4. A. M. Meirmanov, "Example of the nonexistence of the classical solution of the Stefan problem," Dokl. Akad. Nauk SSSR, 258, No. 3 (1981).

DEVELOPMENT OF A TEMPERATURE FIELD IN A TURBULENT FLOW WITH UNSTEADY HEAT TRANSFER

B. V. Perepelitsa and Yu. M. Pshenichnikov

UDC 536.24

Heat-transfer processes occurring under unsteady conditions are encoutnered fairly often in different areas of modern technology. The theory of unsteady heat transfer in turbulent flows is still far from complete, which has to do with the serious difficulties encountered in attempting to mathematically describe the processes. Calculation of these processes is also considerably complicated by the need to solve a coupled problem, since processes of heat transfer in the heat carrier are inextricably allied with the development of a temperature field in the walls of the channel [1, 2].

The experimental study of unsteady heat transfer in turbulent flows is a rather complicated technical problem, due both to the effect of a large number of parameters on the character of the process and to the need to rapidly collect and analyze a large volume of information. Measurements show that the effect of transience on heat transfer may be substantial [2-4]. At the same time, calculations with models which include the hypothesis of a quasisteady structure for the turbulent flow do not always yield satisfactory results [5]. In connection with this, a deeper understanding of the processes taking place in unsteady heat transfer requires sufficiently complete and reliable information on the velocity and temperature fields in the immediate vicinity of the wall, including the region of the viscous and thermal sublayers.

Here we report results of measurement of the development of the temperature field in a turbulent flow of water with a sudden change in heat release in the channel wall. The measurements were made in the Reynolds number range from 11,200 to 112,000 and embrace the region near the wall, including the viscous sublayer. The tests were conducted on a closed hydrodynamic loop which included a constant-level tank, working section, receiving tank, cooler, and pump. The working section (Fig. 1) was a channel 1 of rectangular cross section measuring 20 × 40 mm and consisting of a hydrodynamic stabilization section 96 diameters long and a heating section 3 which was 36 diameters long. Three of the walls of the heated section were made of organic glass, while the remaining wall (40 mm wide) was made of stainless steel 0.1 mm thick. The steel wall was stuck onto a glass–textolite base. The strip was washed by the flow of working fluid and heated by the passage of an electrical current through it.

The temperature in the flow was recorded with a specially made thermocouple probe 2 of the needle type. The transverse dimension of the hot junction was about 5 μm. The probe was inserted into the flow through the top, unheated wall of the channel 78 cm from the beginning of the heating section. Temperature in the flow was measured relative to the temperature of the cold wall in the test section. This kept the test results from being affected by small fluctuations n the temperature of the working liquid during the tests. The temperature drop between the hot and cold walls of the channel was no greater than 10 K. The absolute error of the measurements of instantaneous temperature was ±0.07 K. More details concerning the design of the probe and the set-up of the experimental unit are available in [6].

The test unit was supplied with heat from a dc generator. The process of unsteady heat transfer caused a sudden change in the amount of electric power supplied to the strip heater, which in turn led to a sharp change in heat release. Results of measurements of static characteristics of temperature pulsations in a turbulent flow during steady heat transfer were published in [7].

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 84-88, July-August, 1986. Original article submitted May 23, 1985.

0021-8944/86/2704-0554$12.50

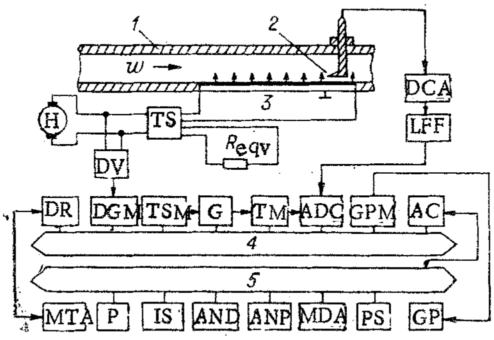

Fig. 1

The experiment was controlled and the experimental data was collected and analyzed with the "MERA-60" microcomputer system. This system is based on an "Elektronika-60" microcomputer. The system (Fig. 1) contains a processor (P), internal store (IS), alphanumeric display (AND), alphanumeric printer (ANP), accumulator on flexible magnetic disks (MDA), perforated-tape station (PS), and a CAMAC adapter 4 connected with the channel of the microcomputer 5 through an adapter—controller (AC). The presence of the CAMAC adapter in the system makes it possible to use standard program-control modules to link transducers with the microcomputer.

