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ALUMINUM AS A HIGH-TEMPERATURE
HEAT-TRANSFER AGENT

by

S. S. Filimonov, M. G. Kryukova,
and S. V. Teplov



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ALUMINUM AS A HIGH-TEMPERATURE HEAT-TRANSFER
AGENT

By: S. S. Filimonov, M. G. Kryukova,
and S. V. Teplov

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ABSTRACT: This work considers increasing power plant economy and reducing heat-exchanger size through the use of aluminum as the heat-transfer agent. The physical characteristics of aluminum are given and discussed. The advantages of impurities of certain metals in aluminum, the reactions of aluminum at high temperatures (720-1200°C), and the disadvantages of high chemical activity, are discussed and compared with the thermophysical properties of the alkali metals. The use of graphite as the structural material to be in contact with liquid aluminum is proposed for direct thermal-to-electric energy conversion and in atomic reactors. An experimental installation developed at the G. M. Krzhizhanovskiy Power Engineering Institute is described and evaluated. The thermophysical characteristics of Al and using graphites as the structural material permit considering aluminum a prospective heat-transfer agent for application in solving a number of problems. The difficulties in the way of practical use of aluminum as a heat-transfer agent can be successfully surmounted. Heat exchange during motion of liquid aluminum in pipes can be calculated by equations that are correct for calculation of heat exchange of other liquid-metal heat-transfer agents. Work carried out in the Power Engineering Institute opens practical possibilities for use of aluminum as a heat-transfer agent. Technological part of this work can be used by the metallurgical industry for solution of problems connected with continuous

casting of metals, pressure die casting, and other questions of
founding. English translation; 26 pages. Orig. art has:
5 tables and 4 figures.

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

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

* ye initially, after vowels, and after ъ, ь; e elsewhere.
 When written as ѣ in Russian, transliterate as yě or ě.
 The use of diacritical marks is preferred, but such marks
 may be omitted when expediency dictates.

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ALUMINUM AS A HIGH-TEMPERATURE
HEAT-TRANSFER AGENT

S. S. Filimonov, M. G. Kryukova,
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One of the effective ways of increase of power plant economy and decrease of dimensions of heat exchange equipment is increase of temperature of working substance — heat-transfer agent. For this reason liquid-metal heat-transfer agents, which have a number of advantages as compared to other liquid-metal heat-transfer agents [1], have been used all the more frequently. At present as liquid-metal heat-transfer agents there are mainly used alkali metals and their eutectic alloys, since while possessing good heat physical properties they have a rather low melting point, comparatively high critical temperature, and they weakly interact with structural materials which are widely applied in technology.

However, requirements of contemporary technology are so wide and various that in certain cases the application of such excellent heat-transfer agents, which are alkali metals, is connected with many difficulties. Such difficulties appear for instance during development of heat exchangers of various assignment, operating at high temperatures of heat-transfer agent (over 1200°C). During the analysis of such problems it is expedient to consider the question on selection of new

heat-transfer agents, which would allow simplification of their solution. One of such heat-transfer agents, from our point of view, is aluminum, which possesses good heat-physical characteristics, as follows from Tables 1 and 2.

Table 1

Characteristics	Numerical value	Literary source
Melting point (content of Al-99.99%), °C . .	660	[2]
Latent heat of fusion kilocalorie/kilogram	93.96	"
Boiling point, °C	2300-2500	"
Latent heat of vaporization, kilocalorie/kilogram	2107-2305	"
Capture cross section for thermal neutrons, barn	0.22	[8]

The ability to give amphoteric oxides is characteristic for aluminum. Aluminum is active with oxygen. Even at room temperature it is easily covered in air by a thin, very dense, film of oxides, which protects the metal from further oxidation. Aluminum reduces the majority of metallic oxides to metal. It is energetically connected with halogens, and at moderately high temperature — with sulfur, nitrogen, and phosphorous. During heating aluminum is easily dissolved in diluted nitric and sulfuric acids. Aluminum forms aluminated in alkalis.

Of the gases hydrogen is dissolved the most actively in aluminum. Solubility of hydrogen depending upon temperature is shown below.

Temperature, °C . . .	0	300	400	500	600	660	
Solubility of H ₂ cm ³ /100 g Al . . .	10 ⁻⁷	10 ⁻³	5 · 10 ⁻³	1.25 · 10 ⁻²	2.6 · 10 ⁻²	3.6 · 10 ⁻²	
Temperature, °C . . .	Liquid metal	600	700	725	750	800	850
Solubility of H cm ³ /100 g Al . . .		0.60	0.02	1.07	1.23	1.67	2.15

