AERODYNAMICS OF A JET IN A FLUIDIZED BED

N. A. Shakhova and G. A. Minaev

UDC 532.517.4

We investigated experimentally the development of unbounded and semibounded, vertical and horizontal, circular and annular turbulent, isothermal gas (air) jets in a fluidized bed in particles measuring from 1 to 5 mm. The characteristics of the particles are given in Table 1. The experiments were carried out on a specially developed laboratory device with three apparatuses (cylindrical with a diameter of 125 mm, rectangular measuring 95 × 125 mm and 120 × 220 mm) and also in experimental industrial granulators with an area of the gas distribution grates F_{gr} = 0.36 and 0.6 m^2. The jets were discharged from nozzles with a diameter d_0 = 2, 3, 4, 5, 6, 8, and 10 mm shaped according to Vitoshinskii's equations, cylindrical nozzles of diameter d_0 = 4 and 10 mm (h/d_0 = 2.5), and annular nozzles d_0/d = 8/5, 10/5, 10/7, 24.5/21.5, 46/43, and 70/40 mm. The inside surface of nozzles with diameter $d_0 \leq 10$ mm was ground whilst that of nozzles with diameter $d_0 > 10$ mm was left as finished; the degree of waisting was 6.25.

The initial discharge velocity of the jet was varied from 12.8 to 310 m/sec, the initial height of the bed from 0.25D to 1.5D, and the fluidization number from 1 to 2.5; the temperature of the jet and bed was 28 ± 3°C.

In the experiments we measured the barometric pressure and air flow rate for fluidization by a diaphragm to within ± 1.7%; the air flow rate for the jet by RS-3, RS-5, and RS-7 rotameters to within ± 2.9%; total air pressure in the nozzle by U-shaped or standard manometers to within 3%; temperature of the jet and fluidizing agent by laboratory TL-4 mercury thermometers to within ± 0.7%; and local gas velocities in the jet sections by the pneumometric method to within ± 2.6%; we also took motion pictures of the semibounded jet and bed at speeds of 24 and 600 frames per second. The Pitot–Prandtl tube (diameter 1.2 mm) was moved by means of a coordinate device with an accuracy of 0.01 mm.

Visual observations and motion picture filming at speeds of 24 and 600 frames/sec of vertical semibounded jets (a typical assembly of the semibounded jet is shown in Fig. 1) show that the development of the gas jet in the fluidized bed (when $X_s \leq H_W$) is characterized by a periodic disruption of continuity due to separation of the gas stream with simultaneous covering of the nozzle orifice by particles of the bed and subsequent deformation of the stream with the formation, growth, and rise of a bubble. The bubble is a separated and deformed stream of the jet [1, 2]. The growth and rise of the bubble are the consequence of its supply at the expense of the initial and added mass of the jet. The size of the stream increases with rise of the bubble, and with escape of the bubble from the supply zone, which slightly exceeds the maximum (in a given hydrodynamic situation) length of the gas stream X_S, the next separation of the jet occurs with the initiation of a bubble and recurrence of a new cycle of jet development, the period (τ) of which and the picture of the jet flow, as an investigation showed, depend considerably on the ratio of the maximum length of the gas stream X_s to the working height of the bed over the nozzle H_W. With an increase of the value of the parametric criterion X_S/H_W the zone of bubble initiation (zone of the initial equilibrium position of the separated and deformed stream) shifts to the upper half of the bed. In this case the residence time of the bubble in the bed, its volume at the exit from the bed, and the duration of the cycle of development of the jet decrease. In the experiments the conditions of which are given above, the main period of development of the jet τ varied from 1/2 to 1/48 of a second and less, i.e., the frequency of the cycles of development of the jet (initiation of a bubble) was f_b = 2-48 Hz and more. The main period τ was determined by us on the basis of the frames of the motion picture film of the unbounded jets under different conditions of their discharge into the fluidized bed (U_0, d_0, d_e, ρ_e, H_W varying).

Institute of Chemical Plant Design, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 19, No. 5, pp. 826-836, November, 1970. Original article submitted September 17, 1969.

