REDUCTION OF TURBULENT HEAT TRANSFER IN TUBE FLOWS OF LOW-CONCENTRATION POLYMER SOLUTIONS

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The reduction of turbulent friction [1] when a liquid containing small amounts of certain soluble polymers flows along a smooth surface is associated with a reduction of the intensity of the transverse turbulent fluctuations in a layer directly adjacent to the surface. Measurements of the velocity profiles show that adding polymers considerably increases the thickness of the viscous sublayer [2]. This effect is associated with the formation in the solutions of large associations of polymer macromolecules and solvent molecules, which affect the development of turbulent eddies [3, 4].

The reduced level of turbulent mixing near the wall due to the addition of a polymer should lead not only to a reduction in momentum transfer but also to a reduction in turbulent heat transfer. Gupta et al. [5] report reduced heat transfer from the wall of a tube carrying polyacrylamide solutions. In the paper we investigate the heating of guar gum solutions flowing through a tube.

The experiments were conducted on the apparatus shown schematically in Fig. 1. Depending on the experiment, water of aqueous solutions of guar gum were driven by a pump 4 through a flow-regulating valve 3 into a calibrated copper tube 1, 7.82 mm in diameter and 240 cm long, part of which was enclosed in a steel jacket 2. A temperature drop between the wall of the copper tube and the liquid flowing through it was maintained by circulating through the jacket water heated to 60–90° C. The jacket extended for 165 cm along the tube. The pressure drop was measured on a section 182 cm long. The length of the entrance section was approximately equal to 65 diameters. The pressure drop was measured with a differential manometer 8 filled with mercury or carbon tetrachloride, depending on the magnitude of the drop. The liquid temperature rise was determined by means of thermometers 10 in thermally insulated mountings 9 at the beginning and end of the tube. The temperature of the water at the inlet and outlet of the heat-exchanger jacket was also recorded. The heat exchanger and the tube were insulated on the outside. In this way it was possible to determine the amount of heat transferred in the heat exchanger to the liquid flowing through the tube.

The temperature of the tube wall was determined with copper-constantan thermocouples 11 located 8 cm from the junctions of the jacket and the tube. The thermocouple emf's were measured with a UPIP-60M potentiometer.

After leaving the measuring section the liquid entered a cooler 5, which made it possible to maintain a constant liquid temperature at the measuring section inlet. The liquid flow rate was measured with an orifice plate 6 fitted with a differential manometer 7. This plate had an orifice 14 mm in diameter and was mounted in a tube with an inside diameter of 20 mm. Volume calibration of the plate showed that the pressure drop across it was somewhat lower for guar gum solutions than for ordinary liquid. The reduction was 6–8% at a solution concentration of $3 \cdot 10^{-4}$ by weight. (A similar reduction is also observed in connection with polyoxyethylene solutions [6].) Small values of the flow rate were measured volumetrically.

The experiments were performed on water and aqueous solutions of guar gum. The dry gum was mixed with distilled water at room temperature, after which the solution was kept for 2–3 days. Values of the dynamic coefficients of viscosity η are plotted in Fig. 2 as a function of the concentration C and temperature of the solution. The viscosity was determined with an Ostwald viscometer, capillary diameter 1.16 mm. At these concentrations the density of the solutions was practically the same as the density of the water.

Values of the resistance coefficient λ for water and guar gum solutions are shown in Fig. 3 as a function of the Reynolds number $R = wd\rho/\eta$. The resistance coefficient λ was determined from the relation

$$\Delta p = \lambda \frac{l}{d} \frac{\rho w^2}{2}.$$

In these equations w is the mean velocity of the liquid in the tube, d is the tube diameter, η is the dynamic coefficient of viscosity, ρ is the liquid density, and l is the length of the tube section on which the pressure drop Δp was measured. In Fig. 3 points 1 relate to water, and points 2, 3, and 4 to guar gum solutions at concentrations of $1.5 \cdot 10^{-4}$, $3 \cdot 10^{-4}$ and $5 \cdot 10^{-4}$, respectively. As follows from the data of Fig. 3, in the turbulent flow regime at low values of the Reynolds number the shear stresses at the tube wall are the same for the ordinary liquid and for guar gum solutions. They differ only at quite high Reynolds numbers, the drag reduction for the polymer solution being the greater, the higher the value of that number. As the concentration of the guar gum solution increases from zero to $3 \cdot 10^{-4}$, the drag reduction effect increases; however, a further increase in concentration produces practically no change in the effect. This is in good agreement with the experimental data already published.

