23. V. V. Klimenko and S. Yu. Snytin, Teploénergetika, No. 3, 22-23 (1983).
24. G. I. Balashov, I. I. Berlin, V. G. Karavaev, and V. V. Kostyuk, Tr. V.Z.M.I., Vol. 10, No. 3, 148-162 (1974).
25. J. Ruzicka, Bull. de la Inst. Internat. du Froid, Annexe 1958-1, pp. 323-329.
26. V. S. Barsukov, I. I. Berlin, V. V. Kostyuk, and S. I. Tarasov, Tr. V.Z.M.I., No. 9, 50-57 (1980).
27. V. V. Klimenko, A. A. Kurilenko, V. I. Panevin, and V. P. Firsov, Tr. M.É.I., No. 589, 38-43 (1982).
28. V. V. Samsonov and A. V. Gomelauri, Tr. M.É.I., No. 310, 58-61 (1976).
29. V. V. Klimenko, Tr. M.É.I., No. 310, 37-41 (1976).
30. M. E. Ivanov and N. K. Elukhin, Kislorod, No. 3, 19-28 (1958).
31. A. A. Kurilenko, V. A. Semiglazov, V. I. Panevin, et al., Inzh.-Fiz. Zh., 44, No. 3, 421-425 (1983).
32. Khis and Kostello, The Development and Technology of Mechanical Engineering [in Russian], Vol. 88, No. 1, 11-19 (1966).
33. C. R. Class, J. R. de Haan, M. Piccone, and R. B. Cost, Adv. Cryog. Eng., 5, 254-261 (1960).
34. Y. Y. Hsu and J. W. Westwater, A.I.Ch.E. J., 4, 58-62 (1958).

INVESTIGATION OF THE INSTANTANEOUS TEMPERATURE FIELD IN A FLUID STREAM AROUND A HEATED CYLINDER

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UDC 536.24

Temperature fields in a fluid stream are investigated by a pulse holographic interferometry method at low Reynolds numbers.

In the majority of papers [1-3] devoted to investigation of the heat transfer of a cylinder, a method is used to determine the temperature profile in the fluid stream and to measure the heat elimination of the cylinder by using a different kind of sensor which possesses thermal inertia in addition to introducing a perturbation into the stream being studied, causing averaging of the quantities being measured over time. Consequently, it is interesting to investigate the instantaneous values of the temperature in the streaming fluid flow and, particularly, the temperature fluctuations in the thermal boundary layer.

At the present time, experimenters have a method permitting the investigation of the rapidly changing temperature field in a fluid flow. The method of two exposures described in literature devoted to holographic interferometry is used for the investigation. The research is performed by using the installation UIG-12.

A low-power ruby laser with a 1 mm diameter iris, a phototropic shutter that is a solution of vanadium phthalacionine in chlorobenzyl, and a positive long-focus sens installed within the resonator was the source of coherent radiation. The vanadium phthalacionine concentration was selected so that one short pulse would be obtained at the laser output.

Radiation of the master oscillator was incident in a ruby amplifier with a multiplication factor of 5-10.

Holograms of focused images were used for the research. This is associated with two reasons: firstly, application of focused image holograms reduces the requirement on coherence of the light source and permits utilization of light scattered by matte glass resulting in a reduction in the hologram and interferogram diffraction noise; secondly, a white light source can be utilized to restore such a hologram permitting rejection of the interferogram speckle structure. This would afford the possibility of investigating the thermal boundary

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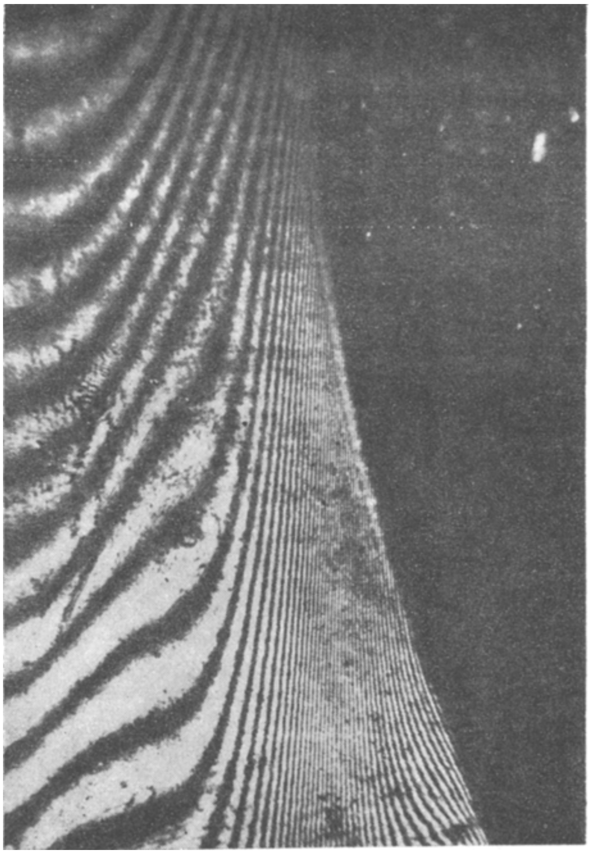