Table 2

Characteristic	Temperature, °C										Lit- erary source
	700	800	900	1000	1100	1200	1300	1400	1500		
Vapor pressure, mm Hg	2.10^{-8}	2.10^{-6}	$5.6 \cdot 10^{-5}$	$5.4 \cdot 10^{-4}$	$4.1 \cdot 10^{-3}$	$2.5 \cdot 10^{-2}$	$1.08 \cdot 10^{-1}$	$4.5 \cdot 10^{-1}$	1.5	[3]	
Speed of evaporation, g/cm ² s.	10^{-9}	$2.8 \cdot 10^{-8}$	$4.5 \cdot 10^{-7}$	$4.7 \cdot 10^{-6}$	$3.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$8.8 \cdot 10^{-4}$	$3.5 \cdot 10^{-3}$	10^{-2}	[3]	
Coefficient of thermal conductivity λ , Cal/m·h·deg	77.2	80.2	83.1	85.7	88.0	90.2	92.3	94.4	96.3	[5]	
Kinematic viscosity $\nu \cdot 10^8$, m ² /s	48.4	42.0	36.8	33.0	30.5	28.5	27.0	26.0	25.0	[6]	
Specific gravity γ , g/cm ³	2.36	2.33	2.29	2.26	2.23	2.2	2.17	2.14	2.11	[7]	
Coefficient of temperature conductivity $a \cdot 10^3$, m ² /h	125.73	132.3	139.7	145.7	151.7	157.7	163.7	169.8	175.4	*	
True specific heat capacity C_p , Cal/kg·deg	—	0.2571	0.266	0.2667	—	—	—	—	—	[2]	
Prandtl number $Pr \cdot 10^2$	1.39	1.14	0.95	0.81	0.72	0.65	0.59	0.55	0.51	*	
Specific electrical resistance $\rho \cdot 10^{-6}$, $\Omega \cdot \text{cm}$	24.7	26.2	27.7	29.2	30.6	32.1	—	—	—	[4]	

*During computation of coefficient of a and Pr number there were used data of [5-7]. during which value of C_p was taken equal to 0.26.

The presence in aluminum of impurities of certain metals, (manganese, nickel, magnesium, iron, chromium, tantalum, and certain others) essentially increases the solubility of hydrogen, especially in liquid metal. Aluminum will form aluminum nitride with nitrogen: this reaction starts at temperatures over 800°C.

Melted aluminum at high temperatures enters into reaction with carbon monoxide, carbon dioxide, and sulfurous gasses. As a result of these reactions there are formed aluminum oxide, aluminum carbide, and aluminum sulfide which contaminate the metal and increase solubility of different gases in it. Aluminum, being connected with carbon, will form aluminum carbide Al_4C_3 .

This reaction (pieces of Al were heated in coal dust) is started already at the melting point; however, it flows so slowly right up to 1000°C that the formed Al_4C_3 does not affect physical characteristics of aluminum. In usual melting conditions of aluminum in carbon crucibles or under a coating of charcoal the formation of Al_4C_3 was observed only at temperatures on the order of 1700°C [2].

There is very little data on interaction of liquid aluminum with different metals and other structural materials [9-12]. Table 3 contains our experimental data, purpose of which is to clarify the possibility of usage of certain structural materials for work in contact with liquid aluminum. For this the samples from investigated materials were placed in liquid aluminum and were held in it at a specific temperature for 2-5 hours. Samples were weighed before placing in aluminum and after being in it. Purification of aluminum samples before the second weighing was produced by means of their treatment in alkali solutions if the tested material did not interact with alkali, or by means of atomization of aluminum in a vacuum.

Table 3

Tested material	Temperature °C	Weight of sample		Time of test, hours
		before test	after test	
Tantalum	720	5,955	5,858	4
"	1020	12,169	8,89	1,5
"	1100	8,838	4,63	4
Molybdenum	1000	8,85	0	2
Tungsten	1020	9,6	1,44	2
Zirconium	1000	3,5	0	2
Heat-resisting chromium-molybdenum steel	1000	3,5	0	2
Gray cast iron	700	1,430	1,283	2
"	1000	1,430	0	2
Tantalum with borated surface	950	0,433	0,433	2
The same	1100	0,391	0,38	5
"	1200	0,591	0,568	5
Molybdenum with silicified surface	1100	Corrosion of metal by microcracks		5
Titanium carbide	1070	1,263	1,28	3
Titanium boride	1070	0,929	1,072	3
"	1070	0,948	1,112	3
Zirconium boride	1070	3,052	3,11	3
Zirconium oxide	1070	1,683	1,683	3
Reactor graphite	1100	5,351	3,351	4
Talc steatite	1100	3,241	3,241	5
Chloride talc	900	3,150	3,150	4
Graphite alloy with boron nitride	1100	6,750	6,750	5
Quartz	900	Structure of material was completely changed		0,5
Porcelain	900			0,5

From comparison of given data for aluminum with heat-physical characteristics with alkali metals, it follows that boiling point and thermal conductivity of aluminum is considerably greater, and capture cross section of thermal neutrons is considerably less than corresponding magnitudes for alkali metals. Considering that the remaining heat-physical characteristics of comparable metals are approximately identical, and also considering small vapor pressure of aluminum at high temperatures, the conclusion can be made that from the point of view of heat-physical characteristics, aluminum as a heat-transfer agent has definite advantages as compared to alkali metals during solution of problems, connected with high temperature of the heat-transfer agent.

On the other hand, high chemical activity of aluminum creates many difficulties in selection of structural materials, which

undoubtedly will considerably hamper its practical application. As follows from Table 3, pure metals and their alloys without special protective coatings cannot be used as structural materials for work in contact with liquid aluminum. Subsequently, there will be developed special coatings which reliably protect metal from the influence of melted aluminum. At present during work with liquid aluminum, as structural materials there can be used first of all different graphites, and also graphite with coatings of carbides of certain metals, graphite with a protective film from pyrolytic carbon, silicified graphite, and other materials produced on the basis of graphite. There can probably be applied carbides, borides, and nitrides of certain metals [10]. Thus, during work with liquid aluminum there is a considerably more limited selection of structural materials as compared to possibility of their selection during work with alkali metals.

