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HEAT EXCHANGE IN THE FLOW OF A SYSTEM OF AXISYMMETRIC LIQUID JETS ONTO A NORMALLY PLACED PLANE BARRIER

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The influence of the geometrical and physical parameters of a system of axisymmetric jets impinging on a barrier on the heat-transfer coefficient and the final temperature of the liquid is analyzed.

The flow arising in the region of interaction of a turbulent jet with a barrier has a whole series of peculiarities. The pattern of motion is so complicated in details that a theoretical calculation of the boundary layer becomes very difficult [3]. It is therefore necessary to conduct experimental investigations.

A number of reports [1, 5, 6, 8, 9, 10] have been devoted to heat exchange in the interaction of single jets of dropping liquids with barriers, but there is an absence of investigations in which heat exchange in the interaction of a system of axisymmetric nonflooded jets of dropping liquid with a surface is analyzed, which might be used to design and build highly efficient liquid-jet heat exchangers. In the given case it should be noted that the average heat-transfer coefficient from a wall to a liquid depends on the velocity of the liquid, the geometrical characteristics of the system, and the thermophysical properties of the liquid:

$$\alpha = \varphi(w;\ d_e;\ f;\ F;\ \rho;\ \lambda;\ \nu;\ c_p). \tag{1}$$

Using dimensional analysis, in dimensionless form we find

$$\frac{\alpha d_e}{\lambda} = \varphi\left(\frac{\nu}{w d_e};\ \frac{\lambda}{\rho c_p \nu};\ \frac{f}{F}\right)$$

or

$$\mathrm{Nu} = \varphi(\mathrm{Re};\ \mathrm{Pr};\ A_f). \tag{2}$$

To obtain Eq. (2) in explicit form we constructed a model of a jet heat exchanger and carried out experimental investigations. The area of the heat-exchange surface of the apparatus was $0.0145\ m^2$, the number of nozzles in the perforated plate ranged from 33 to 121, and the dimensionless distance between the heat-exchange surface and the nozzles ranged from 50 to 100. The nozzle diameter was the same in all the tests and equalled 0.5 mm. Water was used as the liquid and moist steam from an industrial boiler served as the heat-transfer agent.

The final temperature of the falling liquid film was taken as the controlling temperature in the treatment of the test data. The height L of the heated plate was taken as the characteristic dimension in the Nusselt number. The Reynolds number was converted to the form $\mathrm{Re} = 4\Gamma/\rho\nu$.

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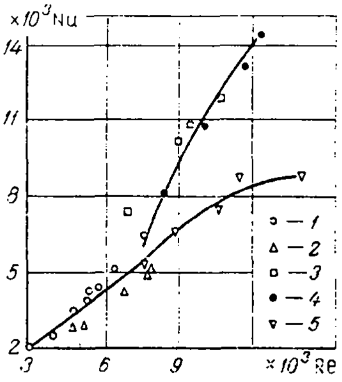

Fig. 1

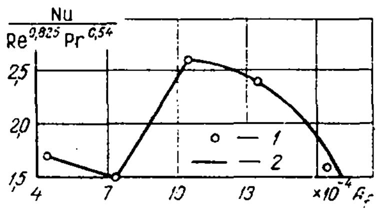

Fig. 2

Fig. 1. Dependence of Nusselt number on Reynolds number: 1) $A_f = 4.5 \cdot 10^{-4}$; 2) $7.5 \cdot 10^{-4}$; 3) $10.5 \cdot 10^{-4}$; 4) $13.5 \cdot 10^{-4}$; 5) $16.5 \cdot 10^{-4}$.

Fig. 2. Generalized experimental data on heat transfer: 1) experimental points; 2) calculation by Eqs. (3), (4), and (5).

