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UNSTEADY FREE-CONVECTION HEAT TRANSFER DURING VORTEX FLOW IN A HORIZONTAL TUBE

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We conducted a theoretical and experimental investigation of the hydrodynamic structure and unsteady free-convection heat transfer in a round horizontal tube under different conditions of the second kind. During the experiment the Grashof number varied from $Gr = 1.54 \cdot 10^5$ to $Gr = 7.9 \cdot 10^5$. Using the interferometric method we investigated the distribution of the temperature field for different structures of a free-convection flow in the tube.

In the present work we give results of a theoretical and, mainly, experimental investigation of unsteady heat transfer in a round cylindrical tube under boundary conditions of the second kind. The hydrodynamics and heat transfer during natural convection in closed volumes of cylindrical geometry were the objects of a thorough investigation (for example, in [1, 2]); however, the number of works dealing with free convection in a horizontal tube is relatively few. The process of free-convection heat transfer in a horizontal tube in the case of a uniform temperature distribution on the wall was investigated in [3, 4]. The flow in the tube was laminar and had the form of two oppositely rotating vortices in the range of Rayleigh numbers $Ra = 3 \cdot 10^3 - 10^7$. With a further increase in Ra a gradual transition to turbulence was observed. The aim of the present work was to investigate the temperature distributions and the dynamics of vortical structures in a cylindrical tube under unsteady conditions of heating with the aid of optical methods.

We consider a round horizontally oriented tube on whose walls a constant heat flux is generated that is directed inside. This gives rise to nonstationary temperature field in the tube and after a while to nonstationary free convection, which, as shown below, exerts a substantial effect on the temperature field. We idealize the situation by neglecting free convection at the first stage of the investigation and considering only the process of pure heat conduction as if the gas in the tube had been replaced by a solid body. As a result, the primary problem is reduced to the problem of a cylinder heated by a constant heat flux. The second assumption consists in the replacement of the finite-length cylinder by an infinite one. The solution of the heat conduction problem for an infinite cylinder under boundary conditions of the second kind gives the following temperature distribution in the interior of the cylinder [5]:

$$\frac{T(r,\tau) - T_0}{T_0} = \frac{qR}{\lambda T_0} \left[2\frac{a\tau}{R^2} - \frac{1}{4}\left(1 - 2\frac{r^2}{R^2}\right)\right] +$$

$$+ \sum_{n=1}^{\infty} \frac{2}{T_0 \mu_n^2 J_0(\mu_n)} J_0\left(M_n \frac{r}{R}\right) \exp\left(-\mu_n^2 \frac{a\tau}{R^2}\right). \quad (1)$$

The parabolic form of the developing temperature field, starting with the values $a\tau/R^2 \geq 0.2$ (at these values the contribution of the series is negligibly small), permits one to consider the medium as a light-focusing one. In this case the temperature field of the medium is described by the expression

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$$\Theta = Q\left[2\,\mathrm{Fo} - \frac{1}{4}(1 - 2r^2)\right]. \tag{2}$$

The problem of determining the temperature field in a round tube with allowance for free convection is rather complex as regards to its mathematics specifically due to the fact that the small parameter is absent in it at rather large heat fluxes. This explains the reason why we selected an experimental study of a transient pattern on the basis of an interferometric method to investigate the time evolution of the temperature field.

The main objective of the experimental investigation was to determine the temperature field at each specified instant of time. In connection with this the investigation was made by an interferometric method, making it possible to obtain an instant picture of the temperature distribution throughout the entire field without distorting the temperature field by various probes. In the present work we used an IZK-454 two-beam Mach-Zehnder-type interferometer.

The experimental setup is a 0.3-m-long steel cylinder with a wall of thickness of 0.0027 m, heated by electric current. To measure the temperature of the cylinder wall, six copper-constantan thermocouples are imbedded along its perimeter and length. The change in the emf of the thermocouples was measured by an R-386 digital voltmeter with output to a printer. The outer surface of the cylinder was thermally insulated by asbestos cord. A parabolic form of the temperature field develops on the walls of the tube under boundary conditions of the second kind. This field has axial symmetry, but the presence of a radial temperature drop in the gas medium leads to the appearance of buoyancy perpendicular to the cylinder axis. As a result, lateral circulation of the heated gas arises, which distorts the temperature profile and substantially influences the process of heat transfer. An effective means of suppressing free-convection flow in a cylinder is rotation of it about its own axis [6]. The design of the setup allowed for rotation whose speed was controlled with the aid of a stroboscope. To reduce end effects at both ends of the tube we installed hydraulic brakes.

