logical that the determination in this range of values a is connected with considerable errors. To obtain any reliable results at the temperatures, which approach on 100-200°C maximum ones, during the use of this method is impossible in principle.

The complexity of a sufficient reliable measurement of temperatures in the zone of small in value jump/drop in the center of specimen/sample forced the authors of the named above works to develop the new modification of method [3-28], instituted on the study of the electrical resistance of working section. Initial idea is simple: if the resistivity of material depends on temperature, then at the known law of the temperature distribution in specimen/sample in the value of resistance it is possible to make quantitative conclusions. Without giving here intermediate lining/calculations, let us write the final expression, which connects value a in expression (3.40) with the electrical parameters:

$$a_i' = \frac{3S(R_m - R)}{2\beta\rho_m x_0^3}. \qquad (3\text{-}43)$$

Here: R - resistance of section by length $2x_0$ under conditions of working temperature field; R_m - resistance of the same section at constant temperature over its length, equal to T_{mk}; ρ_m - corresponding value of resistivity; $\beta=\frac{1}{\rho}\cdot\frac{d\rho}{dT}$ — temperature coefficient of electrical resistance, received in constant within the limits of working temperature interval.

For an experiment with two short specimen/samples at the identical temperature of center T_{mk} calculated expression for thermal conductivity will take the form

$$\lambda=\frac{\rho_m^2(I_1^2-I_2^2)\beta x_0^3}{3S^2(R_2-R_1)}. \qquad (3\text{-}44)$$

With entire attractiveness of a similar procedure, it is not possible to overestimate its advantage. Is Achilles its heel - in the need for "driving in" temperature curve in its place between potential diversion/taps after a change in the length of specimen/sample.

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Derivation (3.44) assumes that neither character the curve nor coordinate of maximum with respect to the places of fixation of potential derivations during the exchange of specimen/sample change -

the requirement, difficultly feasible in practice.

Estimating the possibilities of the method of parabola, one cannot fail to say about the reliability of those measurements which give basic information for the calculation of thermal conductivity.

As we already spoke, strictly experiment regarding thermal conductivity consists of the measurement of the temperature distribution in the zone of its maximum. The obtained points in coordinates $T_{mk}-T$ and x^2 serve for determining value a, which is usually located through the slope tangent by that smoothing straight line. During this treatment one ought not to forget that this straight line exists only a first approximation to the real form of dependence $T_{mk}-T=f(x)$. In each specific case are necessary their estimations of the admissibility of this approach/approximation. It is real/actual, even during satisfaction of condition (3.42) one should remember that from the surface of filament is lost the heat, and consequently, in initial differential equation necessary to leave the term, which expresses communication/connection of the heat losses with temperature. In linear approach/approximation, introducing constant on the section being investigated heat-transfer coefficient α, we come to the distribution of the temperatures of the form

$$T_{mk}-T=\frac{T_{\infty}-T_{0}}{\mathrm{ch}\,\frac{kL}{2}}\,[\mathrm{ch}\,(kx)-1], \qquad (3.45)$$

where $k=\sqrt{\frac{4\alpha}{\lambda D}-\frac{i^2\rho_0\beta}{\lambda}}$; D - thread diameter; L - length of the section cn end/leads of which T=T_0, while in middle when $x=0$ $T=T_{mk}$.

After expanding hyperbolic cosine in a series, we will obtain the following expression:

$$\frac{T_{mk}-T}{x^2}=a+\frac{ak^2}{12}x^2+\ldots=a\left(1+\frac{k^2x^2}{12}+\ldots\right), \quad (3\text{-}46)$$

where

$$a=\frac{T_\infty-T_0}{2\mathrm{ch}\frac{kL}{2}}k^2.$$

Thus, calculated relationship/ratio (3.38) must, strictly speak with the contraction of the length of working section Δx to zero.

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Working in practice with the section of the finite length x and the finite range of temperatures ΔT, we overstate value a on $\frac{ak^2}{12}x^2$. This error acts to the side of the understating of data on thermal conductivity is greater, the wider the operating range $T_{mk}-T$ and than higher absolute value of temperature. Thus, for instance, in work [3-26] for the rod of tantalum with a diameter of 1 mm working section reached $x=\sqrt{0,3}$ cm, and the temperature drop ΔT, on which was studied a, it was equal to 200°K when $T_{mk}=1875$°K. According to rough estimate for this case, it is possible to accept $a \approx 9.4 \cdot 10^{-3}$

W/(cm²•deg) and k^2=0.89 1/cm² (all values are designed on the data of work [3.26]. Then the possible error in determination of a composes 0.74o/o with x^2=0.1, 1.48o/o with x^2=0.2 and 2.22o/o with x^2=0.3. The increase of mean temperature of the section being investigated to 2500°K) (k^2=2.72) will lead to the systematic errors, equal to with respect 2.27; 4.54 and 6.8o/o. It is possible to assume that the understated data on the thermal conductivity of molybdenum and tantalum, obtained in works [3.26-3.30], are connected precisely with this fact.

It should be noted that in experiment with two short specimen/samples it is possible, apparently, to partially exclude error in value a, since into calculation is introduced difference a_1-a_2.

Equation (3.36) leads to interesting results not only in the case of very short specimen/samples, but also in the case of sufficiently long filaments. We saw (see Fig. 3.3) that with an increase in the length of conductor the difference $T_\infty - T_{mk}$ can be made how convenient to small. This makes it possible to disregard the second term in (3.36). Linearizing from a known manner the third term, we will obtain equation of the type

$$\frac{d^2\theta}{dx^2}=B\theta, \qquad (3\text{-}47)$$

where

$$B=\frac{4P\varepsilon\sigma}{\lambda S}T_{\infty}^{3};\ \vartheta=T_{mk}-T.$$

Its solution under condition $x\to\infty,\ \vartheta\to 0$ is the function of the form

$$\vartheta=Ae^{-\sqrt{B}x}$$

or

$$\ln\vartheta=\ln A-x\sqrt{B}. \qquad (3\text{-}48)$$

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Thus, the slope/inclination of straight line in coordinates $\ln(T_{mk}-T)$, x makes it possible to find value $\sqrt{B}$, and from it to calculate the coefficient of the thermal conductivity:

$$\lambda=\frac{4P\varepsilon\sigma T_{\infty}^{3}}{SB}=\frac{4I^{2}\rho}{S^{2}BT_{\infty}}. \qquad (3\text{-}49)$$

Emissivity factor and specific resistance are here averaged in interval $T-T_{mk}$. The account to the temperature dependence of these parameters leads to expression [3-32]

$$\lambda=\frac{\rho I^{2}}{BS^{2}}\left(\frac{4}{T_{mk}}+\frac{d\ln\varepsilon}{dT}-\frac{d\ln\rho}{dT}\right). \qquad (3\text{-}50)$$

Thus, for the experimental determination of thermal conductivity it is necessary to measure the value of operating current, the maximum temperature $T_{mk}=T_{\infty}$ and the temperature distribution through which is located B. The value of resistivity is assumed to be known. The laws governing the exponential temperature distribution were used for the first time for determining the coefficient of thermal conductivity of Krishnan and Jane [1-12] which investigated platinum in the range of 1000-1800°K.

At higher temperatures this method used Allen, Glazir and Jordan [3-33], that measured the thermal conductivity of molybdenum, tantalum and tungsten. It must be noted that the sharp divergence of the obtained in this work data is caused by the erroneous method of determining the actual temperature of conductor [3-34] and connected with the essence of the method of measuring the thermal conductivity.

Most careful realization method found in L. P. Filippova's works with colleagues [3.32, 3-35, 3-36], of the investigated with his aid a series refractory metals. A maximum error in L. P. Philipp's method is estimated by value 7-9o/c, which for high-temperature measurements characterizes this method as one of most precise ones. The fact calls attention to itself that the method is applicable precisely in that range, close to T_{mk}, where the approach of Vorting becomes too rough. One cannot fail to note that the successful application of the method of exponential distribution is connected in works [3-35, 3-36] with the development of the special differential photoelectric pyrometer, which made it possible to raise the accuracy of the measurements of small differences in the temperatures.

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The special feature/peculiarity of these experiments is the use of a special rider, hung up in the zone of constant temperature. The heat removal to it leads to shaping of the section of the disturbance/perturbation, well described by exponent. The study of temperature field on working section before the installation of rider and after it it allowed the authors to eliminate the effect of the local heterogeneities of temperature field, caused by imperfection of specimen/sample.

3.5. Other methods of study with use of dielectric heating wire of specimen/samples.

Above we indicated the existence of specific communication/connection between length L of conductor with current and temperature of its maximum T_m at specific current I (see Fig. 3-3).

It is turned out that when $T_m \rightarrow T_\infty$ this communication/connection can be used for determining the coefficient of thermal conductivity. It suffices, changing the length of filament, to fix (during maintenance I=const) change T_m, as on the angle of the slope of dependence $\ln \frac{T_\infty - T_m}{T_\infty} = f(L)$ it is possible to make calculation of the coefficient of thermal conductivity. This method they proposed by Kobushko, Merisov and Khotkevich [3.37]. Initial equation (3-34) under the conditions $x=0,\ T=T_0;\ x=L,\ T=T_0;\ x=L/2,\ T=T_m$ and dT/dx=0 and under the assumption $\alpha=(T_\infty-T_m)/T_\infty \to 0$ they record/write in the form

$$L = \frac{1}{i}\sqrt{\frac{\lambda (T_\infty^4 - T_0^4)}{\rho T_\infty^3}}(D - \ln \alpha), \qquad (3\text{-}51)$$

where D - the little changing in dependence on L function $\eta = 1 - \frac{T_0}{T_\infty}$.

Equation (3.51) is actually identical to equation (3.48); however, approach to experiments with their use is completely various. During the practical use of a method, the authors [3.37] propose measurement $(T_\infty-T_m)/T_\infty=\alpha$ to replace with the measurement of the electrical resistance of the central section of specimen/sample R_∞ and R, where R_∞ - resistance at condition to the constant temperature T_∞ on it, and R - resistance of the same section under the nonisothermic conditions, which are changed during a change in the common/general/total length of conductor L.

In the case of the linear dependence of resistivity on temperature value α and relative resistance $(R_\infty-R)/R_\infty$ are connected by constant coefficient, which makes it possible to process data of experiment in the form of dependence $L\left(\ln\frac{R_\infty - R}{R_\infty}\right)$. The corresponding calculation formula is obvicus:

$$\lambda=\frac{I^2R_\infty}{l_0S}\,\frac{T_\infty^3}{T_\infty^4-T_0^4}\left[\frac{dL}{d\left(\ln\frac{R_\infty-R}{R_\infty}\right)}\right]^2, \quad (3\text{-}52)$$

where l_0 - length of the central section of the specimen/sample, in which are conducted the measurements of temperature.

A common/general/total error in this method according to the estimations of the authors composes ±5o/o. It is probable, this is all the same lower boundary of possible error. One should note the large practical inconvenience of method the comparison, for example, with the method of L. P. Fillipov or Jane and Krishnan. Each experimental point corresponds to its length of specimen/sample; judging by the data of work [3-37], of such points it is remove/taken not less than ten. Method, thus, becomes low-productive. The difficulty of inversion with the wire specimen/samples, which was at high temperature, is led also to the fact that in the range of the high (higher than 2000°K) temperatures of realization of method is extremely hinder/hampered (authors' not without reason data are limited by a comparatively narrow temperature interval).

3.6. Realization of methods of radial heat flux in conductors with current.

As it was shown abcve, at the sufficiently large length of conductor in the energy balance of central zones, participate only the heat release and the heat losses from lateral surface. Connection between temperature drops in section and the intensity of the heat losses of relationship/ratic for the coefficient of thermal conductivity. In the simplest case for circular or circular cross section, we deal with one-dimensional problem. Its mathematical analysis is given in Chapter 1.

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In the case of other geometries (for example, rectangle or ellipse) the problem in the general case is two-dimensional, although for separate specific conditions (for example, the strip of very fine/thin foil) allow/assumes one-dimensional representation. In connection with large ones by simplicity and accuracy of calculated relationship/ratios one-dimensional version found most wide propagation.

One of the first it utilized Engell [3-47] for measuring the thermal conductivities of nickel and aluminum. In high-temperature range, it was for the first time realized by Powell and Shoffield

[3-41], which investigated graphite at temperatures up to 2700°K. It is worth examining the basic torque/moments of this experiment, very characteristic for similar investigations.

The specimen/sample being investigated, carried out in the form of thick-walled tube, was clamped between two water-cooled electrodes, placed within vacuum cylindrical chamber. The walls of the latter were cooled by flowing water. End window on flange and window in the camera/chamber made it possible to monitor specimen/sample from lateral surface and end/face. With the diameter of specimen 2.5 cm, its length was 75 cm. This geometry made it possible to form isothermal zone by length on the order of 20 cm at temperatures of approximately 1200°K. A reduction in the temperature narrowed working section and, furthermore, it led to the decrease of temperature differentials according to the thickness of specimen/sample. Reliable measurements could be carried out only at the temperatures higher than 750°C.

Temperature was measured by the optical pyrometer with the disappearing filament. The internal duct of specimen/sample 3 mm in diameter, overlapped in the working zone of stopper made of ceramics (or simply anechoic boring to working zone), was the model of blackbody and it made it possible to measure the internal temperature. On the surface of specimen/sample, was measured the temperature brightness. For the calculation of actual temperature, were drawn the data according to the monochromatic emissivity of graphite.

For the calculation of the isolated power, were measured the current and a drop in voltage U on the working section L. As potential derivations were utilized the fine/thin graphite rods, sealed by their cold end/leads into graphite blocks.

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The latter were connected by two quartz rods, which provided the preservation/retention/maintaining of the length of working section during changes in the temperature of specimen/sample. As the first approximation for calculation λ, was utilized relationship/ratio (1-104) (see Chapter 1).

The tendency to raise the accuracy of measurements because of an increase in the working difference in the temperatures assigned before Powell and Shoffield the mission of the account to the temperature dependence of heat- and electrical conductivity of material.

During the use of calculated relationship/ratios of type (1-104) or of simpler formula of Engell (case r=0)

$$\lambda=\frac{q_V\, r_2^2}{4\,(t_0-t_2)}=\frac{U^2 r_2^2}{4L^2\rho\,(T_0-T_2)} \qquad (3\text{-}53)$$

This problem consisted of the determination of reference temperature for λ and ρ. Electrical and geometric measurements made it possible to calculate the average value of resistivity $\rho_c=SU/IL$, connected with the temperature distribution by the means of the relationship/ratio

$$\frac{1}{\rho_c}=\frac{1}{r_2^2}\int\limits_0^{r_2}\frac{2r\,dr}{\rho_0\,[1+\beta(T-T_0)]}. \qquad (3\text{-}54)$$

Set/assuming dependences λ(T) and ρ(T) by linear ones within the limits of temperature drop in wall, Powell and Shoffield obtained for temperature distribution the following expression:

$$T_0-T_2=Ar_2^2\Big[1+\Big(\frac{2\alpha+\beta}{4}\Big)Ar_2^2+ \\ +\frac{18\alpha^2+11\alpha\beta+5\beta^2}{36}(Ar_2^2)^2+ \\ +\frac{360\alpha^3+266\alpha^2\beta+145\alpha\beta^2+59\beta^3}{576}(Ar_2^2)^3+\ldots\Big]. \qquad (3\text{-}55)$$

Here:

$$A=\frac{U^2}{4L^2\lambda_0\rho_0};\ \alpha=\frac{1}{\lambda_0}\cdot\frac{d\lambda}{dT};\ \beta=\frac{1}{\rho_0}\cdot\frac{d\rho}{dT};$$

thermal conductivity and electrical resistance are referred to temperature on the axis of rod.

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The knowledge temperature curve makes it possible to find reference temperature T_c. From equations (3.54) and (3-55) it follows:

$$T_c - T_0 = -\frac{Ar_2^2}{2}\left[1 + \frac{\alpha+\beta}{3}(Ar_2^2) + \right.$$
$$\left. + \frac{18\alpha^2 + 23\alpha\beta + 17\beta^2}{72}(Ar_2^2)^2 + \ldots\right]. \qquad (3\text{-}56)$$

Two last/latter expression make it possible to calculate the difference between reference temperature and mean arithmetic temperature. After being restricted to the first term, we will obtain:

$$T_c - \frac{T_2 + T_0}{2} = \frac{2\alpha - \beta}{24}(Ar_2^2)^2 = \frac{2\alpha - \beta}{24}(T_0 - T_2)^2. \qquad (3\text{-}57)$$

Thus, depending on the relationship/ratio between the temperature coefficients of heat- and the electrical conductivity the reference of the measured electrical resistance to the mean arithmetic temperature of section can be accompanied by the error, is greater, the greater the difference in temperatures T_0-T_2. Error can both overstate and understate findings.

After determining ρ_0, from equation (3.55) it is possible to calculate the unknown value of thermal conductivity λ_0.

if for describing the temperature distribution is are utilized mean arithmetic values $\lambda_{a.c}$ and $\rho_{a.c}$, then expression (3.55) will be replaced as follows:

$$T_0 - T_2 = Cr_2^2\left[1 - \frac{\beta}{4}Cr_2^2 - \frac{\beta(5\alpha-\beta)}{72}(Cr_2^2)^2 - \right.$$
$$\left. - \frac{\beta(14\alpha^2 - 29\alpha\beta - 7\beta^2)(Cr_2^2)^3}{576} + \ldots\right]. \quad (3\text{-}58)$$

where, $C = \frac{U^2}{4L^2\lambda_{a.c}\rho_{a.c}}$.

Resulting expressions are obtained for rod (r_1=0); the corresponding series for a duct with an increase in the inside radius converge increasingly slower, which noticeably complicates the problem of finding the local values of the parameters being investigated. The method of Powell and Shoffield render/showed effective means the investigation of the thermal conductivity of graphites at very high temperatures.

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It used extensively Razor and Mac-Clelland [3-48, 3-49], that investigated the thermal conductivity of a series of graphites up to 3000°C, Anakker and Reinhold [3-42, 3-44], that were raised up to maximum temperatures of approximately 3500°C, Strauss [3-45, 3-46] and other researchers.

In a series of works [3-45, 3-48] attention is drawn to not the entirely correct method of measuring the temperature in the axis of rod. In specimen/sample is drilled the radial channel to bottom of which is sighted the optical pyrometer. It is assumed that effective emissivity factor of this channel (with the reference of the measured temperature to its bottom) is equal to one. The analysis, given in Chapter 2, shows that this assumption with known approach/approximation can be accepted only for graphites, and that under conditions of certain limitation of the permissible radial gradients. In the remaining cases the longitudinal nonisothermicity of pyrometric channel unconditionally must be considered.

Interesting fact is given in work of Strauss [3-45]. In the zone of temperatures of 1000-1200°C during the treatment of experiments, it was necessary to accept emissivity factor of the surface of the equal to unity. Otherwise the temperature, measured on the bottom of radial pyrometric channel, prove to bed itself below the temperature of the surface of specimen/sample. This, in our opinion, proves, that even under these conditions (comparatively small temperature differentials) the effective emissivity of the bottom of cavity due to longitudinal nonisothermicity was lesser than unity. The calculation of actual temperature on axis here required the introduction of correction for the incompleteness of emission/radiation.

In work with the materials, emissivity factor of surface of which noticeably differs from unity and little it is studied, it can render/show the effective method of two specimen/samples (different thickness).

After processing here all the measured parameters in the form of the function of the temperature brightness of external wall, it is possible, by comparing conditions/modes with identical temperature brightness, to calculate thermal conductivity, without utilizing data according to emissivity factor.

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It is real/actual, from formula (1-104) for this case it follows:

$$\lambda=\frac{q_{V_1}\Gamma_1-q_{V_2}\Gamma_2}{4(T_{01}-T_{02})}, \quad (3\text{-}59)$$

where T_{01} and T_{02} - temperature on inside radii of the rod (in particular, especially opportunity - temperature of the internal surface of tubes); q_{V_1} and q_{V_2} — heat releases in the conditions/modes in question: $\Gamma=R^2-r^2-2r^2\ln\frac{R}{r}$ - the geometric parameters of specimen/samples.

Is especially convenient for treatment the case, when one of radii of specimen/sample is retained constant/invariable.

As we already indicated, the circular form of the cross section of specimen/sample is not the only possible during the study thermal conductivity on the section of longitudinal isothermicity.

As an example of using other airfoil/profiles, it is possible to indicate the works of Langmuir [3-43] and of investigation of N. P. Kiselev and I. N. Aleynikova [3-50]. Here were utilized the specimen/samples of rectangular cross section. It is completely obvious that under conditions of comparatively small transverse temperature differentials the problem allow/assumes the linearization of the temperature dependence of heat emission and the limitation of a number of terms of the series, which represent solution under these conditions for the selected geometry, can be designed the coefficients, which connect the coefficient of thermal conductivity with common/general/total heat release in rod and the temperature differential along airfoil/profile.

Comparatively high thermal conductivity of the electro-conductive materials for which can be used these methods, leads to the fact that the acting in section temperature drops are small. This fact in combination with the approximate character of analytical description determines a comparatively low accuracy of results. In experiments [3-50] the authors speak about error during the investigation of molybdenum 20-30o/o in the range of temperatures of 2500-1500°K. The increase of temperature, increasing the absolute value of working temperature ones, but, on the other hand, increases the systematic error, connected with the desensitization of problem by the linearization of heat exchange.

The development of similar works is connected with the refinement of theory and the development of technology of scanning differential pyrometry.

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Chapter Four.

EXPERIMENTAL INVESTIGATIONS OF THERMAL CONDUCTIVITY BY METHOD OF LONGITUDINAL HEAT FLUX WITH EXTERNAL HEAT SOURCE.

4.1. Zone of moderate temperatures.

A large number of experimental data according to the coefficient of thermal conductivity is obtained by the methods of longitudinal heat flux. Let us for a reduction in the recording call so the large group of the methods, designed for the application/use of the comparatively long test samples, heat flux in which is directed predominantly along the axis of rod. Their wide application during the study of the properties of metals is caused mainly by the high thermal conductivity of the latter. Only in comparatively long specimen/samples in such cases at available to experimenter heat-flux densities it is possible to realize temperature drops, which can be sufficiently accurately measured and, that it is not less importantly, are referred to the sufficiently specific value of the working length of specimen/sample.

Characteristic for the methods in question is the presence in the cross sections of the specimen/sample of the radial temperature gradients, caused by heat exchange with medium on its lateral surface.

The construction of adiabatic insulation along the surface of nonisothermal specimen/sample in principle is impossible, it is possible to speak only about degree of approximation to it. This essentially differs the methods of longitudinal heat flux from the examined in Chapter 1 cases of the flat/plane unlimited plate with isothermal surfaces. The presence of heat losses introduces known indeterminancy/uncertainty into values of the heat flux, measured in experiment. On the other hand, the bending of isothermal surfaces in the cross sections of specimen/sample requires the refinement of the sense of the temperature drop, measured between the isolated points of specimen/sample. Thus, and numerator, and denominator in the right side of equation (1.22), derived for the idealized diagram, require the specific adjustment, which is greater, the more intense the lateral heat exchange.

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Characteristic for materials with high thermal conductivity is, as this will be shown below, the low value of the correction, connected with transverse nonisothermicity, that makes it possible to disregard it in the very wide range of the realizable in experiments conditions of heat exchange. This makes it possible to consider problem as one-dimensional and to direct main efforts for the organization of the reliable measurements of heat fluxes.

In first works [4.1, 4.2, 4.4], carried out the method of longitudinal heat flux in the zone of comparatively low temperatures (to 300-400°C), during the measurements of the thermal conductivity of metals it was assumed that heat exchange with medium can be disregarded and into the calculated relationship/ratio

$$\lambda_{cp} = \frac{Ql}{F(T_m - T_n)} \quad (4\text{-}1)$$

introduced the heat flux Q, measured either according to net power of heater or by calorimetric measurement in cooler.

In formula (4.1) λ_{cp} - mean value of the coefficient of thermal conductivity in the range of temperatures $T_m - T_n$; l - the length of working section; F - cross-sectional area of specimen/sample.

For decreasing heat losses, the specimen/sample was placed into the guard cylinder, on which with the aid of special heater was

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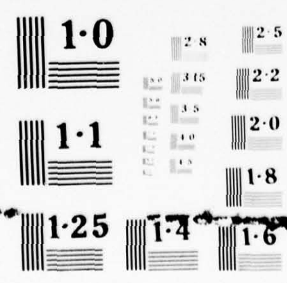

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created the compensating temperature field; This diagram was utilized already by Williams [4.4] and by Donaldson [4.1].

The first was used it for studying the thermal conductivity of the alloys of copper and aluminum to 350°C; The diagram of its installation is given to Fig. 4.1. By the source of heat flux was electrical heater 500 W in power. Two iron-constantan thermocouples 6 made it possible to measure a difference in the temperatures on the working section of specimen/sample 150 mm in length at the diameter of specimen/sample 25 mm.

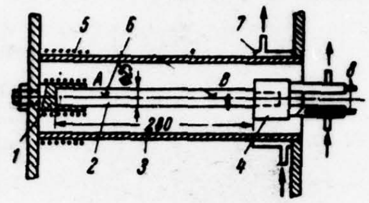

Fig. 4.1. Diagram of installation of Williams [4-4]. 1 - block/module/unit of heater; 2 - specimen/sample; 3 - guard cylinder; 4 and 7 - coolers; 5 - heater of guard cylinder; 6 and 8 - thermocouple.

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Cooler 4, cooled by a running water, was utilized as calorimeter. The temperature field of guard cylinder was regulated by heater and cooler 7.

It must be noted that the guard cylinder with one heater cannot solve the problem of the adiabatic insulation of lateral surface, since temperature distribution along it is form/shaped under the effect of heat losses, and consequently, is characterized by the specific curvature. Thus, in similar systems always will cost the problem of estimation of error, caused by the application/use to them of calculation formula (4-1).

This error thoroughly examined Bode and Fritts [4.3]. In their work were utilized the specimen/samples with a diameter of 50 and 70 mm in long. Heat flux was created by electrical heater. For the elimination of losses from it, it was surrounded by compensative heater. Heat flux from specimen/sample was remove/taken by water cooler. Guard cylinder surrounded specimen/sample with clearance 2 mm and, just as at Donaldson and Williams, it could on top be preheated, but be cooled from below. The temperature state of system was monitored from readings of thermocouple, two of which gave the temperatures of the compensative and basic of heaters (respectively T_1 and T_2) (neq) another pair characterized the temperature distribution along the axis of specimen/sample (T_3 and T_5) (neq) two thermocouples gave temperatures T_4 and T_6 in the points of guard cylinder, arrange/located against the working sections of specimen/sample.