Program control of the channel heater was accomplished through the thyristor-switch module (TSM). The thyristor switch (TS) switches the generator current from the heater to an additional equivalent resistance R_{eqv} and back. The rated switching voltage of the generator is 5-100 V, and the current is 1-150 A. The duration of transients during the power switch is no greater than 0.5 msec. The voltage fed to the heater is monitored by a digital voltmeter (DV) connected with the trunk of the CAMAC through a digital module (DGM).

The signal from the thermocouple probe is sent to a dc amplifier (DCA) with a galvanically separated input and output. The level of the noise reaching the input does not exceed 1.5 V. The working frequency band is bounded above by the parameters of the DCA (400 Hz) and an adjustable low-frequency filter (PFF). A voltage proportional to the local heating of the working liquid travels from the output of the LFF to an analog—digital converter (ADC). The converter is started by pulses from a timer (TM) which divides the frequency of a stable generator (G) and starts the ADC at the moments required by the computer. For more accurate coupling of the ADC and the phases of the test signals, the frequency generator is synchronized with the heater switching pulses.

The test data was stored on an ES 9002 magnetic tape accumulator (MTA) connected to the trunk of the CAMAC through a data register module (DR). A graph plotter module (GPM) connected an N-306 graph plotter (GP) to the adapter to allow the results to be displayed in the form of graphs.

The heating and cooling times were chosen for each flow regime so that the temperature would reach a steady-state value. The period of startup of the ADC was changed by the program during the heating (cooling) phase so as to reveal the most characteristic sections of transient processes at the minimum of the counts. The trigger period of the ADC was one order less at the initial stage of heating than at the concluding stage. The equipment made it possible to start the ADC with a minimum period of 2 msec. Time was counted from the moment of application and removal of the thermal load.

During the experiment, we periodically connected and disconnected the heater, and at prescribed moments of time (40 values for the heating and cooling phases) we measured instantaneous values of temperature in the flow. These values were recorded in the computer store. After 100 heating periods, the initial file of instantaneous temperatures was moved fro the internal store to magnetic tape, and the data storage cycle was repeated.

The initial files of instantaneous temperature (N = 16,000) were used to calculate mean values of the intensity of temperature pulsations at different moments of heating and cooling of the working liquid. The confidence intervals associated with the error of mean temperature, with a confidence level of 95%, were no larger than ±0.05 K.

