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CALCULATING THE TEMPERATURE FIELDS IN THE BUCKET OF A GAS TURBINE COOLED THROUGH SLOTS IN THE ASSEMBLY

Ye. I. Molchanov and A. R. Khenven

The article lists the results of calculating the temperature fields appearing in the cooled bucket of a gas turbine. The effect of limiting conditions and of heating and cooling regimes on the temperature drop in the bucket cross-section is clarified. Temperature distribution along the elevation of the bucket is investigated and the heating of the coolant air is estimated.

The increase in the efficiency of modern gas turbines demands the use of a working substance with high initial temperature. The need arises to use different kinds of cooling systems in order to protect the components of gas turbines functioning in the high temperature region. The efficiency of the cooling system adopted is determined by its functional reliability, consumption of fluid coolant, structural shape, and a number of other factors.

Despite the use of a cooling system in a number of high-temperature gas-turbine installations, damage to the most heavily loaded subassemblies, particularly to the bucket device, takes place. It is assumed that one of the causes of this damage is the high thermal stresses arising in the cooled elements of gas turbines.

The present article demonstrates the calculation of temperature distribution in the transient and steady thermal currents appearing in a bucket cooled through slots in the assembly and investigates heat exchange between the bucket with its air coolant and the gas.

In the present work we have calculated the temperature field of the bucket on the hydraulic integrator constructed by V. S. Luk'yanov which enables us rapidly to carry out a series of computations to determine the temperature fields of the components in different work regimes and at any given configuration of boundary and initial conditions.

The working buckets, the temperature fields of which we are investigating in the present work, are part of the first stage of a two-stage gas turbine. The stage consists of 80 buckets and the temperature of the gas in front of it equals 760° under nominal operating conditions. The turbine plates are cooled through clearances or slots in the assembly at the base points of attachment of the buckets. Each stage is provided with its individual supply of coolant air.

A bucket of the first stage was chosen for research on the temperature fields since it exists under the most difficult temperature conditions. Our work consists of two sections.

In the first section we have determined the temperature fields which arise along the elevation of the bucket when it is warmed up in a stationary regime. As a result of these calculations the cross-section was made apparent in which we may leave out of consideration the radial thermal currents — a condition necessary for further investigation of temperature fields in the cross-section of the bucket.

Furthermore, we derived the values of the thermal currents from the bucket's point of base attachment toward the air coolant, as well as the temperature distribution along the elevation of the bucket, for different values of coefficients of heat exchange on the blade of the bucket and in the slotted channels of the base attachment and at various temperatures of the air coolant.

In the second section of the work we investigated the temperature fields which appear in the cross-section of the bucket in transient regimes of heating and cooling. In doing this we examined the two-dimensional plane problem, i.e., the problem in which no consideration was taken of the radial thermal current.

In doing the calculations we allowed for a change in the geometric dimensions along the length of the blade of the bucket. When investigating the temperature change there, we divided the blade into nine blocks; and when making the cross-sectional calculations, into 29 blocks, also allowing for a temperature-conditioned change in the physical parameters of the bucket material — the coefficients of heat conductivity λ and specific heat c. Table 1 lists the data on the physical parameters.

TABLE 1

Physical Parameters of Bucket Material.

t, °C	100	200	300	400	500	600	700	800
λ, $\frac{\text{kcal}}{\text{m·hr·degree}}$	8.28	9.72	11.15	12.95	14.75	16.55	18.70	20.65
c, $\frac{\text{kcal}}{\text{m}^3\text{·degree}}$	0.090	0.096	0.105	0.115	0.120	0.130	0.140	0.145
		γ = 8400 kg/m³						

The result of these calculations was the determination of the temperature drops across the bucket section in regimes corresponding to different limiting and initial conditions. We ascertained the temperature drops Δt as the difference between the trailing edge and bucket cross-section center temperature.

Calculation of the Temperature Field Along the Bucket Elevation

Investigations of the heat exchange between the bucket and the gas and the air coolant were conducted for a wide value of heat exchange coefficients along the blade of the bucket α_{ft} and in the slots of the base attachment α_{τ} (500, 1000, 2000, and 4000 kcal/m²·hr·degree). On the facial surface of the bases the heat-exchange coefficient is assumed to be constant and equal to 600 kcal/m²·hr·degree. Calculations were made for a number of values of the temperature of the air coolant passing through the slots at the base attachment t_a = 170, 300, and 450° in order to explain its effect.