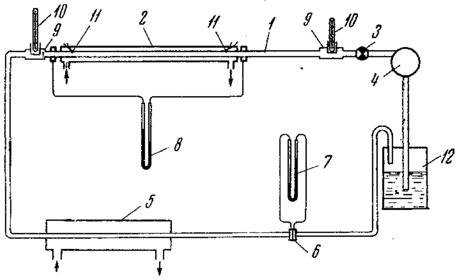

Fig. 1

The heat transfer coefficient α was determined from the relation $\alpha s \Delta t = q$, where s is the area of the heated surface of the tube, Δt is the mean temperature difference between the wall of the tube and the liquid flowing through it, and q is the amount of heat transferred to the liquid per unit time. The quantity q was determined from the temperature rise and the flow rate of the liquid. In view of the low concentrations of the polymer solutions it was possible to take their specific heat equal to that of water.

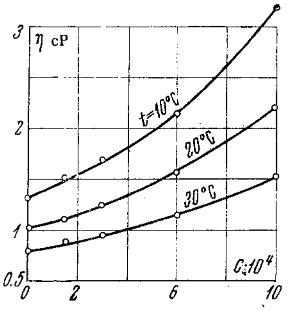

Fig. 2

In the experiments we observed a reduction of the heat transfer coefficient analogous to the reduction of the resistance coefficient. Like the hydrodynamic resistance, the heat transfer to water and guar gum solutions is the same at small Reynolds numbers in the turbulent flow regime. This indicates, in particular, that the thermal conductivities μ of dilute guar gum solutions and water practically coincide.

The heat transfer data are presented in Fig. 4 in dimensionless coordinates, using the same notation as in Fig. 3. Along the axis of abscissas we have plotted the Reynolds number, along the ordinate axis the complex $N^* = NP^{-0.43}(P/P_1)^{-0.25}$, where $N = \alpha d/\mu$ is the Nusselt number, and $P = \eta c_p/\mu$ the Prandtl number; the subscript 1 means that the Prandtl number was calculated from the mean wall temperature. As with the quantities entering into the Prandtl number without a subscript, in calculating the number N the thermal conductivity μ was taken at the mean temperature of the liquid [7].

Like the hydrodynamic resistance, the turbulent heat transfer is reduced when a polymer is dissolved in the water. As the concentration of the solution increases from zero to $3 \cdot 10^{-4}$, the heat transfer falls. A further increase in concentration has almost no effect on heat transfer. The data on this limiting value of the heat transfer for guar gum solutions lie approximately on a straight line parallel to the straight line $0.17 R^{0.33}$, which corresponds to the heat transfer in a perfectly laminar flow. The relative reduction is approximately the same for the heat transfer and the hydrodynamic resistance. At $R = 5 \cdot 10^4$ and a solution concentration of $3 \cdot 10^{-4}$ or above a quadruple reduction of heat transfer is observed.

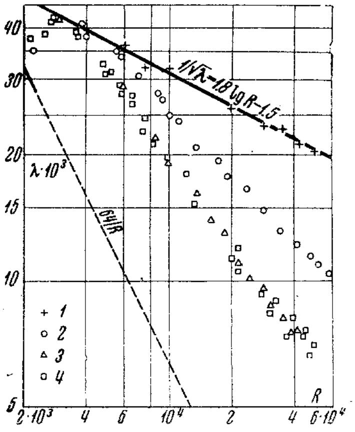
40
30
20
15
10
5
$\lambda \cdot 10^3$
$1/\sqrt{\lambda} = 1.8 \lg R - 1.5$
64/R
+ 1
○ 2
△ 3
□ 4
R
$2 \cdot 10^3$
4
6
10^4
2
4
$6 \cdot 10^4$

Fig. 3

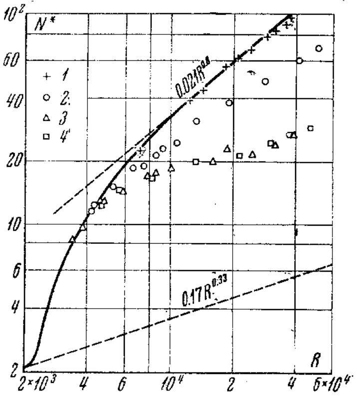
10^2
N^*
60
40
20
10
6
4
2
+ 1
○ 2
△ 3
□ 4
$0.021R^{0.8}$
$0.17R^{0.33}$
R
2×10^3
4
6
10^4
2
4
6×10^4

Fig. 4

In conclusion the authors thank G. I. Barenblatt for his interest in their work.

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