EXPERIMENTAL STUDY OF LOCAL HEAT TRANSFER IN HORIZONTAL ENCLOSED LAYERS

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Experimental results are presented for the local coefficient of heat transfer in horizontal enclosed layers over the range of Rayleigh numbers $1 \cdot 10^3 < Ra_m < 6 \cdot 10^4$. It is shown that the local coefficient of heat transfer is essentially unstable in time. Its limiting values at $Ra_m > 3 \cdot 10^3$ can differ by as much as a factor of four from the average value.

Heat transfer in a layer of gas heated from below has been studied for several decades. Most of the work in this field was devoted to a determination of the mean surface coefficient of heat transfer and to the establishment of the limits for the production of convection. The question of the profiles of temperature fields and of temperature pulsations in gas or fluid layers has not been given as much study [1-3]. Local heat transfer in horizontal layers was discussed in [4] where the distribution of thermal fluxes at a heated wall was obtained from numerical calculations for a fixed horizontal scale of the convective cell N/L = 1 (Fig. 1a).

The structure of fluid flow was investigated in a number of papers which are listed in [5]. It was established that a cellular flow structure (Fig. 1a) exists in horizontal layers when $1.7 \cdot 10^3 < Ra_m < 5 \cdot 10^4$. The thermal flux distribution at the lower surface of the layer is shown in Fig. 1b as given by theoretical data [4]. It was further established that the variation of the coefficient of heat transfer depends on the Rayleigh number. If one compares the results of experimental studies of temperature pulsations [1-3] and the distributions of local thermal fluxes [4], one can assume that pulsations of thermal fluxes should also exist. However, we have not succeeded in finding data on the measurement of local thermal fluxes at horizontal walls in the literature.

The results of our experimental studies are given below.

Measurements of local thermal fluxes were made with special heat meters in the form of a thin metal plate – the disk 2 (Fig. 2a) – in the cylindrical cavity 7 created in one of the plates 1 forming the layer, for example, in the hotter plate; there is a narrow gas gap between the heat meter and the plate.

The thermal flux $P(\tau)$ which is dissipated from the outer surface of a heat meter into the gaseous medium in a time $d\tau$ and recorded by the heat meter can be determined from the following condition:

$$P(\tau)\, d\tau = C_T dt_{Tv} + \sigma S'_T (t_p - t_{Ts})\, d\tau. \qquad (1)$$

on the basis of the law for conservation of energy.

If there is no temperature gradient over the thickness of the heat meter, $t_{Ts} = t_{Tv} = t_T$ and Eq. (1) takes the form

$$P(\tau) = C_T \frac{dt_T}{d\tau} + \sigma S'_T (t_p - t_T). \qquad (2)$$

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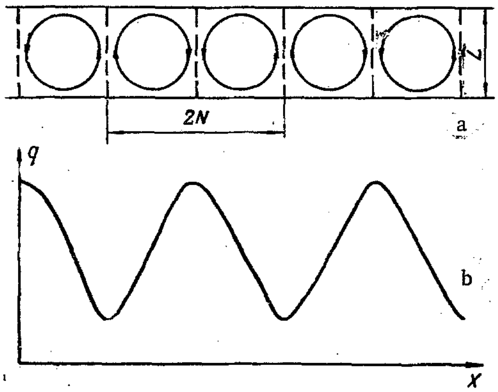

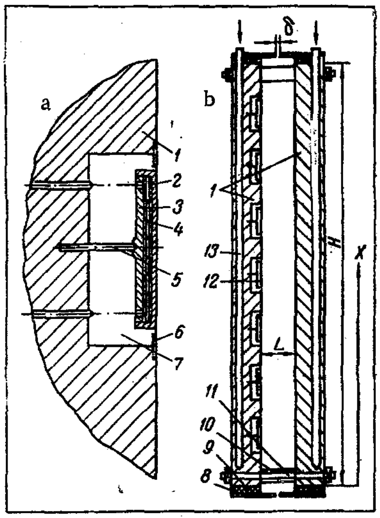

Fig. 1 Fig. 2

Fig. 1. Diagrams of: a) fluid circulation; b) distribution of heat on lower surface.