All the calculations to determine the temperature fields along the elevation of the buckets were conducted with an instantaneous rise in the temperature of the gas and the air coolant to a nominal value (t_g = 760, t_a = 170, 300, and 450° C). In doing this it is assumed that the thermal current to the plate from the base attachment of the bucket is lacking and all the heat going through the bucket hinge is transferred in its entirety to the air coolant. This assignment of limiting conditions is most favorable from the point of view of uniformity of temperature distribution along the elevation of the bucket.

In order to select a section in which it would be possible to neglect the radial thermal current we examined a transient problem of temperature distribution along the elevation of the bucket with a maximum value of the coefficient of heat exchange in the slots of the basal connection (α_τ = 4000 kcal/m²·hr·degree) and minimum value toward the blade of the bucket (α_{ft} = 500 kcal/m²·hr·degree). The temperature of the air coolant was, moreover, taken as minimum (t_a = 170°C).

Under these conditions the greatest portion of the blade of the bucket will have a non-uniform temperature.

When we calculated the physical parameters (λ and c) we selected them by starting from the block temperature to be determined under a steady heat regime.

Figure 1 shows the results of calculating temperature distribution in transient and steady heat regimes along the elevation of the bucket. The section chosen for the transient regime in which it would be possible to neglect the radial thermal current was situated 58 mm from the root section. In the second section of the work we investigated heat distributions at different transient regimes for this section.

The same graph shows the results of calculating the temperature field along the elevation of the bucket in a steady heat regime for the case t_a = 300 and 450° C.

From the cited calculations it follows that on a substantial portion of the blade of the bucket in the steady heat regime the temperature is close to that of the gas and only in the regions near the basal attachment are there observed radial temperature gradients. For heat-exchange coefficients in the slots of the basal connection α_τ = 4000 kcal/m²·hr·degree the temperature of the end of the base of the bucket is close to that of the air coolant. When this coefficient is decreased eightfold the base temperature increases 30-70°. The lesser difference can be referred to the higher temperature of the air coolant. A change in the coefficient of heat exchange in the flow-through part also alters the character of temperature distribution along the bucket in the steady heat regime. With the rise in the coefficient of heat exchange in the flow-through portion the temperature of the basal connection also rises, and under these circumstances the higher the value of α_τ, the less the effect of α_{ft} on the temperature of the base. We may draw the conclusion based on analysis of the data obtained that in the empirical investigation of temperature fields in a cooled bucket of a gas turbine it is desirable to have the lowest possible temperature of the air coolant. This enables us to estimate with greater accuracy the coefficients of heat exchange in the different regions of the bucket.

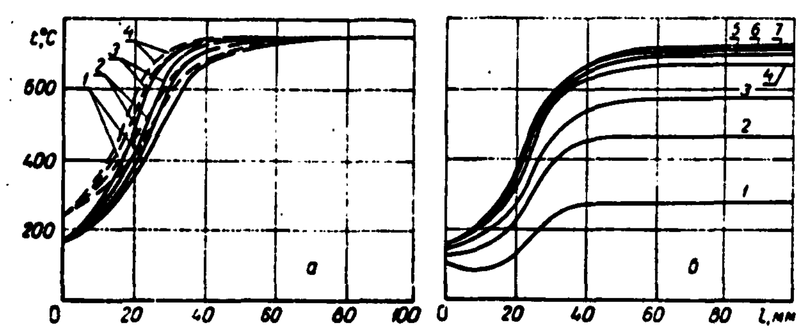

Fig. 1. Change in temperature along elevation of bucket when t_a = 170°. Steady heat regime (a): 1) α_{ft} = 500 kcal/m²·hr·degree; 2) 1000; 3) 2000; 4) 4000 (solid line — α_τ = 4000 kcal/m²·hr·degree; dashed, 500); transient heat regime (b): α_{ft} = 500, α_τ = 4000 kcal/m²·hr·degree; 1) τ = 2 sec; 2) 4; 3) 6; 4) 10; 5) 15; 6) 20; 7) 40.

In the process of solving these problems on the integrator we also measured the thermal currents going from the bucket to the air coolant (Fig. 2). The calculations show that in the case of the greatest thermal current q = 452 kcal/hr·degree, observed when α_{ft} = = 4000 kcal/m²·hr·degree, α_{τ} = 4000 kcal/m²·hr, and t_a = 170°, the temperature of the air coolant on leaving the base of the bucket will equal t''_a = 197.4° C and the temperature of the entrant air t'_a = 142.6.

