EXPERIMENTAL DETERMINATION OF THE DIMENSIONS FOR A GAS–LIQUID SPRAY PLUME IN A FLUIDIZED BED

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We present results from an experimental investigation of the temperature fields in the zone of a liquid-spray plume. We have derived the criterial equations for the calculation of the geometric plume dimensions.

To determine the geometric parameters of apparatus and for the proper positioning of auxiliary equipment within a bed (thermocouple cases, heat-exchanger surfaces, etc.) we have to calculate the dimensions of the liquid-spray plumes in a fluidized bed.

In the drying of solutions and suspensions, it is not desirable for the various surfaces to be located near the effective zone of the plume, since this invariably leads to the formation of incrustations on such surfaces.

The literature presently contains no working relationships for the determination of the geometric dimensions of liquid-spray plumes. The working functions derived on the discharge of freely immersed jets [1] are not suitable in this case. It has been demonstrated by a number of authors [2-4] that the discharge of isothermal turbulent gas jets into a fluidized bed differs fundamentally from the propagation of freely immersed jets. The plume closes up in a fluidized bed [2] because of the momentum transfer in phases of unequal density, so that the geometric dimensions of the plume differ substantially from the dimensions of a freely immersed jet.

When a cold gas–liquid jet discharges into a heated fluidized bed, a temperature field is formed [5, 6], and here we observe the formation of two zones: a zone of evaporation for the drops of the liquid spray and a superheat zone for the vapor–gas stream. The dimensions of these zones are governed by the discharge velocity of the atomization agent, the liquid flow rate through the spray nozzle, as well as the temperatures and grain size of the material making up the fluidized bed.

We performed more than 250 tests to determine the effect of various parameters on the geometric dimensions of the nonisothermal zone of the atomized liquid. The experimental method and installation were described earlier in [6].

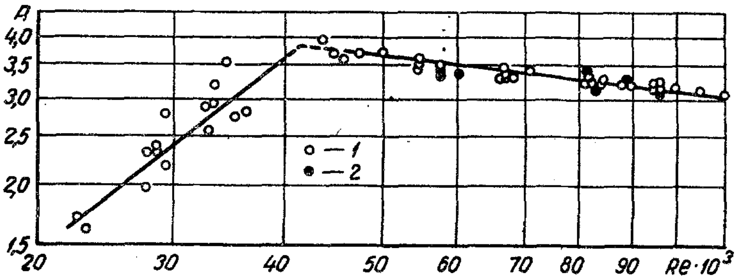

Fig. 1. Relationship giving $(d_1/d_0)/(w_{mix}/w_{dis})^{-0.625} = A$ as a function of Re for K = 10.57: 1) Alundum with d_{av} = 0.896 mm; 2) sand with d_{av} = 1.07 mm.

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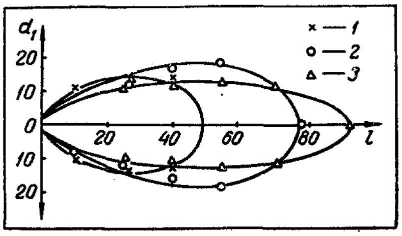

Fig. 2. Effect of Re on the geometric limits of the atomization plume: 1) Re = $33.5 \cdot 10^3$; 2) $44.8 \cdot 10^3$; 3) $65.2 \cdot 10^3$ (K = 10.57; w_{mix}/w_{dis} = 0.27); d_1 and l are given in mm.

The temperature in the plume zone was measured with a movable Chromel–Alumel thermocouple. Air was used in all of the tests as the atomization and fluidization agent; tap water served as the liquid being atomized. The water flow rate varied from 0.5 to 20 liters/h. The tests were carried out for a fluidized-bed temperature range of 150-600°C. The following materials were used for the fluidized bed in the tests; alundum granules (d_{av}:0.896 and 0.57 mm); quartz sand (d_{av}:0.47, 1.07, 1.8 mm); corundum (d_{av}: 0.1, 0.4, 0.5, 0.77 mm); chamotte fireclay (d_{av}; 0.5, 0.829 mm).