Assuming that the lateral losses are linear relative to a difference instantaneous values of temperatures on the surfaces of specimen/sample and guard cylinder, but on the end/faces of the specimen/sample of temperature are constant (isothermal heating), the authors [4.3] obtained the following expression, connecting the apparent $\lambda_к = Q_0 l / F(T_3 - T_5)$ and true λ of the thermal conductivity:

$$\frac{\lambda_x}{\lambda}=1+(R_I+R_{II})\left(\frac{T_2-T_4}{T_3-T_5}+\frac{T_5-T_4}{T_3-T_5}\cdot\frac{R_I-R_{II}}{R_I+R_{II}}\right). \quad (4\text{-}2)$$

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Here R_I and R_{II} - parameters, which are determined by the geometry of specimen/sample, by its thermal conductivity and the intensity of lateral heat exchange; makes sense to write expressions for them in more detail:

$$R_I=\frac{l}{L}\cdot\frac{4\frac{\alpha R_1}{\lambda}\sum\limits_{1,3,5\,\ldots}^{\infty}\Phi_n}{1-\frac{R_1}{L}4\frac{\alpha R_1}{\lambda}\sum\limits_{1,3,5\,\ldots}^{\infty}\frac{\sin\left(\frac{n\pi}{2}\right)\cos\left(\frac{n\pi}{L}\cdot\frac{l}{2}\right)}{I_1(\rho_n)}\Phi_n}; \quad (4\text{-}3)$$

$$R_{II}=\frac{4\frac{\alpha R_1}{\lambda}\sum\limits_{2,4,6\,\ldots}^{\infty}\Phi_n-\frac{R_1}{L}4\frac{\alpha R_1}{\lambda}\sum\limits_{2,4,6\,\ldots}\frac{\cos\left(\frac{n\pi}{2}\right)\sin\left(\frac{n\pi}{L}\frac{l}{2}\right)\Phi_n}{I_1(\rho_n)}}{1+\frac{R_1}{L}4\frac{\alpha R_1}{\lambda}\sum\limits_{2,4,6\,\ldots}^{\infty}\frac{\cos\left(\frac{n\pi}{2}\right)\sin\left(\frac{n\pi}{L}\cdot\frac{l}{2}\right)}{I_1(\rho_n)}\Phi_n}; \quad (4\text{-}4)$$

$$\Phi_n=\frac{1}{\rho_n^2\left[1+\frac{\alpha R_1}{\lambda}\cdot\frac{1}{\rho_n}\cdot\frac{I_0(\rho_n)}{I_1(\rho_n)}\right]}, \quad (4\text{-}5)$$

where $\rho_n=n\pi\frac{R_1}{L}$; $I_0(\rho_n)$ and $I_1(\rho_n)$ - Bessel function of zero and first order; R_1 - radius of specimen/sample; L - its length; l - distance between the thermocouples, symmetrically arrange/located in specimen/sample; α - coefficient of heat transfer through the clearance, determined from the equation

$$-\lambda\left(\frac{\partial T}{\partial r}\right)_{R_1}=\alpha\,[T(z,R_1)-T_{\text{вп}}(z). \qquad (4\text{-}6)$$

In the case of a small clearance, it is possible to count that the convection will no (Gr Pr little); then heat transfer will be determined by thermal conductivity and emission/radiation. Coefficient α can be calculated from expression

$$\alpha=\frac{5\lambda_{\text{эф}}}{R_2-R_1}, \qquad (4\text{-}7)$$

where $\lambda_{\text{эф}}$ - effective thermal conductivity of medium in the clearance (in experiences in Bode and Fritz - gas).

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From formula (4.2) it follows that only under conditions of adiabatic curve on lateral surface ($T_3=T_4$ and $T_5=T_6$) the designed for equation (4.1) value of the coefficient of thermal conductivity will correspond to truth. Otherwise it is necessary to introduce correction. The direction, formed by works [4.1-4.4], was developed in the investigations of Sheffield [4.5], of Powell [4.7], of Armstrong and Dofini [4.8], concealing Quinn [4.6], Laubitts [4.9] and other researchers.

One should note some specific torque/moments of a series of works, So, Shoffield [4,5], but after it and Powell [4-7] they placed working heater not on end/face, but in the middle of specimen/sample. During the equalization of thermal resistance to that and other of the sides of heater heat flux is identical into both of sides and can be accurately designed. This reception/procedure makes it possible to forego compensative heater and to raise the accuracy of measurements of heat flux.

A known deficiency/lack in the majority of the enumerated works is the calculation of thermal conductivity according to a difference in the temperatures in two sections of specimen/sample. This impedes the determination of the local values of the coefficient of thermal conductivity in the case of its complex temperature dependence. Reference it to mean temperature dependence. Reference it to mean temperature of interval can cause appreciable error. Are exponential in this respect the results of Shoffield on nickel. At mean temperatures 196, 290, 353 and 491°C jump/drops ΔT composed with respect to 75, 81, 100 and by 105°C. The average values of the coefficient of thermal conductivity gave the here very flat minimum, while in the works where the thermal conductivity was averaged in substantially smaller temperature interval [4.11], is planned sharp fracture curved λ(T). In work by Quinn [4-6] with the preservation/retention/maintaining of the common/general/total diagram of method with adiabatic insulation they were accepted measure for a check of the local value of the temperature gradient: in the working zone of specimen/sample were fastened not two, but four thermocouples.

Upper temperature limit in the named installations was limited by temperatures of 700-800°C. Further increase of temperatures ever more complicates the problem of developing of the adiabatic insulation of the lateral surface of specimen/sample.

To a certain degree more effective is proved to be another path - assumption of heat losses.

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In this case, calculated relationship/ratios are constructed on the basis of the laws, which describe temperature field in systems with losses. With sufficiently fine/thin specimen/samples a radial temperature differential in them can be disregarded and considered problem as one-dimensional. A similar approach was used already in the work of Baratt and Winther [4-10]. One of the most elegant experimental solutions in this direction is the work of Hogan and Sawyer [4-11], that increased operating temperature in its measurements approximately to 1000°C. The schematic of their experimental installation is represented in Fig. to 4.2.

The experimental model, on one of end/leads of which is mounted the low-power heater, which is the source of heat flux, it is placed along the axis of tube furnace in the zone of constant temperature. Temperature field along specimen/sample and furnace is monitored by thermocouples. Two current inputs are allowed, furthermore, to pass throughout specimen/sample current.

At the basis of the derivation of calculated relationship/ratios, lie/rests the assumption about the fact that the specimen/sample is the semi-bounded rod whose temperature at infinity approaches ambient temperature T_0. In the zone of the final temperature drops between the specimen/sample and the furnace, the heat losses of specimen/sample are linearly connected with this jump/drop. Under such conditions the longitudinal temperature distribution is described by the exponential dependence

$$T-T_0=\vartheta(x)=\vartheta_0 e^{-ax}, \qquad (4\text{-}8)$$

where

$$a=\sqrt{\frac{2\alpha}{\lambda R}}=\sqrt{\frac{2h}{R}}. \qquad (4\text{-}9)$$

If the coefficient of heat exchange α is known, then on two temperature measurements from (4.8) can be found value a, and on it from (4.9) can be determined the unknown coefficient of thermal conductivity λ.

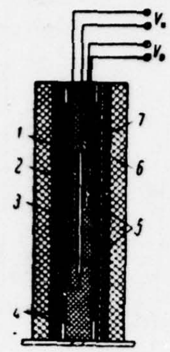

Fig. 4.2. Diagram of installation of Hogan and Sawyer [4.11]. 1 - heater - source of heat flux; 2 - specimen/sample; 3 - leveling cylinder; 4 - insulation/isolation; 5 - thermocouple; 6 - heater of furnace; 7 - jacket of furnace.

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The coefficient of heat exchange α in the work of Hogan and Sawyer was determined experimentally in experiment with the electrical preheating of specimen/sample. After measuring the heat release and the corresponding to it difference in the temperatures between the specimen/sample and the furnace, it is possible to easily calculate the coefficient of heat exchange in known relationship/ratios.

Characteristic ones for this work are strict mathematical analysis of problem and the careful experimental realization of method.

Comparing strict solution of the problem of temperature distribution, that has the form

$$\vartheta(r,z)=\sum_{i=1}^{\infty} A_i J_0\left(n_i \frac{r}{R}\right) \exp\left(-n_i \frac{z}{R}\right), \quad (4\text{-}10)$$

where n_i — the roots of equation $nJ_1(n)=hRJ_0(n)$, and

$$A_i = \frac{\mid 2n_i\theta_0 J_1(n_i)}{[n_i^2 + (hR)^2]\, J_0^2(n_i)}.$$

with approximate relaticnship/ratio (4-8), the authors show that for their specific conditions (diameter of specimen/sample 6 mm, its length of approximately 30 cm; λ<0.25 cal/(cm•s•deg)) the use of relationship/ratio (4-8) is connected with error in temperatures not more than 1o/o. The requirement of the linearity of heat losses is fulfilled first of all because of a small difference in the temperatures between the specimen/sample and the furnace, which does not exceed 5°C. By Hogan and Sawyer were investigated different steels, Inconel and nickel in interval to temperature of 25-1000°C.

The possibility of the sufficiently strict analytical description of temperature field in fine/thin specimen/samples with the Newtonian character of heat losses on lateral surface makes it possible to utilize other systematic schematics. So, Lippman [4-12] proposed the sufficiently ingenious version of systematic schematic for measuring the longitudinal thermal conductivity of thin-walled tubular specimen/samples.

Tubular specimen/sample is placed in furnace with temperature T_0. With the aid of guard heaters the temperature of jets is maintained by identical: $T_1=T_2>T_0$.

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Inside pipe at an equal distance from both of end/leads, is introduced small supplementary heater. When it is switched off, temperature field is concave to furnace because of heat losses. According to the measured temperatures at end/leads and in the center of tube, by utilizing the analytical dependence T(z), it is possible to determine parameter $h=\alpha/\lambda$, which characterizes the intensity of lateral heat exchange.

The second part of the experiment consists of the investigation of the temperature distribution along tube, which arose with the connected central heater. (Temperatures of end/leads are maintained as before by constants). In this case, knowing h, it is possible to accurately calculate the values of the longitudinal gradients of temperature dT/dz on both sides of central heater, and hence, after measuring its power, to determine the coefficient of thermal conductivity. Lippman recommends his method for temperature interval of 500-1000°C. Checking method in the specimen/samples of Armco iron showed his efficiency.

The described works sufficiently fully characterize the systematic and technical special feature/peculiarities of the experimental installations of the method of longitudinal heat flux in the range of the moderate temperatures.

The solution of the problem of measuring the coefficient of thermal conductivity by this method at higher temperatures (1500-2500°C) requires, however, the serious review both of the principles of structural solution and the essence of systematic approach. It is possible to call/name the following basic problems, which appear during transition to high temperatures. The first of them is connected with the intensification of the chemical interaction of structural materials (heaters, screens, insulation/isolation, etc.) with the increase of temperature. In connection with this any kind the insulating fillings around the lateral surface of specimen/sample, so/such characteristic for the zone of the low and moderate temperatures, become extremely undesirable. The traditional schematic of the execution of working heater (source of useful heat flux), instituted on insulation/isolation of working spiral by ceramics, proves to be barely effective due to rapid change in working characteristics in time, and at maximum temperatures is generally unrealizable. Heating specimen/sample in furnace at high temperatures even in the absence of its direct contact with heating element is connected with the contamination of specimen/sample by the products of the sublimation of the material of heater.

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The ideal schematic, which ensures the preservation/retention/maintaining of the purity of the material being investigated, would be that, with which hot specimen/sample would be surrounded by comparatively cold walls with the carrying out of bracing struts of specimen/sample into its most cold, nonoperative part. Space between the specimen/sample and walls must be evacuated.

The method of solution of the problem of the protection of specimen/sample presented is connected with the complication of the mathematical description of the temperature distribution in specimen/sample. This is determined by the fact that under the described conditions the temperature field in specimen/sample will be form/shaped mainly under the effect of radiation heat exchange on its lateral surface. The nonlinear form of boundary conditions does not make it possible to here find the simple and convenient for treatment analytical form of the description of the character of the temperature distribution, as this occurred in works described above. In systematic plan/layout the experiment must undergo substantial changes.

Experiment must be constructed in such a way that the measurements could give the values of heat flux and longitudinal gradient of temperatures, in reference to the specific section of specimen/sample. This approach was used more than 100 years ago by Forbs [4-13] for measuring the thermal conductivity of metals near room temperature. In his experiments was investigated in detail the longitudinal temperature distribution in the long rod, heated from one of the end/faces and cooled from lateral surface. The knowledge temperature curve made it possible to calculate the values of the gradient of the temperatures in any section of specimen. Furthermore, in special experiment with the short cut of rod was remove/taken the curve of its cooling in this same medium. With known heat capacity hence it was possible to calculate the value of specific losses depending on temperature. The obtained thus data were utilized for the plotting of curves of the distribution of lateral losses along the length of rod in basic experiment. The unknown heat flow in any section was computed as sum of losses on the section of rod from this section to end/lead. By the more detailed analysis of the work of Forbs we occupied will not be. This work is interesting for us not by its results, but is faster as historical example of the successful systematic approach, most effective in high-temperature range.

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4-2. High-temperature range. Method of electronic heating.

During the organization of the measurements of thermal conductivity by the method of longitudinal heat flux in high-temperature range gets up a question concerning the effect of the two-dimensional character of temperature field in rod. Carrying out experiment under conditions, formulated at the end of the preceding/previous paragraph, we unavoidably will clash with the development of radial jump/drops in temperatures, the more noticeable, the greater the difference in the temperatures between the specimen/sample and the environment.

Is it possible to count under these conditions the problem of one-dimensional and to use the calculated relationship/ratios of longitudinal method? Answer/response to this question is connected with the solution of the corresponding two-dimensional problem. To a certain degree by it were occupied, for example, Tsuy and Tsou [4-14]. They calculated the ratio of radial heat flux Q_r with the surface of the limited circular cylinder to the common/general/total heat flux Q, going into cylinder. It was assumed that the end/faces of specimen/sample were isothermal, and heat exchange with medium obeys the law of Newton. Calculation was carried out for the values of parameter hR from 0.01 to 1 and the relative lengths of specimen/sample L/R=8 and L/R=4. Accepting as the criterion of the unidimensionality of heat flux in rod inequality $Q>4Q_r$, the authors obtain, what for L/R=4 problem cannot be considered as one-dimensional, beginning with hR=0.07, but when L/R=8 - already with hR>0.015.

The work indicated solves the which interests us problem only qualitatively. The chosen criterion of unidimensionality does not answer a question concerning possible errors connected with heat exchange on the lateral surface of rod. Strict examination must be constructed on the analysis of the field of the gradients of temperatures in the studied section of specimen/sample.

The value of the heat flux dq, passing through arbitrarily oriented in space area/site df, can be represented by the expression

$$dq=-\lambda \operatorname{grad}_n T df, \qquad (4-11)$$

where n - a direction of standard to area/site df; $\lambda \operatorname{grad}_n T$— normal component of vector of heat flux.

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Examining the total flux of heat Q, passing through the selected cross section of specimen/sample, it is possible to write:

$$Q = -\lambda_{\text{ист}} \int_F \text{grad}_n T\, df, \qquad (4\text{-}12)$$

where $\lambda_{\text{ист}}$ - the value of the coefficient of thermal conductivity, averaged within the limits of temperature drop in this section; F - cross-sectional area. It is obvious that expression $F^{-1} \int_F \text{grad}_n T\, df$ determines by itself the value of the average longitudinal gradient of temperatures $\overline{\text{grad}_n T}$, which desirable it would be to obtain on the basis of measurements. Then expression (4-12) with measured Q (this a comparatively simple problem) would make it possible to calculate the unknown coefficient of thermal conductivity $\lambda_{\text{ист}}$. In practice the study of the field of gradients in a comparatively fine/thin specimen/sample is virtually impracticable problem. At best the corresponding sensors make it possible to obtain the longitudinal distribution curve of temperatures either on surface or on the axis of rod. Introducing the local importance of gradient into the calculation of the coefficient of the thermal conductivity, we allow/assume the error

$$\delta\lambda = \frac{\lambda_{\text{ист}} - \lambda_{\text{расч}}}{\lambda_{\text{ист}}} = 1 - \frac{\overline{\text{grad}_n T}}{\text{grad}_n T_r}, \qquad (4\text{-}13)$$

calculation by which is feasible on the basis of the solution of the corresponding boundary-value problem.

Let us assume that the cylindrical specimen/sample with a radius of R with a length of L is heated from one of the end/faces and is cooled by emission/radiation from rear end/face and lateral surface.

Boundary conditions let us write as follows:

$$\left.\begin{aligned} z=0;\ r<r_1;\quad & -\lambda\frac{\partial T}{\partial z}=q_0; \\ r_1<r<R;\quad & -\lambda\frac{\partial T}{\partial z}=0; \end{aligned}\right\} \tag{4-14}$$

$$z=L;\ -\frac{\partial T}{\partial z}=hT; \tag{4-15}$$

$$r=R;\ -\frac{\partial T}{\partial r}=hT. \tag{4-16}$$

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The solution of the placed thus boundary-value problem can be written in the form of the series

$$\vartheta=\sum_{k=1}^{\infty}\varphi(r_1)J_0\left(n_k\frac{r}{R}\right)\Phi_k(z), \tag{4-17}$$

where $\vartheta=\frac{\lambda}{2q_0r_1}T$ — relative temperature;

$$\varphi(r_1)=\frac{J_1\left(\frac{r_1}{R}n_k\right)}{J_0^2(n_k^2)\,[n_k^2+(hR)^2]};$$

$$\Phi_k(z)=\frac{\mathrm{sh}\left(\frac{L-z}{R}n_k\right)+\frac{n_k}{hR}\mathrm{ch}\left(\frac{L-z}{R}n_k\right)}{\mathrm{ch}\left(\frac{L}{R}n_k\right)+\frac{n_k}{hR}\mathrm{sh}\left(\frac{L}{R}n_k\right)};$$

n_k — the roots of the equation

$$nJ_1(n)=hRJ_0(n). \quad (4\text{-}18)$$

Work [4-15] shows, that the temperature field, described by expression (4-17), is characterized by one important special feature/peculiarity. It consists in rapid shaping of the stable radial airfoil/profile of temperature during removal/distance from hot end/face. Independent of conditions on end/face during removal/distance from it on (1-1.5) R the temperature distribution in the cross sections of rod depends only on parameter hR and with error not more than 1o/o is described by the first term of series (4-17).

This substantially simplifies the calculation of the possible error in the estimation of longitudinal gradient. During the measurements of the temperature by the optical pyrometer in the pyrometric channels, drilled in specimen/sample, the most probable is obtaining information about the longitudinal gradient, which corresponds to the axis of rod. In this case the use of expression (4-17), makes it possible to write relationship/ratio (4-18) as

$$\delta\lambda = 1 - \frac{2hR}{n_1^2} J_0(n_1). \qquad (4\text{-}19)$$

With the small ones hR (to $200 \cdot 10^{-3}$) with error not more than 0.1-0.2o/o Bessel function in last/latter expression it is possible to replace two first terms of their expansion in a series.

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This makes it possible to simplify (4-19) and to find convenient calculated relationship/ratio for the evaluation of the error:

$$\delta\lambda = 0{,}25hR - \frac{(hR)^2}{4(4+hR)}. \qquad (4\text{-}20)$$

Definite interest is of the estimation of the absolute value of a radial jump/drop in temperatures $T_{r=0} - T_R = \Delta T_{0R}$.

Under conditions of the same simplifications

$$\Delta T_{0-R} = T_{r=0}\left[\frac{2hR}{4+hR} + \frac{(hR)^2}{(4+hR)^2}\right]. \qquad (4\text{-}21)$$

To Fig. 4-3, are given the results of calculation of $\delta\lambda$ and ΔT_{0-R} for cylindrical specimen/samples made of tungsten and tantalum. The diameter of specimen/samples is selected as being equal to 10 mm; the necessary data on their properties are undertaken from works [4-16, 7-20]. Figure shows that, in spite of the noticeable value of absolute jump/drops in temperature in the cross section of specimen/sample, the error, caused by the divergence of the utilized value of longitudinal gradient from mean with respect to section, is comparatively small and with wish can be decreased by the introduction of the corresponding correction. However, in this case, one ought not to forget that the introduction of this correction is virtually possible only for the zone of the stabilized temperature profile where a radial temperature differential is determined by pillar by the level of heat losses from lateral surface.

Thus, the carried out estimations make it possible on the whole to positively solve a question concerning the realization of the idea of longitudinal heat flux for measuring the coefficient of thermal conductivity in the range of very high temperatures.

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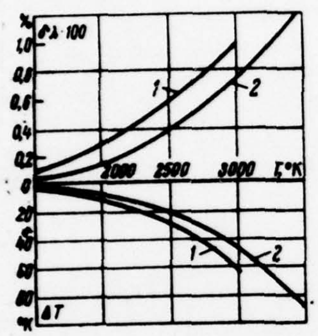

Fig. 4.3. Radial temperature gradient ΔT in a cylindrical sample with longitudinal thermal flow and the error in the determination of the coefficient of thermal conductivity. Material of the sample: 1 - tantalum; 2 - tungsten.

One of the first operational versions of the corresponding procedure and installation was proposed for the first time by D. L. Timrot and V. Ye. Peletskiy [7-20].

The basic torque/moments of method we will explain on basis Fig. 4-4, that reflects the most ideal and convenient version of proposed by them procedure [4-17]. Its corresponding structural/design embodiment is shown on Fig. 4-5.

The specimen/sample of the material being investigated, carried out in the form of cylinder with a length of L=50-70 mm and with a diameter of D=8-12 mm, is suspended on fine/thin tungsten filaments in vacuum chamber whose walls are cooled by water. For heating of specimen/sample, is utilized its bombardment on surface by the electrons, source of which are two cathode systems. One of them (cathode of lateral heating) provides power supply to lateral surface of specimen/sample, another (end cathode) makes it possible to independently heat it from one of the end/faces. Between cathodes and the specimen/sample applied accelerating voltage of 5-10 kV. Specimen/sample is together with the cathode system of lateral heating surrounded by the mesh antidynatron screen (see Chapter 2), on which is supplied negative with respect to cathode voltage (to 500 V. This same potential has the shielding shielding ring, which surrounds with small clearance specimen/sample rear hot end/face.

High electric intensity in radial clearance excludes the possibility of the inrush/breach of the electrons of end cathode to the lateral surface of specimen/sample. The geometry of system end cathode - the electrode - guard ring - specimen/sample near the cathode creates the electric field whose configuration provides the necessary focusing of electron beam on the end/face of specimen/sample.

The geometry of system suppressor grid - the filament of lateral cathode - specimen/sample, on the contrary, leads to the spread of electrons over the lateral surface of specimen/sample. The system of the suspension of specimen/sample, which simultaneously plays the role of current input to it, is shielded by the supplementary screen, connected with the line of high voltage by separate electrical lead. This screen intercepts the electrons of the high energies, which burst open through the antidynatron to riding-crop to the side of the system of suspension.

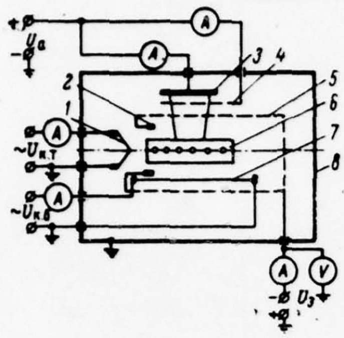

Fig. 4-4. Schematic diagram of the method of electronic heating [4-17]. 1 - end cathode; 2 - shielding ring; 3 - system of the suspension of specimen/sample; 4 - screen of the protection of the system of suspension; 5 - antidynatron screen; 6 - specimen; 7 - cathode of lateral heating; 8 - housing of unit.

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The described system makes it possible to realize the conditions, necessary for measurement of two values - specific radiant flows from the surface of specimen/sample $q_s(T)$ and strictly the coefficient of thermal conductivity.

It is real/actual let us assume that the lateral cathode is switched off. Works only end cathode. Energy of electron beam, isolated on the end/face of specimen/sample, is transferred along it because of thermal conductivity and is scattered by emission/radiation from lateral surface and cold end/face.

In steady state this process leads to shaping of the specific temperature field characterized by a decrease in the temperature from hot to cold end/face. Let us allow in the first approximation, that radial temperature differentials can be disregarded and field is one-dimensional: T (z). Then the equation of heat balance for the section of specimen/sample from the cold end/face z=L to cross section with coordinate z can be written in the form

$$\lambda F \operatorname{grad}_z T = \pi D \int_z^L q_s \, dz + F q_s (T_L), \qquad (4\text{-}22)$$

i.e. entire heat flux, which entered through the selected section the isolated part of the specimen/sample, is equal to the sum of heat losses from the surface, which limits its this part.

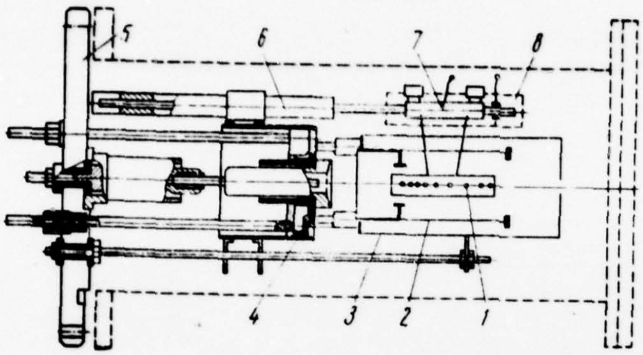

Fig. 4-5. Working section of the installation of D. L. Timrot and V. Ye. Peletskiy [4-17]. 1 - specimen/sample; 2 - cathode of lateral heating; 3 - antidynatron wire screen; 4 - assembly of end cathode; 5 - mounting flange; 6 - tubular insulator of the system of suspension; 7 - arm of the system of suspension; 8 - screen of arm.

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Calculated relationship/ratio for the coefficient of thermal conductivity takes the form

$$\lambda = \frac{4\int_{z}^{L+D/4} q_{s}\,dz}{D\,\mathrm{grad}_{z} T}. \qquad (4\text{-}23)$$

Thus, if in experiment we measured T(z) and $q_s(T)$, then these data are sufficient for determining the local value of the coefficient of thermal conductivity. Corrections, which consider the two-dimensional character of problem, can be introduced to the basis of the given above analysis. Under the condition of the introduction in (4-22) of mean longitudinal gradient, the coefficient of heat conductivity must be referred to mean temperature of section $T=\frac{T_{r=0}+T_R}{2}$. The recording of upper integration limit in the form of sum L+D/4 makes it possible to uniformly consider the contribution of losses from cold end/face.

