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Experimental study of free-convective flow on a vertical plate with a constant heat flux in the presence of one or more steps

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Abstract—Free-convective heat transfer on a vertical plate with a constant heat flux in the presence of one or more regular steps on a plate was studied experimentally. Temperature fields were investigated by a Mach–Zehnder interferometer. The structure of free-convective flows on a plate was studied by the method of tracking visualization using a laser knife. A circulation free-convective flow, having the shape of two oppositely rotating vortices, was observed directly behind a step. During the experiment the Rayleigh number varied from zero to $Ra = 2.8 \times 10^3$. The maximum Rayleigh number attained had a value $Ra \sim 2 \times 10^4$. The free-convective flow rate grew with Ra; however, qualitative changes in the structure of flow and of a temperature field were not observed in this case. The flow was visualized at different distances between the steps. As the width of the spacing between the steps increased, the vortices, arising in the separation zone, became more extended downstream. With the ratio of the step height to the spacing width equal to 1 : 3 and greater, a stagnation zone appeared near the first upstream step. A vortex flow between the steps enhanced heat transfer between the plate and environment.

1. INTRODUCTION

Recently free-convective heat transfer on a vertical flat surface with steps on it has been a highly studied aspect of natural convection [1–4]. This type of heated-surface geometry is used in many practical problems and engineering devices and is also one of the means for heat transfer enhancement.

The influence of steps on natural-convective heat transfer in a vertical liquid layer with isothermal side walls at temperatures T_1 and T_2 ($T_1 > T_2$) was studied in ref. [5]. One step, which was placed on a vertical wall and the height of which corresponded to double the distance from the wall to the maximum velocity zone, exerts insufficient effect on the velocity profile just at a distance of the order of 3.5 of the step height. In the presence of a step with a height of the order of the boundary-layer thickness its effect on the temperature profile is already small at a step-height distance from the step, and the deviation of the local Nusselt number value from the experimental relation for a flow without steps does not exceed 13% [5]. Experimental data on heat transfer are obtained for single steps with a height $\Delta x = 10$ mm and a width 10 mm, as well as for regular steps with $\Delta x = 5$ mm and a pitch equal to 20 mm.

An experimental study of free convection on a vertical surface at a constant temperature with a downstream-facing step is detailed in ref. [6]. The correlations for the heat transfer coefficient obtained for $Pr = 0.7$ and $Gr_x = 2 \times 10^5$–8×10^7 describe experimental data with an error of 20%. Heat transfer decreases before a separation point; at this point it has a zero value and then it grows upstream, and at a substantial distance from the separation point it attains a constant value characteristic for a flat plate [7]. In ref. [8] the effect of four configurations of side ribs, with different material and geometric dimensions, on the free-convective heat transfer of a vertical isothermal copper plate is studied experimentally. An empirical relation describing experimental data for Pr numbers ranging from 4.75 to 5.25 and Ra numbers ranging from 8.5×10^7 to 10^9 has an error of $\sim 1\%$. A universal relation is also obtained for heat transfer of single bodies of various shapes positioned on a vertical wall of a flat channel in a free-convective air flow [9]. Short cylinders and rectangular parallelepipeds, made of steel and aluminum, were the objects of the study. A correlation for an average heat transfer coefficient is valid for $1.5 \times 10^3 \leqslant Gr \leqslant 1.1 \times 10^6$.

Unsteady-state free-convective heat transfer in vertical parallel plates with a rectangular rib was studied experimentally for transient processes with heating ‘switch-on’ and ‘switch-off’ [10] and for a local steady-state regime under the conditions of asymmetric uniform heating [11]. It is shown that the characteristics of heat transfer in the downstream region behind the obstruction are similar to those of a turbulent flow, though the Rayleigh number in the experiments varied from 3.75×10^8 to 1.93×10^9, thus corresponding to a laminar regime for an equivalent heated flat plate. A convective heat flux is measured and new relations are

NOMENCLATURE

n_0	coefficient of air refraction under normal conditions
P_∞	pressure of surrounding air [Pa]
q_w	heat liberation rate on a wall [W m^{-1}]
T_i	temperature corresponding to the ith interference fringe [°C]
T_∞	temperature of surrounding air [°C]
z	coordinate in the direction of probing radiation propagation [m].

