9. C. A. Foster, K. Kim, R. J. Turnbull, and C. D. Hendricks, Rev. Sci. Instrum., 48, No. 6, 625 (1977).
10. G. E. Mase, Theory and Problems of Continuum Mechanics, McGraw-Hill, New York (1970).
11. L. D. Landau and E. M. Lifshits, Mechanics of Continuous Media [in Russian], Gostekhizdat, Moscow (1954).

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

Yu. G. Nazmeev

UDC 536.242.001.5

The results are given on an experimental investigation of the intensification of convective heat exchange in anomalously viscous media through the use of inserts of twisted ribbon.

The intensification of convective heat exchange in pipes and channels of heat-exchange apparatus is a most important problem for many branches of industry. Solving this problem enables one to reduce the size of heat-exchange apparatus and to increase their output.

A well-known means of intensifying convective heat exchange in pipes is the use of helical inserts of twisted ribbon. By now extensive experimental material has been accumulated on heat exchange in pipes containing helical intensifiers [1-5]. All the available test data pertain to the case of the flow of viscous liquids, however. In this case it is seen from an analysis of the well-known reports [1, 5-7] that the use of ribbon swirlers intensifies heat exchange in viscous liquids by up to 2.5 times, with the largest increase in the coefficients of heat transfer being observed in the region of Reynolds numbers from 3000 to 6500. The cause of the increase in heat transfer in viscous liquids is the formation and development of secondary flows of the first and partly of the second kind under the action of centrifugal forces. In addition, the use of an insert of twisted ribbon increases the heat-exchange surface and an increase in heat transfer also occurs due to the ribbing effect. With an increase in the Reynolds number above 6500 turbulence has the prevailing effect on the intensity of heat transfer, while the role of secondary flows decreases.

Unfortunately, up to now test data are entirely absent on the intensification of heat exchange by the indicated means in the flow of anomalously viscous liquids, which find very wide application in modern technology.

On the basis of the fact that the use of ribbon swirlers provides a considerable gain in heat transfer in the flow of viscous liquids, in the present report an attempt was made to experimentally determine the possibilities for the intensification of heat exchange in anomalously viscous media using the given swirlers, as well as to estimate the efficiency of their use.

The tests were conducted on the experimental installation described in [8]. A pipe of 1Kh18N10T stainless steel with an inner diameter of 12 mm and a length of 1200 mm was used as the working section. The treatment of the inner surface of the pipe corresponded to the eighth class of purity. The tests were conducted with helical inserts of twisted brass ribbon 0.5 mm thick. The pitch of the ribbon swirlers (in a rotation of the ribbon by 180°) lay in the range from 38 to 600 mm. All the tests were conducted under steady thermal and hydrodynamic conditions.

Tests with water and transformer oil, which showed good convergence with the well-known generalizing criterial equation of [6] were made preliminarily on the experimental installation. Aqueous solutions of sodium carboxymethylcellulose (Na-CMC) of different concentrations were used as the model anomalously viscous liquids. The rheological characteristics of the model liquids were determined on a Rheotest rotary viscosimeter and on a Höppler viscosimeter. The results of the viscosimetric measurements of two model liquids in the temperature range from 20 to 80°C are presented in Fig. 1. The thermophysical characteristics of the anomalously viscous liquids were determined in accordance with [9, 10]. The results of the thermophysical measurements are given in Table 1.

S. M. Kirov Kazan Chemical Engineering Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 37, No. 2, pp. 239-244, August, 1979. Original article submitted July 3, 1978.

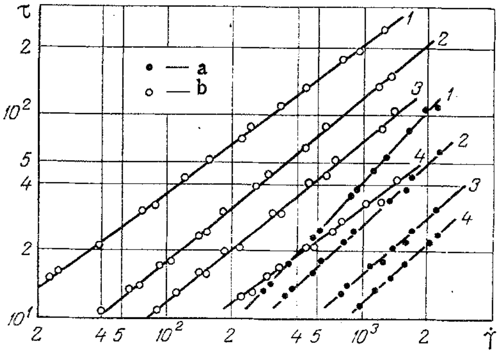

Fig. 1. Results of viscosimetric measurements of the model anomalously viscous liquids: a) 3.8% Na-CMC; b) 7%; 1) 20°; 2) 40; 3) 60; 4) 80°C. τ, Pa; $\dot{\gamma}$, $\sec^{-1}$.