However, the possibility to use graphite as such, and also successes attained in producing highly dense graphites and their protection from oxidation and mechanical erosion by application coatings from different materials, permit considering that for work in contact with liquid aluminum in a rather wide range of temperature change there is a good structural material. It is also necessary to bear in mind that use of alkali metals at temperatures above 1000°C is also connected with many difficulties in the selection of structural materials, since the most frequently used materials are not applicable in these conditions.

Graphite, as a structural material, possesses both positive and negative qualities. Physical and chemical characteristics of synthetic graphite (practically all articles are made from synthetic graphite) depend to a considerable measure on initial material and method of its treatment [13-15].

All the produced industrial graphites are characterized by considerable porosity, where the pores, as a rule, are open. Volume weight of graphites varies from 1.4 to 1.8 g/cm³, whereas theoretical density of graphite is equal to 2.27 g/cm³ at a temperature of 20°C. Density of graphite is somewhat increased with increase of temperature. Graphite with higher volume weight is produced by means of packing the graphite: either by means of repeated impregnations of blanks from graphite of low density, or by packing them with pyrolytic carbon by its deposition from gas phase. Technology of graphite packings at present can be considered worked out [13, 15-17]. By means of packings it is possible to produce graphite with volume weight close to theoretical. Such graphite is practically gastight.

Graphite possesses entirely acceptable mechanical strength [13, 15]; it is increased considerably with increase of volume weight of graphite. A valuable feature of graphite is the fact that its mechanical strength is considerably increased with increase of temperature and is doubled at temperatures on the order of 2400°C as compared to strength at room temperatures [13].

One of the important properties of graphite is its high heat resistance. Graphite is a highly thermal conductive material. Coefficient of thermal conductivity of graphite depends on its volume weight, initial material from which it is produced, method of its production, and several other factors. Therefore, coefficients of thermal conductivity of different grades of graphite can differ essentially from each other. On the average at room temperature it is close to thermal conductivity of liquid aluminum. Coefficient of thermal conductivity of graphite is decreased with increase of temperature.

Electrical resistance of graphite, just as coefficient of thermal conductivity, depends on many factors. Its mean value at $t = 20^{\circ}\text{C}$ is equal to $0.028 \Omega \cdot \text{cm}$. Electrical resistance is decreased with increase of temperature [2]. Coefficient of linear expansion of graphite essentially depends on type and quality of initial materials and can be changed within limits of $2 \cdot 10^{-6} - 4 \cdot 10^{-6}$ at $t = 1000^{\circ}\text{C}$ [13]. Coefficient of linear expansion of graphite highly depends on temperature: its mean value is decreased with increase of temperature.

When using graphite as a structural material special attention should be paid to the possibility of its oxidation. Graphite starts to be oxidized in air at $t = 520 - 560^{\circ}\text{C}$, in steam atmosphere at $t = 700^{\circ}\text{C}$, and in CO_2 atmosphere at 900°C . Speed of oxidation is increased with increase of temperature. Nuclear radiation of high intensity also contributes to increase of speed of oxidation of graphite. For protection of graphite from oxidation a number of measures are applied. First of all, inasmuch as porosity increases speed of oxidation, we try to close the pores. Methods of surface and volume packing of graphite by means of deposition of carbon from gas phase have received wide usage [13]. This method of protection of graphite essentially increases its mechanical strength simultaneously. Good results are given by coatings from carbides of different metals. Technology of protective coatings on graphite is worked out at present.

Thus, from the above it follows that good heat-physical characteristics of aluminum, on the one hand, and possibility of use of graphites as structural materials, on the other, permit considering aluminum a sufficiently prospective heat-transfer agent, which will find application during solution of problems connected with usage of

heat exchangers which operate at high temperatures of heat-transfer agents. Such conditions take place in particular in heat exchangers applied in various systems of direct conversion of thermal energy into electric [18].

A prospective field of application of aluminum, from our point of view, is its usage for heat removal in high-temperature atomic reactors. Use of aluminum as a heat-transfer agent in reactors working on thermal neutrons is advantageous, on the one hand, from the point of view consumption of neutrons, inasmuch as capture cross section of neutrons of thermal energies for aluminum is more than two times less [0.22 barn] than for sodium (0.49), which is characterized by minimum capture cross section of thermal neutrons as compared to other alkali metals. On the other hand, use of aluminum as a heat-transfer agent, considering its compatibility with graphite in distinction from alkali metals, will make it possible to essentially simplify the construction of active zone of reactor, since it permits considering the question on elimination from active zone of reactor. Finally application of aluminum will permit essentially increasing parameters of working substance of second circuit and will facilitate problems of second circuit in practice because of absence of explosive hazard during contact of aluminum with water.

The above permits making the conclusion that aluminum is a prospective heat-transfer agent which can find a rather wide field of application. In the G. M. Krzhizhanovskiy Power Engineering Institute since 1959 there have been conducted works directed on the basis of aluminum as a heat-transfer agent from a technological point of view, and also works connected with investigation of heat exchange during movement of liquid aluminum in graphite pipes.

