FEATURES OF HEAT TRANSFER FOR CURRENT-STABILIZED CONDUCTORS

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Fluctuation regimes of heat transfer of current-stabilized conductors have been discovered and investigated, characterized by the fact that the stochastic time variation of both local temperatures and temperatures that are integral over the length of the conductor vary in time, attaining recurring minimal and maximal values. A physical model of the fluctuation mechanism of heat transfer is proposed, and correlation relationships are given to calculate fluctuation regimes.

Among the variety of electrotechncial devices, apparatus for which the regime of power supply is specified as a parameter has a wide application. Such devices as transformers and reactors operate in the regime of voltage stabilization across the winding (U = const), while such devices as solenoids operate in the region of current stabilization in the circuit (I = const).

Thermal states and heat transfer of conductors for a specified power-supply regime can be determined correctly only when a conductor and a heat-sensing medium are considered simultaneously, i.e., when solving a conjugated conductor—medium problem.

Under the conditions that U = const across the conductor, where it is found under homogeneous conditions of heat removal and its temperature is constant lengthwise, when certain conditions are satisfied, a sharply inhomogeneous steady distribution of temperature T and electric field E forms spontaneously and exists over time; i.e., a thermoelectric domain forms, which is a region where T_d and E_d exceed considerably similar characteristics of the conductor regions free of the domain [1-5]. The possibility of spontaneous formation of a thermoelectric domain should be taken into account when evaluating the thermal stability of electric devices, when conducting thermophysical investigations, where a conductor with current serves as a sample under condition U = const [6, 7].

In [8-11], it is shown and confirmed experimentally that heat removal for stabilized-current conductors is characterized as fluctuating; both local temperatures and temperatures that are integral over the length of the conductor vary stochastically in time, attaining recurring minimal and maximal values. The cause of this phenomenon is the alternation of positive and negative feedbacks in the conductor—medium system. For example, a random local deterioration in heat exchange for I = const and $\rho = \rho(T)$ results in an avalanche increase in the local temperature (a positive feedback: a primary pulse of T tends to grow, because when T is raised, ρ and heat evolution $(I^2 \rho l)/S$ increase, where l is the length of the region, and S is the cross section of the conductor). At a certain time interval, a negative feedback starts acting in the system, the conductor temperature starts diminishing due to intensification of heat exchange that results from the relative overheat of the heat carrier that borders the region under consideration. A delay in the mechanism of heat removal with respect to the mechanism of the Joule heat is explained by a reduced time constant of the heating process. The intensification of heat removal over the region with increasing temperature in the process of heat removal in the regime of free convection, for example, is related to the increase in the buoyancy force near the overheated region and subsequent longitudinal subcurrent of the heat carrier to the region.

In the given work, an experimental investigation of fluctuation regimes of heat removal is conducted for the horizontally oriented cylindrical conductors under natural convection of different heat carriers, results are generalized, and correlation relationships are proposed to calculate heat removal.

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Experiments were conducted with samples from electrotechncial copper with diameters 0.03; 0.08, 0.12; 0.31; 0.5; 0.67; and 2.3 mm, aluminum of grade A-999 (d = 0.11; 0.32; and 0.94 mm), platinum (d = 0.1 mm) and indium (d = 0.5 mm) for heat removal in the regime of natural convection of liquid hydrogen (ambient temperature $T_0 \approx 20.4$ K), liquid nitrogen ($T_0 \approx 77.4$ K), liquid oxygen ($T_0 \approx 90$ K), gaseous nitrogen and helium ($T_0 \approx 80$ K), air, and transformer oil ($T_0 \approx 300$ K).

The experiments for heat removal by cryogenic liquids were conducted in glass cryostats; the set-up contained a light source, an optical system, and a shadow screen that allowed us to obtain an approxiamtely ten-fold magnification of the conductor and to observe motion of the liquid near the sample.

We started the experiment by assembling the sample on the current leads, soldering (for the case of aluminum, welding) potential conductors (at a distance of 10-15 mm from the current leads), and individual calibration of each sample, i.e., obtaining dependencies R(T) in the temperature range for which the conduction of the experiment had been scheduled. As a result of the experiment for a fixed current I, we obtained the dependence of the voltage drop U on time τ, which was recorded on a self-recording potentiometer. The dependencies $U(\tau)$ for a number of values of I, and the temperature dependence of the resistance of a sample, measured in advance, contained all the factual material required for further processing. For each value of the current we can determine instantaneous minimal and maximal integral lengthwise thermal heads $(\Delta T_{int})_{min}$ and $(\Delta T_{int})_{max}$, specific density of the thermal flow q_{int}, and the heat-transfer coefficient α_{int}.

