POROUS BLOWING IN AND DRAWING OFF IN THE CASE OF FREE CONVECTION ON A HORIZONTAL PERMEABLE SURFACE

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UDC 532.546:536.25

The process of formation of a thermal layer near a horizontal surface in free convection is studied. The experimental apparatus is described. It is shown that there is an outer, and a central zone with their own heat-exchange laws. Formulas are given for calculation of heat exchange in each of these zones.

In view of its considerable practical importance, the problem of heat exchange on a horizontal surface, with the heated side turned upwards (downwards) is constantly the subject of careful study. A whole series of works, especially those of an experimental nature have been carried out so far; these works give theoretical relationships for finding the mean heat-exchange coefficients, [1-6], and an experimental temperature profile in the layer of air adjoining the heated horizontal surface is plotted in [2]. The difference in the choice of the characteristic temperature, the characteristic dimension, and the method of processing the experimental data, which leads to differences in theoretical formulas, must be pointed out.

Attempts have been made to give a simplified physical model and theoretical relationships to find heat-exchange coefficients for a horizontal surface with the heated surface turned upwards [8], and downwards [7].

In this work the heat exchange on the horizontal surface, complicated by a uniform blowing in (drawing off) is examined. A mathematical formulation of the stated problem for the heat-exchange zone close to the edge of the plate was given previously in [9] and [10] from the point of view of the boundary layer.

Experimental investigation has shown that there are two zones with their characteristic laws of the formation of the boundary layer: a zone influenced by the edges, and the central zone where the edges have no influence; this is clearly seen on the interferograms in Fig. 1 (the heated plate is seen as a black solid strip).

In order to study the heat-exchange process experimentally an experimental apparatus was designed. The diagram, and a detailed description of this apparatus were given in [14]. Porous copper plates with a porosity factor of 0.5 served as the working surfaces. The dimensions of the heat emitting surface were 300 × 400 mm. The plate was heated by means of infrared incandescent lamps provided with reflectors, which enabled a uniform temperature to be obtained over a large part of the surface. The discharge of blown in (drawn off) air was measured by the rotameters RS-3a and RS-5. The experiments were carried out with air. The range of variation of the main parameters was as follows: the temperature drop between the porous surface and the surrounding medium was 5-50°C, the Grashof number reached a value of $1.5 \cdot 10^7$, and the blowing in (drawing off) parameter for the boundary zone was $0 \leq \omega_1 \leq |0.6|$, and for the central zone – $0 \leq \omega_2 \leq |0.4|$. For blowing in ω_1 and ω_2 are positive, but for drawing off they are negative. The temperatures of the surface, and of the surrounding medium were taken as the characteristic temperatures in $\mathrm{Re_W}$ and $\mathrm{Gr_X}$ numbers, respectively.

Investigation of the formation of thermal layers near the walls, and the finding of the heat-exchange coefficients (Figs. 2 and 3), and the temperature profiles (Fig. 4) were carried out by the Mach–Zehnder interferometer of the type IZK-454 with a working field diameter of 225 ± 5 mm.

Scientific-Research Institute of Structural Physics, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 18, No. 4, pp. 617-623, April, 1970. Original article submitted July 1, 1969.