Greek symbol

λ	wavelength of probing radiation [μm].

suggested for Nusselt numbers that describe the local characteristics of a rib in a downstream region.

Air laminar natural convection in a vertical channel with a single obstruction was experimentally and theoretically studied in ref. [11]. By optical methods and using a Wollaston prism interferometer and a Mach–Zehnder interferometer the distributions of temperature and heat flux are obtained for an isothermal wall and visual flow patterns. Numerical calculations are performed for two cases of boundary conditions: constant temperature and constant heat flux on a channel wall. The presence of the obstruction leads to a substantial change in the heat transfer rate as compared with the unobstructed walls. As the velocity of flow increases in the vicinity of the obstruction, the local heat transfer coefficient increases to a maximum value, then decreases further up the channel, where velocity decreases to a minimum value and then increases again. This tendency is noted for all the studied values of the *Ra* number, which varied from 10^2 to 10^4. However, an average value of the heat transfer coefficient turns out to be smaller than an unobstructed channel; this fact is stipulated by the decrease in the flow velocity and origination of circulation flows caused by the presence of an obstruction. Here an average Nusselt number reduces by 5% at $Ra = 10^4$ and by 40% at $Ra = 10$ for the case of constant temperature at the channel wall.

Flow visualization and measurements of a temperature field in the zone behind the downstream-facing obstruction, in a water natural-convective flow near a vertical plate with a rectangular bend, were conducted in ref. [2]. Flow and heat transfer behind a two-dimensional obstruction in de-aerated water on a vertical plate surface are experimentally studied in ref. [3]. The obstruction surface and vertical heat transfer surfaces were heated by uniform heat fluxes. Grashof numbers at the separation zone entrance ranged from 4×10^6 to 2×10^9. With the surface length in front of the step being 30, 60 and 120 mm, its height varied from 0 to 70 mm. Temperature fields were measured by chromel–alumel thermocouples. To visualize a flow and a temperature field use was made of dyes and thermally sensitive liquid-crystal plates. At a small step height a non-separation flow is observed, but with the growth of height the flow separates and a transition to turbulent flow occurs. The modes of free-convective heat transfer and of wall temperature distributions along a vertical flat plate in application of different steps are also thoroughly studied in ref. [4].

2. EXPERIMENTAL TECHNIQUES AND EQUIPMENT

In the present paper a steel plate with dimensions 0.2×0.3 m^2 and 2 mm in thickness was used as a test object. The plate was heated by transmitting a.c. through copper contact busbars fastened at the ends. 0.2 m-long fluoroplastic obstructions with dimensions 10×10 mm^2 were mounted on the plate. During the experiment the heat liberation rate on the plate, the number of obstructions and the spacing between them were changed. The temperature field in a boundary layer was studied with a Mach–Zehnder interferometer (Fig. 1). The test plate was vertically positioned in the interferometer operation region. A 1 kW power mercury lamp, whose radiation was transmitted through an interference filter selecting the light with wavelength $\lambda = 0.543$ μm, was used as a light source. A visual flow pattern near a vertical plate with an obstruction was registered by a photographic camera with a frequency of shooting of 2 frames per second and exposure times 1/8, 1/4, 1/2, and 1 s. Before the experiment the interferometer was adjusted to the infinite-width fringe.