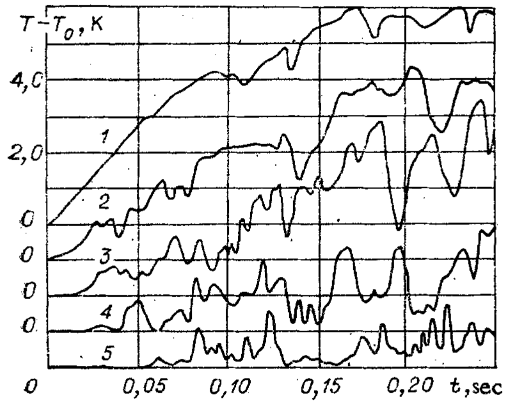

Fig. 2

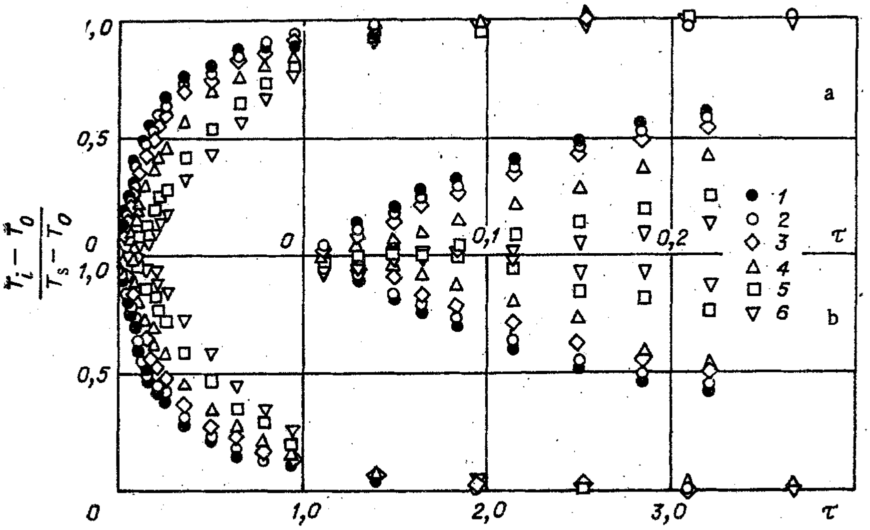

Fig. 3

Figure 2 shows characteristic oscillograms of the development of instantaneous temperature during the initial stage of heating of the liquid at different distances from the wall with Re = 29,100. Here, T is the instantaneous temperature at the test point and T_0 is the temperature of the incoming flow. Curves 1-5 correspond to the coordinates y = 20; 45; 80; 130; 300 μm. The Reynolds number was determined as Re = wD_h/ν (w is the mean-flow-rate velocity, D_h is the hydraulic diameter of the channel, and ν is the kinematic viscosity of the liquid). The initial temperature of the water (T_0 = 291-297 K) was taken as the determining temperature when we calculated the physical properties of the liquid. It can be seen from the graph that there is asharp, almost linear increase in temperature near the wall at the initial moment of time. The process of heat transfer at this stage is determined mainly by pure heat conduction. However, a deviation in temperature toward lower values is seen early in the development of the temperature field close to the wall zone. Such fluctuations in temperature are caused by the penetration of cold moles of liquids from the external region of the flow to the wall. The opposite pattern is seen with increasing distance from the wall: sharp deviations of temperature take place in the positive direction. These deviations may be regarded as ejections of heated liquid from the wall region.

Figure 3 uses dimensionless coordinates to show the time change in mean temeprature across the channel for Re = 61,000 with application (a) and removal (b) of the thermal load. As the dimensionless temperature, we took the ratio of the current overheating of the incoming $T_i - T_0$ at the given point to its value under steady-state conditions $T_s - t_0$, where T_i is the mean temperature in the flow at the moment t and T_s is the steady-state local temperature in the flow with the heater turned on. As the dimensionless time, we took $\tau = tw/L$ (L is the distance from the beginning of heating to the measured section and t is the current time). POints 1-6 correspond to the dimensionless coordinates $Y^+ = yv_*/\nu$ = 1.1; 1.9; 2.8; 6.8; 20.5; 71.2 (v_* is the dynamic velocity). The test data obtained shows that the change in temperature occurs at a decreasing rate and asymptotically approaches a steady-state