TABLE 1. Characteristics of Granular Materials

No.	Material	Screen size	d_e, mm*	Density ρ_s, kg·sec²/m⁴	w_0, m/sec	U_b, m/sec	Shape and surface of particles
1	Aluminum silicate catalyst	1,5—2,0	1,70	118	0,65	5,0	Spherical, smooth
		2,0—2,5	2,34	116	0,82	5,8	
		2,5—3,0	2,82	115	0,99	6,6	
		3,0—4,0	3,40	116	1,13	7,3	
		4,0—4,5	4,35	116	1,36	8,5	
2	Granulated Nitrophoska	2,0—2,5	2,36	177	1,00	7,5	Round, rough
		1,0—4,0	2,12	177	0,90	7,0	
3	Urea-Ammo-Phos	1,0—4,0	2,00	153	0,80	6,3	
4	Glass beads	1,25—1,40	1,30	280	0,75	5,9	Spherical, smooth
		2,0—2,5	2,28	280	1,20	9,4	

*In a monodisperse bed $d_e = \sqrt{d_1 d_2}$, where d_1 and d_2 are sizes of the minus and plus screens; in a polydisperse bed $1/d_e = \Sigma X_i/d_i$, where X_i is the weight portion of the particles of the narrow fraction with diameter d_i.

After initiation of the bubble and up to the instant of its emergence from the supply zone the flow of the jet can exhibit the character of a flow both with and without separation; however, it does not change the general picture of the development of a jet since, for an increase of the volume of the initiated bubble, what the character of the flow of the fluid supplying it is entirely indifferent.

Thus the flow of a jet in a fluidized bed represents the superposition of flows of a different physical nature.

For a value of the parametric criterion $H_s/H_w \geqslant 0.6$ this super position of motions in the bed is realized in a mixed flow representing the statistical population of the high-frequency ($f_b \geqslant 6$ Hz) flow with separation (bubble flow) and without separation (jet flow). The fraction of the latter in this population decreases (when $X_s < H_w$) with increase in the value of the ratio U_0/U_b, i.e., with increase in the velocity of filling of the stream volume at a constant percolation flow rate through the porous walls of the upper "roof," and increases when $X_s > H_w$. Under these conditions visual observation and motion picture filming (at a speed of 24 frames/sec) do not reveal disruption of the continuity of the flow and formation of a bubble. The positions of the gas stream boundaries are stable in time, and quenching of the kinetic energy of the jet is completed both within and beyond the limits of the bed. At the boundary of the stream in the narrow gas–solid particles zone [1, 2] there occurs (see Fig. 1) an intense organized movement of the particles (with an average velocity $w_p \simeq 0.1$-0.4 m/sec) in the direction of the principal movement of the jet. Individually flying (in an air-transport mode) particles are observed inside the gas stream. The volume of the stream is supplied with particles only near the outflow of the jet on a length equal to about one nozzle diameter.

We called the process in which flow took place with the parameters indicated above the jet mode, a particular case of which is the mode of "local spouting" in which the kinetic energy of the jet is quenched inside the bed (a characteristic hillock and a fanlike motion of the particles appear on the surface), the organized circulation of the particles through the stream being retained. The geometric dimensions of the gas stream in the local spouting mode increase with increasing discharge velocity and initial diameter of the jet, and also with decreasing diameter and density of the particles and fluidization number (maximum at W = 1.0*).

Filming at a speed of 600 frames/sec in the jet mode, and particularly in the local-spouting mode, reveals intermittence of the jet and bubble flows and, characteristic of the latter, disruption of the continuity of the flow: the dimensions of the stream fluctuate and it breaks away, while bubbles form and rise as the detached flow pattern varies over a period of $\tau \geqslant 1/6$ sec. Since the length of the gas stream X_s and the working height of the bed above the nozzle H_w are commensurate, the separation of the stream in the phase of detached (bubble) flow is only accompanied by a change of shape with practically no development (growth) of the bubble, since the bubble emerges instantaneously from the bed, transporting the mass of the jet in bubble shape. In the jet-flow phase the jet emerges from the bed (for constant maximum dimensions of the stream) through a well-formed channel, which is open (when $X_s \geq H_w$) or closed (in the local-spouting mode), and represents a heterogeneous ascending flow.

*In the range of investigation $1.0 \leq W \leq 2.5$.

