ASYMMETRY OF THE PROFILE OF TEMPERATURE WAVES PROPAGATING THROUGH A PACKING UNDER THE ACTION OF A GAS STREAM

V. P. Kharitonov

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The behavior of temperature waves of different amplitude in a fine-grained packing is examined. It is established that the asymmetry of the temperature wave profile is different for metals and materials with adsorption properties.

There have been many studies [1-3] of the use of a constant-temperature gas flow to cool or heat a fixed bed of fine-grained material (adsorbents – zeolites, silica gel, activated charcoal, and regenerator packings and other granular materials). The analytic solution of the boundary value problems has made it possible not only to calculate the temperature field in the bed, i.e., determine the rate of the above-mentioned processes and compute the outlet temperature curves, but also to develop a method of determining the coefficient of heat transfer between the gas and the packing (from the Schumann curves). A recent publication, also devoted to nonstationary heat transfer in a fixed bed [4], examines the case of arbitrary variation of the gas temperature at the bed inlet and, in particular, computes the temperature field for intermittent (pulsed) variation of the gas temperature. This pulsed thermal action on the inlet portions of the bed creates a temperature wave that moves through the bed in the direction of motion of the gas stream. In this case the profile of the temperature wave remains almost symmetrical.

This problem, like all the previous ones, involves a number of assumptions, the most debatable of which is clearly the assumption of invariability of the thermophysical properties of the gas and the packing with temperature.

In our experiments to compare the actual and theoretical profiles of low-temperature waves we established that agreement good enough for engineering calculations is possible only in the case of small-amplitude waves corresponding to a minimum profile temperature of the order of −50 to −70°C. At lower temperatures we observed a sharply expressed asymmetry of the wave profile, whose character was qualitatively different for different packings.

The experiments were performed on a fixed bed of granular material, namely, aluminum spirals (low-temperature regenerator packing) and SKT-M activated charcoal.

The characteristics of these packings are presented in Table 1. The experimental setup is shown in Fig. 1a. The packing was arranged in a thin cylindrical shell 1 with vacuum thermal insulation 2; the diameter of the shell was 136 mm, the wall thickness 0.6 mm, and the material 1Kh18N10T steel. The thickness of the bed was up to 1400 mm. The position of the bed was fixed by means of two grids 3 and 4, over which fine brass mesh was stretched.

TABLE 1. Characteristics of Packings

Packing	Specific surface, m^2/m^3	Bulk density, kg/m^3	Porosity	Shape of particles	Mean pore diameter, mm
Aluminum spirals	1290	870	0,68	Spirals of 1-mm wire	2,1
SAT-M activated charcoal	2100	470	0,5	Cylinders, diameter 0.75, height 1-4 mm	0,95

Dry air freed of carbon dioxide was admitted at a constant flow rate to the packing either through line 5 or through line 6 from a refrigerator 7 operating on a high-pressure open cycle with single-stage throttling. The temperature of the air reaching the packing through

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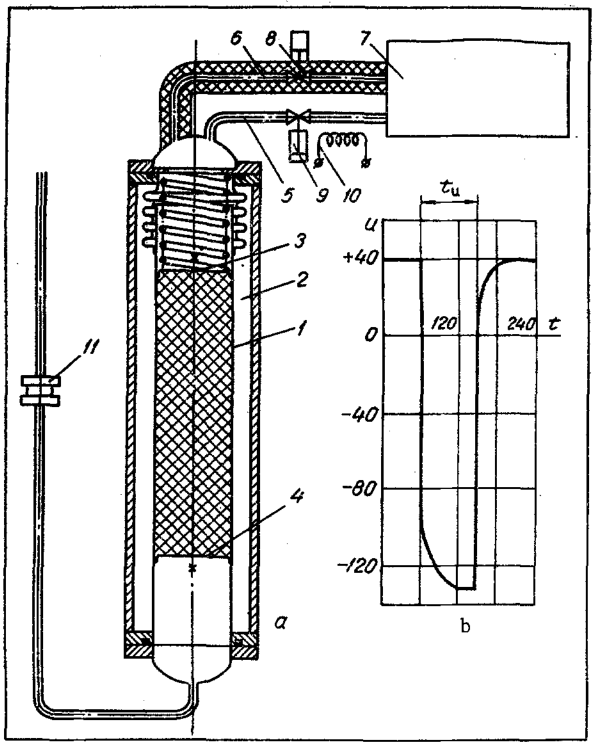

Fig. 1

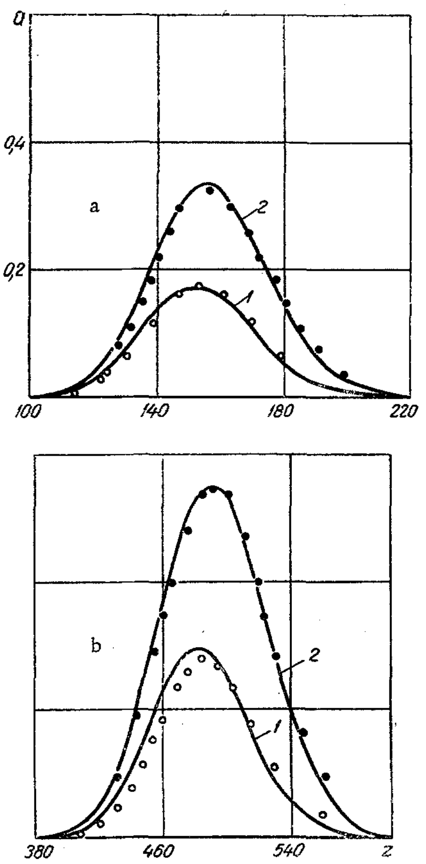

Fig. 2

Fig. 1. Diagram of experimental setup (a) and variation of air temperature at bed inlet (b).

