COOLING OF HORIZONTAL POROUS TUBES BY A LOW TEMPERATURE HELIUM FLOW

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Heat transport during flow of low temperature helium in a metalloceramic tube is studied. The effect of free convection on temperature fields and Nusselt number is considered. Expressions are presented for evaluation of local heat exchange.

The effect of free convection on turbulent flow in horizontal tubes for Re > 10^4 with no mass removal on the wall has been studied quite fully [1-5]. Under certain conditions this phenomenon proves to be quite significant, manifesting itself in a change in velocity and temperature fields over the tube section. This is especially significant in the motion of a liquid the density of which is strongly dependent on temperature. For example, for flow of carbon dioxide in horizontal tubes temperature differences of the order of hundreds of degrees have been recorded between the upper and lower directrices of the tube [1].

Computation formulas which consider the effect of free convection in constrained motion of flow through tubes were presented in the reviews [1, 2]. But those expressions all consider essentially impermeable tubes, i.e., cases where there is no removal of mass through the wall during flow.

Free convection also has a significant effect on the temperature field over tube section and the Nusselt number in forced motion of a flow in heated horizontal tubes with mass suction through a permeable porous wall. These effects were measured experimentally for flow of low temperature helium in a horizontal metalloceramic tube, prepared by sintering of bronze powder with particle dimensions of 0.25-0.315 mm. The tube had inner and outer diameters of 13 and 17 mm, respectively, a length of 600 mm, and maximum pore size of 190 μm.

The experimental apparatus used was a conventional horizontal helium cryostat with working volume in the form of a tube 40 mm in diameter and 3000 mm long. The porous metalloceramic specimen, enclosed within a screen, together with a preconnected hydrodynamic and thermal stabilization unit 2000 mm long was located in the center of the working volume. The specimen was heated by a dc electric current. Excess heat flow along the tube perimeter was excluded, since the thermal conductivity of the sintered bronze was low, 15.6 W/(m·K) at 20 K.

Temperatures of the flow and wall were measured by copper (copper–iron) thermocouples. To measure the former the thermocouples were inserted in thin medical needles 0.4 mm in diameter, and installed at several points at various sections as well as the input and output of the tube. To record the wall temperature thermocouples were calked into four points on the periphery of the porous tube in four different sections along the tube length, such that their junctions were located flush with the internal surface of the tube. To monitor temperature across the wall thickness thermocouples were installed at three points spaced 1 mm apart in two sections.

When an electric current is passed through the porous tube a power UI is dissipated, which is partially compensated by the flow of helium moving within the tube, and partially by helium which is extracted through the wall, which latter can be defined as $q = M_s c_p \Delta T_s$, where M_s is the mass of gas suctioned, c_p is the specific heat, and ΔT_s is the difference in temperature of the suctioned helium behind and ahead of the porous wall, which quantity could not be measured, since it varied within the limits of measurement accuracy (0.2-0.3 K).

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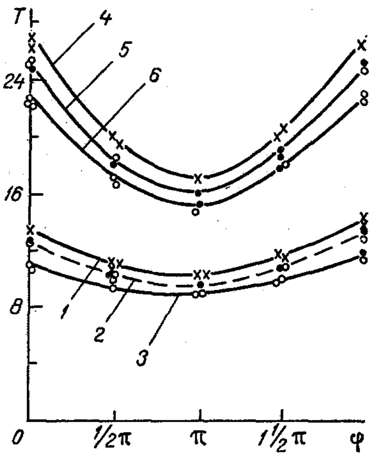

