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Free-convective heat transfer on a vertical surface with heat-flux discontinuity

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Abstract—The character of free-convective flow near a vertical plate with a heat-flux jump on the surface is studied experimentally. Two cases of plate spatial orientation are investigated. The temperature field is measured and the velocity field is visualized in the free-convective flow near a surface. For the case of a higher heat flux from the lower portion of the plate, a change is noted in the character of the temperature profile in a boundary layer in the plate upper portion as compared with the constant heat flux surface. The shift of a temperature local maximum in a boundary layer to some distance from the surface into the flux depth is revealed. For the case of a large density of heat liberation at the initial stage of free-convective flow formation, the appearance of a two-dimensional vortex, originating from the interaction of the heated air flow with motionless cooler air in the upper portion of the plate, is found.

INTRODUCTION

At present in the scientific literature there are a great number of papers devoted to the study of free convection near a nonuniformly heated vertical surface. Among the first publications dealing with this problem ref. [1] should be mentioned in which the authors measured the temperature-field profile using positioned thermocouples. Theoretical studies of free convection started by Pohlhausen were successfully continued in works [2–4] where approximate solutions were obtained for the problems of free convection near a surface with nonuniform boundary conditions of the first and second kind. Later, a number of papers appeared [5, 6], which presented the results of numerical simulation of heat and mass transfer processes near a vertical surface with different nonuniform boundary conditions. In ref. [7] the parameters of heat transfer under nonuniform boundary conditions of the first and second kind were studied using a self-similar solution as the first approximation. On the basis of this method solutions were obtained for exponentially and linearly varying heat flux on a vertical surface. Reference [8] presents the results of numerical simulation of transport processes near a vertical surface with different boundary conditions as well as for two finite plates, positioned one above the other in a vertical plane. In a monograph [9] theoretical studies from different authors in the field of free convection near a vertical surface under various second-kind boundary conditions are generalized.

However, in spite of the great interest in this problem, the number of papers dealing with the experimental study of free convection near vertical surfaces with nonuniform boundary conditions is scanty. Among them a paper may be distinguished [10] in which free convection in air near a vertical surface with localized heat sources was experimentally investigated based on interferometric methods and the velocity field in a liquid boundary layer was visualized by smoke as well. In ref. [11] the processes of heat transfer from a local heat source placed in the lower portion of an adiabatic insulated surface were studied. Temperature fields were investigated by a copper–constantan thermocouple.

In the present paper, using optical methods, the structure of temperature and velocity fields with free convection near a plate with a heat-flux jump on its surface is studied in detail. The character of the development of temperature fields in a boundary layer is investigated on a Mach–Zehnder interferometer by a technique similar to that of ref. [12], and the development of a velocity field is studied by the method of visualized particles described in ref. [13].

EXPERIMENTAL UNIT

A stainless steel plate, with dimensions 0.2×0.3 m and thickness varying in a jump-wise manner from 1 mm to 2 mm, was used as the studied object (Fig. 1). Electric current, supplied through copper contacts to the upper and lower plate edges from a reducing transformer through a copper cable with a cross-section of 6 cm^2, was transmitted through a plate. Heat liberation on the copper contacts and the feeder cable was neglected. In the course of the experiment the density of heat liberation from thick and thin portions of the plate was equal to 220 W m^{-2} and 64 W m^{-2}, respectively. Owing to the fact that the plate surface was polished, virtually all of the heat was spent on plate heating; radiation losses, according to ref. [14],

NOMENCLATURE

Nu_x	local Nusselt number	y	coordinate across the boundary layer [m].
Ra_x	local Rayleigh number		
x	coordinate along the plate [m]		

amounted to not more than 10% of the total supplied power. All the results presented in the paper, were obtained at linear increase in the surface temperature, and longitudinal heat transfer along the plate was considered insufficient. Experimental methods for studying temperature and velocity fields are similar to those used in ref. [15]. The experiments were conducted in air at normal atmospheric pressure.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 presents the interferogram of a free-convective flow near a vertical plate with a heat-flux jump on the surface (the higher values of heat flux correspond to the upper portion), made 50 s after heating switch-on, and a three-dimensional graph of temperature distribution in a boundary layer, constructed