A free-convective flow near a vertical plate with a constant heat flux, on which one or more rectangular obstructions were positioned, was visualized by a laser knife (Fig. 2). An ionized laser, whose radiation was formed as a thin light strip of the required dimensions by an optical system consisting of three lenses (two spherical focusing and one cylindrical), was used as a light source. Visualizing particles were fine powder [12]. On photographic recording of the process, the axis of a photographic chamber objective was directed perpendicularly to a laser beam. To eliminate hotspots the test plate was thoroughly blackened.

3. EXPERIMENTAL STUDY OF A TEMPERATURE FIELD

The study of temperature fields on a vertical surface with a constant heat flux was performed for a plate with one, two or three rectangular steps with a spacing between them equal to 30 mm. The heat flux value on a wall varied within the limits $q_w = 0$–10^3 W m^{-2}. An

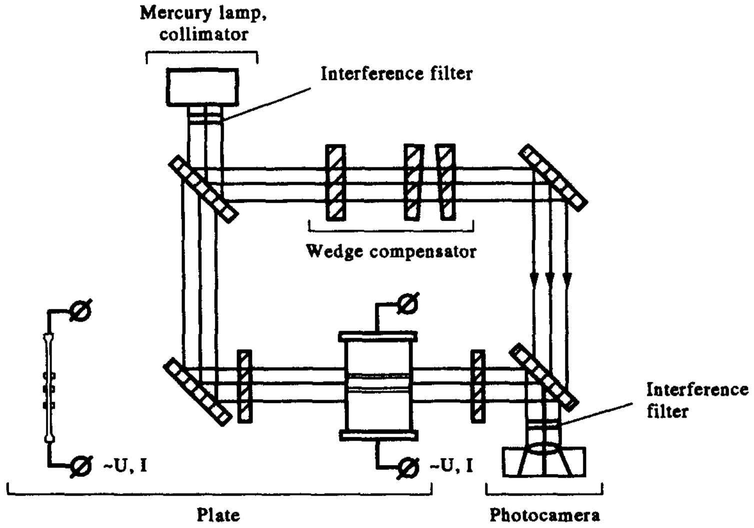

Fig. 1. Schematic diagram of studying the temperature field on the plate with a Mach–Zehnder interferometer.

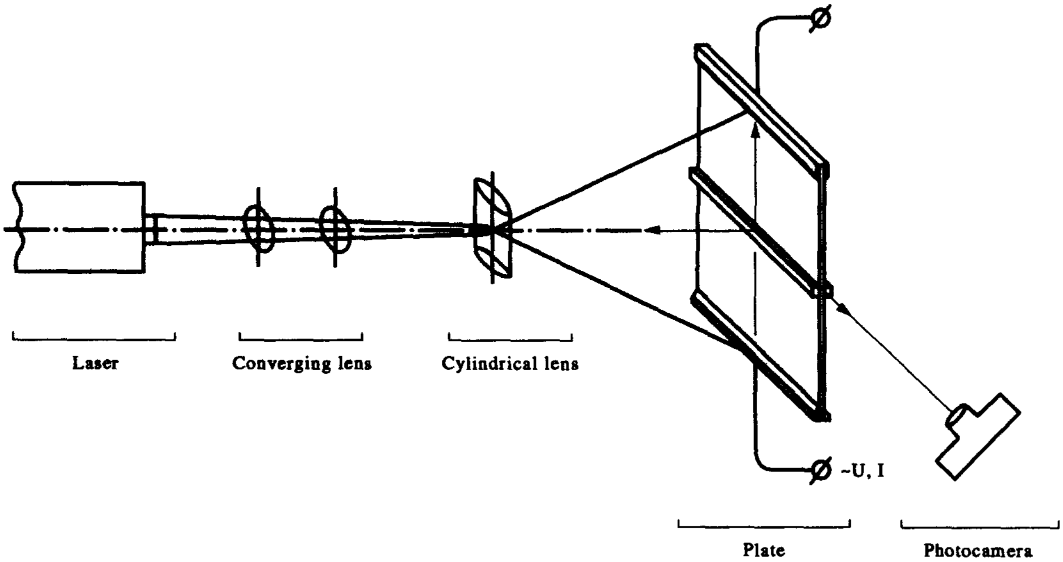

Fig. 2. Schematic diagram of tracking visualization of free-convective flow on the plate using a laser knife.