The tests to determine the influence of the dimensionless distance $\bar{h}$ on the heat transfer were conducted at water and steam pressures of 0.2 and 0.3 MPa, respectively. At high water velocities and the maximum value of A_f the thickness of the turbulent film at the heat-exchange surface reaches 10-15 mm by visual observations. Partly for this reason, as well as from structural considerations, the minimum value of the dimensionless distance was taken as $\bar{h} = 50$.

It was discovered that α and Nu do not depend on $\bar{h}$. This can be explained by the small range of variation of h (25 mm), the small nozzle diameter (0.5 mm), and by the fact that the water jets propagated in an air medium up to the impact, i.e., they were nonflooded jets.

The dependence of the Nusselt number on the Reynolds number is presented in Fig. 1. The bend in the region of Re = $(6\text{-}8) \cdot 10^3$, which indicates the existence of a transitional mode of flow, is clearly expressed. The maximum value of the mean coefficient of heat transfer attained in the tests was $\alpha = 76{,}000$ W/m$^2\cdot$deg K.

The experimental data on heat transfer were generalized in the coordinates $Nu/Re^{0.825} \cdot Pr^{0.54}$ and A_f (Fig. 2). The curve has two inflection points. The laminar boundary layer at the plate changes into a turbulent one at $A_f = (7.5\text{-}10.5) \cdot 10^{-4}$; the turbulent boundary layer stabilizes at $A_f \geq 10.5 \cdot 10^{-4}$. Similar graphs showing the transition of a laminar to a turbulent boundary layer are presented in [2, 4, 7].

In the laminar region of flow the criterial dependence for the heat transfer has the form

$$\mathrm{Nu} = 0.137 \mathrm{Re}^{0.825} \mathrm{Pr}^{0.54} A_f^{-0.333}. \qquad (3)$$

The dependence (3) isvalid in the following ranges of values of the criteria and simplices: Re = 2900–7800, Pr = 2.46–4.07, $A_f = (4.5\text{-}7.5) \cdot 10^{-4}$.

In the transitional region the heat transfer is described by the equation

$$\mathrm{Nu} = 2.85 \cdot 10^5 \mathrm{Re}^{0.825} \mathrm{Pr}^{0.54} A_f^{1.69}. \qquad (4)$$

Equation (4) is valid in the ranges of Re = 4500–10,600, Pr = 2.78–4.54, and $A_f = (7.5\text{-}10.5) \cdot 10^{-4}$. For the turbulent region of flow the dependence

$$\mathrm{Nu} = 4.72 \cdot 10^{19} \mathrm{Re}^{0.825} \mathrm{Pr}^{0.54} A_f^{5.68} \exp(-5130 A_f) \qquad (5)$$

is derived, which is valid in the ranges of Re = 6800–14,000, Pr = 3.56–5.50, and $A_f = (10.5\text{-}16.5) \cdot 10^{-4}$.

The derived equations (3)-(5) can be used to calculate the mean coefficient of heat transfer from wall to liquid in a jet heat exchanger.

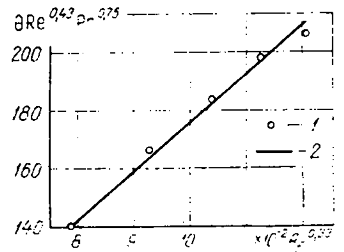

Fig. 3. Generalized temperature dependence: 1) experimental points; 2) calculation by Eq. (8).

A problem of practical importance is the determination of the final product temperature for heating by the impact of jets on a heat-exchange surface. One can assume that the final liquid temperature depends on its initial temperature, the steam temperature, the discharge velocity, and the thermophysical properties of the liquid, as well as on the geometrical characteristics of the system:

$$T_2 = \varphi(T_1;\ T_s;\ w;\ \nu;\ a;\ d_e;\ f;\ F). \tag{6}$$

Applying dimensional analysis, we find (in dimensionless form)

$$\frac{T_s - T_1}{T_s - T_2} = \varphi\left(\frac{\nu}{wd_e};\ \frac{a}{wd_e};\ \frac{f}{F}\right)$$

or, knowing that $Pe = RePr = wd_e/a$,

$$\Theta = \varphi(\mathrm{Re};\ \mathrm{Pr};\ A_f). \tag{7}$$

To obtain Eq. (7) in explicit form we used the results of the experimental investigation described above. The generalized temperature dependence is presented in Fig. 3. It is found that the higher the discharge velocity of the liquid in a jet and the larger the value of A_f, the lower the final liquid temperature which is attained. If the other parameters of the system remain constant, then T_2 rises with an increase in the temperature of the heating stream.