For measuring the temperature in specimen/sample, are drilled several radial pyrometric channels of a small diameter (0.5-1 mm) not less than 5-6 diameters deep. These channels make it possible to simulate in the separate sections of specimen/sample blackbody and thereby they make it possible in work with the optical pyrometer to study the field of actual temperatures in specimen/sample.

The study of the temperature dependence of specific radiation losses is carried out by pi to the work of lateral cathode (sometimes for equalization of temperature field - in combination with end). In this case, besides temperature, are measured also complete emissive current I, caught into specimen/sample, and accelerating voltage U, and also the electrical power of cathodes. In steady state entire/all conducted/supplied to specimen/sample power is expend/consumed on emission/radiation (by work function of electrons, by losses to

X-radiation, by the dissipation of energy in clearance cathode - the anode with vacuum 10^{-5} mm Hg with accelerating voltages of 5-10 kV it is possible to disregard). Heat withdrawal on the filaments of suspension (tungsten wire 0.1-0.2 mm in diameter) can be disregarded. Under these conditions the energy balance appears as follows:

$$UI+\Delta Q_k=\int_S q_s(T)\,ds, \qquad (4\text{-}24)$$

where ΔQ_k radiant flux from cathodes, perceived by specimen/sample; S - surface of specimen/sample.

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If is calculated the average value of specific radiation in this conditions/mode $q_s=(UI+\Delta Q)/S$, where $\Delta Q=\Delta Q_k-S_0\times\left(q_0-\frac{UI}{S}\right)$; q_0- the specific radiation of blackbody; S_0 - total surface of the cross sections of pyrometric channels, then, as shown in [4-17], q_s and q_0 they must be referred to mean temperature determined by the relationship

$$T=\left[\frac{1}{S}\int_S T^4(S)\,dS\right]^{1/2}. \qquad (4\text{-}25)$$

The error, connected with this character of averaging, will not exceed 0.05-0.1o/o.

Let us note that this part of the experiment has independent value, since it makes it possible to obtain the important characteristic of material - integral hemispheric emissivity factor. The latter can be found from the formula

$$\varepsilon=\frac{q_0}{\sigma T^4}\left[1-\frac{S_0}{S}\left(\frac{\sigma T^4}{q_0}-1\right)\right]. \qquad (4\text{-}26)$$

where σ - constant of stefana - Boltzmann's law; T - temperature calculated according to equation (4-25).

One should indicate the possibility in principle of another type that instituted on equation (4-23). Let us examine the differential equation (in one-dimensional approach/approximation), which describes the process of thermal conductivity under conditions of the experiment in question:

$$\frac{\pi D^2}{4}\cdot\frac{d}{dz}\left(\lambda\frac{dT}{dz}\right)-\pi Dq_0=0. \qquad (4\text{-}27)$$

Utilizing the known conversion

$$\frac{d}{dz}(-q)=-\frac{dq}{dT}\cdot\frac{dT}{dz}=\frac{q}{\lambda}\frac{dq}{dT},$$

where $q=-\lambda\frac{dT}{dz}$ – heat-flux density, it is possible to lead (4-27) to the form

$$dq^2=\frac{8}{D}\lambda q_s dT. \qquad (4\text{-}28)$$

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Approximating the radiation losses by the exponential function of form $q_s=AT^n$ and after passing to the total flux through section $Q_\lambda=Fq$, we will obtain:

$$\frac{dQ_\lambda^2}{d(q_sT)}=\frac{\pi^2D^3}{2(n+1)}\lambda. \qquad (4\text{-}29)$$

Thus, the derivative of the square of heat flux on the product of specific losses to temperature is directly proportional to the true coefficient of the thermal conductivity of substance. The experimental data, processed in coordinates Q_λ^2 and q_sT, must be placed to the curves whose curvature is determined by the temperature course of the coefficient of thermal conductivity. For the small intervals of temperature in which the thermal conductivity virtually remains constant, it is possible to expect the linear dependence Q_λ^2 on q_sT. It is real/actual, after integrating (4.29), we will obtain:

$$Q_\lambda^2 = \frac{\pi^2 D^4}{2(n+1)} \bar{\lambda}(q_sT) + C, \qquad (4\text{-}30)$$

where C - constant, which considers boundary conditions; Q_λ — the total flux of heat in some section at temperature T; q_s — specific radiant flux at this temperature.

Maximum relative error of the determination of the coefficient of thermal conductivity by the described method lie/rests within limits of 10-15o/o for the average zones of specimen/sample at the range of temperatures to 2500-2800°K. By this method were carried out the measurements of the coefficient of the thermal conductivity of tungsten (in the interval of temperatures of 1200-3000°K [7-20]), zirconium (1200-1900°K [4-17]), niobium (1400-2300°K [4-18]), tantalum (1300-2900°K [4-16]), hafnium (1300-2000°K [4-19]) and other metals and the alloys.

The version of procedure presented, providing simplicity and sufficient reliability of experiment, and also its high productivity, at the same time possesses the number of deficiency/lacks.

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So, in particular, lower measurement range was limited by temperature of 1300-1200°K. With approach to it, already from temperatures of 1500-1400°K noticeably grow/rose the error: a reduction in the intensity of radiant heat emission was led with these temperatures to the decrease of longitudinal heat fluxes and the increase of error in the determination of temperature gradients. On the other hand, measurement with maximum temperatures they hindered due to the shielding effect of circular reflector. And if during measurements $q_s(T)$ circular reflector could with wish be abstract/removed from specimen/sample, then in experiment with end heating its presence was necessary. In connection with this the value of the actually lost radiant thermal flux decreased more noticeably the nearer to this ring was arrange/located the cell/element being investigated on surface of specimen/sample. In the first approximation, this charge could be taken into account by the correction $\varkappa$ of the form

$$q_{\text{бэф}} = q_{б}(1 - \varkappa);$$

$$\varkappa = \frac{L_к}{D_к - D} \cdot \frac{D_к}{D} \cos^3 \alpha \frac{\varepsilon q_к}{q_б}. \qquad (4\text{-}31)$$

Here: $L_к$ – the length of the ring of reflector; $D_к$ – its diameter; $q_к$ – its own specific emission/radiation from its surface, turned to specimen/sample; $\alpha = \operatorname{arctg} \frac{2x}{D_к - D}$, where x – distance from reflector to the circular cell/element of the specimen/sample, for which is examined the energy balance; ε – emissivity factor of this cell/element.

Derived by the method of relationship of projections [2-60] formula (4-31) makes it possible to faster only rate/estimate the character of a change in the correction along the length of specimen/sample (in the range, external with respect to ring), rather than to give its sufficiently precise value. The study of formula (4-31) shows that already during approach/approximation to the zone of reflector for the distance, equal to three clearances, the correction can have noticeable value and its introduction compulsorily. The presence of the shielded zone near hot end/face narrows the working zone of specimen/sample and with respect noticeably is decreased upper temperature boundary of reliable data.

To a certain degree with this, it is possible to reconcile, since the large part of the zone, being the section of shaping of temperature profile, nevertheless must be reject/thrown. However, can be found other, more effective solutions.

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One should indicate one additional deficiency/lack in the first version. Any change in an experiment in integral emissivity factor immediately will lead to the error in the measurements of thermal conductivity, to reveal/detect this change is sufficiently difficult. One of the paths is here checking thermal balance, instituted on assumption about equality the introduced into end/face thermal electronic power (measured with error not more than 2-3o/o) and leakage flux from an entire surface of specimen/sample. However, the information of this balance is hinder/hampered, since under conditions of heating from end/face the large part of radiant energy is scattered precisely from those most heated zones, temperature check of which is virtually impossible (hot end/face and the shielded zone of shaping of temperature profile). At the same time a change of emissivity factor due to the chemical interaction of the material of specimen/sample with residual gases can be observed precisely in the range of moderate temperatures (1000-1600°K) the contribution by emission/radiation of which to total energy balance is very small.

Output from the difficulties indicated is the direct measurement of the working heat fluxes, returned frcm cold end/face and lateral surface of specimen/sample.

On Figs. 4-6 and 4-7, are represented schematic diagram and the construction/design of the working section cf experimental installation of V. Ye. Peletskiy and Ya. G. Sobcl', created taking intc account the given requirements.

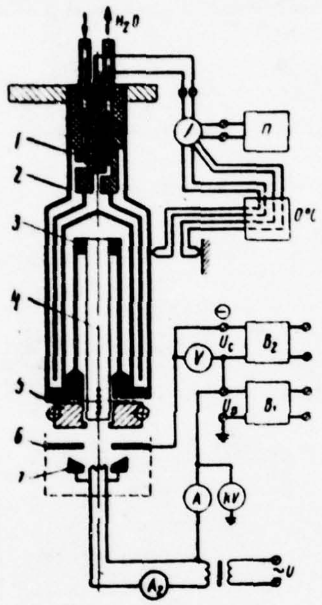

Fig. 8-6. Schematic diagram of installation of V. Ye. Peletskiy and Ya. G. Sobol'. 1 - thermometric sensor (differential thermopile); 2 - housing of calorimeter; 3 - ampule; 4 - specimen/sample; 5 - screen; 6 - focusing electrode; 7 - cathode assembly.

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Experimental model by one of its end/leads is attached in the special ampule, made from the stainless steel, with copper cap. The cap of ampule screws itself into the working zone of the water continuous-flow calorimeter whose internal beaker is made from copper. Threaded connection together with contact on end of surface they provide low thermal resistance between the cap of ampule and the calorimeter, which makes it possible to support here sufficiently low temperature (300-400°K).

The upper plane of the cap of ampule determines by itself the working section of the specimen/sample in which are conducted the measurements of heat flux and gradient of temperatures. For the protection of calorimetric part of radiant fluxes from the lateral surface of the zone of specimen/sample, which protrudes above the cap, and the cutoff of energy flows of cathode assembly the protruding part of the specimen/sample is surrounded by the massive water-cooled copper screen. Its lower plane disengages the cap of ampule the minimum clearance (0.5-0.8 mm), fixed/recorded with the aid of the setting drum, made from organic glass. The construction/design of the point of attachment of screen and its installation relative to the cap of ampule is selected so that to ensure considerable thermal resistance between them. This makes it possible to exclude the error, connected with the change-over of heat by thermal conductivity from screen to calorimeter or vice versa.

The length (height/altitude) of screen is determined by the need for the arrangement/position above the working section of the specimen/sample one or two of the pyrometric channels, necessary for the reliable measurement of temperature field. Furthermore, as shown above, these channels must be located in the zone of the formed temperature profile. This requirement with respect increases the necessary length of screen but that means and of the nonoperative part of the specimen/sample). Virtually depending on the conditions of the focusing of electron beam on the end/face of specimen/sample, the length of the zone of shielding lie/rests within limits (1-1.2) D. Lower than working section specimen/sample has an additional two radial pyrometric channels.

Over entire length of working zone (from lower to upper pyrometric channel) the cap of ampule and screen have radial slot 1.2-1.5 mm in wide.

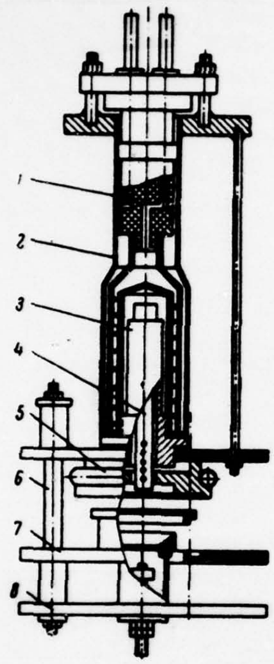

Fig. 4-7. Working section of installation of V. Ye. Peletskiy and Ya. G. Sobol'. 1 - thermometric sensor; 2 - housing of calorimeter; 3 - ampule of specimen/sample; 4 - specimen/sample; 5 - screen; 6 - insulator of cathode system; 7 - flange of the focusing electrode; 8 - flange of cathode assembly.

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One should emphasize the value of the ampule: with a comparatively short specimen/sample (about 70 mm) it, possessing high thermal resistance, makes it possible to raise the temperature of the "cold" end/face of specimen/sample on several hundred degrees above the temperature of calorimeter itself. Changing the thermal resistance of ampule (both selection of material and by the geometry), we can over wide limits affect the level of the gradients of temperature in the working section of specimen/sample. One should note also that this measuring circuit allow/assumes the use of radiation screening of specimen/sample and thereby it makes it possible to change the relationship/ratio between lateral losses and longitudinal heat flux.

Calorimetric beaker in upper part has contraction into which is introduced thermometric sensor. Sensitive element it is multicleavage differential thermocouple (copper-constantin, or chromel-Copel), the reguluses of joints of which are derived on the axis of channels for feed and derivation of water in calorimeter. Water first enters from the thermostat through the small tank of the fixed level into external radial clearance of calorimetric beaker, then washes internal copper beaker - heat receiver and is derive/concluded from the calorimeter through the central opening/aperture of temperature-sensitive element.

During calibration into calorimeter instead of the specimen/sample, is introduced special heater. They are measured the consumption of water (by the gravimetric method), of emf of temperature-sensitive element (by potentiometer P), of the temperature of the beaker of calorimeter and wall of vacuum water-cooled chamber. Is monitored the temperature of screen.

ab These data are sufficient in order to obtain the information about the heat flow, introduced into the calorimetric system through the working section of specimen/sample in basic experiment, with accuracy not worse ±(2-3)o/o.

Heating specimen/sample, as in the preceding/previous version, it is realized by the electrons, accelerated by electric field. Electron source is filamentary tungsten cathode. Accelerating voltage is supplied from the high-voltage rectifier B_1 (see Fig. 4-6).

Focusing is provided with the aid of the governing circular electrode, to which is supplied negative displacement from rectifier B_2. Cathode assembly is fastened to the mounting flange of screen with the aid of tubular insulators. In experiments the assigned conditions/mode is monitored with the aid of kilovoltmeter kV and ammeter A_1, shielded by interlock system B.

Calculation of the coefficient heat conductivity of work during this installation is performed on the basis of equation (4-12), in which value Q exists the heat flux, measured by calorimeter and corrected taking into account corrections. The latter are connected mainly with a difference in radiant fluxes into radial clearances specimen/sample - the cap of calorimeter to the side of screen and specimen/sample - screen to the side of calorimeter. Difference is caused by the presence of the gradient of temperatures in specimen/sample.

Allowance is calculated on the basis of the data on the coefficients of the irradiance of system [2-4, 2-17, 4-20] indicated.

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The described installation provides higher accuracy and the reliability of experimental data. A maximum systematic error in the results lie/rests within limits ±(5.5-6) o/o. Its considerable portion is caused by the systematic error in the determination of the longitudinal gradient of temperatures, which is found in this case (during the use of a micropyrometer of the type OMP-054) in range ±(4-4,5)o/o. The scatter of points at separate investigation lie/rests within limits ±(4-5)o/o. Reproducibility between the series, conducted with different specimen/samples of one and the same material, also is placed in this value.

The experience, acquired in work during installations with electronic heating, makes it possible to assert that and in the range of high temperatures, the method of longitudinal heat flux in the appropriate formulation can be the effective instrument for studying the coefficient of the thermal conductivity of metals and alloys, which are not inferior on accuracy to the best versions of other procedural approaches.

Chapter Five.

HIGH-TEMPERATURE STUDIES OF RESISTIVITY.

5-1. Ohm's law and its use in experiment.

As is known, specific conductivity σ in anisotropic body in the general case is tensor of second order and connects vector of density of electric current $\vec{j}_i$ and the vector of electric intensity $\vec{E}_k$ by the relationship

$$\vec{j}_i=\sigma_{ik}\vec{E}_k \ (i,\ k=1,\ 2,\ 3). \qquad (5\text{-}1)$$

The matrix/die, to the reciprocal matrix of specific conductivity, determines by itself the tensor of resistivity ρ_{ik}, that making it possible to connect the value of intensity/strength and electric current density:

$$\vec{E}_i=\rho_{ik}\vec{j}_k \ (i,\ k=1,\ 2,\ 3). \qquad (5\text{-}2)$$

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(In both formulas the repeated index k is the index of addition). It is obvious that for isotropic materials σ and ρ they are scalar quantities. This substantially simplifies their measurement and the calculation of current distribution in bodies.

Equations (5-1) and (5-2), that determine specific conductivity and specific resistance, cannot be directly used as the basis of experimental procedure. They must be supplemented by the equation, which determines the distribution of electric potential in the body in question. Such equation, as is known, is the equation of continuity (expressing condition of conservation of charge), which in the case of steady currents takes the form of the equation of Laplace

$$\Delta V=0.$$

For a uniform linear conductor by section S, loaded by current, the solution of boundary-value problem especially simple allows, after measuring total current I and a drop in voltage $U=V_1-V_2$ on section $x_2-x_1=L$, to calculate the unknown value of specific resistance:

$$\rho=\frac{U}{I}\cdot\frac{S}{L}. \qquad (5\text{-}3)$$

Let us note that in this case to lateral surface of the conductor of leakage of current are assumed to be equal to zero, i.e., $\left.\frac{\partial V}{\partial r}\right|_{r=R}=0$. This condition is equivalent to the assumption about the adiabatic insulation of system in problems in thermal conductivity. In the preceding/previous chapters we saw, which more difficulty causes the realization of this condition in studies of the coefficient of thermal conductivity. During the measurements of electrical conductivity, the situation is substantially simpler. The levels of the specific conductivity of different materials are distinguished on many orders, and the sufficiently strict realization of the boundary conditions in question is not any complex problem. This in turn, determine the possibility of the essential increase of accuracy during the measurements of electrical conductivity. So, for the problem, formulated above (and most by frequently utilized during measurements), the systematic errors, connected with the inaccurate realization of boundary conditions, are virtually absent.

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The error for experiment determines errors of measurement of difference potentials δU, total current δI and the geometric dimensions of conductor by length δL with cross-sectional area δS. During the precision analysis of the conductivity of conductive materials (metals and alloys) most wide propagation will obtain compensative measuring circuits with direct current. Here consecutively with the specimen/sample being investigated is included specimen normal resistance, and in the working zone of specimen/sample by fine/thin conductors are made two potential derivations. This schematic makes it possible one and the same potentiometer to measure voltage drops across specimen resistance and working section of specimen/sample and to eliminate the effect of contact resistance in the places of the connection of measuring meters. The commutation of measuring current makes it possible to eliminate in this case the effect of parasitic thermoelectromotive force in metering circuits.

The contemporary potentiometers of direct current provide accuracy to the thousandth fields of percentage, and specimen coils - to 0.01o/o. Thus, the measurement of electrical resistance R=U/I of working section can be carried out with error from several hundredth to the tenths of percentage. Let us note that in this case is indifferent the level of temperature of specimen/sample. The calculation of specific resistance is connected with the use of results of the measurements of the geometry of specimen/sample. With not too small size/dimensions its corresponding errors also can be sufficiently small.

The object/subject of special studies is the temperature dependence of conductivity. If specimen/sample is nonisothermic, arises the question concerning the calculation of the reference temperature of the specific conductivity, designed on the total resistance of section. With the known character of temperature field, this does not cause difficulties and it can be carried out with sufficiently high accuracy.

In summary simplicity and reliability of the realization of most simple boundary conditions in combination with high precision of instruments for measuring of electric currents and voltages create the prerequisites for the precision measurements of the specific conductivity of materials in all interval of temperatures.

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Difficulties, with which we collide in high-temperature range, are caused by the common/general/total problems of high-temperature techniques related to making more active of the processes of destroying (change) in material, the complexity of the creation of the assigned type of temperature distribution and its reliable measurement. Even in the simplest methods these factors sometimes become determining. We will consider, for example, experiment in the wire specimen/samples, heated by the passing current.

The strong dependence of the electrical resistance of the majority of materials or temperature imposes stringent requirements to the reliability of the determination of temperature of reference. In the range of high temperatures, this problem is solved mainly methods of optical pyrometry, which require the knowledge of emissivity factor of material.

The essential dependence of the latter on the physicochemical and mechanical states by that radiating surface conductor forces to carry out vacuum-thermal treatment of specimen/sample, maintain/withstanding it sufficiently for long with very high temperatures in fine vacuum. In this case, it is necessary to consider the action of two effects: collecting recrystallization and the sublimation of material. The consequence of the first can be the disturbance/breakdown of the physical uniformity of conductor, caused by the mutual shift/shear of the separate crystallites, which grew for all the section of specimen/sample [5-1]. In this case resistance of conductor noticeably grow/rises; the calculation of specific resistance becomes complicated due to the indeterminancy/uncertainty of shape factor.

The second effect, on one hand, leads to a change in the microroughness of specimen/sample (and, consequently, of its emissivity factor), but on the other hand - changes its cross section. With temperature rise, the rate of this change can become so/such essential, that it will exclude the possibility of the nonautomated (by the way speaking, now most precise) measurements of the electrical parameters. The calculation of specific conductivity under these conditions requires cooling specimen/sample and measurement of its geometry after each "hot" conditions/mode.

The action of the factors indicated is exhibited more powerfully, the thinner the conductor. Despite the fact that the suppressing number of reference data on the electrical resistance of metals in high-temperature range obtained precisely in wire specimen/samples, was necessary precaution when selecting and realization of this method.

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The action of the factors indicated is exhibited much more weakly during the use of massive specimen/samples.

It is certain, the realization of heating specimen/sample by the direct/straight passage of current here becomes unsuitable. On one hand, this is connected with a sharp increase of the strength of current (to several thousand amperes), with another - with the need for considerable increase in the length of specimen/sample for decrease to the acceptable value of the degree of the nonisothermicity of working section. Experiment can be placed in comparatively short specimen/samples, heated because of external sources. This somewhat complicates the construction/design of installation; however, guarantees higher accuracy of measurements. An increase in the diameter of specimen/sample to several millimeters and more it makes it possible to disregard the sublimation and other phenomena, connected with mass transfer either chemical reactions on the surface of specimen/sample, or to consider by their path of the introduction of a small correction.

Further, which is very substantial, an increase in the diameter makes it possible to organize the reliable measurements of the actual temperature of metal to which must be referred the found value of electrical conductivity. During high-temperature precision measurements of electrical conductivity, everything said above forces to give preference to the methods, oriented for the use of massive specimen/samples.

5-2. The method of measuring specific electrical resistance at temperatures higher than 1000°C with the use of electronic heating.

The considerations presented higher than were taken into account during the development of the high-temperature version of compensative the method of direct current, developed by the authors of work [5-2] on the basis of the electronic heating of specimen/sample.

The use of the latter dictated mainly by the tendency to exclude the contamination of specimen/sample by the products of the sublimation of foreign substances and to bring the level of working temperatures to temperatures of melting the materials being investigated.

To these requirements resistance furnace (indirect heating) cannot be satisfied. Direct/straight heating by the passing current it is difficult to realize due to the large diameter of specimen/sample (8-15 mm).

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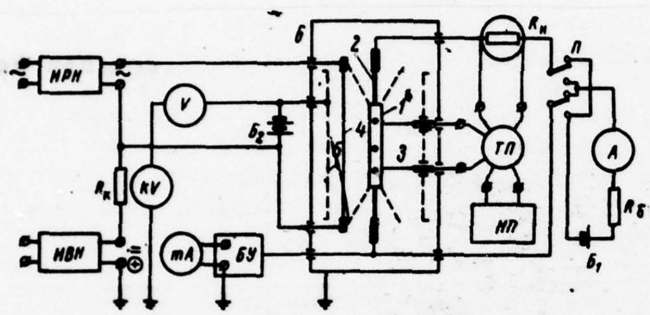
The application/use of electronic heating, having indisputable its deficiency/lacks, as a whole it successfully solves stated problem. The electrical circuit of installation is represented on Fig. 5-1.

The specimen/sample being investigated, jammed between two current electrode-holders, closes the measuring high-current circuit, which consists of the source of voltage (storage battery B_1 by capacitance/capacity several hundred ampere-hours), ballast resistance $R_б$, switch of polarity P and of normal resistance $R_н$. By low-resistance potentiometer NP is measured a voltage drop across specimen coil and the working section of specimen/sample (with the aid of potentiometric probes); switching is conducted by thermocouple switch TP. One of the current electrodes of specimen/sample is grounded through milliammeter mA and blocking equipment/device BU. Introduction of the latter cell/element was caused by the use of a specimen/sample as the anode in the system of electronic heating, made according to the schematic of vacuum-tube diode. The electrons, emitted by cathode, are accelerated electrical field created with the aid of the source of high voltage of IVN, between the cathode and the anode-form, bombard and heat the latter. Plus of rectifier is grounded. The electrical circuit of the system of electronic heating is closed through the earth circuit of specimen. The located in this circuit milliammeter it is utilized for a check of the amount of power, introduced into specimen/sample (but thereby indirectly and after the temperature conditions of heating). Blocking equipment/device BU shunts milliamperemeter with the kicks of emissive current, possible in the conditions/modes of vacuum training/aging and annealing of specimen/sample. For limiting the value of these kicks and softening of the work of an entire schematic, is utilized resistance $R_{н}$, which includes nonlinear component, made on the basis of lamps NG-51 (220 V, 300 W).

The source of high voltage is made according to three-phase bridge circuit and has an output voltage, adjusted within the limits 5.6-10 kV.

Fig. 5-1.

Schematic diagram of installation for measurement of the specific resistance of metals with high temperatures. 1 - specimen/sample; 2 - holders; 3 - potentiometric probes; 4 - cathode; 5 - screen; 6 - Vacuum chamber.



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The supply of cathodes (filamentary) is realized by alternating current from the source of variable voltage IBN, that includes isolation transformer with the intensive electrical insulation of windings. With datum to the schematic of grounding the cathodes are found under high potential relative to the earth/ground.

For the prevention/warning of the incidence/impingement of electrons to the grounded housing of vacuum chamber between cathode system and housing, is placed the cylindrical screen, on which is supplied the negative with respect to cathode bias voltage from auxiliary battery B_2, controlled by voltmeter V.

Thus, the common/general/total electrical installation diagram consists in this case of two main subcircuits, united by overall section - specimen/sample with current electrodes. In this case, immediately arises the question concerning the value of the possible errors, connected with the presence in the specimen/sample and other cell/elements of the anode current circuit of the schematic of heating. So that the study of this problem will be more concrete/specific/actual, it is convenient to here examine the special feature/peculiarities of the structural/design realization of the working section of installation. It is represented in Fig. 5-2.

Specimen/sample 1 being investigated is manufactured in the form of rod with a diameter of 8-14 60-70 mm in long. On the height/altitude of specimen/sample, is made a series of radial cylindrical channels 1.0-1.2 -mm in diameter at the depth of order one and one-half radii of specimen/sample. During the measurements of temperature, these channels perform the role of the models of blackbody.