Fig. 1. Fragment of a thermal boundary layer.

layer (during observation through a microscope) directly from the hologram obtained, i.e., the temperature field in the whole volume occupied by the working beam was initially recorded impulsively and then point-by-point investigation of the thermal boundary layer image restored from the hologram is performed under a microscope. A typical thermal boundary layer interferogram on a cylinder is shown in Fig. 1 for a 20 times magnification.

The duration of the master oscillator pulse fluctuated between 40 and 60 nsec, which permitted consideration of the obtained temperature distribution by the instantaneous values at given stream points. The coefficient of refraction was determined from the obtained interferograms by starting from the hypothesis that the coefficient of refraction varies slightly in a direction parallel to the cylinder axis, i.e., a two-dimensional temperature distribution was assumed. The coefficient of refraction is related to the temperature by the empirical equation [1]

$$n - 1.3331733 = -(1.936T + 0.1699T^2) \cdot 10^5. \tag{1}$$

The heat elimination coefficient $\alpha = q_t/(t_w - t_f)$ and the Nusselt number Nu were calculated in terms of the thermal flux $q_t = \lambda_w \Delta T/L$, t_{in} was determined from the readings of the thermocouple clamped on the inner wall surface, and t_w from measurements from the interferograms.

The experimental cylinder was fabricated in the form of three coaxial cylinders that fit within each other. The outer cylinder is bored out of ebonite with a 2 mm wall thickness, the middle from copper to equalize the warming temperature field, and the inner from graphite and was heated by using direct current, the inner surface temperature of the ebonite cylinder was measured by using embedded copper—constantan thermocouples whose cold junction was placed in the stream being investigated. The cylinder was in a small hydrodynamic, closed type, tunnel with 10 × 10 cm working section. The maximal fluid velocity in the experiment was 0.15 m/sec.

The dependence of the local heat elimination coefficient of the cylinder and the temperature distribution in the flow around the cylinder surface was investigated as a function of the Reynolds number and barricading of the channel q = d/D.