Processing of the experimental data enables us to derive the following relationships:

for the temperature penetration of the plume

$$\frac{l}{d_0} = 1.32 \cdot 10^{-2}\left(\frac{w_{mix}}{w_{dis}}\right)^{-0.35}\mathrm{Fr}^{0.5}\mathrm{K}^{0.1}A, \quad (1)$$

for the length of the evaporation zone

$$\frac{l_0}{d_0} = 5.65 \cdot 10^{-3}\left(\frac{w_{mix}}{w_{dis}}\right)^{-0.5}\mathrm{Fr}^{0.5}\mathrm{K}^{0.065}\left(\frac{d_{av}}{d_0}\right)^{-0.2}B. \quad (2)$$

The temperature penetration is understood to refer to the distance from the orifice of the spray nozzle, along its axis, to the point at which the temperature differs by 3-5 deg from the temperature of the fluidized bed. The length of the evaporation zone is the distance from the spray nozzle to the point at which the temperature corresponds to the boiling point for the liquid. Since the jet was approximately in the shape of an ellipsoid in most of the tests, we derive empirical relationships even in the case of small axes, i.e., for the maximum diameters of the nonisothermal zone:

for Re ≥ 42,000

$$\frac{d_1}{d_0} = 25.5\left(\frac{w_{mix}}{w_{dis}}\right)^{-0.625}\mathrm{Re}^{-0.25}\mathrm{K}^{0.29}; \quad (3)$$

for Re ≤ 42,000

$$\frac{d_1}{d_0} = 1.58 \cdot 10^{-7}\left(\frac{w_{mix}}{w_{dis}}\right)^{-0.625}\mathrm{Re}^{1.6} \quad (4)$$

and for the evaporation zone:

for Re ≥ 46,000

$$\frac{d_2}{d_0} = 0.0182\left(\frac{w_{mix}}{w_{dis}}\right)^{-1.2}\mathrm{Re}^{0.287}\mathrm{K}^{0.375}; \quad (5)$$

for Re ≤ 46,000

$$\frac{d_2}{d_0} = 2.37 \cdot 10^{-3}\left(\frac{w_{mix}}{w_{dis}}\right)^{-0.85}\mathrm{Re}^{0.538}\mathrm{K}^{0.23}. \quad (6)$$

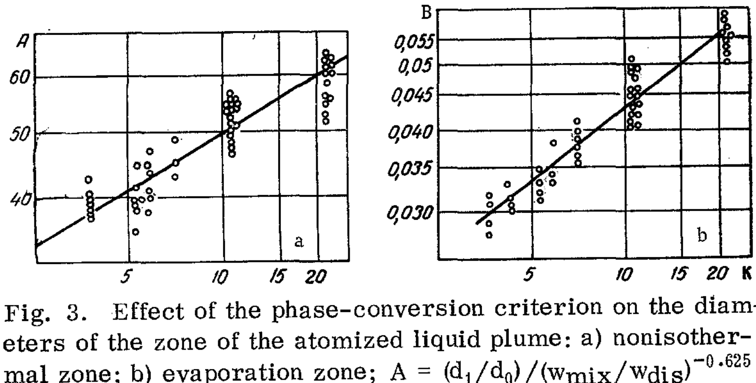

Fig. 3. Effect of the phase-conversion criterion on the diameters of the zone of the atomized liquid plume: a) nonisothermal zone; b) evaporation zone; $A = (d_1/d_0)/(w_{mix}/w_{dis})^{-0.625} \cdot \mathrm{Re}^{-0.25}$; $B = (d_2/d_0)/(w_{mix}/w_{dis})^{-1.2}\mathrm{Re}^{0.287}$

The effect of Re on the maximum diameter of the nonisothermal zone differs substantially from its effect on the length of the evaporation zone. With an increase in Re there is, initially, an increase in the zone diameter (Fig. 1). When Re > 42,000, the zone diameter begins gradually to diminish. The plume acquires a markedly elongated shape (Fig. 2).

The complex w_{mix}/w_{dis} also exerts substantial influence on the zone diameters. With a constant value for w_{dis} the magnitude of w_{mix}/w_{dis} is determined from the flow rate of the atomized liquid. An increase in G_l leads to a reduction in w_{mix}/w_{dis}. Consequently, the spray density of the plume is increased, thus resulting in an increase of its geometric dimensions. The effect of the K criterion is less significant for the nonisothermal zone. For the evaporation zone the rise in temperature intensifies the evaporation process, leading to the more rapid reduction of the diameter of this zone (Fig. 3). As demonstrated by our experiments, to form a stable plume in a fluidized bed we must satisfy the following condition:

$$w_{mix} \geqslant 2w_{free}. \tag{7}$$

It was demonstrated by a number of authors [2-4] that two zones are formed as an isothermal gas jet discharges into a fluidized bed: the first zone contains the gas, free of any material particles from the bed, and the second zone is made up of the gas and solid particles.