increase in heat liberation power results in the growth of the plate heating rate and in heat transfer enhancement, but it does not qualitatively change the observed interference flow pattern. Figure 3 depicts the interference pictures of a temperature field in a boundary layer in the vicinity of a vertical plate with one (a), two (b) and three (c) steps at a constant heat flux on a wall $q_w = 325\ \mathrm{W\ m^{-2}}$. Photographing was performed with an exposure time of 1/15 s in 45 s starting from the onset of plate heating. The results of longitudinal visualization showed that, with a very good accuracy, a free-convective flow near a plate in these experiments may be considered two-dimensional. Therefore, on processing the interferograms for calculating the temperature field near the plate it was assumed that temperature is independent of the coordinate z in the direction of propagation of the probing radiation in the interferometer, excluding the plate edges where end effects manifest themselves.

To calculate the temperature corresponding to the ith interference fringe the following relation was used [13]:

$$T_i = \frac{(n_o - 1)P_\infty T_o T_\infty z}{(n_o - 1)P_\infty T_o z - k\lambda P_o T_\infty}. \tag{1}$$

In Fig. 3, next to the corresponding interferograms, the graphs of temperature distribution in the boundary layer near the vertical obstructed plate are presented. In this case a fluoroplastic step is not a heat releasing element and it is heated from a steel plate; therefore the step surface temperature is somewhat lower than the plate surface temperature. In the case of one step, as follows from the interferogram and the temperature-field graph given in Fig. 3, the tem-