Fig. 2. Diagram of measuring devices: a) heat meter; b) layer.

The thermal flux P(τ) from the surface S_T'' of a heat meter passes through the layer to the "cold" plate and therefore

$$P(\tau) = kS_T''\Delta T. \tag{3}$$

We introduce the notation

$$\frac{dt_T}{d\tau} = b; \quad \frac{C_T}{S_T''} = A; \quad \frac{\sigma S_T'}{S_T''} = B$$

and substitute the value of P(τ) from Eq. (3) into Eq. (2):

$$k = A\frac{b}{\Delta T} + B\frac{t_p - t_T}{\Delta T}. \tag{4}$$

The coefficients A and B can be determined from calibration experiments. To accomplish this, conditions are first created for which there is no convection in the layer and the thermal flux is transported only by radiation and conduction, which makes it possible to determine the coefficient of heat transfer k from the equation

$$k = k_1 + k_2 = \frac{\lambda_m}{L} + \varepsilon_l \cdot 5{,}67\,\frac{\left(\frac{t_p + 273}{100}\right)^4 - \left(\frac{t_x + 273}{100}\right)^4}{\Delta T}. \tag{5}$$

To determine the coefficient A, one should first heat the heat meter to a temperature higher than that of the hot plate and then turn off the heater. The heat meter begins to cool and at the time the temperatures of the heat meter and hot plate are the same, there will be no heat transfer between them; as a consequence σ = 0 and the second term in Eq. (4) will be zero, i.e.,

$$A = \frac{k\Delta T}{b}. \tag{6}$$

The temperatures t_p and t_x and the cooling rate [6] b are measured at that time. In a stationary mode we also have from Eq. (4)

$$B = \frac{k\Delta T}{t_p - t_T}, \tag{7}$$

where the parameters t_p, t_T, and ΔT are determined experimentally.

A heat meter consists of the two chrome-plated copper disks 2 and 3 which are 15 mm in diameter (core) and each 0.5 mm thick. The thermocouple 4 is placed between the disks and is used both for temperature measurement and for heating the core. The heat meter is fastened to the plate 1 by means of the ebonite stud 5, which is 1 mm in diameter. Between the core and the plate there is the air space 7. The outside slot is covered by the thin flat ring 6. The outer surfaces of this ring, of the disk 3, and of the plate 1 are polished and chrome-plated (Fig. 2a).

The seven heat meters 12 are located in one of the plates forming a layer with a spacing of 25 mm (Fig. 2b). Constancy of the temperature of the plate 1, which is 200 × 200 × 15 mm in size, is ensured by pumping a thermostatically controlled fluid through the pipe 13 sealed into the body of the plate; the variation in water temperature was no greater than ±0.1°K. The end slots are covered along the perimeter by the caps 8 at the junction of which a gap $\delta \approx 0.1$ mm is left to reduce heat transfer. The 3-mm-thick Teflon gasket 9 is placed between the caps and the plates 1. The thickness of the layer is established by means of the textolite spacers 10 which are slipped onto the studs 11 that pull the plates 1 together. All internal surfaces of the layer are brilliantly chrome-plated in order to reduce radiative heat transfer.

Calibration experiments to determine the coefficients A and B performed with the measuring device described above showed that $2714 \leq A \leq 3414$ and $1.02 \leq B \leq 1.20$ for various heat meters. In the measurement of B, the temperature difference $(t_p - t_T)$ was expressed in microvolts and therefore B has the dimensions $W/m^2 \cdot \mu V$.