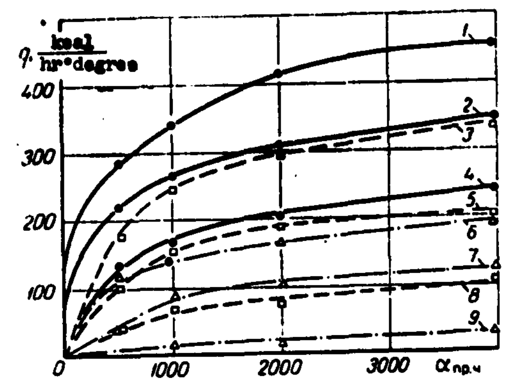

Fig. 2. Magnitude of thermal current from hinge of bucket to air coolant depending on coefficients of heat exchange in flow-through portion and base connection and on temperature of air coolant. 1, 3, 6) 170° C; 2, 5, 7) 300; 4, 8, 9) 450; for different α_{τ}: 1, 2, 4) 4000 kcal/m²·hr·degree; 3, 5, 8) 2000; 6, 7, 9) 1000.

Calculating the Temperature Field on the Bucket Cross-Section

The temperature field and the drops on the bucket cross-section were ascertained for different coefficients of heat exchange in the flow-through portion (α_{ft} = 4000, 2000, 500 kcal/m²·hr·degree) and for different times of gas temperature rise $\Delta\tau$ from initial 20 to nominal 760°. In doing so, $\Delta\tau$ was chosen equal to 0, 5, 15, and 30 sec. The regime $\Delta\tau$ = 0 corresponds to an instantaneous rise in gas temperature to the nominal. The temperature of the gas was raised to the nominal value in accordance with a linear law. In addition, we ascertained the temperature fields for the case of instantaneous drop in the gas temperature from the nominal to 170° C for the same values of α_{ft}, corresponding to a flame-out in the combustion chamber when the gas temperature falls to that of the air entering the chamber from the compressor.

The investigation of the temperature fields on the bucket cross-section showed that substantial temperature jumps occur in it in warming up and in cooling.

Figure 3 displays the graphs of the change in the temperature drop on the bucket cross-section Δt as a function of time when $\alpha_{ft} = 4000$ kcal/m²·hr·degree and when $\Delta\tau$ assumes different values. By Δt is understood the difference which arises between the center of the thickest part of the cross-section and the trailing edge.

In the initial period Δt increases, reaching its greatest value Δt_{max} at the moment in time $\tau_{\Delta t_{max}}$, and falls thereafter.

With a rise in the value of $\Delta\tau$ the curves have a more sloping character and the maximum value of the temperature change decreases, nevertheless remaining sufficiently high; the time of appearance of the maximum temperature change is displaced to the side of the larger values of τ. With the decrease in the coefficient of heat exchange in the flow-through portion the temperature changes on the cross-section decrease.

As the calculations showed, the greatest effect of the rise time of the gas temperature $\Delta\tau$ on the maximum temperature change $\Delta\tau_{max}$ is observed in the region of larger values of α_{ft}; when α_{ft} decreases, Δt_{max} drops; but the degree of the effect of $\Delta\tau$ on the maximum change

Δt_{max} simultaneously decreases.

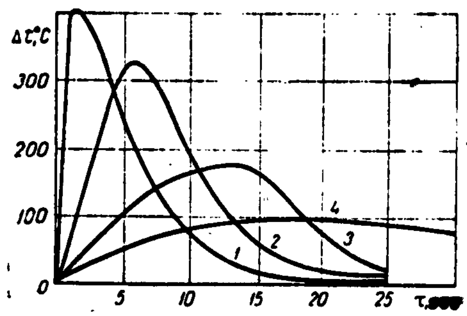

Fig. 3. Change in time of temperature alteration on bucket cross-section for $\alpha = 4000$ kcal/m²·hr·degree, λ and $\underline{c}$ at 300° C, and different $\Delta\tau$: 1) 0; 2) 5; 3) 15; 4) 30.

