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HEAT TRANSFER BY NATURAL CONVECTION AND HYDRODYNAMICS ON A VERTICAL PLATE WITH A DISCONTINUITY IN THE HEAT FLUX

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It is observed that the temperature distribution in the boundary layer changes qualitatively and the heat transfer in the upper part of a plate intensifies substantially in comparison with a surface with a continuous heat flux. For the case of substantial heat flux density in the initial stage of formation of a free convective flow a two-dimensional vortex is found to appear.

At present in the scientific literature there are a large number of works devoted to free convection at a nonuniformly heated vertical surface. Among the first publications on the subject one can distinguish work [1], whose authors measured the distribution of the temperature field by positioned thermocouples. The theoretical studies of free convection started by Polhausen were continued successfully in [2-4], where approximate solutions were obtained for the problems of free convection at a vertical surface with inhomogeneous boundary conditions of the first and second kind. Later, publications appeared that presented results of numerical simulation of heat and mass transfer processes at a vertical surface with various inhomogeneous boundary conditions [5-7] and results for two finite plates located one over the other in a vertical plane [8]. Monograph [9] generalizes theoretical studies of various authors in the field of free convection at a vertical surface with various boundary conditions of the second kind.

However, in spite of substantial interest in this problem, the number of experimental studies of free convection at vertical surfaces with inhomogeneous boundary conditions is small. Among them we can distinguish work [10], in which interferometric methods were used to carry out an experimental study of free convection in air at a vertical surface with localized heat sources, and smoke visualization of the velocity field in the boundary layer of the liquid was conducted. In [11] heat transfer from a local heat source located in the lower part of an adiabatic insulated surface was studied. The temperature fields were investigated using a copper-constantan thermocouple.

In the present work optical methods were used to investigate thoroughly the structure of the temperature and velocity fields with free convection at a vertical plate with a discontinuity of the heat flux on its surface in the case of a higher heat flux in the lower part of the plate. The development of the temperature fields in the boundary layer was studied on a Mach-Zehnder interferometer by a method similar to that described in [12], and the development of the velocity fields, by the method of visualization of particles described in [13].

Experimental Setup. A plate of stainless steel, 0.2 m × 0.3 m, was used as the object of study. The thickness of the plate changed in a stepwise manner at the half-length from 1 to 2 mm. Electric current was passed through the plate. It was supplied to the upper and lower edges of the plate through copper contacts from a step-down transformer by a copper cable with a cross section of 6 cm^2. Heat release at the copper contacts and cables was neglected. In the experiment the heat flux density in the lower and upper halves of the plate was 220 and 64 W/m^2, respectively. Because the surface of the plate was polished, almost all heat released was spent on heating the plate: according to [14] radiative losses constituted at most 10% of the whole power input. All the results presented in this article have been obtained with a linear increase in the temperature of the surface. The experimental methods

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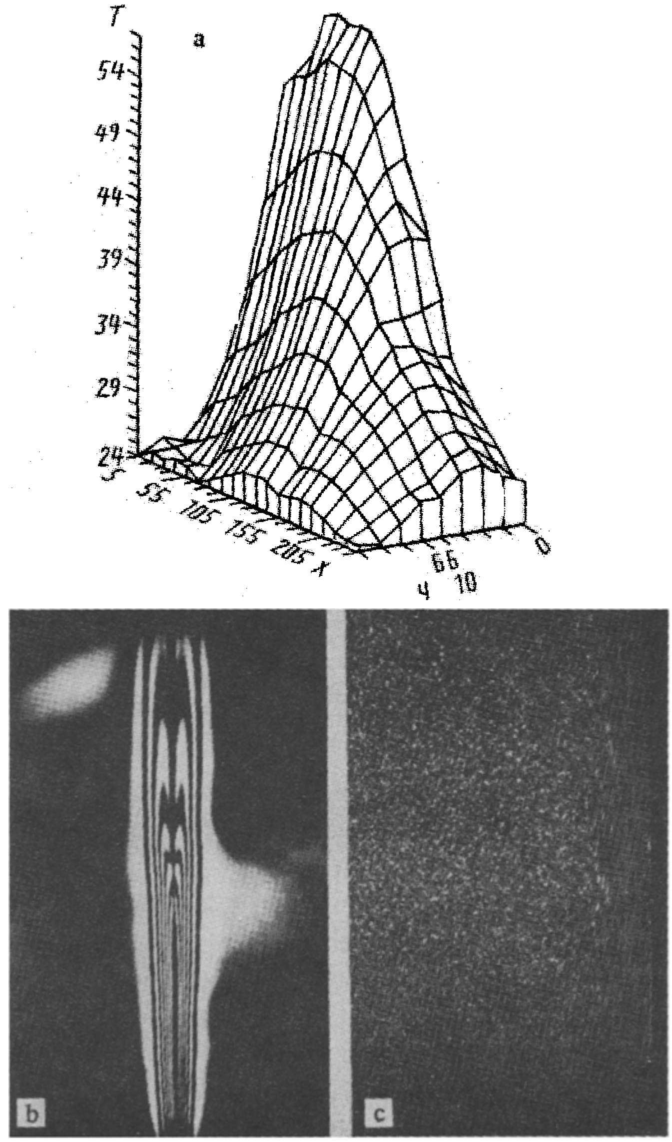