Current electrodes 2, between which is clamped the specimen/sample, are manufactured from the tungsten pointed rods 2 mm in diameter. Potentiometric electrodes 3 are made from tungsten wire 0.5 mm in diameter; with the aid of springs 4, they are pressed by points against by the surface of specimen/sample. With heating of the sample in a vacuum the points are welded with the surface of the sample providing the stability of contact resistance. Cathode 5 is made in the form of vertical filaments from tungsten wire 0.2 mm in diameter, attached on lamellar U-shaped compensators.

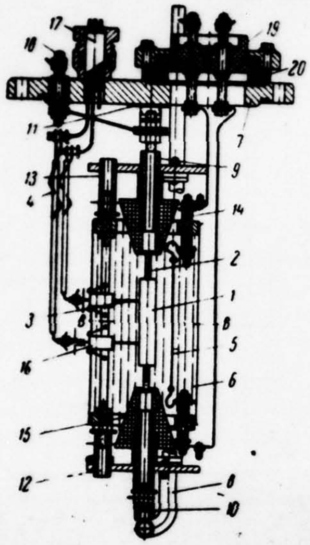

Fig. 5-2. Construction/design of the working section of installation for measuring specific resistance of metals by the method of electronic heating.

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These filaments are arrange/located around specimen/sample and parallel-connected between themselves. Screen assembly has a form of the squirrel cage, arrange/located concentrically with respect to specimen/sample; its grid 6 is made from molybdenum wire 0.5 mm in diameter. Cathode-screen assembly has a joint in vertical plane for convenience in installation and replacement of specimen/sample and cathodes.

All cell/elements of electronic heater are fastened under the upper flange of 7 vacuum camera/chambers to water-cooled U-shaped tube with 8. Insulation/isolation of specimen/sample with electrodes from vacuum chamber is realized with the aid of directing porcelain tubes with 9 and end insulators - lower 10 (porcelain) and upper 11 (mica). Insulation/isolation of cathode-screen assembly from vacuum chamber and specimen/sample - electrode system is made in the form supporting/reference 12 and directing 13 porcelain tubes it is designed on 10 kV. The clearances between the separate elements of these systems compose value not less than 6 mm. Insulation/isolation between the cathode and the screen is realized with the aid of wall entrance insulators by 14, made from porcelain ones beads and quartz capillary, and it is designed to the bias voltage on the order of 300 V.

All insulators are protected from becoming dusty by the products of the sublimation of specimen/sample by washers made of sheet tantalum, which excludes the possibility of surface breakdown or leakage of measuring current on insulators.

For the protection of the holders of current electrodes from the electron bombardment, are establish/installed cone-shaped reflectors 15 of the wiring, to which is supplied the potential of cathode. Holders of the potentiometric electrodes are protected from electron bombardment with tantalum tubes 16, which have the potential of screen.

From the side of inspection window of the vacuum camera/chamber, screen grid forms a slot through which is conducted the pyrometry. All electrodes are arrange/located on upper flange. The vacuum packing/seal of potenticmetric electric lead-ins is realized in standard mushroom connection 17.

The electric lead-ins of measuring current are made in the form of stud bolts 18, condensed by teflon bushings. High-voltage electric lead-ins are attached in teflon insulator 19, condensed with the aid of rubber packing 20.

Cathode assembly with specimen/sample is placed into vacuum chamber where during work is supported pressure order 10^{-6} mm Hg, controlled by vaccummeter VMB-2 in assembly with sensor MM-8.

The combined examination of the schematic diagram (see Fig. 5-1) and the construction/designs of installation (Fig. 5-2) makes it possible to make conclusion about the inevitability of the appearance of secondary stresses on the different sections of measuring circuit, which is located in the zone of a cathode-anode assembly.

Struggle for the isothermicity of specimen/sample forces to allow/assume the considerable scatter of electron beam from cathode in interelectrode space. To shield potentiometric probes from electrons under these conditions is proved to be impossible.

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The portion of common/general/total electronic flux, coming to probe to specimen/sample, will cause the appearance on it of a parasitic potential difference

$$\Delta U_3 = \beta_3 I_э,$$

where $I_э$ — the total current of emission; β_3 - coefficient, depending on the geometry of system, potential distribution in screen - filament system - specimen/sample, the material of probe and series of other factors. The currents, which fall from cathode to specimen/sample, are accumulated to ground point, being distributed in accordance with effective resistances of metering circuit. To analytically calculate the caused by them supplementary voltage drop across working section ΔU_p is sufficiently difficult, since in the general case this problem of two-dimensional (at least) potential distribution in system with arbitrary density distribution of current on the lateral surface of specimen/sample. Total analysis, however, makes it possible to note that value ΔU_p is proportional to common emissive current $I_э$ and, just as for probes, can be written in the form $\Delta U_p = \beta_p I_э$. Proportionality factor is determined by the conditions, enumerated for β_3. Coefficients β_3 and β_p in the first approximation, do not depend on the direction of measuring current I. This allows with sufficient for an experiment accuracy to exclude the effects in question, utilizing the measurements, made in two directions of measuring current.

It is real/actual, the overall potential drop on working section will be equal in one case

$$U_1 = I_1 R + \beta_p I_э + \beta_3 I_э$$

and in other

$$-U_2 = -I_2 R + \beta_p I_э + \beta_3 I_э$$

where R - resistance of working section. Thus, with $I_э$ = const (value $I_э$ is monitored with accuracy not less than 0.1-0.2o/o), after deducting one expression of another, we will obtain equality

$R(I_1+I_2)=(U_1+U_2)$, in which the additive terms, caused by the electron bombardment, are absent. Let us note, besides the fact that the value of measuring current usually not less than by an order exceeds the value of emission current $(I_{изм} \approx 10\ A;\ I_э' < 0.5\ A)$.

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The reception/procedure of the use of a commutation of measuring current indicated in the general case makes it possible to remove effect of parasitic thermoelectromotive force, caused by a difference in the temperatures in the specimen/sample between the contact area/sites of probes. Taking into account that currents I_1 and I_2 are determined from drops in voltage U_{01} and U_{02} on the specimen coil R_0, final calculated relationship/ratio for resisting the working section can be written in the following form:

$$R = R_0 \frac{U_1 + U_2}{U_{01} + U_{02}}, \qquad (5\text{-}4)$$

where the different indices are related to the different directions of measuring current.

The calculation of specific conductivity according to the data on the value of total resistance of working section is feasible, if is known the form of the function of density distribution of current according to section S of conductor. In the case of constant density, the value impedance is connected with resistivity ρ by the known relationship/ratio $R=\rho L/S$. However, the possibility of using this relationship/ratio under our conditions (short specimen/sample) requires special examination, instituted on the solution of the corresponding boundary-value problem.

The realized in construction/design (Fig. 5-2) version of current input to specimen/sample corresponds to the assignment of the specific potential on the section of butt end of specimen/sample with a radius of r_0 (equal a radius of current electrode). On remaining surfaces, disregarding the emissive current (for this problem this admissibly), it is possible to take as equal to zero potential gradient along the normal to surface.

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Under these conditions the solution of equating Laplace for potential distribution Φ is represented by relationship/ratio [5-3]

$$\frac{\partial^2\varphi}{\partial z^2}+\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)=0; \qquad (5\text{-}5)$$

$$\varphi-\varphi_0=I\rho\frac{z}{\pi R^2}+I\rho\frac{2}{\pi r_0}\times$$

$$\times\sum_{n=1}^{\infty}\frac{\mathrm{sh}\left(\gamma_n\frac{z_0}{R}\right)}{\mathrm{ch}\,(\gamma_n H/2R)}\,\frac{J_1(\gamma_n r_0/R)\,J_0(\gamma_n r/R)}{\gamma_n^2 J_0^2(\gamma_n)}, \qquad (5\text{-}6)$$

where I - current; ρ - resistivity; J_0, J_1 - Bessel function of first kind of zero and first order; γ_n — positive the roots of equation $J_1(\gamma)=0$. With z=0 (middle of cylinder) $\varphi_0=0$. Formula (5-3) it is convenient to present in the form

$$\varphi=\left(I\rho\,\frac{z}{\pi R^2}\right)(1+\mu),$$

where the multiplicand corresponds to the known formula of the distribution of current potential for the case of constant current density over section, and value

$$\mu=\frac{2}{(z/R)(r_0/R)}\sum_{n=1}^{\infty}\frac{\mathrm{sh}\,(\gamma_n z/R)}{\mathrm{ch}\,(\gamma_n H/2R)}\,\frac{J_1(\gamma_n r_0/R)J_0(\gamma_n r/R)}{\gamma_n^2 J_0^2(\gamma_n)}$$

determines allowance for the nonuniformity of current density. For a cylindrical specimen/sample with ratios H/R=65/7 and $r_0/R=1/7$, the results of the calculation of correction μ with r=R (for the surface of specimen/sample) are represented below.

$\Delta H/R$	0	0,143	0,643	1,143	1,64
$-\mu$	$8,17\cdot10^{-2}$	$5,64\cdot10^{-2}$	$1,22\cdot10^{-2}$	$2,19\cdot10^{-3}$	$3,82\cdot10^{-4}$
$\Delta H/R$	2,14	2,64	3,14	3,65	4,64
$-\mu$	$6,76\cdot10^{-5}$	$1,25\cdot10^{-5}$	$2,45\cdot10^{-6}$	$5,50\cdot10^{-7}$	0

Here ΔH/R - relative removal/distance of calculation point from the end/face of specimen/sample. Allowance changes from several percentages near end/face (ΔH/R≈0) to zero in the center of specimen/sample (ΔH=H/2). On the basis of this calculation, it is determined, that the potenticmetric electrodes must be distant from the end/faces of specimen/sample up to distance not less than its one diameter (ΔH/R≥2). In this case the correction for bending of equipotentials composes the value of order 0.01o/o and less and it can be disregarded.

During the calculation of specific resistance, it is necessary to consider certain increase in resistance, caused by pyrometric channels on the working section of specimen/sample.

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In the first approximation, it is possible to consider that the total resistance of section with a length of L, can be presented in the form of the sum of resistance of zone without channels R_0 and resistance of the zone of conductor whose section decreased by radial borings with a diameter of d and with a depth of R:

$$R=R_0+R_к n=\rho\frac{L-nd}{S_0}+nR_к,$$

or

$$R=\frac{\rho L}{S_0}\left[1+\frac{nd}{L}\left(\frac{R_к}{R_{0к}}-1\right)\right]. \qquad (5\text{-}7)$$

where $R_{0к}=\rho d/S_0$, and the second term in the brackets $\frac{nd}{L}\left(\frac{R_к}{R_{0к}}-1\right)=\eta$ is correction for n of pyrometric cavities. If is allowed uniform density distribution of current in all sections of conductor, then resistance $R_к$ it will be computed completely simply:

$$R_к=\rho\int_0^d\frac{dz}{S(z)}=\frac{\rho}{h}\left(\frac{2}{\sqrt{1-\varkappa^2}}\operatorname{arctg}\sqrt{\frac{1+\varkappa}{1-\varkappa}}-\frac{\pi}{2}\right), \qquad (5\text{-}8)$$

where $\varkappa=hd/S_0$.

During practical use results are conveniently presented in the form of curve/graph $(R_к/R_{0к}-1)=f(\varkappa)$. Allowance η with the selected geometry of specimen/sample varies within the limits of 0.02-0.04 increase in the diameter of specimen/sample with the preservation/retention/maintaining of the geometry of the pyrometric channel of constant it makes it possible to noticeably lower value of η. It must be noted that calculation according to formulas (5-8) and (5-7) gives lower boundary of possible correction. In the real case the bending of isopotentials around opening/apertures, noticeable in range by size/dimension to 1.5-2 diameters of pyrometric channel, causes the nonuniformity of density distribution of current. Real disturbance/perturbation is greater than the values, predicted by formula (5-8). However, as showed measurements, probable deviations do not exceed the limits of 0.2o/o of measured values of resistance, which corresponds to the error in very allowance 10-15o/o.

Essential characteristic of heating system is the degree of isothermicity, which it in state to ensure in the working zone of specimen/sample. In the described installation is used the maximally simple cathode system: the filament cathode in the form of one or several tungsten filaments, stretched along the specimen/sample between its surface and the screen grid.

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At sufficient length of cathode filaments, the density of electronic flux along the length of specimen/sample is proved to be in effect constant. Longitudinal nonisothermicity is developed in essence due to the uncompensated heat losses from butt ends and on working section does not exceed 0.5-1o/o of maximum temperature.

The temperature distribution in the cross sections of specimen/sample is form/shaped under the effect of the nonuniformity of the angular distribution of electrons. In the most unfavorable case (heating one cathode) relative value of nonisothermicity here can reach 1-2o/o. During the arrangement/position of pyrometric cavity along mean isotherm, this can lead to the error in the determination of the reference temperature, which reaches 0.2-0.5o/o (at temperatures of 3000°K and low thermal conductivity of specimen/sample). Taking into account entire this a maximum relative error in the results during the use of this method does not exceed the limits of 1.5-2o/o with the scatter of points 0.5o/o (see [5-4]). This makes it possible to consider this method as instrument for the precision absolute measurements of the specific resistance.

5-3. Noncontact methods of measuring electrical conductivity.

The examined above methods of measuring electrical conductivity assume the physical contact of specimen/sample with the cell/elements of power and metering circuits. They are connected with the use of direct current. The application/use of alternating current of sufficiently high frequency expands the circle of the physical laws which could be the basis of experimental procedure. So, in particular, the use of a phenomenon of mutual induction makes it possible to carry out the diverse variants of the methods, which do not require direct contact with specimen/sample.

Among them most wide acceptance found the so-called method of the rotating magnetic field, instituted on the measurement of the torsional moment, caused by power interaction of external magnetic field with induced in specimen/sample vortex field currents. For the first time realized in the version of relative method of Braunbek [5-5], Grube and Speidel [5-6], it is most thoroughly studied by A. R. Riegel [5-7, 5-8]. Utilizing the general solution, given in hertz [5-9], A. R. Rigel' will bring it to the calculation formulas, valid at any frequencies, and will check experimentally the effect of probable deviations from ideal conditions.

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Examining spherical specimen/sample with a radius of R, which is located in uniform magnetic field by intensity/strength H, which rotates with angular velocity ω, it is possible to find taking into account self-induction the following expression for the Joule heat W, isolated by vortex currents:

$$W = \frac{3}{4}\omega R^3 H^2 N(t), \qquad (5\text{-}9)$$

where

$$N(t)=\frac{t(\mathrm{sh}\,2t+\sin 2t)-(\mathrm{ch}\,2t-\cos 2t)}{t^2(\mathrm{ch}\,2t-\cos 2t)}; \quad (5\text{-}10)$$

$$t=R\sqrt{2\pi\omega\sigma/c^2}. \quad (5\text{-}11)$$

Here: [W] = erg/s; [R] = cm; [ω] = rad/s; [H] = Oe; [c] = cm/s - speed of light; [σ] = un. CGSE.

It is possible to show that torque/moment acting on sphere, it is connected with heat release in it by the relationship/ratio

$$M=W\omega^{-1}. \quad (5\text{-}12)$$

Then, by knowing from experiment R, H, M and ω, it is possible to find t, but from it - the unknown conductivity. Function N(t) is computed previously. In work [5-7] for it is given the corresponding Table. Let us here point out that if is is restricted to accuracy 1% then function N(t) it is possible to represent it in the following expressions:

(1) при $t \leqslant 0,85$ $N_1(t) = 8,88(8) \cdot 10^{-2}t^2$; (5-13)

(1) при $t \geqslant 2,5$ $N_2(t) = (t-1)/t^2$. (5-14)

Key: (1). with.

If self-induction can be disregarded, then formula (5-9) is simplified:

$$W_1 = \frac{2\pi}{15} \cdot \frac{\sigma\omega^2 H^2 R^5}{c^2}. \quad (5\text{-}15)$$

With the determining role of the self-induction

$$W_2 = \frac{3}{4} \cdot \frac{cH^2R^2\sqrt{\omega}}{\sqrt{2\pi\sigma}}. \quad (5\text{-}16)$$

Let us note that for a sphere the problem is solved accurately. This creates basis for the absolute measurements of resistivity. The value of torque/moment can be determined by the angle of twist ϕ of the elastic thread, on which is suspended the specimen/sample.

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As is known, between these values with small ones φ there is the single bond:

$$M=K_{\text{н}}\varphi, \quad (5\text{-}17)$$

where the factor of proportionality $K_{\text{н}}$, called of the constant filament of suspension, depends on a radius of filament, its length and modulus of shear of the material of filament.

If as the sources of magnetic field are utilized coils with current I (without core), then is direct proportionality between magnetic intensity H and current I makes it possible to conduct experiment, measuring the current.

A. R. Riegel [5-8] estimates a possible error in the method during the absolute measurements by the value of order 1o/o. In relative version without taking into account of the error for standard, it is possible to speak about the even lower value of order 0.5o/φ [5-11].

In the latter case for $t\ll 1$, basic calculated relationship/ratio can be used in the form

$$\rho = \frac{1}{\sigma} = K \frac{I^2}{\varphi} V^{5/3}, \qquad (5\text{-}18)$$

where the constant of instrument $K = \frac{\rho_э}{V_э^{5/3}} \left(\frac{\varphi}{I^2}\right)_э$ is determined in special experiment with the standard material whose resistance $\rho_э$ is studied sufficiently reliably.

In formula (5-18) is introduced into examination the volume of specimen/sample V. As shown in work [5-7], the use of an equivalent volume of sphere makes it possible to decrease the effect of the inadequacies of the geometry of specimen/sample. Let us note that the accuracy of the measurements of a radius must be very high ($W_1 \sim R^5$). The results of measurements are very sensitive to changes in the size/dimensions of specimen/sample. In connection with this during the investigation of the temperature course of conductivity, the knowledge of the coefficient of expansion is completely necessary.

Spherical form is not always convenient. For the number of materials and, in particular, for studying conductivity change with the melting of specimen/sample more convenient is cylindrical specimen/sample. For an infinitely long cylinder the solution of the problems of the torsional moment of specimen/sample, which is located in the uniform rotating magnetic field, can be found in Ya. I.

Frenkel [5-10]. The problem of final specimen/sample is not finally studied.

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In connection with this in works with cylindrical specimen, are utilized, as a rule, the relative measurements, instituted on the assumption that with the identical geometry of standard and investigated specimen/samples the effect of end effects will be identical independent of conductivity [5-5, 5-6]. This assumption confirmed experimentally Ecll [5-11], shown that the corresponding correction depends only that of a radius of specimen/sample. It is possible to assume that this will be valid, while self-induction is unessential.

The basic calculated relationship/ratic of method in this case usually [5-5, 5-11-5-17] is utilized in the form

$$\rho = K_{\text{u}} \frac{t^2}{\varphi} l R^4, \qquad (5\text{-}19)$$

where K_{u} — the constant of installation, determined in experiments with standard specimen/sample; l - height/altitude of specimen/sample; R - its radius.

A series of the entering formula (5-19) values includes the corrective corrections. Thus, for instance,

$$\varphi=(\varphi_{изм}-\varphi_0-\Delta\varphi_{шк})(1-\Delta\nu/\nu_0), \quad (5\text{-}20)$$

where $\varphi_{изм}$ — measured in experiments divergence; ϕ_0 - divergence of system with the removed specimen/sample, caused by the effect of the scattered magnetic field on the metallic elements of register system; $\Delta\varphi_{шк}$ — correction, which appears during use in report equipment/device of the flat dial (in place of cylindrical); $\Delta\nu/\nu_0$— correction for the divergence of current frequency during measurements from normal, that occurred with calibration.

$$l=l_{изм}-K_l \quad (5\text{-}21)$$

where $l_{изм}$— actual length of specimen/sample; K_l— correction for the finiteness of specimen/sample [is located for a given radius in experiments with the specimen/samples of different length through dependence $\varphi/l^2=f(l)$]: $K_l \doteq l_{\varphi/l^2=0}$.

If into formula (5-19) are introduced the geometric characteristics, undertaken at room temperature, then whole expression must be multiplied by the corrective factor of form (1+5$\alpha\Delta T$), that considers the thermal expansion of the specimen/sample where α - a coefficient of linear expansion.

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Until now, we say nothing about the temperature boundaries of method. From the overall considerations it is possible to make the conclusion that these boundaries must be sufficiently wide. It is real/actual, on one hand, for the work of installation it is substantial so that in the zone of specimen/sample works external magnetic field. This problem with any furnace is comparatively simply solved by appropriate selection of nonmagnetic materials (copper, brass, stainless steel, tungsten, graphite, etc.). It is substantial so that the proper magnetic field of heater will be sufficiently little. This problem is also solved simply (double winding, duct in duct, etc.). Most complex problem is the thermostating of the elastic thread on which will hang the specimen/sample. Traditional reception/procedure is here the use of intermediate rigid rod, which transmits the torsional moment from furnace into the shielded zone; the filament of suspension is placed in the water-cooled duct above the furnace. The connection of rod with the filament through the plate of dielectric (mica) makes it possible to considerably decrease the possible heating of filament and, consequently, also the change in its elastic constant. Check of the torsion of filament is realized usually on the rotation of the mirror, attached on transient plate.

The solution of the named problems, of course, hinders during transition into high-temperature range, however, as it shows experiment, it is attained within the framework of acceptable accuracy. As an example it is possible to indicate the work [5-15], in which are made conductivity measurements of nickel fusions with carbon to 1900°C (in solid and liquid states), to works [5-16, 5-17], in which operating temperatures reach 2100°K (in particular measured the electrical resistance of chromium).

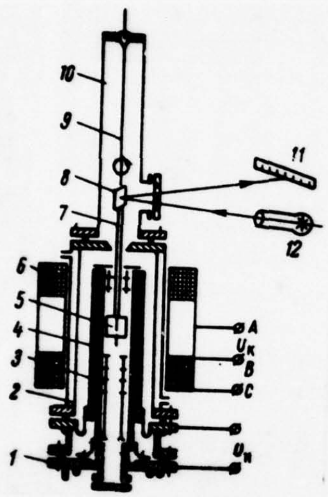

Fig. 5-3. Schematic diagram of construction of installation with the rotating magnetic field.

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The schematic diagram of the construction/design of the high-temperature experimental installation, working according to the method of the rotating magnetic field, is represented in Fig. 5-3.

On bearing flange 1, which has water cooling, is installed the electric furnace whose heating element 4 is made according to schematic duct in the duct (or it has double winding for decreasing the proper magnetic field). Furnace body 2 is equipped by the jacket of water cooling and is made from nonmagnetic materials. Three pairs of coils 6 are placed at angle of 120° in plan/layout and are included by star in the circuit of three-phase current (terminal ABC). in Soviet works [5-7, 5-8] usually are utilized the coils without core in order to ensure the mutual proportionality of current and magnetic field strength. In the works of Boll [5-11] successfully is utilized the usual stator of the electrical asynchronous engine with the pole pieces. As shown in this work, and in this case over wide limits is satisfied the condition of direct proportionality between the current strength in coils and magnetic intensity. Let us note that usually the coils thermostatically control. Riegel [5-8] for this purpose places them into special oil thermostat with water cooling. During coil setting in his work, it is recommended, furthermore, to separate/liberate mechanically this thermostat from the housing of unit, removing thereby the transmission of the appearing sometimes vibrations to housing and system of suspension. In the upper part of the installation, is secured thermostatically controlled duct 10 with elastic thread 9 whose torsion is monitored according to the divergence of that reflected from mirror (light spot of illuminating system 12 on scale 11. Turning moment from specimen 5 is transferred to the elastic thread by rod 7, suspend/hung to plate with mirror. The system of screens 3 in furnace provides the isothermicity of specimen/sample, and on end in lower flange makes it possible to carry out the measurements of its temperature by optical methods.

In the works, made by the method of the rotating magnetic field, attention is drawn to the small value of the scatter of experimental data. This testifies to the sufficiently high resolution of method. Basic error store/adds up in essence from the systematic errors, connected with the temperature dependence of constant installation and the inadequacy of the geometry of specimen/sample.

In a series of the cases researchers does not succeed in considering these factors entirely. A characteristic example is disagreement of the data of potentiometric and contactless measurements, discovered during the investigation of the conductivity of chromium - silicon system in work [5-17]. With scatter in both series of order 0.5o/o, the disagreement indicated reaches 10o/o.

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We give this numeral not in order to express distrust to the method in question, but, in order emphasize the need for careful inversion with it. In our view, are here laid the great possibilities, up to now not exhausted by experimenters. The idea of the use of a power effect, which appears during interaction of conductor with the magnetic field of the controlled/inspected value, that move relative to each other can be realized in the most diverse versions for the most varied geometries of specimen/sample. It is possible as an example to indicate the work [5-18] in which the calculation of resistance is performed on the measurements of the logarithmic decrement of damping the torsional oscillations of specimen/sample in known magnetic field, or in works [5-20, 5-21], where as the basis of calculation were placed forces acting on specimen/sample in heterogeneous magnetic field.

Sufficiently strict theory, the possibility of organizing the absolute and relative measurements very wide range of operating temperatures, high accuracy - all this makes the examined method with the effective instrument of the investigation of electrical conductivity of materials both in solid and in liquid states.

Considerable number of works in the range of conductivity measurements of different structural materials made noncontact methods, instituted on a change in the impedance of the solenoid, supplied by alternating current, during the introduction into it of the conductor of one or the other form.

If R_0 and L_0 - respectively active constituent of resistance and the inductance of the isolated/insulated coil, then after the introduction into it electroconductive specimen/sample these parameters will change. The new effective resistance R will now stored two components: R_0 and R', where R' - component of resistance, that corresponds to the increase of ohmic losses because of eddy current in the specimen/sample (active component resistances of R we define as relation to the active power P to the square of effective current I, i.e., $R=P/I^2$).

Similarly during the introduction of specimen/sample, inductance L, defined as relation to the stored up reactive energy E to the square of current I, i.e., E/I^2, decreases by value L' - change of the inductance as a result of the effect of the field of eddy currents.

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Values L' and R' can be found from the solutions of the equations of Maxwell in the form of the functions of the circuit parameters. Thus, for instance, for a spheroid with a radius of a for sinusoidal fields the corresponding relationship/ratios take the form [5-22]

$$a\,\frac{R'}{\omega L_0}=\frac{6}{y^2}\left[1-\frac{y}{2}\cdot\frac{\operatorname{sh} y+\sin y}{2\operatorname{ch} y-\cos y}\right]; \qquad (5\text{-}22)$$

$$a\,\frac{L'}{L_0}=\frac{3}{y}\cdot\frac{\operatorname{sh} y-\sin y}{\operatorname{ch} y-\cos y}-1, \qquad (5\text{-}23)$$

where $y^2=2\omega\sigma\mu_v a^2$.