The system investigated was placed in the measuring branch of the interferometer and was adjusted on its axis. The interferometric patterns were recorded by an RFK-5 photocamera. The frequency of recording was prescribed by an IKZ-15 counter divider, and the time of recording by an F5007 program-simulated reversible counter. The interferometer was tuned to bands of infinite width in such a manner that we could obtain entirely uniform shading of the field during visual observation of the interference pattern. This makes it possible [4] to both increase the accuracy of tuning to an infinitely wide band and determine the initial point of the counting of bands assuming that the dark interference band observed is the zero one. In this case the temperature of the gas in the tube is equal to the ambient temperature T_0. After the supply of a heat flux through the wall the gas in the tube begins to warm up and this leads to a change in the optical length in the measuring branch of the interferometer and to the appearance of successive interference bands. A change in of the optical length by $\lambda/2$ gives the first light band, by λ the first dark band, etc. The process of gas warming is accompanied by the appearance of the high-order interference bands shifting to the center of the tube. After a time, heating of the gas on the tube axis occurs and with a change in the path difference on the axis by $\lambda/2$ the dark band at the center of the tube converts to a light one. With a further increase in temperature it changes to the first dark band, etc. The instants of the replacement of the bands at the center of the tube should be fixed, i.e., the frequency of the frames should be higher than the frequency of the appearance of new interference bands as a result of gas heating.

As is known [5], when the interferometer is tuned to bands of infinite width, the interferogram is represented (if the refractive index depends only on the temperature) by lines of equal temperatures, the spacing between which depends on the temperature gradient.

The gas temperature T_i corresponding to the interference bands can be determined from the equation

$$\Delta T = T_i - T_0 = \frac{\lambda}{l \cdot dn/dT} N_i . \tag{3}$$

In our case $\lambda = 0.5461 \cdot 10^{-6}$ m, $l = 0.3$ m, $dn/dT = 0.927 \cdot 10^{-6}\ \mathrm{K}^{-1}$, which gives $\Delta T = 1.96$°C. With a known ambient temperature T_0 the interpretation of the interference pattern yields $T_i(x_i, y_i)$ for $N_i = 1$.

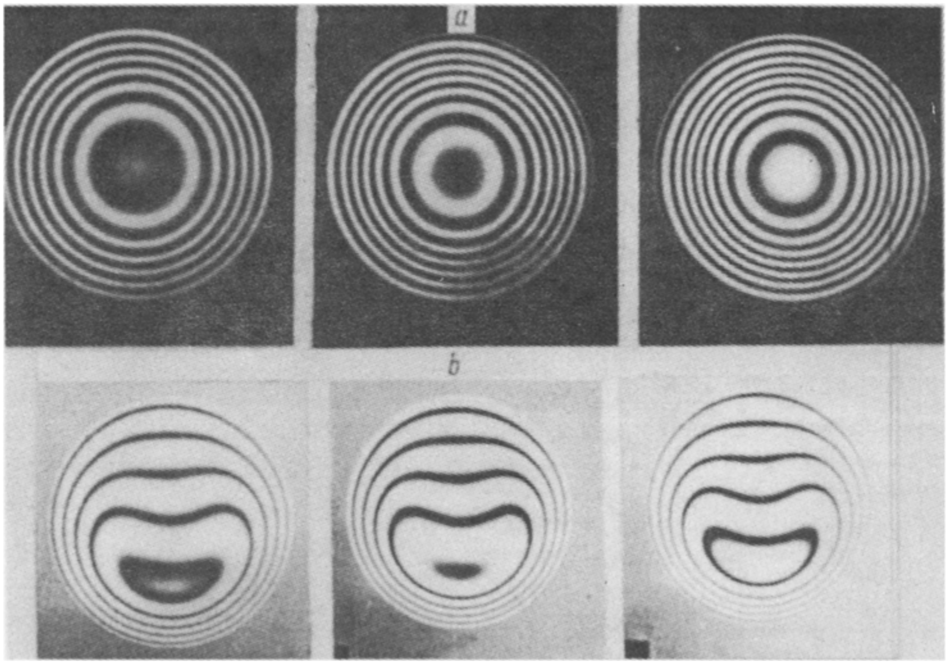

Fig. 1. Shift of interference bands at the center of the tube without (a) and with (b) rotation, $q = 25\ W/m^2$.

