forces on the formation of a turbulent boundary layer along a vertical wall. The computer program written by the author on the basis of the modified model produced results which are in satisfactory agreement with experiment. The calculated results for the boundary layer demonstrate the limited applicability of the Boussinesq hypothesis on the turbulent viscosity for flow in the presence of buoyancy forces.

NOTATION

$k = 0.5\overline{u_i'u_j'}$, turbulent energy; ε, rate of dissipation of turbulent energy; U_i, average velocity in the i-th direction; u_i', fluctuation component of the velocity in the i-th direction; U_e, velocity of the approach stream; T, average temperature; t', fluctuation component of the temperature; $Re = U_e x/\nu$, Reynolds number; $Re_t = \sqrt{kL}/\nu$, turbulent Reynolds number; $Gr^* = g\beta q_w x^4/\lambda\nu^2$, modified Grashof number; $Nu = \alpha x/\lambda$, Nusselt number; Nu_f, Nusselt number for forced flow; $Pr = \nu/a$, Prandtl number; $Pr_t = \nu_t/a_t$, turbulent Prandtl number; Pr_{tf}, turbulent Prandtl number for forced flow; δ_{ij}, Kronecker–Kapelli delta.

LITERATURE CITED

1. M. M. Gibson and B. E. Launder, Teploperedacha, No. 1, 86-93 (1976).
2. M. M. Gibson and B. E. Launder, J. Fluid Mech., 86, 491-532 (1978).
3. B. E. Launder, J. Fluid Mech., 67, 569-581 (1975).
4. M. M. Pimenta, R. J. Moffart, and M. M. Kays, Rep. HMT-21, Mech. Eng. Dept., Stanford Univ. (1975).
5. Yu. P. Semenov, MLTI, No. 175, 114-123 (1985).
6. M. Miamoto, H. Kajino, J. Kurima, and I. Takanami, Heat Transfer 1982, Proc. 7th Int. Heat Transfer Conf., Paper No. 34, Munich (1982).

EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER AND HYDRODYNAMICS IN STEADY AND PULSATING LAMINAR FLOW OF A NONLINEARLY VISCOUS FLUID IN A TUBE WITH A HELICAL TAPE INSERT

Yu. G. Nazmeev, A. G. Yakupov, and A. M. Konakhin

UDC 536.242.0015

The steady and pulsating laminar flow of a non-Newtonian fluid in a helical duct is investigated experimentally.

The laminar flow of viscous fluids is frequently encountered in equipment used in the chemical and petrochemical industries. Heat transfer is limited in such equipment by the low heat-transfer coefficients of viscous fluids flowing in smooth tubes. A well-known and simple technique for the augmentation of convective heat transfer in tubes is the application of twisted-tape inserts. Exhaustive experimental data have now been accumulated on heat transfer in tubes with tape augmenters [1-5]. However, in the study of heat-transfer augmentation methods it is useful to investigate the combined effects of several heat-transfer augmentation techniques.

Several authors (e.g., Fedotkin and Firisyuk [6]) have investigated and analyzed a number of possible combinations of augmentation methods, mainly of a design nature, and then in application to viscous Newtonian fluids. Considerable attention has been given to the study of phenomena associated with the unsteady (fluctuating) flow of non-Newtonian fluids and their influence on heat transfer and hydraulic friction [7, 8].

The objective of the present study is to investigate the influence of the superposition of pulsations onto a nonlinearly viscous fluid flow on heat transfer and hydraulic friction

Branch of the Moscow Power Institute, Kazan.

Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 62, No. 2, pp. 211-216, February, 1992. Original article submitted June 13, 1991.