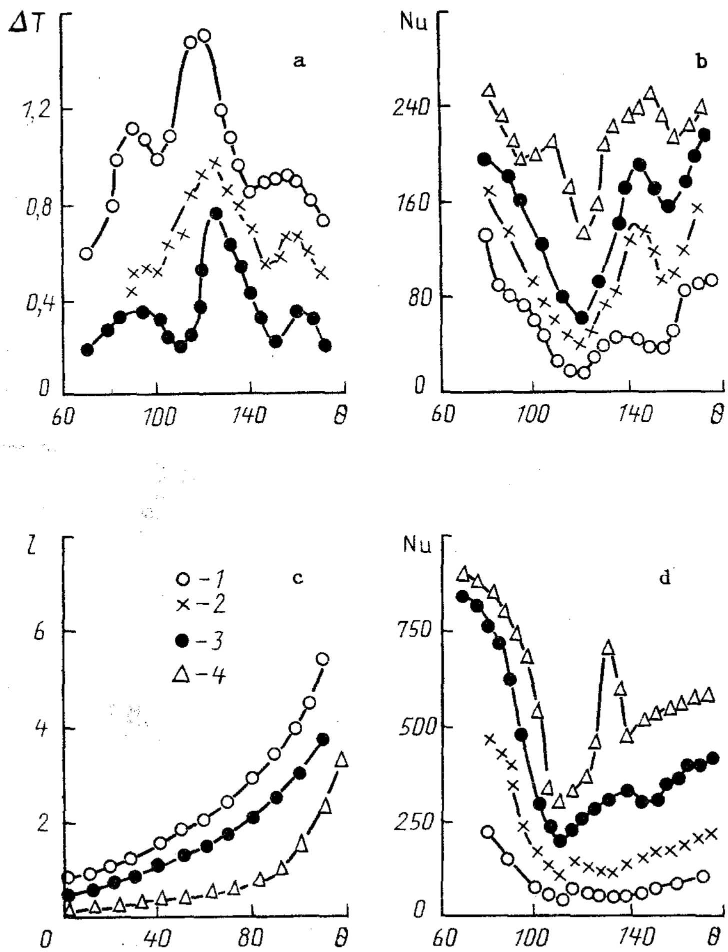

Fig. 2. Dependence of the fluid temperature T, °C, the boundary layer thickness, and the Nusselt number Nu on the Reynolds number: 1) Re = 550; 2) 620; 3) 760; 4) 1320; a, b, c) q = 0.24; d) 0.84. Θ, deg.

The error of the experimental data was combined from both random and systematic errors. Among the systematic should be, firstly, the error following from the assumption about two-dimensionality of the object of measurement. The reliable interval depends in this case mainly on the influence of heated cylinder endfaces on distortion of the stream two-dimensionality and was determined approximately by starting from the condition that the cylinder endfaces affect the fluid stream domain constrained in thickness (along the optical ray path). It was assumed that this domain does not exceed 5 mm in thickness. Then, to cause a shift in the interference fringe by one-tenth of a width, it is necessary that this bounded domain differ in temperature from the remaining domain above the cylinder of total length 100 mm by 3°C, and since the greatest temperature difference between the cylinder and the fluid stream was 2.8°C in the experiments, i.e., the temperature above the cylinder endfaces could not be greater than the given temperature head, then the error caused by the cylinder endfaces could also be considered less or equal to the error caused by a 0.1 width shift in the interference fringes. Also among the systematic errors is inaccuracy in determining the temperature in terms of the water refractive index found by means of (1); however, as the author of [1] writes, the final error in determining the water temperature for temperatures close to the room value does not exceed 0.2%, which is completely acceptable.

Among the fundamental random error is the error in measuring the shift of the interference fringes and it is governed by the accuracy of finding the coordinates of the middle of the fringe. As follows from [1], the error is 0.1 the width for a determination of the interference fringe shift with the naked eye. However, it diminishes with the application of optical devices. Since the fringe shift was measured in our experiment by using a coordinate grid superposed on the microscope eyepiece and by an optical magnification of the interference pattern, then the error in determining the fringe shift could not exceed 0.1 the width of the interference fringes.

The total error in the experiment is found by the method of probabilistic addition and is 2-3% for the case of determining the stream temperature. The error is up to 8% for the determination of the Nusselt number since in this case the error in determining the thermal flux through the cylinder wall is slipped in. However, these errors occur only in the case of determining the absolute value of the temperature and the Nusselt number. Variations in the experimental results of determining the temperature of the experimental cuvette with the fluid is 0.01°C under invariant external conditions.

Dependences of the temperature drop at a certain distance from the cylinder surface and the local Nusselt number over the cylinder surface are presented in Fig. 2 for different Reynolds numbers, the experimental points are superposed on graphs starting with 80° from the frontal point of the cylinder since the domain near the flow separation point is of greatest interest.

The dependence of the fluid temperature on the number Re is represented in Fig. 2a at a distance of 0.57 from the cylinder surface of small diameter for q = 0.24. It is seen from the figure that as the Reynolds number grows, a diminution is observed in the fluid temperature around the cylinder surface.

A change in the Nusselt number over the surface is shown in Fig. 2b for the same experimental cylinder. The form of the curves corresponds to the graph of the temperature distribution in the fluid stream at a distance of 0.57 mm from the surface (Fig. 2a) except with the opposite sign. The domain of Reynolds numbers under investigation with small stream barricading is characterized by the presence of a stable pair of vortices behind the circular cylinder and located symmetrically relative to the wake axis and rotating in opposite direction. The length of the circulation zone here starts to diminish from their maximal value as the Reynolds number grows further, which agrees with the diminution in the boundary layer thickness (Fig. 2c).

