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FREE CONVECTIVE FLOW ON A VERTICAL PLATE WITH A CONSTANT HEAT FLUX IN THE PRESENCE OF ONE OR MORE STEPS

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We carried out an experimental investigation of free convective heat transfer on a vertical plate subjected to a constant heat flux in the presence of one or several rectangular steps. Temperature fields were investigated with the help of a Mach-Zehnder interferometer. During the experiment the Rayleigh number changed from zero to $Ra = 2.8 \cdot 10^3$. *The flow was observed by the method of track visualization by means of a laser knife. Directly behind a step we observed a circulating free convective flow having the shape of two oppositely rotating vortices.*

For some time now, considerable attention has been paid to studying free convective heat transfer on a vertical plane surface with steps on it. Such a geometry of the heated surface is used in many practical problems and technical instruments and also as one of the means of heat transfer enhancement.

The effect of steps on heat transfer by natural convection in a vertical liquid layer with isothermal side walls at the temperatures T_1 and T_2 ($T_1 > T_2$) was investigated in [1]. A single step, which is installed on a vertical wall and whose height corresponds to twice the distance from the wall to the region of the velocity maximum, exerts an insignificant effect on the velocity profile already at a distance on the order of 3.5 step heights. In the presence of a step having a height of the order of the boundary layer thickness its effect on the temperature profile is small already at a distance from the step equal to the height of the latter, which the deviation of the local Nusselt number from the experimental relationship for a flow without steps does not exceed 13% [1]. Experimental data on heat transfer were obtained for single steps of height $\Delta x = 10$ mm and width equal to 10 mm, as well as for regular steps of height $x = 5$ mm installed at intervals of 20 mm.

An experimental investigation of free convection on a vertical surface of constant temperature with an upstream-facing step was performed in [2]. Generalized relations obtained for the heat transfer coefficient at Pr $= 0.7$ and $Gr_x = 2 \cdot 10^5 - 10^7$ describe experimental data with an error of 20%. The heat transfer coefficient decreases up to the point of discontinuity, has zero value at the point, then increases downstream, and attains a constant value typical of a flat plate at a sufficient distance [3]. In [4] an experimental study was performed concerning the effect of four configurations of side fins, differing in material and geometric dimensions, on the free convective heat transfer of a vertical isothermal copper plate. An empirical relation describing experimental data within the range of Pr numbers from 4.75 to 5.25 and Ra numbers from $8.5 \cdot 10^7$ to 10^9 has an error of about 1%. A universal relation was also obtained for the rate of heat transfer from single bodies of different shapes located on the vertical wall of a plane channel with free convective motion of air [5]. Short cylinders and rectangular parallelepipeds made from steel and aluminum were used as the objects of investigation. A generalized relation for the mean value of the heat transfer coefficient is valid within the range of Grashof numbers $d1.5 \cdot 10^3 \le Gr \le 1.1 \cdot 10^6$.

Unsteady-state free-convective heat transfer in vertical parallel plates with a rectangular fin was investigated experimentally for the cases of transient processes upon the turning-on and turnining-off of heating

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[6] and local steady-state conditions with asymmteric uniform heating [7]. It is shown that the heat transfer characteristics in the region downstream of a barrier are similat to the characteristics of a turbulent flow, even though the Rayleigh number in the experiments changed from $3.75 \cdot 10^8$ to $1.93 \cdot 10^9$, which corresponds to a laminar mode for an equivalent heated flat plate. Measurements of convective heat flux were made and new relations for the Nusselt numbers were suggested that described the local characteristics of the fin in the downstream region.

An experimental and theoretical investigation of laminar natural convection of air in a vertical channel with a single barrier was carried out in [8]. Using optical methods with a Wollaston prism interferometer and a Mach-Zehnder interferometer, the distributions of temperature and heat flux were obtained for an isothermal wall, as well as visual flow patterns. Numerical calculations were performed for two types of boundary conditions: constant temperature and constant heat flux on the channel walls. The presence of the barrier leads to a substantial change in the intensity of heat transfer compared to smooth walls. As the flow velocity near the barrier increases, the local heat transfer coefficient rises up to a certain maximum value, then falls to a minimum together with the velocity, and then increases again. This tendency was noted for all of the values of the Ra number investigated, which changed from 10^2 to 10^4. However, the mean value of the heat transfer coefficient turned out to be smaller than that for a smooth channel, which is due to the decrease in the flow velocity and the occurrence of circulational flows caused by the presence of the barrier. In this case, the mean value of the Nusselt number decreases by 5% at $\mathrm{Ra} = 10^4$ and by 40% at $\mathrm{Ra} = 10$ for the case of a constant temperature on the channel walls.

