EXPERIMENTAL STUDY OF HEAT TRANSFER IN THE STAGNATION ZONE ARISING WHEN A PLANE SEMIBOUNDED JET INTERACTS WITH A NATURAL-CONVECTION STREAM AT A VERTICAL ISOTHERMAL SURFACE

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Inzhenerno-Fizicheskii Zhurnal, Vol. 13, No. 6, pp. 860–864, 1967

UDC 536.25

An experimental study is made of heat transfer in the stagnation zone formed when a plane semibounded jet interacts with a descending free-convection stream at a vertical wall. An attempt was also made to determine experimentally the boundaries of the stagnation zone as a function of the jet parameters and the natural-convection stream.

It is well known that the propagation of a semibounded jet is a case of retarded motion. When there is flow around a thermally conducting wall this may result in natural convection having a marked effect on the nature of the surface flow at some distance from the mouth of the nozzle. It will be particularly apparent in those cases when the free convection at the vertical wall is in the opposite direction to the plane semibounded jet. It is just such a case which is treated in the present paper.

The tests were carried out on the experimental apparatus, a sketch of which is given in Fig. 1.

The variable parameters in the tests were the Reynolds number, calculated from the initial flow conditions, and the Grashof number. An optical method employing an IZK-454 interferometer was used for the experiments. A monochromatic light source was used and the interference pattern photographed for various settings of the apparatus.

Fringes of finite width oriented vertically to the surface enabled temperature profiles to be determined immediately for the region under observation. Photographs of the infinitely wide fringes gave a clear physical picture of the phenomenon to be investigated. The interaction of oppositely directed semibounded jets and the formation of a stagnation zone at the surface of the heat exchanger appeared quite distinctly.

The interferograms were processed, and the field densities in the temperature field were calculated by the method described in papers [1, 2]. The intersection of the jets was taken to be the point on the wall where the thickness of the thermal boundary layer in the interferograms for fringes of infinite width (Fig. 2a and b) was largest. The points where the boundary layer detaches from the wall (stagnation-zone boundary) were determined from the cross section where the interferograms for fringes of finite width exhibited a double discontinuity of the temperature profile at the surface (Fig. 2c and d).

Figure 2 gives interferograms for the longitudinal flow of a plane jet around an isothermal wall, the temperature t_w of which is less than the temperature t_∞ of the surrounding medium. It is clear from the figure that when the initial temperature conditions for the flow are constant, an increase in the Reynolds number leads to an upward displacement of the stagnation zone along the surface of the heat exchanger, and to an increase of its dimensions (Fig. 2a and b). There is also an accompanying increase of fluctuation phenomena. The greatest fluctuations of the isotherms are observed at the place where the boundary layer detaches from the wall, and in the outer region of the stagnation zone. The layer of air which attaches directly to the surface is least subject to fluctuation.

The processed experimental data is given in Fig. 3 enabling us to determine the relationship between the characteristic coordinates of the stagnation zone (stagnation-zone upper boundary x_u, stagnation-zone lower boundary x_l, and the intersection x_i of the natural convection stream and the semibounded jet) plus the initial flow conditions and the natural-convection parameters. The experimental points are grouped around the curves 1, 2, and 3 of Fig. 3, which have the following equations:

for the intersection of the jet and the natural-convection stream (curve 2),

$$\mathrm{Re}_a = 8.65\mathrm{Gr}_{l-x_i}^{1/3}\,\bar{x}_i^{1/2}/(\bar{l}-\bar{x}_i); \quad (1)$$

for the point where the boundary layer of the plane semibounded jet detaches from the wall (stagnation-zone lower boundary, curve 1),

$$\mathrm{Re}_a = 10.3\mathrm{Gr}_{l-x_l}^{1/3}\,\bar{x}_l^{1/2}\,/\,(\bar{l}-\bar{x}_l); \quad (2)$$

and for the point where the boundary layer governed by natural convection detaches from the wall (stagnation-zone upper boundary, curve 3),

$$\mathrm{Re}_a = 7.2\mathrm{Gr}_{l-x_u}^{1/3}\,\bar{x}_u^{1/2}\,/\,(\bar{l}-\bar{x}_u). \quad (3)$$

