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HEAT RELEASE IN A GAS FLOW AT THE JUNCTION OF CHANNELS
WITH DIFFERENT SURFACE ROUGHNESSES

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A measurement is made of the thermal polarization which develops in a gas flow in a nonuniform channel due to the dependence of the mechano-caloric heat flux on surface roughness.

In accordance with nonequilibrium thermodynamics, in a compound channel or V-shaped pipe with parts having different surface roughnesses, a heat flux should develop on the wall J_q in the region of the junction of dissimilar parts when an isothermal gas flows through the pipe [1]. This effect is related to the accommodation pumping effect observed by Hobson [2]. The latter phenomenon involves the formation of a longitudinal flow of gas particles when the temperatures of the walls at the junction of dissimilar channels deviate from the temperatures of their free ends. Measurement of the heat flux J_q is of scientific interest, since it makes it possible to prove hypotheses regarding the nonequilibrium thermodynamics of discontinuous systems and determine the value of the kinetic coefficient L_{qp} , which characterizes the release of heat in the region of the joint of dissimilar parts of a compound channel.

The authors of [3] proposed a theoretical model to calculate the above-mentioned effect for small Knudsen numbers. The method is based on the solution of problems of continuum mechanics with the use of slip boundary conditions.

We write as follows the temperature and pressure fields in the flow of a gas in a long ($L \gg R$) isothermal nonuniform channel when the conditions correspond to the viscous slip

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flow regime ($Kn \sim 10^{-2}-10^{-1}$) and small Reynolds numbers ($Re < 10$) [3]:

$$T(r, z) - T_0 = - \left(\frac{\partial p}{\partial z} \right)^2 \left\{ \frac{(R^2 - r^2 + 2\sigma\lambda R)^2}{32\kappa\eta} + \frac{R^2}{8\eta} \times \right. \\ \left. \times \left(\frac{2\sigma\lambda}{\alpha} - \frac{\sigma^2\lambda^2}{\kappa} \right) \right\} + \frac{\partial}{\partial z} \left(A_r \frac{\eta}{\rho} \frac{\partial P}{\partial z} \right) \left(\frac{r^2 - R^2}{4\kappa} - \frac{R}{2\alpha} \right), \quad (1)$$

$$P(z) = \frac{\sqrt{P_1'^2 - (P_1'^2 - P_2'^2) \frac{z}{L}}}{1 + 4\sigma Kn}, \quad (2)$$

where $P_i'(z) = P_i(z)(1 + 4\sigma Kn)$.

We should point out the mechanisms of heat transfer corresponding to different terms of Eq. (1). The first term corresponds to viscous friction in the gas with its expansion during motion. The second term is connected with the mechano-caloric heat flow ($\sim A_h$).

To check the prediction of the mechano-caloric polarization temperature of the gas, we performed experimental measurements at the joint in a compound wall. The experiment was initially conducted on a glass capillary tube of the length $L = 0.15$ m and radius $R = 1.1 \cdot 10^{-3}$ m [3]. We created a local gradient of A_h by abrading the inside surface on end sections of the length $L/3$. The temperature difference was measured at the points of the greatest gradient of A_h . Specifically, it was measured at distances $L/3$ and $2L/3$ from the end of the channel with the aid of copper-constantan thermocouples. The measurements obtained for helium and xenon showed that the temperature difference ΔT is proportional to P^2 in the range of Knudsen numbers $Kn < 0.05$ [which corresponds to the viscous mechanism, in accordance with Eq. (1)], while a change in the sign of ΔT is seen for helium at low pressures ($Kn \geq 0.1$). This sign change is evidently due to the mechano-caloric component of Eq. (1).

To determine the role of the mechano-caloric effect, and the degree of weakening of the influence of dissipative effects ($\sim P^2$), we modified the measurement cell. We used a cell made of two identical nonuniform glass capillaries. One half of each capillary was abraded to create surface roughness. The capillaries were oriented differently relative to the direction of the flow: the smooth part was counter to the flow in one tube and the rough part was counter to the flow in the other tube. Using thermocouples located at the centers of these two channels, we measured the temperature difference due to the gradients of A_h of opposite sign. In accordance with Eq. (1), at $r = 0$ and $\alpha \rightarrow \infty$, this difference does not include dissipative effects and is equal to

$$\Delta T \simeq \frac{R^2}{2\kappa} \frac{\eta}{\rho} \frac{\partial P}{\partial z} \frac{\partial A_h}{\partial z}, \quad (3)$$

i.e., ΔT exists only in the presence of a dependence of the thermal creep A_h on the coordinate z .