On discharge of a gas–liquid jet the evaporation zone is thus apparently a gas zone containing only liquid drops. Let us examine the expansion of the gas–solid boundary zone. We will assume that the coordinate is positioned at the center of the small ellipse. In this event, the equations for the small ellipse in parametric form is given by

$$x = \frac{l_0}{2}\cos t, \qquad y = \frac{d_2}{2}\sin t, \tag{8}$$

and for the large ellipse

$$x = \frac{l}{2}\cos t - m, \qquad y = \frac{d_1}{2}\sin t, \tag{9}$$

where

$$m = \frac{1}{2}(l_0 - l).$$

The increase in the thickness of the boundary zone is characterized by a change in the distance M_1M_2 along the spray drawn from the coordinate origin to the point of intersection with the inside and outside ellipses (Fig. 4). The instantaneous value of the segment M_1M_2 will then be expressed as

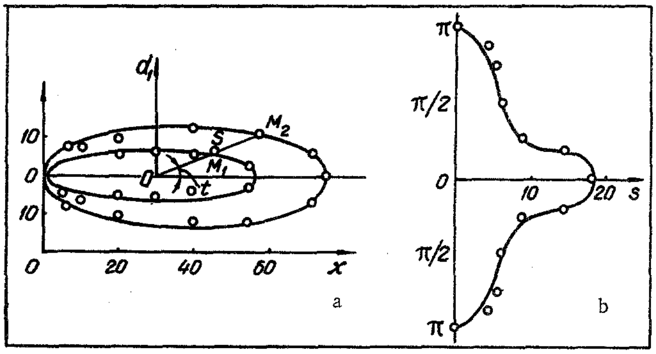

Fig. 4. Comparison of the experimental (points) and theoretical (solid lines) of jet configurations: a) lateral cross section of the plume along the axis of the spray nozzle; b) change in the thickness of the boundary zone along the length of the plume; d_1, in mm; x, in mm; s, in mm.

$$s=\frac{1}{2}\sqrt{[\cos t(l-l_0)-(l_0-l)]^2+[\sin t(d_1-d_2)]^2}, \tag{10}$$

where $0 \leq t \leq 2\pi$. The maximum value of s will be $l-l_0$ (when t = 0).

The nature of the change in the thickness of the boundary layer is shown in Fig. 4. As we can see from the figure, with an increase in t from 0 to $\pi/2$ we have a pronounced reduction in s, and this is followed by a slow drop to zero. The resulting relationships (1-6 and 10) for specified technological parameters of operation for the installation enables us to calculate the geometric dimensions of the plume for the atomized liquid, as well as the magnitude of the boundary zone.

NOTATION

l and l_0	are, respectively, the temperature penetration and the length of the evaporation zone;
d_1 and d_2	are, respectively, the diameters of the nonisothermal zone and of the evaporation zone;
d_0	is the diameter of the gas nozzle;
d_{av}	is the average diameter of the particles in the material making up the bed;
δ	is the thickness of the gas-nozzle slit;
w_{free}	is the free-wall velocity for particles with d_{av};
w_{dis}	is the discharge velocity for the atomization agent from the spray nozzle;
w_{mix}	is the velocity of the mixture after the mixing of the atomization agent and the liquid, equal to $\varphi G_g w_{dis}/(C_g + G_l)$;
g	is the acceleration of the force of gravity;
G_g and G_l	are, respectively, the weight flow rate of the gas and the liquid;
ν	is the coefficient of kinematic viscosity;
r	is the heat of phase conversion;
c_p	is the specific capacity of the vapor;
$\Delta t = t_{fb} - t_{bl}$	is the temperature head;
t_{fb}	is the temperature of the fluidized bed;
t_{bl}	is the boiling point for the liquid;
φ	is the coefficient by means of which we account for losses in the nozzle;
$Re = w_{dis} d_0/\nu$	denotes the Reynolds number;
$K = r/c_p \Delta t$	denotes the phase conversion;
$Fr = w_{dis}^2/gd_0$	denotes the Froude number;
$A = 1.75\ (\delta/d_0)^{0.2}$;	
$B = 1.62\ (\delta/d_0)^{0.2}$.	

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