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INTENSIFICATION OF CONVECTIVE HEAT EXCHANGE IN ANOMALOUSLY VISCOUS MEDIA BY THE APPLICATION OF ARTIFICIAL PERIODIC ROUGHNESS

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The results of an experimental investigation of the intensification of convective heat exchange in the flow of anomalously viscous liquids in pipes with artificial periodic roughness are presented. An estimate is made of the thermohydrodynamic efficiency of the application of this means of intensification to anomalously viscous media.

One of the most critical problems facing industry is to increase the unit output and productivity of equipment, particularly heat exchangers. The most effective way of solving this problem is to develop and investigate methods for the intensification of convective heat exchange.

A well-known means of intensification of heat exchange is to use pipes having an artificial periodic roughness in the form of different kinds of projections or diaphragms on the inner surface of the pipe as the working channels of the heat-exchange apparatus. However, all the test data available in the literature on the intensification of heat exchange in this way pertain to the case of flow of viscous liquids in channels [1-5]. In this connection, it is known [1] that the given method intensifies the heat exchange in viscous liquids by an average of 2.5 times. It is also known [6] that a change in the shape of the profile of a projection when the spacing and height are unchanged has a weak effect on the change in heat transfer while it affects to a considerably greater extent the change in the coefficient of hydraulic resistance, which decreases in proportion to the decrease in the coefficient of profile drag. For example, the lowest hydraulic losses, at a practically equal gain in heat transfer, are achieved in the case of smoothly profiled diaphragms by rolling the outer surface of pipes with rollers. The technology for making such pipes is very simple and the cost of the rolling is a few percent of the cost of a smooth pipe [1]. Moreover, it becomes possible to intensify heat transfer to the outer surface of the pipe also.

Unfortunately, experimental data on the intensification of heat exchange by the indicated means are presently absent for the flow of anomalously viscous liquids.

Since the use of pipes with artificial periodic roughness in the form of rolled smoothly profiled diaphragms yields a considerable gain in heat transfer in the flow of viscous

TABLE 1. Thermophysical Characteristics of Polymer Solutions

Aqueous solution	ρ, kg/m^3	$c_p \cdot 10^{-3}$, J/kg·deg	λ, W/m·deg
PVA, 9%	1020	3,607	0,674
Na CMC, 8.5%	1080	3,289	0,476

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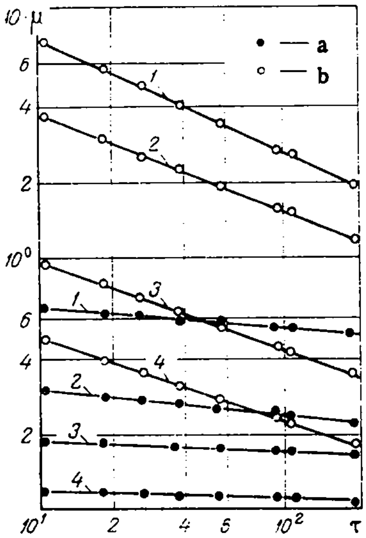

Fig. 1. Results of viscosimetric measurements of model liquids: 1) 20°C; 2) 40°C; 3) 60°C; 4) 80°C; a) 9% PVA; b) 8.5% Na-CMC. μ, Pa·sec; τ, Pa.

liquids, we attempted to experimentally clarify the possibilities for the intensification of heat exchange in anomalously viscous media and to estimate the thermohydrodynamic efficiency of the use of this means of intensification for anomalously viscous media.

The tests were conducted on an experimental installation described in [7] under the conditions of heating of the liquid. Steel pipes with an inner diameter of 18 mm were used as the interchangeable working sections of the test installation. Their inner surfaces corresponded to purity classes 8-9. The test pipes were rolled on the outer surface with rollers on a lathe to obtain smooth diaphragms on the inner surface. The diaphragms were rolled with a range of relative spacing S/D = 0.3-1.94 and of height d/D = 0.80-0.98.