Visualization of the flow and measurement of the temperature field in the region behind a downstream-facing step in the case of natural convection of water near a vertical plate with a rectangular bend were made in [9]. The flow and heat transfer behind a two-dimensional step in a flow of deaerated water on a vertical plane surface were investigated experimentally in [10]. The surface of the step and the vertical heat transfer surfaces were heated by uniform and homogeneous heat fluxes. The range of Grashof numbers at the entrance to the separation zone amounted to $4 \cdot 10^6 - 2 \cdot 10^9$. With the length of the surface ahead of the step being equal to 30, 60, and 120 mm, the height of the step varied from 0 to 70 mm. Temperature fields were measured by Chromel-Alumel thermocouples. To visualize the flow and the temperature field, dyes and thermosensitive plates on liquid crystals were used. When the step had a small height, a separationless flow was observed, but as the height increased, separation of the flow and transition to a turbulent flow occurred. Natural convection regimes of heat transfer and wall temperature distributions along a vertical flat plate with various steps were also investigated in [11].

Experimental Methods and Equipment. As the object of investigation in the present work we used a steel plate having a thickness of 2 mm and overall dimensions of 0.2×0.3 m. The plate was heated by passing an alternating current through it and through copper contact leads fastened at the ends. On the plate we mounted fluoroplastic steps of length 0.2 m and transverse dimensions 10×10 mm. During the experiment we varied the power of heat release on the plate, the number of steps, and the spacing between them. The temperature field in the boundary layer was investigated with the use of a Mach-Zehnder interferometer. The plate was installed vertically in the test section of the interferometer. As a source of light we used a 1-kW mercury lamp, the radiation from which was passed through an interference filter emitting light with the wavelength $\lambda = 0.543$ μm. A picture of the flow near the vertical plate with the step was recorded by a photographic camera with a framing speed of 2 frames/sec and exposure times of 1/8, 1/4, 1/2, and 1 sec. Before the start of the experiment, the interferometer was tuned to a band of infinite width.

Free convective flow near a vertical plate, which was subjected to a constant heat flux and on which one or several rectangular steps were installed, was visualized by means of a laser knife. As a light source we used an ion laser whose emission was shaped in the form of a thin band of light of the required dimensions by means of an optical system consisting of three lenses: two spherical focusing ones and a cylindrical one. The flow was visualized using fine powder [12]. During the photographic recording of the process the axis of the camera objective was directed normally to the laser beam. To eliminate reflection glare, the plate was thoroughly blackened.

Experimental Investigation of the Temperature Field. The investigation of the temperature fields on a vertical surface subjected to a constant heat flux was carried out for a plate with one, two, and free rectangular steps spaced 30 mm apart. The magnitude of the heat flux on the wall varied within the limits $q_w = 0 - 10^3$ W/m^2. An increase in the power of heat release leads to an increase in the rate of the heating of the plate and in the heat