We started investigating heat exchange of current-stabilized conductors by studying the hydrodynamics of the process with heat removal by cryogenic liquids. We conducted observations of free convection of liquid nitrogen with samples from constantan (d = 0.3 mm, length from 19 to 30 mm) and aluminum (d = 0.11-0.73 mm, length from 9 to 32 mm). Similar observations were conducted with an aluminum sample (d = 0.32 mm, l = 27.4 mm) with heat removal by means of free convection of liquid hydrogen.

We reached a conclusion, important for further analysis, about the fundamental difference of hydrodynamic patterns for the case when the specific electric resistance of samples does not depend on the temperature (constantan in liquid nitrogen and aluminum in liquid hydrogen), and for the case when $\rho = \rho(T)$ (aluminum in liquid nitrogen).

In the first case we observed lengthwise homogeneous and steady in time, seemingly layered motion of the heated liquid upwards from the conductor with an increase in the heat load up to the point of the liquid boiling; a hydrodynamic picture of free convection fully corresponds to the data of similar observatons represented in the literature (e.g., [12]).

In the second case, i.e., when $\rho = \rho(T)$, the nature of motion of the liquid does not differ from that described above for small loads; however, when the load increases, a sharp distinction between them becomes obvious: when the current increases, the motion of the heated substances becomes more random, sharply inhomogeneous along the length of the sample; we observe longitudinal motion of liquid, local turbilization with the formation of stagnant zones and regions of accelerated motion. An annular interlayer, whose thickness grows with the increase in the load, forms along the entire length of the conductor, then is preserved unchanged, and collapses from time to time.

We discovered that the relative thickness of the annular interlayer (the ratio between the diameters of the interlayer and the conductor) diminishes with the increase in the diameter of the sample. This fact is explained by the fact that the thickness of the annular interlayer is defined by the depth of penetration of the thermal and hydrodynamic perturbations from the heated wall into the heat carrier and, when all other conditions are the same, it depends on the thermophysical properties of the heat carrier.

The motion of the liquid in the interlayer is random, and when this interlayer transfers heat from the conductor, it represents a thermal resistance. For small diameters, the presence of the thermal resistance in the interlayer, the width of which is much larger than the conductor diameter, decreases the intensity of heat removal as compared with autonomously heated samples, where this interlayer is absent. For large diameters, the thickness of the annular interlayer is much less than the conductor diameter and its thermal resistance should not practically affect the intensity of heat removal. Random motion of the heat carrier near the surface of the conductor deforms the hydrodynamical boundary layer, which, apparently, should lead to an increase in the coefficient of heat removal as compared with autonomously heated samples.

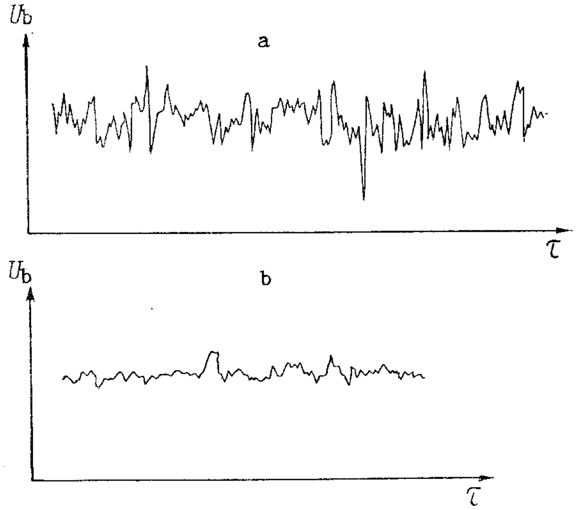

Fig. 1. Dependences U_b (τ) for the samples of copper ($d = 1 \cdot 10^3$ m) and nichrome ($d = 0.4 \cdot 10^{-3}$ m) with heat removal by liquid nitrogen (heat load $q \leq q_{i.bp}$, where $q_{i.bp}$ is the initial boiling point): a) copper, b) nichrome; the tape velocity is 30 cm/min.