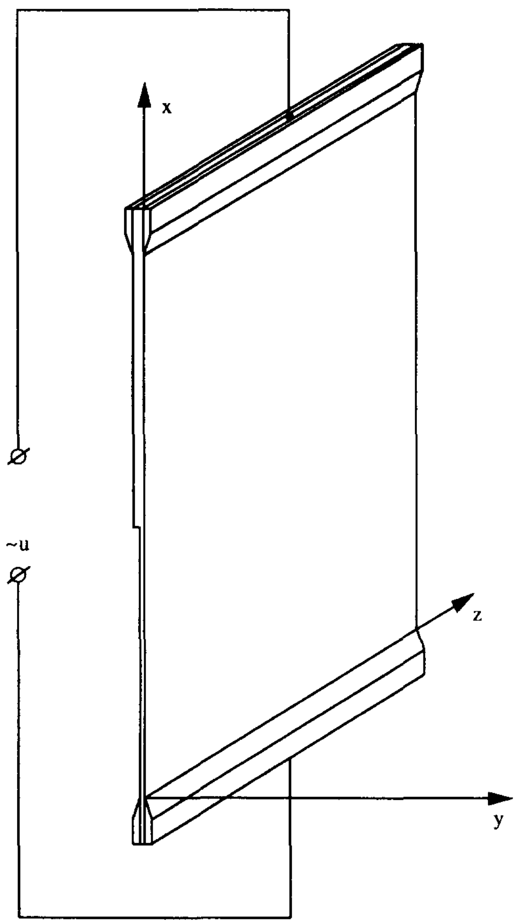

Fig. 1. Design of a studied plate with heat-flux discontinuity.

based on this interferogram. The coordinate x is reckoned along the plate, zero corresponds to its lower edge, and the coordinate y is reckoned across the boundary layer.

The existence of the heat flux on the surface leads to a considerable change in heat transfer character. Figure 2(a) presents a graph of the distribution of the local heat transfer coefficient along the plate length. The solid line corresponds to the interpolation relation $Nu_x = 0.55(Ra_x^*)^{1/5}$, suggested in ref. [16] for a vertical plate in air at uniform second-kind boundary conditions. According to ref. [9], this relation gives a difference from a self-similar solution not exceeding 0.5%, for a range of Rayleigh number $20 < Ra_x^* < 5 \times 10^7$. The interpolation relation was calculated for a heat flux equal to 220 W m^{-2}. It should be noted that the values of the local heat transfer coefficient on the upper and lower portions of the plate fall by an exponential law, thus being in qualitative agreement with the theoretical [8] and experimental [10] results obtained for a jump of the first-kind boundary conditions on a vertical surface. However, the values of the local heat transfer coefficient for the lower portion of the plate turn out to be 20–30% higher than those for the plate at constant heat flux. In the latter case, in the zone lying directly behind the boundary of heat flux separation, a considerable growth (up to 40%) of the local heat transfer coefficient is observed, which is caused by a sharp increase in the temperature gradient, and then, downstream, a reduction of the local heat transfer coefficient, up to a value of about 50% of the mean value for a plate with a constant heat flux, is noted. This may be attributed to the heated air flow from the lower portion of the plate. However, the qualitative character of the temperature-field profile remains similar to that for the case of a uniform heat flux.

Figure 4 shows the interferogram and the corresponding graph of a three-dimensional temperature-field distribution for surfaces with a large heat flux on the lower portion of the plate. The interferogram was taken 75 s after heating switch-on. The existence of three characteristic regions in the temperature-field distribution near a plate may be noted (Fig. 5). Region I is formed near a lower half of the surface with a high heat flux. The temperature field is similar to the temperature distribution on the plate with a uniform flux (i.e. it has an exponential character), in this case the temperature maximum is on the surface. Region II is a transitional one and is formed in a narrow interval a little bit higher than the zone of the bound-

