INTENSIFICATION OF HEAT TRANSFER AND REDUCTION OF THE RESISTANCE UNDER CONDITIONS OF FLOW IN CHANNELS WITH A MAGNETIC-FLUID COATING. 1. PLANAR COATING

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It is demonstrated theoretical by that low-viscosity coatings can, in principle, intensify heat transfer and at the same time reduce the hydraulic resistance in laminar flow in channels.

One of the main problems in building heat-exchangers is to increase the coefficient of heat transfer from a liquid moving in the pipes or channels of the heat exchanger. If the motion of the liquid is turbulent, then the heat-transfer coefficient is usually quite high or can be easily increased by using different types of turbulizers. The problem becomes significantly more complicated if a highly viscous heat-transfer agent, moving in the laminar regime, is employed. Making the surface of the heat exchanger more complicated (creating protuberances of different types in the channel) increases the heat transfer, but at the same time it sharply increases the hydraulic resistance of the channel. For this reason it is believed that it would be useful to modify the surface of the heat exchanger so that heat exchange increases more rapidly than the resistance.

Modification of the surface of the heat exchanger is not the only possible method for increasing the efficiency of heat exchangers. After all, heat transfer also depends on the velocity profile of the fluid flow.

Heat exchange in the starting thermal section in the case of the flow of a liquid between two flat surfaces with a constant temperature, different from the temperature of the liquid, was studied for a Poiseuille flow and a rod flow (the velocity is constant over the entire cross section of the channel) in [1]. Figure 1, based on the data of [1], shows the dependence of the local Nusselt number on x (x is the dimensionless longitudinal coordinate measured from the start of the channel). Although, here, the heat-exchange surfaces are identical the local Nusselt number is everywhere higher for the rod flow. Thus there is apparently one other way to intensify heat transfer — to modify the velocity profile rather than the heat-exchange surface.

The main mechanism of intensification of heat transfer accompanying transition from a Poiseuille flow to a rod flow is the increase in the velocity of the heat—transfer agent at the wall. Indeed, if the dependence of the velocity on the transverse coordinate at the channel wall is represented in the form of a series expansion $v \sim y^k + (y^k)$ (the dimensionless coordinate y is measured from the channel wall), then it can be shown that the dependence $Nu(x)$ in the boundary-layer approximation has a power-law character, and in addition $Nu \sim x^{-n}$, where $n = 1/(k + 2)$. As the exponent k increases the velocity near the wall and the Nusselt number drop simultaneously. For a Poiseuille flow $k = 1$ and $Nu_p \sim x^{-1/3}$, while for a rod flow $k = 0$ and $Nu_r \sim x^{-1/2}$, so that $Nu_r > Nu_p$, in addition, this inequality is satisfied along the entire channel for both the starting thermal section and the region of stabilized heat transfer. In particular, in the limit $x \to \infty$ the limiting Nusselt number $Nu_{r\infty}$ is approximately 30% higher than $Nu_{p\infty}$.

It should be noted that the transition from Poiseuille flow to a rod flow simultaneously with intensification of heat transfer results in a reduction of the hydraulic resistance of the channel, since the tangential stresses at the wall are proportional to the gradient of the velocity $\tau \sim dv/dy \sim ky^{k-1}$ and $\tau \to 0$ as $k \to 0$.

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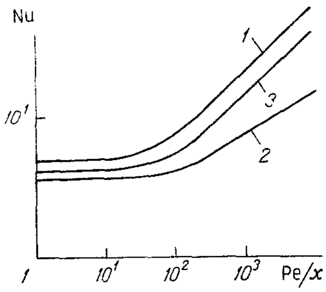

Fig. 1

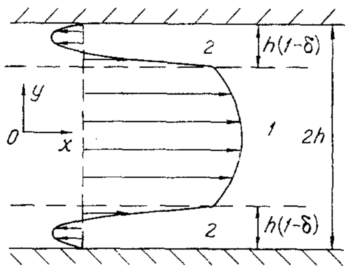

Fig. 2

Fig. 1. The distribution of the local Nusselt number along the channel: 1) rod flow; 2) Poiseuille flow; 3) flow in the presence of a flat magnetic-liquid coating; $\eta_1/\eta_2 = 100$, $1-\delta = 0.05$

Fig. 2. The velocity profile for flow in a channel with a magnetic-liquid coating.