Fig. 1

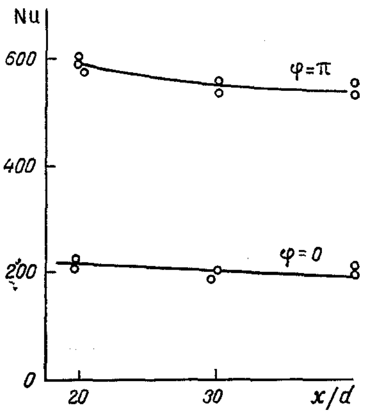

Fig. 2

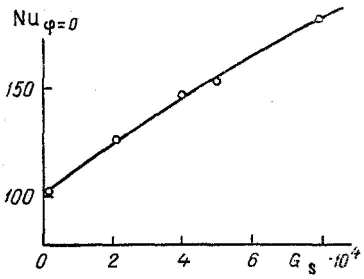

Fig. 3

Fig. 1. Wall temperature distribution over circumference of horizontal porous tube, $G = 0.8 \cdot 10^{-3}$ kg/sec: $q = 320$ W/m^2: 1) zero suction; 2) 50% suction; 3) 90% suction; $q = 2700$ W/m^2: 4) zero suction; 5) 50% suction; 6) 90% suction. T, K.

Fig. 2. Nusselt number distribution over porous tube length.

Fig. 3. Nusselt number along upper directrix of porous tube vs suction through wall. G_s, kg/sec.

Therefore, the thermal flux density was defined as the power referred to a unit internal surface of the porous tube.

The physical parameters in the calculations of local heat exchange coefficients were referred to the temperature of the gaseous helium in the given section.

A relatively small range of flow velocities was studied, defined by Reynolds number at the tube input $Re_{in} = (1\text{-}5) \cdot 10^4$ with the condition that the thermal flux density over tube length was constant.

Cases were considered in which the entire flow was forced through the tube without suction at the wall, where a portion of the flow was suctioned, and finally, where approximately 90% was suctioned, 10% passing within the tube.

Local heat exchange coefficients along the perimeter and length of the tube were determined. As is evident from the results shown, the effect of free convection proved significant. Figure 1 shows wall temperature distribution over tube circumference for one and the same flow rate at the input, equal to $0.8 \cdot 10^{-3}$ kg/sec, and thermal fluxes of 320 and 2700 W/m^2 for various values of through-wall suction. The temperature difference between upper and lower directrices reaches several degrees, and is larger, the higher the thermal flux density. For $q = 2700\ W/m^2$ the helium densities along the upper and lower directrices differ by a factor of almost two, which leads to wall temperature differences of 10 K. For one and the same helium flow rate, increase in suction can decrease this difference, reducing the effect of free convection on temperature distribution over the tube circumference.

The maximum temperature difference between upper and lower directrices is found for zero suction, with the minimum at 90% suction (Fig. 1). The case of 50% suction is intermediate. From this we may conclude that radial filtration of a portion of the flow significantly smooths nonuniformity of the temperature distribution over tube circumference.

The differing intensity of the heat exchange process on the upper and lower directrices is clearly illustrated by the values of the Nusselt number for the top and bottom of the tube. Figure 2 shows calculations of local heat exchange for conditions where the helium flow rate at the tube input is constant at $0.8 \cdot 10^{-3}$ kg/sec, at a constant thermal flux of 320 W/m^2. Over its time of passage through the porous tube practically the entire flow is suctioned through the wall. The total effect of free convection and radial filtration is shown by the fact that the Nusselt number along the lower directrix is almost twice as high as on the upper, and constant along the length. But while in impermeable tubes at $x/d > 20$ these curves diverge [1], i.e., depend significantly on length, in a permeable tube because of radial mass suction on the wall heat transport upward and downward at $x/d > 20$ is practically independent of length.

The effect of suction on the temperature distribution over the circumference, shown in Fig. 1, allows evaluation of the Nusselt number as a function of the amount of suction with other parameters being equal (Fig. 3). We see that radial filtration has a significant effect on heat exchange. Increase in suction from zero to 90% doubles the Nusselt number, with more intense growth occurring for increase from zero to 40%, with the growth rate then decreasing.

In [1] the effect of free convection on heat exchange for turbulent stabilized flow in horizontal tubes was evaluated by the ratio of the Grashof number, calculated for parameters in the flow section, to Gr_ℓ, defined by the expression

$$Gr_l = 3 \cdot 10^{-5} Re^{2,75} Pr^{0,5} [1 + 2,4 Re^{-0,125} (Pr^{2/3} - 1)]. \tag{1}$$

The authors of that study estimated the effect to be very small, if the ratio $Gr/Gr_\ell < 30$. In the present experiments this ratio did not exceed that value, but as is evident from the results presented, the effect of free convection proves to be very significant, leading to variation in the Nusselt number over tube circumference.