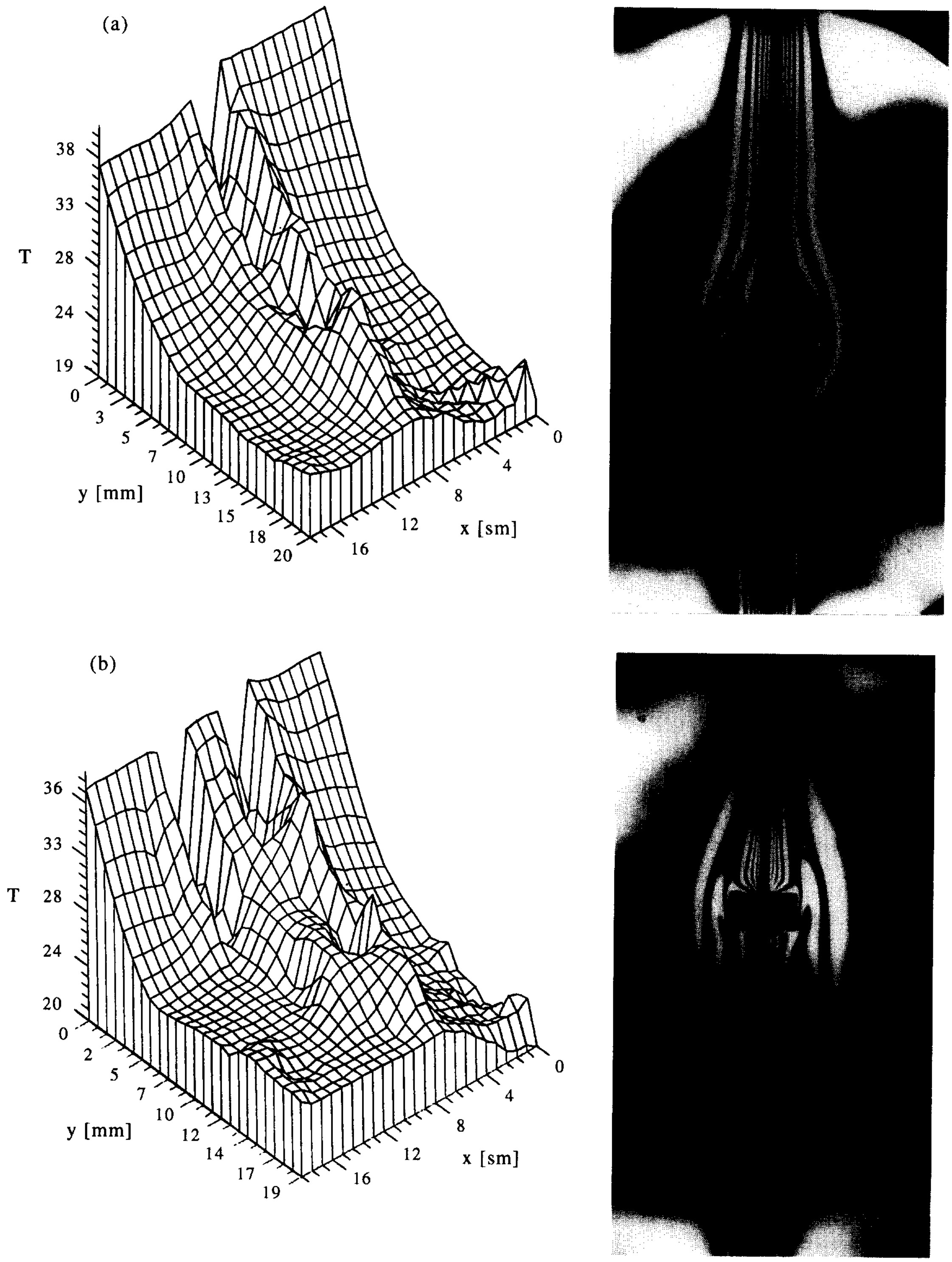

Fig. 3. Interferogram and the corresponding graph of temperature distribution on the plate in the presence of (a) one, (b) two and (c) three steps.

