FORMATION OF BUBBLES DURING DISCHARGE OF A JET INTO A FLUIDIZED BED

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A description of the mechanism of formation and growth of bubbles in a fluidized bed is presented on the basis of a jet model proposed earlier.

It is known that with nonuniform fluidization considerable pulsations in the pressure drop in the bed are observed in comparison with its value determined as

$$\Delta p_{bed} = g\rho_s (1-\varepsilon) l_{bed} = \lambda \frac{l_{bed}}{d_e} \frac{w^2 \rho_g}{2\varepsilon}. \quad (1)$$

The jet theory of [1-4] explains the appearance of such pulsations as a peculiarity of the development of jets in a medium of higher density. The pressure pulsations indicate the breakup of the jets and the formation of bubbles. With any construction of the gas-distributing grid the fluidizing agent discharges into the bed in the form of jets with the subsequent total or partial degeneration of the jet flow into filtration flow — in the gaps between particles (Fig. 1).

Let us consider the case of the discharge of fluidizing agent from an orifice of the gas-distributing grid with a velocity exceeding the velocity of particle floating ($u_0 > u_f$). According to [1, 2] a jet tongue whose shape is shown in Fig. 2 will form in this case. If the entry of fluidizing agent into such a tongue exceeds its flow rate through the cross section A–A (Fig. 1), then an excess pressure unavoidably develops in the tongue and the pressure drop (Δp_{bed}) increases in comparison with the value determined from Eq. (1). Furthermore, the increase in the pressure drop leads to an increase in the velocity of filtration of the fluidizing agent in the gaps between particles. However, the increase in the pressure drop is limited by its maximum value $\Delta p_{bed.max}$, upon which the eruption of the jet through the bed occurs in the form of torn-off tongue-bubbles. Thus, the breakup of the jet and the formation of bubbles in a fluidized bed are determined by the disruption of the continuity of the jet stream [2, 4]

$$\pi r_0^2 u_0 > \pi b_A^2 w \varepsilon_c \quad (2)$$

and of the equilibrium of the forces acting on the tongue at the moment of its tearing off [1, 4]:

$$\Delta p_{bed.max} \pi r_0^2 \geqslant \Sigma p_{res}, \quad (3)$$

where Σp_{res} is the sum of the forces resisting the tearing off of the tongue.

If the tongue is considered as a hollow permeable body pressed against the orifice by the bed and one assumes that the principal force preventing the tearing off of the tongue is the force of hydrostatic pressure of the bed, then on the basis of (3) one can write

$$\Delta p_{bed.max} \pi r_0^2 = \int_0^{S_t} p_v ds. \quad (4)$$

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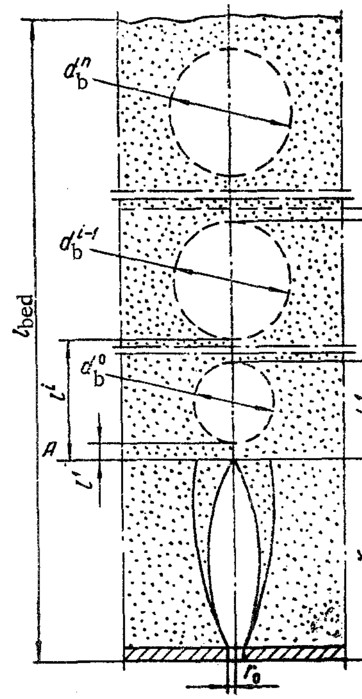

Fig. 1

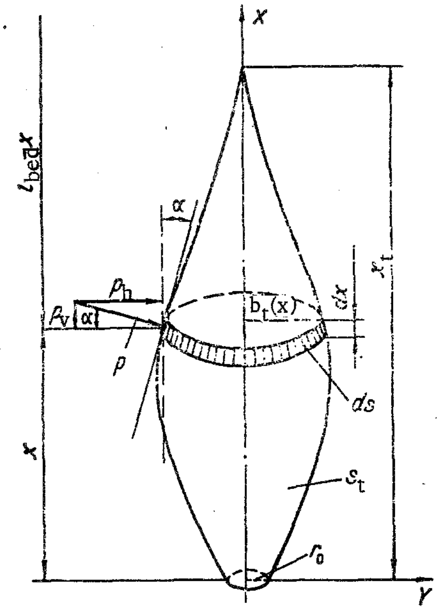

Fig. 2

Fig. 1. Diagram of formation of bubbles during discharge of a jet into a fluidized bed.