The experimental data can be generalized quite well by the empirical equations presented in [1]:

$$Nu_\pi / Nu_0 = [1 + (Gr/Gr_l)^3]^{0,048}, \tag{2}$$

$$Nu_\pi / Nu_t = 1 + 0,035 (Gr/Gr_l)^{0,43}, \tag{3}$$

where Nu_t is determined by the equation [6]

$$Nu_t = 0,041 Re_{in}^{0,8} Pr^{0,43} [1 + 0,06 (Re_s / Re_{in})^{0,57}]. \tag{4}$$

The accuracy of the experimentally obtained Nusselt numbers comprises 30%.

NOTATION

x, distance from beginning of heating, m; d, tube internal diameter, m; q, thermal flux density, W/m^2; G, mass flow rate, kg/sec; T_w, tube wall temperature, K; φ, angle measured from tube upper directrix; α, heat exchange coefficient, $W/(m^2/K)$; T_ℓ, helium temperature, K; ρ, helium density, kg/m^3; λ, helium thermal conductivity coefficient, $W/(m \cdot K)$; β, helium volume expansion coefficient, K^{-1}; a, thermal diffusivity coefficient, m^2/sec; ν, kinematic viscosity coefficient, m^2/sec; $Pr = \nu/a$, Prandtl number; $Gr = g\beta(T_w - T_\ell)d^3/\nu^2$, Grashof number; $Nu = \alpha d/\lambda$, Nusselt number; $Re_{in} = wd/\nu$, Reynolds number; w, helium velocity, m/sec.

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TRANSFER COEFFICIENT OF MULTICOMPONENT AIR WITH SUBLIMATION PRODUCTS OF GRAPHITE

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An economical method of calculating the viscosity, thermal conductivity, binary diffusion coefficient, and thermodiffusion coefficient is proposed, for a mixture of dissociated air and subliming graphite.

1. In investigating the heat transfer in a high-temperature viscous shock layer close to a graphite surface which is undergoing breakdown, the transfer coefficients (viscosity, heat conduction, diffusion) of multicomponent air with an admixture of the sublimation products of graphite must be determined.

Calculations of the characteristic parameters of molecular transfer both by kinetic theory [1] and by approximate methods [2, 3] are based on data regarding the elastic interaction potentials between the mixture components. Experimental investigation of the transfer coefficients to date has been restricted to the range T ≤ 2000 K [4, 5], and, as noted in [6], rigorous quantum-mechanical calculation of elastic-interaction processes is only possible for atoms and molecules with a simple electron structure [7]. The basic sources of information on the interaction of molecules at high temperatures are experimental results on the scattering of fast molecular beams. Numerous data on the molecule–molecule and atom–molecule interaction were obtained in [8-11], for example. The first investigations [11] were based on the assumption of an inverse power dependence of the interaction potential $V = K/R^s$ on the distance between the centers of mass of the molecules. At the same time, analysis of the experimental conditions in [9] shows that s is not constant. Evidently, the most preferable form of repulsive potential is the exponential approximation $V = A\exp(-\beta R)$. This approximation has been successfully used to describe the interaction of identical atoms (especially of inert gases [9]). The additive-potential method, proposed in [11] for approximate calculation of V(R), gives good accuracy in calculating the parameters of the atom–molecule and molecule–molecule interaction. According to this method, the interaction potential of the molecules AB and CD is written as follows [9]

$$V(R) = V(r_{AC}) + V(r_{BC}) + V(r_{AD}) + V(r_{BD}), \tag{1}$$

where r is the interatomic distance.

The potential in Eq. (1), averaged over equiprobable orientations, determines the effective spherically symmetric potential corresponding to the point force center. Here, it is possible to choose parameters of the exponential function approximating cumbersome analytical expressions for the mean potential. This procedure was described in detail in [12,

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