The solution of problem for infinite cylinder can be found in [5-22].

In equations (5-22) and (5-23) it is constant α - attenuation factor, equal for sphere $A^2/2a^3$, where A - radius of coil. Ratio $\omega L'/R'$ does not depend on attenuation factor and is only the function of frequency ω, of magnetic permeability μ_v, of a radius of sphere and, that the very important, electrical conductivity of material σ. If dependence $\omega L'/R'$ on y^2 is known (by calculation or from experiments with standard materials), then the measurement of unknown conductivity is reduced to determination R' and L'. The corresponding schematics make it possible this to make sufficiently accurately. We will not give their diverse variants; if necessary with them, it is possible to be introduced in original works [5-22-5-24]. Let us note only that most frequently are utilized the schematics of balanced bridge, which allow by the selection of calibrated cell/elements in the arm of comparison to attain balance with very high accuracy. So, Zimmerman [5-22] speaks about the sensitivity of his bridge circuit, equal to 0.005o/o, which allowed it to determine R' and L' with accuracy 0.1o/o at frequency of 25 Hz. The schematic, used by Josim [5-23], will allow it to obtain error in the measurements of electrical conductivity not more than 1-1.5o/o with σ>1000 $(\Omega\bullet cm)^{-1}$. The frequency range of similar schematics is very wide and oscillates within limits from several hertzes to several ten kilohertzes. Estimating the possibility of using similar methods for high temperatures, it is necessary to keep in mind the dependence of readings on the geometric parameters of solenoid. So, in particular, in the examined above work [5-22] of value R' and L' they are located by subtraction from the measured values R and L of the parameters of the empty coil R_0 and L_0.

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The preservation/retention/maintaining of these values during the considerable heating of coil is virtually impossible. the latter is unavoidable, since to place the furnace between the specimen/sample and the coil, shielding the latter, means to introduce the difficultly controlled/inspected distortions, but for high frequencies to generally exclude the possibility of measurements. The maximum temperatures which were reached in these methods during the sufficiently precise measurement of conductivity, do not exceed 400-500°C [5-23].

The known possibilities of the increase of temperature appear in work at high frequencies with coincidence in one coil of the functions of heating inductor and cell/element of metering circuit. In one of such works [5-25] it will be possible to attain accuracy by 10-20o/o for range of specific resistances $2 \cdot 10^{-4}-10$ Ω•cm. Calibration is conducted on silicon. Maximum temperature reaches 2000°K.

Is virtually free from limitations according to temperatures and the method, proposed by Kheyst [5-26]. The studied specimen/sample here is heated in the separate furnace, placed above the coil, and then is discarded through it into special receiver. Coil is included in resonant circuit of the generator on triode, working at frequency of 14 MHz. The decrease of the grid current of generator at the moment of an incidence/drop in the specimen/sample connected with electrical conductivity of the latter is the useful signal, recorded by schematic. Method is relative and requires calibration against known specimen/samples. Its advantage, besides temperature level, is the possibility of the consecutive level of scanning on the height/altitude of specimen/sample. If, for example, in specimen/sample created specific temperature field, then the written signal will give immediately the temperature dependence of specific resistance. Due to skin effect in measurements, participates the very thin layer of material. The range of the application/uses of a method on specific resistance is 10^{-6}-10^{8} Ω•cm. Let us note that to resistance change to 14 orders corresponds a change in the signal in all to 4 orders, from what author correctly is drawn a conclusion about the inapplicability of method for precision measurements. However, for a series of technical problems, this version can be of considerable interest.

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The investigations of electrical conductivity of conductors are characterized at present, as we see, by the wide development of the noncontact methods of the measurements, instituted on the use of a phenomenon of electromagnetic induction. The diversity of the concrete/specific/actual forms of its manifestation in combination with the development of means radio engineering and electrical measurements creates basis for development all of new systematic reception/procedures. At present, however, one should count that the circle of the experimental methods, which ensure the acceptable accuracy at high temperatures, is very small and in essence limited by the diverse variants of the methods of the rotating magnetic field.

Being inferior on accuracy to traditional methods with contact compensative measurements, the methods of the rotating magnetic field significantly expand the possibilities of researcher and sometimes can be very effective ones.

Chapter Six.

PECULIARITIES OF THE PRACTICAL APPLICATION OF METHODS OF RADIAL HEAT FLUX.

6-1. Comparative description of two basic concepts of method.

Whole diversity of the works, made by the method of radial heat flux, is reduced to two schematic diagrams. Their basic cell/elements are represented in Fig. 6-1. The essential difference, which determines the level of maximum temperatures and the methods of measurement of a quantity of heat, is the direction of heat flux.

In version a (Fig. 6-1a) the flow is directed from the axis of cylinder toward periphery. The specimen/sample being investigated surrounds the source of working heat flux. To measure the power, passed through the working zone of specimen/sample, it is possible both from the electrical parameters corresponding to the zone of heater and by calorimetric measurement over external surface.

In version b (Fig. 6-1b) heat flux is directed toward the axis of specimen/sample. The heater being the source of working heat flux, surrounds specimen/sample outside.

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Power measurement from the electrical parameters of heater is virtually impossible due to difficultly considered scattering of the considerable portion of power to the housing of installation. As a rule, in this schematic is applied calorimetric equipment/device, working according to the method of continuous-flow calorimeter. The working medium/propellant of the latter is usually water, although excluded the application/use of gases.

The selection of one or the other schematic depends on the specific conditions of investigation (range of operating temperatures, the allowed values of gradients, the level of the conductivity of specimen/samples).

The second schematic is more complex, bulkier, more connected with the noticeably larger expenditures of electrical power; however, it clearly one should give preference, if the problem of investigation is the achievement of maximum temperatures. This one can see well from Table 6-1, which illustrates the results of the calculation of the basic parameters of two circuits with the same the temperature of **heater** $T_{н}$. Calculation is carried out for the simplified problem: emissivity factor of the surfaces of specimen/sample, heater and cooler it is accepted equal to unity: the clearances between the specimen/sample and the heater, the specimen/sample and the cooler the specimen/sample and cooler are close to zero; heat transfer between the surfaces of specimen/sample and heater, specimen/sample and cooler is limited by radiation; the temperature of cooler is low. Geometry of the specimen/sample: outside diameter 4.0 cm, internal 1.0 cm; λ=0.5 W/(cm•deg).

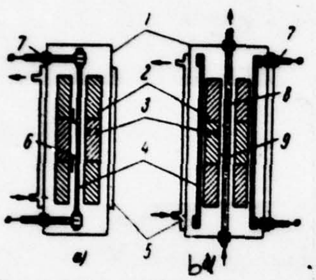

Fig. 6-1. Schematic diagrams of the method of radial heat flux. a — internal heater; b — the external heating of specimen/sample; 1 - housing of unit; 2 - set of specimen/samples; 3 - heat sensors, which measure a radial temperature differential in specimen/sample; 4 - heater; 5 - external cooler; 6 - measuring electrodes; 7 - current guides of heater; 8 - continuous-flow calorimeter; 9 - temperature-sensitive element of calorimeter.

Table 6-1. A comparative characteristic is the temperature of conditions in specimen/sample for two schematics of radial heating.

$T_{н}$, °K	Схема установки (1)	T_{1}, °K	T_{2}, °K	ΔT, °K	Q, вт/см (2)
1 500	а	1 035	1 000	35	70
	б	1 435	1 400	35	70
2 000	а	1 430	1 330	100	230
	б	1 920	1 830	90	210
2 500	а	1 830	1 620	210	490
	б	2 400	2 220	180	420

Key: (1). Installation diagram. (2). W/cm.

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One should, of course, bear in mind, that within limits and that, and other of schematics it is possible to carry out a number of the structural/design measures, which make it possible to noticeably affect basic parameters of the experiment, by approaching the possibilities of one schematic another. So for example, in work according to schematic a between the specimen/sample and the walls of working chamber can be introduced the screens, which lower radial heat flow and which heave mean temperature of specimen/sample. On the other hand, in schematic b in principle can be introduced one or the other highly heat-conducting filling between the specimen/sample and the heat receiver, which makes it possible to increase heat removal from the internal surface of specimen/sample and to increase the temperature differentials.

6-2. Longitudinal nonisothermicity in specimen/sample and heater.

During the construction of installation a serious question is the selection of the size/dimensions of specimen/sample and heater. It is real/actual, the calculated relationship/ratios of the method of radial heat flux proceed from assumption about the absence in the specimen/sample of longitudinal heat flow, i.e., dT/dx=0. This condition it would be possible to realize for the infinitely extended or adiabatically isolated/insulated from two sides of cylindrical system, evenly loaded by transverse heat flux. In practice we deal with the absence of adiabatic insulation and by the heater of finite length. This poses the problem of estimating the virtually acceptable lengths of the working section of specimen/sample and heater.

As an example of such estimations, it is possible to indicate on Van-Van-Rinzum's works [6-1] and Newman [6-2]. To the latter, in particular, it is shown, that for providing the sufficiently isothermal (along the length) zone in experimental model the ratio of its common/general/total length to diameter must be not less than 4. In this case, it is assumed that the temperature of heater is in effect constant.

It is certain, a similar kind of recommendation they bear the most approximate character. Upon the setting of experiment, a question concerning temperature field in specimen/sample must be studied in each specific case.

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As the basis of the corresponding estimations, can be placed one of the two solutions, given aby Karslou [6-3] for it is gently a cylinder with a radius of a<r<b and by length 0<z<1. If on the internal surface r=a of this cylinder maintains temperature f(z), and other surfaces lose heat by heat exchange with the medium of zero temperature, then the temperature distribution in cylinder is described by the expression

$$\vartheta = 2 \sum_{n=1}^{\infty} \frac{(\alpha_n \cos \alpha_n z + h \sin \alpha_n z)\, \varphi(r, n)}{[(\alpha_n^2 + h^2)\, l + 2h]\, \varphi(a, n)_0} \int_0^l f(z)\, (\alpha_n \cos \alpha_n z + h \sin \alpha_n z)\, dz, \qquad (6\text{-}1)$$

where α_n — positive the roots of the equation

$$\operatorname{tg} \alpha l = 2\alpha h/(\alpha^2 - h^2); \qquad (6\text{-}2)$$

$$\varphi(r, n) = I_0(r\alpha_n)\,[\alpha_n K_1(b\alpha_n) - hK_0(b\alpha_n)] + K_0(r\alpha_n)\,[\alpha_n I_1(b\alpha_n) + hI_0(b\alpha_n)]. \qquad (6\text{-}3)$$

Parameter h exists a ratio of heat-transfer coefficient on surface to the coefficient of the thermal conductivity of specimen/sample. I_0, K_0, I_1 and K_1 - Bessel function from apparent/imaginary argument.

If on the internal surface r=a is assigned the heat flux,

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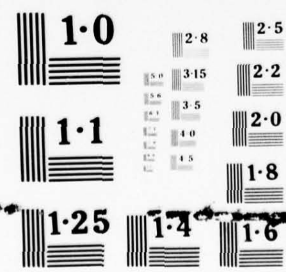

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entering inside solid body, f(z), and at other surfaces is maintained zero temperature, then solution is represented by the expression of the form

$$\vartheta=-\frac{2}{\lambda\pi}\sum_{n=1}^{\infty}\frac{F_0\left(\frac{n\pi r}{l};\frac{n\pi b}{l}\right)}{nF_1\left(\frac{n\pi a}{l};\frac{n\pi b}{l}\right)}\sin\frac{n\pi z}{l}\int_0^l f(z')\sin\frac{n\pi z'}{l}dz', \tag{6-4}$$

where

$$F_0(x;y)=I_0(x)K_0(y)-K_0(x)I_0(y); \tag{6-5}$$

$$F_1(x;y)=I_1(x)K_0(y)+K_1(x)I_0(y), \tag{6-6}$$

where λ - a coefficient of thermal conductivity.

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It must be noted that the second solution to preferably utilize during the estimations of the temperatures in specimens of substances with the low coefficient of thermal conductivity, such, as oxides, porous materials, etc. During the emission/radiation of temperature field in the metallic specimen/samples, which possess the high coefficient of thermal conductivity, the first problem can give more reliable results.

For purpose of the decrease of the role of the two-dimensional character of temperature field working specimen/samples usually are manufactured in the form of the set of separate washers. This especially favorably manifests itself during the investigation of metals. The increased thermal resistance in the zone of contact of surfaces decreases longitudinal heat fluxes. On the end/leads of the set, frequently are establish/installed supplementary washers from porous ceramics and other materials with the low coefficient of thermal conductivity. Finally, strictly the zone of the measurements of a jump/drop in the temperatures in specimen/sample and of the corresponding heat flux occupies only small along the length section in the center of entire set (to several ten millimeters).

Vital importance has a character of temperature field along heater, especially for schematic a, where the calculation of heat flux is conducted on the basis of the measurements of electrical power, isolated on the section of final extent.

The lower the coefficient of the thermal conductivity of the material being investigated, the is insulated the lateral surface of heater, the more powerful is exhibited the effect of longitudinal heat fluxes (along heater). In this case are necessary the experimental emission/radiation of the gradient of the temperature in the zone of potential derivations and the introduction of the corresponding correction to the measured power.

6-3. Some design features of high-temperature installations with radial heat flux.

Current inputs. Successful realization of the method of radial heat flux is connected to a considerable extent with the rational engineering solution of number of specific problems. Their appearance is caused by the fact that conducting measurements in the specimen/samples of acceptable geometry in high-temperature range is possible only with the aid of the heating elements, loaded by the currents of the significant magnitude.

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In the case of rod heaters as in schematic a, operating currents they reach hundred and thousand amperes; in work according to schematic b, they increase still more. From the correct selection of construct/designing the electric lead-in under these conditions, depend the stability and the reliability of the operation of installation. One should consider that the cooling system of current guides must accept to itself to 20-30o/o of overall power, liberated as heater, and ensure under these conditions compensation the thermal expansion of heater and the preservation/retention/maintaining of its orientation with respect to specimen/sample.

The thermal design of contacts is connected directly with the estimate of the magnitude of the actually contacting part of the surface. It depends on the physical properties of materials, character of their mechanical treatment and mechanical effort/forces in the contact zone. In the case of elastic contact (usually occurring with repeated ones loading) in work [6-6] is recommended the following relationship/ratio for determining the relation to actual contact area to contour:

$$\eta=\left(\frac{b}{2}\right)^{\frac{1}{2\nu+1}}\left(\frac{r}{h_{макс}}\right)^{\frac{\nu}{2\nu+1}}\left[\frac{2,35\,(1-\mu^2)\,q_c}{kE}\right]^{\frac{2\nu}{2\nu+1}}. \quad (6\text{-}7)$$

Here: q_c — contour pressure r - radius of bending of the apex/vertexes of projections, changing from 30-40 μm with widening to 300-500 μm with polishing; $h_{макс}$ — the maximum altitude of inequalities; E - Young's modulus; μ - Poisson ratio; b, ν — constants, which characterize reference line.

With polishing $\nu=3$; b=4-6; with polishing $\nu=3$; b=5-10.

Coefficient k depends on ν and is equal to with respect 0.8; 0.67; 0.62; 0.58; 0.55 with $\nu=2$; 3; 3; 5; 6.

Formula (6-7) is derived for the contact of rough and smooth surfaces if both of surfaces they are rough ones, then into formula (6-7) are substituted the effective values of constants, determined by the relationship/ratios

$$\nu=\nu_1+\nu_2;$$

$$b=\frac{k_1 b_1 b_2 (h_{1\text{макс}}+h_{2\text{макс}})^{\nu_1+\nu_2}}{h_{1\text{макс}}^{\nu_1} h_{2\text{макс}}^{\nu_2}};$$

$$r=\frac{r_1 r_2}{r_1+r_2};$$

$k_1=f(\nu_1,\nu_2)$; in particular, when $\nu_1=2$ and $\nu_2=2$ $k_2=0.16$; when $\nu_1=3$ and $\nu_2=2$ $k_2=0.1$; with $\nu_1=\nu_2=3$ $k_2=0.05$.

$$\frac{1-\mu^2}{E}=\frac{1-\mu_1^2}{E_1}+\frac{1-\mu_2^2}{E_2}.$$

For the case of the well run in surfaces both movable (sliding) and fixed contacts in work [6-6] is recommended the simplified formula

$$\eta=3,4\left(\frac{q_c}{Eh_{\text{макс}}}\right)^{10/11}. \qquad (6\text{-}8)$$

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The estimation of actual contact area makes it possible to calculate the value of the increase of the temperature ΔT in contact area/sites, caused by the passing through them current. The limiting value ΔT, which occurs for contact of two semi-bounded arrays, is calculated from Holm's known relationship/ratio (see Chapter 3)

$$\Delta T = \frac{1}{8} \cdot \frac{U_{\kappa}^2}{\lambda \rho}, \qquad (6\text{-}9)$$

where U_{κ} – a voltage drop across contacts.

In the case of the contact of two plates with a thickness of d, actively cooled outside by water, temperature on the contact pad in [6-7] are higher than the temperature of cooling water by value

$$\Delta T = \frac{1}{8} \cdot \frac{U_{\kappa}^2}{\lambda \rho} \left[1 - \frac{2}{\pi} \arcsin \frac{a}{\sqrt{(2d)^2 + a^2}} \right], \qquad (6\text{-}10)$$

where a - a radius of contact area/site.

Relationship/ratios (6-7), (6-8) and (6-10) it makes it possible to introduce into the thermal design of electrical conductors of refinement, connected with the disruptive character of the areas of contact in real construction/designs.

Examples of the structural formulation of current inputs are given in Fig. 6-2 and 6-3. the first is the version of the rigid fastening of rod heater, used V. A. Zeygarnik in work [6-32]. The contact of heater with the copper housing of current input is realized through the intermediate insert/bushing, made from graphite (sometimes from copper). Preliminarily urged over the conical surface of landing seat/socket insert then is cut.

With the tightening of pressure nut, the cell/elements of insert/bushing are moved relative to the conical surface of seat/socket, providing the necessary effort/force on contact surfaces. The conicity of landing seat/socket usually ranges from 1:7 to 1:10; the surface of seat/socket is processed to 9-10th classes of purity. The housing of current input is cooled by the running water, passing here on the ring groove with internal ribbing.

The construction/design, shown on Fig. 6-2, does not contain the elements of the system of the compensation the thermal expansion of heater. In the simplest cases (at the moderate temperatures) the problem of compensation is frequently solved by the less dense attachment of upper sectional insert/bushing (here, as a rule, graphite), which provides the possibility of the slippage of heater relative to current input.

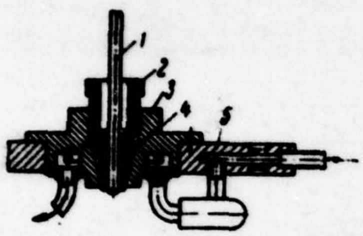

Fig. 6-2. Rigid fastening of rod heater [6-32]. 1 - heater; 2 - clamp nut; 3 - housing of current input; 4 - sectional insert/bushing; 5 - flange of current input.

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During the use of a heater in the range of limiting temperatures, is applied the flexible coupling of the contact refrigerated electrode with the housing of unit. Bellows or special spring is selected so that the preliminarily expanded heater on the achievement of maximum temperatures would prove to be unloaded from any longitudinal forces. In spite of the fact that the absolute elongation of heater can be designed previously, the calculation of an entire system of compensation is extremely inexact. Under these conditions the necessary preliminary strain of elastic cell/element is selected experimentally.

As the example of the practical application of this method of the compensation to Fig. 6-3 it is given designs of movable current input of the installation of N. V. Boyko and E. E. Shpil'rayn [6-8]. As elastic cell/element is here used the spring, compressed between the plate and the supporting/reference platform, connected with the housing of unit. A deficiency/lack in the construction/design is the impossibility of effect on elastic cell/element without the decompression of installation and disconnection of all current-conducting busbars.

6-4. Structural/design measures, which ensure the measurement of heat flux.

The serious potential advantage of schematic a (see Fig. 6-1) is the possibility of the electrical measurement of the power, introduced into the working zone of specimen/sample. During the sufficiently high stability of the power supply and the use of potentiometer methods of measuring the strength of current and voltage drop across working section, an error of measurement of power can be limited to value 1-2c/o. *In this case,* measurements themselves are maximally simple and reliable. However, utilizing them, always one should bear in mind those distortions in the three-dimensional/space heat-flow distribution and temperatures which are connected with the organization of potential derivations from heater.

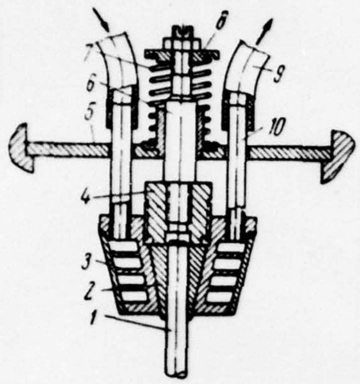

Fig. 6-3. Movable current input with the spring compensation thermal expansion [6-8]. 1 - heater; 2 - insert/bushing; 3 - housing of current input; 4 - pressure/clamping nut; 5 - supporting/reference platform; 6 - thrust/rod; 7 - spring; 8 - plate; 9 - vacuum hose of cooling system; 10 - branch pipe.

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Are applied at present in essence three schematics of the potential derivations: external radial probe, external longitudinal (axial) probe and internal longitudinal probe.

In the first schematic potential rod or lead/duct is derive/concluded along the normal to the heater through radial boring in specimen/sample. The size/dimensions of the latter are sufficiently great in order to place insulation/isolation of derivation and (especially in the case of rod rigid version) especially in the case of rod rigid version) to ensure the longitudinal travel of probe during the thermal deformations of heater and specimen/sample. With the sufficiently large thickness of heater (D>4-5 mm) are applied the pressing rod probes from refractory metals or graphite, introduced into small conical or cylindrical deepening in heater. One of the versions of this schematic was realized in work [6-8]; the potential probe, made from graphite rod 2,5-3 mm in diameter, it is pressed against the upper surface of deepening in heater. The latter is graphite rod 10 mm in diameter. Compression is realized because of the torque/moment, created by special small weight at the end/lead of the probe.

A deficiency/lack in this construction/design are bending stresses for rod, and hence the need for an increase in its diameter in comparison with the version in which the rod is loaded by longitudinal forces. An increase of the diameter in turn, is connected with the amplification of the disturbance/perturbations of temperature field in specimen/sample and heater. Tendency to reduce to a minimum these factors leads to the wire version of radial schematic. In this case fine/thin (0.1-0.15 mm) wire from refractory metal is secured (sometimes by the weld of end/lead by the arc in argon, sometimes by the pressing of end/lead into eyelet, sometimes simply cables itself in the zone of small transverse notch) to heater, it goes around it in circumference and with small elongation is derive/concluded through the insulator outside.

The application/use of a schematic of external longitudinal probe is explained by the tendency to exclude the technological complication of specimen/sample and the disturbance/breakdown of its correct geometry. Here the potential lead/duct, attached at one or the other point of heater, is insulated by ceramic covering and is derive/concluded outside in space between the heater and the specimen/sample.

A similar schematic used by Mikol' and is in detail described in [6-39].

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In our view, in the range of very high temperatures its application/use inexpediently, since this is connected with a noticeable increase in the clearance between the heater and the specimen/sample, but thereby with a reduction in the maximum temperature of specimen/sample. Furthermore, it is necessary to keep in mind the disturbance/breakdown of the axial symmetry of problem in the zone of the passage of potential derivation. With a small extent of working section, this can directly pronounce on the form of internal isothermal surfaces.

With the minimum perturbation action is connected third schematic, used, in particular, D. L. Timrot and S. A. Serdobol'skaya. In this case the heater is made in the form of the hollow duct, which has in the zone of working section the reduced diameter of internal boring. In this projection rest the graphite shaped bushings into which are inserted the graphite rods, which are potential conclusions. Common/general/total length of heater (graphite) of 310 mm, outside diameter 16 mm, internal boring on working section 8 mm, in the zone of derivations 8.5 mm. Diameter of potential rods 6 mm.

A deficiency/lack in this construction/design is the complexity of check of possible change in an experiment in the length of the section, on which is measured the voltage drop. Furthermore, in the zone of maximally high temperatures the results of measurements can be distorted by the phenomenon of the thermionic emission, calling the disturbance/breakdown of the insulating properties of the clearance between the heater and the internal electrode.

Thus, the electrical measurement of the introduced into specimen/sample power in practice is always connected with introduction into the ideal schematic of different disturbance/perturbations, which distort distribution of temperatures, heat fluxes, the productivity of thermal sources in working zone. Appear the sources of the systematic errors whose estimations are sometimes virtually impossible.

The definite advantages in this sense it has use of special calorimetric systems. In this case, the calorimeter performs the role of thermal flow and measures the flow, which left one or the other zone of specimen/sample. As a rule, calorimetric measurement it is applied in work according to schematic diagram b. However, some researchers prefer this method of measurement of power, also, in installations according to schematic diagram a.

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So, the authors of [6-9], investigating the thermal conductivity of oxides (zirconium, magnesium, aluminum), will fulfill the external wall of the housing of unit as calorimetric equipment/device, operating according to the schematic of flowing water calorimeter. In this case, gauging consumption of water with error ±0.25o/o and the value of preheating with error about 1o/o, they will obtain error in the measurement of the heat flux of order ±1.5c/o. This is fair result.

In their classical performance in connection with schematic b the calorimeters are made usually in the form of the tube, arrange/located along the axis of specimen/sample. Inside tube is introduced the body of differential temperature-sensitive element - the multicleavage differential thermocouple, attached on rod from thermally low-conducting material (glass, organic glass, etc.). The working medium/propellant of calorimeter for the most part is water [6-10-6-12]; however, can be used other heat-transfer agents. V. S. Chirkin [6-13] describes the instruments where as the working medium/propellant of calorimeter was applied helium or nitrogen, and preheating gas on working section was measured with the aid of platinum-platinum-rhodium thermocouples.

Gas heat-transfer agent makes it possible to work at the higher temperatures of calorimeter, which in turn, leads to the increase of mean temperature of specimen/sample at the same temperature of heater. However for schematic b this it is not decisive. The temperature differentials here and are so small.

The development of water calorimeter for installations with radial heat flux requires the careful calculation of all sides of heat exchange in system. The importance this is clear, if one considers that the heat fluxes, received by calorimeter, can reach 10^6 kcal/(m²•h). The removal of such flows under conditions of the inadmissibility of effervescence (but the more the formation/education of steam films) on working section is feasible only at the considerable rates of the motion of water. at the same time an increase of the consumption is limited by the requirement of obtaining such jump/drops in the temperatures along the length of the working section of calorimeter, which can be reliably measured. As a result the calculated clearances between the wall of calorimetric tube and the internal rod of sensor become sufficiently small. In this case, sharply becomes complicated the problem of the measurement by the regulus of the thermocouple of the average (over section) temperature of flow (temperature of mixing).