Fig. 2. Theoretical and actual outlet temperature curves for small-amplitude waves: a) aluminum [1) $\Delta z = 7.5$; 2) 15]; b) activated charcoal [1) $\Delta z = 24$; 2) 47].

line 5 with valve 9 open could be kept constant in the range from +18 to +40°C by means of the variable electric heater 10. The temperature of the air reaching the packing through insulated line 6 with valve 8 open could be kept constant in the range from −186 to + 0°C for a certain period of time (up to 3 min).

The air temperatures at the bed inlet and outlet were measured with copper–constantan low-inertia thermocouples with registration on a single-point quick-response potentiometer. The thermocouple junctions were arranged along the center of the flow at a distance of 20 mm from the bed (indicated by crosses). The air flow rate was measured at the the packing outlet with an ordinary measuring orifice 11.

A temperature pulse was created by switching the flows of warm and cold air supplied to the packing. Accuracy was ensured by using automatic valves 8 and 9.

Before the low-temperature pulse was applied, warm air was passed through the packing at a constant mass flow rate until the inlet and outlet air temperatures were constant and equal. Then valves 8 and 9 were switched and for a certain interval of time t_i cold air flowed into the packing at the same mass flow rate. At the end of the pulse (from 5 to 200 sec) the valves were again switched and a stream of warm air again flowed through the packing. The actual temperature variation of the air at the inlet to the bed was almost step-shaped (Fig. 1b).

The change in inlet air temperature created a temperature wave in the packing, which traveled with the air stream toward the outlet from the bed. As a result of these experiments we obtained measured outlet curves showing the variation of the air temperature at the bed outlet with time. In Fig. 2 we have plotted the temperature waves recorded for an aluminum packing and activated charcoal in the presence of small temperature perturbations. The results of the measurements are presented in the form of curves of the relative air temperatures in dimensionless coordinates. The experimental data are denoted by dots and circles, the calculated curves [4] by continuous lines.

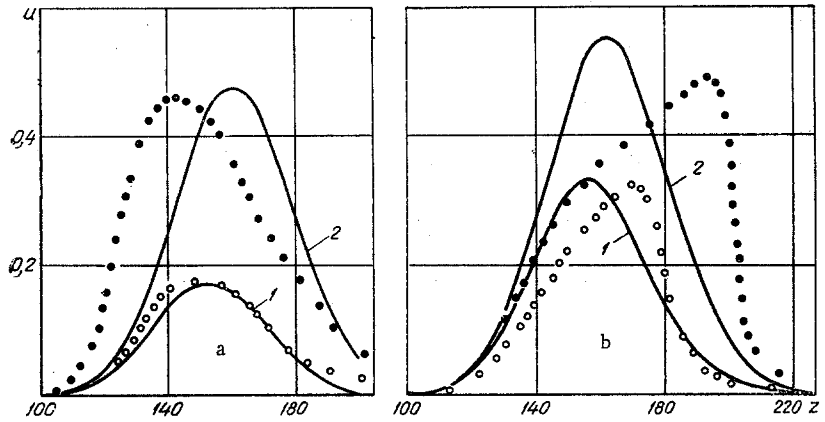

Fig. 3. Theoretical and actual outlet temperature curves for large-amplitude waves: a) aluminum [1) $\Delta z = 7.5$; 2) 22]; b) activated charcoal [1) $\Delta z = 15$; 2) 27].

In Fig. 2a the outlet temperature curves are for a bed of aluminum packing with a dimensionless length $y = 150$. The dimensionless pulse length Δz was 7.5 and 15, the initial pulse amplitude 55 and 73°C, the warm stream temperature 16°C. The curves in Fig. 2b are for a bed of activated charcoal with dimensionless length $y = 470$. The pulse length Δz was equal to 24 and 47, the initial pulse amplitude was 43 and 45°C, the warm stream temperature 21°C.

At temperature wave amplitudes exceeding 100°C (minimum pulse temperature −70 to −150°C) sharp distortion of the temperature profile is observed.

The outlet curves for a bed of aluminum packing are shown in Fig. 3a. The length of the bed $y = 150$, the pulse length $\Delta z = 7.5$ and 22, the initial pulse amplitude was 161 and 172°C, the warm stream temperature 13°C. The outlet curves in Fig. 3b are for a bed of activated charcoal. The length of the bed $y = 150$, the pulse length $\Delta z = 15$ and 27, the initial pulse amplitude was 195 and 192°C, the warm stream temperature 29°C.