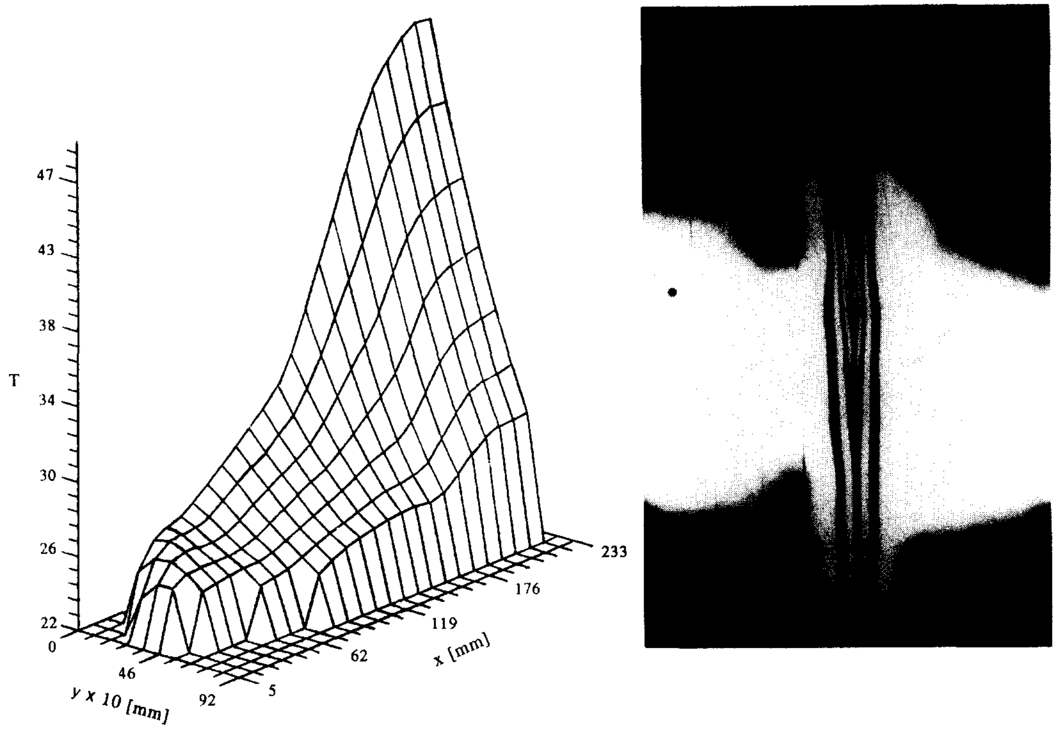

Fig. 2. Interferogram and the recovered temperature distribution in a boundary layer near a vertical plate with heat-flux discontinuity. The greater flux is from above.