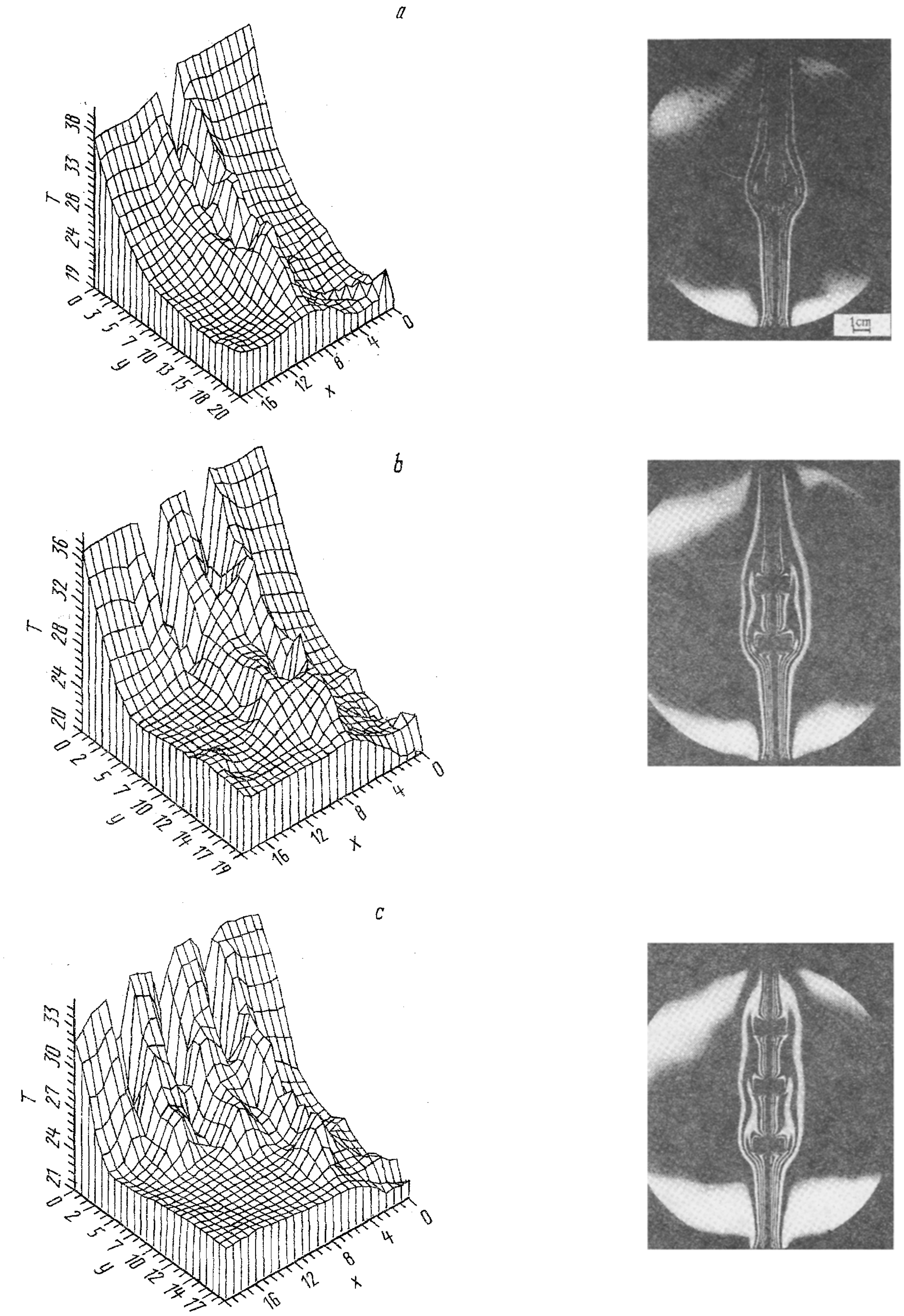

Fig. 1. Interferograms and corresponding graphs of temperature distribution on a plate with one (a), two (b), and three (c) steps.

transfer enhancement, but does not change the qualitative interference pattern of the flow. The interference pictures of the temperature field in the boundary layer near the vertical plate with one, two, and three steps at a constant heat flux on the wall of $q_w = 325$ W/m^2 are presented in Fig. 1. The pictures were taken with an exposure time of 1/15 sec after a lapse of 45 sec from the start of plate heating. The results of longitudinal visualization showed that in these experiments the free convective flow near the plate can be considered to be two-dimensional with a sufficiently high degree of accuracy. Therefore, when processing interferograms in order to calculate the temperature field near the plate we assumed that the temperature was independent of the coordinate in the direction of the probing radiation propagation in the interferometer except for the ends of the plate, subject to end effects.