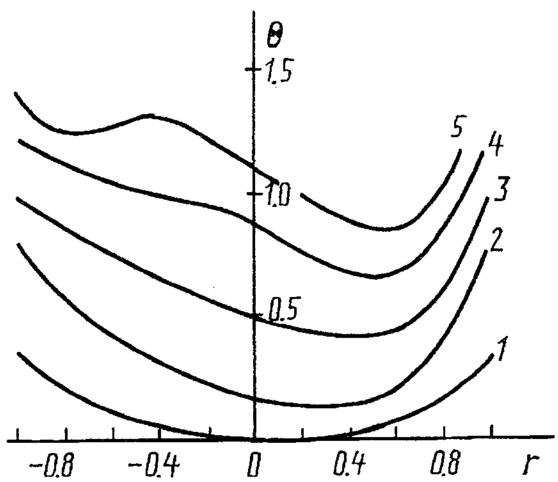

Fig. 2. Distribution of the dimensionless temperature along the vertical diameter of the tube at $Gr = 4 \cdot 10^5$.

During the tuning of the interferometer the focal plane is selected to be in the middle of the object investigated, since in this case the error in the determination of the coordinate occurring due to deflection of light rays on the optical inhomogeneity is the minimum.

The interference pattern was recorded with a frequecy of 10 frames/sec on Mikrat-200 film. When interpreting the results, this speed was sufficient to follow the change in the order of the interference bands on the tube axis, from which the counting of the bands N_i was made. In Fig. 1 we present photographs of interferograms at definite intervals of time from the start of tube wall heating. The frames are selected so as to demonstrate the shift in the number of the bands at the center of the object investigated during both free-convection motion in the tube and tube rotation.

The experimental setup created and the procedure for measurements made it possible to follow the development of unsteady free convection in a horizontal round tube and its effect on the development of the temperature fields. During the experiment we selected three regimes of heating: $q = 25$, 65, and 115 W/m^2, where q is the heat flux directed inside the tube. The tube wall was heated by electric current. The maximum heat flux

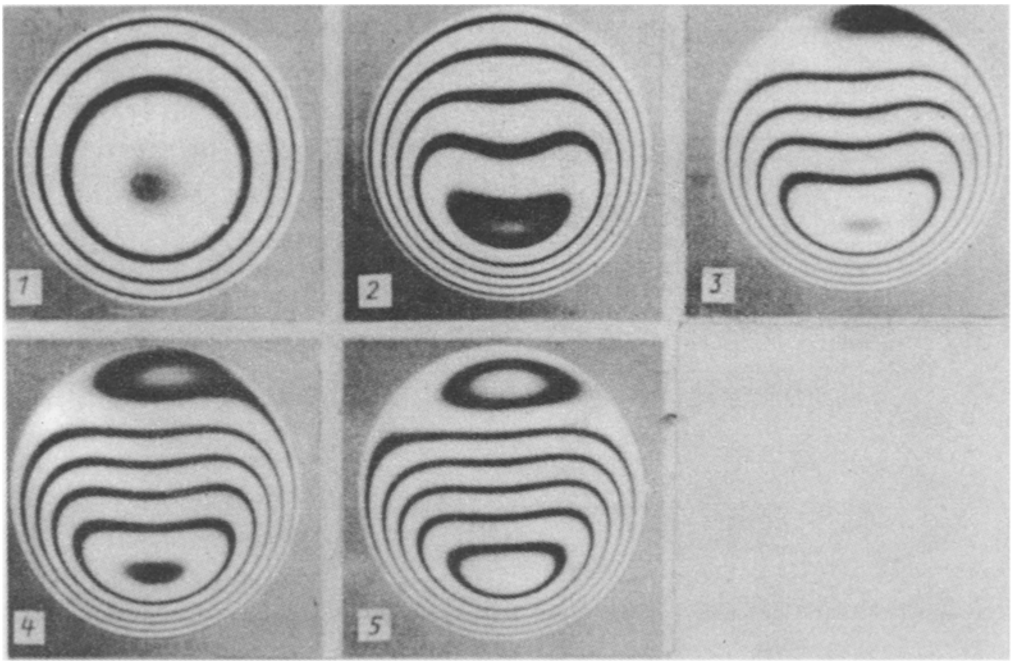

Fig. 3. Interferograms of the temperature distribution at $Gr = 4 \cdot 10^5$.