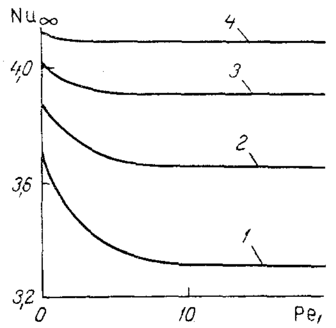

Fig. 3

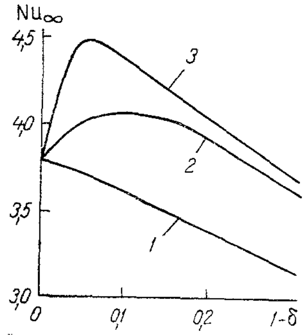

Fig. 4

Fig. 3. Curves of the maximum Nusselt number versus the Peclet number of the main flow ($\delta = 0.8$): 1 — $\eta_1/\eta_2 = 1$; 2 — 5; 3 — 20:4 — 1000

Fig. 4. Curves of the maximum Nusselt number versus the thickness of the magnetic-liquid coating 1 — $\eta_1/\eta_2 = 1$; 2 — 20; 3 — 100

Thus by modifying the velocity profile it is in principle possible to intensify heat transfer and at the same time to reduce the hydraulic resistance. Only the question of the realization of this method remains open.

The realization of the method is apparently determined by the possibility of reducing the tangential stresses at the channel walls. The traditional methods for lowering the tangential stresses in the flow of a highly viscous liquid are hardly realizable. In the last few years, however, a method based on coating the surface over which the fluid flows with a layer of magnetic liquid with low viscosity, confined by permanent magnets placed outside the channel, has been developed [2]. The questions of creating such layers and their stability are investigated in detail in [2, 3], where it is shown that there exists a range of Reynolds numbers in which the coating is stable; this range depends on the thickness of the layer and the properties of the magnetic liquid. In this case a circulation flow is realized in the layer of magnetic liquid having a finite length along the channel, and the velocity profile in the main flow (1) becomes uniform and approximates a rod flow (Fig. 2). As follows from the experimental data of [2], the hydraulic resistance of the channel can be reduced by a factor of two.

If the length Λ of the layers of magnetic liquid is large compared with the length of the starting thermal section L, and the thickness of the layers (2) $(1 - \delta)h$ is small, then edge effects can be neglected and the interface between the magnetic liquid and the main flow

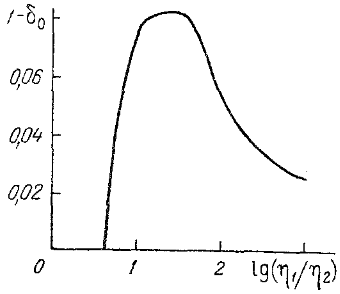

Fig. 5. The optical thickness of the coating versus the ratio of the viscosity of the main flow and the viscosity of the magnetic liquid

can be assumed to be flat. The velocity in this case has only one component v_x, which is oriented along the axis of the channel and depends on the transverse coordinate y. There is no difficulty in solving the corresponding Navier–Stokes equation, since the convective term is absent in this approximation. The velocity profile, satisfying the condition of attachment on the solid surface and the conditions that the velocities and the tangential stresses at the interface are equal, has the form [2]:

$$\begin{gathered} v_1 = 3A_1y^2 + C_1;\ v_2 = 3A_2y^2 + 2B_2y + C_2; \\ A_1 = \{\delta^2[4\delta + 3(1-\delta)\eta_1/\eta_2]\}^{-1}; \\ A_2 = -\frac{3}{2}A_1\delta(\eta_1/\eta_2)/(1-\delta); \\ C_1 = 1/2\delta - A_1\delta^2; \\ B_2 = A_2(2+\delta);\ C_2 = A_2(1+2\delta), \end{gathered} \tag{1}$$

where $1 - \delta$ is the dimensionless thickness of the coating.

Analysis of the expression (1) shows that for $\eta_1/\eta_2 > 4$ the resistance of the channel starts to decrease and the same time the velocity profile in the main flow becomes uniform and as η_1/η_2 increases the flow approaches a rod flow.

If the thickness of the magnetic-liquid coating $1 - \delta$ is small, then the thermal resistance of the coating is also small and the thermophysical characteristics of the coating as $\delta \to 1$ should not affect the heat transfer from the main flow to the channel walls. In this case the coating can affect the heat transfer only through a change of the velocity profile. Since with the use of a low-viscosity coating the velocity profile becomes uniform and approaches a rod flow, it can be expected that the heat transfer from the main flow also increases.