The actual profile is distinguished from the theoretical by its sharply expressed asymmetry. In the case of the aluminum packing the leading wave front corresponding to the cooling process is compressed, whereas in the experiments with activated charcoal compression of the wave front corresponding to the heating process was recorded.

The reason for the asymmetry, which is qualitatively different for metals and adsorbents, is to be found, in our opinion, in the variability of the thermophysical properties of the packing with temperature, particularly its heat capacity. In fact, if we take into account the temperature dependence of the heat capacity of the packing and the effect of the heat of adsorption (desorption) on the heat transfer process, then the corresponding system of differential equations can be written in the following form (for simplicity we disregard the change in mass flow rate due to adsorption and desorption of the gas):

$$\frac{\partial u}{\partial t} + \omega \frac{\partial u}{\partial x} = -\frac{\alpha s}{c_p \rho f}(u - v), \tag{1}$$

$$\frac{\partial v}{\partial t} = \frac{\alpha s}{C(v)}(u - v), \tag{2}$$

where the symbol C(v) denotes a certain function of the packing temperature v determined from the formulas presented below.

For adsorbents (in the presence of heat release in the bed in the sorption processes)

$$C(v) = \rho_{\mathrm{pa}} c_s(v) - q_d \frac{da(v)}{dv}; \tag{3}$$

for metals (in the absence of heat release in the bed)

$$C(v) = \rho_{\mathrm{pa}} c_s(v). \tag{4}$$

In the first approximation the differential heat of adsorption q_d in (3) may be assumed constant, and the derivative with respect to temperature of the sorption capacity of the absorbent da/dv is easily determined from the adsorption isobar.

We will determine the rate of propagation along the bed of a certain point on the temperature wave profile corresponding to a fixed value of the gas temperature u:

$$W = \left(\frac{\partial x}{\partial t} \right)_{u=\text{const}}. \tag{5}$$

By virtue of the equations of the system, assuming that along the lines u = const (du = 0)

$$W = -\frac{\partial u}{\partial t} \Big/ \frac{\partial u}{\partial x}, \tag{6}$$

we have

$$W = \frac{w}{1 + \dfrac{C(v)}{c_p \rho f} \dfrac{\partial v}{\partial t} \Big/ \dfrac{\partial u}{\partial t}}. \tag{7}$$

It is clear from the last formula that the rate of propagation of different points on the temperature wave profile is, generally speaking, different and depends on the value of the quantity C(v) at the temperature in question. This is attributable to the distortion of the profile with time: some points move ahead, others lag behind. It is easy to see that in a bed of metallic packing the leading front of the low-temperature wave corresponding to the cooling process should be compressed. For the same reasons the trailing front of the same wave should be strongly broadened. For adsorbing packings, as distinct from metals, the quantity C(v) may either remain constant or increase as the temperature falls. For a bed of activated charcoal at temperatures from 100 to 200°K the quantity C(v) increases with fall in temperature and, as follows from (6), the rate of propagation of a point on the wave profile will be the greater, the higher the temperature. Therefore in the case of low-temperature waves in a bed of activated charcoal the nature of the symmetry is quite different from that in a bed of aluminum: compression of the profile is observed at the trailing front of the low-temperature wave corresponding to the heating process, whereas the leading front is strongly broadened.

It can be shown [5] that the irreversibility of the heat transfer process determined by the small but finite temperature difference between the gas and the packing leads to broadening of both the leading and trailing front of the temperature wave. This broadening will be the stronger, the steeper the wave profile and hence the greater the temperature difference $|u - v|$. Another consequence of this broadening is a reduction in the amplitude of the wave as it travels through the bed [4]. When a high-intensity low-temperature wave travels through the bed, the mechanisms of both effects – distortion of the profile as a result of the variability of the heat capacity of the packing with temperature and broadening of the profile due to the irreversibility of the heat transfer process – act simultaneously. If they act in the same direction and mutually reinforce each other, the wave front will be strongly broadened (expansion front); however, if they counteract each other, then, probably, there will be a certain limiting position of the compression front which, in accordance with mass transfer terminology, might be called asymptotic.

An asymptotic solution can exist only under certain conditions. It would be interesting and useful to establish these conditions and calculate the asymptotic position of the compression front, which would make it possible to solve the problem of the correctness of the experimental determination of the low-temperature coefficient of heat transfer between a gas and a packing (including one possessing adsorption properties) from the Schumann curves. There is no doubt that the ability to calculate the asymptotic position of the compression front of the temperature wave would be of considerable practical value in calculating the cooling or heating times of adsorbers and other equipment with a fine-grained loose packing.

NOTATION

u	is the gas temperature;
v	is the packing temperature;
x	is a coordinate;
t	is time;
w	is the linear gas velocity;

α is the heat transfer coefficient;
s is the specific surface of packing, m^2/m^3;
c_p is the specific heat of gas;
c_s is the specific heat of packing;
ρ is the gas density;
ρ_g is the density (bulk) of packing;
f is the porosity;
W is the propagation velocity of temperature wave;
q_d is the differential heat of adsorption;
y is the dimensionless length;
z is the dimensionless time.

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