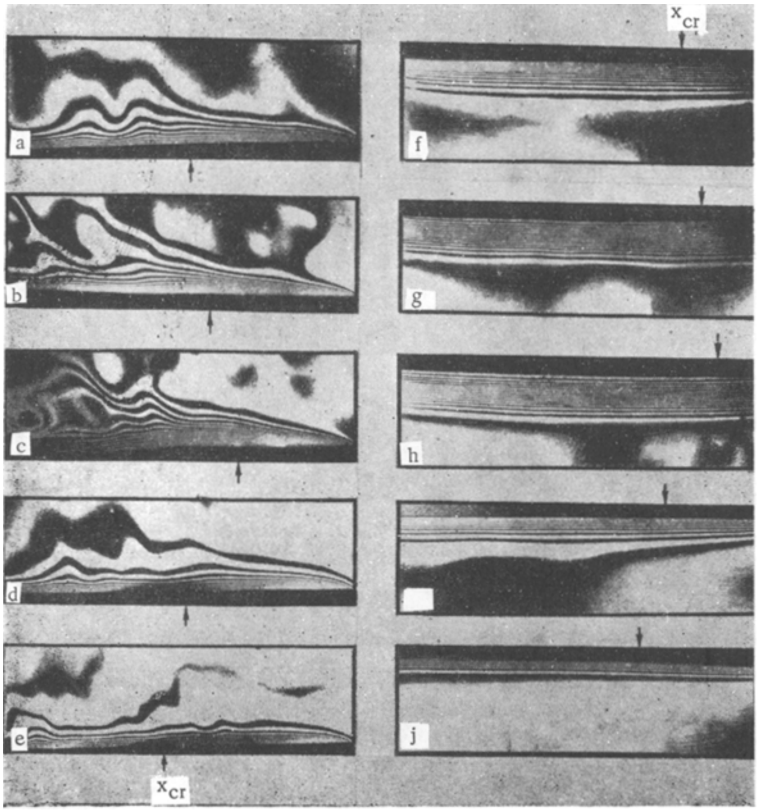

Fig. 1. Interferograms of the thermal boundary layer on free convection on the heated permeable horizontal surface turned upwards [a) $\omega_2 = 0$; b) 0.13; c) 0.27; d) −0.15; e) −0.36], and downwards [f) 0; g) 0.1; h) 0.17; i) −0.125; and j) −0.2].

It appeared possible to study the heat-exchange process over the whole heated surface by displacing the interferometer in a horizontal direction. The method of reading the interferograms was taken from [11]. The length of the model along the path of the light beam was 400 mm.

Visual study of the formation of a heated layer near the wall in the edge zone for the top and the bottom reveal features characteristic of a laminar boundary layer, that is, increase of the thickness with increase of the coordinate x, and the steady nature of the flow. The thermal boundary layers of the central zones for the top and the bottom differ sharply from one another. In connection with this it is useful to examine them separately.

1. The Heated Surface Turned Upwards. The nature of the formation of a thermal boundary layer under the influence of blowing in (drawing off): is clearly seen on the interferograms (Fig. 1a–e). The boundary layer begins from the edge of the plate, and increases towards the center. Ascending air currents in the form of a flare in which irregular waves are observed are noticeable in the central zone. The boundary layer is forced back in the presence of blowing in (Fig. 1b, c), and, consequently, the heat exchange is reduced; in the case of drawing off, on the other hand, the picture is the reverse. The boundary of the intermediate zone x_{cr} marked with arrows on the interferograms was determined by visual observation beyond the boundary layer, and from the variation of the local heat-exchange coefficient which is proportional to $Gr_x^{1/5}$ for the boundary zone, and to $\sim Gr_x^{1/3}$ for the central zone. We also note here that the critical Grashof number, which characterizes the transition of the flow from the edge zone to the central zone, can be found from the following relationship in the presence of blowing (drawing off):

$$\frac{Gr_{x\,cr}}{Gr_{x_0 cr}} \approx 1 - (0.2\text{-}0.3)\,\omega_1. \qquad (1)$$

The Grashof number used in the expression ω_1 must be less than the critical $Gr_{x\,cr}$. It is established experimentally that the critical Grashof number for an impermeable surface $Gr_{x_0 cr} \sim 2 \cdot 10^5$, which is

