THERMOANEMOMETRIC MEASUREMENTS OF THE PULSATIONS OF THE HEAT-TRANSFER COEFFICIENT IN A FLUIDIZED BED

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The article examines the method of measuring pulsations of the heat-transfer coefficient in a fluidized bed with the aid of a dc thermoanemometer and presents obtained experimental data.

Measurements of the pulsations of the heat-transfer coefficient in a fluidized bed make it possible to establish to what extent the models of heat exchange suggested by various authors give a true picture of the actual situation. Insufficiently accurate measurements and incorrect manipulation with the obtained data sometimes lead to erroneous conclusions in evaluating models of heat exchange. The present work attempts to find an accurate method of measuring the pulsations of the thermal flux from the surface to the fluidized bed.

As a rule, pulsations of thermal flux are determined by the method of dc aneomometer from a foil. The considerable forces originating in a fluidized bed make it necessary to glue the foil to a rigid substrate. Part of the heat liberated in the foil is accumulated by the substrate, and this greatly complicates the calculation of the thermal flux according to the experimentally obtained dependence of the foil temperature on time. The thermal flux accumulated by the substrate can be calculated by the method of modeling the changes of the temperature field in the substrate [1]. For that it is necessary to know accurately the dimensions and the thermophysical properties of the foil and of the substrate, and, in addition, to evaluate the effect of the layer of glue joining them (if there is such a layer).

The characteristics of the sensor used in thermoanemometric measurements are determined by dynamic calibration or by an intermittent stream of the medium (direct method), or else by the action of electric standard signals (indirect method) [2-4]. In our case the anemometer is not used for its direct purpose (for measuring speed) but as a sensor of thermal flux. Most suitable for calibrating such sensors is the indirect method, and as actuating signal it is best to use a single stepwise change in intensity of the current passing through the foil, with constant heat-transfer coefficient from the sensor to the environment (e. g., when a stream of air is blown past the sensor at constant speed). Since the sensor has high thermal inertia, the reference characteristic can be recorded on an ordinary loop oscillograph. By comparing the obtained curve with the analytical solution, we can obtain the characteristics that interest us.

The analytical dependence of the foil temperature on time upon stepwise change of current intensity is obtained from the solution of the equation of thermal conductivity in the substrate

$$\frac{\partial T}{\partial \tau} = a \frac{\partial^2 T}{\partial x^2} \tag{1}$$

with the initial condition $T_{\tau=0} = T_1$. On one side the substrate is heat-insulated by an interlayer of air $(\partial T/\partial x)_{x=0} = 0$, and on the other side ($x = l$) there is concentrated specific heat (foil) $(c\rho\delta)_f$ in which a thermal flux $q = I_1^2 R_1/S$, W/m^2 is liberated because of the passage of the current. In the initial steady state ($\tau < 0$), all the liberated heat (if we neglect the heat losses through the opposite surface of the substrate that is thermally insulated by an air interlayer) is transferred to the environment with a temperature T_0 according to Newton's law $q_1 = \alpha(T_1 - T_0)$. When $\tau = 0$, the intensity of the current passing through the foil changes stepwise, and the boundary condition (for x = 1) has the form

$$(c\rho\delta)_f \frac{\partial T}{\partial \tau} + \lambda \frac{\partial T}{\partial x} = \frac{I_2^2 R}{S} - \alpha (T - T_0). \tag{2}$$

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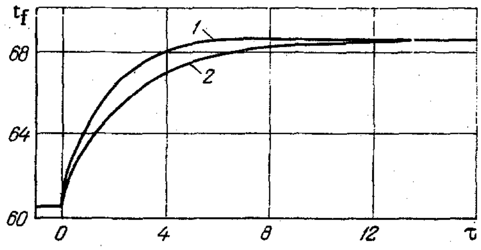

Fig. 1. Reference characteristic of the sensor with I = const: 1) α = 700 W/m^2·°K; I_1 = 0.9 A; I_2 = 1.0 A; 2) α = 300 W/m^2·°K; I_1 = 0.66 A; I_2 = 0.75 A. t_f, °C, τ, sec.