The variation of the local heat-transfer coefficient in the stagnation zone is shown in Fig. 4. When the experimental data between the point where the boundary layer of the semibounded jet detaches from the wall and the intersection ($x_l < x < x_i$) is processed, we see that the variation of the local heat-transfer coefficient in this region may be approximated by the expression (Fig. 4a)

$$\mathrm{Nu}_{l-x} = 2.5\cdot 10^{-3}\,\mathrm{Re}_a^{0.7}\,\mathrm{Gr}_{l-x}^{1/3}\,\bar{x}_*^{-0.2}. \quad (4)$$

The local heat-transfer coefficient at the meeting point of the jets is equal to

$$\mathrm{Nu}_{l-x_i} = 2.5\cdot 10^{-3}\,\mathrm{Re}_a^{0.7}\,\mathrm{Gr}_{l-x_i}^{1/3},$$

and for $x \geq x_u$ $\mathrm{Nu}_{l-x} = 0.12\,\mathrm{Gr}_{l-x}^{1/3}$ [3].

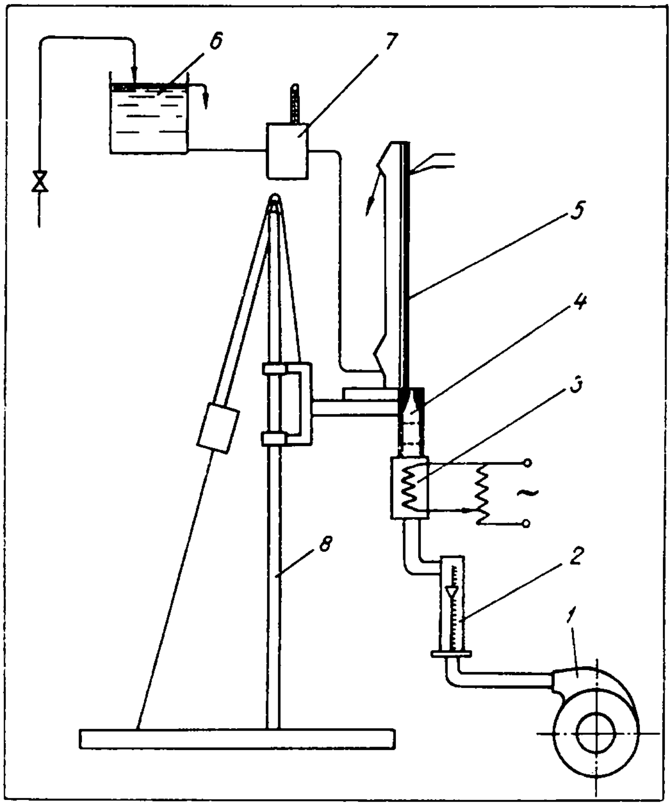

Fig. 1. Sketch of the experimental apparatus: 1) blower; 2) rotameter; 3) heater; 4) nozzle; 5) heat exchanger; 6) water reservoir; 7) thermostat; 8) stand.

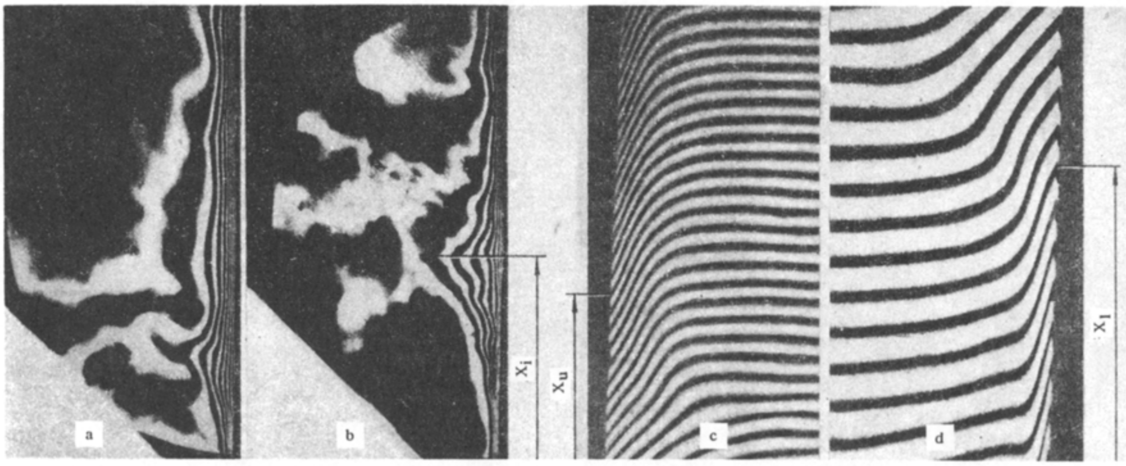

Fig. 2. Interferograms for the longitudinal flow of a plane jet around a vertical isothermal wall, the temperature of which is lower than the temperature of the surrounding air: a) $Re_a = 210$; b) 253; c) 366; d) 190.