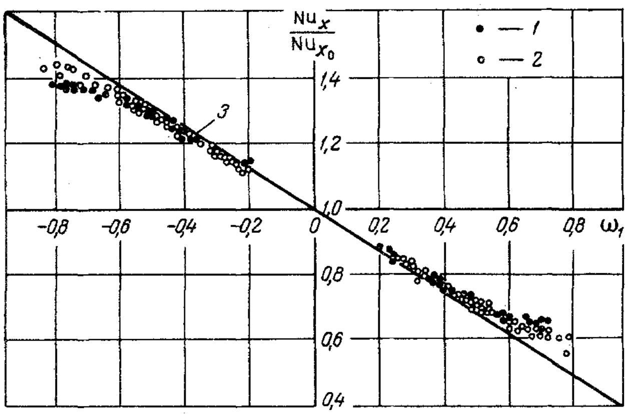

Fig. 2

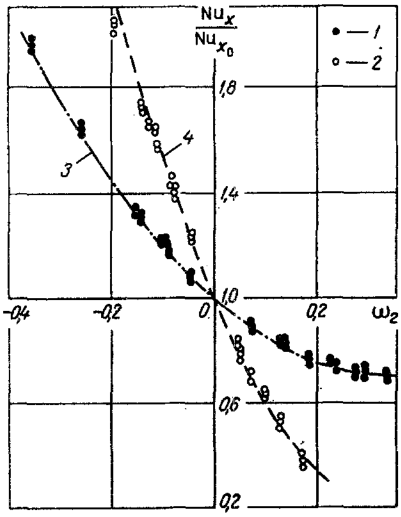

Fig. 3

Fig. 2. The influence of blowing in (drawing off) on the dimensionless local heat-exchange coefficient where $Gr_x < Gr_{xcr}$ for Pr = 0.72 [1, 2) experimental data for a horizontal surface turned upwards, and downwards, respectively; 3) theoretical solution of the authors [9, 10]].

Fig. 3. Influence of blowing in (drawing off) on the dimensionless local heat-exchange coefficient where $Gr_x > Gr_{xcr}$ for Pr = 0.72 [1, 2) experimental data for a horizontal surface turned upwards, and downwards, respectively; 3, 4) curves according to formulae (4), and (7)].

considerably lower than for a vertical surface ($Gr_{xcr} \sim 2 \cdot 10^7$). Such a decrease of the critical value of the Grashof number in comparison with the vertical surface is determined by the presence of a lateral pressure gradient, which promotes turbulence of the boundary layer.

a) The Edge Zone. The processing of experimental data is given in Fig. 3 where the relative values of the dimensionless local heat-exchange coefficient Nu_x/Nu_{x_0} are given on the ordinate, and the dimensionless parameter of blowing in (drawing off) is given on the abscissa. The theoretical curve obtained previously by the authors [9, 10] is also plotted there for comparison. In order to evaluate the influence of blowing in (drawing off) on the heat exchange a heat-exchange value Nu_{x_0} was adopted on the impermeable surface. As seen from Fig. 2, the theoretical and experimental data correspond satisfactorily. Where $\omega_1 \geq |0.6|$ a certain deviation of the experimental points from the theoretical curve took place. In order to calculate the heat exchange in the edge zone (laminar flow) where $Gr_x < Gr_{xcr}$ a formula is obtained according to [9, 10] for Pr = 0.72

$$\frac{Nu_x}{Nu_{x_0}} = 1 - 0.615\omega_1, \tag{2}$$

where for Pr = 0.72

$$Nu_{x_0} = 0.465 Gr_{x_0}^{1/5}. \tag{3}$$

The experimental values of the dimensionless temperature ϑ as functions of the dimensionless coordinate η_1 for various blowing in (drawing off) parameters agree satisfactorily with the theoretical solution [9, 10].

b) Central Zone. The variation of the heat-exchange coefficient in relation to the blowing in (drawing off) parameters is shown in Fig. 3 (curve 3). The following empirical formula is obtained on the basis of processing of experimental data

$$\frac{Nu_x}{Nu_{x_0}} = 1 - 1.75\omega_2 + 2.57\omega_2^2, \tag{4}$$

where

$$Nu_{x_0} = 0.12 Gr_x^{1/3}. \tag{5}$$

The more marked steepness of the approximating curve 3 (Fig. 3) in the region of negative parameters (drawing off) is worthy of note. Consequently with the same intensity of blowing in (drawing off), the drawing off contributes to the variation of the heat exchange to a greater degree than blowing in. The relationships between the dimensionless temperature ϑ obtained experimentally and the dimensionless coordinate $\eta_2 = (y/x)(Gr_x/3)^{1/3}$ in the case of various blowing in (drawing off) parameters ω_2 are shown in Fig. 4a.