power was determined by the characteristics of the current transformer. The time for recording the process did not exceed 5 sec. As shown above, a parabolic profile of the temperature distribution over the tube cross section occurs when the wall temperature is varied linearly with time.

The development of the hydrodynamic structure of unsteady convection in a horizontal tube in the case of sudden jumpwise heating of the wall is characterized by the same stages of development of unsteady flow as in a horizontal layer of liquid [7]: a period of induction of convection during which unsteady-state conductive heating of the gas occurs and a transient period from the instant of occurrence of convective cellular flow to the development of stable intense cellular convection. The duration of the conduction period is dictated by the thermophysical properties of the medium, the dimensions and geometry of the surface, the quantity of heat supplied, etc. The experiment showed that these times amount to tenths of a second. Thus, at $q = 65$ W/m^2, which corresponds to the Grashof number $Gr = 4 \cdot 10^5$, a temperature profile asymmetry in the vertical section of the tube is observed already after the lapse of 0.5 sec ($Fo = 0.048$), and at $q = 115$ W/m^2 ($Gr = 7.9 \cdot 10^5$) after 0.3 sec ($Fo = 0.028$). Starting with these times, a transient period of the appearance of a two-cellular hydrodynamic gas flow begins. The calculated time for the development of a quasistationary thermal regime was equal to about 0.6 sec ($Fo \approx 0.6$). Figure 2 presents graphically the temperature distribution along the vertical diameter of the tube for $\tau = 1, 2, 3, 4$, and 5 sec ($Fo = 0.096$; 0.19; 0.29; 0.38; 0.48) (curves 1–5, respectively) from the start of wall heating at the Grashof number $Gr = 4 \cdot 10^5$. The interferograms corresponding to each of the curves of the dimensionless temperature distribution are presented in Fig. 3.

An analysis of the interferograms that characterize the development of unsteady free convection shows that the character of circulation flow in the interior of the tube begins to change as the Grashof number increases. In the dynamics of the process represented in Fig. 3 ($Gr = 4 \cdot 10^5$) we can see the development of the so-called two-cellular structure of the temperature distribution, which forms beginning from the fourth second ($Fo = 0.38$) after the start of the tube wall heating. The presence of the two-cellular structure of the temperature field in a horizontal tube seems to be associated with the appearance of a three-dimensional free-convecton flow. As the heating time increases, the temperature distribution along the tube wall becomes nonuniform due to conductive and radiative removal of heat from the end faces. The resulting transverse and longitudinal free-convection gas flows lead to a substantial change in the distribution of the length-average temperature. It should be noted that the process of the appearance of a two-cellular structure of the temperature field in a horizontal tube requires additional investigation at higher recording speeds of the interferograms.

Thus, the process of heat transfer in a horizontal tube of circular cross section under boundary conditions of the second kind can be divided arbitrarily into three stages: heating of the gas in the tube due to conductive heat transfer; two-vortex free-convection heat transfer during which the velocity and temperature fields can be described by means of two-dimensional functions; the occurrence of a complex three-dimensional circulational flow in the tube leading to the appearance of a temperature field with a two-cellular structure.

NOTATION

J_0, Bessel function; μ_n, the roots of this function; R, radius of the tube; r, dimensionless radius of the tube; a, thermal diffusivity; q, heat flux on the tube wall; τ, time; T, temperature; $\Theta = (T - T_0)/T_0$, dimensionless temperature; k, thermal conductivity; $Q = qR/kT_0$, dimensionless heat flux on the wall; T_0, ambient temperature; T_i, gas temperature corresponding to the i-th band of the interference pattern; N_i, number of the interference band; λ, radiation wavelength; Ra, Rayleigh number; $\mathrm{Fo} = a\tau/r_0^2$, Fourier number; l, length of the tube.

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