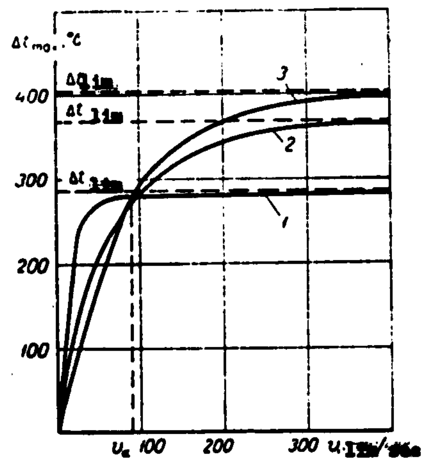

Fig. 4. Dependence of maximum temperature change on bucket cross-section on velocity of gas temperature rise for various α_{bl}: 1) 500 kcal/m²·hr·degree; 2) 2000; 3) 4000.

With the increase in the velocity of gas-temperature rise $\underline{v}$ the maximum temperature change Δt_{max} increases and at the infinitely large value of $\underline{v}$, corresponding to $\Delta\tau = 0$, reaches the limit value Δt_{lim}. Each coefficient of heat exchange of α_{ft} has its own value of

Δt_{lim}, the latter increasing with the former.

The graph in Fig. 4 makes clear that at a definite velocity of gas-temperature increase v_α the maximum temperature change Δt_{max} does not depend on α_{ft}.

When the value of $v > v_\alpha$, the maximum change increases with an increase in α_{ft}; when $v < v_\alpha$, a reverse picture is presented — larger values of Δt_{max} correspond to lesser values of α.

At high velocities of gas-temperature rise v, however, the maximum temperature change practically does not depend on it and is determined only by the coefficient of heat exchange of α_{ft}.

These calculations also showed that the instant of the appearance of the maximum temperature change $\tau_{\Delta t_{max}}$ depends on both the gas-temperature rise period (velocity) and the coefficient of heat exchange in the flow-through section α_{ft}. It may be seen from the calculations that with the growth of α_{ft} the instant of the appearance of the maximum change decreases for all values of v.

The especially great influence of the velocity of the gas-temperature rise on the instant of appearance of the maximum change is observed at small values of $v < 200$ deg/sec, the maximum change entering the period where the gas temperature attains the nominal value. At larger values of v this effect is less pronounced and the instant of appearance of maximum temperature change on the cross-section is close to the moment which corresponds to instantaneous gas-temperature rise to nominal value.

Similar relationships for Δt_{max} and $\tau_{\Delta t_{max}}$ have been derived also for the regime of instantaneous gas-temperature drop from nominal to 170° C.

English Summary from Original Article

The investigation of temperature fields appearing in a cooled bucket of a gas turbine was carried out.

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A STUDY OF THE ELECTRICAL CONDUCTIVITY OF A FLAME BY THE MICROWAVE METHOD

E. P. Zimin and V. A. Popov

This work examines the microwave method of measuring the electrical conductivity of a flame. The results of experiments conducted in a methane-air flame with additions of potassium are given.

The importance of the study of the electrical conductivity of weakly ionized gases, in particular of combustion products, is explained by the fact that chemical reactions in gases are accompanied by the formation of charged particles. Knowledge of the mechanism of the formation of these particles and of the quantitative relationship between their concentration and the reaction parameters would place in the hands of researchers a method no less valuable than the spectroscopic method.

Study of the electrical conductivity of flames is important also because of the advent of a new direction in the area of power engineering: magnetohydrodynamic power engineering.

A flame, obviously, is the most likely source of high-temperature conducting gases, which are the working substnace of an MHD generator.

The required electrical conductivity of the flame in such a generator can be provided either by nonequilibrium chemical ionization, or by introducing into the flame additives with a low ionization potential.

Up to the present time, however, no effective methods of ionization and reliable means for measuring experimentally the electrical conductivity of a flame have been developed.

This work studies ionization in methane-air flames with additions of easily ionized substances.

Experimental Apparatus

A mixture of methane and air was burned over a flat burner of the type described by Spalding [3], which is a porous disk with pores on the order of 0.1 to 0.15 mm. By previous formation of the fuel mixture, and also by uniform supply of it to the combustion zone, a flat flame is created over the surface of the burner. In this flame all parameters vary only along the axis perpendicular to the plane of the flame front (the plane of the burner). The low burning rates of methane-air mixtures allow the flat flame to be raised above the burner to a distance of 6 to 8 mm.

In a flat flame, along the axis perpendicular to the flame front, there occurs a change in temperature, concentration of charged particles and chemical composition. Pressure over the entire region of the flame is constant and equal to the pressure of the surrounding medium. However, in the region beyond the flame, at a sufficient distance from the front, it is possible to isolate a certain plane above which the medium is in a state of equilibrium, and, in addition, its temperature and chemical composition do not vary, for all practical purposes.