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Readings of temperature-sensitive element begin to depend on the random strains of tube, vibrations, etc. Calculation of heat flux according to the measured values of consumption, difference in the temperatures and heat capacity does not give the true value of the introduced into tube power.

Known output from this problem is the calibration of calorimetric equipment/device at the fixed values of the consumption of water. In this case, heat flux is created by the transmission of current on the external tube of calorimeter. It is assumed that the temperature fields in flow and the reaction on them of temperature-sensitive element will be identical with one and the same flows under the conditions of the experiment and calibration. As a rule, calibrated completely equipment/device is not dismantled, but wholly (by separate block/module/unit) it is introduced into the working zone of installation. As an example it is possible to indicate the design features of the installation of Razor and Mac-Clelland [6-12], used extensively the method of radial heating in version b. The range of operating temperatures of specimen/sample during their measurements comprises 1000-2700°C. The external and inner diameters of specimen/samples comprise with respect to 50.8 and 12.7 mm. The length of working set is equal to 76.2 mm.

Calorimetric tube was made made of the stainless steel and it has outside diameter 9.6 mm and thickness of walls 0.25 mm. By the housing of temperature-sensitive element is glass small tube 6 mm in diameter with the walls with a thickness of 1 mm. To the surface of this tube with special cement, adhere the lead/ducts of differential copper-constantan thermocouple with the distance between joints 25 mm. Entire/all surface of glass tube was covered with the rough sand, performing the role of vortex generator. Input and output of water were made on the one hand of calorimeter; thus, water heaves on radial clearance and is derive/concluded within glass tube. According to the estimations of the authors, any kind the overflows of heat both along the duct and through the glass wall could be disregarded.

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6-5. Some observations about the conditions of temperature measurements in radial method.

For the calculation of the coefficient of thermal conductivity [see formula (1-98)] it is necessary to measure the temperatures in two points, arrange/located on different distances from the axis of specimen/sample. For this purpose, in specimen/sample usually are drilled special cavities. During the measurements by thermocouples these cavities, as a rule, were parallel to the axis of specimen/sample. Thus, in the ideal case thermo-electrode lead/ducts for sufficiently large extent/elongation go along isothermal surface, which removes the distortion of their readings because of heat withdrawal from regulus.

During the use of optical pyrometry, sometimes are applied the radial channels, in the ideal case which make it possible to measure the temperature of the bottom of this cavity. Speaking here about the ideal cases, we are distracted OGT of a number of factors, which contribute of the error in measurements.

Pyrometric channel has finite dimensions. The consequence this are, in the first place, the distortion of temperature distribution around it and, in the second place, the appearance of a nonisothermicity along the surface of this channel. Thus, arises the question concerning that which will measure our sensor (or pyrometer) in this channel and as measured value is correlated with the temperature, characteristic for this coordinate in the absence of disturbance/perturbations. In the case of radial channel to the foreground, is advanced the problem of the effect of the longitudinal nonisothermicity of cavity on the effective emissivity of its bottom. Basic questions of pyrometry in nonisothermal cavities are already examined in Chapter 2. Here has sense to note only some torque/moments of the first problem - the distortion of temperature field in the range of pyrometric channel.

For linear heat flux (in the undisturbed zone) this question is most thoroughly examined by V. N. Popov [6-15]. In accordance with his derivations the value of the distortion of the temperature field, caused by the presence of the cylindrical inclusion, oriented normal to the direction of heat flux, noticeably decreases during removing of inclusion from the plane, which limits half-space.

If is introduced the dimensionless temperature $T = (t-t_0)\lambda_{11} / q_0 a$, radius $R=\rho/a$ and a relative removal/distance $\varkappa=\delta/a$ is searched for the solution of equating Laplace $\nabla^2 T=0$ in the form of the sum of the undisturbed solution and disturbance/perturbation, i.e., $T=T^*+\theta$ at the *boundary conditions*

$$\left.\begin{aligned} &T=0 \text{ при } R=\varkappa/\sin\varphi; \\ &T^*=\varkappa-R\sin\varphi \text{ при } R\to\infty, \end{aligned}\right\} \quad (6\text{-}11)$$

Key: (1). with.

the disturbance/perturbation at the central point of the range of inclusion (Fig. 6-4) can be it will be presented in the form

$$\theta_0 = 2\sqrt{\varkappa^2-1}\sum_{n=1}^{\infty}\frac{(1-r_1^{2n})}{\left[1+\left(\frac{1+\alpha}{1-\alpha}\right)r_1^{-2n}\right]}. \quad (6\text{-}12)$$

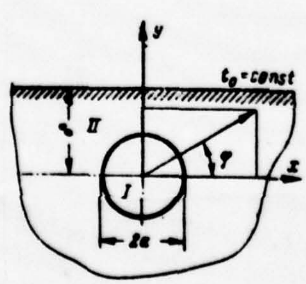

Fig. 6-4. Half-space with cylindrical inclusion [6-15].

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Are here used the following designations: t - current temperature; t_0 - temperature on the surface of the semi-bounded array; q_0 - heat flux in the direction of axis y at infinite removing from range I; a - radius of range I, λ_{II} and λ_I - coefficients of the thermal conductivity of ranges II and I;

$$r_1 = (x + \sqrt{x^2 - 1})^{-1}; \quad \alpha = \lambda_I / \lambda_{II}. \qquad (6\text{-}13)$$

large x (>5-6) with an accuracy to 1-2o/c, equation (6-12) is led to the simpler form:

$$\theta_0 = \frac{1}{2\pi}\left(\frac{1-\alpha}{1+\alpha}\right). \qquad (6\text{-}14)$$

Value of disturbance/perturbation, calculated in [6-15] according to equation (6.12), represented in Fig. 6-5. Utilizing these data, it is possible to estimate the error during the measurements of temperatures by thermocouples.

In the case of applying the pyrometric methods to more expediently examine not disturbance/perturbation in center, but field distribution of the disturbance/perturbations of the temperatures on the duct/contour of channel, i.e., with $r=r_1$ ($R=1$). The latter is described by the following expression:

$$\theta=-2\sqrt{\varkappa^2-1}\sum_{n=1}^{\infty}A_n\times$$
$$\times(r_1^n-r_1^{-n})\cos n\nu, \quad (6\text{-}15)$$

where

$$A_n=\frac{1}{1+\left(\frac{1+\alpha}{1-\alpha}\right)r_1^{-2n}}; \quad (6\text{-}16)$$

$$\cos\nu=\frac{1-\varkappa\sin\varphi}{\varkappa-\sin\varphi}. \quad (6\text{-}17)$$

In this case, for the majority of structural materials in temperature range to 2,000-2,500°K in expression (6.16) it is possible to assume $\alpha=0$. For materials with very low thermal conductivity and high emissivity factor in high-temperature range for shaping of temperature field on canal surface, will noticeably affect the heat exchange by emission/radiation. In this case the given laws can prove to be already ineffective.

Are interesting absolute magnitudes of error, introduced by channel, during the measurements of thermal conductivity.

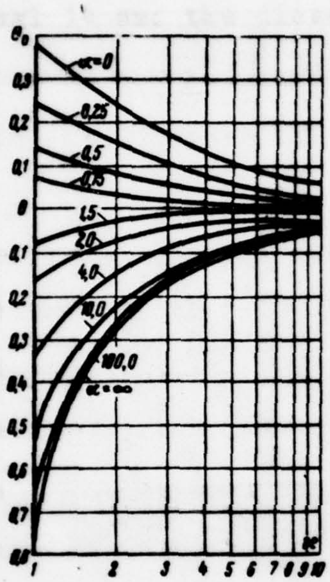

Fig. 6-5. Distortion of temperature field at the central point of circular range on [6-15].

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Such estimations, in particular, were conducted by V. A. Zeygranik, who used the basic results of work [6-15] to the analysis of radial problem.

The outside diameter of specimen/sample is equal to 65 mm, internal 14 mm; the diameter of the pyrometric channels, drilled in parallel to the axis of specimen/sample at distances from it 10 and 27.5 mm, it is equal to 2.5 mm.

With calculation the thermal conductivity of specimen/sample was accepted equal to 40 W/(m•deg), and $\alpha=\lambda_{I}/\lambda_{II}=0.1$. During a change in the heat flux (directed outside) from 300 to 2,600 W/m the value of disturbance/perturbation for external and internal pyrometric channels comprises with respect to 0.005-0.5 and 0. 09-0.75°. The temperature differential on the appropriate radii changes in this case within limits from 3 to 50° C. Thus, the distortion of field, caused by the arrangement/position of temperature-sensitive element in pyrometric channel (with the relative thermal conductivity of the substance of temperature-sensitive element $\alpha=0.1$), in this case conducts to the error in the measurements of thermal conductivity from 3o/o at low temperatures to 1.5o/o with high ones.

Calculations show that for decreasing the error the most vital importance has removal/distance from the axis of internal duct; it is expedient to have $\varkappa>4$.

6-6. Examples of the use of a method of radial heat flux.

For the illustration of the possibilities of the examined method of measuring the coefficient of thermal conductivity in Table 6-2, is represented the group of the typical works, which cover the very wide circle of materials and temperature range.

With acceptable for practical needs accuracy the method makes it possible to obtain information about the conductivity virtually of any structural materials, used in contemporary high-temperature technology from special compositions on oxide or carbon-graphite basis to dense metals and their alloys.

The lower level of temperatures noticeably depends on conductivity; it is characteristic that for metals it lie/rests at area of 1200°K, for oxides of 300-600°K. Upper temperatures are limited by the stability region of the work of heater and they reach 2,800°K.

The majority of the works, presented in table, is made according to schematic a. This is not random, the complexity of the realization of schematic b in the majority of the cases when is not placed the problem of achieving the maximum temperatures, forces to give preference to schematic with internal heating.

Is characteristic the scatter of of these indicated by authors of errors. Minimum value ±5o/o reflects in essence random measuring error. The account of systematic ones errors leads to the more reliable values, which lie at range 8-15o/c.

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6-7. Use of two-dimensional problems for measuring the coefficient of thermal conductivity.

The use of electronic computers makes it possible at present considerably expand the circle of the problems which could be placed as the basis of the experimental determination of coefficient of heat conductivity. In large measure experimenters' tendency toward one-dimensional heat fluxes is explained by the natural wish to exclude large volume of calculated works, appearing during analysis two- and three-dimensional temperature fields.

Table 6-2. Realization of the method of radial heat flux in the measurements of the coefficient of thermal conductivity.

(1) Работы	(2) Вариант схемы метода	(3) Исследованные материалы и диапазон температур, °К	(4) Погрешность (по оценке авторов)
(5) [Л.6-9]	а	(6) Окись магния, окись алюминия, окись циркония (до 2 000)	±9%
[Л.6-10], [Л.6-11], [Л.6-19]	б	(7) Молибден (1 200—2 800), тантал (1 300—2 800), графит и углеграфитовые материалы	±5%
[Л.6-20], [Л.6-21]	в	(8) Карбиды титана и циркония (800—2 400), окись бериллия (600—2 300)	±5%
[Л.6-25]	а	(9) Окись алюминия (900—1 700), окись циркония (900—1 900)	±20%
[Л.6-26], [Л.6-27]	а	(10) Окись бериллия (до 2 300)	±10%
[Л.6-28]	а	(11) Двуокись урана (600—2 300)	(12) ±(6÷8)% при работе с пирометром; ±(9÷15)% при работе с термопарами (13)
[Л.6-29], [Л.6-30], [Л.6-31], [Л.6-32]	а	(14) Графит, карбид кремния и углеграфитовые материалы различной плотности (до 1 500)	±(6÷10)%
[Л.6-16]	(15) Дифференциальный вариант схемы а	(16) Плавленый кварц (300—2 100)	—

Key: (1). Works. (2). Version of schematic of method. (3). Investigated materials and temperature range, °K. (4). Error (according to estimation of authors). (5). [6-9]. (6). Oxide of magnesium, oxide of aluminum, oxide of zirconium (to 2,000). (7). Molybdenum - tantalum - graphite and carbon-graphite materials. (8). Carbides of titanium and zirconium - oxide of beryllium. (9). Oxide of aluminum - zirconium oxide. (10). Oxide of beryllium (to. (11). Uranium dioxide. (12). in work with pyrometer; (13). in work with thermocouples. (14). Graphite, carbide of silicon and carbon-graphite materials of different density (to. (15). Differential version of schematic a. (16). Vitreosil.

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At the same time with temperature rise, the organization of uniform heat flux becomes ever more complex technical problem. Researchers, armed by contemporary computer technology, increasingly more frequently give preference to comparatively simple experimental equipment/devices, which make it possible to create and to investigate three-dimensional/space temperature field in specimen/samples, transferring the center of gravity of work to the mathematical perfecting results of measurements.

As an example it is possible to indicate the work of Glezer etc. [6-34]. The diagram of the used in this work installation is given in Fig. 6.6. Specimen/sample is arrange/located in the focus of the mirror of arc reflecting furnace.

For decreasing with radial component of the gradient of temperatures, the authors make the diameter of specimen/sample less than the size/dimensions of focal spot and, furthermore, they shield his lateral surface by platinum screen. The diameter of specimen/sample of approximately 9.5 mm, thickness 1.6-3.2 mm. The clearance between the screen and the specimen/sample is equal to approximately 0.8 mm. The attachment of specimen/sample is realized by three tungsten needles, attached in holder.

Two prisms make it possible with the aid of optical micropyrometer to measure the temperature distribution over butt ends. Monochromatic emissivity is considered known. Furthermore, opening/aperture in holder and lateral screen makes it possible to determine the temperature of midpoint of lateral surface. The area/site of the sighting of the used micropyrometer does not exceed in diameter 0.1 mm.

The heat flux, scattered from the rear end/face of specimen/sample, in steady state is measured with the aid of radiometer. The special system of the cooled and uncooled diaphragms makes it possible to remove parasitic heat fluxes. During the measurements of flows, prism 3 is derive/concluded from the zone of the cone of radiant flux, which goes to radiometer.

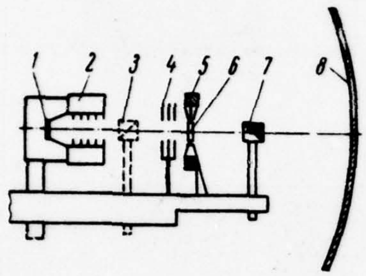

Fig. 6-6. Diagram of installation of Glezer [6-34]. 1 - radiometer;. 2 - cooler with screens (cooled diaphragms); 3 and 7 - prisms; 4 - uncooled diaphragms; 5 - sample holders; 6 - specimen/sample;. 8 - mirror.

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The exception/elimination of the emission/radiation reflected during the pyrometry of front face is reached with the aid of the special filters (see Chapter 2), which divide the spectral sections of that heating and measuring the luminous fluxes.

Thus, the used equipment/device makes it possible to heat specimen/sample up to necessary temperature, to investigate the temperature distribution on its lateral surface and to measure the heat flow, lost from rear surface. These data are sufficient for the calculation of the coefficient of thermal conductivity. The first space is the numerical solution of equating Laplace for finding volumetric distribution of temperatures on assigned distribution on surface. With this authors they assume that the problem is axisymmetric, but the coefficient of thermal conductivity does not depend on temperature. Is utilized the known method of relaxation [6-35; 6-36]. The section of specimen/sample by the plane, passing through its axis, is approximated by the square carrying out grid (with the size/dimension of cells 0.32X0.32 or 0.16X0.16 mm).

The consecutive relaxation of remainder equations is conducted until residue/remainders at nodal points become less than $5 \cdot 10^{-3}$. After this with the aid of electronic computer, is calculated normal temperature gradient at the nodal points of the rear surface of specimen/sample, and then by summation over it is determined its integral value

$$\int_F \mathrm{grad}_n T\, df.$$

The coefficient of thermal conductivity is calculated from the obvious relationship/ratio

$$\lambda = \frac{Q}{\int_F \mathrm{grad}_n T\, df}, \qquad (6\text{-}18)$$

where thermal flux Q is located as sum of the flow, perceived by radiometer, and correction (to 10o/o) for convective losses from the surface of the specimen/sample (experiment is conducted in air).

That found from (6-18) the coefficient of heat conductivity was referred to mean temperature of the rear surface of the specimen/sample

$$T_{cp} = \frac{1}{F} \int_F T\,df. \qquad (6\text{-}19)$$

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A common/general/total error of measurement the authors estimate by value ±10o/o. It is possible to agree with their opinion that the basic contribution to error gives not the method of calculation (so, the decrease of the space of grid from 0.32 to 0.16 mm it changed result in λ not more than for 5o/o), but the accuracy of measurements of temperature and heat fluxes. During the described installation the authors will fulfill the measurements of the coefficient of the thermal conductivity of zirconium oxide in the range of temperatures of 1,200-1,500°C.

It must be noted that the chosen in this work method of measurement of heat flux from rear surface is permissible only if the emission/radiation of specimen/sample obeys the law of Lambert. For the metallic specimen/samples of the measurement of radiant fluxes in normal direction to radiating surface, do not make it possible to rate/estimate the value of hemispheric emission/radiation with it.

To the direction, presented by the work of Glezer, on spirit its adjoins the series of the experiments, made by Khoch and colleagues [6-37, 6-38]. Here also is examined two-dimensional temperature field in limited cylinder. Just as in the preceding/previous work, the temperature gradient, introduced during the calculation of coefficient, is calculated on the basis of the solution of the problem of temperature distribution. Heating specimen/sample is conducted by induction method with frequency of 500 kHz. In this case, according to the estimations of the authors, the depth of the zone of heat release does not exceed 0.08 mm with the diameter of specimen/sample 12-25 mm. The length of specimen/sample is varied within the limits of 6.5-38 mm.

In experiment is measured the temperature distribution over butt end of specimen/sample, approximated by the parabola

$$\psi(r, L) = a(R^2 - r^2), \qquad (6\text{-}20)$$

where $\psi = T_R - T$; T_R - temperature on an external radius; R - radius of specimen/sample; r - instantaneous radius; T - temperature.

On the basis of the fact that in margins of error in the pyrometry does not succeed in reveal/detecting changes in the temperature along the lateral surface of cylinder, as the first approximation during the formulation of boundary conditions, it is accepted that on lateral surface the temperature is constant, i.e., $\psi(R,z)=0$.

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Under these boundary conditions the problem is simply solved by the method of separation of variables. Temperature field is described by the infinite series

$$\psi(r,z)=4aR\sum_{n=1}^{\infty}\left[\frac{R}{\delta_n^2}\cdot\frac{J_2(\delta_n)}{J_1^2(\delta_n)}\frac{\mathrm{ch}\left(\delta_n\frac{z}{R}\right)}{\mathrm{ch}\left(\delta_n\frac{L}{R}\right)}J_0\left(\delta_n\frac{r}{R}\right)\right]. \quad (6\text{-}21)$$

Hence it is possible to calculate the value of the longitudinal gradient of the temperatures in plane z=L. For the axis of specimen/sample, its value is represented as follows:

$$-\left(\frac{\partial T}{\partial z}\right)_{0,L}=4aR\sum_{n=1}^{\infty}\left[\frac{J_2(\delta_n)}{\delta_n J_1^2(\delta_n)}\,\mathrm{th}\left(\frac{\delta_n}{R}L\right)\right]=4aRK_0. \quad (6\text{-}22)$$

In the last/latter expression K_0, is the certain shape factor, which depends only on the relationship/ratio of the size/dimensions of specimen/sample (for this type of boundary conditions). However designed, it is utilized during the treatment of an entire series of experiments. The gradient of temperatures (6-22) characterizes the heat flux, scattered from the cell/element of the surface of specimen/sample by emission/radiation (in vacuum).

The authors assume that the integral hemispheric degree of blackness ε is known. Then for the calculation of thermal conductivity it suffices to know temperature $T_{\substack{r=0\\ z=L}} = T_0$:

$$\lambda = \frac{\varepsilon\sigma T_0^4}{4aRK_0}. \qquad (6\text{-}23)$$

Final calculated relationship/ratio is constructed taking into account the possible nonisothermicity of the lateral surface whose effect is described by additive term in the denominator of expression (6-23):

$$\lambda' = \frac{\varepsilon\sigma T_0^4}{4aRK_0 + 2ma'L^{m-1}K'_0}, \qquad (6\text{-}24)$$

where a' and m characterize the temperature distribution over the lateral surface:

$$\psi'(R, z) = -a'(L_m - z_m), \qquad (6\text{-}25)$$

and K'_0 - one additional shape factor; values K_0 and K'_0 depending on L/R on the data of work [6-37] are given in Fig. 6-7.

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The introduction of the corrective term in (6-23) changes the coefficient of thermal conductivity to the value, which reaches 5o/o, which indicates the importance of the reliable determination of temperature conditions on the lateral surface of specimen/sample.

The authors investigated the thermal conductivity of molybdenum in the range of temperatures 2100-2,400°K and Bandl' (1,600-1,800°K). An error in the data is estimated at ±15o/o (molybdenum) and 20o/o (vanadium). In [6-38] it is communicated about the results of the investigation of the thermal conductivity of graphites.

It should be noted that the serious limitation of procedure is the need for the enlistment of external data both according to integral and according to monochromatic emissivity factor. The dependence of these characteristics on experimental conditions and the possibility of changing them in the process of experiment can lead to serious errors of measurements.

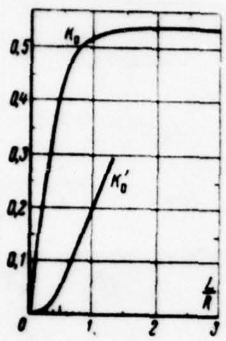

Fig. 6-7. Values of shape factors in the method of Khoch [6-37].

Chapter Seven.

RESULTS OF THE EXPERIMENTAL INVESTIGATICN CF THE THERMAL CONDUCTIVITY CF REFRACTORY METALS IN HIGH-TEMPERATURE RANGE.

7-1. The temperature dependence of the coefficient of the thermal conductivity of metals.

The basis of contemporary high-temperature metallic materials compose the cell/elements of the fourth, by heel, the sixth and partly seventh and eighth of the groups of the periodic system, arrange/located in the fourth, by post and the eighth its series. Among them most wide acceptance as the basis of heat-resistant alloys they will find titanium, nichium, tantalum, molybdenum and to the Wolfs.

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Remaining cell/elements either due to their high costs or according to physical properties in essence are utilized as addition and the information about them thus far they have mainly theoretical and metrological value.

The range of temperatures, that is of interest for high-temperature technology, it lie/rests within limits of 1,000-2,500°K, but sometimes also it is above. Comparing this level with the values of Debye temperatures $\theta_{д}$ for the examine/considered by us metals, it can be assumed that the analysis of experimental data their thermal conductivity and the electrical resistance should be conducted, relying on the derivations of the theory of transport phenomena, obtained under condition $T>\theta_{д}$.

Characteristic for this temperature range can be considered following basic facts. The distribution of electrons according to energies is characterized by the presence of the "washed away" layer with a width of order of kT near Fermi surface. The basic reason for the limitation of the mean free path of electrons becomes their interaction with lattice vibrations.

The wavelengths of phonons and conduction electrons become the values of one order. The consequence this is the fact that the impurity/admixture (with too great a difference in valence) they begin in identical measure to scatter these types of excitations. The heat capacity of lattice takes the constant value, determined by Dulong and Petit's rule and equal to 3 Nk.

Let us point out for the basic derivations of theory of transfer [7-11], that are the basis of the qualitative (and sometimes also quantitative) analysis of the results of experimental investigations.

It is possible to assume that total heat transfer in metals and alloys can be represented in the form of the sum of its two main components - heat flow, transferred by lattice, λ_p and the flow, transferred by conduction electrons, λ_e, i.e.

$$\lambda=\lambda_p+\lambda_e. \quad (7\text{-}1)$$

Set/assuming by valid it guides Mathiessen, for reciprocal value of screen conductivity, it is possible to write the relationship/ratio

$$\frac{1}{\lambda_p}=W_U+W_l+W_B+W_e, \quad (7\text{-}2)$$

where W_U - the thermal resistance, caused by the Umklapp processes during phonon-phonon interactions, i.e., by the processes, during which the wave vector of phonons changes to final value; W_l - resistance, caused by scattering on lattice defects; W_B - on the boundaries of specimen/sample; W_e - on conduction electrons.

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condition T>0 for value W_U can be obtained following expression [7-11]:

$$W_U \sim \frac{\gamma^2 T}{D_0 s^3 a}, \quad (7\text{-}3)$$

where γ - constant Gruneisen D_0 - material density; s - speed of sound; a - lattice constant.

If the speed of sound is expressed by the Debye temperature θ, then expression (7-3) on the assumption that other mechanisms of scattering are absent, it leads to following formula for the thermal conductivity of lattice (formula of Leibfreid and Shleman):

$$\lambda_p = \lambda_0 \frac{\theta}{T}. \quad (7\text{-}4)$$

where $\lambda_0 \sim \frac{\bar{A} a \theta^3}{\gamma^2}$.

Here: $\bar{A}$ - average atomic weight; [a] = Å; [θ] = °K.

The estimations of the mean free path of phonon, the which characterize the type in question scatterings, can be carried out on the formula, also obtained by Leibfreid and Shleman [7-18]

$$l \sim \frac{20}{\gamma^2} \cdot \frac{T_{nn}}{T} a, \quad (7\text{-}5)$$

where $T_{пл}$ - melting point.

One should note the approximate character of the given relationship/ratios for λ_p. Ziman emphasizes that them one should consider as lower limit of thermal conductivity which is connected with application/use in the derivations of variational method.

That composing resistances W_i in high-temperature range can be accepted by constant; its value depends on form and concentration of lattice defects. Value W_B in high-temperature range can be disregarded.

For metals and alloys, special interest is shown the examination of the role of last/latter term in expression (7-2) - resistance, caused by phonon-electronic interaction.

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Ziman showed that in the temperature range higher than the Debye his value can be estimated in accordance with the expression

$$W_e < \frac{\rho_\Phi n_a^2}{(k/e)^2 T}, \qquad (7\text{-}6)$$

where ρ_Φ - the electrical resistance of metal, connected with electron scattering as a result of lattice vibrations. Taking into account that at high temperatures ρ_{ϕ} ~T, it is possible to draw the conclusion that during changes in temperature W_e it will remain constant.

According to the estimations of Ziman at Debye temperature for the monovalent metals $W_e \approx 0.1 W_U$. At higher temperatures the effect of phonon-electronic interaction on the total resistance of lattice must, therefore, decrease.

