EFFECT OF THE THERMOPHYSICAL PROPERTIES OF THE SURFACE ON HEAT TRANSFER IN TURBULENT FLOW

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Until recently the solution of the problem of heat transfer accompanying turbulent flow was thought to involve only the determination of the temperature field in the flow regardless of the properties of the surface. It is now recognized that the problem of heat transfer between the surface and any medium is a conjugate problem, i.e., the temperature field in the flow and therefore the coefficient of heat transfer also depend on the physical properties of the surface.

In studying this phenomenon and the factors responsible for it, two fundamentally different effects must be distinguished. One effect is quite well known and is associated with heat flows along the wall in the presence of a temperature gradient along the flow or in a direction transverse to the velocity vector. These could be the conditions of the initial thermal section in the channels [1-8] as well as nonuniformities of the temperature along the length [9-14] or along the periphery of the exothermic surface, as in the case of a longitudinal flow over bunches of rods [15-18] or a sphere [19, 20].

Another less well-known reason for the coupling of the temperature fields in the wall and in the fluid in the presence of a turbulent flow past the wall is the local (in the small) nonstationarity of the velocity and temperature fields owing to the periodic turbulent structureof the flow in the layer near the wall. This phenomenon is similar to the well-known effect of the surface material on heat transfer accompanying boiling and condensation, though it is of a completely different nature [21, 22].

In studying the turbulent flow we shall use the results of recent works as well as earlier ones, which are not yet adequately understood.

In [23, 24] it is shown that the pulsations in the temperature of the wall over which the liquid metal flows are quite large and depend linearly on the heat flux density. The average frequency of the temperature pulsations was equal to several hertz. In [25] the scales of the temperature perturbations in mercury, lead, and water as well as the probabilities of the amplitudes of the temperature pulsations were measured. It was established that as the wall is approached the deviations from the normal distribution law increase, and the excess and asymmetry of the temperature pulsations change. If the heat flux is directed away from the wall into the liquid, then the probability for the appearance of large positive temperature pulsations near the wall drops below that of the case when the heat flux is directed from the liquid toward the wall. Analogous conclusions can be drawn from the results of experiments in air, presented in [26, 27].

The data on heat transfer, published in [29, 30], where results of a study of heat transfer to sodium in four vertical pipes made of different materials (see Table 1) are given, were analyzed in detail in [28]. All conditions of the experiments as well as the purity of the sodium were practically identical; the pipes operated simultaneously in one loop and were connected in series. The traditional presentation of the data on heat transfer in liquid metals in the coordinates log Nu—log Pe with a large number of experimental points, referring to different Re, Pr, and wall materials, does not reveal the effect of the separate factors. If, however, data referring to one number Pr ≈ 0.0065 and two materials with very different (differing by a factor of four) heat penetrabilities* $b = \sqrt{\lambda c \rho}$ (copper, 1Kh18N9T steel) are se-

*The quantity $b = \sqrt{\lambda c \rho}$ has the dimensions $W \cdot sec^{1/2}\ m^{-2} \cdot K^{-1} = J \cdot m^{-2} \cdot sec^{-1/2} \cdot K^{-1}$. The terminology used for this quantity has apparently not yet been settled. In the Soviet literature it is often called heat uptake, which is not very apt. In the English literature the term thermal responsivitiy, which can be translated as "heat susceptibility" or "heat responsiveness" is used, while in the German literature the term Warmedringfahigkeit (heat penetrability) as opposed to Warmeleitfahigkeit (thermal conductivity) is used.