As is known, diminution in the circulation zone length behind a circular cylinder is characterized by systematic boundary layer separation from the body surface in the form of a Karman vortex street. Therefore, the diminution in the fluid temperature near the body surface or the increase in the heat elimination coefficient of a circular cylinder is the result of periodic rupture of the boundary layer from the body surface. Hence, if the first minimum in the distribution of the local value of the heat elimination over a circular cylinder surface corresponds to boundary layer separation, then the second minimum in the 150° domain corresponds to additional heating of this part of the body by the rotating vortices in the circulation zone. It must be noted that we have a quite definite second heat elimination minimum for small stream barricadings during a study of the instantaneous flow pattern, which is not always detected in ordinary investigation methods. For large stream barricadings (Fig. 2d) the second heat elimination minimum vanishes as the Reynolds number diminishes, gradually being smoothed out. This is explained by the general large turbulence in the root domain of the body under large compressions of the stream. As is seen from the figure, there is a quite definite minimum heat elimination for a large value of the Reynolds number. It can be explained by the presence of a crisis streamline mode because of the high free-stream turbulence. The first heat elimination minimum here characterizes boundary layer turbulization and the second, separation from the body surface. Therefore, a maximum heat elimination should be quite definite in the domain of boundary layer transition from the laminar to the turbulent. There is still another maximum in the 90° area on the temperature graph that is not quite so definite on the graph of the Nusselt number and becomes noticeable only as the Reynolds number increases. The extremum in the 90° area is not recorded for experimental cylinders with large diameter, thus the Nusselt number distribution is shown in Fig. 2d for the barricading case q = 0.84. There was indeed no such maximum at intermediate barricading values, that are not presented in the paper.

Measurements of the instantaneous temperature field show that in the cylinder domain starting with $\Theta = 75°$ and up to $\Theta = 130°$, there are significant temperature fluctuations for small barricadings, that result in a change in the heat elimination. These fluctuations reach values of ±18% in the 90-120° domain. Large velocity fluctuations are actually observed in the domain mentioned, where the intensity of turbulence reaches 50-60% and where fine-scale turbulence is characteristic. Therefore, measurement of the instantaneous temperature field pattern clearly determines the above-mentioned changes in the hydrodynamic stream characteristics. For instance, values of the fluid temperature around a cylinder, determined in different repeated experiments (i.e., without changing any of the external

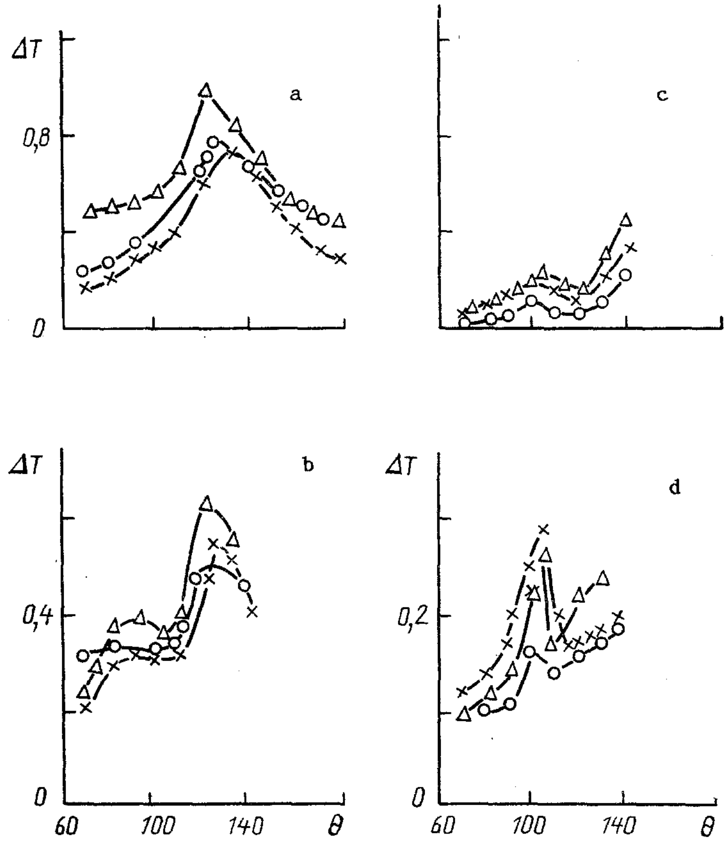

Fig. 3. Values of the fluid temperature around a cylinder q = 0.24 obtained in different experiments for Re = 880; a) on the cylinder surface; b, c, d) at distances from the cylinder surface of n = 0.57, 1.04, and 1.71 mm.