An advantage of the method of studying the properties of conducting gases in a flame is the fact that the electron concentration and the frequency of their collision with other particles, two fundamental values which determine the electrical conductivity of the gas, can be assigned independently of one another.

Measurement of ionization in a flame is done by the method of microwave attenuation, which is based on a calculation of the parameters of the medium through which the electromagnetic wave passes, by the weakening of the power of the latter.

An essential advantage of the microwave method is the possibility of determining the electron component directly.

In order to make measurements in a flame, we introduced a waveguide section which satisfied, on the one hand, the requirement of electromagnetic hermeticity for high-frequency oscillations, and, on the other hand, did not introduce substantial oscillations into the hydrodynamic pattern of the flow of combustion products beyond the flame front. These requirements were satisfied by a waveguide whose two opposite wide walls were made in the form of grids of platinum wires with a diameter of 0.2 mm.

Heat deformation was prevented by shielding the wires with quartz capillary tubes with a diameter of 0.4 mm; the capillary tubes lay freely in grooves in the framework of the waveguide, which was made of stainless steel. The grid spacing was 3 mm, which ensured electromagnetic hermeticity of the working section. The waveguide working section, with a cross section of 23 X 1 mm, was connected to a standard waveguide line (23 X 10 mm) by transition sections with oblique walls.

The working section of the waveguide operated stably for approximately 30 min, after which it was replaced because the quartz burned up.

Easily ionized additives were introduced into the fuel mixture in the form of a mist created by atomization of an aqueous solution of K_2CO_3.

The measuring system included an oscillator, a waveguide circuit and a receiver.

Attenuation of Electromagnetic Waves in a Homogeneous Conducting Medium

An electromagnetic field in a medium consisting of neutral molecules and free electrons is described by the Maxwell equations

$$c \operatorname{rot} \mathbf{E} = i\omega\mu \mathbf{H}, \quad c \operatorname{rot} \mathbf{H} = -i\omega\varepsilon \mathbf{E}, \tag{1}$$

where

$$\varepsilon = \varepsilon_c + i4\pi\sigma/\omega, \quad \mathbf{H} = \mathbf{H}_0 \exp(-i\omega t), \ \mathbf{E} = \mathbf{E}_0 \exp(-i\omega t). \tag{2}$$

For a plane wave propagated along the z-axis, Eqs. (1) reduce to the system

$$\frac{d^2A}{dz^2} + k^2A = 0 \ (A = E_x, E_y, H_x, H_y), \tag{3}$$

where

$$k^2 = (\alpha + i\beta)^2 = \frac{\omega^2}{c^2}\mu\left(\varepsilon_c + i4\pi\frac{\sigma}{\omega}\right).$$

The solution of Eq. (3) has the form

$$A = A_0 e^{(i\alpha - \beta)z},$$

where α is the refraction index,

$$\alpha = \left\{\frac{\mu\omega^2}{2c^2}\left[\varepsilon_c + \sqrt{\varepsilon_c^2 + \left(4\pi\frac{\sigma}{\omega}\right)^2}\right]\right\}^{1/2}; \tag{4}$$

β is the attenuation factor,

$$\beta = \left\{\frac{\mu\omega^2}{2c^2}\left[-\varepsilon_c + \sqrt{\varepsilon_c^2 + \left(4\pi\frac{\sigma}{\omega}\right)^2}\right]\right\}^{1/2}. \tag{5}$$

By examining the equation of motion of an electron in a harmonic electromagnetic field in the form

$$\frac{d\mathbf{v}}{dt} + \mathbf{F} = \frac{e}{m} \mathbf{E}_0 \exp(-i\omega t)$$

and bearing in mind that at low degrees of ionization, in practice, it is necessary to take into account collisions of electrons only with neutral particles, i.e., with polarized molecules, when the potential energy of interaction and the collision frequency are not functions of velocity (i.e., $\mathbf{F} = \nu\mathbf{v}$), it is not difficult to determine the polarization vector for electrons

$$\mathbf{P} = n_e e^2 \frac{-\omega + i\nu}{\omega m(\omega^2 + \nu^2)} \mathbf{E}.$$

Similarly, we can determine the polarization vector for ions. However, if the medium is quasi-neutral, they can be negligible in comparison with the polarization vector for electrons, since the mass of an ion considerably exceeds the mass of an electron.