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TABLE 1. Characteristics of Sodium and of the Experimental Sections (temperature 250°C)

Characteristic	Sodium	Copper	Nickel	No. 10 steel	1Kh18N9T steel
Inner diam. of tube, mm	—	39,9	36,5	39,4	35,3
Wall thickness, mm	—	5	4	2,8	0,35
λ, W/(m·K)	78,7	374	71	51	18,4
ρ, kg/m^3	891	8800	8750	7800	7900
c_p, kJ/(kg·K)	1,302	0,410	0,460	0,502	0,490
$a\cdot10^6$, m^2/sec	67,8	104	17,6	13,0	4,75
$b\cdot10^{-3}$, W·sec$^{1/2}$/(m^2·K)	9,56	36,7	16,95	14,17	8,44
$\Lambda=b/b_{Na}$	1,00	3,84	1,77	1,48	0,88

lected, then a stratification of points is clearly evident in the Nu–Re plane (Fig. 1). The same difference is also obtained in measurements of the temperature fields in sodium, flowing in pipes made of different materials (Fig. 2). The coefficients of heat transfer of a stainless steel wall turned out to be approximately 20-25% higher than for copper walls under the same conditions.

The results of measurements of temperature pulsations (amplitude–frequency characteristics and spectra) near the heat-exchange surface [31-34], over which the turbulent flow flows, indicate unequivocally that the nature of the pulsations of the amplitudes and of the spectra are different for different combinations of the wall material and the flow.

In [35, 36] the conjugate problem of pulsations of the temperature in a viscous layer of turbulent flow and in the wall was solved analytically. The calculations showed that the magnitude and nature of the temperature pulsations near the surface for different combinations of the heat-transfer agent and wall materials are different. From the results of these works it follows that the wall can have a substantial effect on the spectrum and intensity of the temperature pulsations in the viscous layer. The dependence of the dimensionless intensity of the temperature pulsations on surfaces made of different materials and with different wall-fluid combinations, characterized by the ratio of the thermal responsivities

$$\Lambda = \frac{b_w}{b_f} = \sqrt{\frac{(\lambda c\rho)_w}{(\lambda c\rho)_f}},$$

based on the calculations performed by A. F. Polyakov [36], is shown in Fig. 3. For $\Lambda < 0.2$ the dimensionless intensity of the temperature pulsations at the surface for a definite heat-transfer agent is independent of Λ. As the thermal responsivity of the wall increases for one and the same heat-transfer agent, i.e., as the quantity Λ increases, the intensity of the temperature pulsations drops substantially. Figure 4 shows the spectra of pulsations of the temperature of walls made of different materials with mercury flowing over them (Pr = 0.025) calculated in [36]. These calculations also indicate that the effect of the wall on the temperature pulsations in a viscous layer is manifested primarily in the low-frequency part of the spectrum. This effect propagates over much larger distances in water than in air.

In liquid-metal flows the effect of the wall is even larger than the ordinary liquids, and can be observed at a distance of $y^+ = 30$–50. It is concluded in [36] that "this can noticeably affect turbulent heat transport and heat transfer in a liquid metal." This proposition was confirmed in an analysis of the experimental data of [29, 30] in [28].

The results of measurements of the spectral densities of the temperature pulsations in a viscous layer of water flowing over copper and stainless steel walls are presented in [37, 38]. Analysis of these data for the same Reynolds numbers ($\sim 2\cdot10^4$) shows that within the viscous layer at a copper wall the spectrum of the temperature pulsations in the range 2-200 Hz remains practically unchanged as a function of the distance from the wall, and in the case of flow over a stainless steel wall the spectrum changes especially in the frequency range 30-200 Hz (Figs. 5a and b).

Based on the aforementioned calculations of A. F. Polyakov as well as the results of the experimental studies [23-25, 37, 38] it may be concluded that the wall material has a substantial effect on turbulent heat transport in liquid metals as quite large distances from the heat-transfer surface. These facts indicate at the same time that the heat-transfer intensities of one and the same heat-transfer agent flowing over walls made of different materials are different.