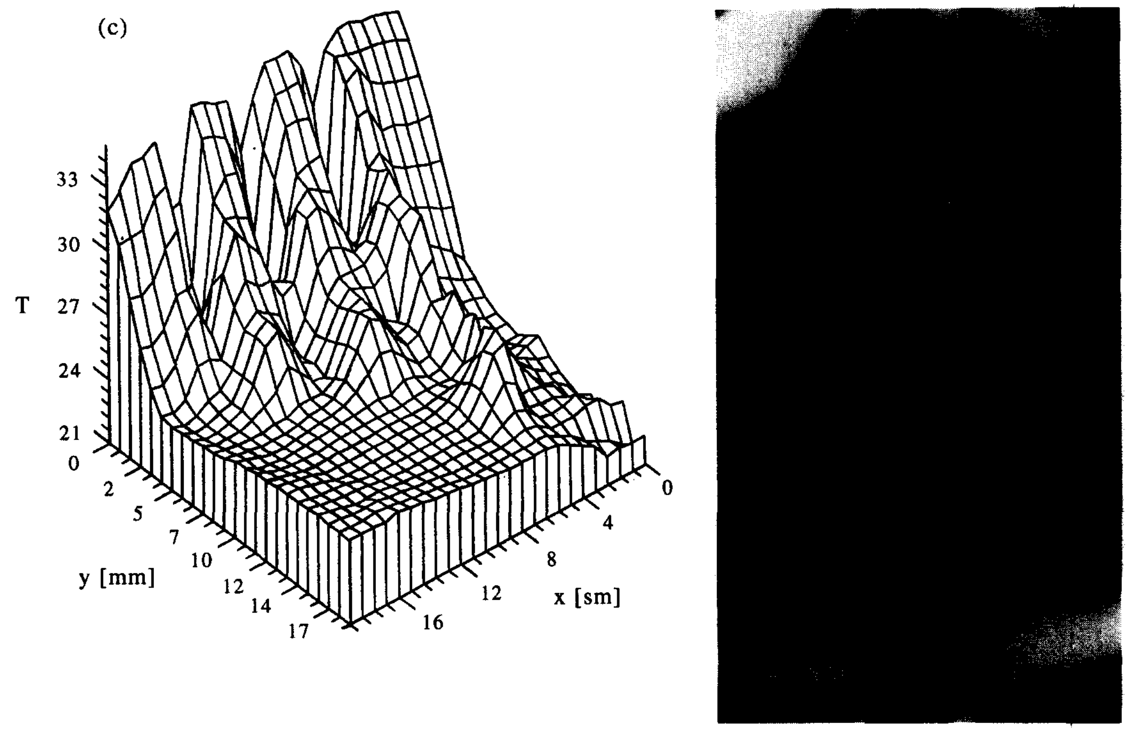

Fig. 3—*continued.*

perature distribution across a boundary layer (along the coordinate y) is monotonous in front of and behind a step. Here, the thermal boundary-layer thickness in these regions becomes approximately twice as large as that of a non-disturbed zone of a free-convective flow in front of a step. The temperature distribution opposite a step has a wavy character, which is observed on the interferogram in the form of alternating fringes with close numbers in this region. Such temperature variation character may be explained by hot gas flow into the space between a boundary layer on the step surface and by a colder region of surrounding gas, resulting from the decelerating effect of a step. A relatively low transverse temperature gradient in the zone directly behind the step, which indicates the presence of intense convective heat transfer in it, should be noted. In the case of two or three steps positioned on a vertical plate (Fig. 3(a) and (b)) the temperature field in the vicinity of obstructions is similar to the temperature distribution near one step; however, here, the reduction of the transverse temperature gradient in a boundary layer downstream of the steps is observed. The disturbing effect of steps results in a 'wavy' temperature distribution along a boundary layer. The regions of the temperature field between the steps are characterized by a smaller transverse temperature gradient. This is related to the presence of convective mixing of gas layers having different temperatures. It should be noted that in the presence of two, and especially three steps, the transverse temperature gradient on a plate increases at some distance behind the obstruction relative to the gradient on the plate before the steps.

4. RESULTS OF FLOW VISUALIZATION

The tracking visualization photographs of a free-convective flow on a vertical plate with a constant heat flux in the presence of one or several rectangular steps with a spacing of 20 mm between them are presented in Fig. 4. As is seen from the figure the presence of steps on the plate causes the separation of a dynamic boundary layer which smoothly bends the zone of obstructions. Near-wall circulation flows composed of two oppositely rotating vortices are observed in the separation zone directly behind a step. It is obvious that the presence of a relatively low transient temperature gradient in the zone between the steps, recorded in the interferometric measurements, is stipulated by the existence of these vortical flows providing intense convective heat transfer. As is seen from Fig. 4, a vortical gas flow occupies the entire zone between the steps, though in front of the second and third steps one should expect the origination of the stagnation zone.

Figure 5 presents the flow patterns that were obtained by the visualization of flow on a vertical plate at different values of the width of a spacing between two steps in order to reveal its effect on the arising vortex flow. The distance between the steps given on the photographs amounted to 10 mm and 30 mm. For a distance 10 mm (the region between the steps has a shape of a square), the arising separation flow represents two oppositely rotating vortices. With an increase in the spacing width to 30 mm (this corresponds to a ratio of the spacing width to the step height equal to 1 : 3) the shape of the vortices becomes