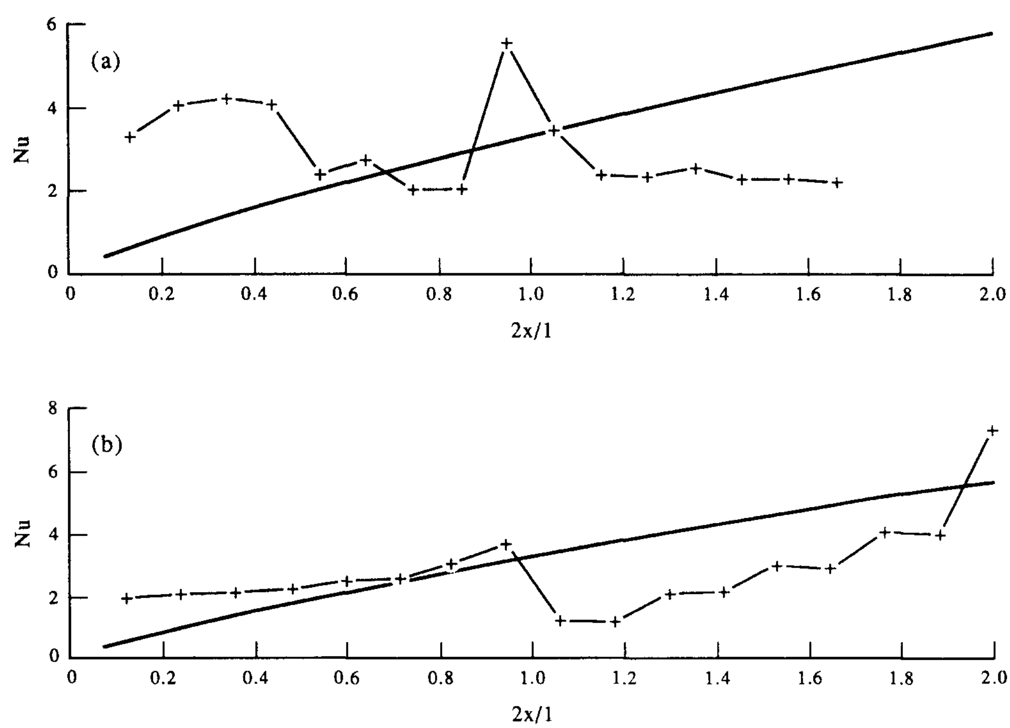

Fig. 3. Distribution of the local heat transfer coefficient along a vertical plate with heat-flux discontinuity on a wall: (a) greater heat flux from above; (b) greater heat flux from below.

ary separating the surface into two parts. In this zone the character of the temperature fall across the flow changes due to the contact of gas, having a higher temperature, with a cooler part of the plate. As a result the gas is cooled and in the temperature field profile a characteristic plateau appears near the surface.

Region III is formed further downstream, where as

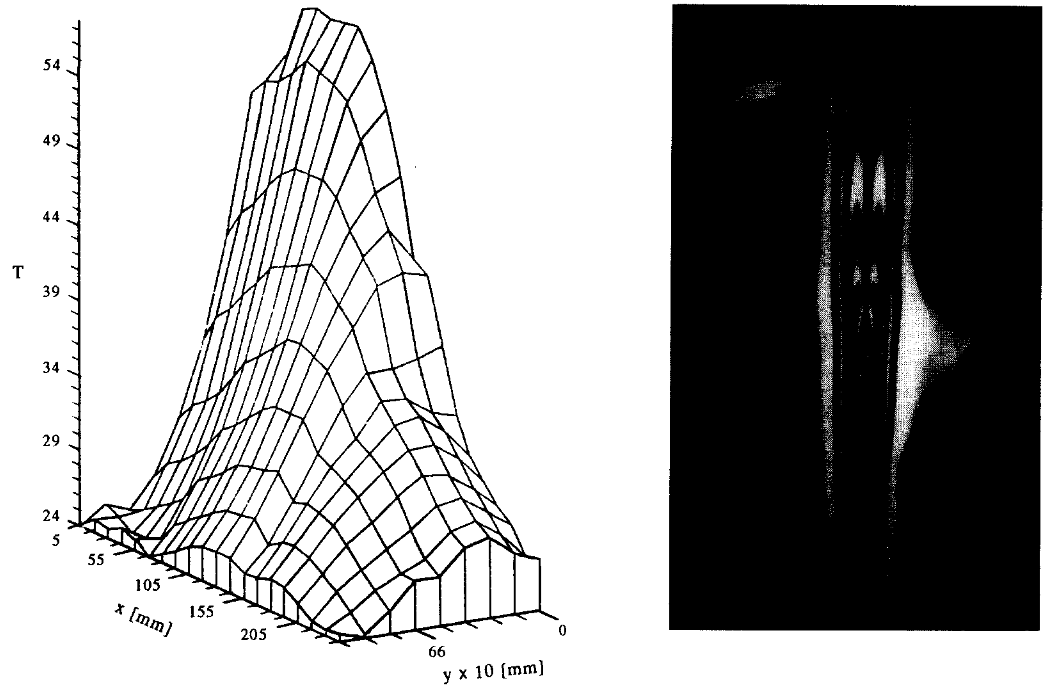

Fig. 4. The interferogram and recovered temperature distribution in a boundary layer near a vertical plate with heat-flux discontinuity. The greater flux is from below.

a result of heat exchange between a hot gas and a cooler surface the near-wall gas layer is cooled and a local temperature maximum shifts deep into the boundary layer, thus forming a parabolic temperature profile in this region. With the greater plate length, due to heat exchange between neighbouring flow layers this maximum should disappear and the temperature profile should again approach the profile near the uniformly heated surface. However, this fact was not observed with the studied plate dimensions.

