pressure drag for the first sphere of straight-line packing; C_{x_0}, coefficient of drag of a sphere in a free stream; U_0, voltage of output of thermoanemometer; U_0', apparent zero voltage at output of thermoanemometer; B, filament constant (proportionality factor), determined by calibrating the filament in an airstream; U_{*0}, voltage at output of thermoanemometer in the absence of gas motion near the wall; v', magnitude of longitudinal velocity pulsation; δ_1, displacement thickness of boundary layer; δ_2, thickness of momentum loss; $H_{1,2} = \delta_1/\delta_2$, form factor of boundary layer; Nu, Nusselt number; α_{loc}, local heat-transfer coefficient of a spherical element; q_{loc}, local heat flux from surface of a spherical element; t_d, detector temperature; t_{in}, t_{out}, air temperatures at inlet and outlet of channel; K_α, heat-transfer coefficient of nonuniformity over surface of a spherical element.

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INTENSIFICATION OF CONVECTIVE HEAT EXCHANGE BY SPIRAL SWIRLERS IN THE FLOW OF ANOMALOUSLY VISCOUS LIQUIDS IN PIPES

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The results of an experimental investigation of the intensification of convective heat exchange in the flow of anomalously viscous liquids are presented. An estimate is made of the thermodynamic and energy efficiencies of the use of longitudinal spiral swirlers.

One of the well-known means of intensification of heat exchange in pipes consists in acting on the boundary region of flow using spiral wire swirlers, very effective technologically in preparation and utilization. Investigators have now accumulated extensive experimental material on heat exchange in pipes containing various types of intensifiers, including spiral wire swirlers [1-3]. It should be noted that all the papers have been devoted to the intensification of heat exchange during the motion of viscous liquids in pipes.

Now from an analysis of the known work it is seen that the use of spiral wire swirlers intensifies the heat exchange in viscous liquids up to 3 times [2], with the greatest increase in the heat-transfer coefficients being observed in the region of Reynolds numbers from 3500 to 8000. This is connected with the formation and development of vortices intensifying the process of heat exchange. With the gradual development of turbulence the quantity Nu/Nu_0 decreases somewhat, nevertheless remaining considerably higher than unity, since at $Re > 8000$ turbulence begins to have the dominant effect on the heat exchange in a viscous liquid while the role of vortices gradually decreases.

Unfortunately, data on the intensification of convective heat exchange in the flow of anomalously viscous liquids, which find the widest application, are entirely absent at present.

On the basis of the fact that the use of spiral wire swirlers gives a considerable gain in heat transfer in the flow of viscous liquids, we attempted to experimentally determine the possibilities of the intensification of heat exchange in anomalously viscous media using the indicated swirlers and to estimate the efficiency of their use.

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TABLE 1. Thermophysical Characteristics of Polymer Solutions

Aqueous solution	t, °C	ρ, kg/m³	c_p, J/kg·deg	λ, W/m·deg
Na — CMC, 1%	20	1022	3572	0,5612
	40	1017	3510	0,5610
	60	1012	3530	0,5608
	80	1008	3540	0,5606
Na — CMC, 3%	20	1034	3315	0,5535
	40	1026	3235	0,5533
	60	1020	3220	0,5531
	80	1015	3315	0,5528

The tests were performed on an experimental installation for which a schematic diagram is presented in Fig. 1. The working liquid from the preliminary thermostatic-control tank 1 was fed by the pump 2 through the following closed loop: a heat exchanger 4 for final thermostatic control (3 is a thermostat), a damping chamber 5. the working element 7, and a mixing chamber 11. The liquid flow rate was regulated by varying the speed of the pump 2 and by the valve 14. The tests were performed under conditions of heating of the liquid. The working section 7 was heated by successive sectional Nichrome electric heaters 9. Different thermal boundary conditions at the wall of the working section could be achieved by the appropriate switching of the sections and regulation of the strength of the current in each of them. Leakage of heat into the surrounding medium was compensated for by an additional electric heater laid above the main sections. The wall temperature was measured by the potentiometer 13 using a system of Chromel — Copel thermocouples 12 with leads 0.12 mm in diameter. The liquid temperature at the inlet and outlet of the working section was measured with standard thermometers 10. A pipe of 1Kh18N10T stainless steel with an inner diameter of 11 mm and a length of 1750 mm was used as the working section of the installation. The cleanness of the inner surface of the pipe corresponded to the eighth class of cleanness. The tests were performed with spiral wire inserts 6 made of steel wire with a diameter d = 0.8-1.2 mm and a spacing S = 5-47.5 mm. The pressure drop in the working section was measured with a mercury differential manometer 8. All the tests were performed under steady thermal and hydrodynamic conditions.