As the model liquids we used a 9% aqueous solution of polyvinyl alcohol (PVA) and an 8.5% aqueous solution of sodium carboxymethyl cellulose (Na-CMC). The results of viscosimetric measurements of the model liquids in the temperature range of 20-80°C are presented in Fig. 1. The thermophysical characteristics, determined from the data of [8, 9], are presented in Table 1. The experimental values of the mean heat-transfer coefficients were determined through the logarithmic-mean temperature head,

$$\bar{\alpha} = \frac{Q}{F\Delta\bar{t}_{\log}}, \qquad (1)$$

with allowance for the ribbing of the heat-transfer surface. The wall temperature of the pipe was computed as the weighted mean along the length:

$$\bar{t}_{\text{w}} = \sum_{i=1}^{k} l_i (t_i + t_{i+1})/2 \sum_{i=1}^{k} l_i. \qquad (2)$$

The test pipes each had six Chromel—Copel thermocouples embedded in the inner and outer surfaces of the pipe wall, with the help of which the wall temperature was monitored and the thermal boundary conditions were maintained.

To estimate the size of the effect of an increase in the heat-transfer coefficients in a rough pipe in comparison with the heat-transfer coefficients in a smooth one and to find that region of Reynolds numbers where this increase is greatest, we analyzed the test results for anomalously viscous liquids in the form of the dependence $\overline{\text{Nu}} = f(\text{Re})$ (Fig. 2). The inner diameter of the smooth pipe was taken as the characteristic geometrical size in the analysis, and the effective viscosity of the liquid was determined at the temperature and shear stresses averaged over the stream cross section. For comparison we made tests in smooth pipes of the same inner diameter having a heat-transfer surface of the same area as the rough pipes.

In comparing the test data with the results of [1], it is seen that the effect of an increase in the heat-transfer coefficients in the case when pipes with artificial roughness are used to intensify the heat exchange in anomalously viscous media far exceeds the same effect in viscous liquids. Under certain conditions the increase in the heat-transfer intensity in comparison with that for a smooth pipe can reach a tenfold value (Fig. 2, family of lines b).

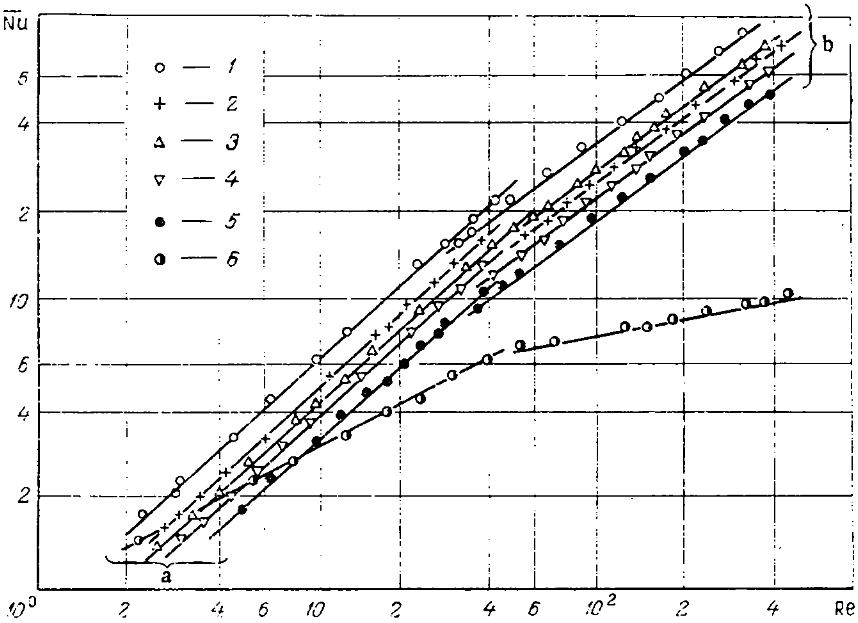

Fig. 2. Dependence $\overline{Nu} = f(Re)$ for the test liquids (d/D = 0.91): 1) S/D = 1.22; 2) 0.66; 3) 1.66; 4) 1.94; 5) 0.33; 6) smooth pipe; a) 8.5% Na-CMC; b) 9% PVA.