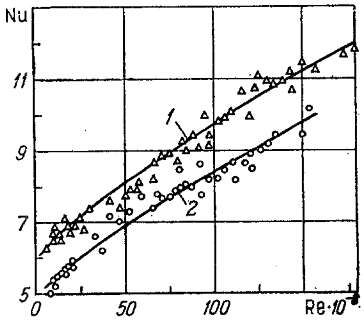

Fig. 1

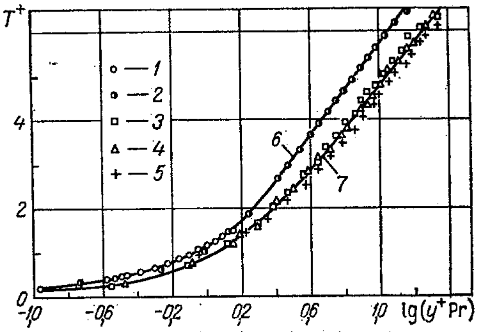

Fig. 2

Fig. 1. Effect of the wall material on heat transfer from sodium: 1) 1Kh18N9T steel and 2) copper.

Fig. 2. Temperature distribution in a sodium flow in a circular pipe made of copper (1, 2, 6) and 1Kh18N9T steel (3, 4, 5, 7): 1) Re = $1.41 \cdot 10^4$, Pr = 0.0069; 2) $9.34 \cdot 10^4$ and 0.0065; 3) $1.39 \cdot 10^5$ and 0.0064; 4) $1.42 \cdot 10^5$ and 0.0064; 5) $1.73 \cdot 10^5$ and 0.0063.

Prandtl's hypothesis of a purely laminar boundary layer [39, 40], confirmed by measurements of the velocity field [41, 42], appear to be so valid and convincing that for a long time, at least up to the beginning of the 1950s, it one way or another held up the development of a different, more accurate, physical picture of the phenomena occurring in the region of the turbulent flow near the wall. Taylor [43] formulated the idea that the velocity in a turbulent flow is a random continuous function of the coordinates and time. He introduced the concept of the correlation of velocity fluctuations at two points, but this for all practical purposes referred only to the turbulent core of the flow.

In the last 10 years the understanding of the nature of turbulence has changed. Almost ordered structures in practically all forms of turbulent flows and, which is especially important, in the layer near the wall have been discovered. Thus, turbulence is created in a structured form. The existence of structured elements in the layer near the wall enables a new approach to the problem of heat transfer also. It is established in [44-47] that the laminar and turbulent states in the boundary layer alternate with one another. This phenomenon is called intermittency. Korino and Brodki [48] studied the motion in the layer near the wall with the help of colloidal particles. The motion picture film moved with the velocity of the flow. It was found that the region $y^+ = 0$-30 is characterized by ejections of volumes of the medium away from the wall and injections of structured elements from the core of the flow into this region (Fig. 6). The ejections are intermittent, their position in space varies, and their dynamics includes a series of processes: 1) reduction of the axial velocity; 2) ejection of liquid out of the near-wall zone; 3) acceleration of the flow; 4) intrusion of a vortex (shock) into the region near the wall from the core of the flow.

Studies of turbulent flow near the wall have shown that the short periods of strong turbulent activity (injection and ejection) alternate with much longer periods, in which the effects of viscosity dominate. This alternation has a quasiperiodic character. According to observations made by Offen and Kline [49], in the zone near the wall owing to the stopping of the flow at the wall there arises a region of elevated pressure, which causes the stream to separate from the wall, and between the stream and the stopped liquid there appears a vortex whose axis is oriented transverse to the velocity. Stretching, the vortex assumes a horseshoe shape. The superposition and intersection of "horseshoes" create explosions-ejections and cause the vortices to decay, which determines the energy transport along the scale spectrum. The results of these observations are illustrated in Figs. 7 and 8. The measurements in [50] showed that most of the tangential stress at the wall ($y^+ < 15$) is associated with the vortices and ejections and also with the interaction of the injected and ejected elements of the flow. Observations with the help of visualization of the flow by injection of dye and hydrogen bubbles [51] also showed that when $y^+ < 10$ structures consisting of low-velocity elements (bursts), rising away from the wall, are observed. The stage of these bursts is described in detail in [52].