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

$$\bar{\alpha} = Q/F\overline{\Delta t}_{\log} \tag{1}$$

without allowance for the ribbing of the heat-transfer surface.

The temperature of the pipe wall was calculated as the weighted mean over 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 estimate the size of the relative increase in the coefficients of heat transfer in a pipe containing a helical insert relative to the coefficients of heat transfer in a smooth pipe and to determine that region of Reynolds numbers where this increase is largest, we analyzed the experimental results for anomalously viscous liquids (Fig. 2) in the form of the dependence $Nu/Nu_0 = f(Re)$. The results of [5], also presented in Fig. 2, were analyzed similarly. The inner diameter of the pipe was taken as the characteristic geometrical size in the analysis, i.e., the values of Nu and Re were normalized to the same 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. 2 that when helical inserts are used to intensify heat exchange in anomalously viscous media the effects which develop exceed the analogous effects in viscous liquids by several times. A 12-fold growth in the effect of an increase in heat transfer is observed under the conditions of these tests. In comparing the results of the tests with 3.8 and 7% solutions of Na-CMC one can conclude that the effect of a relative increase in the coefficients of heat transfer grows sharply with an increase in the effective viscosity of the liquid. Although the range of effective viscosity of the anomalously viscous liquids studied is very wide, an absolute maximum in the growth of heat transfer was not reached in the tests, and the tendency of an increase in the coefficients of heat transfer with an increase in the effective viscosity was traced very clearly. In this case with an increase in the effective viscosity the maximum values of the ratios of Nusselt numbers are shifted toward a decrease in the Reynolds numbers.

When helical inserts are used the rotational – translational motion of an anomalously viscous liquid is accompanied by the development of centrifugal forces leading to perturbation of the flow over the entire cross

TABLE 1. Thermophysical Characteristics of Polymer Solutions

Aqueous solution	Temperature of measurement	ρ, kg/m³	C_p, J/kg·deg	λ, W/m·deg
Na-CMC, 3.8%	20	1040	3370	0,5537
	40	1034	3315	0,5535
	60	1029	3236	0,5532
	80	1025	3310	0,5529
Na-CMC, 7%	20	1071	3051	0,4930
	40	1060	2986	0,4927
	60	1052	2910	0,4922
	80	1043	2940	0,4917

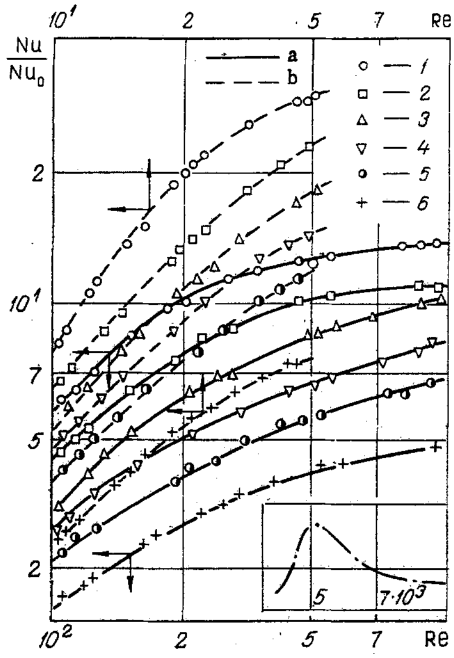

Fig. 2. Dependence of relative increase in heat transfer on Reynolds number for the anomalously viscous liquids investigated: a) 3.8% Na-CMC; b) 7%; 1) S/D = 3.1; 2) 4.17; 3) 9.6; 4) 12.5; 5) 18.75; 6) 28.3; dashed line) analysis of results of [5] with S/D = 3.16.