To calculate the temperature corresponding to the i-th interference band we used a relation obtained in [13]:

$$T_i = \frac{(n_0 - 1)\, P_\infty T_0 T_\infty z}{(n_0 - 1)\, P_\infty T_0 z - k\lambda P_0 T_\infty}. \tag{1}$$

In Fig. 1, graphs of the temperature distribution in a boundary layer near a vertical plate with steps are presented alongside the corresponding interferograms. In the given case the fluoroplastic step is not a heat-producing element; it is heated from the steel plate and therefore the surface temperature of the step is somewhat lower than that of the plate. In the case of one step (see Fig. 1a) the temperature distribution across the boundary layer (along the y coordinate) is monotonic in the region upstream and downstream of the step. In these regions the thermal boundary layer thickness almost doubles compared to the nonperturbed region of the free convective flow ahead of the step. The temperature distribution in the region facing the step has a wavy character, which is observed on the interferogram in the form of alternating bands with close numbers. Such a behavior of the temperature can be explained by the inflow of a hotter gas into the space between the boundary layer on the step surface and the colder region in the surrounding gas as a result of the retarding effect of the step. We should note a relatively low transverse temperature gradient in the region located immediately behind the step, indicating the presence of intense convective heat transfer in it. With two or three steps located in a vertical plate (Figs. 1b and c) the temperature field near the barriers is similar to the temperature distribution near a single step, but in this case we observe a decrease in the transverse temperature gradient in the boundary layer on the steps farther downstream. The perturbing action of the steps leads to a wavy character of the temperature distribution along the boundary layer. The temperature field regions between the steps are characterized by a smaller transverse temperature gradient. This is associated with convective mixing of gas layers having different temperatures. It should be noted that in the case of two and especially three steps the transverse temperature gradient on the plate increases at a certain distance downstream of the barriers compared to the gradient on the plate upstream of the steps.

Results of Flow Visualization. As is seen from Fig. 2, the presence of steps on a plate spaced 20 mm apart causes separation of the dynamic boundary layer, which flows smoothly past the barriers. In the separation region immediately behind the step one observes circulational flows at the wall consisting of two oppositely rotating vortices. It is obvious that the presence of the relatively low transverse temperature gradient in the region between the steps that is recorded during interferometric measurements is caused by the existence of these eddy flows, which ensure an intense convective heat transfer. The vortex motion of the gas occupies the entire region between the steps, though one should expect the occurrence of a stagnation zone upstream of the second and third steps.

In the case where the spacing between the steps is 10 mm (the region between them has the shape of a square), the separation flow that appears consists of two oppositely rotating circular vortices. With an increase in the width of the gap to 30 mm (which corresponds to a ratio of the gap width to the step height of 1:3), the vortices become more elongated and a small stagnant zone is formed in the region immediately adjacent to the second step. A further increase in the width of the gap leads to an increase in the stagnant zone dimensions and ends with the attachment of the dynamic boundary layer to the plate in the region between the steps.

Conclusions. In natural convection on a vertical heated plate in the presence of one or several rectangular steps, separation of the dynamic boundary layer occurs, which is accompanied by the appearance of a circulating