Fig. 2. Diagram of the gas tongue of a jet.

We can transform Eq. (4) by determining the vertical component of the bed pressure on the tongue and expressing a surface element through the coordinate x (Fig. 2):

$$\Delta p_{bed.max}\, r_0^2 = 2g\rho_s\,(1-\varepsilon_c)\int_0^{x_t}(l_{bed}-x)\, b_t\, \operatorname{tg}\alpha\, dx. \tag{5}$$

Equation (5) allows one to calculate the maximum pressure in the bed at the moment the tongue tears off and, with its value known, to determine from Eq. (1) the maximum velocity of filtration of the fluidizing agent in the gaps between particles, assuming that the porosity of the continuous phase is equal to the porosity of the bed in the state of minimal fluidization. The geometrical characteristics of the tongue (tan α, b_t, x_t, and V_t) can be determined by the method presented in [3, 5, 6].

Thus, Eq. (5) allows one to determine the amplitude of the pulsations in the pressure drop in the bed. To determine the frequency of the pulsations we assume roughly that the time of formation of the tongue and of the rise of pressure in it can be expressed as the ratio of the volume of the tongue to the flow rate of fluidizing agent through the orifice, i.e.,

$$\tau_t = \frac{V_t}{\pi r_0^2 u_0}. \tag{6}$$

We assume that the bubble which is formed through the tearing off of the tongue has a spherical shape and its volume is equal to the volume of the tongue. Then the diameter of such a bubble is determined as

$$d_b^0 = \sqrt[3]{\frac{6V_t}{\pi}}. \tag{7}$$

The velocity of ascent of the bubble can be calculated from the following equation, well-known in the literature [7]:

$$u_b^0 = 0{,}717\sqrt{g d_b^0}. \tag{8}$$

After the formation of the bubble the tongue recovers its dimensions and the pressure again increases in it. We will assume that the recovery time for the tongue dimensions is equal to the time of its initial formation and is determined from Eq. (6). When the pressure in the tongue reaches the tear-off value the tongue again tears off and a second bubble is formed. In this case, however, the value of the tear-off pressure is determined not by the entire height of the bed, but by the distance between the tongue and the first bubble, which has been able to travel a certain distance by this time. Thus, one now substitutes into Eq. (5) not l_{bed} but a distance equal to (Fig. 1)

$$l^1 = h^1 - d_b^0. \tag{9}$$

Here the distance traveled by the first bubble by the time of formation of the second can be expressed as

$$h^1 = u_b^0 \tau_t. \tag{10}$$

In a similar way a third bubble is formed following the second, and so forth.

It is known that the bubbles which ascend after the first have a considerably higher velocity [8]. As a result, at a certain distance they can overtake the first bubble and merge with it. We assume that the succeeding bubbles which overtake the first have the same velocity and therefore do not interact with each other but merge with the first. This makes it possible to divide all the bubbles which form during the discharge of a jet into a fluidized bed into primary (first) and feeding (succeeding) bubbles. With each interaction of a feeding bubble with the primary bubble the latter abruptly changes its dimensions and velocity of ascent. Assuming that the volume of the feeding bubbles is constant and equal to the volume of the tongue, the diameter of the primary bubble after the interaction with the i-th feeding bubble can be determined as

$$d_b^i = \sqrt[3]{\frac{6(i+1)V_t}{\pi}}. \tag{11}$$

Then the velocity of ascent of such a bubble is equal to

$$u_b^i = 0{,}717\sqrt{g d_b^i}. \tag{12}$$

The pressure in the tongue during the formation of the i-th feeding bubble can be determined by substituting into Eq. (5) the distance between the tongue and the primary bubble, equal to (Fig. 1)

$$l^i = h^i - d_b^{i-1}. \tag{13}$$

The distance traveled by the primary bubble by the time of formation of the i-th feeding bubble can be determined through successive calculation in accordance with the expression

$$h^i = u_b^0(\tau_t^1 + \tau_m^1) + u_b^1(\tau_t^2 + \tau_m^2) + \ldots + u_b^{i-1}\tau_t^i. \tag{14}$$

We can determine the time in which the i-th feeding bubble overtakes the primary bubble from the following considerations. The distance traveled by the primary bubble by the time the i-th feeding bubble merges with it is equal to

$$h^{i-1} = u_b^0(\tau_t^1 + \tau_m^1) + u_b^1(\tau_t^2 + \tau_m^2) + \ldots + u_b^{i-1}(\tau_t^i + \tau_m^i). \tag{15}$$