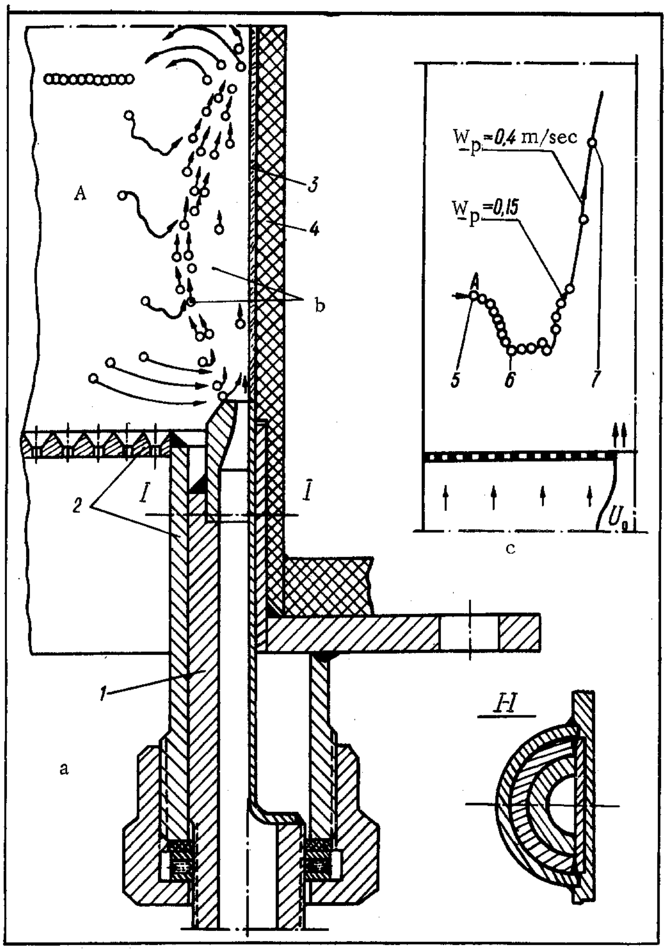

Fig. 1. Assembly of semibounded nozzle. a) Diagram of circulation of particles through the stream on discharge of the jet into the fluidized bed under conditions of local spouting; b: 1) semibounded nozzle; 2) gas distribution grate; 3) glass, $\delta = 2$ mm; 4) housing of apparatus (organic glass) and typical path of an individual particle at the boundary of the main section of the stream; c: 5) $\tau = 0$; 6) $\tau = 1$; 7) $\tau = 2$ sec.

For a value of the parametric criterion $X_s/H_w < 0.6$ transport of the mass of the jet to the surface of the bed is accomplished in the form of a percolating flow (through the walls of the stream and bubble) and rigorously periodic bubble breakthrough, with a frequency $f_b < 6$ Hz. Under these conditions, filming at a speed of 24 frames/sec (and even visual observation) reveal discontinuity of the flow – separation of the gas stream and the initiation, growth, and rise of a bubble, the volume of which on emerging from the bed considerably exceeds the original volume of the detached stream. The emergence of the bubble to the surface of the bed is accompanied by its "inflation" and bursting, with the subsequent ejection of particles into the separation space. The height of the gas stream fluctuates practically from zero (after separation) to a maximum (at the instant of separation) corresponding to the visually observed length of the stream in the local-spouting mode; in this case the organized circulation of the particles in the zone of action of the jet is absent.

We called the process in which the jet flowed with the parameters indicated above the bubble mode. Increasing the filming speed to 600 frames/sec in this mode does not substantially refine the picture of jet development observed when filming at 24 frames/sec.

The mode of development of the gas jet in the fluidized bed (jet and bubble) depends on the discharge conditions and is determined by the totality of parameters of the bed and jet (U_0, d_0, d_e, ρ_s, H_w, W), so that