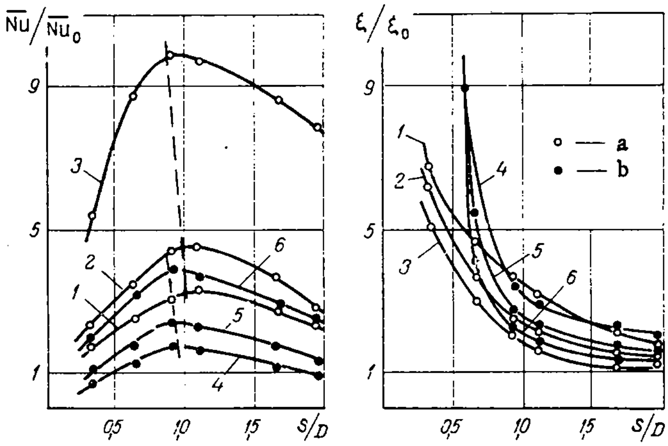

Fig. 3. Influence of spacing of diaphragm distribution on relative change of heat-transfer coefficient and hydraulic resistance (d/D = 0.91). Notation analogous to that of Fig. 2.

Heat exchange in the flow of anomalously viscous liquids in smooth pipes and channels is distinguished by low values of the heat-transfer coefficients in comparison with those for Newtonian liquids owing to the large thermal resistance and the high values of the Prandtl numbers (Pr >> 1). When rolled diaphragms are used as heat-exchange intensifiers in anomalously viscous media the relative increase in the heat-transfer coefficients occurs through disturbances of the stream in the boundary region. Just as in the case of a Newtonian liquid, these disturbances, caused by the replacement of elementary volumes of liquid in the boundary region, have the form of a vortex whose intensity depends not only on the shape, spacing, and height of the projections but primarily on the value of the effective viscosity and the index of non-Newtonian behavior of the liquid.

In examining the influence of the relative spacing on the heat transfer it is seen that the maximum increase in heat transfer (reaching a tenfold value) falls in the region of a relative spacing S/D = 0.85-1.25, depending on the Reynolds number. A tendency toward a decrease in the most efficient, in the sense of heat transfer, relative spacing with an increase

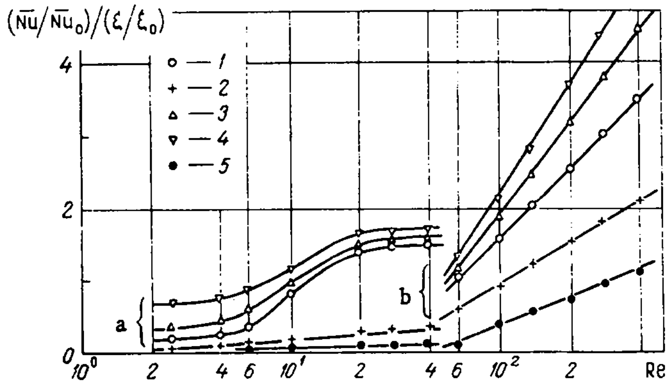

Fig. 4. Thermohydrodynamic efficiency of the use of periodic rolling to intensify convective heat exchange in anomalously viscous media. Notation analogous to that of Fig. 2.

in the Reynolds number is clearly traced (Fig. 3, dashed line). In an estimate of the influence of the diaphragm spacing on the relative change ξ/ξ_0 in the coefficients of resistance it was established that the coefficient of hydraulic resistance grows sharply with a decrease in the spacing. Its growth also occurs with a decrease in the Reynolds number.

When the relative spacing of the diaphragms is decreased ($S/D < 0.85$) a pipe with artificial rolling should be treated as a rough channel, in which the heat-transfer intensity is considerably lower while the relative increase in hydraulic resistance is very high. An increase in the relative spacing above the experimentally determined optimum range ($S/D > 1.25$) leads to the formation of stagnant zones ahead of the diaphragms, which also worsens the heat exchange.

In examining the influence of the height of the roughness on the coefficients of heat transfer and hydraulic resistance it is seen that in the region of small heights the rate of increase in resistance is lower than at small d/D, which is in good qualitative agreement with the conclusions of [1]. At the same time, the region of small heights is the most promising for the intensification of heat transfer in anomalously viscous media in connection with the fact that the increase in the coefficient of resistance is practically the same as the increase in heat transfer in the region of low Reynolds numbers. With an increase in Re (9% solution of PVA) the increase in heat transfer far exceeds the increase in hydraulic losses. As the tests showed, the range of diaphragm heights $d/D = 0.91$–0.98 must be considered as optimum from both the energetic and the technological points of view.