Therefore, we might observe a "scale effect": heat removal for conductors with a small diameter is realized as "deteriorated," while for conductors with a large diameter it is realized as "improved," as compared with heat removal of autonomously heated samples in the regime of natural convection.

In the work, a documental confirmation of fundamental differences in hydrodynamic patterns was obtained, when using conductors with $\rho = \rho(T)$ and alloys with $\rho \neq \rho(T)$ (which corresponds to the samples with autonomous heating). As an illustration, Fig. 1 shows voltage oscillations across a ballast resistor R_b = 1 kΩ, connected in series with a photoresistor, which is mounted on a shadow screen above the image of the conductor (at a distance $\delta \approx d$). Motion of the liquid produces a "shadow effect": local eddies and discrete jets of the heat carrier have less illumination than the liquid, which is at rest or moving with a relatively uniform speed. When the wave or eddy of the liquid moves past the light-sensitive surface of the photoresistor (2 × 2 mm), the conduction of the photoresistor drops (it is shadowed), the current in the circuit drops, and the voltage across R_b diminishes. An analysis of the dependence $U_b(\tau)$, where τ is time, allows us to evaluate qualitatively dynamic characteristics of the flow: the higher the amplitude U_b, the larger the range of visible frequencies, and the higher is the degree of turbulence and randomness of the flow. From Fig. 1 (the record $U_b(\tau)$ is obtained on a Hewlett Packard 3390-A potentiometer for the samples of copper [$\rho = \rho(T)$] and nichrome [$\rho \neq \rho(T)$] for the same sensitivity of the device) it is seen that in the case $\rho = \rho(T)$ the flow regime is extremely random and in this way it is sharply distinguished from the relatively quiet flow for $\rho \neq \rho(T)$.

When we investigated heat removal experimentally, one of the first problems solved was a fundamental problem on reproducibility of maximal and minimal values in the dependence $U(\tau)$ for the given current. Investigations with different metals (Al, Cu, Pt) show that the values $(U_{int})_{max}$ and $(U_{int})_{min}$ for the given current are reproducible, although time intervals for the repetition of extremal values are different. In Fig. 2, the dependencies $U(\tau)$ are ahown for samples of copper and aluminum with heat removal by liquid nitrogen (the record is obtained on a PDS-021 potentiometer). It should be noted that the probability of expectation of $(U_{int})_{max}$ and $(U_{int})_{min}$ in all conducted experiments was relatively high; the extremal values were repeated on average no more than in 30-35 sec.

The next important issue is the effect of the length of a sample on the mean-integral characteristics of heat removal. The technique of conducting further investigations depends greatly on the degree of difference of local characteristics from integral characteristics.

Experiments on studying the effect of the sample length on its mean-integral characteristics are conducted in liquid nitrogen with aluminum samples with diameter 0.11 mm ($l/d \approx$ 150-950) and 0.32 mm ($l/d \approx$ 18-330).

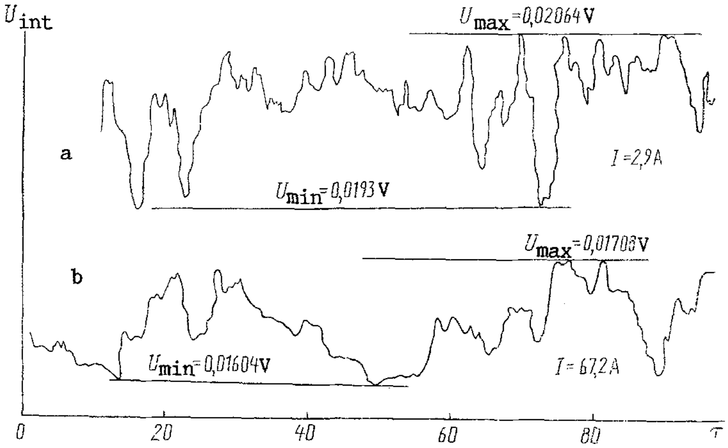

Fig. 2. Dependencies $U_{int}(\tau)$ for conductors from aluminum and copper with heat removal by liquid nitrogen in the regime of free convection: a) aluminum, $d = 0.11 \cdot 10^{-3}$ m, $l = 18.6 \cdot 10^{-3}$ m; b) copper, $d = 0.67 \cdot 10^{-3}$ m, $l = 30 \cdot 10^{-3}$ m. τ, sec.