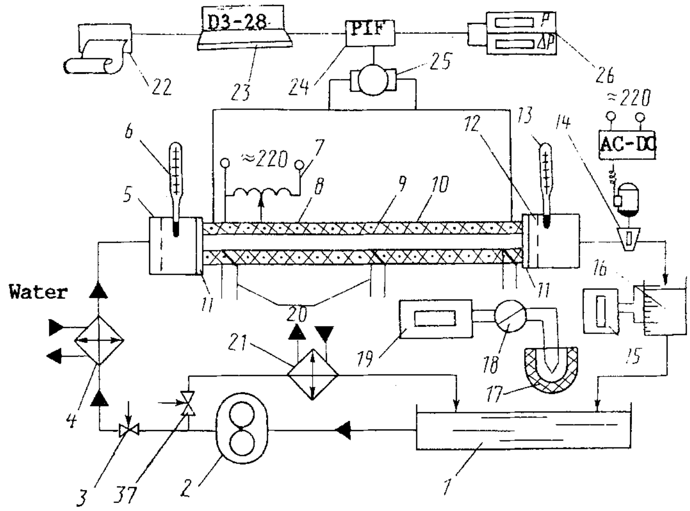

Fig. 1. Experimental apparatus. 1) Collecting tank; 2) pump; 3) control valve; 4, 21) heat exchangers; 5, 12) inlet and outlet quieting chambers; 6, 13) laboratory thermometers; 7) power supply; 8) electric heaters; 9) heat-transfer tube; 10) thermal insulation; 11) measurement thermopiles; 14) pulsator; 15) STTs-1 electronic timer; 16) flowmeter; 17) Dewar flask; 18) thermocouple switch; 19) V7-21 digital voltmeter; 20) thermocouples; 22) printer; 23) D3-28 microcomputer; 24) physical (analog-to-digital, data channel—computer) interface (PIF); 25) pressure transducer; 26) F-30 voltammeter.

during flow in a tube with helical inserts. The flow region is laminar. The working medium is a 7% aqueous solution of sodium carboxymethyl cellulose (Na-CMC). The experiments were carried out on the experimental apparatus shown in Fig. 1.

The apparatus consisted of a closed circulation loop for the working fluid. The gear pump 2 transferred the fluid from the collecting tank 1 to the heat exchanger 4 for cooling and thermostatting and then to the inlet quieting chamber 5 for the suppression of any possible turbulence. The fluid was then transferred into the heat-transfer tube 9, the interior of which was fitted with helically twisted tapes of various geometries. The fluid left the working section through the outlet quieting chamber 12 and flowmeter 16 and was returned to the tank 1.

The tests were carried out with heating of the fluid; the tube was heated by means of the cascaded sectional electric heaters 8. Each section had an autonomous regulated power supply 7. The current and voltage were monitored by control-panel electrical instruments. Uniform Dirichlet-type boundary conditions were established at the wall of the heat-transfer tube by regulating the current in each section. The wall temperature of the tube was monitored and regulated by means of a system of chromel—copel thermocouples. The diameter of the thermocouple wire was 0.15 mm. Five thermocouples were set up along the working section. The thermocouple junctions were soldered into recesses in the tube wall by Wood's alloy. The sites of the thermocouple junctions were isolated from the rest of the tube by thermal chokes. The latter consisted of small annular ducts running from the outer surface of the tube to a depth of approximately half the wall thickness. The chokes were used to diminish the influence of stray heat input from the heating elements on the thermocouple readings.

Pulsating flow was imparted to the working fluid in the heat-transfer tube by the pulsator 14, which was driven by a dc motor through a reduction gear. The apparatus was capable of generating continuous pulsating fluid flow with a frequency of 0.1-2 Hz.

A special apparatus for the measurement and automatic recording of differential pressures was provided to measure the hydraulic friction in the heat-transfer tube with pulsating fluid flow. It consisted of an MPÉ-MI magnetic-flux-compensating measurement transducer, a Sapfir-22DD pressure-sensing measurement transducer, a D3-28 microcomputer, two F-30 voltammeters, and an ATsSKS-1024-001 physical interface (PIF). This apparatus made it possible

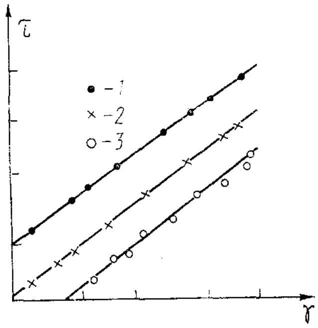

Fig. 2

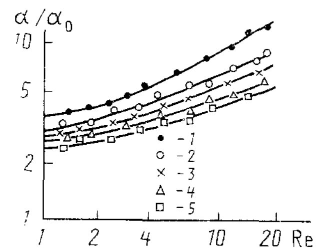

Fig. 3

Fig. 2. Results of viscometric measurements in Na-CMC, τ (Pa) vs γ (sec^{-1}). 1) 20°C; 2) 40°C; 3) 60°C.

Fig. 3. Relative increase in heat transfer vs Reynolds number for the investigated fluid in steady flow. 1) S/D = 3.57; 2) 7.14; 3) 10.7; 4) 14.2; 5) 21.4.

to measure the pressure at the inlet to the working section and the differential pressure at a rate of 16 measurements per second and to average and record the measurement results.

