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MEASUREMENT OF PULSATIONS IN HEAT FLOW ON THERMALLY LOADED SURFACES

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Pulsations in heat flow on a surface, washed by a fluidized bed, are measured with the help of a sensor.

Various methods are used to measure the heat flow and heat transfer coefficient in experimental studies of external heat transfer in a fluidized bed. In order to determine the time-averaged heat transfer coefficient, massive calorimeters are used with different configurations: spherical, cylindrical, and flat. Heat transfer is calculated starting from the solution of the heat conduction equation for a sensing body (local values) by the regular thermal regime method or the balance method, namely, by the electrical power supplied to the heater of the calorimeter (surface-averaged values).

In order to find the instantaneous values of the coefficient of heat transfer, constant current thermoanemometers are widely used. First used only for a qualitative verification of the nonstationary nature of the external heat exchange in the bed [1] (after refining the measuring procedure), they were then used to obtain a quantitative description of the process [2, 3]. The equation for α was based on the equation of heat balance of the foil in the thermoanemometer. Calculations using this equation, as shown in [4], could only give a heat transfer coefficient averaged over a half period of the oscillations. Analysis of the nonstationary temperature field of the substrate, performed in [4], permitted eliminating in the calculation such quantities as the effective heat capacity of the foil and the heat loss in

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the substrate, which increased the accuracy of the measurements of the instantaneous value of the heat flux.

However the area of application of thermoanemometric sensors is restricted to low (room) temperatures. It is difficult to perform measurements in hot beds using a thermoanemometer because of the measuring method itself. On the other hand, interest in high-temperature beds is increasing.

For this reason, methods and setups for measuring nonstationary heat flows, described in [5-8], are interesting. In order to clarify the possibilities of these methods and setups for determining pulsations in the heat flux on a surface located in a fluidized bed, we performed a series of experiments. The results showed that the methods and setups that have been created can be used to study heat transfer in fluidized beds.

Let us consider in more detail the method used for performing the measurements. This method is based on the approximate solution of the heat conduction equation for a plate

$$\frac{\partial^2\vartheta}{\partial\bar{x}^2}=\frac{\partial\vartheta}{\partial\,\mathrm{Fo}}\quad(-1\leqslant\bar{x}\leqslant 1,\ \mathrm{Fo}\geqslant 0)\tag{1}$$

under the boundary conditions

$$\vartheta(-1,\ \mathrm{Fo})=\vartheta_1(\mathrm{Fo}),\ \vartheta(1,\ \mathrm{Fo})=\vartheta_2(\mathrm{Fo}),\ \vartheta(\bar{x},\ 0)=0.\tag{2}$$

Eqs. (1) and (2) were solved for two stages of the process. The first stage proceeds from the initial time to some time Fo* when an isothermal region exists in the plate and the plate can be viewed as a half-space; the second stage (Fo > Fo*) corresponds to times when the action at the boundaries reaches the center of the plate and the half-space model cannot be used. The working equations have the form [7]

$$q_{\mathrm{I}}(\mathrm{Fo})=\frac{\lambda n\sqrt{\mathrm{Fo}^*}}{L}\left\{\frac{\vartheta_1(\mathrm{Fo})}{\sqrt{\mathrm{Fo}}}-\frac{1}{2}\int\limits_0^{\mathrm{Fo}}\frac{\vartheta_1(\mathrm{Fo}')-\vartheta_1(\mathrm{Fo})}{(\mathrm{Fo}-\mathrm{Fo}')^{3/2}}\,d\,\mathrm{Fo}'\right\},\tag{3}$$

$$q_{\mathrm{II}}(\mathrm{Fo})=\frac{\lambda n\sqrt{\mathrm{Fo}^*}}{L}\left\{\frac{\vartheta_1(\mathrm{Fo})}{\sqrt{\mathrm{Fo}^*}}-\frac{1}{2}\int\limits_{\mathrm{Fo}-\mathrm{Fo}^*}^{\mathrm{Fo}}\frac{\vartheta_1(\mathrm{Fo}')-\vartheta_1(\mathrm{Fo})}{(\mathrm{Fo}-\mathrm{Fo}')^{3/2}}\,d\,\mathrm{Fo}'\right\}-$$

$$-\frac{\lambda}{L}\mu\int\limits_0^{\mathrm{Fo}-\mathrm{Fo}^*}\left\{\frac{1}{2}\vartheta_2(\mathrm{Fo}')+\left(n-\frac{1}{2}\right)\vartheta_1(\mathrm{Fo}')\right\}\exp\left[-\mu(\mathrm{Fo}-\mathrm{Fo}'-\mathrm{Fo}^*)\right]d\,\mathrm{Fo}'.\tag{4}$$

The maximum error in calculations using (3) and (4) does not exceed 5%, which is acceptable, considering the simple form of the dependence compared to the exact solution.

The pulsations in the heat flow were measured with the help of a sensor consisting of a $20\times 20\times 1$ mm devitrified glass plate on both surfaces of which copper resistance thermometers (δ = 1 μm), protected by a thin chromium film, were deposited in a vacuum. The thermometers were artificially aged and were calibrated. The resistance of each thermometer equalled 130 Ω at 20°C and the temperature coefficient equalled β = 0.5 Ω/K with a linear characteristic with error not exceeding 0.3%.