Fig. 1. Three-dimensional distribution of the temperature field (a), reconstructed from the interferogram (b) and flow pattern (c) in the boundary layer at a vertical plate with a discontinuity in the heat flux. x, y, mm.

used to investigate the temperature and velocity fields are completely indentical to those used in [15]. The experiments were carried out in air at normal atmospheric pressure.

Results and Discussion. Figure 1 is a three-dimensional diagram of the temperature distribution in the boundary layer plotted on the basis of an interferogram of the free convective flow on the surface taken 75 sec after the start of heating. Two typical regions were found in the distribution of the temperature field. The first region is formed at the lower half of the surface, and the temperature distribution in it is similar to the temperature field at a plate with a homogeneous heat flux (i.e., it is a power distribution). In this distribution the temperature maximum is located on the surface of the plate. The second region is transient and is formed behind the interface of the heat fluxes. In this region the temperature profile is parabolic. This is caused by the parabolic velocity profile in the boundary layer, because of which the gas having a higher temperature than the upper part of the plate is carried beyond the heat flux interface. Then, upstream the temperature profile again approaches a power distribution. It can be suggested that in the further flow along the plate there is one more region in which the effect of the lower part of the plate becomes insignificant and the temperature distribution corresponds to the temperature profile at a plate with a homogeneous heat flux. However, because of the limited size of the plate this region was not observed in the present experiment.

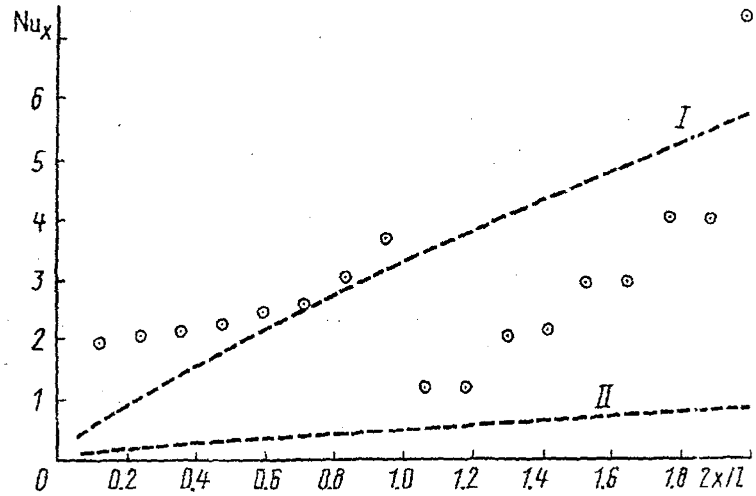

Fig. 2. Distribution of the local heat transfer coefficient along a vertical plate with a discontinuity of the heat flux on the wall.