II. The Heated Surface Turned Downwards. It is seen from the interferograms given in Fig. 1f-j that the nature of the formation of a thermal boundary layer is different from that for a heated surface turned upwards. The air near the surface is heated, and begins to slide along the surface to the edges. As a result of visual observation behind the flow, and according to the laws of variation of the heat-exchange coefficient, the presence of an edge zone and of a central zone was also observed at the heated surface which was turned downwards. We will refer to the central zone as the region of "creeping flow" in accordance with the terminology adopted in [7]. The transfer from one zone of flow to another can be expressed by using the empirical ratio (1). Only in this case will the Grashof number, which fixes the limit of the two regions of flow, be adopted according to [7] for a nonpermeable surface.

a) Edge Zone. Starting from the correspondence of the thermal boundary layers for edge zones of horizontal heated surfaces turned upwards (downwards) noted previously, the processing of the interferograms is carried out in the same dimensionless variables, and is given in Fig. 2. Where $\omega_1 > |0.6|$ a certain deviation of experimental data from the theoretical curve is observed. We propose to carry out calculation of the heat exchange in the edge zone according to expression (2), and we will adopt a value of the dimensionless heat-exchange coefficient on the impermeable surface equal to

$$Nu_{x_0} = 0.415 (Gr_{x_0})^{1/5}. \tag{6}$$

b) Central Zone. The profiles of the heat-exchange temperature (Fig. 4a, 3) are treated in variables, which we previously examined for a heated surface turned upwards. The values of dimensionless local heat-exchange coefficients obtained experimentally with sufficient accuracy for practical calculations can be approximated by the following relationship:

$$\frac{Nu_x}{Nu_{x_0}} = 1 - 4.8\omega_2 + 7.0\omega_2^2, \tag{7}$$

According to our data, and [7], Nu_{x_0} is equal to

$$Nu_{x_0} = 0.056\, Gr_{x_0}^{1/3}. \tag{8}$$

for an impermeable surface.

It is of interest to compare the influence of blowing in (drawing off) on the heat exchange for a horizontal heated permeable surface turned upwards, and downwards. It is seen from Fig. 2 that for $Gr_x < Gr_{xcr}$ the variation of the heat-exchange coefficient can be calculated according to the same formula (2), whereby the maximum variation of the heat-exchange coefficient under the influence of blowing in reaches 0.6 of its value on an impermeable surface. In the case of drawing off, an increase of the heat-exchange coefficient by 1.4 times cannot take place. The agreement of theoretical and experimental data according to the heat-exchange coefficient is satisfactory.

For the central zones it can be seen from Fig. 3 that the heat-exchange coefficient decreases, in the case of blowing in, to 0.3 from the value on an impermeable surface for lower heating, and to 0.7 in the case of upper heating. In the case of drawing off for lower heating the heat-exchange coefficient assumes values double the values on an impermeable surface, and in the case of upper heating it can increase 1.9 times in comparison with Nu_{x_0}.

The values of the heat-exchange coefficients of the central zone on an impermeable surface, according to formulas (5) and (8) differ somewhat from each other, which is explained by the effect of orientation of the heat emitting surface relative to the gravitational force field, which leads to the appearance of honeycomb flow in the case of upper heating, that is, complex alternation of ascending air currents introducing turbulence to the boundary layer of the central zone. The turbulence, caused by the effect of gravity promotes the intensification of heat exchange, and leads to different deformation of the temperature profile in the thermal layer near the wall, the central, and edge zones, which is seen from Fig. 4a and b for $\omega_2 = 0$. As experiments in the edge zone have shown, this influence is quite insignificant.

