HEAT TRANSFER FROM FLAT BODIES ON AN AIR CUSHION

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Results of experimental studies of the heat transfer and hydrodynamics of plates floating on an air cushion are presented and discussed.

A distinguishing feature of heat transfer for a gas cushion is its association with complex vibrational motion of the body whose role in heat transfer is practically uninvestigated.

A study of the effect of the motion on heat transfer was performed on an experimental device (Fig. 1). In plan view, the size of the grid was 1450 × 220 mm. The arrangement of identical holes was staggered with respect to the axes of the grid at spacings of 6 × 6 and 10 × 10 mm. Hole diameters were 0.9, 1.65, and 2.3 mm. The sensor plates, which were made of electrolytic copper, were 110 × 140 mm in size and their thicknesses varied from 2 to 8 mm. The purity of the active surface of the plates was ∇5. A sensor, placed in a copper-foil jacket 0.1 mm thick, was heated in a thermostat to a temperature of 150-180°C. The plate was then quickly freed of the jacket and slid onto the air jets; after cooling, it was dropped into a calorimeter. The cooling time was measured with a stopwatch. The final cooling temperature was determined by computation of the calorimetric process.

The average coefficient of heat transfer α_1 on the side facing the gas-jet cushion was calculated from the expression

$$\theta = \exp\left(-\frac{\mathrm{Bi}_1 + \mathrm{Bi}_2}{2}\mathrm{Fo}\right). \tag{1}$$

Equation (1) was obtained by transformation of the solution [1] of the problem of nonstationary thermal conductivity of an unbounded plate for asymmetric boundary conditions of the third kind as $\mathrm{Bi}_1 \to 0$ and $\mathrm{Bi}_2 \to 0$. The value of the coefficient of heat transfer α_2 on the passive side was calculated from the equations of heat transfer for natural convection, since it is precisely that process which occurs on the protected side of the plate because of the low rates of flow around the plate. Heat transfer from the end surfaces was not taken into consideration, which led to a systematic overestimate of α_1 by approximately 5%.

The height of rise was measured with a microscope having a micrometer attachment. Sighting was accomplished by means of a reference line scribed on an end of the plate. Since its vertical oscillations were practically centered, the average height of rise is given by

$$H = H_{\max} - A_{\max}. \tag{2}$$

The sensor plate occupied a small portion of the grid and therefore the average jet velocity in the gas cushion could not be determined from the total air-flow rate. From experiments with a separate model, it was established that

$$w = k\sqrt{\frac{2(P_{\mathrm{b}} - P_{\mathrm{pl}})}{\rho_{\mathrm{a}}}}, \tag{3}$$

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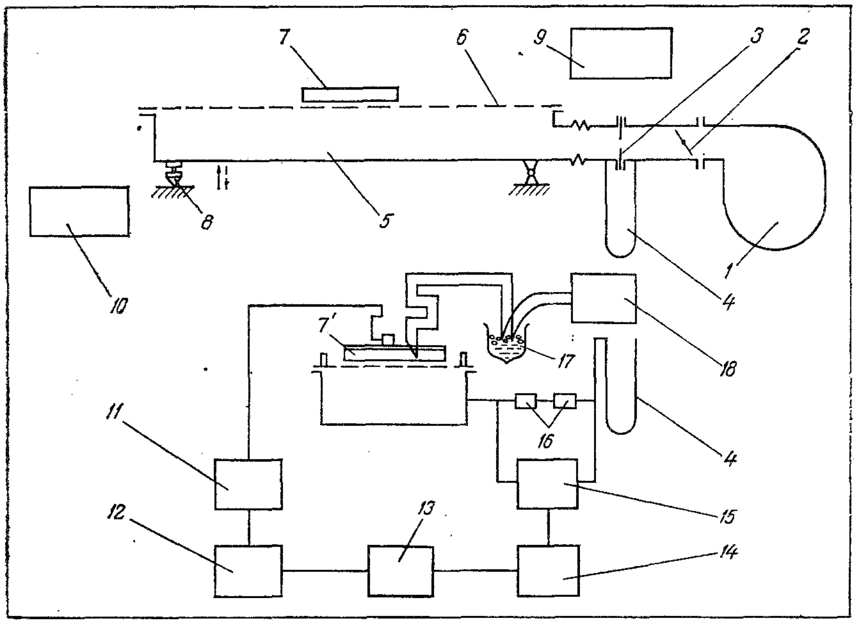

Fig. 1. Diagram of experimental device: 1) VVD No. 5 fan; 2) damper; 3) diaphragm; 4) differential manometer; 5) blast box; 6) removable jet grid; 7) sensor plate; 7') plate with 4332 accelerometer; 8) adjustable support; 9) TS16 thermostat; 10) OQ-202 adiabatic calorimeter; 11) 1606 preamplifier; 12) 2107 analyzer; 13) N700 oscilloscope; 14) TDZ-1-1 strain amplifier; 15) tensomanometer; 16) damping chamber; 17) null thermostat; 18) ÉPP-09 potentiometer.

under our conditions, where $k = f(P_b - P_{pl})$ and varied between 0.8 and 0.95. The air parameters in the blast box were determining factors.