Thus, in range T>θ we right to expect the following temperature dependence of the screen comprising of the metals:

$$\lambda_p = \frac{1}{AT + B}, \qquad (7\text{-}7)$$

where constants A and B depend on the structure of matter and its physical characteristics.

The second component of thermal conductivity λ_e, caused by the transfer of thermal energy by conduction electrons, also is determined by the joint effect of different mechanisms of scattering. The important ones among them are scattering electrons during lattice vibrations (electron-phonon interaction) and scattering on different structural defects. If corresponding component of thermal resistance are designated $W_{e\phi}$ and $W_{eд}$, then it will be possible to write:

$$\frac{1}{\lambda_e} = W_{e\phi} + W_{eд}. \qquad (7\text{-}8)$$

In high-temperature range, the thecry predicts the existence of single bond of both of components with the appropriate components of the electrical resistance of metal.

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The expression of this connection is Wideman - Franz's law, which acts always, when scattering can be considered elastic. In accordance with it

$$W_{e\phi}=\frac{\rho_\phi}{L_0T} \qquad (7\text{-}9)$$

and

$$W_{e\pi}=\frac{\rho_i}{L_0T}, \qquad (7\text{-}10)$$

where $L_0=\frac{\pi}{3}\left(\frac{k}{e}\right)^2=2{,}45\cdot10^{-8}$ V²/deg². Thus, electronic component of thermal conductivity of metals and alloys can be expressed through Lorentz number and electrical resistance ρ:

$$\lambda_e=\frac{L_0T}{\rho}=L_0\sigma T, \qquad (7\text{-}11)$$

where σ - electrical conductivity.

Bloch's known formula [7-19]

$$\rho_\phi\sim\rho_0\frac{T}{\theta} \qquad (7\text{-}12)$$

makes it possible to make the conclusion that in the absence of admixed scattering in ideal metal the coefficient of electronic thermal conductivity will not depend on temperature. In the more general case we must, it is probable, to expect a temperature dependence of the type

$$\lambda_e = \frac{L_0}{a + \frac{\beta}{T}}. \qquad (7\text{-}13)$$

For a series of transition metals, this dependence even more becomes complicated in connection with the increasing with the temperature role of electron scatterings from S-zone in d-zone. To curve $\rho(T)$ this is expressed into form of divergence from linear dependence to the side of decrease $d\rho/dT$. The relative change in the resistivity, caused by this process, negatively and according to Ziman can be estimated on the formula

$$\frac{\delta\rho}{\rho} = -\frac{\pi^2}{24}\left(\frac{kT}{\varepsilon_{Fd}}\right)^2, \qquad (7\text{-}14)$$

where ε_{Fd} - a distance from Fermi surface to the ceiling of d- zone. Taking into account this expression (7.13) should be written in the form

$$\lambda_e \sim \frac{L_0}{a(1-\gamma T^2) + \beta T^{-1}}. \qquad (7\text{-}15)$$

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Thus, electronic component of thermal conductivity of metals in the general case can grow/rise with temperature.

Taking into account screen component the common/general/total thermal conductivity of metals and alloys in dependence on the temperature in range T>6 can be written as

$$\lambda=\frac{1}{AT+B}+\frac{L_0}{\alpha(1-\xi T^2)+\beta T^{-1}} \qquad (7\text{-}16)$$

and be characterized both by the positive and negative values of temperature derivative.

It must be noted that in high-temperature range in accordance with the theory of the conductivity of metals and alloys the experimental values of Lorentz number (considering and screen component) cannot be lower than theoretical value. This gives known evaluation criteria of the authenticity of one or the other results.

In spite of the doubtless successes of theory, reached at present, its level still does not allow with sufficient for technology accuracy to predict the absolute value of one or the other kinetic properties not cnly for complex contemporary structural materials, but also for the majority of pure/clean cell/elements. The decisive word thus far belongs to experiment. To the lot of theory, here remains thus far finding the approximate physical model, which qualitatively explains one or the other special feature/peculiarity of the investigated phenomenon.

7-2. The experimental data on heat- and of electrical conductivity of refractory metals in high-temperature range.

In present paragraph are given some results of our investigations, obtained during installations with the electronic heating (see Chapters 4 and 5). Where this is proved to be possible, is conducted their comparison with other authors' results. In this case, in this stage, the circle of the compared works is limited only by those, in which is measured precisely the coefficient of thermal conductivity. The analysis of data, obtained from experiments the measurement of thermal diffusivity, with the rare exception/eliminations of composite measurements, will take away us to the side of the critical examination of data on heat capacity and densities and, perhaps, will not explain common picture.

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Metals of the fourth subgroup of periodic system titanium, zirconium, hafnium, thorium.

Of all refractory metals this group in the temperature range higher than 1,000°K is least investigated. The experimental data on the thermal conductivity of titanium and thorium generally are absent. If necessary for the sufficiently approximate estimate in the case of titanium, it is possible to use the value of thermal diffusivity, measured in work [7-11]. On its authors' data, in the temperature range of 1,156-1,500°K (beta-phase) the thermal diffusivity of titanium is constant and equal to $6.0 \cdot 10^{-6}$ m^2/s. In the range of phase transformation, it experience/tests jump, descending to $5.1 \cdot 10^{-6}$ m^2/s. The characteristic of specimen/sample is assigned by the value of the relation of resistances $\rho_{298°K}/\rho_{4.2°K}$ =40.

Zirconium is studied better. In [7-2] are given the data of Fieldhouse, obtained by the method of radial heat flux in the temperature range of 484-1925°K.

The investigated in this work material contains 99.95o/o Zr, 0.029o/o Fe, 0.017o/o C and 0.0045o/o Hf. Findings are represented curved of 4 on Fig. 7-1. Here are given results of the investigations of D. I. Timrot and V. E. Peletskiy [4-17] (curves 1 and 2) and the recent data of V. E. Peletskiy and Ya. G. Sobol' (curve 3 and experimental points). In work [4-17] is investigated iodide zirconium by purity 99.5o/o with specimen/sample density at the room temperature of 6.45 g/cm³. Investigations were made on one of the first versions of the installation, working according to the method of the electronic heating (see Chapter 4). Before measurements the specimen/sample passes as three-hour annealing in vacuum 10^{-5} mm Hg at temperature of 1,800°K. Results (curve 1) detect the increase of the coefficient of the thermal conductivity of iodide zirconium with temperature.

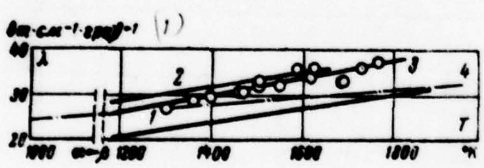

Fig. 7-1. Thermal conductivity of zirconium.

Key: (1) W·cm⁻¹·deg⁻¹.

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Under these conditions were carried out the measurements in the specimen/sample, prepared from the material, obtained by the remelting of iodide zirconium in electric-arc furnace. Crucible was made from graphite. Smelting occurs in the medium of argon. The results of measurements (curve 2) will prove to be higher than the data for an initial iodide material on the average by 30-35o/o with the maximum error for single measurement not more than 12-15o/o.

V. E. peletskiy Ya. G. Sobol' (curve 3) also investigate remelted zirconium. Billet for a specimen/sample is prepared with the method of cathode-ray zone remelting for vacuum. The composition of specimen/sample with the content of base metal not less than 99.9o/o is characterized by following impurity/admixtures, o/o: 0.01 C; 0.005 N_2; 0.01 O_2; 0.009 Fe; < 0.002 Al; 0.03 Nb; <0.005 Cu; <0.003 Ti; <0.005 Si. The resistivity of specimen/sample at the room temperature t=23.5°C will be 44.2 μΩ•cm. Measurements were made during installation with the calorimetric measurement of heat flux in the working section (see Chapter 4) with an error in the single measurement not more than 6-8o/o.

Experimental data are represented by circles. They will confirm the values of the thermal conductivity of the remelted material: temperature course and the absolute values of curves 2 and 3 were very close. Curve of Fieldhouse occupies the intermediate position between our curves for remelted and iodide zirconium and it is characterized by weaker temperature dependence.

It is not-without-interest together with these data to examine the temperature dependence of resistivity. The necessary measurements of electrical conductivity of that remelted by the method of zone melting of zirconium were made by V. P. Druzhinin. They are represented on Fig. 7-2. Curve detects the presence of weak maximum in the range of temperatures of 500-600°K that it correlates well with low-temperature data on Moss's thermal conductivity [7-3].

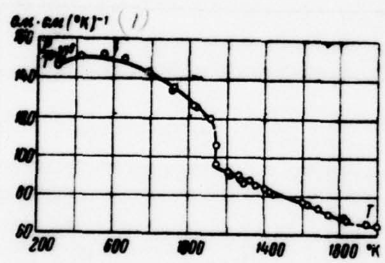

Fig. 7-2. The temperature dependence of the resistivity of zirconium according to data of V. P. Druzhinin and V. E. Peletskiy.

Key: (1). Ω•cm(°K) $^{-1}$.

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In the range of polymorphic conversion, is observed characteristic jump. in the range of beta-phase (cubic lattice) is observed further reduction in value ρ/T. Calculation of Lorentz number according to these data gives for a temperature range 1, 200-1,400° K of the values, which are changed from $2.42 \cdot 10^{-8}$ to $2.50 \cdot 10^{-8}$ V^2/deg^2, i.e., virtually corresponding to theoretical value. We can, thus, indicate that in the high-temperature range, which directly adjoins the zone of polymorphic conversion, the conductivity of compact zirconium is determined by electronic component, which detects tendency toward weak increase.

To Fig. 7-3, given data of the authors on the thermal conductivity of iodide hafnium [4-19]. Experimental model is sharpened from the bar of iodide hafnium. Its average density at room temperature is 13.06 g/cm^3. Material contains to 1.5o/o of zirconium; spectral analysis will reveal/detect the traces of iron and copper (<0.001o/o), the weak traces of silicon and nickel.

The error of result is estimated in these measurements by value by 10-12o/o. Like zirconium, hafnium will reveal/detect the increase of the coefficient of thermal conductivity with temperature. Its absolute value changes from 23.2 W/(m•deg) at 1,300° K to 28.8 W/(m•deg) at 2,000°K and it is very close to the value of the coefficient of the thermal conductivity of iodide zirconium. It must be noted that given data characterize the conductivity of specimen/sample in the direction, perpendicular to the direction of crystal growth in the production of billet. Specimen/sample consists cf the elongated of radial direction coarse grains with weakened communication/connections between them. It is possible, one of the reasons for the observed in zirconium increase of thermal conductivity after remelting consists precisely of a change in the structure of specimen/sample. It is possible to expect analogous change, also, at hafnium, it can be even intensified by the fact that in entire area of exploration it retains hexagonal lattice.

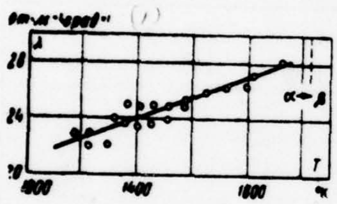

Fig. 7-3. Thermal conductivity of iodide hafnium on the data of work [4-19].

Key (1). Ohms•m•deg.

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The investigated hafnium then was smelted by the method of zone electron-beam melting. In the obtained specimen/sample were carried out the measurements of resistivity. At room temperature (20°C) the impedance of the remelted specimen/sample decreases from 37.3 to 36.2 μΩ•cm. Results in high-temperature range are given to Fig. 7-4. Character of change curved the same as of zirconium. Value ρ/R monotonically falls from jump in the region of polymorphic conversion (2030±20°K). A change of the resistivity in region $\alpha \rightarrow \beta$ junction is approximately 9o/o.

In absolute value our data lie/rest approximately to 5-7o/o below result of work [7-4], made in the wire specimen/samples of hafnium, of containing 4.9 at. o/o zirconium, and to 9-10o/o lower than the data of work [7-5], measurements in which were made on the material, containing 5.7 at. o/o zirconium. The disagreement of these data with ours can be connected with different content of zirconium in specimen/samples. Utilizing data on electrical resistance, it is possible to rate/estimate the value of Lorentz number of hafnium. On our data, it is not lower than the values, determined curved monotonically decreasing from $2.8 \cdot 10^{-8}$ V²/deg² or 1,300°K to $2.5 \cdot 10^{-8}$ at 2000°K.

The evaluation of these values as maximum is connected with the fact that for reasons indicated above the thermal conductivity along the axis of iodide bar (not subjected thermomechanical treatment/working), probably, lie/rests below possible values for a compact polycrystalline material after its remelting.

Metals of the fifth subgroup of periodic system.

Vanadium. The investigations of the coefficient of the thermal conductivity of vanadium in the field of high temperatures will begin to be carried out most recently.

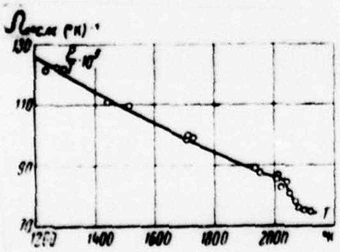

Fig. 7-4. The temperature dependence of the resistivity of hafnium (V. Ya. Voskresenskiy, V. E. Druzhinin, V. I. Feletskiy, D. L. Timrot).

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In handbook [7-2] are given the results a total of two works. One of them is done by Fieldhouse and Lang, the other - Hoch and Nitti.

The first investigated material by purity 99.74o/o (basic impurity/admixtures, o/o: 0.073 O; 0.048 Fe; 0.043 N; 0.042 C); specimen/sample density is equal to 6.05 g/cm³. For measurements was used the absolute method of radial heat flux. By Hoch and Nitti as is known (see Chapter 6), is utilized the method, instituted on the analysis of two-dimensional temperature distribution in a limited cylinder, heated by high-frequency currents. The calculation of the coefficient of thermal conductivity of them is compulsorily connected with the enlistment of data according to the emissivity of material and in the general case washes to be accompanied by the appearance of an uncontrollable in experiment systematic error.

We are inclined more reliable to consider data of Fieldhouse. The comparison of the results of that and other of the works is carried out on Fig. 7-5. Unfortunately, in the data of Hoch and Nitti, given in [7-2], there is no information about the purity of material. Nevertheless even if one takes into account the possible difference in compositicn, it is nct possible tc explain the difference in data, that reaches 100-70c/o, ctherwise as by systematic measuring errcr. Examination Fig. 7-5 makes it possible to draw cnly a conclusion about the need for the supplementary measurements of the coefficient of thermal ccnductivity of vanadium for the zone of high temperatures.

Niobium. In spite cf the wide applicaticn cf this metal and allcys on its basis, its physical prcperties and, in particular, the coefficient of thermal conductivity in the regicn of high temperatures, are studied far not ccmpletely.

Data of Fieldhouse, Hedge and Lang, giver in handbook [7-2], are limited by temperature cf 1,900°K and, unfcrtunately are not described by the composition of material.

Fig. 7-5. Thermal conductivity cf vanadium. 1 - data of Fieldhouse and Lang [7-2]; 2 - data cf Hoch and Nitti [7-2].

Key: (1). W m^{-1} deg^{-1}.

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L. P. Filippov and I. N. Makarenko [7-21] communicate on value the coefficient of the thermal conductivity of niobium at temperature of 1,660°K [0.691 W/cm•deg)], obtained during installation with induction heating. The investigated by them specimen/sample contains 99.2o/o Nb, 0.3o/o Ta, 0.08o/o Ti, 0.04o/o Fe and 0.04 Si it has density 8.54 g/cm³ and specific impedance at the room temperature of 16.4 μΩ•cm. (For reasons presented above we do not give data from the earlier works of L. P. Filippov, calculated on thermal conductivity. They are thoroughly examined by it in its work [3-32]).

New data on niobium in wide temperature interval are recently obtained by B. E. Neymark and L. K. Voronin [7-7]. Initial material in their measurements was obtained by electron-beam melting in vacuum and contains following impurity/admixtures, o/o: 0.3 Ta; 0.01C; 0.001 O; 0.001 N; 0.001 H.

Resistivity at room temperature composes $15.2 \cdot 10^{-6}$ Ω•cm. Measurements cover temperature range from 400 to 2000°K.

It should be noted that to 1200°K experiments were carried out by the method of Jager and Diesselhorst, but at higher temperatures - by Bode's method. Good mating of results taking into account the high reliability of the method of Jager and Diesselhorst makes it possible to consider sufficiently reliable and high-temperature data this work.

Our measurements [4-18] of the coefficient of the thermal conductivity of niobium were made in the range of temperatures of 1400-2300°K on the material, obtained by electron-beam smelting and containing 99.5o/o Nb, 0.17o/o Ta, 0.025o/o Ti, 0.06o/o Si and 0.03o/o Fe. Material density and specific resistance ρ with room temperature (20°C) will compose respectively 8.56 g/cm^3 and 15.6 $\mu\Omega \cdot cm$.

Other researchers' comparison our these with results is carried out on Fig. 7-6. Taking into account an error of measurement (about 10o/o at us, 7-10o/o - at L. P. Filippov, 5o/o - according to the evaluations of Fieldhouse, 10-15o/o - at E. E. Neymark) it is possible to speak about good agreement of the presented in figure data. Made by us the measurements of the resistivity of the same sample (Fig. 7.7) make it possible to calculate values of Lorentz number: it monotonically grow/rises from $2.60 \cdot 10^{-8}$ V^2/deg^2 at 1400°K to $2.72 \cdot 10^{-8}$ V^2/deg^2 at 2300°K. On E. E. Neymark's data in the region of temperatures 1200-2000°K L it grow/rises from 2.56 to $2.61 \cdot 10^{-8}$ V^2/deg^2. For Filippov with 1660°K $L = 2.74 \cdot 10^{-8}$ V^2/deg^2.

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Tantalum. To the study of the properties of tantalum devoted considerable number of works. Only in the region of high temperatures it is possible to call/name seven investigations, made the leading thermophysical laboratories. their enumeration is given in Table 7-1, and the obtained results are represented on Fig. 7-8. As can be seen from figure, data only do not diverge in absolute value (to 200o/o), but sometimes contradict some others according to the type of temperature dependence. So, by Allen [3-33] and by V. V. Lebedev was obtained the negative value of the temperature coefficient of thermal conductivity, while the majorities of works gives an increase in the thermal conductivity of tantalum with temperature. Our data [4-16] (curve 6) occupy the central region of figure and make it possible to draw a conclusion about the weak increase of the thermal conductivity of tantalum with temperature. A maximum error in the single measurement is here estimated at ±12o/o; the scatter of the majority of points around that smoothing curve does not exceed 5-6o/o. The obtained results will agree well with the data of Rasor and McClelland [7-2] and the recently published data of E. E. Neymark and L. K. Voronin [7-7].

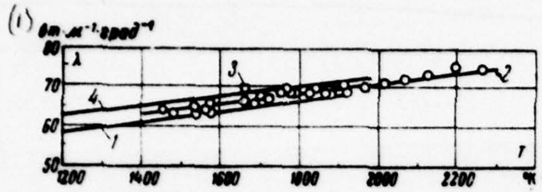

Fig. 7-6. Thermal conductivity of niobium. 1 - data of Fieldhouse, Hedge and Lang [7-2]; 2 - our data; 3 - L. E. Filippova's data [7-2]; 4 - data of B. E. Neymark and L. K. Vorcnin [7-7].

Key: (1). W·m⁻¹·deg⁻¹.

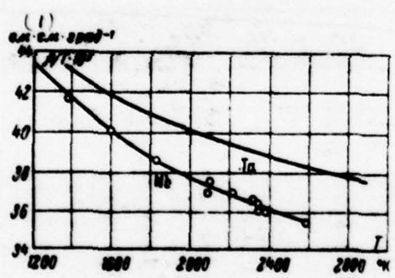

Fig. 7.7. Temperature dependence of the specific electrical resistance of niobium and tantalum accordint to our measurement.

Key: (1). Ω·cm·deg⁻¹.

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Table 7-1. Enumeration of works on the thermal conductivity of tantalum.

(A) № п/п.	(B) Авторы	(C) Год и литература	(D) Метод	(E) Температурный интервал, °K	(F) Характеристика образца (химический состав, %; плотность, $г/см^3$)
1	A. G. Worthing	1914 [Л.3-21]	(1a) Нить с током в вакууме	1 700—2 100	—
2	I. B. Fieldhouse, J.C. Hedge, T. E. Waterman	1956 [Л.7-2]	(2a) Метод радиального потока с внешним источником тепла	800—1 820	(2b) 0,12 O_2; 0,044 N_2; 0,0061 H_2, следы Al, Ca, Cu, Fe, Mg; γ=16,5 $г/см^3$ (2c)
3	N. S. Rasor, J. D. McClelland	1957 [Л.7-2]	(3a) То же	1 300—2 600	0,0073 Zr; 0,0073 Cu; 0,0021 Fe; 0,0009 Ni; 0,008 C; 0,0007 Co; 0,0003 Mn; 0,0002 Si; 0,00017 Al
4	Robert D. Allen, Louis F. Glasier, Jr., Paul L. Jordan	1960 [Л.3-33]	(4a) Нить с током в вакууме. Метод Кришнана и Джайна	2 300—3 200	(4b) Образец № 1: 0,005 Fe; <0,02 Si; 0,0008 C; 0,0033 Mo; 0,052 других составляющих; образец № 2: 0,0028 Fe; 0,0035 Nb; 0,0016 C; 0,0032 O_2; <0,001 N_2; прочих—0,0175
5	В. С. Гуменюк, В. В. Лебедев, В. Е. Иванов	1962 [Л.3-31]	(5a) Нить с током в вакууме. Параболический участок	1 200—2 900	(5b) Тантал промышленной чистоты
6	В. Э. Пелецкий, В. Ю. Воскресенский	1966 [Л.4-16]	(6a) Продольный поток в стержне с внешним источником	1 300—2 900	99,61 Ta; 0,33 Nb; 0,01 Fe; <0,01 Ti; <0,01 Si; 0,02 Mo; 0,014 W; $\rho_{20°C}=13,7\cdot10^{-6}$ ом·см; γ=16,57 $г/см^3$ (6b)
7	Б. Е. Неймарк, Л. К. Воронин	1968 [Л.7-7]	(7a) Метод Боде	700—1 900	0,3 Nb; 0,015 C; 0,003 O_2; 0,002 N_2; 0,001 H_2; $\rho_{20°C}$=15,0 мком·см (7b)

Key: (A). No in sequence. (B). Authors. (C). Year and literature. (D). Method. (E). Temperature interval, °K. (F). Characteristic of specimen/sample (chemical composition, o/o; density, g/cm^3). (1a). Filament with current in vacuum. (2a). Method of radial flow with external heat source. (2b). traces. (2c). g/cm^2. (3a). The same. (4a). Filament with current in vacuum. Method of Krishnan and Dzhayn. (4b). Specimen/sample No 1: 0.005 Fe; <0.02Si; 0.0008 C; 0.0033 Mo;

0.052 other components; specimen/sample No 2: 0.0028 Fe; 0.0035 Nb; 0.0016 C; 0.0032 O_2; <0.001 N_2; other - 0.0175. (5). V. S. Gumenyuk, V. V. Lebedev, V. Ye. Ivanov. (5a). Filament with current in vacuum. Parabolic section. (5b). Tantalum of industrial purity. (6). V. E. Beletskiy, V. Yu. Voskresenskiy. (6a). Longitudinal flow in rod with external source. (6b). Ω•cm; γ=16.57 g/cm³. (7). B. Ye. Neymark, L. K. Voronin. (7a). Bode's method. (7b). Ω•cm; γ=16.57 g/cm³. (7b). μΩ•cm.

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From this series drop out the results, obtained by Worthing [3-21] (one of the first slave in this region) and by Fieldhouse [7-2].

On the basis of known information, it is difficult to find the reasonable explanation to the disagreement of the results of the works of Fieldhouse and Rasor. The utilized by them methods are sufficiently reliable in order to ensure the coincidence of results to 10-15o/o. The sources of possible systematic errors here more easily yield to exception/elimination, than, for example, in the methods of the heated filament where they can noticeably distort absolute values and the temperature course of real curved.

To give on the basis of the described picture any specific reccmmendations to us seems by premature. This will become possible cnly after the systematic studies, ccvering wide temperature region and made by independent methods in the close in ccmpcsition specimen/samples of metal.

The measurements of the resistivity (see Fig. 7-7) make it possible to calculate the values of Lorentz number and to compare them with the results of ctter investigaticns (Table 7-2).

All the given results were obtained during measurements λ and ρ in one and the same specimen/samples. This eliminates the error, connected with the joining of heat- and electrical conductivity to the specimen/samples of assorted compositicn.

Is focused on itself attention of the very low value of Lorentz number, obtained by V. S. Gumenyuk, by V. V. Lebedev and V. Ye. Ivanov.

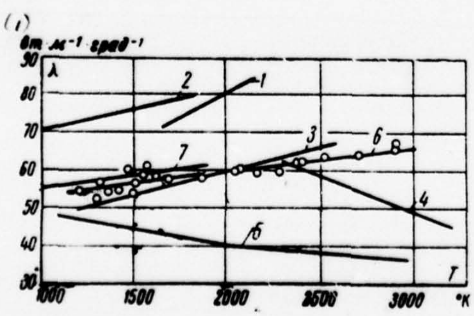

Fig. 7-8. Thermal conductivity of tantalum. The designations of

curves correspond to the reference numbers of works in Table 7-1.

Key: (1). W•m⁻¹•deg⁻¹.

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It is not excluded that these results are erroneous ones, since as yet there are no bases to assume the possibility of considerable divergences from Videman - Franz's law for tantalum in zone T>θ. Our measurements, and also E. Ye. Neymark's last/latter data make it possible to assert that in the region of high temperatures the Lorentz number of tantalum is in effect equal to theoretical value.

Metals of the sixth subgroup of periodic system.

The greatest interest for high-temperature technology among them they represent molybdenum and tungsten. It is logical that this will find its reflection, also, in the development of the investigations of their properties. A number of works only in the range of direct measurements of the coefficient of thermal conductivity will exceed ten both for that and for other materials. However, this will not reveal/detect/expose in any way the final picture of its temperature course for that and other cell/elements.

Molybdenum. The enumeraticn of the basic wcrks, dedicated to the measurement of the coefficient cf the thermal ccnductivity of mclybdenum in high-temperature range, is given in Table 7.3. The crder of their location is establish/installed in the conformity in the course of time of the executicr cf work. The corresponding data are given to Figs. 7-9 and 7-10. (Numbers of curves in figures correspcnd to the reference numbers cf works in table).

We will consider as advisable to divide Scviet and foreign data. Partly this is connected with the tendency tc scmewhat unload figures. However, main reascn will be the tendency tc decrease during comparison the effect of possible differences in technology of obtaining and respectively in structure and purity of the materials being investigated.