The measurements conducted show that when l/d changes from ≈18 to ≈950, the range of values of $q_{int}(\Delta T_{int})$ bounded by the extremal values does not change practically, i.e., the sample length has practically no influence on the mean-integral characteristics of heat removal.

The investigations of local fluctuation heat removal, i.e., experiments for $l/d \leq 1$, entail considerable methodological and experimental difficulties. A decrease in the sample length results in an increase in the influence of "end" effects: as $l \to d$, potential probes play the role of fins and the correct determination of the coefficient of heat removal from the "finned" conductor becomes very difficult.

Therefore, when we conduct investigations, we assume that for $l/d \gg 10$, mean-integral lengthwise characteristics of fluctuation heat transfer do not depend on the sample length.

The next important stage in studying heat exchange of stabilized-current conductors is to obtain information on reproducibility of the range of extremal values ΔT_{int} and q_{int} when the load over the same sample is cyclic.

We conducted experiments in liquid oxygen and nitrogen with samples from aluminum and copper (d = 0.11-1.0 mm) of different length while increasing the load up to the boiling point of the liquid, then decreasing the load down to zero with subsequent repetition of the experiment at a 5-7 min interval. Although the frequency of appearance of extremal values of voltage drop across the sample varied from one experiment to another, the absolute values of $(U_{int})_{min}$ and $(U_{int})_{max}$ were reproduced quite satisfactorily.

After the above-listed problems have been solved, we conducted basic experiments on studying fluctuation heat exchange. The first series of experiments was conducted on samples from electrotechnical copper, aluminum, platinum, and indium with heat removal by means of liquid nitrogen and oxygen. When we conducted these experiments, we assumed that the dependence ρ(T) for metals is lienar in the range of temperatures of 77.4-100 K; we measured the sample temperature by comparing its resistance with the linear dependence R(T), plotted on the basis of two values of resistance, namely: resistances at the boiling points under atmospheric pressure of liquid nitrogen and oxygen.

The results obtained show that the intensity of heat exchange depends substantially on the conductor diameter: for samples with a small diameter we observe "deteriorated" heat exchange, and for samples with a large diameter we observe an "improved" heat exchange as compared with samples that are heated by means of an autonomous heater. The dependence Nu(Ra) for samples with autonomous heating is defined by the dimensionless equation

$$\mathrm{Nu}_{d,\infty} = C\,\mathrm{Ra}_{d,\infty}^{n}, \tag{1}$$

where the indices d and ∞ indicate that the conductor diameter is a characteristic dimension, and the controlling temperature is the temperature of the liquid at a distance from the sample; C = 1.18 and n = 0.125 at $1 \cdot 10^{-3} \leq \mathrm{Ra}_{d,\infty} \leq 500$, C = 0.54 and n = 0.25 at $500 \leq \mathrm{Ra}_{d,\infty} \leq 2 \cdot 10^{7}$.

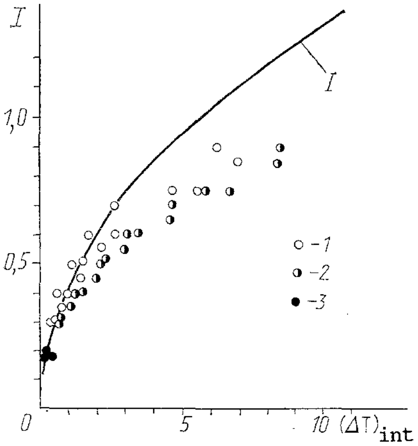

Fig. 3

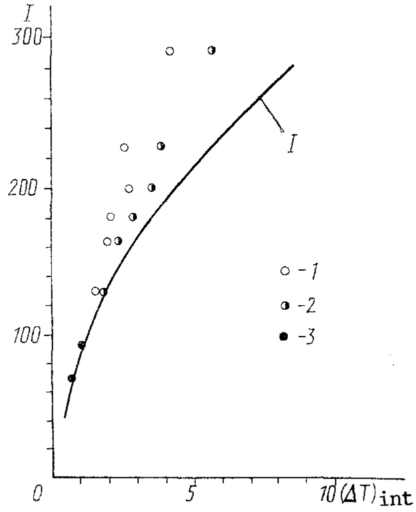

Fig. 4

Fig. 3. Dependence $(\Delta T)_{int}$ on I for a copper sample with a diameter of $0.03 \cdot 10^{-3}$ m, $50 \cdot 10^{-3}$ m in length with heat removal by liquid nitrogen [$\rho(T) = 1.67 \cdot 10^{-9} + 0.0449 \cdot 10^{-9}$ $(T - T_0)$, Ω·m] (the dependence ρ(T) is obtained by calculating the experimentally measured dependence R(T) for each sample): I) calculation from (1); 1) $(\Delta T)_{int} = (\Delta T_{int})_{min}$. 2) $(\Delta T)_{int} = (\Delta T_{int})_{max}$, 3) $(\Delta T_{int})_{min} = (\Delta T_{int})_{max}$, temperature oscillations are not observed. $(\Delta T)_{int}$, K; I, A.