The final liquid temperature can be determined by the equation

$$\Theta = 1760\,\mathrm{Re}^{-0.43}\,\mathrm{Pr}^{-0.75}\,A_f^{0.33}. \tag{8}$$

The dependence (8) is valid for Re = 2900-14,000, Pr = 2.46-5.50, and A_f = (4.5-16.5)$\cdot 10^{-4}$. The values of T_2 calculated from (8) fit with the directly measured values with an accuracy of 4-14%.

NOTATION

α, mean heat-transfer coefficient; w, velocity of liquid in jet; d_e, equivalent diameter; $f = \pi d^2 n/4$, through cross section; d, nozzle diameter; n, number of nozzles; F, area of heat-exchange surface; $A_f = f/F$, dimensionless through cross section; ρ, density; λ, coefficient of thermal conductivity; a, coefficient of thermal diffusivity; ν, kinematic viscosity; c_p, heat capacity; Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number; L, height of heated plate (heat-exchange surface); Γ, mass quantity of liquid flowing down per second per running meter of film width; h, distance between heat-exchange surface and nozzle system; $\bar{h} = h/d$, the same in dimensionless form; T_1, initial liquid temperature; T_2, final liquid temperature; T_s, temperature of heating steam; $\Theta = T_s - T_1/T_s - T_2$, temperature simplex.

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HEAT-TRANSFER MECHANISM AT A GAS-FIBER BOUNDARY

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Heat conduction in a fibrous dispersed material with a gas filler is studied.

Molecular thermal conductivity of a gas in a free volume, introduced by the molecular-kinetic theory, results from intermolecular interactions in the gas.

In dispersed two-component materials there are not only intermolecular interactions but also interactions of gas molecules with the solid component. The heat-transfer mechanism by gas molecules in a dispersed material is studied together with the interaction at the boundary between the gas and the solid component, and the corresponding molecular thermal conductivity of the gas λ_m is determined, e.g., from the relation [1]

$$\lambda_M = \lambda_g [1 + B/(H\bar{\delta})]^{-1}, \tag{1}$$

where B is a constant for a given gas and H is the pressure of the gas.

The simultaneous study of intermolecular interactions and interactions at the gas–solid boundary in a dispersed material complicates the study of the separate mechanisms. At the same time, knowledge of the physics of the heat-transfer process in a boundary layer whose thickness is comparable with the mean free path of gas molecules enables us to study the heat-transfer mechanism in dispersed materials more completely, to discover the physical nature of the transport coefficients, and to establish their qualitative behavior and numerical values.

Since heat transfer between a gas and a solid takes place in a layer of thickness $\bar{l}^*$, it is expedient to study heat transfer by the thermal conductivity of a gas filler in a dispersed material by taking separate account of intermolecular interactions and interactions of gas molecules with the solid. Therefore, we use a model with interpenetrating components [1] to represent fibrous materials with a random structure, and introduce a supplementary thermal resistance of a layer of thickness $\bar{l}^*$ at the gas–fiber boundary. Figure 1a shows one-eighth of the elementary cell under study, and Fig. 1b the circuit diagram of the thermal resistances.

Figure 1b illustrates the physical meaning of the proposed method for taking separate account of intermolecular interactions and interactions at a gas–fiber boundary. Suppose there are N gas molecules in an elementary cell. Since air at atmospheric pressure is a rarefied gas in which binary molecular interactions predominate, at any arbitrary instant a

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