Table 7.2. Lorentz number of tantalum $L \cdot 10^8\ V^2/deg^2$ from data of various studies.

(1) Литература	(2) Температура, °K							
	573	873	1 173	1 273	1 300	1 900	2 500	2 900
(3) Наши данные [Л.4-16]	—	—	—	—	2,42	2,40	2,44	2,48
[Л.3-31]	—	—	—	—	1,94	1,68	1,53	—
[Л.7-8]	2,48	2,72	3,04	3,17	—	—	—	—
[Л.7-7]	2,56	2,51	2,48	2,47	2,47	2,44	—	—

Key: (1). Literature. (2). Temperature, °K. (3). Hour data.

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Table 7-3. Enumeration of works on the thermal conductivity of molybdenum.

(A) № п/п.	(B) Авторы	(C) Год, литература	(D) Метод (погрешность)	(E) Интервал температур, °K	(F) Характеристика образца (химический состав, %; плотность, г/см³; удельное сопротивление при 20° С, ом·см)
1	R. H. Osborn	1941 [Л.3-22]	(1a) Нить с током в вакууме. Метод теплового баланса на конечном участке	1 200—1 900	(1b) Следы металлических примесей
2	I. B. Fieldhouse, J. C. Hedge, J. I. Lang, A. H. Takata	1956 [Л.7-2]	(2a) Метод радиального теплового потока	500—1 900	(2b) $\gamma=10,21$ г/см³
3	N. S. Rasor, J. D. McClelland	1956—1960 [Л.7-13]	(3a) То же, $\delta\lambda=\pm5\%$	800—3 000	0,073—0,063 Si; $3\cdot10^{-4}$ Cr; 0,013 Cu; 0,25 Fe; 0,021 Ti; 0,007—0,008 C; $\gamma=10,22$ г/см³ (2b)
4	Р. Л. Рудкин, У. Дж. Паркер, Р. Дж. Дженкинс	1959 [Л.3-23]	(4a) Нить с током в вакууме. Метод баланса тепла, $\delta\lambda=\pm10\%$	1 500—2 100	—
5	R. D. Allen, L. F. Glasier, P. L. Jordan	1960 [Л.3-33]	(5a) Нить с током в вакууме. Метод Кришнана и Джайна	2 400—2 900	(5b) Молибден получен дуговой плавкой в инертной среде. Состав: 0,18 Fe; 0,036 Mn; 0,073 Si; 0,04 C; 0,005 O_2
6	K. H. Bode	1961 [Л.1-16]	(6a) Метод вариации рабочего тока	1 100—1 200	99,98 Mo
7	В. С. Гуменюк, В. Е. Иванов, В. В. Лебедев	1962 [Л.7-14]	(7a) Нить с током в вакууме. Параболический участок	1 200—2 500	(7b) Промышленный Mo

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Continuation, Table 7-3.

(A) № п/п.	(B) Авторы	(C) Год, литература	(D) Метод (погрешность)	(E) Интервал температур, °K	(F) Характеристика образца (химический состав, %; плотность, $г/см^3$; удельное сопротивление при 20° С, ом·см)
8	M. Gutler, G. T. Cheney	1963 [Л.3-4]	(8a) Дифференциальный вариант метода Кольрауша	1 100—1 700	(8b) Состав не приводится
9	Л. П. Филиппов	[Л.3-32]	(9a) Нить с током в вакууме. Экспоненциальный участок	1 600—2 400	99,8 Mo; 0,1 Fe
10	Д. Л. Тимрот, В. Э. Пелецкий, В. Ю. Воскресенский	1966 [Л.7-15]	(10a) Метод электронного нагрева, $\delta\lambda = \pm 10\%$	1 300—2 400	(10b) Поликристалл: 99,95 Mo; $\gamma = 10,20$ $г/см^3$
11	Д. Л. Тимрот, В. Э. Пелецкий, В. Ю. Воскресенский	1966 [Л.7-15]	(11a) То же, $\delta\lambda = 10 \div 12\%$	1 400—2 200	(11b) Монокристалл: 99,95 Mo; 0,005 C; 0,001 O_2; 0,00001 H_2; 0,001 N_2; $\gamma = 10,20$ $г/см^3$; (11c) $[X \wedge 100] = 26°$; $[X \wedge 100] = 24°$; $[X \wedge 111] = 32°$
12	В. Э. Пелецкий, Я. Г. Соболь	1968	(12a) Метод электронного нагрева с калориметром, $\delta\lambda = \pm 8\%$	1 200—2 200	Технический Mo: 99,9 Mo; (12b) 0,01 полуторных окислов
13	В. Э. Пелецкий, Я. Г. Соболь	1968	(11a) То же	1 200—2 200	(13a) Монокристалл [100]; 99,98 Mo; 0,01C; $\rho_{20°C} = 5,404$ мком·см (13b)
14	В. Э. Пелецкий, Я. Г. Соболь	1968	(11a) То же	1 200—2 200	99,8 Mo; 0,15 (14a) металлических примесей; 0,01 $(N_2+O_2+H_2)$; $\gamma = 10,20$ $г/см^3$ (11c)

Key: (A). No in sequence. (B). Authors. (C). Year, literature. (D). Method (error). (E). Range of temperatures, °K. (F). Characteristic of specimen/sample (chemical composition, %; density, g/cm^3; specific impedance with 20°C, Ω•cm). (1a). Filament with current in vacuum. Method of heat balance on finite segment. (1b). Traces of metallic impurity/admixtures. (2a). Method of radial heat flux. (2b). g/cm^3. (3a). The same. (4). R. L. Rudkin, W. J. Parker, R. J. Jenkins. (4a). Filament with current in vacuum. Method of the balance of heat, $\delta\lambda=\pm 10o/o$. (5a). Filament with current in vacuum. Method of Krishnan and Dzhayn. (5b). Molybdenum is obtained by arc smelting in inert medium. Composition: 0.18 Fe; 0.036 Mn; 0.073 Si; 0.04 C; 0.005 O_2. (6a). Method of a variation in the operating current. (7). V. S. Gumenyuk, V. e. Ivanov, V. V. Lebedev. (7a). Filament with current in vacuum. Parabolic section. (7b). Industrial Mo. (8a). Differential version of Kohlrausch's method. (8b). Composition is not given. (9). L. P. Philipp. (9a). Filament with current in vacuum. Exponential section. (10) and (11). D. L. Timrot, V. E. Peletskiy, V. Yu. Voskresenskiy. (10a). Method of electronic heating, by $\delta\lambda=+10o/o$. (10b). Polycrystal: 99.95 Mo; γ=10, 20 g/cm³. (11a). The same, $\delta\lambda$=10-12o/o. (11b). Single crystal. (11c). g/cm³. (12), (13) and (14). V. E. Peletskiy, Ya. G. Sobol'. (12a). Method of electronic heating with calorimeter, $\delta\lambda=\pm 8o/o$. (12b). Technical Mo: 99.9; 0.01 one-and-one-half oxides. (13a). Single crystal. (13b). μΩ•cm. (14a). metallic impurity/admixtures.

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(It is possible to assume that Soviet measurements taken in specimen/samples, very close in technology of obtaining and purity). On the foreign data given to Fig. 7-9, it is difficult to make any judgements about the thermal conductivity of molybdenum with temperatures higher than 1500°K.

Soviet data lie/rest more mound. Data, obtained in the institute of high temperatures (curves 10-14) in the massive specimen/samples of Soviet molybdenum, delineate a comparatively narrow zone [±(5-8)o/o] the possible values of the coefficient of thermal conductivity. It must be noted that different curves are obtained in different time during installations with different working sections (Table 7-3).

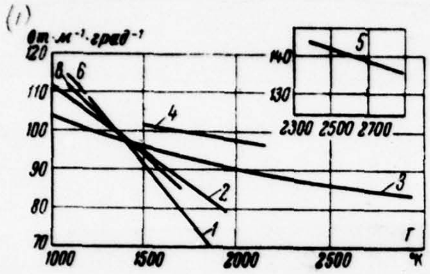

Fig. 7-9. Foreign data on the thermal conductivity of molybdenum.

Key: (1). W•m⁻¹•deg⁻¹.

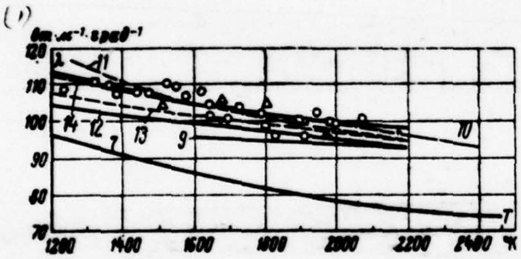

Fig. 7-10. Soviet data on the thermal conductivity of molybdenum.

Key: (1). W•m⁻¹•deg⁻¹.

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As the illustration of the value of the random error for curve 14 are presented the experimental points, obtained in three different specimen/samples, cut out from one and the same bars of the material being investigated. As is evident, the scatter of points does not exceed ±(4-5) o/o. By dotted curves are represented the results of investigation of the single crystals of molybdenum (curves 11 and 13). For their coincidence with data for polycrystalline specimen/samples places in the doubt the conclusions of Jun and Hoch [7-16] about the essential effect of scattering on grain boundaries of high-temperature range. Our data they close to adjoin the results, obtained by L. P. Filippov (curve 9).

Completely noticeably differ from the series of our data results [7÷14] (curve 7). As in the case with tantalum, the obtained by the authors this works of value correspond to the very low values of Lorentz number: in average segment of a curve they approximately to 20o/o lower than theoretical value.

The comparison of those observed by the experimenters of the values of Lorentz number is carried out on Fig. 7-11.

Our measurements (necessary data on ρ acquired were on the same specimen/samples and shown on Fig. 7-12), I. P. Filippov's results as direct measurements of Lorentz number, made by Cutler and Cheney [3-4], make it possible to speak about the noticeable manifestation of the phonon component of thermal conductivity of molybdenum and are characterized by exceeding of the measured values of Lorentz number above theoretical ones.

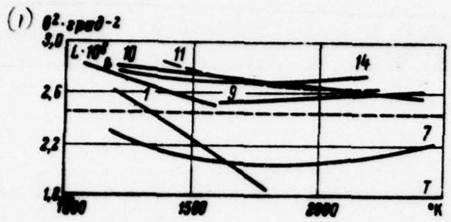

Fig. 7-11.

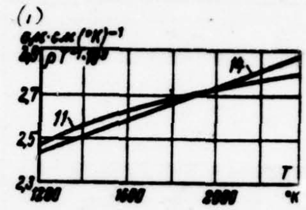

Fig. 7-12.

Fig. 7-11. Lorentz number of molybdenum. The designations of curves correspond to the reference numbers of works in Table 7-3.

Key: (1). $V^2 \cdot deg^{-2}$.

Fig. 7-12. The resistivity of molybdenum (our data). The designations of curves correspond to the reference numbers of works in Table 7-3.

Key: (1). $\Omega \cdot cm (^{\circ}K)^{-1}$.

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The results of Osborne and V. V. Lebedev do not give grounds for this conclusion. Figures 7-9 - 7-11 make it possible to make the assumption that curves 1, 2, 5, 7 and 8 will contain the disregarded systematic error, that distorts the true character of temperature dependence of the thermal conductivity of molybdenum. All remaining data delineate the range of the possible values, comparable in width with the values of maximum errors, capable of occurring upon the correct setting of experiment.

The value of this range with temperature of 1300°K covers approximately interval ±(8-10) o/o around the average value equal to to 107-108 W/(m•deg) and ±(6-8)o/c around 93-94 W/(m•deg) at 2200°K.

Tungsten. The enumeration of the basic works, which contain the results of direct measurements of the coefficient of the thermal conductivity of tungsten in high-temperature range, is given in Table 7-4. The corresponding data are represented on Figs. 7-13 and 7-14.

Just as for molybdenum, works examines in separate figure. Situation on the basis of foreign sources virtually the same as for the molybdenum: the scatter of data is so great that does not make it possible to say anything that determined about the value of thermal conductivity. The results of Soviet works lie/rest denser and are characterized by the identical sign of temperature derivative.

Our data are represented by circular points and to that smoothing curved 7. With them will excellently agree the results, obtained of B. E. Neymark and by L. K. Voronin (curve 11).

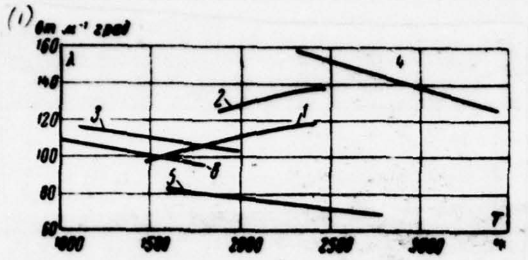

Fig. 7-13. Foreign data on the thermal conductivity of tungsten. The designations of curves correspond to the reference numbers of works in Table 7-4.

Key: (1). W•m⁻¹deg.

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Table 7-4. Enumeration of works on the thermal conductivity of tungsten.

(A) № п/п.	(B) Авторы	(C) Год и литература	(D) Метод (погрешность)	(E) Интервал температур, °К	(F) Характеристика образца (химический состав, %; плотность, $г/см^3$; удельное сопротивление при 20° С, ом·см)
1	A. G. Worthing	1914—1925 [Л.3-21, 7-9]	(1a) Нить с током в вакууме. Метод баланса тепла на конечном участке образца	1 500—2 500	(1b) Проволока
2	C. Zwikker	1925 [Л.7-10]	То же (2a)	1 800—2 400	—
3	Robert H. Osborn	1941 [Л.3-22]	То же (2a)	1 100—2 000	(3a) Спектрально чистый. Следы металлических примесей
4	Robert D. Allen, Louis F. Glasier, Paul L. Jordan	1960 [Л.3-33]	(4a) Нить с током в вакууме. Метод Кришнана и Джайна	2 400—3 400	(4b) Материал получен методом порошковой металлургии; чистота первого образца: 99,95 (0,002 Cu; 0,04 Mo); второго: ~99,91 (0,004 Fe; 0,005 Ti; 0,005 Ni; 0,006 O_2; 0,04 Mo)
5	Р. Л. Рудкин, У. Дж. Паркер, Р. Дж. Дженкинс	1960 [Л.3-23]	(5a) Нить с током в вакууме. Метод баланса тепла на конечном температурном интервале, $\delta\lambda = \pm 10\%$	1 600—2 800	(5b) Спектрально чистый
6	В. С. Гуменюк, В. В. Лебедев	1961 [Л.3-30]	(6a) Нить с током в вакууме. Параболический участок, $\delta\lambda = \pm 6\%$	1 200—2 500	(6b) Промышленный вольфрам
7	Д. Л. Тимрот, В. Э. Пелецкий	1963 [Л.7-20]	(7a) Метод электронного нагрева, $\delta\lambda = \pm 15\%$	1 300—2 900	(7b) Вольфрам электроннолучевой плавки. Чистота 99,9%

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Continuation, Table 7-4.

(A) № п/п.	(B) Авторы	(C) Год и литература	(D) Метод (погрешность)	(E) Интервал температур, °К	(F) Характеристика образца (химический состав, %; плотность, г/см³; удельное сопротивление при 20° С, ом·см)
8	M. Gutler, G. T. Gheney	1963 [Л.3-4]	(8a) Дифференциальный вариант метода Кольрауша	600—1 800	(8b) Монокристаллический образец; состав не приводится
9	Е. С. Платунов, В. Б. Федоров	1964 [Л.2-38]	(9a) Нить с током в вакууме. Расчет второй производной температурного распределения	1 300—3 300	(9b) Промышленный вольфрам
10	Ю. Н. Симонова, Л. П. Филиппов	1965 [Л.7-12]	(10a) Нить с током в вакууме. Экспоненциальный участок, $\delta\lambda = \pm 9\%$	1 400—3 000	(10b) Вольфрам марок ВА-3П и В4
11	Б. Е. Неймарк, Л. К. Воронин	1968 [Л.7-7]	(11a) Метод Боде	600—2 500	(11b) Чистота 99,95%
12	В. Э. Пелецкий, Я. Г. Соболь	1968	(12a) Метод электронного нагрева с калориметром, $\delta\lambda = 6 \div 8\%$	1 300—2 300	(12b) Основа W; 2,3 Y_2O_3; 0,04 Mo; 0,015 R_2O_3; 0,007 CaO; 0,01 SiO_2; $\gamma = 17,9$ г/см³; (12c) $\rho_{20°C} = 6,21$ мком·см (12d)

Key: (A). No in sequence. (B). Authors. (C). Year and literature. (D). Method (error). (E). Interval of temperatures, °K. (F). Characteristic of specimen/sample (chemical composition, o/o; density, g/cm³; specific impedance with 20°C, Ω•cm). (1a). Filament with current in vacuum. Method of the balance of heat on the finite segment of specimen/sample. (1b). Wire. (2a). The same. (3a). Spectrally pure/clean. Traces of metallic impurity/admixtures. (4a). Filament with current in vacuum. Method of Krishnan and Jain. (4b).

Material is obtained by the method of powder metallurgy; the purity of the first specimen/sample: 99.95 (0.002 Cu; 0.04 Mo); the second: ~99,91 (0.004 Fe; 0.005 Ti; 0.005 NI; 0.006 C_2; 0.04 Mo). (5). R. L. Rudkin, U. J. Parker, R. J. Jenkins. (5a). Filament with current in vacuum. Method of the balance of heat in finite temperature interval, $\delta\lambda=\pm10$o/o. (5b). Spectrally pure/clean. (6). V. S. Gumenyuk, V. V. Lebedev. (6a). Filament with current in vacuum. Parabolic section, $\delta\lambda=\pm6$o/o. (6b). Industrial tungsten. (7). D. L. Timrot, V. E. Peletskiy. (7a). Method of electronic heating, by $\delta\lambda=\pm15$o/o. (7b). Tungsten of electron-beam melting. Purity 99.9o/o. (8a). Differential version of Kohlrausch's method. (8b). Single-crystal specimen/sample; composition is not given. (9). E. S. Platunov, V. b. Fedorov. (9a). Filament with current in vacuum. Calculation the second derivative of temperature distribution. (9b). Industrial tungsten. (10). YU. N. Simonov, L. P. Filippov. (10a). Filament with current in vacuum. Exponential section, $\delta\lambda=\pm9$o/o. (10b). Tungsten of brands VA-3P and V4. (11). B. E. Neymark, L. k. Voronin. (11a). Bode's method. (11b). Purity 99.95o/o. (12). V. E. Peletskiy, Ya. G. Sobol'. (12a). the method of electronic heating with calorimeter, $\delta\lambda=6-8$o/o. (12b). Basis, (12c). g/cm³. (12d). μΩ•cm.

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Within limits of error in the corresponding measurements, it is possible to speak about the coincidence of our data with results [2-38, 3-30]. Curved 10, obtained of Yu. N. Simonovoy and by L. P. Filippov, give, it is probable, the high values.

To this same conclusion it is possible to arrive, by examining a change of Lorentz number of tungsten (Fig. 7-15) p curve 10 in the range of temperatures of 1500-2500°K it gives the highest values of Lorentz number.

Combined analysis Figs. 7-13 - 7-15 makes it possible to assume that during the generalization of experimental data on tungsten for basis could be undertaken Osborne's works (curve 3), Cutler and Cheney (curve 8) and the results of Soviet works, with exception curved 10. This series delineates the band of the possible values of the coefficient of thermal conductivity 8-10o/o in wide around the average value, which is charged from 108 W/(m•deg) at 1300°K to 96 W/(m•deg) at 2500°K.

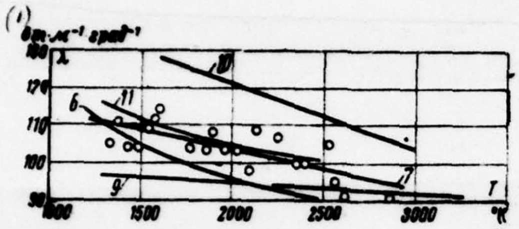

Fig. 7-14. Domestic data on the thermal conductivity of tungsten. The designations of curves correspond to the reference numbers of works in Table 7-4.

Key: (1). W•m-1•deg-1.

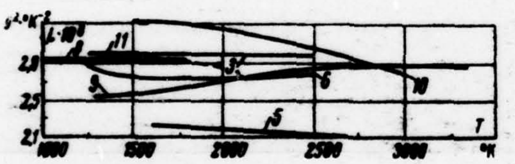

Fig. 7-15. Lorentz number of tungsten. The designations of curves correspond to the reference numbers of works in Table 7-4.

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It is possible also to assume that with the high degree of the probability of transfer of heat in tungsten is characterized by noticeable participation by phonon component, which appears in the excess of the measured values of Lorentz number above the theoretical. Most reliable works are determined it by the values, which lie at range $(2.8-3.0) \cdot 10^{-8}$ V^2/deg^2.

V. E. Peletskiy and Ya. G. Sobol' will conduct measurements of heat- and electrical conductivity of cermet tungsten with the additions of oxide of yttrium (work 12 in Table 7-4). In accordance with technology of the production of specimen/samples this tungsten could be considered as two-phase system, and taking into account the fact that the conductivity of oxide phase substantially lower than the conductivity of matrix/die, it was possible in the first approximation, to speak about material with conditional bulk porosity P. In this case, in the first examination, it is possible to count that the function, which corrects the values of conductivity depending on P, will be identical both for heat transfer and for the transfer of charge $\lambda=\lambda_0 f(P)$; $\sigma=\sigma_0 f(P)$. In this case the presence of porosity (second phase) must not noticeably distort the value of Lorentz number of this system. Actually, as shows Fig. 7-16, value L, obtained for the investigated system [$(2.9-3.1) \cdot 10^{-8}$], excellently coincides with reliable data for the pure tungsten (see Fig. 7-15). Let us note that the discussed results indirectly confirm reliability of the data of D. L. Timrot and V. E. Peletskiy [7-20] (curve 7 on Fig. 7-15). If on V. I. Odelevskiy's formula [7-17] for statistical mixtures is calculated a change in the conductivity $\delta\lambda=(\lambda_0-\lambda)$, then in our case ($\Pi_{усл}=8,5\%$) it will prove to be equal to approximately

13c/o. Experiment gives change δλ frcm 15o/c with 1400°K to 10o/o with 2200°K - agreement entirely fair.

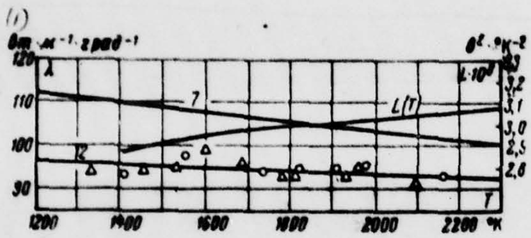

Fig. 7-16. Thermal conductivity and Lorentz number of tungsten with the additicns of oxide.

Key: (1). W•m⁻¹•deg⁻¹.

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By the named works it is possible to restrict survey/coverage of the existing these on thermal conductivity base refractory metals in high-temperature range. It bears several one-sided character, since it does not consider investigations, made by unsteady methods.

In conclusion we give the instituted on our measurements data on the coefficient of thermal conductivity and the resistivity of base refractory metals. With error not more than 4-8c/o on thermal conductivity and 2-3o/o on resistivity they characterize the properties indicated for the materials of the highest purity, reached in their industrial production at present.

Table 7-5. Coefficients of the thermal conductivity of base refractory metals λ.

(1) Металл	(2) λ, вт·м⁻¹·град⁻¹, при T, °K									
	1 200	1 400	1 600	1 800	2 000	2 200	2 400	2 600	2 800	3 000
Zr	27,4	30,9	34,4	37,9	—	—	—	—	—	—
Hf	22,5	24,0	25,6	27,2	28,8	—	—	—	—	—
Nb	60,2	62,8	65,4	68,0	70,6	73,2	75,8	—	—	—
Ta	54,4	55,8	57,2	58,6	60,0	61,4	62,8	64,2	65,6	67,0
Mo	111	106,5	103	100	97,4	94,8	92,2	—	—	—
W	112	110	108	106	103,5	101,5	99	97	96	93,5

Key: (1). Metal. (2). λ, $W \cdot m^{-1} \cdot deg^{-1}$, with T, °K.

Table 7-6. The resistivity of base refractory metals.

(1) Металл	(2) ρ, мком·см, при T, °K									
	1 200	1 400	1 600	1 800	2 000	2 200	2 400	2 600	2 800	2 900
Zr	112	118,3	123,1	126,9	130,1	—	—	—	—	—
Hf*	151,0	160,5	167,4	170,3	173,0	—	—	—	—	—
Nb	52,01	58,10	64,00	69,79	75,44	81,14	86,71	92,46	—	—
Ta	—	60,4	67,1	73,6	80,0	86,4	92,8	99,2	105,6	108,8
Mo	29,5	35,49	41,57	47,77	54,08	60,90	67,17	—	—	—
W	30,2	37,05	43,95	50,85	57,75	64,65	—	—	—	—

(3) *При T>2 000 °K для Hf имеем:

T, °K	2 040	2 080	2 100
(4) ρ, мком·см	165,8	159,5	158,5

Key: (1). Metal. (2). ρ, μΩ•cm, with T, °K. (3). *With T>2000°K for Hf, we have. (4). μΩ•cm.

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HIGH-TEMPERATURE INVESTIGATIONS OF HEAT - AND OF ELECTRICAL CON--ETC(U)

SEP 78 V E PELETSKIY, D L TIMROT

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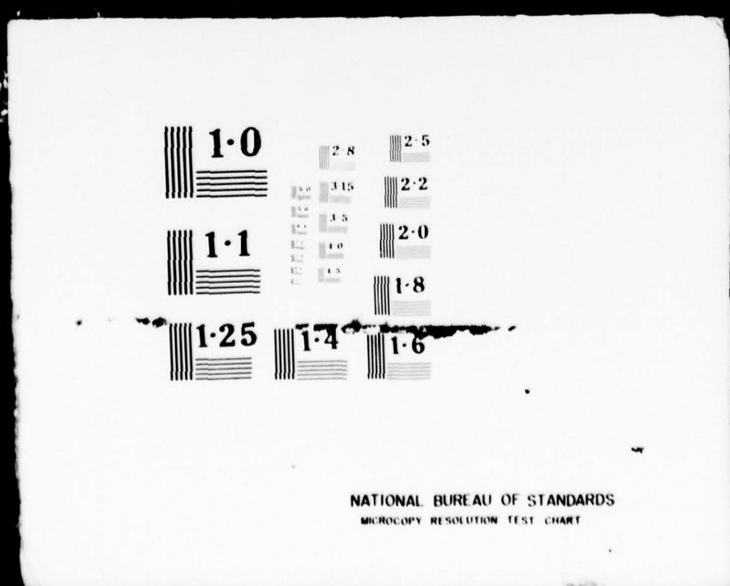

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