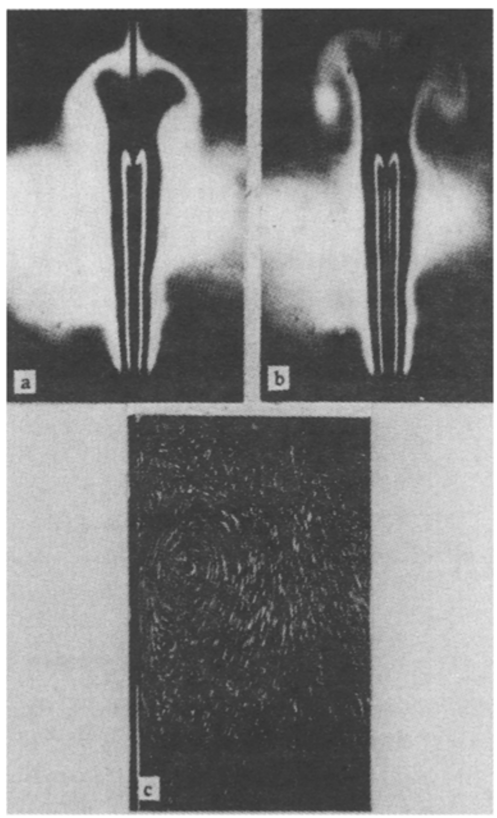

Fig. 3. Interferograms (a, b) and flow pattern (c) in the initial stage of development of free convective flow on a plate.

The discontinuity in the heat flux on the surface changes the heat transfer process substantially. In Fig. 2 one can see the distribution of the local heat transfer coefficient along the plate. The lines correspond to the interpolation relation $Nu_x = 0.55(Ra_x^*)^{1/5}$ suggested in [16] for a vertical plate in air with homogeneous boundary conditions of the second kind. According to [9], this relation differs from the self-similarity solution by no more than 0.5% in the range of Rayleigh numbers of $20 < Ra_x^* < 5 \cdot 10^7$. The interpolation relations are calculated for heat fluxes of 220 (I) and 64 (II) W/m^2. As can be seen from Fig. 2, at the upper part of the plate ($q_0 = 64$ W/m^2) heat transfer is enhanced substantially. In this region, because of the well-developed flow from the lower part of the plate, the Nusselt number Nu_x is 2 to 4 times higher than for a plate with a homogeneous heat flux of the same value.

In Fig. 1c one can see a photograph of visualization of the hydrodynamic flow at the plate studied. The experimental conditions in track visualization are completely identical to those in taking the interferograms. For this plate on the lower part of the surface the thickness of the boundary layer increases smoothly up to the heat flux interface, where it reaches a maximum, and then a slight decrease in it is observed upstream.

The case of rapid heating of the plate with a higher heat flux on the lower part of the surface (the heat flux densities at the upper and lower parts of the plate are 170 and 600 W/m^2, respectively) is of some interest. As a result of a more rapid rise of the temperature, on the lower part of the surface a free convective flow is formed much earlier than on the upper part. Interaction of the flow with the stationary air at the upper part of the plate gives rise to an upward two-dimensional vortex. In Fig. 3 one can see interferograms of the arising circulation flow taken 9 and 11 sec after the start of heating. It can be clearly seen from the figure that the air flow with a higher temperature from the lower part of the plate reaches the stationary region with a lower temperature, is not mixed with the latter, and is forced away from the surface of the plate. Deceleration of the heated air gives rise to a vortex with cooler air as the core. Having been formed, the vortex is carried away by the free convective flow and moves upward along the surface of the plate (Fig. 3c).

Conclusion. For the plate studied with a higher heat flux on the lower part of the surface, because of the parabolic velocity profile in the boundary layer, the temperature profile in the upper part of the plate is also parabolic. In the case of a well developed free convective flow, the values of the local heat transfer coefficient on the upper part of the plate are much higher than for a plate with a homogeneous heat flux on its surface. At a substantial heat flux density in the initial stage of formation of a free convective flow a two-dimensional vortex is found to appear at the heat flux interface.

NOTATION

x, coordinate along the plate; y, coordinate across the boundary layer; q_0, heat flux on the surface of the plate; ϑ_0, dimensionless temperature of the wall; λ, thermal conductivity of the air; $Nu = q_0 x/\lambda\vartheta_0$, Nusselt number; Ra, Rayleigh number.

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