STUDY OF HEAT EXCHANGE IN CLOSED AIR INTERLAYERS AT REDUCED PRESSURE

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The heat transfer coefficient is measured in air interlayers at reduced pressure. The results are compared with criterial relationships.

The general procedure for obtaining the computational equations enabling one to calculate the coefficients of heat exchange and heat transfer at different gas pressures if the form of the criterial heat exchange equations is known at normal pressure is examined in [1]. The scarcity of the literature data on heat exchange of natural convection under conditions of rarefication leads to the necessity of experimental verification of the proposed computational equations. Moreover, a comparison of the criterial equations on heat transfer in interlayers proposed by different investigators reveals considerable discrepancies in the estimate of the intensity of heat exchange (Fig. 1).

Heat transfer in interlayers is usually described in the form of the dependence of the convection coefficient $\varepsilon_c = \lambda/\lambda_2$ on the Rayleigh number $(\mathrm{Ra})_{m0} = (\mathrm{GrPr})_{m0}$. The physical parameters entering into the Gr and Pr numbers are selected for the mean arithmetic temperature (index m) of the walls bounding the interlayer under conditions of normal pressure (index 0); the thickness L of the interlayer is taken as the reference dimension. As follows from Fig. 1, the scatter in the convection coefficients from different authors reaches 35%. Such great discrepancies go beyond the range of the measurement errors and are probably caused by the different conditions under which the experiments were conducted (geometry of interlayers, boundary conditions, etc.). Because the information on these conditions is incomplete it is difficult to give preference to one or another of the results. Therefore, we conducted preliminary measurements of the heat exchange coefficient in interlayers at normal gas pressure for the selection of the criterial equations. We note that the curve constructed from M. A. Mikheev's equation [6] lies approximately in the middle of the field of scatter of the convection coefficient for horizontal and vertical interlayers. Therefore one can use the one dependence of [6] for an approximate estimate of ε_c independent of the orientation of the interlayer.

A general view of the measuring instrument is shown in Fig. 2. The method of a secondary wall was used to study the surface-average heat transfer coefficient in a flat interlayer. The experiments were conducted with an air interlayer formed by two metallic isothermal plates 1 and 2 200 × 200 mm in size and enclosed along the perimeter by eight end covers 6. Teflon spacers 5 and 3 mm thick are set between the covers 6 and the plates 1 and 4. The gap δ between neighboring covers is ~0.1 mm. The necessary thickness of the interlayer was provided by mounting textolite brace bushings 7 (outer diameter 7 mm, inner 6 mm) between plates 1 and 2, fixed with textolite pins 8 (4 mm in diameter) and nuts 9. Plate 1 was made from brass 15 mm thick. The other wall consisted of a flat calorimeter made up of a set of plates: brass 4 (15 mm thick), copper 2 (3 mm thick), and rubber 3 (2 mm thick). Plates 2, 3, and 4 were joined with BF-2 adhesive. Coils 10 of copper 5 mm in diameter are sealed into the channels of plates 1 and 4. Water whose temperature is kept constant with an error of ±0.1°K is circulated through the coils. To decrease radiant heat exchange all the inner surfaces of the interlayer were polished and glossy chrome plated.

The temperature of the plates was measured by nichrome-constantan thermocouples with an electrode diameter of 0.1 mm. The temperature of the hot and cold plates was measured relative to a cold

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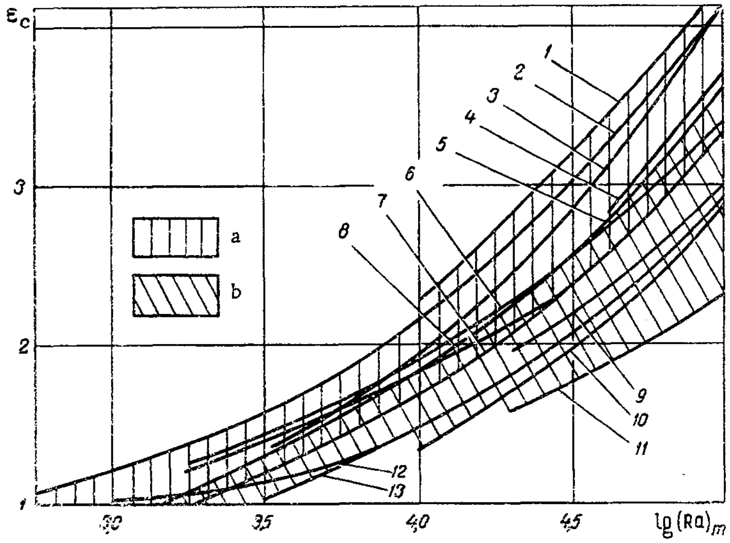

Fig. 1. Comparison of functions $\varepsilon_c = \varepsilon_c\,(Ra)_{m0}$ from data of different authors: a) region of scatter for horizontal orientation of interlayer; b) region of scatter for vertical orientation of interlayer; 1) [9]; 2) [5]; 3) [3]; 4) [8]; 5) [4] at L/H = 0.25; 6) [7]; 7) [6]; 8) [8]; 9) [2] at L/H = 0.5; 10) [3]; 11) [2] at L/H = 0.025; 12) [5]; 13) [4] at L/H = 0.025.

junction placed in a Dewar flask. The temperature drop at the working insulation layer was measured with a thermopile, 14 junctions of which were uniformly distributed along the length of the interlayer. The temperature drops were recorded with a PPTN-1 potentiometer with a M 195/1 galvanometer as the null instrument.