Fage and Townshend [53], Nedderman [54], Popovich and Hummel [55], Hussain and Reynolds [56, 57] confirm the theory of the penetration of vortices to the wall. It was discovered

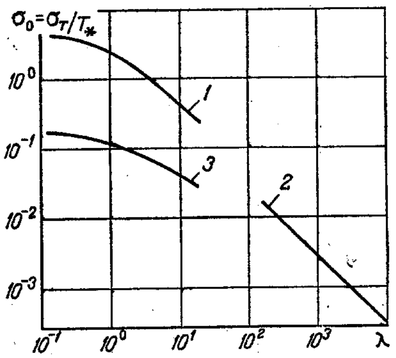

Fig. 3

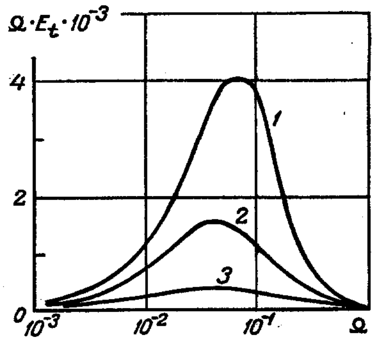

Fig. 4

Fig. 3. The dimensionless intensity of temperature pulsations on the surface of walls made of different materials: 1) water; 2) air; 3) mercury.

Fig. 4. Spectra of temperature pulsations, calculated in [36], in a viscous mercury boundary layer, i.e., on the surface ($y^+ = 0$, Pr = 0.025) with flow over walls made of textolite (1), stainless (2), and copper (3) $\Omega = \omega\nu/v^2{}_*$ is the dimensionless angular frequency and E_t is the spectrum of the temperature pulsations.

that vortices do not reach the surface of the wall itself. The average thickness of the residual sublayer was estimated by Meek and Baer [58] to be $\delta^+ = 1.5$, which is in quite good agreement with the results obtained by Popovich and Hummel [55] and Laufer [59]: $\delta^+ = 1.6 \pm 0.4$.

Thomas [60], analyzing the modern models of the near-wall turbulence, developed a semiempirical model of the mechanism of transport accompanying turbulent ejection. The model depends on four empirical constants. In particular, it was established that the dimensionless period of the ejections is equal to

$$\overline{\tau_e^+} = \frac{\overline{\tau_e} v_*^2}{\nu} = 14{,}93^2 = 223$$

and is independent of Reynolds number. This result is in good agreement with the data of Alp and Strong [61], who measured the time scales of the turbulence at the wall and established that $\overline{\tau_e^+} \approx 250$, as well as with the data of Meek and Baer [58] ($\overline{\tau_e^+} \cong 270$) and Schraub and Kline [62] ($\overline{\tau_e^+} \approx 225$).

The minimum value of the dimensionless period of the ejections was estimated by V. P. Mironov and E. M. Khabakhpasheva to be $\tau^+ = 80\text{-}100$ [63]. It was established that the dimensionless period of jections is independent of the Reynolds number [63-65]. It is important to note that at low frequencies the spectrum of temperature pulsations is associated with the longitudinal component of the velocity [66, 67].

To evaluate the effect of the ratio of the thermal responsiveness of the liquid and of the wall on the coefficient of heat transfer we shall study the model of nonstationary heat conduction from the wall to a vortex, stopped in the layer near the wall. In the first approximation this problem is analogous to the problem of touching of two bodies with different temperature. Let the temperature of the wall be higher than the temperature of the liquid. Then in an idealized formulation the temperature fields in these media (Fig. 9) can be found from the solution of two differential equations:

$$\frac{\partial t_1}{\partial \tau} = a_1 \frac{\partial^2 t_1}{\partial x^2}, \quad (1)$$

$$\frac{\partial t_2}{\partial \tau} = a_2 \frac{\partial^2 t_2}{\partial x^2}. \quad (2)$$

