

PROCESS OF COOLING OF A HIGH-TEMPERATURE TWO-PHASE FLOW

V. I. Volkov and M. A. Utemesov

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A technique and a design of a transducer for measuring the enthalpy of two-phase flows using the thin-wall method have been developed. Working formulas for calculating the heat capacity and the enthalpy of a gas flow are substantiated. Results of a test of the transducer in high-temperature flows of powder gases, including those after the packing of a coolant, are presented. The results obtained show that cooling of powder gases due to an endothermic reaction makes it possible to decrease the enthalpy flux by a factor of 5 and the temperature by a factor of 2.

Jet flows of high-temperature two-phase flows are accompanied, as a rule, by intense processes of heat and mass transfer, especially in cooling of hot gases using an endothermic chemical reaction. These technologies are used for rapid production of large volumes of gas as a result of combustion of powder charges and subsequent cooling of the produced gases by "coolants" – substances absorbing heat in decomposition. In practice this can be used, for example, for rapid inflation of floating devices in emergency.

To evaluate the efficiency of the composition of the coolant, one must know not only the hydrodynamic pattern of the flow and the temperature of the moving gas, but also the values of the heat fluxes before and after the coolant. The intricacy of such measurements is associated with the presence of a second phase in the form of solid microparticles that carry a substantial portion of the heat flux. An enthalpy transducer has been developed for measuring the heat content of high-temperature two-phase flows. To allow for the contribution of the disperse phase to the heat capacity, an additional grid on which particles are entrapped was provided in the transducer. A description of the design characteristics of the setup, metrological problems, and results of calibration tests of the transducer are given in [1, 2]. In what follows we consider some special features of the method and results of determination of the enthalpy of two-phase flows on a setup for rapid production of a large volume of cooled gases using a powder charge.

The setup was an assembly of four sections with a diameter of 3.6 cm and a length of 10 cm each: the first section was a powder charge, the second – a chamber of a high-temperature flow, the third – a coolant in the form of a densely packed charge of pellets, the fourth – a chamber of a low-temperature flow. The coolant was in the form of a random packing of pellets of salts (ammonium oxalate, carbamide) that are capable, under the action of a hot gas flow, of endothermic decomposition with liberation of a large amount of gases. Enthalpy transducers (Fig. 1) were mounted in the second and fourth sections, i.e., before and after the coolant.

The enthalpy was determined from the magnitude of the heat flux to the frame. If the latter is represented in the form of a flat plate onto which the heat flux is supplied on one side and adiabatic conditions are maintained on the other, then the increase in the temperature with time can be expressed (in dimensionless form) by the formula [3]

$$\Theta(\xi, Fo) = Ki \left[Fo - \frac{1}{6} (1 - 3(\xi)^2) + 0.203 \cos \pi \xi \exp(-9.87 Fo) \right], \quad (1)$$

where $\Theta(\xi, Fo) = (T(x, \tau) - T_1)/(T_0 - T_1)$; $\xi = x/\delta_2$; Ki is the Kirpichev number: $Ki = q\delta^2/[\lambda_2 (T_0 - T_1)]$; λ_2 and a_2 are the thermal conductivity and the thermal diffusivity of the frame, respectively; Fo is the Fourier number, $Fo = a_2\tau/\delta_2^2$.

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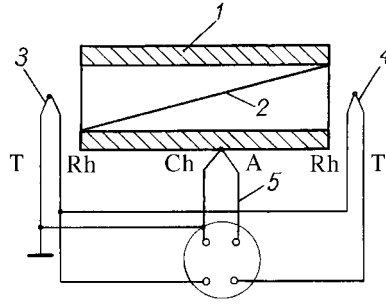


Fig. 1. Schematic diagram of the enthalpy transducer: 1) metal frame; 2) grid; 3, 4) tungsten-rhenium thermocouples; 5) Chromel–Alumel thermocouple.