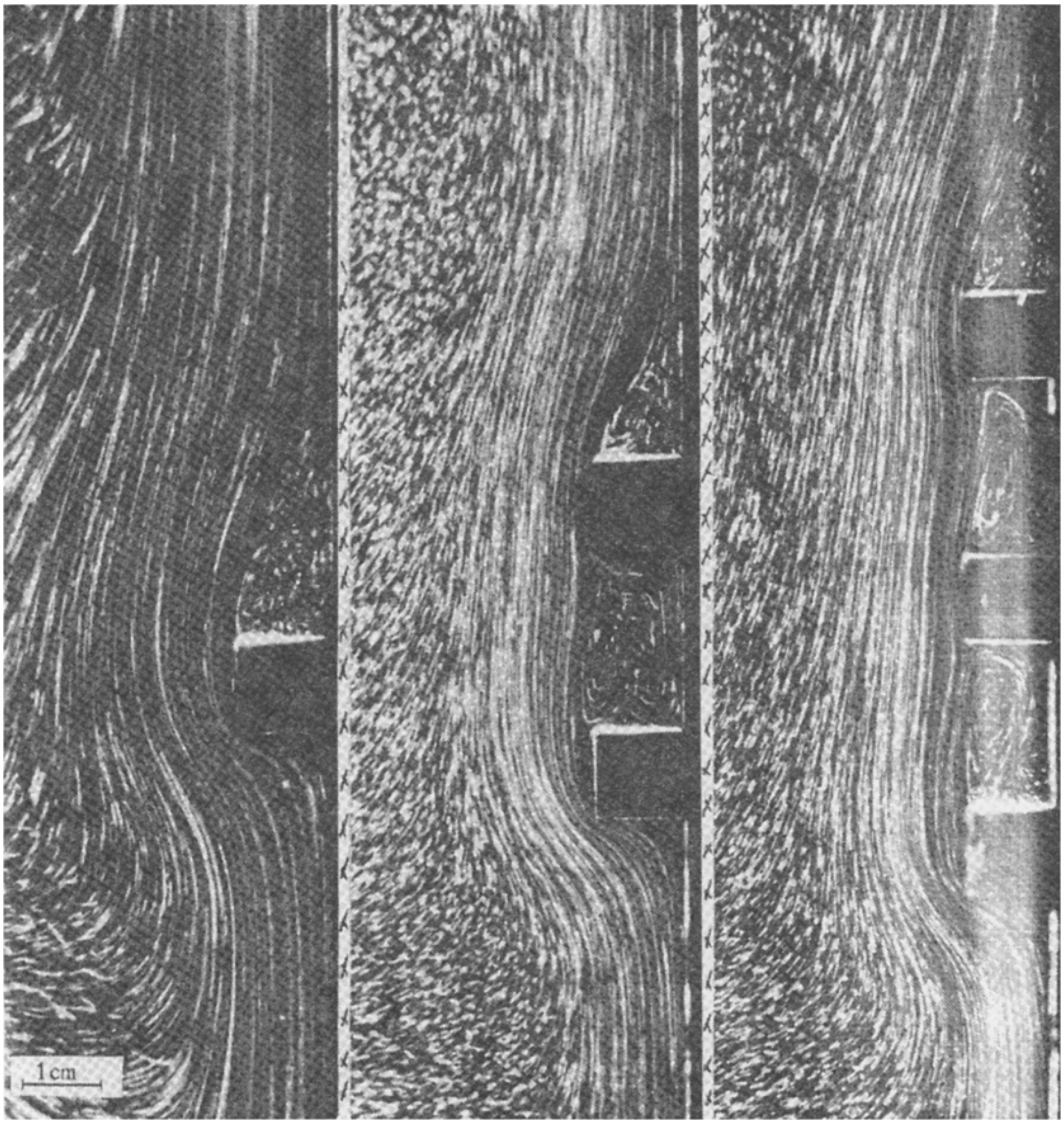

Fig. 2. Photographs of track visualization of a free convective flow on a vertical plate subjected to a constant heat flux in the presence of one or several rectangular steps spaced 20 mm apart.

flow in the separation region consisting of two oppositely rotating vortices. The rotational flow that appears in the region between the steps intensifies the process of heat transfer between the plate and the surrounding medium for ratios of the gap width to the step height from 1:1 to 1:3. At large values of the gap a stagnant zone appears in the gas flow near the upsteam step in which convective heat transfer is virtually absent, and heat is transferred between the plate and the surrounding medium primarily by heat conduction. The thermal boundary layer thickness on the plate increases substantially in the region of the steps. In the case of several steps the longitudinal temperature distribution near the barries has a wavy character clearly demonstrated by the interferograms presented. As a result of the retarding effect of a step near its side surface the regions of the heated and the cold gas mix on the surface of the step and in the surrounding medium, and this weakens the process of heat transfer between them.

NOTATION

λ, wavelength of probing radiation, μm; q_w, power of heat release on the wall, W/m^2; z, coordinate in the direction of propagation of probing radiation, m; T_i, temperature corresponding to the i-th interference band, °C;

n_0, refractive index of air under normal conditions; P_∞, surrounding-air pressure, Pa; T_∞, surrounding-air temperature, $^{\circ}$C.

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