Tests with water and transformer oil, which showed good convergence (within 10% limits for water) with the well-known criterial equations of Shukin [1], were performed preliminarily on the experimental installation. As the model for anomalously viscous liquids, we used 1 and 3% aqueous solutions of sodium carboxymethyl cellulose (Na — CMC). The rheological characteristics of the model liquids were determined on a Rheotest rotary viscosimeter and on a Keppler rheoviscosimeter. The results of the viscosimetric measurements in the temperature range from 20 to 80°C are presented in logarithmic coordinates in Fig. 2.

The thermophysical characteristics of the solutions were determined by the well-known methods [4, 5]. The results of the thermophysical measurements in the investigated temperature range are presented in Table 1.

The experimental values of the average heat-transfer coefficients were determined through the logarithmic-average temperature head:

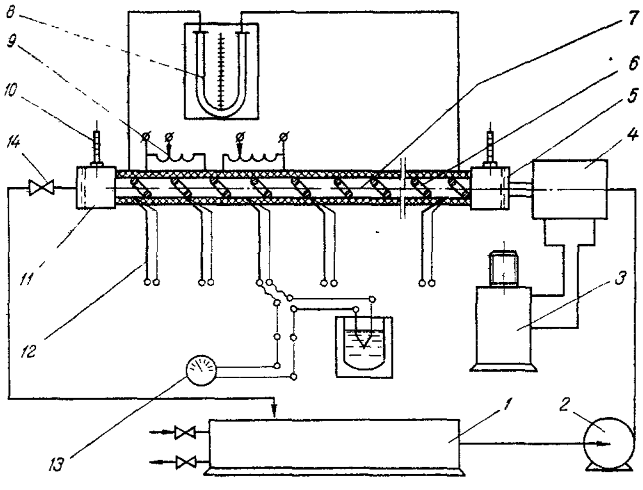

Fig. 1. Diagram of experimental installation.

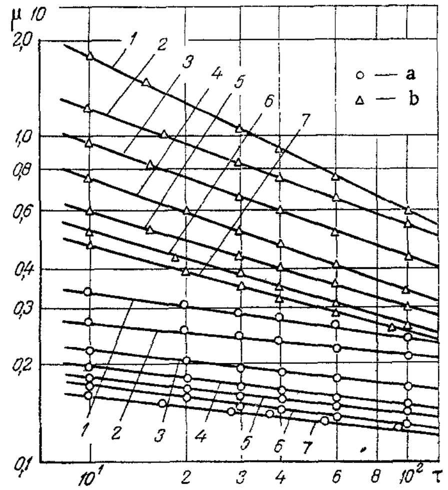

Fig. 2. Results of viscosimetric measurements: a) 1% aqueous solution of Na – CMC; b) 3% aqueous solution of Na – CMC; 1) 20°C; 2) 30; 3) 40; 4) 50; 5) 60; 6) 70; 7) 80°C. μ, N · sec/m^2; τ, N/m^2.

$$\bar{\alpha} = Q/F\,\Delta t_{\log}. \tag{1}$$

The wall temperature of the pipe was calculated as the weighted-mean value along the length:

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

To determine the amount of the relative increase in the heat-transfer coefficients in a pipe containing a swirler in comparison with the heat-transfer coefficients in a smooth pipe and to bring out that Reynolds-number region where this increase is greatest, the experimental results for anomalously viscous liquids, as well as the results of [2], were treated (Fig. 3) in the form of the dependence $Nu/Nu_0 = f(Re)$. In the treatment the inner diameter of the pipe was taken as the characteristic geometrical size while the heat-transfer coefficient in Eq. (1) was determined without allowance for the effect of the ribbing of the inner surface; i.e., the values of Nu and Re were reduced to the same values of the Reynolds numbers with a smooth pipe. The average flow velocity was calculated with allowance for the cross-sectional area of the swirler.