From Eq. (1) for the wall contacting the insulator ($\xi = 0$) we have

$$\Theta(0, Fo) = Ki \left[Fo - \frac{1}{6} + 0.203 \exp(-9.87 Fo) \right]. \quad (2)$$

For the suggested design of the transducer, when $\tau > 0.1$ sec the ratio $\Theta/Ki \approx Fo$ and the heat flux can be expressed by the quantity $q = c_2 \rho_2 \delta \frac{\partial T_H}{\partial \tau}$. Equating it to the heat flux on the transducer surface $q = m_1 c_1 (T_0 - T_1) / (F_2 \tau)$, where $F_2 = 2(d+b)l$ is the area of the inner surface of the transducer, we obtain a computational formula for the heat capacity of the gas flow:

$$c_1 = \frac{2c_2 \rho_2 \delta_2 (d+b) l \frac{\partial T_H(\tau)}{\partial \tau}}{\rho_1 dbw (T_0 - T_1)}. \quad (3)$$

From the density of the enthalpy flux $q_H = \frac{m_1}{\tau F} \int_0^{T_1} c_1 dT_1$ (where $F = db$ is the cross-sectional area of the transducer) and the equation of heat balance we obtain

$$q_H = \frac{c_2 m_2 \frac{\partial T_H(\tau)}{\partial \tau}}{c_1 (T_0 - T_1) F} \int_0^{T_1} c_1 dT. \quad (4)$$

We express the mean heat capacity of the gas within the range from 0 to T_1

$$\langle c_1 \rangle = \frac{1}{T_1} \int_0^{T_1} c_1 dT$$

and rewrite Eq. (4):

$$q_H = \frac{c_2 m_2 \frac{\partial T_H(\tau)}{\partial \tau}}{(T_0 - T_1) F} \frac{\langle c_1 \rangle}{c_1}. \quad (5)$$

We determine the heat capacity of the gas as follows [4]: $c_1 = A + BT + CT^2 + DT^3$. Calculations showed that for most gases in the region of the temperatures studied, the ratio $K_c = \langle c_1 \rangle / c_1$ amounts to 0.7 to

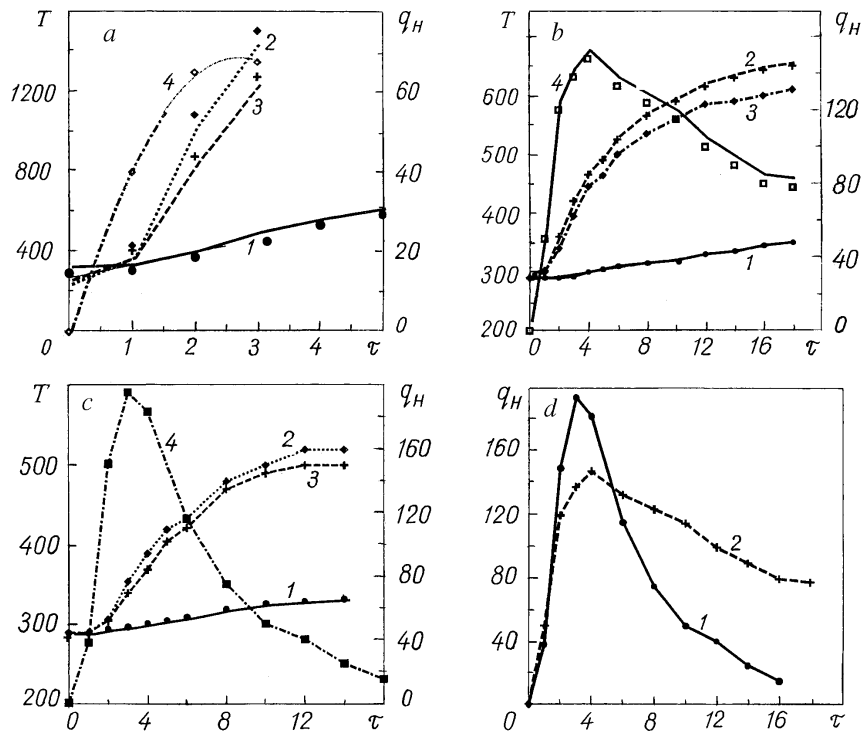


Fig. 2. Change in the temperature and the density of the enthalpy flux of a high-temperature flow [a) before the coolant; b and c) after the coolant; b) transducer with a grid; c) without a grid] and comparison of the enthalpy fluxes (d): a-c: 1) transducer temperature; 2, 3) temperatures of the flux before and after the transducer; 4) density of the enthalpy flux; d: 1, 2) flow enthalpy of the transducer without and with a grid. T , K; q_H , W/m^2 ; τ , $sec \cdot 10^{-2}$.