Practical possibility of use of aluminum as a heat-transfer agent depends on solution of a number of questions of both technological and heat-physical character. Technological questions include the selection of structural materials that are able to work in contact with liquid aluminum, development of high-temperature equipment (pumps for transferring liquid aluminum, heaters, etc.), and also a group of questions connected with the use of graphite as structural material (hermetic coupling of separate parts, protection from oxidation, decrease of gas permeability, compensation of change of linear dimensions, and others). Majority of enumerated questions were not solved earlier. In the G. M. Krzhizhanovskiy Power Engineering Institute there was created an experimental installation, representing a circulation loop of open type. Its creation required solution of the above-mentioned technological questions. Investigations conducted on it made it possible to decide questions of a heat-physical plan and to make recommendations by calculation of heat exchange during movement of liquid aluminum in pipes. The obtained results are called to the attention of the readers.

Experimental installation, diagram of which is presented in Fig. 1, consists of the following basic elements: lower tank 1, electromagnetic pump 2, experimental section 3, upper tank 4, device for measurement of consumption of metal 6, refrigerator 5, rising 7, and lowering 8 pipes, inlets for supply of argon and measurement of pressure 9, and heaters 10.

As was shown above, the most suitable structural material for work in contact with liquid aluminum at the present time is graphite. Therefore, all parts of the experimental installation that are in contact with aluminum are manufactured from graphite. In this

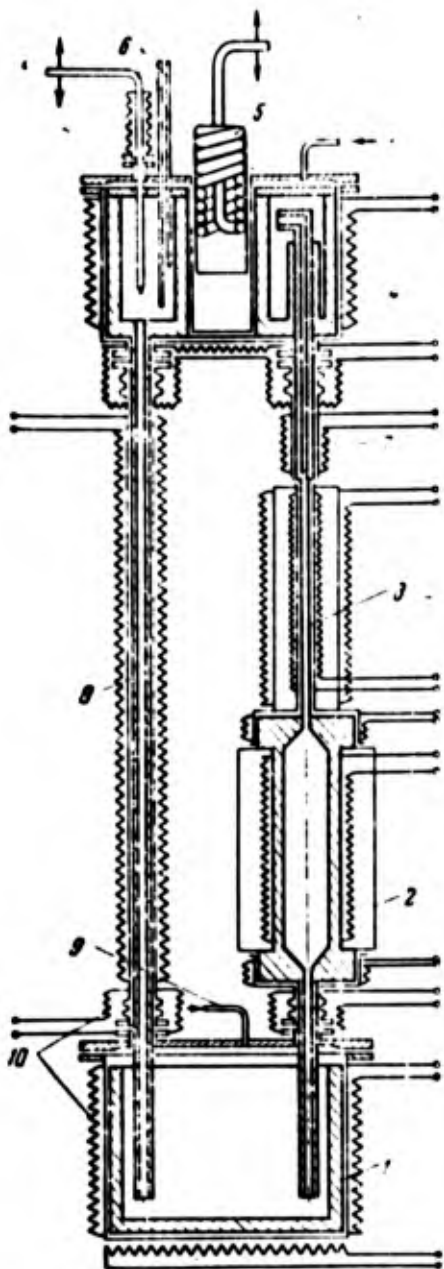


Fig. 1. Diagram of experimental installation.

installation reactor-grade graphite was used. Lower tank 1 is manufactured from sheet stainless steel with 2 mm thickness. In it there is inserted a graphite crucible with height 330 mm and diameter 380 mm (Fig. 2). The stainless steel tank protects the graphite crucible from oxidation, and also permits creating of hermetic volume in which it is possible to raise the pressure to 1 [atm (gage)] at temperatures of 750-800°C. For this the tank is hermetically sealed by a cover, through which the lowering and rising pipes enter the tank. In the cover of the tank there are inlets for supply of argon and measurement of pressure. Lower tank serve as a capacity for aluminum.

The principal element of experimental installation, determining its possibility, is electromagnetic pump 2. At the time of manufacture of experimental installation, as far as we knew generally there were no pumps intended for transferring liquid aluminum. Therefore, for creation of such a pump it was necessary to overcome significant difficulties. The pump utilized in this installation is manufactured in heat exchange laboratory of G. M. Krzhizhanovskiy Power Engineering Institute. Design of basic version of pump is carried out by L. A. Verte.