conditions, ten interferograms were taken sequentially) in approximately 3 min time, are shown in Fig. 3 as an example. This time interval was governed by the time to interchange photographic plates and to charge the condenser module. Such repeated experiments were performed for different Reynolds numbers and different stream barricadings. It was disclosed in the processing of the data from such an experiment that large temperature field fluctuations are observed as the free-stream velocity increases and are especially noticeable for the case of small stream barricadings. Both perfectly identical temperature distributions and with certain variations were observed in the tens of interferograms obtained in this manner. Thus, three curves are presented in Fig. 3, i.e., three kinds of temperature distributions are observed in tens of interferograms, the rest were duplicates. Starting with an angle equal to approximately 130° downstream, the temperature fluctuations diminish strongly and become maximum ±5%. In this domain large-scale turbulence occurs achieving vortex sizes being stripped from the circular cylinder surface and it quenches the large temperature fluctuations. As stream barricading increases, the temperature fluctuations diminish and starting with the barricading q = 0.6 practically vanish by approaching the magnitude of the measurement error. This is related to the change in the nature of the flow from periodic to aperiodic and the flow stabilization by the channel walls at large barricadings. Moreover, diminution of the temperature fluctuations for all barricadings in the root domain is related to the good miscibility of the fluid in the cylinder wake.

The fluid temperature fluctuations acquire several other forms with distance from the cylinder surface. Thus, temperature fluctuations are presented in Fig. 3b at a distance of 0.57 mm from the cylinder wall and it is seen that the nature of the temperature change still does not differ radically from the fluctuation at the cylinder surface; however, in Fig. 3d where the removal is 1.71 mm there is already no domain starting with which the temperature fluctuations diminish strongly. Moreover, the fluctuation values grow in magnitude with distance from the surface. This is explained by the presence of significant transverse velocity gradients, observable on the boundary between the free stream and the boundary layer.

Therefore, in conclusion it can be emphasized that a study of the instantaneous temperature field displayed the significance of temperature fluctuations in the separation domain, especially for low degrees of stream compression, which is not always detected successfully in measurements of the average characteristics. Moreover, by studying the holographic interferograms, the fluctuations in the coordinates of points of boundary layer separation and the size of the circulation zone can be determined with high accuracy, which yields a more complete representation of the flow around bodies.

NOTATION

T, temperature; n, water refractive index; α, heat elimination coefficient; q_t, thermal flux; t_w, temperature of the wall outer surface; f_{in}, temperature of the inner surface of the ebonite cylinder; Nu, Nusselt number; Re = Ud/ν, Reynolds number; U, free-stream velocity; d, cylinder diameter; D, channel width; λ_w, wall heat conductivity; $\Theta°$, angle measured downstream from the cylinder frontal point; ℓ, boundary layer thickness; L, wall thickness of the outer cylinder; n, distance from the cylinder surface along its normal.

LITERATURE CITED

1. C. West, Holographic Interferometry [in Russian], Moscow (1982).
2. A. Zhukauskas and I. Zhyugzhda, Cylinder Heat Elimination in a Transverse Fluid Flow [in Russian], Vil'nyus (1979).
3. M. S. Akylbaev, S. I. Isataev, P. A. Krashtachev, and N. V. Masleeva, Thermal Power Problems and Applied Thermophysics [in Russian], No. 3, Alma-Ata (1966), pp. 179-198.

COMPUTATIONAL AND EXPERIMENTAL INVESTIGATION OF NONSTATIONARY HEAT TRANSFER AT A CRITICAL POINT

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UDC 536.244

Similarity criteria are derived for the conjugate problem of nonstationary heat transfer, and the behavior of the heat transfer coefficient with a sharp change in the boundary conditions is studied.

Heat transfer in modern aircraft and rocket motors often occurs under nonstationary conditions. At the present time the accuracy with which the nonstationary temperature and thermal-stress fields in structures is determined is limited primarily by the accuracy of the boundary conditions, in particular, in the form of nonstationary heat-transfer coefficients. The fact that the heat-transfer coefficient is time-dependent when the conditions of heat transfer change sharply was confirmed experimentally in [1, 2]. In [3] similarity criteria characterizing the rate of change of the temperature of the wall were introduced and criterional dependences making it possible to calculate the nonstationary heat-transfer coefficient were derived. It follows from the estimates of [4] that for bodies in a gas flow the period of time during which the nonstationary heat-transfer coefficient differs from the corresponding stationary value under conditions of large Reynolds numbers Re > 10^4-10^5 does not exceed hundredths of a second. In [5, 6], however, it was found that this time is equal to 3-5 sec, the maximum excess is a factor of 2-3, and neglecting the time-dependence of the heat-transfer coefficient leads to significant errors in the calculation of the temperature of the wall. The present investigation was performed in order to determine more accurately the time dependence of the heat-transfer coefficient accompanying a change in the conditions of heat transfer.

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