To study the heat transfer coefficient at a reduced pressure the measuring instrument was placed in a pressure chamber with a volume of ~0.05 m^3. The vacuum system could create rarefication down to $1 \cdot 10^{-4}$ torr. Pressure in the range of 760-100 torr was measured by a pointer-type manometer of the 1.5 torr accuracy class; in the range of 100-10 torr pressure was measured by a U-shaped mercury manometer. Let us examine the working equation for calculating the heat transfer coefficient in the interlayer from the measurement data. The heat flux Q_h flowing from the hot to the cold plate through the gas interlayer is equal to the flux Q_d determined by the calorimeter after deduction of the loss flux Q_l which arrives at the thermometer through the construction elements (bushings, pins, thermoelectrodes) and through end-type heat exchange between surfaces 2 and 6:

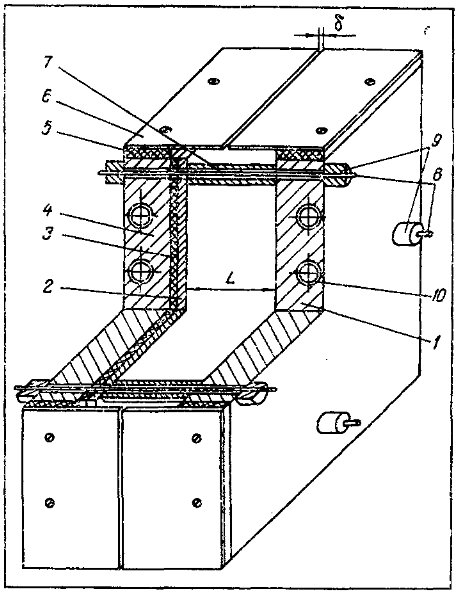

Fig. 2. Diagram of measuring instrument.

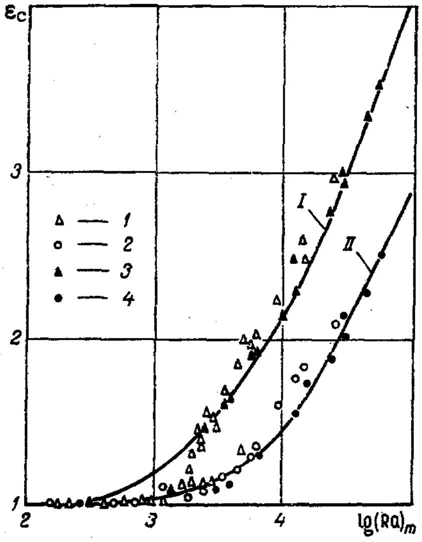

Fig. 3. Comparison of computational equations with experimental data: 1, 2) experimental data obtained with horizontal and vertical orientations of interlayers, P < 700 torr; 3,4) same, but at P ≈ 760 torr; I) calculation from Eq. (7) for horizontal interlayer; II) from Eq. (8) for vertical interlayer.

$$Q_h = Q_d - Q_1, \tag{1}$$

where

$$Q_h = K\Delta t_{12} S_2;\ Q_d = \frac{\lambda_3}{\sigma_3}\Delta t_{24} S_2.$$

Substituting into Eq. (1) the expressions for the heat fluxes we find the heat transfer coefficient K in the interlayer

$$K = \frac{\lambda_3}{\sigma_3}\cdot\frac{\Delta t_{24}}{\Delta t_{12}} - \frac{Q_1}{S_2\Delta t_{12}} = A\frac{\Delta t_{24}}{\Delta t_{12}} - \frac{Q_1}{S_2\Delta t_{12}}. \tag{2}$$

It was possible to determine from the estimating calculations that the heat flux loss through the construction elements is small and does not exceed 0.3% of the measured heat flux. The end-type heat exchange can be found by calculation, knowing the temperature drop Δt_3 in the gap between plate 2 and the covers 6. The measurements of Δt_3 showed that it is practically independent of the interlayer thickness L and is a function only of Δt_{12}, where the last term of Eq. (2) was found to equal 0.05. The numerical value of the coefficient A = 105 was found from calibration tests when the heat transfer in the interlayer was accomplished only by the heat conduction of the air and by radiation. The convection coefficient was calculated from the equations

$$\varepsilon_c = \frac{(K - \alpha_r)\sigma}{\lambda_3},\quad \alpha_r = \varepsilon_{re}\cdot 5.67\frac{\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4}{T_1 - T_2},$$

$$K = 105\frac{\Delta t_{24}}{\Delta t_{12}} - 0.05. \tag{3}$$

The reduced reflectivity $\varepsilon_{re} = 0.045$ of surfaces 1 and 2 was found from tests at a pressure of $1\cdot10^{-4}$ torr.