In the case of a nearly exponential dependence for the molecular dissipation kernel $W(z)$ (at the point $z = L/2$ this quantity changes from W^{sm} in the smooth part to W^r in the rough part), we can estimate the derivative $\partial A_h / \partial z$ near the center of the capillary from the formula

$$\frac{\partial A_h}{\partial z} \simeq \frac{\Delta A_h}{2aR}, \quad (4)$$

where a is a dimensionless constant on the order of 1; $2aR$ is the characteristic distance over which the value of A_h changes from A_h^{sm} to A_h^r ($\Delta A_h = A_h^r - A_h^{sm}$).

If we consider that for long capillaries ($L \gg R$)

$$\frac{1}{P} \frac{\partial P}{\partial z} \simeq \frac{2(P_1 - P_2)}{(P_1 + P_2)L} = \frac{2}{\beta_p L}, \quad (5)$$

then it is easy to use (3)-(5) to obtain the quantity $\beta_p \Delta T$ independently of the pressure at the inlet (P_1) and outlet (P_2) of the channels:

$$\beta_p \Delta T = \frac{4}{15} T \frac{R}{L} \frac{1}{2a} \Delta A_h \quad (6)$$

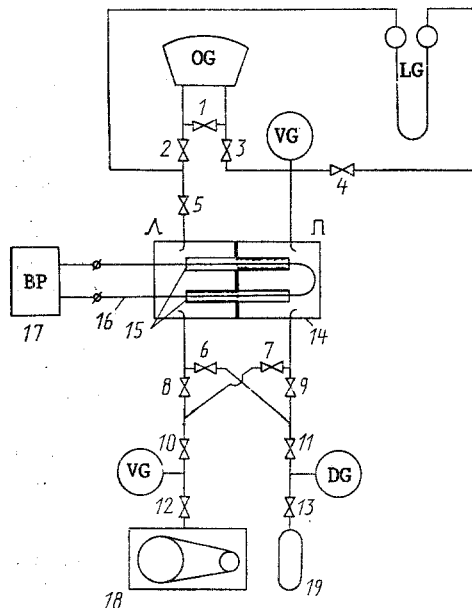


Fig. 1. Basic diagram of experimental unit: 1-13) valves; 14) working chamber; 15) nonuniform capillaries hermetically sealed at the partition in the chamber; 16) thermocouples with junctions at the center of the channels; 17) R-363 self-balancing ac potentiometer; 18) backing pump; 19) cylinder with gas; OG, LG, and DG) optical, oil, and dial pressure gauges; VG) vacuum gauge.

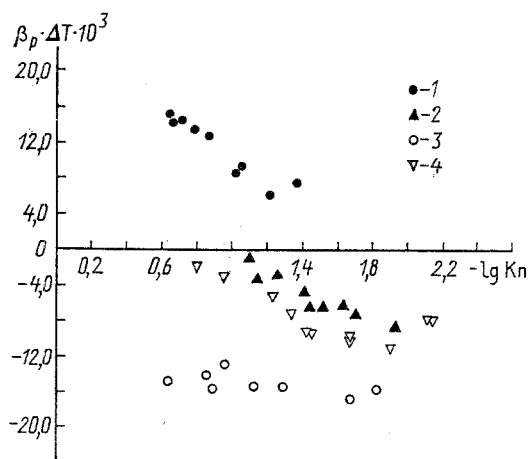


Fig. 2. Empirical relations $\beta_p \Delta T = F(-\log Kn)$: 1) He, 2) Xe - flow direction $R \rightarrow L$; 3) He, 4) Xe - flow direction $L \rightarrow R$; Kn - dimensionless; $\beta_p \Delta T$, K.

Figure 1 presents a diagram of the unit used to measure the temperature difference at the centers of nonuniform capillaries when gas was blown through them. The unit makes it possible to change the direction of the gas flow in the experimental cell, which, according to (6), should lead to a change in the sign of ΔT . As the channels, we used two identical glass capillary tubes of length $L = (0.260 \pm 0.001)$ m and radius $R = (1.39 \pm 0.01) \cdot 10^{-3}$ m. The temperature difference was established from the thermal emf readings of a differential copper-constantan thermocouple with the aid of an R-363 self-balancing ac potentiometer (BP).