The dielectric constant of a medium consisting of s forms of "quasizing" molecules, q forms of solid molecules, and free electrons with density n_e is determined by the relation

$$\varepsilon_c = \varepsilon_0 + 4\pi n \left(\sum_{i=1}^{s} \delta_i \gamma_i' + \frac{1}{3kT} \sum_{j=1}^{q} M_j^2 \gamma_j'' \right) - 4\pi \frac{n_e e^2}{m(\omega^2 + \nu^2)}, \tag{6}$$

where $\gamma_i' = n_i'/n$; $\gamma_j'' = n_j''/n$.

A gas containing molecules and free electrons in a high-frequency field is equivalent to a dielectric with complex dielectric constant (2), the real part of which is determined by relation (6), and into the imaginary part of which enters the alternating-current electrical conductivity, determined by the expression

$$\sigma = n_e e^2 \nu / m(\omega^2 + \nu^2).$$

The direct-current conductivity σ_0 is linked to σ by the following relation:

$$\sigma_0 = \sigma(1 + \omega^2/\nu^2).$$

Calculation of the frequency of collision of electrons with neutral molecules is made by the formula (at $Q \approx 10^{-15}$ cm^2 [4] and $p = 0.981 \cdot 10^6$ d)

$$\nu = \frac{p}{\sqrt{T}} Q \sqrt{\frac{\pi}{2mk}} = 3{,}46 \cdot 10^{12} \frac{1}{\sqrt{T}}.$$

In the combustion products of a methane-air flame, the solid dielectrics are only water molecules ($M = 1.87 \cdot 10^{18}$ CGSE) and CO molecules ($M = 1.18 \cdot 10^{-19}$ CGSE). The mean polarizability of air molecules is $\delta = 1.7 \cdot 10^{-24}$ [4].

Calculations show that at $\sigma_0 < 10^{-2}$ mhd/cm, p = 1 atm (abs) and $\omega = 5.7 \cdot 10^{10}$ sec^{-1}, the term $\sigma/\nu = n_e e^2/m(\omega^2 + \nu^2)$ in expression (6) can be ignored.

Then, if the effect of CO molecules is ignored, the dielectric constant of the medium is determined by the relation

$$\varepsilon_c = 1 + \Delta\varepsilon_1 + \Delta\varepsilon_2,$$

where $\Delta\varepsilon_1 = 0.156p/T$; $\Delta\varepsilon_2 = 780\, p_{H_2O}/T^2$.

Figures 1 and 2 show graphs of the functions $\Delta\varepsilon_1(p)$ and $\Delta\varepsilon_2(p_{H_2O})$, and Fig. 3 shows a graph of the function $\Delta\varepsilon/\Delta\varepsilon_1 = \varphi p_{H_2O}/p$ at various temperatures from 1000 to 1000°K.

From these figures it is apparent that at low values of p_{H_2O}, in the temperature range under consideration, we can assume $\varepsilon_c \approx 1$.

Formulas

Since β, which is determined by Eq. (5), is the attenuation factor for the strength of an electrical field, and the power of a wave $N \sim E^2$, then

$$N = N_0 \exp(-2\beta z). \qquad (7)$$

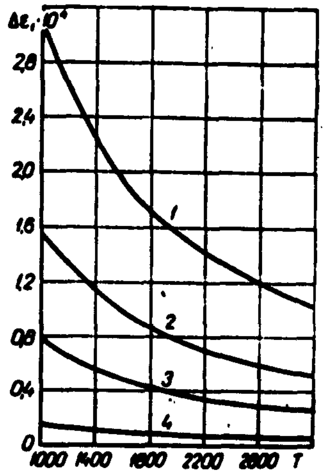

Fig. 1. Dependence of $\Delta\varepsilon_1$ upon temperature ($^\circ$K) at pressures: 1) 2 atm (abs); 2) 1; 3) 0.5; 4) 0.1.

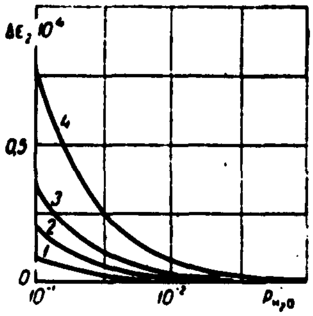

Fig. 2. Dependence of $\Delta\varepsilon_2$ upon partial water-vapor pressure p_{H_2O} at temperatures: 1) 3000°K; 2) 2000; 3) 1500; 4) 1000.