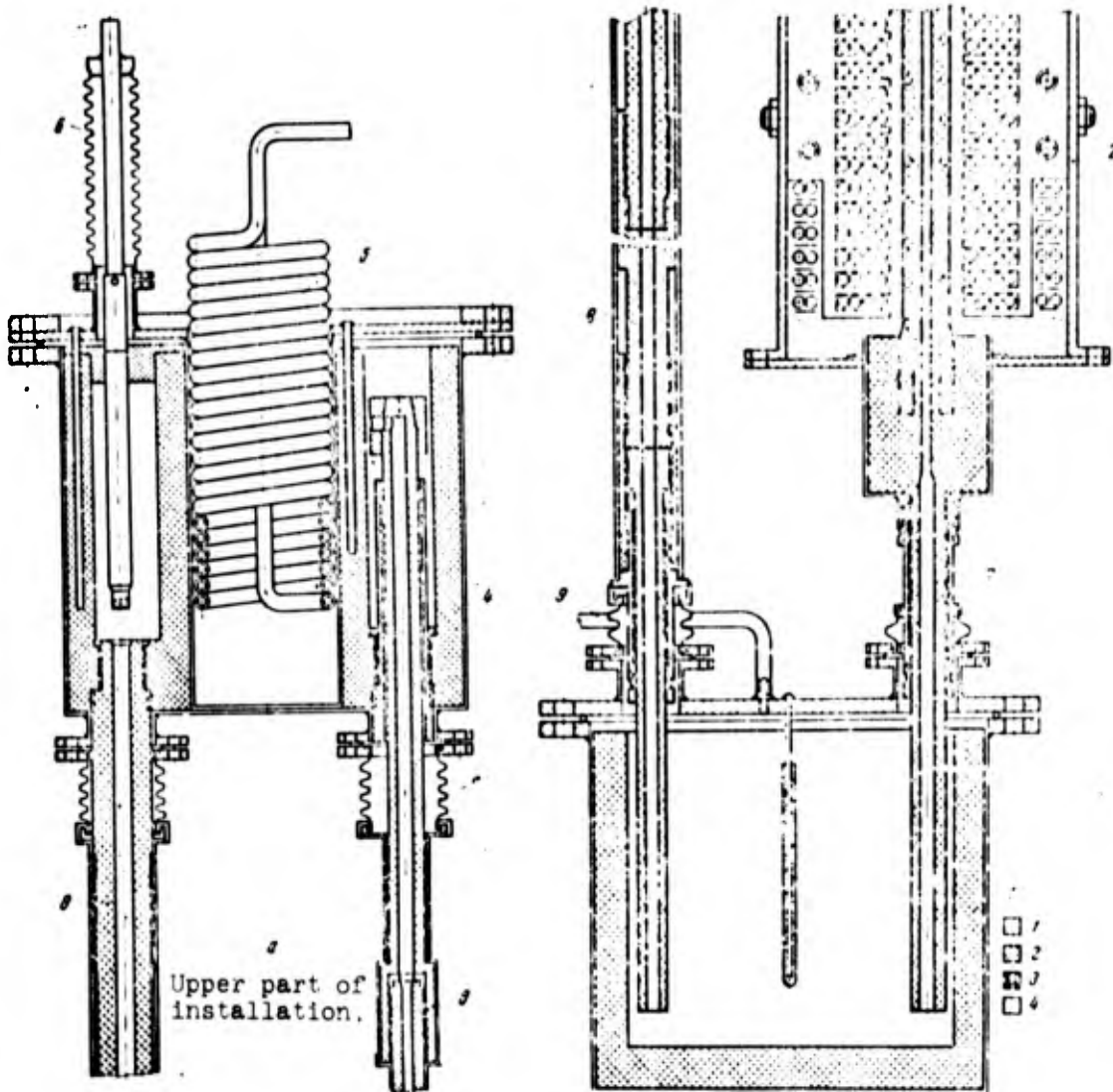


Fig. 2. Structural diagram of installation a) upper part; b) lower part. 1 - metal; 2 - graphite; 3 - dust; 4 - heat-resisting concrete.

Purpose of the pump is to create circulation of metal in loop. With respect to construction of magnetic system it pertains to the class of plane linear induction pumps with inductor in the form of two expanded stators of a three-phase electric motor, facing each other with slots. Three-phase winding creates a traveling magnetic field between the two halves of inductor. In this gap there is placed a channel of rectangular section, manufactured from a whole graphite block. Inasmuch as the channel operates at a temperature above 700°C , winding of pump is cooled by water, for which it is made of copper tube. Heating up of channel before turning on the pump is accomplished by electric heaters, placed on both sides of long generatrix of cross section of channel. On each side of the channel there is installed 14 heating elements, which can be replaced without disassembling the pump (Fig. 2). Part of the heating elements are automatically shut off during operation of pump. Heating of channel in this case is accomplished by heat generated in moving metal. Channel of pump is connected with other elements of the loop with the help of special adapters, in which there is carried out transition from rectangular section of channel to round. After packing of graphite channel inside the assembled inductor, the free space around it is clogged with fireproof concrete. Such clogging of fireproof concrete, besides thermal insulation of graphite channel from iron of the inductor and water-cooled winding, is for ensuring transmission of internal pressure in the channel of pump to the iron inductor and to body of pump in such a manner that graphite would work only by compression.

Selection of the shown type of pump from the large numbers of known types of electromagnetic pumps is caused by the fact that plane

linear induction pumps permit developing considerable outlet pressure and are advantageous from the point of view of assembling of channel and cooling of inductor.

According to calculation data the productivity of pump is $3 \text{ m}^3/\text{h}$ with gauge outlet pressure 5 [atm (gage)]. Data of tests show that pump is in a state to create pressure on the order of 4 [atm (gage)] with productivity about $2.5 \text{ m}^3/\text{h}$.

It is necessary to bear in mind that at less counterpressure the productivity of pump increases essentially.

Upper tank 4, in which the graphite crucible is inserted, just as the lower, is manufactured from sheet stainless steel. However, as can be seen from Fig. 2, in distinction from crucible of the lower tank, it has a different configuration. Crucible of the upper tank represents two coaxial cylinders with height 330 mm and with diameters 380/320 and 200/140, connected together on one side by a common bottom.

Such a structure of crucible permits decreasing quantity of metal circulating in loop, and also makes it possible to conveniently place a surface type refrigerator. On the bottom of the graphite crucible with the help of threaded connection there is fastened an overflow pipe 8 and similarly a pipe through which riser 7 is introduced into the tank. With the help of bolt connections and packing the upper tank is hermetically sealed by a cover, in the central part of which there is welded a container of 140 mm diameter. In the container there is placed refrigerator 5. Through the cover in the upper tank there are inserted a valve which closes the overflow line, and three measuring styluses.