Since the use of heat-exchange intensifiers is accompanied by an increase in hydraulic resistance, the criterion of advisability for the method of heat-exchange intensification will be, according to [1], the relation between the ratios $\overline{Nu}/\overline{Nu}_0$ and the coefficients of resistance ξ/ξ_0 for channels with intensifiers ($\overline{Nu}$, ξ) and for smooth channels ($\overline{Nu}_0$, ξ_0). The attainment of the final goal, a decrease in the overall size of a heat-exchange apparatus or an increase in its thermal efficiency, is possible most often when $\overline{Nu}/\overline{Nu}_0 > \xi/\xi_0$. Upon an increase in the effective viscosity to 0.4-0.5 Pa·sec the disturbances in the boundary region die out and there is axial flow over the projections with the formation of stagnant zones behind them, leading to a decrease in the heat-transfer coefficients. The stagnant zones which develop can also lead to worsening of the heat exchange in comparison with a smooth pipe. But a decrease in the overall size of the heat-exchange apparatus is also possible in this case [1] if intensification also occurs outside the pipes or if the coefficient of heat transfer outside the pipes is much larger than inside them. For an estimate of the overall thermohydrodynamic efficiency the test results were treated in the form of the dependence

$$(\overline{Nu}/\overline{Nu}_0)/(\xi/\xi_0) = f\,(\mathrm{Re}). \qquad (3)$$

Equation (3), which is a development of the well-known method of Kalinin [1] for comparing objects with the same controlling dimensions, also allows one to estimate the efficiency at different mean temperatures of the working medium and to find the preferred region of Reynolds numbers for the use of intensifiers.

The results of the tests with anomalously viscous liquids treated in the form of the dependence (3) are presented in Fig. 4. Here the values of $\overline{Nu}$ and ξ were reduced, in accordance with [1], to the same Reynolds numbers as for a smooth pipe.

An analysis of the dependence of Fig. 4 shows that when diaphragmmed channels are used to intensify heat exchange in anomalously viscous media their efficiency grows sharply and, under the conditions of the tests which were set up, the heat-transfer intensity exceeds the hydraulic losses by five times.

NOTATION

$\overline{Nu}$ and ξ, mean Nusselt number and coefficient of resistance in a diaphragmmed pipe; $\overline{Nu}_0$ and ξ_0, the same in a smooth pipe; Re, Reynolds number; S, spacing of diaphragm distribution; D, inner diameter of smooth pipe; d, inner diameter of a diaphragm; α, mean coefficient of heat transfer; Q, amount of heat; F, area of heat-transfer surface; Δt_{log}, logarithmic-mean temperature head; l_i, distance between thermocouple embedding points; t_i, t_{i+1}, thermocouple readings.

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HYDRODYNAMICS AND MASS TRANSFER IN A LIQUID FILM IN THE PRESENCE OF INSOLUBLE SURFACTANTS OR INACTIVE SUBSTANCES

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Nonlinear problems on the laminar flow of a liquid film subjected to gravity and convective diffusion of substances dissolved in the fluid in the presence of insoluble active or inactive agents on its surface are examined.

The influence of substances altering the surface tension on the interface between two continuous media on the heat transfer in systems of the fluid–fluid and fluid–gas type is due to the appearance of additional tangential stresses on this boundary, which are associated with the surface tension gradient (the Marangone effect [1]). These stresses can result in an essential change in the velocity field both near the interface and in the depths of the viscous fluid, which in turn influences the convective diffusion process and the distribution of the substances mentioned on the surface itself, and therefore, on the surface-tension gradient caused by their presence. Below we call surfactants lowering the surface tension and inactive substances which raise it surfactant (SAS) in all cases when it cannot result in misunderstanding.

The influence of SAS on the mass-transfer process can be manifested because of two fundamental mechanisms. First, both the SAS itself and the homo- or heterogeneous chemical

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