With $\tau \to \infty$, the second steady state begins where the temperature of the foil and of the substrate is equal to T_2, determined from the ratio $I_2^2R_2/S = \alpha(T_2 - T_0)$. The resistance R of the foil usually increases linearly with increasing temperature: $R = R_2[1 + \beta(T - T_2)]$. If we transform the boundary condition (2), we obtain

$$(c\rho\delta)_f \frac{\partial T}{\partial \tau} + \lambda \frac{\partial T}{\partial x} = -\alpha' (T - T_2). \tag{3}$$

Here, $\alpha' = \alpha[1 - \beta(T_2 - T_0)]$.

It should be noted that when α and β are independent of temperature, steady state can exist only up to a definitely determined temperature gradient between the foil and the environment: $T_2 - T_0 = 1/\beta$. When the temperature gradient is larger, the problem becomes unstable and the foil temperature will increase with no limit.

The analytical solution of the stated problem was obtained by the method of the integral Laplace transform [5]:

$$\Theta_{x=l} = \frac{T - T_2}{T_1 - T_2} = \sum_{n=1}^{\infty} \frac{2\,\mathrm{Bi}\exp(-\mu_n^2 \mathrm{Fo})}{\mu_n(2M\mu_n + \mathrm{tg}\,\mu_n + \mu_n/\cos^2\mu_n)}. \tag{4}$$

Here μ_n are the roots of the equation

$$\mu_n\,\mathrm{tg}\,\mu_n = \mathrm{Bi} - \mu_n^2 M.$$

With small Fo, when thermal distortion does not have time to spread to the thermally insulated surface of the substrate, series (4) converges fairly slowly; therefore for calculating the temperature of the foil it is expedient to use a simpler solution in which the substrate is taken as a semiinfinite body. A solution was also obtained by the method of integral Laplace transform on condition that heat transfer to the environment occurs from the boundary surface of the body (x = 0) and that the foil is situated on this same surface. The dependence of the temperature of the surface of the body and of the foil on time has the form

$$\Theta_{x=0} = \frac{T - T_2}{T_1 - T_2} = \frac{1}{\gamma - \xi}\left[\gamma \exp\left(\frac{\xi^2}{4A^2}\mathrm{Fo}'\right)\mathrm{erfc}\left(\frac{\xi}{2A}\sqrt{\mathrm{Fo}'}\right) - \xi \exp\left(\frac{\gamma^2}{4A^2}\mathrm{Fo}'\right)\mathrm{erfc}\left(\frac{\gamma}{2A}\sqrt{\mathrm{Fo}'}\right)\right], \tag{5}$$

where $\gamma, \xi = 1 \pm \sqrt{1 - 4\mathrm{Bi}'A}$ are conjugate coefficients. When $(1 - 4\mathrm{Bi}'A) < 0$, tabular values of the probability integral of the complex argument may be used [6], and the solution of (5) is transformed to the form

$$\Theta_{x=0} = \frac{T - T_2}{T_1 - T_2} = u(\zeta, \omega) + \frac{v(\zeta, \omega)}{\sqrt{4\mathrm{Bi}'A - 1}}. \tag{6}$$

The tabular values of the real $u(\zeta, \omega)$ and of the complex $v(\zeta, \omega)$ parts of the probability integral $w(\zeta, \omega)$ are determined from the argument $\zeta = \sqrt{\mathrm{Fo}'(4\mathrm{Bi}'A - 1)}/2A$, $\omega = \sqrt{\mathrm{Fo}'}/2A$. The determining dimension in the criteria Fo' and Bi' is the thickness of the foil (δ_f).

We tried out a sensor whose sensitive element was a layer of nickel δ_f = 0.5 μm vaporized on the polished surface of a pyroceramic platelet with an area of 4 × 16 mm, 0.6 mm thick. The sensor is fixed flush in a cork base. The experimental reference characteristic of the sensor (Fig. 1) in a stream of air coincides with that calculated by Eq. (5) within the error of measurement when the current intensity changes stepwise because in this case, there are no glue interlayers between the foil and the substrate. Dynamic calibration confirms the efficiency and accuracy of determining the geometric and thermophysical characteristics of the sensor that were used in the calculation.