Thermopiles were installed at the inlet and outlet of the heat-transfer tube to measure the temperature of the fluid at those stations. The pile consisted of eight series-connected, equal-area thermocouples mounted vertically along the diameter of the tube.

The thermoelectromotive force of all the thermocouples were measured by a V7-21 general-purpose digital electronic voltmeter within ±0.001 mV error limits. The average fluid flow was determined with a volumetric flowmeter. The time for the measurement volume to fill up was measured automatically by an STTs-1 timer within ±0.01 sec error limits.

The working section of the apparatus consisted of a brass-L62 tube with an inside diameter of 14 mm, wall thickness of 1 mm, and a length of 1200 mm. Tests were conducted with helical inserts of twisted steel tape having a thickness of 0.5 mm; the pitch of the swirling tapes (i.e., the length of one twist of the tape through 180°) was equal to 50, 100, 150, 200, and 300 mm.

The rheological characteristics of the model fluid were determined on a PIRSP-03 rotating viscometer. The results of the viscometric measurements in the temperature range 20-60°C are shown in Fig. 2. In processing the experimental results, the thermophysical properties of the liquid were evaluated at the average temperature between the inlet and outlet of the tube.

The average hydraulic friction of the duct in pulsating flow was determined from the functional relation

$$\Delta\bar{P} = \sum_{1}^{N} \Delta P_i/(N-1).$$

To assess the influence of pulsations on the heat transfer and hydraulic friction, investigations were carried out for steady and pulsating flows of a non-Newtonian fluid in a tube with helical tapes of various geometries.

In the investigations, the Reynolds number Re was varied from 0.6 to 20, where the velocity used in the number Re was determined from the useful cross section of the duct [9]. The reference length was the equivalent diameter of the duct. For the tube with tape inserts d_e was determined from an equation in [1], and for a smooth tube d_e = D.

The Reynolds number was determined from the expression $Re = vd_e\rho/\mu_0$.

Steady Flow. The results of the heat-transfer experiments in steady flow were processed in the form of the function $\alpha/\alpha_0 = f(Re)$ (Fig. 3). A comparison of the results of the investigations with the data of other authors [1, 4] indicates close agreement between them. Greater augmentation of heat transfer was observed under the conditions of the reported tests.

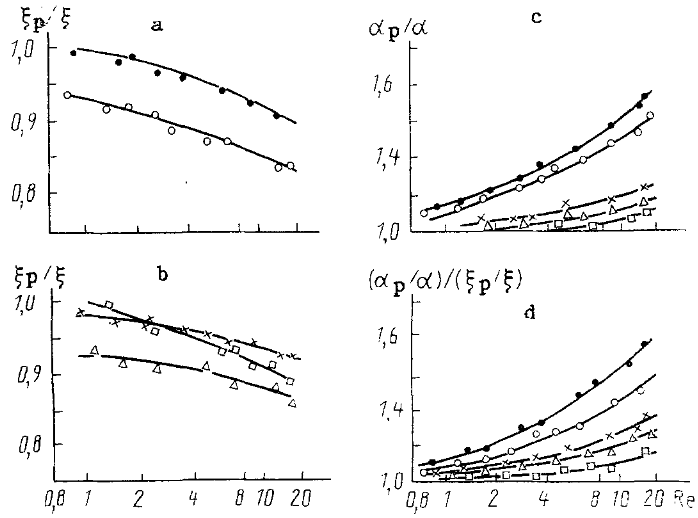

Fig. 4. Relative variations of hydraulic friction, heat transfer, and thermohydrodynamic efficiency in pulsating flow of Na-CMC. The numbering of the curves has the same meaning as in Fig. 3.

The centrifugal forces generated by the reciprocating motion of the anomalously viscous fluid creates a disturbance in the flow over the entire cross section of the duct. This effect produces an abrupt relative increase of the heat-transfer coefficients in the presence of thermal resistance and high Prandtl numbers ($Pr \gg 1$), as has been noted by other authors [1, 2, 4, 5].

We have established the fact that the ratio of the relative heat-transfer rate to the relative hydraulic losses attains values from 1.2 to 6.2, depending on the pitch of the helical tape and the values of Re. The thermohydrodynamic efficiency increases as the pitch of the twisted tape is decreased; this result is confirmed by data in other papers [1, 4].

Pulsating Flow. The objective of the present study is to investigate the combined effect of two heat-transfer augmentation techniques in the flow of a non-Newtonian structurally viscous fluid.