section of the channel formed by the pipe wall and the surface of the insert. Since heat exchange during the flow of anomalously viscous liquids having a high thermal resistance and high values of the Prandtl numbers ($Pr \gg 1$) is distinguished by low values of the coefficients of heat transfer, the perturbations of the flow caused by the action of centrifugal forces lead to a sharp relative increase in the coefficients of heat transfer. And while the intensity of heat transfer in smooth pipes decreases with an increase in the Prandtl number, under the conditions of rotational – translational motion of an anomalously viscous liquid the opposite picture is observed: an increase in the intensity of heat transfer.

In examining the influence of the pitch of the helical insert on the relative increase in the coefficients of heat transfer it is seen that the ratio Nu/Nu_0 increases with a decrease in the relative pitch S/D. With an increase in the Reynolds number the maximum of the relative increase in heat transfer is shifted toward a decrease in the pitch of the ribbon swirler.

Since the use of heat-exchange intensifiers is accompanied by an increase in hydraulic resistance, it is very important to estimate the efficiency of a helical insert by determining its preferable geometrical dimensions and regions of application.

For the estimate of the overall thermohydrodynamic efficiency of a ribbon swirler the results of the tests with anomalously viscous liquids were analyzed in the form of the dependence

$$(Nu/Nu_0)/(\xi/\xi_0) = f\,(Re). \tag{3}$$

Equation (3) characterizes the relative increase in the intensity of heat exchange in a pipe containing a swirler per unit additional energy expended on pumping the liquid. The efficiency estimate using (3) is a development of the well-known method of Kalinin [11] for comparing objects with the same determining sizes, which he used for estimating rough channels. The dependence (3) makes it possible to determine the most preferable region of application of an intensifier with respect to Reynolds number, to determine the optimum geometrical characteristics, and to estimate the efficiency at different average temperatures of the working medium. The results of the tests with model anomalous liquids treated in the form of (3) are presented in Fig. 3. Here the values of Nu and Re were also reduced to the same Reynolds numbers for a smooth pipe.

An analysis of the dependences of Fig. 3 shows that the thermohydrodynamic efficiency of the use of ribbon swirlers to intensify convective heat exchange in anomalously viscous media increases sharply with an increase in the effective viscosity of the liquid, and under these experimental conditions the excess of the heat-transfer intensity over the hydraulic losses reaches 6.5 times. And, as follows from these tests, with a further increase in the effective viscosity the relative increase in heat transfer and thermohydrodynamic efficiency will continue.

In examining the influence of the pitch of a ribbon swirler on the overall thermohydrodynamic efficiency of its application to anomalously viscous media it is seen that the thermohydrodynamic efficiency increases