Experiments were performed for three cases: a) The plate on the air cushion was fixed with respect to the jet grid in plan view; b) the sensor moved along the grid on the air cushion at velocities up to 1 m/sec; c) the sensor plate was rigidly fixed above the jet grid by fast-acting clamps at a distance equal to the average height of rise for case a).

In comparing the coefficients of heat transfer for these cases under identical blast modes, a spread of 2-3% in the experimental data was obtained; i.e., they fell within the limits of experimental error. This result shows that neither oscillation nor longitudinal motion of flat bodies on an air cushion influence the intensity of heat transfer. Consequently, one can use the theoretical equations for jet heat transfer without any corrections whatsoever for a gas cushion by the introduction of an average height of rise. The dependence of the average coefficient of heat transfer α_1 and of the height of rise on jet velocity obtained during the experiments are shown in Fig. 2a. They are linear. The coefficient of heat transfer does not depend on the specific pressure (mass) of the plates, i.e., with established self-similarity with respect to oscillations of the body, on the gap between the grid and plate, which was also observed with small gaps for bodies of small sizes [2] where the effect of exhaust air is small.

For the average height of rise, the functional relation with velocity included an inversely proportional dependence on specific pressure. The linear dependence of α_1 on w is possibly explained by the fact that for an impact gas jet, highly turbulent flow which increases with velocity is typical and has a basic structure made up of Taylor–Hertler vortices formed by the action of centrifugal forces on flow rotating with respect to the stagnation point.

Measurements of temperature variations at the surface of a body oscillating on an air-cushion were made with a low-frequency constant-current thermoanemometer as in [3]. The sensitive element of the thermoanemometer was a platinum foil 5 μ thick and 2 × 20 mm in size mounted with an air gap in the center of a textolite plate 20 mm thick. Under the influence of the jets, this plate was displaced along vertical cylindrical guides installed so that the center of the foil fell on the axis of a hole. It turned out that there were no low-frequency variations in the surface temperature of a body oscillating on an air cushion.

The conditions for dynamic interaction of gas flows and bodies were studied in order to establish the reason for self-similarity of heat transfer during motion of the body.

The small amount of rise made it impossible to place a detector for measuring flow parameters directly in the region of the gas cushion. However, since the velocities of the gas in the cushion during discharge of air into the surroundings are a function of the pressure in the blast box, one can form some idea of the interaction between flow and body from the correlation relations between this pressure and the displacement of the body. A body on a gas cushion undergoes complex motion, the basic components of which are vertical oscillations; consequently, the reliability of judgments about correlation relations remains the same if only the vertical oscillations are introduced as characteristic motions of the body. A low-inertia membrane strain gauge acted as the sensitive element in the circuit for measurement of pressure pulsations (Fig. 1). Its larger chamber — the counterpressure chamber — was connected to the blast box through two damping chambers and the smaller chamber — the pulsed-pressure chamber — had a smooth connecting pipe with a length ≈ 100 mm. This scheme made it possible to record pressure variations reliably at 10 N/m^2 and at a frequency of 0-40 Hz.

A Bruel and Kjaer 4332 accelerometer was fastened at the center of a plate by means of a rigid textolite gasket with threaded connections in order to measure vertical oscillations. The signal from the accelerometer was fed to an oscilloscope through an amplifier–analyzer combination where it was recorded synchronously with pressure pulsations. The sensitivity of this measuring circuit was 0.005 mm in the frequency range 2-30 Hz. The connecting leads were made up in the form of a double loop and the total mass of their suspended parts and of the accelerometer plus fastenings did not exceed 7%, so that one can assume the distortion of plate oscillations introduced by the method of measurement was negligibly small.

The oscillograms were digitized on an F001 digital converter and the resultant punched tape was analyzed by means of a set of programs for a Minsk-32 computer.

To determine experimental conditions more precisely, recordings were made of the oscillations of the jet grid. Analysis of the normal spectra of grid and sensor-plate oscillations showed that low-frequency oscillations of the grid at f $\approx$ 2 Hz were transmitted through the gas cushion to the plate. Based on this, a low-frequency component was filtered out of all input masses by the method of the sliding mean. The filtered dependences of the mean square amplitudes of vertical plate oscillations and of pressure pulsations in the blast box on jet flow velocity are shown in Fig. 2b. In this and subsequent figures, the confidence intervals are not plotted in order not to obscure the curves.