Thus the prerequisites for developing a method for intensifying heat transfer in which the hydraulic resistance of the system is significantly reduced exist.

We shall analyze the laws of heat transfer in a system with a magnetic-liquid coating for the example of the flow of a viscous nonmagnetic liquid between two flat planes, coated with a magnetic liquid. The temperature of the walls is assumed to be constant and different from the constant temperature of the liquid in the input section of the channel.

The system of equations and boundary conditions for the temperature distribution in the liquids can be written in a dimensionless form as follows:

$$\begin{gathered} -\delta < y \leqslant 0:\ \mathrm{Pe}_1 v_1 \partial\Theta_1/\partial x = \partial^2\Theta_1/\partial x^2 + \partial^2\Theta_1/\partial y^2; \\ -1 < y < -\delta:\ \mathrm{Pe}_2 v_2 \partial\Theta_2/\partial x = \partial^2\Theta_2/\partial x^2 + \partial^2\Theta_2/\partial y^2; \\ y = 0:\ \partial\Theta_1/\partial y = 0; \\ y = -\delta:\ \Theta_1 = \Theta_2,\ \lambda_1\partial\Theta_1/\partial y = \lambda_2\partial\Theta_2/\partial y; \\ y = -1:\ \Theta_2 = 0; \\ x = 0:\ \Theta_1 = \Theta_2 = 1. \end{gathered} \tag{2}$$

By virtue of the symmetry of the problem only half of the domain of the transverse coordinate $y \in [-1, 0]$, is studied, and the condition $\partial\Theta_1/\partial y = 0$ is imposed at the center of the channel.

The problem (2) was solved by the method of [4], based on expanding the temperature field sought in a series in the characteristic functions of the heat-conduction equation.

The solution of the corresponding problem (in Eq. (2) Pe_1 and Pe_2 are set equal to zero) has the form

$$\Theta^{(0)}(x, y) = \sum_{n=1}^{\infty} C_n \varphi_n(y) \exp(-\nu_n x),$$

where the characteristic functions $\varphi_n(y)$ are determined by the expression

$$\varphi_n(y) = \begin{cases} \varphi_n^{(1)} = \alpha_n \cos \nu_n y, & -\delta < y \leqslant 0, \\ \varphi_n^{(2)} = \beta_n \cos \nu_n y + \gamma_n \sin \nu_n y, & -1 \leqslant y < -\delta. \end{cases}$$

The set of functions φ_n is orthogonal with the weighting function $\lambda(y)$, equal to the thermal conductivities of the liquids:

$$\lambda(y) = \lambda_1, \quad -\delta < y \leqslant 0; \quad \lambda(y) = \lambda_2, \quad -1 \leqslant y < -\delta.$$

The equation for determining the spectrum of the problem $\{\nu_n\}$ follows from the boundary conditions:

$$\lambda_2 \cos \nu_n + (\lambda_2 - \lambda_1) \sin \nu_n \delta \sin \nu_n (1 - \delta) = 0.$$

Knowing the spectrum and taking into account the normalization condition $\int_0^1 \lambda(y) \varphi_n \varphi_m dy = \delta_{nm}$, the values of the coefficients can be determined α_n, β_n, and γ_n.

Thus the set of functions $\{\varphi_n\}$ is completely determined, and it can be used to solve the problem (2) by the method of [4].

Comparing the computed distribution of the local Nusselt number along the channel (see Fig. 1, curve 3) with the corresponding dependences for the rod and Poiseuille flows confirms the arguments presented above regarding the effect of the velocity profile on the intensity of heat transfer. The velocity profile for a flow a channel with a smooth coating of a magnetic liquid with low viscosity falls between the rod and Poiseuille profiles, and the intensity of heat transfer in this case is also intermediate – higher than for a Poiseuille flow and lower than for a rod flow.

The effect of some parameters of the system on the intensity of heat transfer from liquids to the channel walls, which is characterized by the criterion $Nu_\infty = \lambda_2 (\partial\Theta_2/\partial y|_{y=1})/\lambda_1 \bar{\Theta}$ the maximum Nusselt number, was studied for the region of stabilized heat transfer. The liquids were assumed to have the same thermal conductivity and heat capacity; this made it possible to interpret the differences between the obtained dependences and the corresponding dependences for a Poiseuille flow as being connected precisely with the change in the velocity profile of the liquid in the channel.