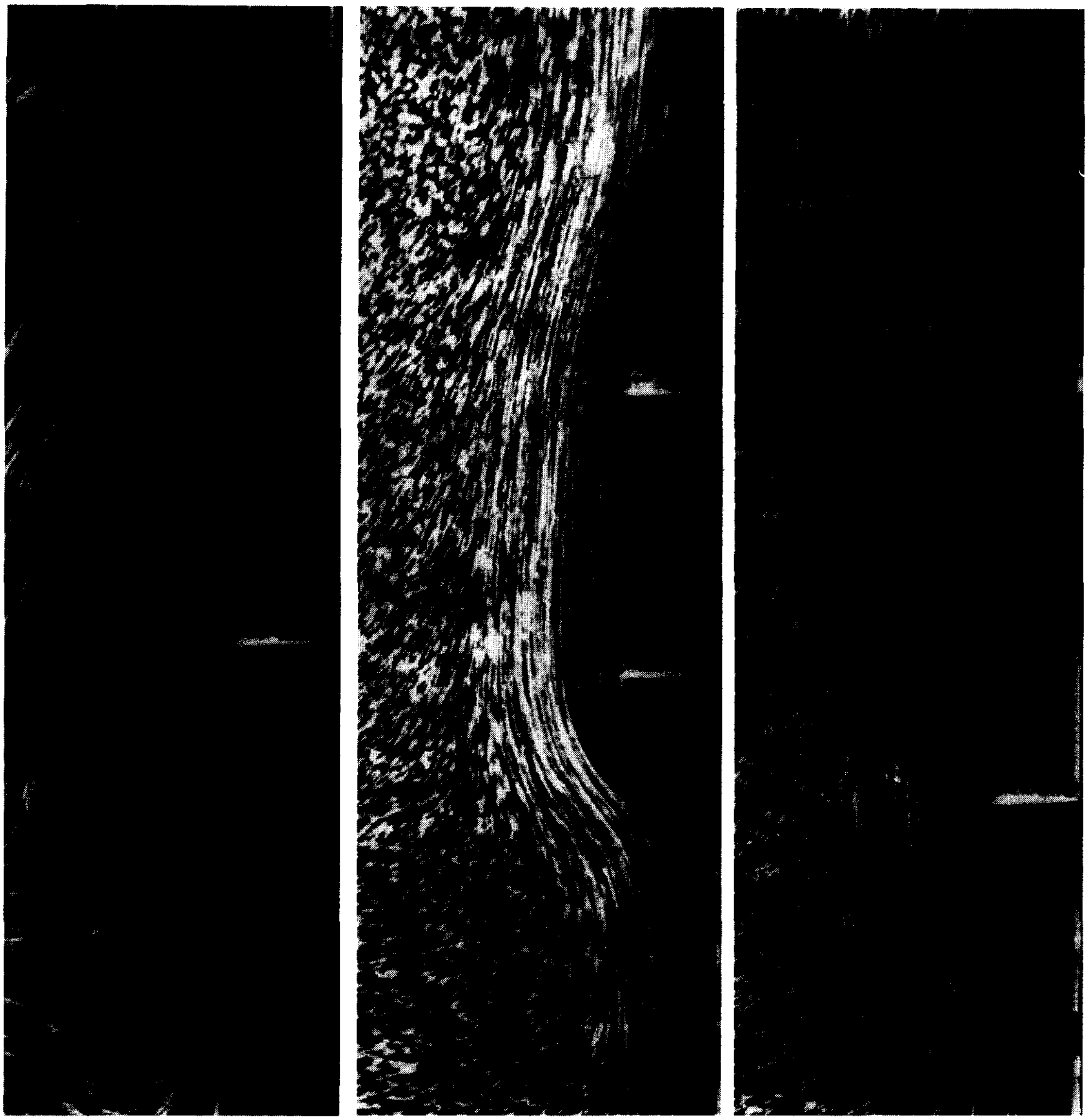

Fig. 4. Photographs of tracking visualization of free-convective flow on a vertical plate with a constant heat flux in the presence of one or more rectangular steps.

more extended and in the region directly attaching to the second step a small stagnation zone is formed. Further growth of the spacing width leads to an increase in the dimensions of the stagnation zone and is completed by a dynamic boundary layer sticking to the plate in the region between the steps.