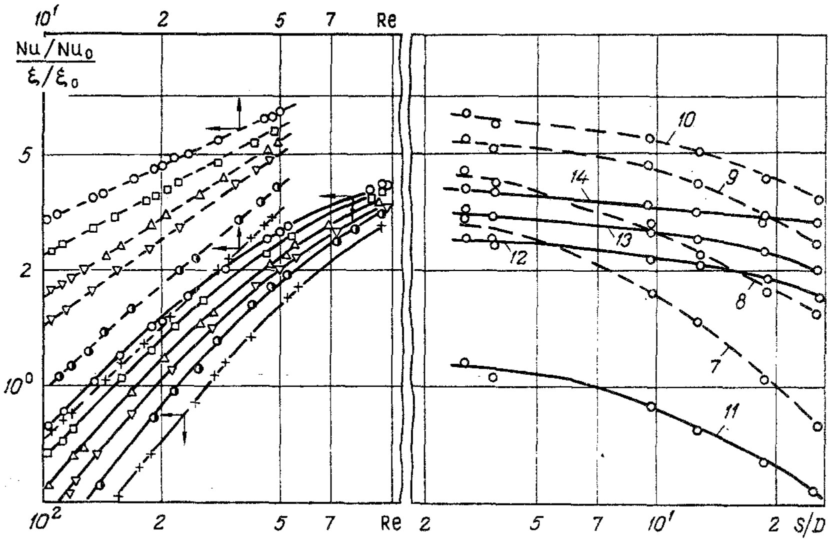

Fig. 3. Dependence of thermohydrodynamic efficiency of ribbon swirlers on the Reynolds number and the relative pitch of the swirler: 7) Re = 10; 8) 20; 9) 40; 10) 50; 11) 180; 12) 500; 13) 700; 14) 1000. Remaining notation analogous to that of Fig. 2.

with a decrease in the pitch. With an increase in the relative pitch of a twisted ribbon the influence of centrifugal forces decreases and the intensity of the relative increase in heat transfer becomes less than the increase in hydraulic losses. In this case the overall thermohydrodynamic efficiency decreases, even for the case of $(Nu/Nu_0)/(\xi/\xi_0) < 1$. On the basis of the presentation it follows that the range of relative pitch of a twisted ribbon of S/D < 6-7 can be considered as optimum. A stable, positive, thermohydrodynamic efficiency was obtained in this range of intensifier geometry, regardless of the Reynolds number or the value of the effective viscosity of the model liquids.

By making a combined analysis of the influence of the geometry of the intensifiers and the Reynolds number in the flow of the two model anomalously viscous liquids (3.8 and 7% Na-CMC) on the thermohydrodynamic efficiency, one can conclude that the influence of the pitch weakens with an increase in the Reynolds number. In this case the hydrodynamic conditions of flow start to have the prevailing effect on the intensity of heat transfer and thermohydrodynamic efficiency, and the influence of the geometry decreases.

NOTATION

Nu and ξ, Nusselt number and coefficient of hydraulic resistance in a pipe containing a swirler; Nu_0 and ξ_0, Nusselt number and coefficient of hydraulic resistance in a smooth pipe; Re, Reynolds number; Pr, Prandtl number; $\bar{\alpha}$, average heat-transfer coefficient; Q, amount of heat; F, area of heat-transfer surface; $\Delta\bar{t}_{log}$, logarithmic-mean temperature head; l_i, distance between points of attachment of thermocouples; k, number of thermocouples; t_i, t_{i+1}, readings of thermocouples; μ, effective viscosity; τ, shear stress; $\dot{\gamma}$, shear velocity gradient; D, inner diameter of pipe; S, pitch of twisted ribbon in a rotation by 180°.

LITERATURE CITED

1. V. K. Shchukin, Heat Exchange and Hydrodynamics of Internal Flows in Mass Force Fields [in Russian], Mashinostroenie, Moscow (1970).
2. E. Smithberg and F. Landis, J. Heat Transfer, 86, No. 1, 39 (1964).
3. M. Kh. Ibragimov, E. V. Nomofilov, and V. I. Subbotin, Teploenergetika, No. 7 (1961).
4. A. Klaczak, J. Heat Transfer, 95, No. 4, 557 (1973).
5. V. K. Ermolin, Inzh.-Fiz. Zh., 3, No. 11 (1960).
6. V. K. Shchukin, Izv. Vyssh. Uchebn. Zaved., Aviats. Tekh., No. 2 (1967).
7. A. W. Date, Heat Vent. Eng. J. Air Cond., 47, No. 556 (1973).
8. Yu. G. Nazmeev, K. D. Vachagin, and M. M. Galimardanov, Inzh.-Fiz. Zh., 32, No. 1 (1977).
9. O. A. Kraeva, Zavod. Lab., No. 2 (1960).
10. G. M. Kondrat'ev, Thermal Measurements [in Russian], Mashgiz, Moscow–Leningrad (1957).
11. É. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, The Intensification of Heat Exchange in Channels [in Russian], Mashinostroenie, Moscow (1972).