We conducted two series of tests: 1) with the direct passage of the gas flow in the working cell from right to left ($R \rightarrow L$); 2) with a change in the flow direction to the opposite, from left to right ($L \rightarrow R$).

The experiment was conducted in the following sequence. We used the backing pump to evacuate the entire system (valves 11 and 13 were closed). The resulting vacuum was recorded by a thermocouple-based vacuum gauge. After the vacuum was established in the system, we closed valves 1, 2 and 6, 7 (for the R → L flow) or 8, 9 (L → R) flow. We opened valve 13 and admitted a portion of gas to the inlet system. This event was recorded by a dial pressure gauge (DG). We then opened valve 11, which regulated the supply of gas to the working cell.

After a steady gas flow was established through the channels, we recorded the readings of the self-balancing ac potentiometer (BP) and we used the oil gauge (LG) or optical gauge (OG) to measure pressure at the inlet P_1 or outlet P_2 in relation to the direction of gas flow.

The flow conditions were changed within the limits $Kn \sim 0.005-0.2$. Pressure in the inlet system was changed within the range $P \sim 100-2000$ Pa. Use of the R-363 self-balancing potentiometer and a differential copper-constantan thermocouple made it possible to achieve a sensitivity of $40 \mu\text{V/K}$ in the electrical circuit.

Figure 2 shows experimental data on the measured quantity $\beta_p \Delta T$ with the flow of gas from left to right and in the reverse direction.

Although the error of the experimental data is relatively high ($\sim 10\%$), the experiment confirms the change in the sign of ΔT with a change in the direction of the gas flow for He and the absence of a change in the sign of ΔT for Xe (for which $A_h^{sm} \approx A_h^r$). The experimental data for xenon shows that despite the fact that the pattern in the cell becomes symmetrical at low Knudsen numbers ($Kn \leq 0.004$), ΔT begins to increase in proportion to P^2 . This is evidently connected with an error in the positioning of the thermocouples at the centers of the channels (there may have been displacements in both the transverse and longitudinal directions), which causes the dissipative terms of Eq. (1) to have a significant effect at sufficiently high pressures. In the region $Kn \sim 0.1$ - where, in accordance with the theory, the mechano-caloric heat flow becomes decisive - we find that ΔT approaches zero for xenon.

It follows from the experimental data on ΔT for helium that the quantity $\beta_p \Delta T$ actually depends slightly on the pressure; in the region of relatively large numbers $Kn \sim 0.2$, the absolute values of this quantity are similar for both directions. This might have been expected from (3).

By averaging the values of $\beta_p \Delta T$ obtained for helium in the region of low pressures ($Kn \sim 0.2-0.07$), we easily see that $\overline{\beta_p \Delta T} = 0.014$ K. Assuming that $a = 1$, $T = 300$ K, we find from Eq. (5) that $\Delta A_h = A_h^r - A_h^{sm} = 0.065$. At $a = 2$, $\Delta A_h = 0.130$. Such values of ΔA_h are in fairly good qualitative agreement with the experimental data on thermal creep in capillaries made of fused glass ($A_h^{\text{He}} = 1.007$, $A_h^{\text{Xe}} = 1.125$) [4]. Measurement of temperature polarization for the conditions described above will make it possible to establish values of ΔA_h if we find the constant a . The latter can be determined on the above-described nonuniform channel for a gas for which the value $\Delta A_h = A_h^r - A_h^{sm}$ is known.

NOTATION

L_{qp} , kinetic coefficient of mechano-caloric heat flux; P , pressure of the gas; α , heat-transfer coefficient; σ , coefficient of viscous slip; λ , mean free path in the gas; L, R , length and radius of the capillary; A_h^{sm}, A_h^r , coefficient of thermal creep for smooth and rough surfaces, respectively; Kn, Re , Knudsen and Reynolds numbers; T, T_0 , temperatures of the gas and the thermostat; κ, η, ρ , thermal conductivity, viscosity, and density of the gas; r, z , cylindrical coordinates.

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