Fig. 4. Dependence $(\Delta T)_{int}$ on I for a copper sample with a diameter of $2.3 \cdot 10^{-3}$ m, 0.3 m in length with heat removal by liquid nitrogen [$\rho(T) = 1.98 \cdot 10^{-9} + 0.0816 \cdot 10^{-9}$ $(T - T_0)$, Ω·m]: I) calculation from (1); 1-3) see Fig. 3.

In order to illustrate a "scale effect", Figs. 3 and 4 represent data for copper conductors with different diameters. Similar results are obtained for conductors from aluminum, platinum, and indium; both fluctuation heat exchange and a "scale effect" are observed when heat excahnge is realized by means of liquid oxygen.

The terms "deteriorated" and "improved" should be considered as conditional, since the fluctuating regime differs from the regime of free convection and has quantitative regularities, peculiar only to it.

The second series of experiments was conducted with heat removal by gaseous nitrogen and helium ($T_0 \approx 80$ K), air, and also transformer oil. In this series we did not observe fluctuation heat exchange; experimental data were in good agreement with calculations (when the temperature head was substantial, we assumed that the defining temperature was equal to the arithmetic mean of the wall temperature and the temperature of the liquid).

Experimental results obtained for different metals in the temperature interval of 20-300 K allow us to formulate a necessary condition: pronounced dependence of the specific electrical resistance on temperature $\rho = \rho(T)$. When this condition is fulfilled, heat exchange by means of free convection is realized as fluctuation heat exchange.

Since for $T \leq \Theta/20$ $\rho \approx \rho_0$, for $\Theta/20 \leq T \leq \Theta/2$, steady heat states cannot be realized [13], then the interval $\Theta/2 \leq T \leq T_{mp}$ is a temperature interval of existence of fluctuation heat exchange. In this temperature interval, the specific electrical resistance of metals is proportional to the temperature, i.e., it can be represented by a linear dependence $\rho(T) = \rho(T_0) + a(T - T_0)$.

Processing of experimental data yields the following results. In a stabilized-current conductor, the steady regime of free convection is realized when

$$0 < \mathrm{Ra}_{int}\left[\frac{a(\Delta T)_{int}}{\rho(T_0)}\right] \leqslant A_1 d^3, \tag{2}$$

where $A_1 = 10^{10}$ $1/m^3$.

When condition (2) holds, experimental data are in good agreement with data calculated from (1).

We start observing temperature oscillations when

$$\mathrm{Ra}_{\mathrm{int}}\left[\frac{a\,(\Delta T)_{\mathrm{int}}}{\rho\,(T_0)}\right] \geqslant A_1 d^3. \tag{3}$$

Equation (3) is a necessary and sufficient condition for the realization of fluctuation heat exchange by means of free convection.

Heat exchange of conductors is characterized as a developed fluctuation heat exchange when

$$\mathrm{Ra}_{\mathrm{int}}\left[\frac{a\,(\Delta T)_{\mathrm{int}}}{\rho\,(T_0)}\right] \geqslant A_2 d^3, \tag{4}$$

where $A_2 = 10^{13}\ 1/\mathrm{m}^3$.

A transition from the steady regime to the developed fluctuation regime occurs when

$$A_1 d^3 \leqslant \mathrm{Ra}_{\mathrm{int}}\left[\frac{a\,(\Delta T)_{\mathrm{int}}}{\rho\,(T_0)}\right] \leqslant A_2 d^3. \tag{5}$$

One of the fundamental questions in the problem under consideration is the determination of maximal temperature heads for the given current. We processed the dependence of $[(\Delta T)_{\mathrm{int}}]_{\mathrm{max}}$ on I for limiting thermal loads, when a developed fluctuation regime takes place. In this case, hydrodynamic patterns of free convection are identical when the conductor diameter varies from 0.03 to 2.3 mm and correspond to extremely random motion for $\mathrm{Ra}_\infty \approx 1.0\text{-}3\cdot10^5$. This value of the Rayleigh number includes both transition and laminar regimes of "classical" free convection. Quantitative characteristics of the developed fluctuation should correlate with the generalized dependence, different from the "classical" dimensionless dependence (1).