An analysis of the results shows that the degree of heat-transfer augmentation depends on Re and on the pitch of the helically twisted tapes. For a relative pitch $S/D = 3.57$ and $Re \leq 4$ the heat-transfer rate does not increase above the steady-flow regime, but for tapes with a large pitch ($S/D = 10.7$, 14.2, 21.4) the augmentation ratio attains 1.05-1.6 over the entire range of numbers $Re > 1$, depending on S/D (Fig. 4c). Such a small degree of augmentation is probably attributable to the fact that the twisted tape exerts a stabilizing influence on the flow, suppressing fluctuations.

As Re increases, the augmentation ratio increases for all tape geometries. A non-Newtonian fluid is characterized by the fact that when pulsations are superimposed on the flow, the hydraulic friction becomes lower than in steady flow (Figs. 4a and 4b). This result can be explained by the intrinsic nature of a non-Newtonian structurally viscous fluid, which has an anomalous dependence of the viscosity on the tangential shear stress intensity. A pulsating variation of the flow velocity causes the rate of shear to increase and the effective viscosity of the fluid to decrease. This phenomenon has been noted previously by Shul'man et al. [7, 8].

It follows from the graphs in Figs. 4a and 4b that the hydraulic friction coefficients decrease by 2-18% in comparison with steady flow, depending on the pitch of the helically twisted tape and the number Re. The maximum reduction of ξ_p relative to ξ is observed for tape with a pitch $S = 50$ mm ($S/D = 3.57$).

The results of the investigations show that the heat-transfer efficiency and the hydraulic friction in pulsating flow depends very little on the pulsation frequency in the investigated frequency range. However, they change from the steady regime. The experimental points are clustered around the best-fit curve within the experimental error limits, independently of the frequency. To estimate the tital thermohydrodynamic efficiency of pulsating flow in tubes with swirling tapes, we processed the results of the tests with an anomalously viscous fluid in the form of the functional relation [4, 10]

$$(Nu_p/Nu)/(\xi_p/\xi) = f(Re).$$

This expression characterizes the relative increase of the heat-transfer rate in a swirled-flow tube with pulsating flow per unit additional energy spent to pump the fluid through the system. The given relation can be used to determine the best area of application of a heat-transfer augmenter in terms of the Reynolds number, to ascertain the optimal geometrical characteristics, and to estimate the efficiency for various average temperatures of the working medium.

An estimation of the thermohydrodynamic efficiency of pulsating flow of a non-Newtonian fluid in comparison with steady swirled flow shows that the best rests in the interval of Reynolds numbers from 0.6 to 20 are afforded by tubes with tape inserts having pitches S/D = 14.3 and 21.4 (Fig. 4d): $(Nu_p/Nu)/(\xi_p/\xi) = 1.15\text{-}1.76$. This indicates that the rate of increase of the heat-transfer rate prevails over the rate of increase of the hydraulic friction. The same trend is observed for all the investigated tapes.

It should be noted that the superposition of pulsations on swirled fluid flow has a stronger influence on the thermohydrodynamic efficiency for non-Newtonian than for Newtonian fluid flow.

This study has been of an exploratory character with a view toward determining the effects of pulsations in helical ducts on heat transfer and hydraulic friction. We have established that an improved thermohydrodynamic efficiency of pulsating flow in tubes with swirling tapes is observed at relatively low Reynolds numbers: Re = 3-20 (Fig. 4d). This interval of Re was our main focus of attention.

An analysis of the total energy efficiency shows that the superposition of pulsations on a non-Newtonian fluid flow in a helical duct lowers the energy expenditures by as much as 70% in comparison with steady flow, depending on the values of Re and the duct geometry.

On the basis of the reported experiments, therefore, we can recommend the combined application of two augmenters – helical swirling tapes with the superposition of pulsations on the flow – for the augmentation of convective heat transfer in non-Newtonian structurally viscous media with large effective viscosities.

The investigations will be continued in order to study the influence of the pulsation frequency on the thermal and hydraulic flow characteristics.

NOTATION

Nu, ξ, Nusselt number and hydraulic friction coefficient in the tube with swirling tape; Nu_p, ξ_p, Nusselt number and hydraulic friction coefficient in the tube with swirling tape and pulsating flow; Re, Reynolds number; Pr, Prandtl number; α_0, $\bar{\alpha}$, average heat-transfer coefficient in the smooth tube and in the tube with swirling tape; $\Delta\bar{P}$, average hydraulic friction of the duct with pulsating flow, Pa; N, number of measurements; μ, effective viscosity, Pa·sec; D, inside diameter of tube; S, pitch of twisted tape (length of one turn through 180°); v, flow velocity calculated over the effective duct cross section, m/sec; τ, shear stress; γ, shear velocity gradient; f, oscillation frequency, Hz.