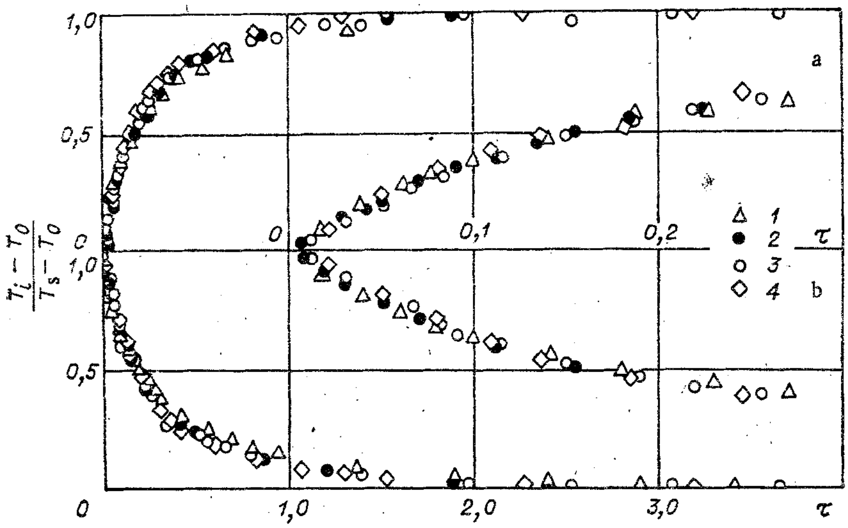

Fig. 4

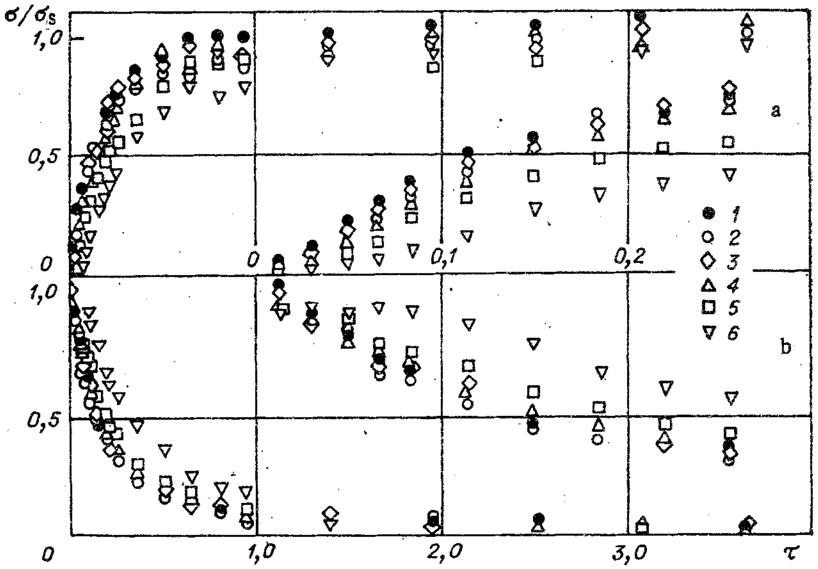

Fig. 5

value. A lower rate of increase in temperature is seen at the initial moment of time with increasing distance from the wall. The temperature subsequently increases, so that by discharge the temperatures are nearly constant over the entire cross section of the channel. The curves depicting the development of relative temperature in the flow at the stages of heating and cooling of the liquid are symmetrical in form. In the region of the viscous sublayer, the path of the temperature curves changes slightly with an increase in distance from the wall. The measurements for the viscous sublayer at different Re (Fig. 4) show that the curves of relative mean temperature in a developed turbulent flow are grouped closely about one line: points 1-4 correspond to Re = 11,200; 29,100; 61,000; 112,000. For the heating phase, the data obtained in the region τ = 0-2 can be approximated by the relation

$$T_i - T_0/T_c - T_0 = \Theta_p = 0{,}94\tau^{(0{,}129-0{,}117\ln\tau)}.$$

This formula was obtained from analysis of 52 experimental values for Re = 29,100; 61,000; 112,000 by the least-squares method. The RMS error of the approximation was 3%. The curves for the cooling phase can be described by the empirical relation

$$T_i - T_0/T_c - T_0 = \Theta_0 = 1 - \Theta_p = 1 - 0{,}94\tau^{(0{,}129-0{,}117\ln\tau)}.$$

At Re = 11,200, the increase in temperature is somewhat slower. For $\tau \lesssim 0.1$, the temperature increase is described by a linear relation $\theta_p = 4\tau$.

Data on the development of the intensity of temperature pulsations at different distances from the wall with Re = 6100 is shown in Fig. 5 (with the same parameters as in Fig. 3).

The RMS value of the temperature pulsations $\sigma = \sqrt{\langle T'^2 \rangle}$ at different phases of heating and cooling of the working liquid are referred to the value of the given quantity under conditions of steady-state heat transfer. The character of development of these relations is similar to that obtained for the data on mean temperature. There is a linear increase in the quantity $\sigma/\sigma_s \approx 4\tau$ at the initial moment of time. The rate of increase subsequently becomes slower than for the mean temperature, so that the steady-state value is attained nearly at $\tau \approx 1$. The measurements of σ/σ_s with different Re in the region of the viscous sublayer are grouped around one line (similar to the data in Fig. 4).

The computed analysis shows that the experimental data obtained on the development of relative temperature and the intensity of temperature pulsations for the viscous sublayer in a turbulent liquid flow can be generalized by means of the dimensionless time scale $\tau = tw/L$. The time $t = L/w$ characterizes the time the liquid is present in the section from the beginning of heating to the measured station. At the initial moment of time, the temperature increase is determined mainly by the mechanism of heat conduction and is negligibly affected by turbulent transport processes.

We thank E. M. Khabakhpashevoi for his discussions and remarks.

LITERATURE CITED

1. A. V. Lykov, Heat and Mass Transfer. Handbook [in Russian], Energiya, Moscow (1978).
2. E. K. Kalinin, G. A. Dreitser, V. V. Kostyuk, and I. I. Berlin, Methods of Calculating Coupled Heat-Transfer Problems [in Russian], Mashinostroenie, Moscow (1983).
3. B. M. Galitseiskii, Yu. A. Ryzhov, and E. V. Yakush, Thermal and Hydrodynamic Processes in Oscillating Flows [in Russian], Mashinostroenie, Moscow (1977).
4. N. M. Belyaev, A. A. Kochubei, A. A. Ryadno, and V. F. Falii, Nonsteady Heat Transfer in Pipes [in Russian], Vishcha Shkola, Kiev—Donetsk (1980).
5. G. A. Dreitser, "Effect of a change in the turbulence structure of a flow on nonsteady heat transfer in the headting of liquids and gases in pipes," Inzh. Fiz. Zh., 43, No. 6 (1982).
6. B. V. Perepelitsa, "Statistical characteristics of temperaure pulsations in a turbulent flow of water," Heat and Mass Transfer — V, Vol. 1, Pt. 1, Minsk (1976).
7. S. S. Kutateladze, E. M. Khabakhpashcheva, and B. V. Perepelitsa, "Temperature pulsations in a viscous sublayer," in: Heat Transfer, 1978. Soviet Investigations, Nauka, Moscow (1980).