It is seen from Fig. 3 that the effect of an increase in the heat-transfer coefficients in the case of the use of spiral wire inserts to intensify the heat exchange in anomalously viscous media exceeds the same effect in viscous liquids by several times. By comparing the results of the tests with 1 and 3% solutions of Na – CMC, one can conclude that the effect of a relative increase in the heat-transfer coefficients grows sharply with an increase in the effective viscosity of the liquid. In addition, the maximum value of the ratio of Nusselt numbers shifts toward a decrease in Reynolds numbers with an increase in the effective viscosity.

The increase in the heat-transfer coefficients in anomalously viscous liquids when spiral wire swirlers are used takes place owing to disturbances of the stream in the boundary region. Since in the flow of anomalously viscous liquids, which have a large thermal resistance and high Prandtl numbers ($Pr \gg 1$), the heat exchange is distinguished by low values of the heat-transfer coefficients, the disturbances of the stream caused by the displacement of elementary volumes of liquid along complicated three-dimensional trajectories in the boundary region lead to a sharp relative increase in the heat-transfer coefficients.

With a further increase in the effective viscosity of the liquid (above the investigated range, Fig. 2) the disturbances caused by the displacement of elementary volumes of liquid in the boundary region die out and axial flow over the wire elements occurs with the formation of stagnant zones behind them, leading to a decrease in the heat-transfer coefficients. The construction of intensifiers producing a disturbance of the entire stream clearly prove to be more effective in this case.

In examining the influence of the spacing of the swirler on the relative increase in the heat-transfer coefficients (Fig. 3), we see that the largest values of Nu/Nu_0 fall in the region of $S/D = 0.6$–3.0, depending on the Reynolds number. At values of $0.3 < S/D < 0.6$ the ratio Nu/Nu_0 decreases and a pipe containing a spiral insert should be considered as a pipe with artificial periodic roughness. With an increase in the Reynolds number the maximum of the relative increase in heat transfer shifts toward a decrease in the spacing of the swirler (dash – dot line).

In connection with the fact that the use of a heat-exchange intensifier is accompanied by an increase in hydraulic resistance, it seems very important to estimate, on the basis of a single and sufficiently general

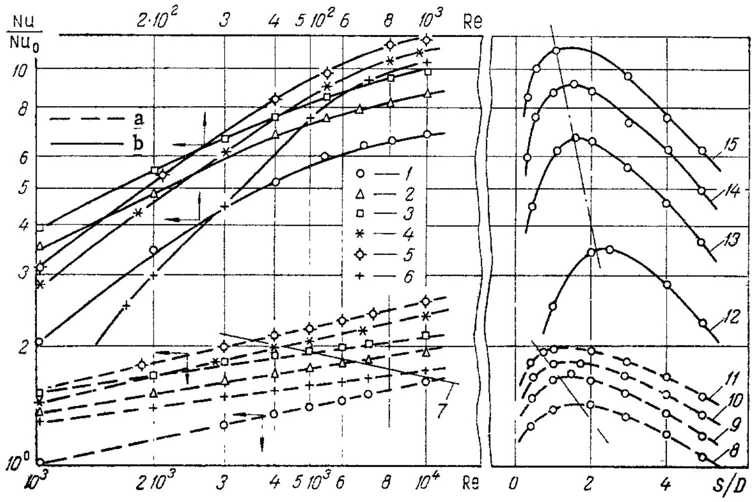

Fig. 3. Dependence of relative increase in heat transfer on Reynolds number and relative spacing of swirler: a) 1% aqueous solution of Na — CMC; b) 3% aqueous solution of Na — CMC; 1) S = 47.5 mm; 2) 27.5 mm; 3) 20 mm; 4) 13.5 mm; 5) 12.5 mm; 6) 5 mm; 7) treatment of results of [2]; 8) Re = 1000; 9) 3000; 10) 5000; 11) 7000; 12) 100; 13) 300; 14) 500; 15) 1000; dashed lines: maxima of relative increase in heat transfer.

criterion, the efficiency of the swirlers and to determine the preferable geometrical dimensions and the region of their application.