Overflow (or lowering) pipe 8 represents a batch of graphite pipes that are connected together with the help of threaded connections.

For convenience of assembly of loop one of the connections of lowering pipe is made without a thread. Internal diameter of lowering pipe $d = 15$ mm is determined from condition of desirable change of level of metal in it with maximum consumption as compared to the level at zero consumption of metal. Overall length of lowering pipe is about 2.5 m. So that change of dimension of lowering pipe, which occurs in process of heating and cooling of the experimental installation, would not create secondary stresses, there is made a free inlet of pipe into lower tank with the help of stainless steel bellows. Construction of this unit is shown in Fig. 2. For protection of graphite pipes from oxidation, they are covered with stainless steel jackets.

Rising pipe 7 consists of several parts with different sections of internal channels: a) intake pipe, which feeds metal from lower tank to lower reducer of pump channel, having round section of channel with 15 mm diameter; b) pump channel with 120 x 10 mm rectangular section with reducers; c) experimental part of round section; d) pipe which connects experimental section with upper tank, diameter 15 mm. Overall length of riser is on the order of 3 m. Since middle of riser is secured (channel of pump), in order to not create secondary stresses with change of its length there is made free inlet of both ends of riser. Construction of inlets of rising pipe (Fig. 2) in lower and upper tanks ensures their airtightness and free shift during heating and cooling.

From the above it is clear that the experimental installation consists of a considerable number of graphite parts, which it was necessary to join together so that places of connections would not admit liquid aluminum. In process of work on installation there

were considered and tested several versions of connections, including connections with the help of graphite glue. However, the usage of glue it was not possible to create either mechanically durable or gastight joints capable of working at temperatures over 700°C. Essence of the proposed method of connection of graphite parts is clear from that presented below. Cylindrical parts are connected together with the help of threads with subsequent packing of joints with finely ground graphite dust: preliminarily heated graphite dust is added in small portions to the gap between connectable parts and is well pressed in. Construction of such a unit is presented in Fig. 2. Generally speaking, a thread is not a necessary element of such connection: it can also be made without it. A version of such a connection is presented in the same Fig. 2. Parts that are not cylindrical are connected similarly. Figure 2 shows structure of the connection of pump channel with reducers. Dimensions of such connections (width of gap and length of packing) should be determined depending upon concrete conditions: pressure in system and desirable degree of airtightness. For pressure in system not more than 1 [atm (gage)] length of packing 50-70 mm with width of gap not more than 1.5 mm turned out to be sufficient. By selection of corresponding dimensions it is possible to achieve gas permeability of such a connection that would not be greater than gas permeability of the graphite part itself. The proposed method of connection of graphite parts deserves attention since it rather simply permits creating a connection with small gas permeability. An important merit of this method of connection of parts is their comparatively easy disassembly and the also possibility of use of parts with complex geometric shape.

As was shown, all synthetic graphites are characterized by considerable porosity. While pores in graphite are open, all

unconsolidated graphites are gas permeable to a strong degree. For decrease of gas permeability of graphite parts, from which our experimental installation is assembled, the latter were packed with pyrolytic carbon by method of its deposition from gas phase. Besides decrease of gas permeability, packing also considerably lowers mechanical erosion of graphite during motion of liquid aluminum.

So that aluminum could circulate in the experimental installation, it was necessary that temperature of all its elements be higher than its melting point. Elements of loop were heated with electric heaters 10 (Fig. 1), which are made from lightweight fire clay bricks. Their heating elements was coils from heat-resisting materials: Nichrome, alloys 1, 2, 3, etc. Heating elements are packed in grooves that are made in bricks. Structural design of heaters depends on shape of separate elements of loop. All of them are made in the form of two symmetric halves, which provides their assembly and disassembly in the assembled loop.

Such construction of heaters ensures transmission of heat from heating elements to elements that are heated mainly by radiation, which facilitates operating conditions of coils and permits raising the temperature of heated elements to temperatures on the order of 1000°C . Temperature of heated elements of loop is kept at the assigned level with help of electronic temperature regulators, which receive impulse from thermocouples installed in the most dangerous, from the point of view of underheating, sections of loop.

In order to be able to investigate heat exchange in stationary conditions, it is necessary to draw off heat that is supplied on experimental section. For this purpose refrigerator 5 is installed in loop. Refrigerator is a cylinder that is coiled from copper tube.

It is placed in the central part of the upper tank. Water is used as liquid coolant (Fig. 2).

Device for measuring metal consumption in experimental installation 6 consists of a valve which covers the inlet of the overflow line, two contact styluses, which separate the control volume, and an electrical timer, which fixes the time of filling of control volume.

Before installation of loop in the lower tank 30 kilograms of aluminum are loaded. When calculating the quantity of metal loaded in the tank, we proceeded from the necessity of having a level of 120-150 mm in the lower tank at the time of maximum intake of metal from it, which occurs during measurement of consumption. After installation of loop the air in it is replaced by argon.

The described experimental installation passed detailed tests, which continued more than 300 hours altogether, including more than 100 hours under conditions of circulation of metal. In process of tests the installation was repeatedly started and stopped. Maximum time of continuous operation of experimental installation in conditions of metal circulation is 30 hours; stopping it is not connected with defects of operation of separate parts. Tests of experimental installation showed that its basic elements operate normally. Analysis of operation of installation permits concluding that from a technological point of view the obstacles for application of aluminum as a heat-transfer agent are removed to a considerable degree.