0.9, where $\langle c_1 \rangle = A + \frac{B}{2} T + \frac{C}{3} T^2 + \frac{D}{4} T^3$. The value of K_c for the studied powders at different temperatures of the tests was taken to be equal to 0.8.

Thus, the computational formula can be written in the form

$$q_H = K_c K_F \frac{c_2 m_2}{F} \frac{T_0}{T_0 - T_1} \frac{dT}{d\tau}, \quad (6)$$

where K_F is a coefficient that depends on the flow area; for the transducer without a grid it is equal to 1. For the transducer with a slope of the grid equal to 15° , the flow area corresponds to half the total cross section and the coefficient K_F is 1.5.

The experiments conducted can be divided into three groups. In the first group, the enthalpy transducer (without a grid) was installed in the second section, and the enthalpy of the gases – combustion products of the powder charge – was measured (Fig. 2a). In the second and third groups, transducers were installed in the chamber of the low-temperature flow; they differed by the presence of a grid in the transducer (Fig. 2b and c).

In the first group of experiments, we were able to follow the process during the first thirty milliseconds, after which the tungsten-rhenium thermocouples were destroyed. It is seen from Fig. 2a-c that the increase in the temperature of the plates can be described by a rectilinear dependence with a rate of heating of 6400 and 350 K/sec for the transducers of the high-temperature and low-temperature chambers, respectively, which confirms the calculations of [2]. From a comparison of curves 1 in Fig. 2b and c we can draw the conclusion that the grid virtually does not affect the change in the temperature of the metal frame. This is a consequence of the fact that the rate of temperature change in the flow is much higher than the time of passage

of the heat flux through the grid and that the mass and consequently the heat capacity of the grid are small compared to the mass of the metal frame.

A comparison of the curves of the enthalpy fluxes (Fig. 2) shows the efficiency of cooling of the flow when endothermically destroyed mixtures are used – the density of the enthalpy flux after the coolant decreases 5–6 times, the gas temperature 2–3 times. Figure 2d gives comparative readings of the transducer without (curve 1) and with a grid (curve 2). The enthalpy flux in the case of the transducer with a grid decreases more slowly. This is caused by trapping of particles of the disperse phase on the grid, which, on the one hand, decrease the magnitude of the heat flux to the wall due to endothermic decomposition directly on the grid (it is seen from a comparison of Fig. 2b and c that the absolute values of the gas-flow temperature in the experiments of Fig. 2b are on the average higher) and, on the other, increase the time lag of the heat transfer, as if "extending" the heat flux in time.

The studies conducted showed that:

1) the suggested technique with allowance for the heat flux from the disperse phase can be used for study of high-temperature two-phase flows and evaluation of the efficiency of coolants of these flows;

2) cooling of hot flows of products of powder combustion using the endothermic reaction of decomposition of ammonium oxalate makes it possible to decrease the enthalpy density by a factor of 5 to 6 and the gas temperature by a factor of 2 to 3.

NOTATION

$A, B, C,$ and D , numerical coefficients in the equation of heat capacity [14]; a , thermal diffusivity, m^2/sec ; $d, b,$ and l , width, height, and length of the transducer frame, m ; c , heat capacity, $\text{J}/(\text{kg}\cdot\text{K})$; m , mass, kg ; q , heat flux, W/m^2 ; T , temperature, K ; x , spatial coordinate, m ; w , linear velocity, m/sec ; δ , plate thickness, m ; λ , thermal conductivity, $\text{W}/(\text{m}\cdot\text{K})$; ρ , density, kg/m^3 ; Θ , dimensionless temperature; τ , time, sec ; ξ , dimensionless coordinate. Subscripts: 0, gas at the transducer inlet; 1, gas at the transducer outlet; H , corresponds to the point at which Chromel–Alumel thermocouple 5 is positioned (Fig. 1).

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