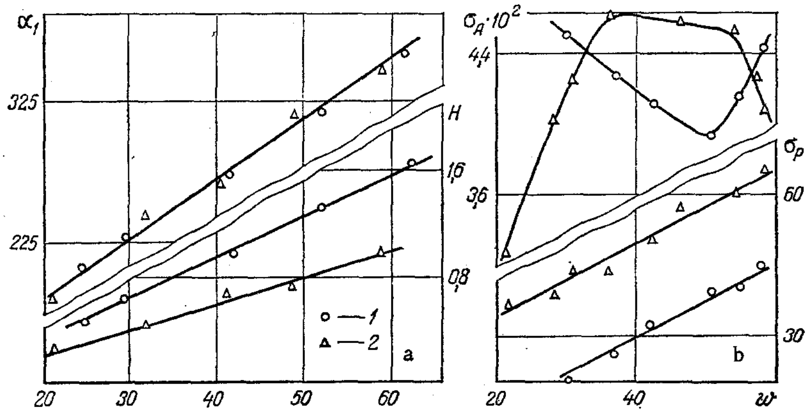

Fig. 2. a) Dependence of average coefficient of heat transfer α_1, W/m$^2\cdot$°C, and of height of rise of plate H, mm, on jet velocity w, m/sec; b) dependence of mean square amplitudes of vertical plate oscillations σ_A, mm, and of pressure pulsations in blast box σ_p, N/m^2, on jet velocity w, m/sec (d = 2.3 mm; S = 10 × 10 mm); 1) δ = 5 mm; 2) δ = 8 mm.

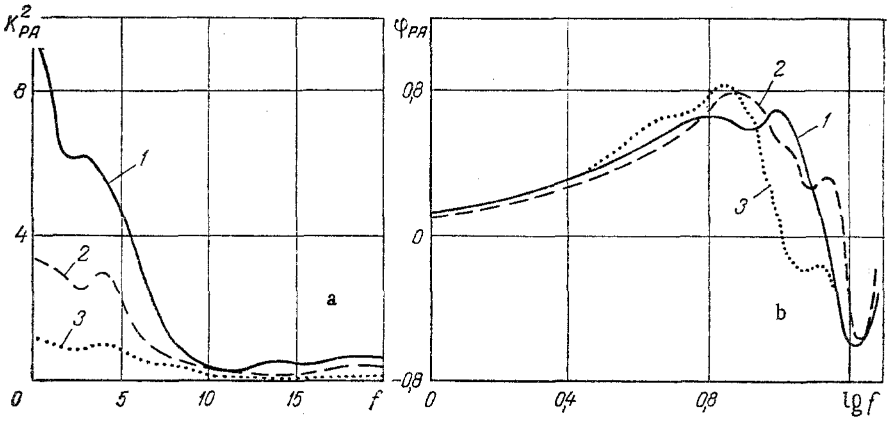

Fig. 3. Estimates of square of coherence spectrum K^2_{PA} (a) and of phase spectrum φ_{PA} (b) of pressure pulsations and body oscillations as a function of frequency f, Hz (d = 2.3 mm, S = 10 × 10 mm, δ = 8 mm); 1) w = 21.7 m/sec; 2) w = 46 m/sec; 3) w = 58.6 m/sec.

The results of the measurements of pressure pulsations lead to the conclusion that great unsteadiness of flow is generally characteristic of jet systems because of the characteristic of the gas channel and that this can introduce a significant contribution to a high level of heat transfer in impact jets.

The correlation relations between plate oscillations and pressure pulsations are represented in the form of smoothed estimates, and estimates smoothed by means of a Bartlett window [4], of the square of the coherence spectrum K^2_{PA} (Fig. 3a), and of the phase spectrum φ_{PA} (Fig. 3b). These characteristic curves show that the correlation is insignificant and decreases as effluent velocity increases with the plate oscillations leading the pressure pulsations in phase at low frequencies. Thus, even for a low specific pressure (mass) of the plates, self-similarity of their oscillations on a gas cushion is observed. Hence, in a simulated representation, motion of a plate can be taken into account by an equivalent addition to the spectrum of pressure pulsations.

Self-similarity of motion makes it possible to explain the absence of differences in the intensity of heat transfer for a free and a fixed body since, according to [5], the effect of pulsations and oscillations is observed when resonance phenomena are present.

NOTATION

$\theta = [t(\tau) - t_a]/(t_0 - t_a)$, dimensionless temperature; t_0, $t(\tau)$, initial temperature of plate and plate temperature at time τ; t_a, air temperature; τ, time; $Bi = \alpha\delta/2\lambda$, $Fo = 4a\tau/\delta^2$, Biot and Fourier numbers; α, average coefficient of heat transfer; δ, plate thickness; λ, a, coefficients of thermal conductivity and of thermal diffusivity; H, H_{max}, average and maximum heights of rise of plate; A_{max}, maximum amplitude of vertical plate oscillations; w, average jet velocity; P_b, pressure in blast box; $P_{pl} = G/F$, specific pressure of plate; G, plate weight; F, plate area; ρ_a, air density, σ_A, σ_P mean square values of amplitudes of vertical oscillations and of pressure pulsations; K^2_{PA}, estimate of square of coherence spectrum; φ_{PA}, estimate of phase spectrum; f, frequency; d, S, diameter and spacing of holes in grid.

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