Here the index 1 refers to the wall and 2 refers to the liquid. We write the initial and boundary conditions in the form

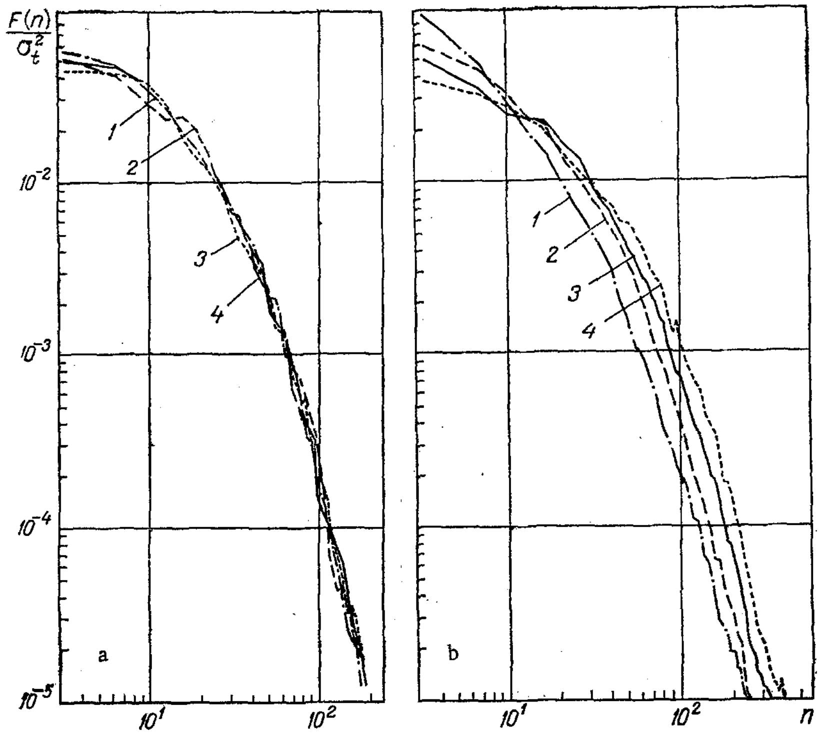

Fig. 5. Spectral density of temperature pulsations in a viscous water boundary layer in a flow over copper (a) and stainless steel (b) walls: a) Re = $2.08 \cdot 10^4$; $y^+ = 1.6$ (1); 2.63 (2); 2.9 (3); 4.7 (4); b) Re = $2 \cdot 10^4$; $y^+ = 1.1$ (1); 2.7 (2); 4.4 (3); 6.3 (4). n, Hz; $F(n)\sigma^2 t$, sec.

$$\begin{aligned} &\text{for}\quad x>0,\quad \tau=0\quad t_1=1,\\ &\text{for}\quad x<0,\quad \tau=0\quad t_2=0,\\ &\text{for}\quad x=0,\ \tau>0\quad t_1=t_2,\ \lambda_1\frac{\partial t_1}{\partial x}=\lambda_2\frac{\partial t_2}{\partial x}\,. \end{aligned} \tag{3}$$

The solution of this problem is well known [68], and is sought in the form

$$t_1=A_1+B_1\Phi\left(\frac{x}{2\sqrt{a_1\tau}}\right)\quad \text{for}\quad x>0, \tag{4}$$

$$t_2=A_2+B_2\Phi\left(\frac{x}{2\sqrt{a_2\tau}}\right)\quad \text{for}\quad x<0, \tag{5}$$

where

$$\Phi(y)=\frac{2}{\sqrt{\pi}}\int\limits_0^y e^{-\xi^2}\,d\xi. \tag{6}$$

The initial conditions give

$$A_1+B_1=t_w=1,\quad A_2+B_2=0. \tag{7}$$

From the boundary conditions it follows that

$$A_1=A_2,\qquad B_1\frac{\lambda_1}{\sqrt{a_1}}=-B_2\frac{\lambda_2}{\sqrt{a_2}} \tag{8}$$