Results of data processing are represented in Fig. 5 as a dependence Nu(Ra); the method of least squares gives the value C = 0.554 and n = 0.267:

$$\mathrm{Nu}_{\mathrm{int}} = 0{,}554\,\mathrm{Ra}_{\mathrm{int}}^{0{,}267}. \tag{6}$$

The maximal deviation of the experimental data from the correlation (6) is 19.7% (for the sample d = 2.3 mm).

In the transition regime, i.e., when condition (5) holds, the following correlation relationship should be used:

$$\frac{\mathrm{Nu}_{\mathrm{int}} - C\,\mathrm{Ra}_{\mathrm{int}}^{n}}{0{,}554\,\mathrm{Ra}_{\mathrm{int}}^{0{,}267} - C\,\mathrm{Ra}_{\mathrm{int}}^{n}} = \frac{\mathrm{Ra}_{\mathrm{int}} - A_1 d^3 \dfrac{\rho\,(T_0)}{a\,(\Delta T)_{\mathrm{int}}}}{d^3\,[A_2 - A_1]\,\dfrac{\rho\,(T_0)}{a\,(\Delta T)_{\mathrm{int}}}}. \tag{7}$$

A comparison of all the experimental data with the data calculated from (1), (6), and (7) indicates that they are in good agreement (see Fig. 6).

As follows from (4), a developed fluctuation regime is realized in the conductor–heat carrier system, for which

$$[\gamma^2 g C\beta/(\eta\lambda)] \geqslant \frac{10^{13}}{(\Delta T)_{\mathrm{int}}}\,\frac{\rho\,(T_0)}{a\,(\Delta T)_{\mathrm{int}}}. \tag{8}$$

In order to satisfy condition (8), the heat carrier should have high density and low viscosity, which is characteristic of cryogenic liquids. When heat removal is realized in the regime of free convection of liquid helium, hydrogen, and neon, the dependence ρ(T) practically does not appear (i.e., $a \to 0$); therefore, we should not expect the heat exchange in the cryogenic agents to fluctuate. An analysis shows that fluctuation regimes can be observed in liquid nitrogen, argon, oxygen, krypton, and xenon, while in gaseous heat carriers (both at low and high temperatures) and in liquids at room temperature and moderately high temperatures, there is no fluctuation in the heat exchange, since condition (3) does not hold.

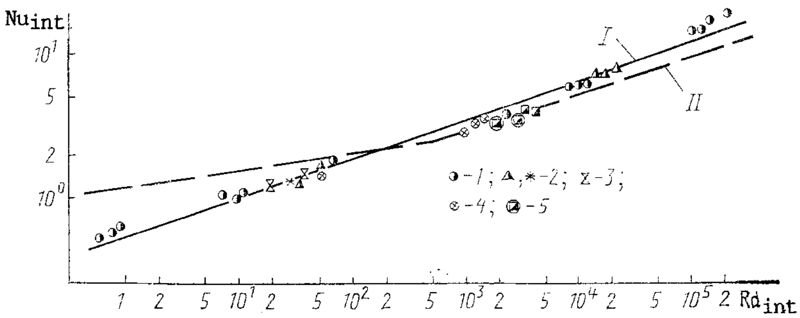

Fig. 5. Dependence $Nu_{int}(Ra_{int})$ for the developed fluctuation regime of free convection: I) Eq. (6), II) Eq. (1); 1, 4) copper, d = 0.03-2.3 mm; 2) aluminum, d = 0.11-0.94 mm; 3) platinum, d = 0.11 mm; 5) indium, d = 0.5 mm; 1-3) heat removal by liquid nitrogen; 4, 5) heat removal by liquid oxygen.