As was already shown, it was also necessary to decide the question on calculation of heat exchange during motion of liquid aluminum in different channels. For this purpose on the installation there was studied heat exchange during turbulent motion of aluminum in pipes. Heat exchange was investigated on experimental section 3, representing

a graphite pipe that is arranged vertically (Fig. 1). Experimental section had the following geometric characteristics (Table 4).

Table 4

Parameters	Dimensions	
	absolute, mm	relative l_1/d
Internal diameter of pipe (d)	7.2	—
External diameter of pipe (D)	27.2	—
Full length of experimental section (l_0)	460	63.8
Heated length of pipe (l)	290	40.2
Unheated length of segment of pipe before start of heating (l_{unh})	87	12.1
Unheated length of segment of pipe after the end of heating (l_{unh})	83	11.5

Experimental section is presented in Fig. 3.

Experimental section was heated by an electric heater of radiation action.

When conducting experiments there are measured temperature of wall of experimental section in zone of supply of heat flow, consumption of flowing aluminum, its temperature on exit from heating zone, and heat that is received by aluminum and lost in external medium.

In experiments there was used aluminum of increased purity of brand of [AV-000] (AB-000) (All-Union Government Standard (GOST) 35-49-59), in which impurities were not more than 0.01%. Before the charge, in the lower tank of installation the aluminum was cleaned by a mechanical method and washed with acetone. For pressing the molten aluminum into pump channel before switching the pump on, pressure was raised in the lower tank with help of a cylinder with argon. In experiments argon was applied with oxygen content not more than 0.05% without

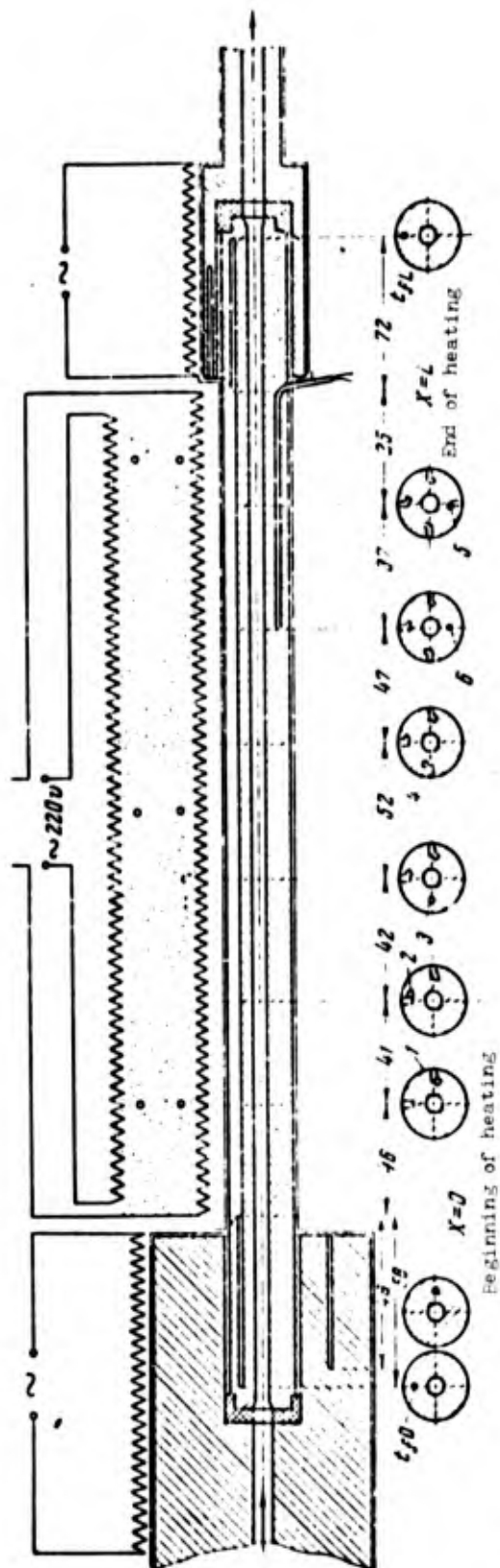


Fig. 3. Experimental section.

additional purification. For decreasing the quantity of oxides circulating in the loop, intake of aluminum was produced from the middle part of volume of liquid metal. Furthermore, part of the oxides were collected by graphite filters, installed in the upper tank.

When conducting experiments the measurements were produced at stationary thermal conditions. Obtained experimental data permitted calculating heat exchange beyond the limits of initial section during turbulent motion of aluminum in graphite pipe and feed of heat flow to it on the side of the wall, power of which is constant along the length of pipe. Method of experiment and treatment of obtained experimental data are presented in detail in [19].

During treatment of experimental data physical parameters of aluminum-coefficient of thermal conductivity, temperature conductivity, kinematic viscosity, specific gravity, and also coefficient of thermal conductivity of graphite, from which the experimental section is manufactured, — were determined by experimental data obtained in the Power Engineering Institute by Nikol'skiy [5], Kalakutskaya [6], Gol'tsova [7]. Our experimental data are shown in Table 5, and results of their treatment — on Fig. 4 in the form of dependence of local values of Nusselt number Nu on Peclet number Pe , calculated on a section of stabilized heat exchange¹. Obtained results may also be used for calculation of average characteristics of heat exchange if the relative length of pipes is $x/d > 20$.