The distribution of the local heat transfer coefficient along the plate length is presented in Fig. 2(b). The form of the curve in this case slightly differs from the interpolation relation calculated for a uniform heat flux [16], i.e. on the upper and lower parts of the plate an exponential growth of the local heat transfer coefficient is observed, and only near the separation zone is its local decrease noted which is caused by heat flux reduction.

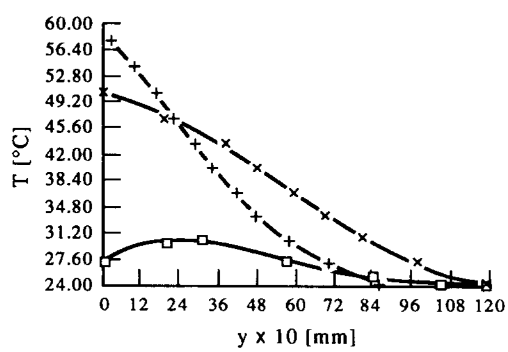

Fig. 5. Temperature distribution in a boundary layer near a vertical plate with heat-flux discontinuity: +, $x = 2.8$ cm, ×, $x = 11.4$ cm, □, $x = 21.8$ cm.

Figure 6 is photographs of the visualization of hydrodynamic flow near the surface with heat-flux discontinuity. The conditions of the experiments in track visualization fully coincide with those in the shooting of the interferogram. For a surface with a greater heat flux, from above a smooth upstream growth of the hydrodynamic boundary-layer thickness is observed. For a plate with a greater heat flux on the lower portion of the surface, the boundary-layer thickness smoothly increases to the boundary separating the heat fluxes, where it attains a maximum, after which some decrease in the boundary-layer thickness is observed.

Of special interest is the case of rapid heating of a plate with a great heat flux on the surface lower portion (the densities of heat liberation from the upper and lower portions of the plate are equal to 170 W m^{-2} and 600 W m^{-2}, respectively). In this case, due to a quicker growth of temperature on the lower part of the surface a free-convective flow is formed much earlier than in the upper part. Flow interaction with motionless air near the plate upper portion leads to the formation of an ascending two-dimensional vortex. Figure 7 shows the interferograms of the originating circulation flow plotted 9 and 11 s after heating switch-on. It is clearly seen how the hotter air flow from the lower portion of the plate reaches a motionless cooler region and, not mixing with it, displaces it from the plate surface. The process of warm-air deceleration