The basic set of measurements in 60 experiments to determine the time-averaged coefficient of heat transfer between horizontal plates and its extreme values k' and k" was made in accordance with the following scheme:

1) definite layer thicknesses L = 5, 10, 15, 20, and 25 mm and temperature differences ΔT between the plates in the range 35-60° were established with a temperature of 25°C at one of the plates;

2) the temperature of the plates was measured after reaching a steady state. The temperature of the heat meter was then recorded with an ÉPP49 MZ electronic potentiometer having a sensitivity of 1.1 mm/μV for a period of 1 h;

3) the average value of the heat-meter temperature, $\bar{t}_T$, during the time of measurement, was determined from the potentiometer chart and $\bar{k}$ was determined by substitution of $\bar{t}_T$ in Eq. (4);

4) the extreme values of the coefficient of heat transfer were also determined from the chart. Usually, k' and k" coincided with cases of maximum deviations of the temperature curve for t_T from its mean value $\bar{t}_T$ with a high rate of change b of the heat-meter temperature also being observed.

Examples of time records of the temperature of the heat meter located at the center of the layer are shown in Fig. 3. The curves were obtained for various layer thicknesses and a temperature difference $\Delta T \approx 40°$ with the temperature of the cold plate being 25°C.

It should be noted that the readings of the seven heat meters agreed within the limits of experimental error for $Ra_m < 4 \cdot 10^4$. With $Ra_m > 4 \cdot 10^4$, the coefficient of heat transfer $\bar{k}$ in the center differs from $\bar{k}$ at the periphery of the layer by 25%. Because of this, we discuss in the following only the characteristics of heat transfer in horizontal layers averaged over the readings of the seven heat meters.

As indicated by Fig. 3, the temperature pulsations are rather disordered, but in first approximation one can talk of a period for these oscillations. In most diagrams one can clearly visualize fundamental oscillations with a long period on which are superimposed more frequent pulsations of small amplitude. The period of the small oscillations falls within the range 30-60 sec, and the period of the large oscillations can reach 300-400 sec.

The results are given in Fig. 4 in the coordinates ε_c, log Ra_m. The convection coefficient ε_c was calculated from

$$\varepsilon_c = \frac{k - k_1}{k_2}. \quad (8)$$

The vertical lines denote the maximum deviations of ε_c (extremes) from its average values given by the points. It is clear that the local convection coefficient can differ considerably from its average value in time (deviations may reach 400%). In turn, the time-

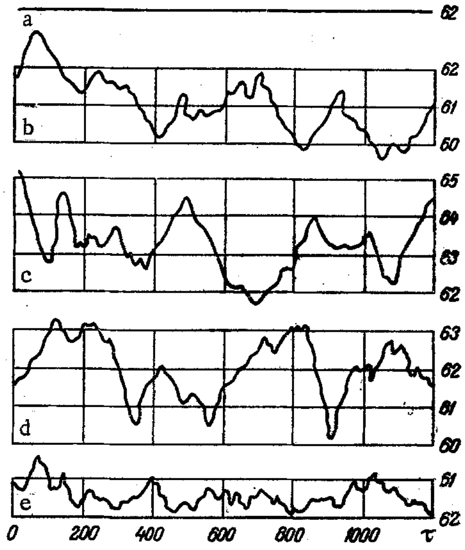

Fig. 3

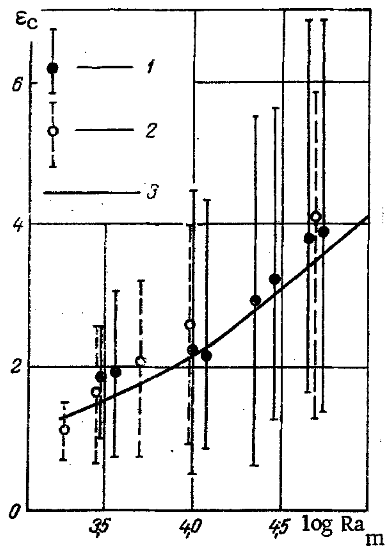

Fig. 4

Fig. 3. Typical time recordings of the temperature of the central heat meter: a) L = 5.1 mm; Ra_m = 362, t_p = 64.8°C; b) L = 10.3, Ra_m = 2980, t_p = 65.0; c) L = 15.2, Ra_m = 10,150, t_p = 66.1; d) L = 20.2, Ra_m = 22,200, t_p = 65.2; e) L = 25.2, Ra_m = 42,700, t_p = 65.6. t, °C.