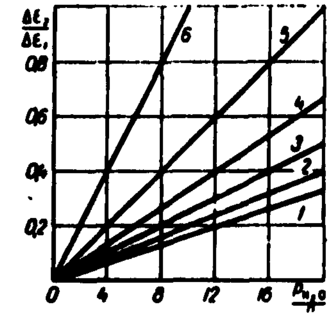

Fig. 3. Dependence of $\Delta\varepsilon_2/\Delta\varepsilon_1$ upon p_{H_2O}/p(%) at temperatures: 1) 3000°K; 2) 2500; 3) 2000; 4) 1500; 5) 1000; 6) 500.

For all practical purposes, in a flame we can assume $\mu \approx 1$. Then, taking into account that $\varepsilon_c \approx 1$, under the condition $4\pi\sigma/\omega \ll 1$, we obtain

$$\beta = \frac{2\pi}{c}\sigma_0 \frac{1}{1+\omega^2/\nu^2}. \tag{8}$$

From relations (7) and (8) we obtain the relationship between the attenuation factor in decibels $\hat{\beta} = 10 \log N_0/N$ and the conductivity of the medium

$$\sigma_0 = 6.16\cdot 10^{-4}(1+\omega^2/\nu^2)\hat{\beta}/z \quad \text{mho/cm}.$$

The limit of applicability of the microwave method for determining the electron concentration, obviously, is that concentration at which complete reflection of electromagnetic radiation from the boundary of the conducting medium occurs

$$n_{cr} = m\omega^2/4\pi e^2.$$

Results of Experiments

By the method of microwave attenuation we measured the conductivity of the combustion products of a methane-air flame with addition of potassium at a partial pressure $p_k = 2.64 \cdot 10^{-3}$ atm (abs) in the temperature range from 1450 to 1550°K.

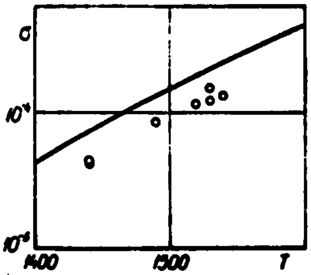

Fig. 4. Dependence of conductivity of combustion products of methane-air flame upon temperature.

The results of the experiments, processed in accordance with the method described above, are shown in Fig. 4. The line on the graph is the theoretical dependence of conductivity upon temperature, calculated by the equations of Saha [5] and Chapman [6]:

$$x^2 = 10^{\lg K(T)}/p_\kappa, \quad a = xp_\kappa, \quad \sigma_0 = n_e e^2/m\nu = 3{,}85 \cdot 10^{-10} a/Q\sqrt{T}$$

The constant of ionization equilibrium is determined by the expression

$$\log K(T) = -6{,}491 - 5041 \frac{U_i}{T} + \frac{5}{2} \log T.$$

The experimental values of the electrical conductivity of a methane-air flame at $T \approx 1500$°K with addition of potassium ($p_K \approx 10^{-3}$ atm (abs)) measured by the microwave-attenuation method are in satisfactory agreement with the calculated values, which were determined assuming the existence of thermodynamic equilibrium.

The work was done in 1960 in the laboratory of member-correspondent of the Academy of Sciences of the USSR L. N. Khitrin, to whom the authors are grateful.

Symbols

ω is the angular frequency of the field;

ε_c and μ the dielectric constant and permeability of the medium, respectively;

σ the conductivity;

v the mean velocity of an electron;

n_i' the concentration of the i-th form of quasi-elastic molecules;

n_j'' the concentration of the j-th form of quasi-elastic molecules;

n the total number of particles per unit volume;

δ the polarizability of a quasi-elastic molecule;

M the electric moment of a solid molecule;

ε_o the dielectric constant of a vacuum;

ν the frequency of collisions of electrons with neutral particles;

Q the effective collision cross section;

p the pressure;

$\Delta\varepsilon_1$ the contribution to the dielectric constant of the quasizing air molecules;

$\Delta\varepsilon_2$ the contribution to the dielectric constant of the solid water molecules;

p_{H_2O} the water-vapor partial pressure in atm (abs);

N_o the power of the incident radiation;

N the power at distance z (the coordinate origin lies at the boundary of the flame);

x and a the degree of ionization of potassium and the mixture, respectively;

U_i the ionization potential in ev.

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