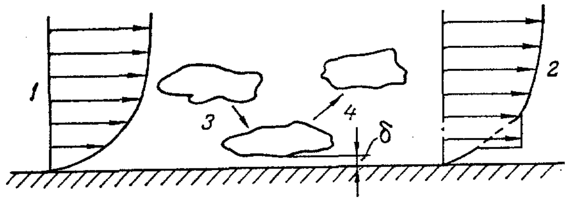

Fig. 6. Intrusion of a vortex and ejection from the region near the wall: 1) time-averaged velocity profile; 2) nonstationary velocity profile at the first moment of restoration of the boundary layer; 3) intrusion of the vortex; 4) ejection.

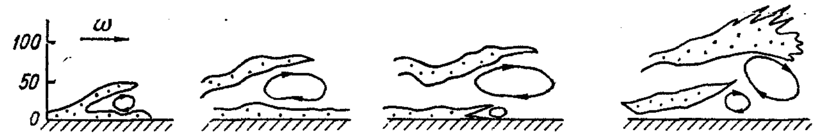

Fig. 7. Formation of vortices and ejections in the zone near the wall (according to [49]).

or

$$B_1 b_1 = -B_2 b_2,$$

where $b_i = \sqrt{(\lambda c \rho)_i}$.

The results of the solution are as follows

$$\frac{t_1}{t_w} = \frac{b_1/b_2}{1+(b_1/b_2)}\left[1+\frac{b_2}{b_1}\,\Phi\left(\frac{x}{2\sqrt{a_1\tau}}\right)\right], \tag{9}$$

$$\frac{t_2}{t_w} = \frac{b_1/b_2}{1+(b_1/b_2)}\,\mathrm{erfc}\left(\frac{|x|}{2\sqrt{a_2\tau}}\right). \tag{10}$$

Under the assumption that the frequency of ejections is of the order of f = 10-20 Hz, which is in good agreement with the data of the works examined above, for example [37, 38], the temperature distribution at the wall under the above-indicated conditions was determined for the case of sodium flow over copper and stainless steel walls. The starting data are given in Table 1.

The results of these calculations are shwon in Fig. 9. When the vortex (having a temperature 0) touches the wall (having a temperature 1) a surface temperature of $t/t_W = 0.79$ is established for copper and $t/t_W = 0.47$ for stainless steel. Thus in the layer near the wall with a flow over a copper wall oscillations of the temperature in the range 0.79-1 dimensionless units should be expected, and oscillations in the range 0.47-1 should be expected for stainless steel. The spread in the temperature oscillations is denoted by $\delta t'$. Under the assumption that the oscillations of the temperature are symmetrical around an average value (this is not exact, but is sufficient for rough estimates), the temperature differentials Δt_α become 0.895 and 0.735 for copper and stainless steel walls, respectively.

Thus, the ratio of the heat-transfer coefficients with flow over copper and stainless steel walls in the first approximation is as follows:

$$\frac{\alpha_{Cu}}{\alpha_{s.s}} = \frac{0{,}735}{0{,}895} \approx 0{,}82. \tag{11}$$

This computed result, though it is of a qualitative character, is nevertheless in good agreement with the results of experiments (see Figs. 1 and 2).

The expressions (9) and (10) show why in experiments in water $b_{20°} = 1580$ W•sec$^{1/2}$/(m^2•K) and in air $b_{20} = 5.6$ W•sec$^{1/2}$/(m^2•K) the effect of the surface material on heat transfer was not observed. The estimates show that the difference in the coefficients of heat transfer to water from the copper wall and from the stainless steel wall is less than 5%, which, of course, falls within range of accuracy of the experiment. For air and other gases this effect is not observable.