Fig. 4. Average and extreme values of ε_c as a function of Ra_m: 1) our measurements; 2) [4]; 3) [7].

averaged local values of ε_c satisfactorily agree with the mean surface values of the convection coefficients given by [7]

$$\bar{\varepsilon}_c = 1 + \frac{0{,}07\ \sqrt[3]{(\mathrm{Ra}_m)^4}}{3{,}2\cdot 10^3 + \mathrm{Ra}_m}. \tag{9}$$

It is necessary to keep in mind that the local convection coefficient may take on values less than one as in vertical enclosed layers [8, 9]. One can arrive at a similar conclusion by considering the distribution pattern for thermal fluxes at a heated wall for various Ra obtained in [4] from numerical calculations (extreme and average values are shown in Fig. 4). The results of the numerical solution for stationary convective heat transfer in a cell with N/L = 1 are in satisfactory agreement with our results.

From an analysis of the results, the following relations are proposed for the calculation of extreme values of ε_c:

for maximum values

$$\varepsilon_c = 3.35\,\lg \mathrm{Ra}_m - 9 \quad \text{for} \quad 3\cdot 10^3 \leqslant \mathrm{Ra}_m \leqslant 6\cdot 10^4, \tag{10}$$

for minimum values

$$\begin{aligned} \varepsilon_c &= 0{,}7 \quad \text{for} \quad 1{,}7\cdot 10^3 < \mathrm{Ra}_m \leqslant 2{,}5\cdot 10^4, \\ \varepsilon_c &= 3\,\lg \mathrm{Ra}_m - 12.5 \quad \text{for} \quad 2.5\cdot 10^4 < \mathrm{Ra}_m \leqslant 6\cdot 10^4. \end{aligned} \tag{11}$$

Thus it was shown experimentally that the local convection coefficient in enclosed horizontal layers can vary in time within broad limits relative to its average value (up to a factor of four) for a variation of the Rayleigh number $3\cdot 10^3 < Ra_m < 6\cdot 10^4$ and can assume values less than one.

The amplitude of the oscillations in the convection coefficient was measured and Eqs. (10) and (11) proposed for its calculation.

The results are in agreement with theoretical estimates obtained in [4].

NOTATION

$Ra = GrPr$, $Gr = \beta g L^3 \Delta T/\nu^2$, $Pr = \nu/a$, Rayleigh, Grashof, and Prandtl numbers, respectively; g, acceleration of gravity, m/sec^2; ν, kinematic viscosity, m^2/sec; β, volumetric expansion coefficient, $1/°K$; a, thermal diffusivity, m^2/sec; λ, thermal conductivity, $W/m \cdot °K$; ΔT, temperature difference between plates forming a layer, °K; L, H, thickness and width of layer, m; N, horizontal dimension of a cell, m; P, thermal flux, W; τ, time, sec; C, heat capacity, J/°K; t, temperature, °C; S_T', S_T'', surface areas of heat meter exposed to heat-releasing and heat-absorbing plates, m^2; k, total coefficient of heat transfer (convection, conduction, and radiation), $W/m^2 \cdot °K$; k', k'', extreme (minimum and maximum) values of the coefficient of heat transfer, $W/m^2 \cdot °K$; k_1, k_2, coefficients of heat transfer for radiation and conduction, $W/m^2 \cdot °K$; ε_c, $\overline{\varepsilon}_c$, local and average convection coefficients, $m^2 \cdot °K$; σ, coefficient of heat transfer between heat meter and heat-releasing plate, $W/m^2 \cdot °K$. Indices: T, heat meter; p, heat-releasing plate; x, heat-absorbing plate; s, mean surface value; v, mean volume value; m, physical parameters at mean arithmetic temperature of walls.

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