LITERATURE CITED

1. Yu. G. Nazmeev, Inzh.-fiz. Zh., 37, No. 2, 230-244 (1979).
2. A. Bergles, "Augmentation of heat transfer," in: Selected Papers from the International Conference on Heat Transfer [Russian translation], Moscow (1981).
3. A. A. Khalatov, Swirled Flows in Theory and Practice [in Russian], Kiev (1989).
4. Yu. G. Nazmeev and N. A. Nikolaev, Teploénergetika, No. 3 (1980).
5. W. J. Marner and A. E. Bergles, "Augmentation of highly viscous laminar tubeside heat transfer by means of twisted-tape insert and internally finned tube," in: 23rd ASME National Heat Transfer Conference, Denver, August 4-7, 1985.
6. I. I. Fedotkin and V. F. Firisyuk, Augmentation of Heat Transfer in Chemical Industrial Equipment [in Russian], Kiev (1971).
7. Z. P. Shul'man, B. M. Khusid, É. A. Zal'tsgendler, and O. R. Dornyak, "Transient processes in fluids with a rigidly comminuted structure in confined flows in long ducts,"

Preprint No. 20 [in Russian], A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk (1989).
8. A. A. Pozdeev and N. V. Shakirov, "What's new in polymer rheology," in: Proceedings of the 12th All-Union Symposium on Rheology [in Russian], Vol. 1, Moscow (1982), pp. 232-233.
9. A. I. Mumladze, Yu. G. Nazmeev, and O. V. Maminov, Izv. Vyssh. Uchebn. Zaved., Neft' Gaz, No. 11, 59-62 (1982).
10. É. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, Augmentation of Heat Transfer in Ducts [in Russian], Moscow (1990).

INTERACTION OF A PLANE SHOCK WAVE IN WATER WITH A THIN LAYER OF LOWER DENSITY

V. I. Bergel'son, I. V. Nemchinov, T. I. Orlova, and V. M. Khazins

UDC 536.6.011

A numerical analysis is conducted on the interaction of a plane shock wave in water with a thin layer of lower density, which is perpendicular to the wave front. Parameters are defined for the perturbed flow structure and for large-scale precursors, which arise ahead of the shock front. Possibilities are discussed of experimentally investigating this phenomena with a cylindrical shock wave using standard explosives.

The "thermal layer" effect occurs when a large-scale wedge-shaped or conical perturbation or "precursor" grows smoothly in time ahead of a shock front, which interacts with a thin flat layer or a cylindrical channel of lower density. Intense vortical motion occurs inside this precursor. As the characteristic dimensions of the precursor increase to values much larger than the thickness of the thermal layer (or channel), the latter stops playing a significant role. Thus, a small (in the limit, infinitely small) extended perturbation of the density leads to a basic and global rearrangement of the flow.

The thermal layer effect was discovered in the 1950s during investigation of a shock wave in gases. Recently it was investigated in some detail, both theoretically and experimentally (see [1] for example, which gives references to previous efforts). It was shown [2] that the same effect can take place in cases when the shock wave propagates in condensed matter. Here a simple equation of state with a constant adiabatic index for the thermal component [3] was used to model the condensed matter. There is interest in investigating the thermal layer effect experimentally. Here we apply the results of [2] to the specific case of an easily compressed material, namely water. We use the tabular equation of state calculated by G. S. Romanov and A. S. Smetannikov using methods similar to those described in [4]. The pressure function $p(e, \rho)$ is shown in Fig. 1. For densities $(\rho/\rho_0) > 1$, a cold component

$$p_c = \frac{\rho_0 c_0^2}{4}\left[(\rho/\rho_0)^{5.122} - (\rho/\rho_0)^{1.122}\right]$$

is added to the magnitude of the pressure, where ρ_0 and $c_0 = 1.5$ km/sec (the contribution of the cold component to the internal energy is also considered simultaneously in the equation of state).

We now present several results of a numerical calculation of the plane piston problem for a Mach number $M = 6.2$ for the basic shock wave, and a relative density $\omega = 0.25$ in the lower-density channel.

Institute of Dynamics of the Geosphere, Russian Academy of Sciences, Moscow. Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 62, No. 2, pp. 217-219, February, 1992. Original article submitted June 17, 1991.