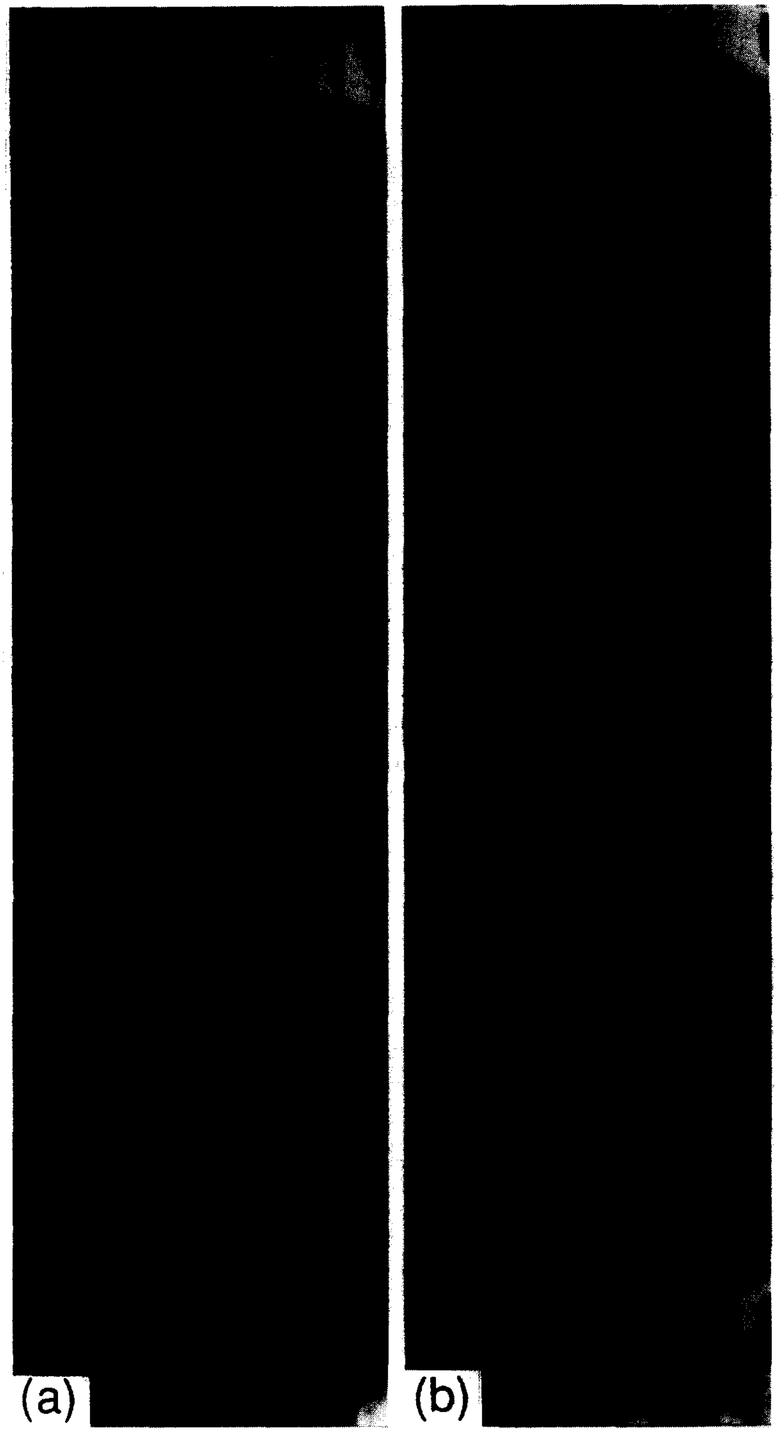

Fig. 6. Visualization of free-convective flow in a boundary layer with heat-flux discontinuity: (a) greater heat flux from above; (b) greater heat flux from below.

results in the formation of a vortex, the core of which involves cooler air. The formed vortex is carried along by a free-convective flow and moves upwards along the plate surface (Fig. 8).

CONCLUSIONS

For a surface with a great heat flux above, the characteristic temperature profile near the plate does not differ qualitatively from the temperature field near a plate with a uniform heat flux, excluding a small zone near the interface. In the presence of a heat-flux jump a smooth transition is observed from a free-convective flow along a surface with a small heat flux to the flow near a surface with a large heat flux. In this case, in the zone behind the heat-flux jump an increase in boundary-layer thickness is observed.