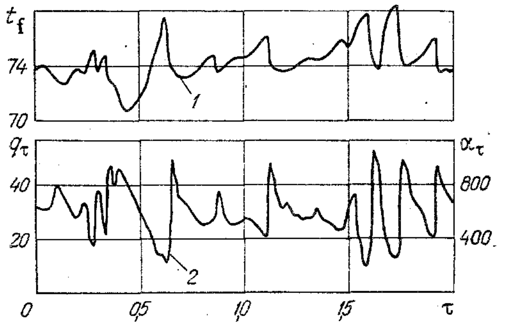

Fig. 2. Temperature pulsations of the sensitive element of the thermal-flux sensor (1) and heat-transfer coefficient (2) in the corundum fluidized bed with mean particle size 0.12 mm. Bed temperature: 24°C; air speed in the installation: 0.12 m/sec. α_T, W/m^2·°K; q_T, kW/m^2.

Figure 2 shows the graph of the temperature pulsations of the sensitive layer of the sensor and the instantaneous thermal flux q_T from the sensor to the corundum fluidized bed d = 0.12 mm calculated by the method of [1]. The question to which temperature gradient the values of the thermal flow should be attributed in the calculation of the heat-transfer coefficient and whether this heat-transfer coefficient corresponds to the conditions when the temperature of the sensor is constant requires separate examination [7]. However, in view of the conditional nature of the concept of heat-transfer coefficient itself, we use for the sake of simplicity the time-averaged difference between the foil and the core of the fluidized bed in calculating α_T. Here, the dependences $q_T = f(\tau)$ and $\alpha_T = f(\tau)$ differ only in scale on the axis of ordinates. In principle, when the instantaneous temperature difference is used, the form of the dependence $\alpha_T = f(\tau)$ changes only slightly between the bed and the foil.

The amplitude of the pulsations of the heat-transfer coefficient amounts to 800-700 W/m^2·°K. These data are close to the results of the calculation obtained by Baskakov et al. [1]. Evidently, the glue interlayer between the foil and the substrate, which was disregarded in the calculation in [1], did not have a substantial effect on the dynamic characteristics of the sensor.

In the analysis of the results obtained with thermoanemometers it is essential to evaluate the effect of deformation of the foil by forces induced on the fluidized bed. A change in resistance associated with deformation and the appearance of microcracks will be recorded by the instrument as temperature pulsation of the foil. The sensors must therefore be checked by measuring the pulsations of the heat-transfer coefficient in experiments that differ only in intensity of the current passing through the foil. If the resistance of the foil fluctuates on account of some mechanical actions, then the pulsation amplitude of the voltage drop on the foil will be linearly dependent on the current intensity. However, if the signal is due to a change in temperature, then the effect of the current intensity will be much greater. Specifically, according to calculations, when $\beta(T-T_0) \ll 1$, the amplitude of the pulsations of the voltage drop on the foil is proportional to the third power of the change in current intensity. This corresponds to the experimental data obtained with the aid of the above-described sensor.

Of considerable interest is the evaluation of the possibility of using constant-temperature thermoanemometers for investigating pulsations of the thermal flow in a fluidized bed. The first work in this field was carried out by Antonishin [8, 9]. When the temperature of the foil is constant, the calculation of the experimental data is much simplified because there is no need to take into account the heat accumulated by the sensor. If such a sensor is to work properly, its time constant must be much smaller than the period of pulsations of the heat-transfer coefficient.

To evaluate the time of the transient process, we will examine the operating conditions of the sensor (foil and substrate). In case of stepwise change of the heat-transfer coefficient from α_1 to α_2, the mathematical statement of the problem differs from that for the dc thermoanemometer described above only by the boundary condition (3) for $x = l$. We will assume that approximately the heat liberation in the foil is proportional to the deviation of its temperature from the setting temperature T_s (the temperature at which the

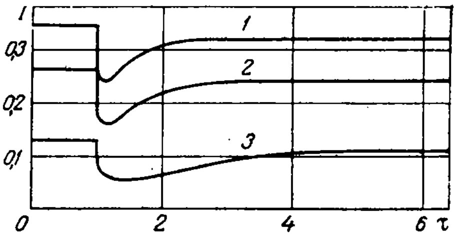

Fig. 3. Reference characteristic of the sensor with T = const: 1) α = 450 W/m^2·°K; 2) 250; 3) 70. I, A.

measuring bridge of the thermoaneomometer is balanced), i.e., that $q = K(T - T_s)$. The proportionality ("gain") factor K has the dimensionality of the heat-transfer coefficient. Then for $x = l$, the boundary condition will have the form

$$(c\rho\delta)_f \frac{\partial T}{\partial \tau} + \lambda \frac{\partial T}{\partial x} = -K(T - T_s) - \alpha_2 (T - T_0). \tag{7}$$