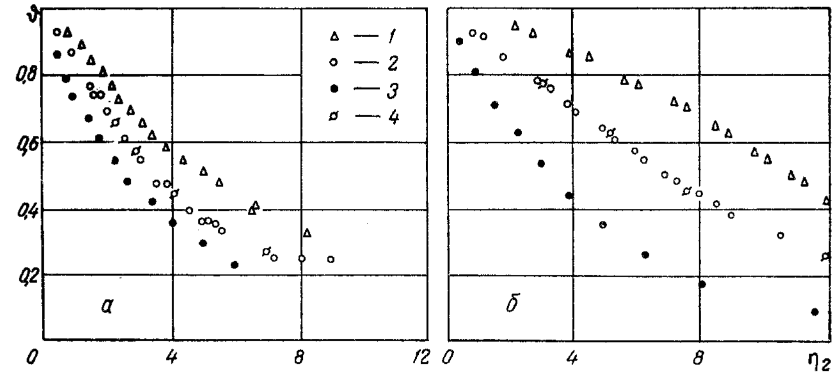

Fig. 4. Temperature profiles on a permeable horizontal surface with the heated side turned upwards (a), and downwards (b) at different values of the parameters. a: 1) $\omega_2 = 0.270$; 2) 0; 3) −0.357; 4) 0 [2]; b: 1) $\omega_2 = 0.171$; 2) 0; 3) −0.193; 4) 0 [2].

The value of the heat-exchange coefficients of impermeable surfaces for the central zones corresponds with the results of other authors [2, 6, 7, 12] within the accuracy limits of the experiment. We note that in [3, 6, 7, 12], and in the present work $\mathrm{Nu}_{x_0} \sim \mathrm{Gr}_{x_0}^{1/3}$ was obtained.

A difference in the behavior of the boundary layers, and curves describing the influence of blowing in (drawing off) on the heat exchange for a case of higher and lower heating values is seen from the interferograms and from Figs. 2 and 3. The thermal boundary layer for upper surface heating, and consequently also the heat-exchange coefficient are subjected to a smaller influence of blowing in (drawing off), than for reduced heating, as a result of turbulence associated with the formation of a honeycomb structure. This can also be observed from the temperature profile graphs of Fig. 4a and b. In the case of reduced heating for high blowing in values $\omega_2 > |0.2|$, the boundary layer begins to be forced back from the surface, and an air layer whose temperature is close to the surface temperature is formed near it. This is clearly seen in Fig. 1h. High drawing off rate has a stabilizing influence on the boundary layers, and especially on the transfer of flow from the boundary region to the central region (Fig. 1e and j).

NOTATION

$\mathrm{Gr}_x = g\beta(T_w - T_\infty)x^3/\nu^2$	is the Grashof number;
$\mathrm{Re}_w = v_w x/\nu$	is the Reynolds number;
$\mathrm{Nu}_x = \alpha_x x/\lambda$;	
Nu_{x_0}	is the Nusselt number on the permeable and nonpermeable surface;
$\omega_1 = (v_w x/\nu)(\mathrm{Gr}_x/5)^{-1/5}$,	
$\omega_2 = (v_w x/\nu)(\mathrm{Gr}_x/3)^{-1/3}$	are the blowing in (drawing off) parameters for the edge and central zones;
$\eta_1 = (y/x)(\mathrm{Gr}_x/5)^{1/5}$,	
$\eta_2 = (y/x)(\mathrm{Gr}_x/3)^{1/3}$	are the dimensionless coordinates for the edge and central zones;
$\vartheta = (T - T_\infty)/(T_w - T_\infty)$	is the dimensionless temperature;
v_w	is the speed of blown in (drawn off) air;
x	is the coordinate from the edge of the plate;
ν, α, λ, β	are the coefficients of kinematic viscosity, heat exchange, thermal conductivity, and volume expansion, respectively;
T	is the absolute temperature;
g	is the acceleration of the gravitational force.

Subscripts

w	denotes on the surface;
∞	denotes at a considerable distance from the surface
cr	denotes critical;
0	denotes relating to an impermeable surface;
1, 2	denote relating to the initial and central zones.

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