The i-th feeding bubble, moving with the velocity u_b^n, travels the same distance in a time τ_m^i, i.e.,

$$h^{i-1} = u_b^n \tau_m^i. \tag{16}$$

Equating the right sides of (15) and (16) with allowance for (14), we obtain an expression for determining the time in which the i-th feeding bubble overtakes the primary bubble:

$$\tau_m^i = \frac{h^i}{u_b^n - u_b^{i-1}}. \tag{17}$$

It follows from Eq. (17) that when the primary bubble attains the velocity of rise of the feeding bubbles merging of the bubbles does not occur ($\tau_m^n = \infty$). In this case the primary bubble departs from the feeding zone and the pattern described above is repeated. The height of the feeding zone is then equal to

$$H_{f.z} = u_b^0(\tau_t^1 + \tau_m^1) + u_b^1(\tau_t^2 + \tau_m^2) + \ldots + u_b^{n-1}(\tau_t^n + \tau_m^{n-1}). \quad (18)$$

The time the primary bubble stays in the feeding zone is

$$\tau_{f.z} = \tau_t^1 + \tau_t^2 + \ldots + \tau_t^n + \tau_m^1 + \tau_m^2 + \ldots + \tau_m^{n-1}. \quad (19)$$

With the discharge of a multitude of jets the transverse interaction of the tongues or rising bubbles is possible. The description of the development of the bubbles is complicated in this case. In any event, however, the nonuniform fluidized bed can be divided into three zones which differ in the mechanism of motion of the fluidizing agent: the tongue zone, the bubble feeding zone, and the main fluidized bed. Jet motion of the fluidizing agent occurs in the tongue zone, while filtration motion with partial passage through in the form of bubbles occurs in the feeding zone and in the main fluidized bed. Merging of the bubbles and variation in their characteristics occur in the feeding zone.

It can be assumed that in the main fluidized bed a bubble has constant characteristics which are determined by the last feeding in the feeding zone. Then the time the bubble spends outside the feeding zone can be calculated on the basis of the following expression:

$$\tau_{out} = \frac{l_{bed} - H_{f.z} - x_t}{u_b^n}. \quad (20)$$

With the velocity of ascent of the feeding bubbles known, the functions obtained allow one to calculate the pulsations in the pressure drop in the bed, the variation over the height of the bed in the diameter and velocity of ascent of the bubbles, the height of the feeding zone, and the time the bubble spends in the bed. Additional data are required to determine the velocity of ascent of the feeding bubbles.

It should be noted that the velocity of ascent of the feeding bubbles actually may not be the same and may vary in proportion to the ascent of the primary bubble. As a result, the feeding bubbles will merge with each other, which hinders the clear differentiation between primary and feeding bubbles, and, accordingly, the description of the laws of bubble development is made considerably more complicated. At the same time, despite this assumption and the fact that the present model does not provide for transverse interaction of the bubbles, it corresponds approximately to the actual pattern of bubble development. For example, the presence of a zone of bubble feeding was established earlier with the help of high-speed motion-picture photography [9]. In addition, according to this model two types of pressure pulsations can be observed in a nonuniform fluidized bed: the main pulsations, which have the same amplitude (the formation of the primary bubbles), and secondary pulsations, which occur between the main pulsations and have a variable amplitude (the formation of the feeding bubbles). Such a nature of the pressure pulsations in the bed was established experimentally [10].

NOTATION

u_0, u_b, u_b^n, u_f, w, velocities of discharge of jet, of ascent of primary bubble, of ascent of feeding bubble, of floating of solid particles, and of motion of fluidizing agent in the gaps between particles; d_e, d_b, diameters of equivalent particles and of primary bubble; r_0, b_t, b_A, radii of orifice, of tongue, and of cross section AA; h, distance traveled by primary bubble; x_t, $H_{f.z}$, l_{bed}, heights of tongue, of feeding zone, and of working fluidized bed; ρ_g, ρ_s, densities of gas and of solid particles; τ_t, τ_m, $\tau_{f.z}$, τ_{out}, times of bubble formation, of motion of feeding bubble, of stay of primary bubble in the feeding zone, and of its stay in the main part of the fluidized bed; V_t, volume of tongue; Δp, pressure drop in the bed; ε_c, porosity of continuous phase; g, free-fall acceleration; λ, coefficient of friction. Indices: 0, primary bubble; i, number of feeding bubble; i = 1, 2, 3, 4, ..., n.

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