In Fig. 4, for comparison there are also drawn curves which are

¹In connection with the fact that data on thermal conductivity of aluminum were modified by author [5], values of Nu and Pe numbers of this work somewhat (~11%) differ from their values in [19].

Table 5

Consumption of metal G kg/h	Quantity of heat		Temperature of internal surface of wall, °C						Temperature of metal, °C		$\Delta t = t_{\text{wall}} - t_{\text{metal}}$ °C	w, m/s	$\alpha \cdot 10^{-4}$, Cal/m ² h X X deg	Re · 10 ⁻¹	Pe	Nu
	Q _{int} , Cal/h	Q _{exp} , Cal/h	t ₁	t ₂	t ₃	t ₄	t ₅	t ₆	t ₀	t _L						
806	265	2063	719.2	722.2	724.0	725.8	727.9	716.4	726.2	2.9	2.27	105.3	34.8	448	9.72	
673	257	2015	716.5	719.1	719.7	722.6	724.8	711.4	722.9	3.4	1.95	90.4	29.7	385	8.37	
730	254	2028	722.1	724.7	724.3	728.5	728.8	717.3	728.1	3.5	2.08	88.3	31.9	411	8.17	
736	237	2035	721.8	722.9	724.7	727.8	729.6	717.1	727.5	3.2	2.19	96.7	33.6	432	9.02	
576	224	2018	722.2	723.5	726.8	730.2	732.8	717.0	730.7	3.5	1.66	89.0	25.5	328	8.23	
500	212	2000	714.5	717.2	719.5	722.9	—	708.0	723.8	4.4	1.45	71.2	22.1	287	6.60	
467	210	2062	717.8	720.2	722.8	727.5	—	710.9	727.9	4.3	1.35	73.0	20.6	295	6.74	
608	220	2029	720.9	722.9	724.9	728.3	—	715.8	727.1	3.8	2.0	81.3	30.6	394	7.52	
486	224	1988	713.7	719.0	723.4	728.5	—	715.7	728.5	4.1	1.76	75.4	27.0	347	6.95	
520	224	1988	719.1	721.7	724.8	727.6	—	709.0	724.7	3.4	1.41	89.1	21.5	276	8.24	
498	230	1974	716.4	719.0	721.4	725.4	—	713.6	728.2	4.3	1.5	70.7	23.0	295	6.55	
416	218	1934	712.0	715.1	717.2	722.3	—	709.3	724.5	5.1	1.44	59.0	21.9	281	5.47	
298	221	1967	712.4	716.2	719.6	724.8	—	704.4	722.7	4.9	1.2	61.0	18.2	238	5.67	
276	220	1962	707.8	711.7	714.8	721.0	—	703.8	729.1	4.8	0.86	62.5	13.13	171	5.78	
442	221	1931	70.0	713.0	716.0	720.6	—	699.0	726.4	4.4	0.8	67.9	12.06	158	6.20	
								704.1	721.2	3.9	1.28	76.7	19.35	233	7.11	

Note. After the fifth experiment thermocouple No. 5 failed. In experiments the value of number Pr ≈ 0.013.

graphic images of equations recommended by various authors for calculation of heat exchange during turbulent motion of liquid metals in pipes [20-22]. From analysis of Fig. 4 it follows that our experimental data are grouped around the curve described by equation

$$Nu = 5.0 + 0.025 Pe^{0.8}, \quad (1)$$

which a number of authors obtained on the basis of treatment of experimental data on heat exchange during turbulent motion of alkali



Fig. 4. Change of Nu from Pe during motion of liquid Al in graphite pipe $d = 7.2$ mm. 1 - $Nu = 7 + 0.025 Pe^{0.8}$; 2 - $Nu = 5 + 0.025 Pe^{0.8}$; 3 - $Nu = 4.8 + 0.014 Pe^{0.8}$; 4 - Experimental points (Al).

metals [22] and mercury [23] in pipes. The same equation is obtained by authors of [24] as an equation which approximates results of theoretical solution.

As follows from graph of Fig. 4, deviation of experimental points from the

curve described by equation (1), with the exception of two points, does not fall outside the limits of $\pm 15\%$.

Thus, derived experimental data permit recommending equation (1) for calculation of heat exchange during turbulent motion of liquid aluminum in graphite pipes.

It is necessary to bear in mind that this conclusion is made on the basis of experimental investigation of heat exchange during use of aluminum of increased purity, circulating in the installation during a comparatively small time interval (about twenty-four hours). It is possible that with application of commercial aluminum and at considerably long time of its usage, the intensity of heat exchange

can be lower as compared to intensity determined by equation (1). Analogous phenomenon, as it is known, occurs for other liquid metal heat-transfer agents [1, 21].

The performed work permits making the following conclusions.

1. Good heat-physical characteristics and the presence of structural material permit considering aluminum a prospective heat-transfer agent, which will find application during solution of a number of problems.

2. Difficulties which stand in the way of practical use of aluminum as a heat-transfer agent can be successfully surmounted: certain possible ways of solution of separate questions are presented in this work.

3. Heat exchange during motion of liquid aluminum in pipes can be calculated by equations that are correct for calculation of heat exchange of other liquid metal heat-transfer agents.

4. Work carried out in the Power Engineering Institute opens practical possibilities for use of aluminum as a heat-transfer agent.

5. Technological part of this work can be used by the metallurgical industry for solution of problems connected with continuous casting of metals, pressure die casting, and other questions of founding.

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