Figure 3 shows the dependence of the maximum Nusselt number on the Peclet number of the main flow for different ratios of the viscosities of the liquids. As the velocity of the main flow increases, i.e., as Pe increases, the maximum Nusselt number decreases; this is connected with the increase of the length of the starting thermal section. Reducing the viscosity of the magnetic liquid below that of the nonmagnetic liquid results in a increase of Nu_∞ owing to the equalization of the velocity profile of the main flow and therefore in an intensification of heat transfer. For $\eta_2/\eta_1 \ll 1$ the flow of the nonmagnetic liquid is close to a rod flow, for which Nu_∞ is characteristically independent of the Peclet number; this is illustrated by the curve 4.

An important factor that affects the velocity profile in the channel and the intensity of heat transfer is the thickness of the coating. As follows from the obtained results (Fig. 4), if the viscosity of the magnetic liquid is higher or of the viscosity of the main flow, then the maximum Nusselt number decreases monotonically as the thickness of the coating increases and is less than the maximum Nusselt number for a channel without a coating. This is connected with the increase of the velocity and decrease of the stresses in the main flow, resulting in a reduction of the intensity of heat transfer. For a coating with low viscosity (curves 2 and 3) and large thickness the intensity of heat transfer is also lower than for a Poiseuille flow. However as the thickness of the coating of magnetic liquid decreases the velocity profile of the main flow becomes uniform, and this results in an increase of the intensity of heat transfer and Nu_∞. For some optimal thickness of the coating Nu_∞ reaches a maximum, and as $\delta \to 1$ the intensity of heat transfer decreases and Nu_∞, $Nu_p = 3.77$ since in this case the velocity profile approaches the Poiseuille Profile.

Thus in the case of low viscosity there exists an optimal thickness of the coating for which the intensity of heat transfer is maximum. Figure 5 shows the dependence of the optimal thickness of the coating on the relative viscosities of the liquids. For $\eta_1/\eta_2<4$ the optical thickness of the coating is equal to zero, i.e., coating the channel walls with a liquid whose viscosity is not low enough results in a reduction heat transfer. If $\eta_1/\eta_2>4$, then there exists an optimal thickness of the coating which at first increases as the viscosity of the magnetic liquid decreases and then decreases and approaches zero as $\eta_1/\eta_2 \to \infty$. It shoud be noted that the threshold value $\eta_1/\eta_2 = 4$ is equal to the corresponding threshold value for the reduction factor for the hydraulic resistance, which also indicates that the intensity of heat transfer is related with the velocity profile in the channel. The maximum value of the maximum Nusselt number is reached in the limit $\eta_1/\eta_2 \to \infty$, $\delta \to 1$. In this case a rod flow is realized in the channel, and the value of Nu_∞ is approximately 30% higher than for a Poiseuille flow.

The reliability of the obtained analytical results is confirmed by controlled numerical calculations, which showed that the accuracy of the obtained analytical solution is quite high (the relative error did not exceed 2 %).

Thus the investigations performed have proved that it is in principle possible to increase the intensity of heat transfer and at the same time to reduce the hydraulic resistance for flow of a nonmagnetic heat-transfer agent in a channel by coating the channel walls with a law-viscosity magnetic liquid.

In the model problem studied it was assumed that the length of the layers of magnetic liquid is large and therefore edge effects can be neglected. In this situation the only nonzero component of the velocity vector is v_x and convective heat transfer occurs in the longitudinal direction, while heat is transferred in the transverse direction only by means of heat conduction.

In real systems the layers of magnetic liquid have a finite length, there exist regions in which the transverse component of the velocity of the liquids is different from zero, and convective heat transfer across the channel occurs. Part 2 of this work will be devoted to the study of this situation.

NOTATION

Here, x and y are dimensionless coordinates along and across the flow; v is the dimensionless velocity of the liquid; 2h is the width of the channel, m; $1 - \delta$ is the dimensionless thickness of the coating; η is the coefficient of dynamic viscosity, Pa·sec; T is the temperature, K; θ is the dimensionless temperature; $\bar{\theta}$ is the mean flow temperature; λ is the thermal conductivity, W/(m·K); $Nu = 2hq/\lambda\Delta T$ is the Nusselt criterion; and $Pe = 2h\bar{v}/\varkappa$ is the Peclet criterion. The indices i = 1 and 2 refer to the main flow and the magnetic-liquid coating.

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