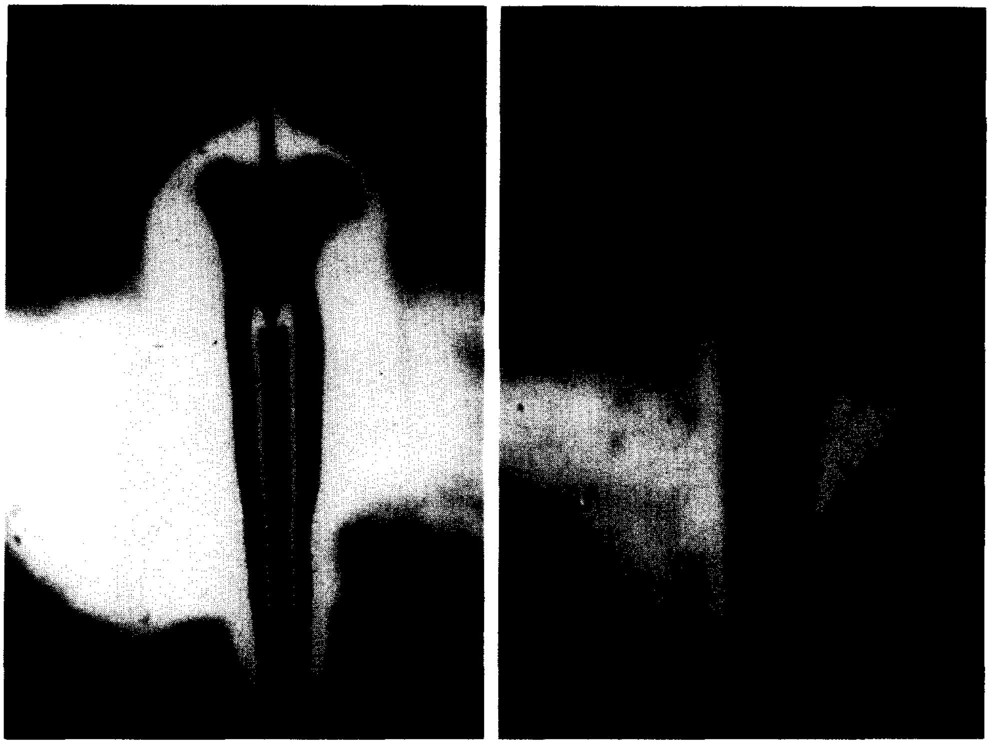

Fig. 7. Interferogram of the initial stage of free-convective flow development on a plate (greater heat flux from below; density of heat liberation 170 W m^{-2} and 600 W m^{-2}).

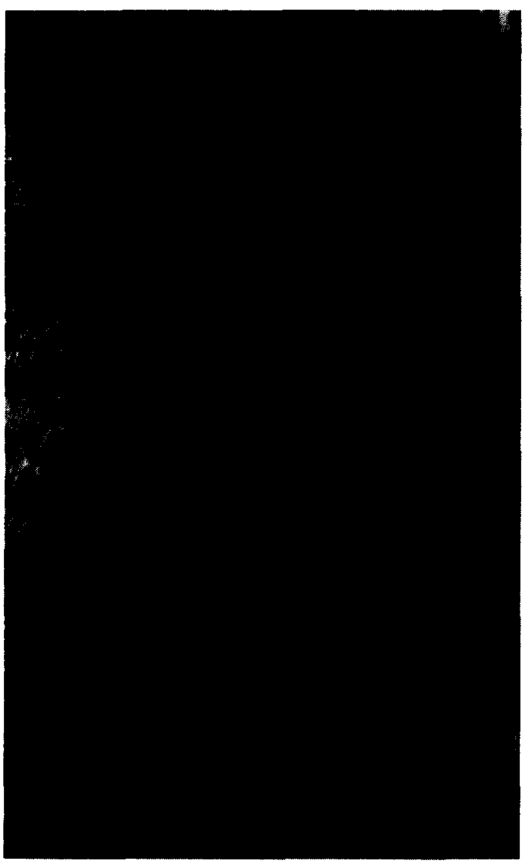

Fig. 8. Visualization of the initial stage of free-convective flow development on a plate (greater heat flux from below; density of heat liberation 170 W m^{-2} and 600 W m^{-2}).

The value of the local heat transfer coefficient on the lower part of the plate turns out to be much higher (to 30%) than for the plate with a constant heat flux; on the upper part of the plate some reduction of the local heat transfer coefficient is observed.

For a surface with a great heat flux from below, the temperature profile changes, having passed the jump, due to heat transfer between a flow with a higher temperature and the upper portion of the plate. This leads to the formation of a colder zone near the surface. As a result a parabolic temperature profile is formed in a boundary layer. In this case the value of the local heat transfer coefficient is virtually equal for the surface with a heat-flux jump and for a uniformly heated surface.

At great density of heat liberation (170 W m^{-2} and 600 W m^{-2} from the upper and lower portions of the plate, respectively) and at the initial stage of free-convective flow formation, the generation of a two-dimensional vortex is observed in a boundary layer.

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