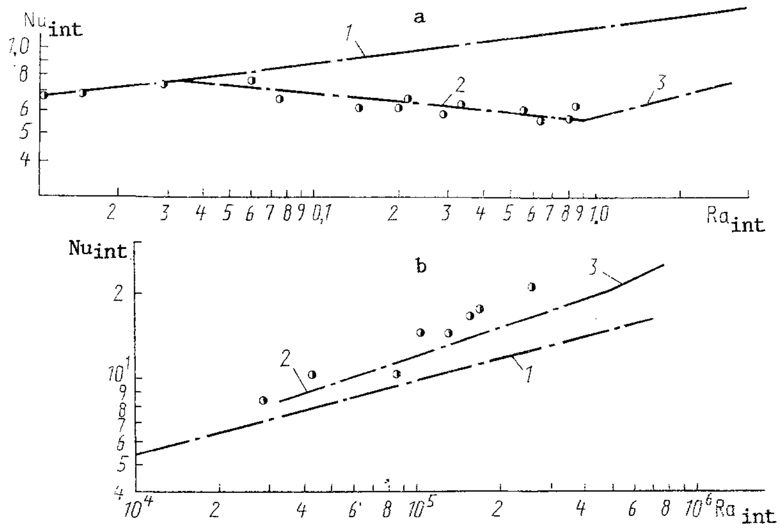

Fig. 6. Dependencies Nu_{int} on Ra_{int} for copper samples with diameter 0.03 mm (a) and $2.3 \cdot 10^{-3}$ m (b) with heat removal by liquid nitrogen: 1) Eq. (1); 2) Eq. (7); 3) Eq. (6); points, $(\Delta T)_{int} = (\Delta T_{int})_{max}$.

Correlation equations (6) and (7) are obtained when liquid oxygen and nitrogen are used as a heat-sensitive medium. Their generalized character is supported by two facts. Firstly, correlations (6) and (7) are obtained in dimensionless form. Secondly, the numerical value of the left side of inequality (8), i.e., the thermophysical complex that defines the relationship between the buoyancy force and forces of molecular friction, practically does not change for different cryogenic liquids. Thus, for liquid nitrogen, argon, oxygen, krypton, and xenon, the values $10^{-12}[\gamma^2 gC\beta/(\eta\lambda)]$ are, respectively, 3.73; 2.75; 2.89, 2.71, and 2.34 $1/(m^3 \cdot K)$.

An estimate of the amplitude of oscillations of the wall temperature for a developed fluctuation regime can be carried out by using the following equation:

$$\frac{[(\Delta T)_{int}]_{max}}{[(\Delta T)_{int}]_{min}} \approx 1 + \frac{a\,[(\Delta T)_{int}]_{max}}{\rho(T_0)}. \tag{9}$$

Estimate (9) is in good agreement with experimental data.

The features of thermal states [13] and heat exchange of stabilized-current conductors should be taken into account when conducting thermal calculations and calculations on thermal stability of electrotechnical devices with cryogenic resistance.

NOTATION

U) voltage; I) current; ρ) specific electrical resistance; T) conductor temperature; d) conductor diameter; R) conductor resistance; ΔT) temperature head; q) heat flow density; α) heat-transfer coefficient; l) conductor length; Nu) Nusselt number; Ra) Rayleigh number; Θ) Debye characteristic temperature; T_{mp}) fusing temperature; γ) density; g) acceleration of gravity; C) specific heat; β) volumetric expansion coefficient; η) dynamic viscosity; λ) coefficient of thermal conductivity. Indices: 0) temperature of heat carrier; max and min) maximal and minimal values; int) integral with respect to the conductor's length.

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NUMERICAL INVERSION OF A LAPLACE TRANSFORM USING A FOURIER SERIES TO COMPUTE NONSTATIONARY TEMPERATURE FIELDS IN LAYERED STRUCTURES

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An algorithm is examined for the selection and assignment of the parameter σ of a numerical inversion of a Laplace transform with the use of Fourier series.

In the field of structural thermal physics, significant attention is allotted to questions of heat- and mass-transport in layered structures. This interest in multilayered systems is explained by the fact that they permit one to more rationally exploit the thermophysical and physical–mechanical properties of building materials.

Examined below is the problem of determining nonstationary temperature fields in multilayered building structures, situated on the ground half-space. In the general case, they are represented as a system of infinite plates with internal heat sources and sinks. Ideal contact is maintained between the layers of the structure and the ground mass, i.e., fourth-order boundary conditions are realized. The thermophysical characteristics of the materials in the layers are different. The temperature of the medium varies harmonically. The heat transfer conditions between the medium and the surface of the structure are subject to Newton's

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