5. CONCLUSIONS

In the process of natural convection on a vertical heated plate in the presence of one or more rectangular steps, a separation of a dynamic boundary layer originates, accompanied by the appearance of a circulation flow composed of two oppositely rotating vortices, in the separation zone. The originating vortical flow in the region between the steps enhances heat transfer between the plate and environment at a ratio of spacing width to step height ranging from 1 : 1 to 1 : 3. At large values of the spacing a separation zone, in which convective heat transfer is virtually absent, appears near the first upstream step, and heat transfer between the plate and environment takes place predominantly due to heat conduction. The thermal boundary-layer thickness on the plate greatly increases in the vicinity of the steps. In the presence of one or more steps, longitudinal temperature distribution near the obstructions has a wavy character, which is illustrated by the interferograms presented in the paper. As a result of step deceleration effects near its side surface, the zones of hot and cold gases on the

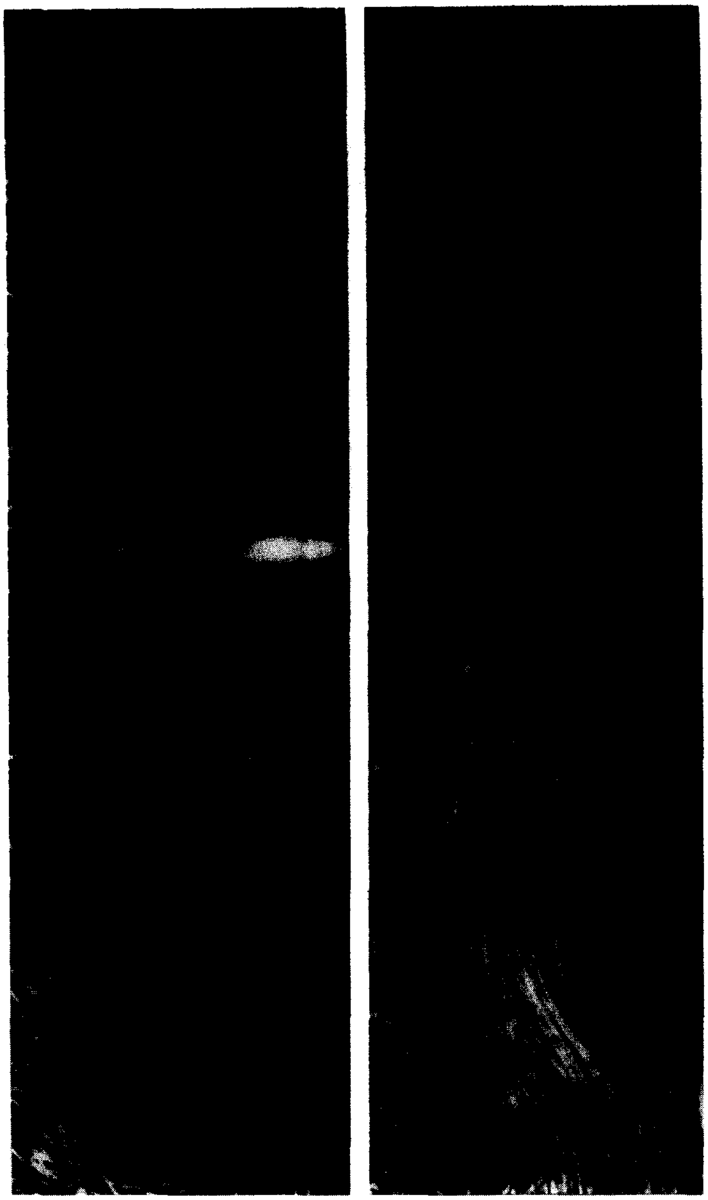

Fig. 5. Visualization results of free-convective flow on the plate with a spacing between the steps of 10 and 30 mm.

step surface and in its environment are mixed, which weakens the process of heat transfer between them.

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