Taking it that in steady state $-K(T_2 - T_s) = \alpha_2(T_2 - T_0) = q_2$, we obtain

$$(c\rho\delta)_f \frac{\partial T}{\partial \tau} + \lambda \frac{\partial T}{\partial x} = -(\alpha_2 + K)(T - T_2). \tag{8}$$

Thus the boundary condition is the same as in (3), only with the difference that instead of the heat-transfer coefficient in the right-hand part, there is the sum of the heat-transfer coefficient and the proportionality factor K. The solution of this problem is also analogous to the solution of (4), with α' in it replaced by $(\alpha_2 + K)$. As with sensors with small values of Bi [10], an increase in the "gain" factor K in this case leads to a decrease of the duration of the transient process.

Figure 3 shows the experimental reference characteristic of the above-described sensor connected to a constant-temperature anemometer TA-7M (designed by the Donets University). The stepwise action was not attained by changing the conditions of heat exchange but by changing the setting temperature (the resistance of one of the arms of the bridge). The duration of the transient process here is shorter than with a dc thermoanemometer and analogous values of α, but it is nevertheless much longer than the period of pulsations α in the fluidized bed.

Analysis shows that when a thermoanemometer TA-7M and a foil of the same size are used (in this case $K \sim 10^4$ W/m^2·°K is ensured), the duration of the transient process will be fairly short only when a cork substrate is used or the substrate is of denser material but very thin (δ = 10–20 μm); however, in both cases the strength of the sensor will be insufficient for operation in the fluidized bed. Another way – to greatly reduce the area of the foil to dimensions commensurable with the particle dimensions – is often unfeasible.

Thus, the use of a constant-temperature thermoanemometer for measuring the pulsations α in a fluidized bed poses technical problems that are difficult to overcome. On the other hand, temperature curves recorded with the aid of a dc thermoanemometer provide in a simple manner a fairly complete pattern of the change in the heat-transfer coefficient with time.

NOTATION

A	is the ratio of volumetric heat of the materials of the foil and of the substrate;
Bi	is the Biot number;
Fo	is the Fourier number;
$M = (c\rho\delta)_f / c\rho l$;	
I	is the current intensity;
T_0	is the temperature of the fluidized bed;
T, T_f	are the temperatures of the substrate and of the foil, respectively;
c, c_f	are their respective specific heats;
ρ, ρ_f	are their densities;
l, δ_f	are their thicknesses;
λ, a	are the thermal conductivity and thermal diffusivity of the substrate, respectively;

R is the electrical resistance of the foil;
S is the area;
β is the resistance temperature coefficient;
α is the heat-transfer coefficient from the surface to the fluidized bed;
q is the specific heat flux;
d is the particle diameter;
τ is the time.

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INFLUENCE OF THE INCOMPRESSIBLE STREAM TEMPERATURE ON COOLING OF A HOT WIRE

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Results are presented of an experimental investigation of the cooling of the hot wire of a thermoanemometer in an air stream for different wire and flow temperatures.

It is known that the results of measuring flow characteristics by a hot wire thermoanemometer contain systematic errors if the stream temperature changes during the experiment, albeit slowly, and differs considerably from the temperature at which the sensor was calibrated. To achieve a measurement accuracy under nonisothermal conditions which is close to the accuracy usually achievable in an isothermal flow, it is necessary to refine how the heat from the wire is eliminated as a function of the stream velocity and temperature and of the wire temperature.

A number of papers [1-12] has been devoted to this problem in recent years. Empirical formulas describing the cooling of the hot wire in a nonisothermal flow which have been proposed by different authors differ significantly among themselves. In discussing their reliability it is necessary to start from the fact that under isothermal conditions these formulas should go over into those verified well, e. g., into the most exact cooling law [5]:

$$\mathrm{Nu} = G(T,\ T_w)[A + B\,\mathrm{Re}^n], \tag{1}$$

$$G(T,\ T_w) = \left(\frac{T + T_w}{2T}\right)^{0.17}. \tag{2}$$

A detailed study [8] showed that the best calibration approximation is obtained for the wires of the thermoanemometer sensor types usually used when the coefficients A and B and the exponent n are determined

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