However, the difference in the intensities of the temperature pulsations in a water flow for two materials of the heated wall was recorded accurately. According to the data of [63, 64], the relative intensity of the temperature pulsations $\sigma/(T_W - T)$ at $y^+ = 1$ is equal to 0.3 and 0.37-0.4 for copper and steel walls, respectively.

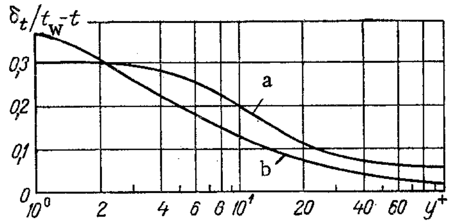

Fig. 8

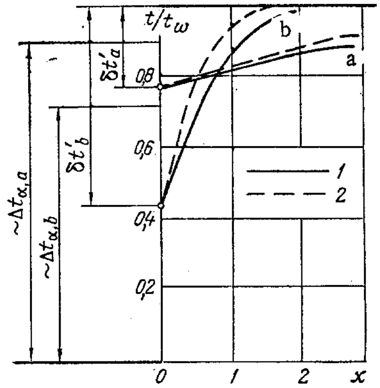

Fig. 9

Fig. 8. Transverse intensity of temperature pulsations: a) copper plate; b) stainless steel ribbon.

Fig. 9. Temperature distribution in the wall over which liquid sodium flows (t_w = const): a) copper; b) stainless steel; 1) τ = 0.10 sec, 2) 0.05 sec. x, mm.

Let us study the problem (1) and (2) under the assumption that q_0 = const, which indicates that the temperature distribution in the wall is initially distributed linearly. In this case the form of the differential equations remains the same while the boundary and initial conditions are written thus:

$$\begin{array}{ll} x>0,\ \tau=0 & t_1=t_{10}+kx; \\ x<0,\ \tau=0 & t_2=0; \\ x=0,\ \tau>0 & t_1=t_2; \\ x=0,\ \tau>0 & \lambda_1\dfrac{\partial t_1}{\partial x}=\lambda_2\dfrac{\partial t_2}{\partial x}. \end{array} \quad (12)$$

Here $k = q_0/\lambda$; t_{10} is the initial temperature at the surface of the heat-emitting wall. After the cold vortex touches the wall, a temperature t_{int} is established at the interface.

We seek the solutions of Eqs. (1) and (2) as before in the form (4) and (5) [68]. We find the unknown coefficients (A_1, A_2, B_1, B_2) from the conditions (12), which lead to the following relations:

$$A_1+B_1=t_{10},\quad A_2+B_2=0,\quad A_1=A_2,\quad \frac{b_1B_1}{\sqrt{\pi\tau}}+q_0=\frac{b_2B_2}{\sqrt{\pi\tau}}. \quad (13)$$

After substituting the coefficients found into (4) and (5) we obtain

$$t_1=\frac{t_{10}b_1+q_0\sqrt{\pi\tau}}{b_1+b_2}+\frac{t_{10}b_2-q_0\sqrt{\pi\tau}}{b_1+b_2}\,\mathrm{erf}\left(\frac{x}{2\sqrt{a_1\tau}}\right)+kx, \quad (14)$$

$$t_2=\frac{t_{10}b_1+q_0\sqrt{\pi\tau}}{b_1+b_2}\left[1-\mathrm{erf}\left(\frac{x}{2\sqrt{a_2\tau}}\right)\right]. \quad (15)$$

The temperature at the boundary is determined by the expression

$$t_b=\frac{t_{10}b_1+q_0\sqrt{\pi\tau}}{b_1+b_2} \quad (16)$$

or in the dimensionless form

$$T_b=\frac{t_b}{t_{10}}=\frac{b_1}{b_1+b_2}+\frac{q_0\sqrt{\pi\tau}}{t_{10}(b_1+b_2)}. \quad (17)$$

From here we conclude that in this formulation of the problem the temperature at the boundary depends not only on the ratio of the properties of the wall and of the flow but also on the heat flux density.