At the basis of one of the methods lies the determination of the energy efficiency of different forms of convection surfaces in the form of functions [6-8]

$$\alpha = f(N_0). \tag{3}$$

The energy efficiency characterizes the degree of utilization of the mechanical energy needed to pump the liquid through the channel in order to provide the assigned heat-transfer intensity. For the anomalously viscous liquids studied the optimum insert was a spiral with a relative spacing S/D = 1.13 which, with resistance losses equal to those with a smooth pipe, provides the maximum increase in heat transfer.

To estimate the overall thermo- and hydrodynamic efficiency of intensifiers it is most advisable, in our opinion, to use the equation

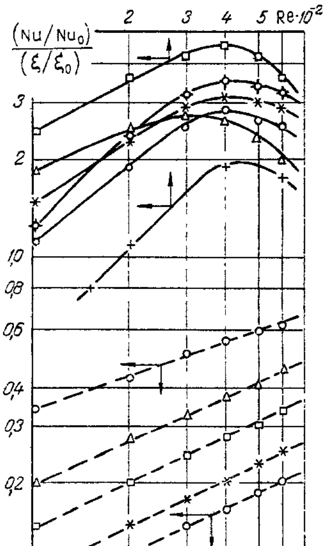

Fig. 4. Thermo- and hydrodynamic efficiency of the use of spiral wire swirlers. Notation analogous to that of Fig. 3.

$$(\mathrm{Nu}/\mathrm{Nu}_0)/(\xi/\xi_0) = f(\mathrm{Re}). \tag{4}$$

Equation (4) characterizes the relative increase in the intensity of heat exchange, in a pipe containing a swirler, per unit extra energy expended. The estimation of the efficiency using Eq. (4) is a development of the well-known method developed by Kalinin [9] for the comparison of objects with the same determining dimensions and used to estimate rough channels. Function (4) differs from (3) in that it allows one to estimate the efficiency at different average temperatures of the working medium, to estimate the most varied constructions of intensifiers, and to find the preferable region of their application with respect to the Reynolds number. The treated results of the tests with anomalously viscous liquids and the test results of [2] are presented in Fig. 4 in the form of function (4). Here the values of Nu and Re were reduced to the same Reynolds numbers with a smooth pipe, in accordance with [9]. An analysis of the functions in Fig. 4 shows that the thermo- and hydrodynamic efficiency of the use of spiral wire swirlers to intensify the heat exchange in anomalously viscous media increases sharply with an increase in the effective viscosity of the liquid and, under the conditions of the tests which were run, the excess of the intensity of heat transfer over the hydraulic losses reaches 4.5 times.

As the preliminary studies showed, with a further increase in the effective viscosity the thermo- and hydrodynamic efficiency of spiral wire swirlers will decrease and swirler constructions which disturb the entire stream will prove more efficient, particularly ribbon and snake intensifiers, about which we will report in subsequent papers.

NOTATION

Nu and ξ, Nusselt number and resistance coefficient in a pipe containing swirlers; Nu_0 and ξ_0, Nusselt number and resistance coefficient in a smooth pipe; Re, Reynolds number; d, diameter of swirler wire; S, spacing of swirler; D, inner diameter of pipe; $\bar{\alpha}$, average heat-transfer coefficient; Q, amount of heat; F, area of inner surface of pipe; $\Delta\bar{t}_{\log}$, logarithmic-average temperature head; l_i, distance between points of attachment of thermocouples; K, number of thermocouples; t_i, t_{i+1}, readings of thermocouples; α, heat-transfer coefficient under the given conditions of bathing of the surface; N_0, energy expended on moving the bathing medium per square meter of surface per second.

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