The local heat-transfer coefficient between the intersection of the jets and the point where the boundary layer of the flow governed by natural convection detaches from the wall is approximated by the formula

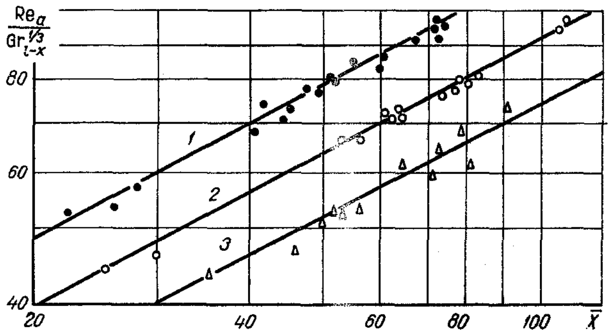

Fig. 3. Graph of the variation of $Re_a/Gr_{l-x}^{1/3}$ as a function of $\bar{x}$ for the points: 1) where the jet boundary layer detaches from the wall; 2) where the jets meet; 3) where the natural-convection stream detaches from the wall.

$$Nu_{l-x} = 2.5\cdot 10^{-3} Re_a^{0.7}\, Gr_{l-x}^{1/3}\left[1-\left(\frac{47}{Re_a^{0.7}}-1\right)\bar{x}'_*\right]. \quad (5)$$

The results of processed experimental data for the local heat-transfer coefficient in the zone $x_i \le x \le x_u$ are given in Fig. 4b. Function (5) is in satisfactory agreement with the experimental data.

It is an interesting fact that when $Re_a = 245$, the local heat-transfer coefficient in this zone is the same as for natural turbulent convection ($Nu_{l-x} = 0.12\, Gr_{l-x}^{1/3}$) and is independent of the longitudinal coordinate.

For the tests represented in Figs. 3 and 4, the variation of the parameters Gr_{l-x} and Re_a was $Gr_{l-x} = 2 \cdot 10^7 - 2 \cdot 10^{10}$ and $Re_a = 190-500$.

NOTATION

a is the slit width (of the nozzle); l is the height of the plate; u_0 is the jet velocity at the orifice; x is the moving coordinate, measured from the jet orifice along the surface of the plate; x_i is the distance from the jet orifice to the place where the turbulent jets meet; x_l is the distance from the jet orifice to the point where the jet boundary layer detaches from the wall; x_u is the distance from the jet orifice to the point where the boundary layer of the natural convection stream detaches from the wall; $\bar{x} = x/a$; $\bar{x}_* = (x - x_l)/(x_i - x_l)$; $\bar{x}'_* = (x - x_u)/(x_i - x_u)$ are the dimensionless coordinates; $Re_a = u_0 a/\nu$ is the Reynolds number; $Nu_{l-x} = \alpha(l -$

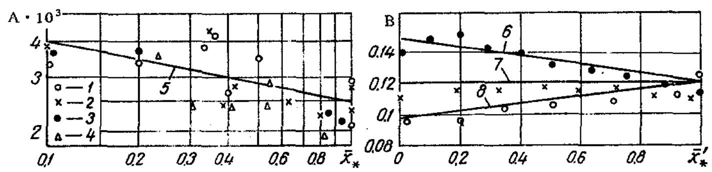

Fig. 4. Variation of the local heat-transfer coefficient in the stagnation zone. ($A \equiv Nu_{l-x}/Re_a^{0.7}Gr_{l-x}^{1/3}$; $B \equiv Nu_{l-x}/Gr_{l-x}^{1/3}$): a) in the region $x_l \le x \le x_i$; 1) $Re_a = 336$; 2) 322; 3) 310; 4) 245; 5) calculations from Eq. (4); b) in the region $x_i \le x \le x_u$; 6) $Re_a = 353$; 7) 245; 8) 210).

$-x)/\lambda$ is the Nusselt criterion; and $Gr_{l-x} = g\beta\Delta t(l - x)^3/\nu^2$ is the Grashof criterion.

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21 February 1967

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