The sensor was placed on the surface of the copper plate 2 (Fig. 1) with heater 4. The copper plate in its turn was fastened in a recess in a Textolite plate 1. The surface of the sensor, copper and Textolite plates were located in a single plane and did not introduce additional distortion into the flow pattern. The Textolite plate 1 was placed vertically in the apparatus with a 200×200 mm square cross section with height 600 mm at a distance 50 mm from the distributing grid. Sand particles with an equivalent diameter of 0.72 mm were fluidized by air at room temperature with a velocity **v** = 0.65 m/sec.

In order to measure and record the signals proportional to the temperatures, two bridge measuring setups, signals from which were fed through amplifiers into a loop N-115 oscillograph, were used (Fig. 2). The bridges were made from MSR-63 class 0.05 resistance boxes. A TÉS-88 stabilized voltage source was used as a power supply. The error due to heating of the resistance thermometers by the measuring current did not exceed 0.1%.

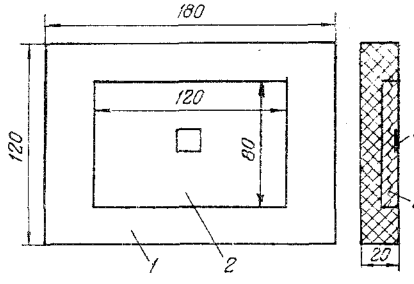

Fig. 1

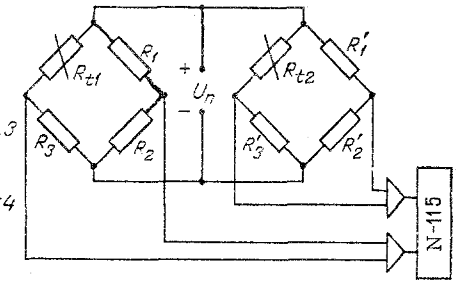

Fig. 2

Fig. 1. Construction of the thermal block: 1) Textolite base; 2) plate; 3) heat flux sensor; 4) heater.

Fig. 2. Electrical circuit used for measurements.

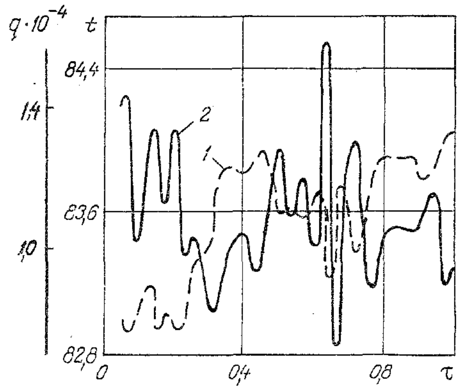

Fig. 3. Results of one of the experiments: 1) surface temperature of a heat flux sensor facing the bed t (°C); 2) heat flux q (W/m²). τ, sec.

As the sensor was heated, before the quasistationary state was reached, the constant component of the measuring current was compensated by one of the boxes in order to decrease the resistance from the nonlinearity of the bridge circuit [9].

The constant of the temperature measuring circuit together with the sensors constituted 0.07°K/mm, which permitted analyzing the oscillograms to within 0.1°K. Instantaneous values of the heat flux were calculated on a computer using the algorithm (3), (4). The discretization time step was chosen as 20 msec and in this case the change in the surface temperature of the sensor was practically linear.

The results of one of the experiments are shown in Fig. 3. This figure also shows the change in the surface temperature of the sensor facing the bed. The average heat flux level in the experiments was $1.15 \cdot 10^4$ W/m². The flux oscillated in the range ±30% of the average value. The temperature of the fluidized bed was 31°C. The difference between the average heat transfer coefficient and the value computed using the well-known equation [10]

$$\alpha = 33.7 \lambda_h^{0.6} d_p^{-0.36} \gamma_p^{0.2} \tag{5}$$

does not exceed 17%.

Comparing the nature of the oscillations in Fig. 3 with the data obtained by thermoanemometric measurement [4] it is possible to observe the effect of the sensor dimensions on the result of the measurements. Indeed, the larger the sensor, the higher is the probability for a different hydrodynamic environment to appear near the sensor surface at each time. Part of the sensor can be closed by the particles and part can be washed by the fluidizing agent or the wake of a rising bubble. Since the sensor integrates the conditions over the surface, local spikes, corresponding to a change in the environment at the part of the sensor surface, should appear on the curve together with peaks with maximum amplitude. The probability for the appearance of sharp jumps with maximum amplitude, corresponding to a change in the environment for the entire surface of the sensor, decreases as its dimensions increase. The amplitude of the oscillations has a tendency to decrease. Thus, when the sensor surface increased by a factor of 8-10 (from the thermoanemometer up to the proposed sensor), the swing in the oscillations decreased from 50-60% to 30% of the average level. In solving the problem of the optimum dimensions of the sensor, it is apparently necessary to start from the characteristic dimensions of the system (size of the material grain, average bubble diameter) and the specific problem of the experiment.

NOTATION

2L, plate thickness; $\bar{x} = x/L$, relative coordinate; $\vartheta(\bar{x}, \mathrm{Fo})$, overheating of the plate relative to the initial temperature t_0; $\mathrm{Fo} = a\tau/L^2$, Fourier number; λ, a, coefficients of thermal conductivity and thermal diffusivity of the substrate material; $\vartheta_1(\mathrm{Fo})$, $\vartheta_2(\mathrm{Fo})$, overheating of the plate surfaces; τ, time.

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