The experiments were conducted in the following ranges of variation of the determining parameters: temperature difference between bounding plates 20-60°, temperature of "cold" plate ~298°K; vertical and horizontal orientations of interlayers 5, 10, 15, and 25 mm thick; air pressure 10-760 torr. The results of the measurements are presented in Fig. 3. The measurements were conducted under continuous conditions with Knudsen numbers Kn ≪ 1; therefore the Rayleigh numbers were calculated from the equation [1]

$$\mathrm{Ra}_m = \mathrm{Ra}_{m,0}\left(\frac{P}{P_0}\right)^2. \tag{4}$$

An estimate of the measurement error showed that the relative instrument error of the indirect measurements of the convection coefficient at normal pressure does not exceed ±2%, while at reduced pressure the error reaches ±4%. We note that the reproducibility of the experiments lay within the same limits.

As seen from Fig. 3, the experimental data agree satisfactorily with curves I and II constructed from Niemann's equations [5] obtained for normal pressure:

horizontal interlayers, heat-emitting surface on bottom:

$$\varepsilon_c = 1 + \frac{0.07\left[(\mathrm{GrPr})_{m0}\right]^{1.33}}{3.2\cdot 10^3 + (\mathrm{GrPr})_{m0}} = 1 + \frac{0.07\mathrm{Ra}_{m0}^{1.33}}{3.2\cdot 10^3 + \mathrm{Ra}_{m0}}, \tag{5}$$

vertical interlayers:

$$\varepsilon_c = 1 + \frac{0.0236\left[(\mathrm{GrPr})_{m0}\right]^{1.39}}{1.01\cdot 10^4 + (\mathrm{GrPr})_{m0}} = 1 + \frac{0.0236\mathrm{Ra}_{m0}^{1.39}}{1.01\cdot 10^4 + \mathrm{Ra}_{m0}}. \tag{6}$$

Substituting the Ra_m of Eq. (4) into (5) and (6) in place of the number Ra_{m0} we obtain equations allowing the calculation of the surface-average convection coefficient at reduced pressures in closed horizontal and vertical interlayers, respectively:

$$\varepsilon_c = 1 + \frac{0.07\mathrm{Ra}_m^{1.33}}{3.2\cdot 10^3 + \mathrm{Ra}_m}, \tag{7}$$

$$\varepsilon_c = 1 + \frac{0.0236\mathrm{Ra}_m^{1.39}}{1.01\cdot 10^4 + \mathrm{Ra}_m}. \tag{8}$$

If $\mathrm{Ra}_m < 1\cdot 10^3$, ε_c should be taken as equal to one.

Let us examine separately the question of the effect of the simplex L/H on heat transfer in a vertical closed interlayer. There is no single opinion in the literature on the need to take this parameter into account. Some authors [2, 4] allow for this factor, others [3, 5, 6] do not. Our experiment was conducted under conditions when $0.025 \le L/H \le 0.125$. Any dependence of the heat transfer coefficient on the ratio of interlayer dimensions was not detected in this interval.

Thus, the results of the measurements confirm the possibility of using the criterial equations (7) and (8) obtained by the method of [1]. The equations make it possible to determine the convection coefficient in flat closed air interlayers under conditions of rarefication when $\mathrm{Kn} \ll 1$ with a root-mean-square error of 6.4% in the interval of $1\cdot 10^3 \le \mathrm{Ra}_m \le 1\cdot 10^5$.

NOTATION

ε_c	is the convection coefficient;
λ, λ_2, λ_3	are the coefficients of equivalent thermal conductivity, thermal conductivity of gas in interlayer, and thermal conductivity of heat insulation plate 3, W/m·°K;
K	is the coefficient of convective, conductive, and radiative heat transfer in interlayer, $W/m^2\cdot$°K;
Ra, Gr, Pr	are the Rayleigh, Grashof, and Prandtl numbers;
δ_3	is the thickness of insulating plate 3, m;
S_2	is the area of heat-absorbing surface of plate 2, m^2;
Δt_{24}, Δt_{12}	are the temperature drops at insulating layer and between hot and cold plates 1 and 2, °K;
P	is the pressure of gas filling interlayer, torr;
T_1, T_2	are the temperatures of plates 1 and 2, °K;
H	is the height of interlayer, m;
α_r	is the coefficient of radiative heat exchange, $W/m^2\cdot$°K.

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