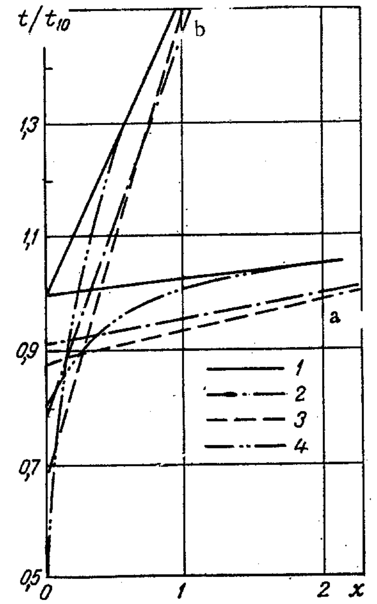

Fig. 10. Temperature distribution in the wall in the presence of a sodium flow over the wall (q = const, $q_0 = 5 \cdot 10^4$ W/m², t_{10} = 5K); a) copper; b) stainless steel; 1) $\tau = 0$; 2) 0.1; 3) 0.05; 4) 0.001, x, mm.

For the case under study the temperature head Δt_α is equal to the time-averaged value of the temperature at the interface, i.e., $\Delta t_\alpha = \bar{T}_b$:

$$\bar{T}_b = \frac{1}{\tau_e}\int_0^{\tau_e} T_b\, d\tau = \frac{b_1}{b_1+b_2} + \frac{2}{3}\,\frac{q_0\sqrt{\pi\tau_e}}{t_{10}(b_1+b_2)}. \tag{18}$$

Here τ_e is the average period between ejections. The temperature distributions in the copper and stainless steel walls are shown in Fig. 10. With an ejection frequency of 10-20 Hz and a heat flux density of ~$5 \cdot 10^4$ W/m², which is close to the experimental conditions in [29], the value of T_b for different combinations of the wall material and heat-transfer agent is equal to 0.85-0.87 (copper—sodium) and 0.62-0.68 (stainless steel—sodium). Therefore the ratio of the heat transfer coefficients (Nusselt's numbers) for the flow of liquid sodium over copper and stainless steel walls is $\alpha_{Cu}/\alpha_{s.s.} \cong 0{,}73$—$0{,}75$. This value is also in good agreement with the experimental data [29]. Using (18), we can study the effect of the properties of the surface on heat transfer for the flow of gas or water over it. If $b_2 \ll b_1$, which is characteristic for gases, then (18) assumes the form

$$\bar{T}_b = 1 + \frac{2}{3}\,\frac{q_0\sqrt{\pi\tau_e}}{t_{10}b_1}. \tag{19}$$

Since the heat-transfer coefficient for gases is quite small (q_0/t_{10} is also small), the quantity $\bar{T}_b$ is close to one. For an air flow over copper and stainless steel walls the difference in the heat-transfer coefficients ($q_0 \approx 10^5$ W/m² is $t_{10} \approx 150$ K). It is difficult to determine such a difference experimentally, since it is comparable to the experimental error.

We shall estimate the difference in the coefficients of heat transfer for a water flow over walls made of different materials. At a temperature of 200°C for water $b = 1540$ W$\cdot$sec$^{1/2}$/(m²$\cdot$K). The quantity q_0/t_{10} is very important (it is proportional to the heat-transfer coefficient) and depends on Reynolds number. Thus when $q_0/t_{10} \cong 10^3$ W/(m²$\cdot$K) we have $\alpha_{Cu}/\alpha_{s.s.} = 0{,}906$; and when $q_0/t_{10} \cong 10^4$ W/(m²$\cdot$K) we have $\alpha_{Cu}/\alpha_{s.s.} = 1{,}108$. Therefore the properties of the wall material in this case do not have a unique effect. To check the estimates presented above, specific experiments in which good accuracy is ensured must be performed. The main idea that "turbulence is created in a structured form" [69] is, however, absolutely certain, and this has a fundamental effect on heat transfer.

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