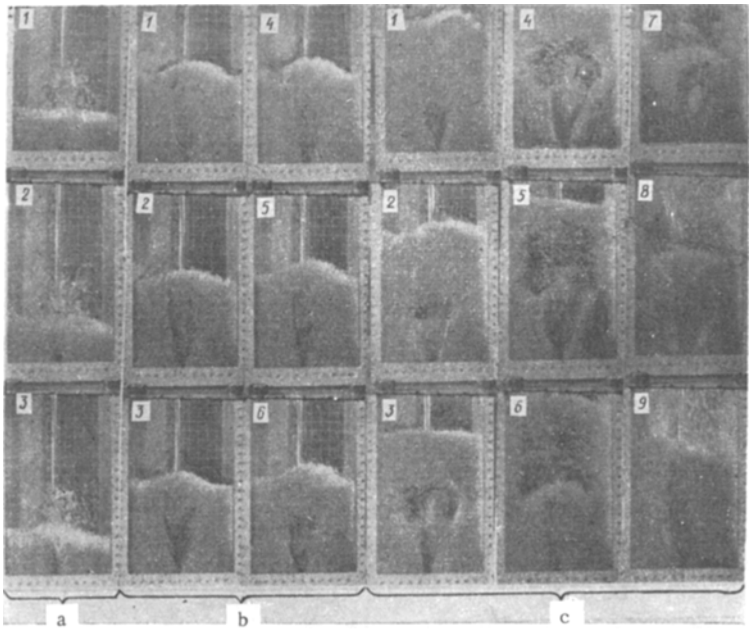

Fig. 2. Modes and character of development of a gas jet in a fluidized bed. a, b) Jet mode; c) bubble mode. Semibounded jet, $U_0 = 26.2$ m/sec, $r_0 = 0.005$ m; material of bed, aluminum silicate catalyst of fraction 2-2.5 mm, $W = 1.0$; filming speed 24 frames/sec, apparatus 95 × 125 mm: a) $H_0 = 0.032$ m, $X_s/H_w = 1.8$; b) respectively 0.090 and 0.6; c) 0.130 and 0.42.

for constant jet parameters (U_0, d_0) the jet can be realized in different modes depending on the bed parameters (H_w, W, d_e, ρ_s). The bubble mode of jet development occurs upon a change of the discharge conditions (U_0, d_0, H_w, W, d_e, ρ_s) such that the value of the parametric criterion X_s/H_w becomes less than ~ 0.6 (see Fig. 2), i.e., when the maximum length of the stream becomes small in comparison with the height of the bed. The length of the stream, as the investigation showed, being a function of U_0, d_0, W, d_e, and ρ_s, does not depend on the height and mass of the bed. Consequently the value of the parametric criterion X_s/H_w can serve (within the investigated range $0.26 \leq X_s/H_w \leq 2.4$) as a characteristic of the mode of development of the gas jet in a fluidized bed.

In the case of a vertical jet (unbounded and semibounded) the following relationships hold for the modes indicated above:

bubble mode

$$X_s/H_w < 0.6, \qquad (1)$$

jet mode

$$X_s/H_w \geqslant 0.6, \qquad (2)$$

local-spouting mode

$$0.6 \leqslant X_s/H_w \leqslant 0.85, \qquad (3)$$

$1.3 \leq d_e \leq 4.35$; $115 \leq \rho_s \leq 280$; $1.00 \leq W \leq 2.50$; $2U_b \leq U_0 \leq 310$; $2 \leq d_0 \leq 70$; $0.26 \leq X_s/H_w \leq 2.4$.

Thus, to determine the mode of jet development it is necessary to know the working height of the bed above the nozzle H_w and the maximum length of the gas stream X_s. In the experiments X_s was determined by direct measurement (for discharge of a semibounded jet) and by the indirect method (for discharge of an unbounded jet) as the abscissa of the point of the graph $U_m = U_m(X)$ at which the velocity is equal to the "velocity on the boundary of the gas stream" U_b, predetermined experimentally. The working height of the bed was determined by direct measurement.

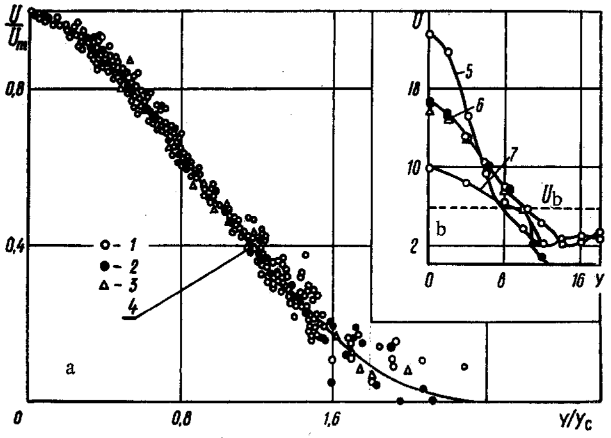

Fig. 3. Universal profile of dimensionless gas velocity in the principal region of the jet (a) for $2U_b \leq U_0 \leq 310$; $2 \leq d_0 \leq 10$; $1.3 \leq d_e \leq 4.35$; $115 \leq \rho_s \leq 280$; $1.0 \leq W \leq 2.5$; $0.6 \leq X_s/H_w \leq 2.4$; and typical velocity profiles of the gas in different sections (b) (U, U_0, U_b, m/sec; y, d_e, d_0, b, mm; ρ_s, kg·sec^2/m^4): 1) vertical circular jet; 2) horizontal circular jet; 3) annular jet; 4) Schlichting profile:

$$\frac{U}{U_m} = \left[1 - \left(\frac{y}{b}\right)^{1,5}\right]^2 \left(\text{when } \frac{y_c}{b} = 0{,}44\right);\ 5 - x = 15\ \text{mm},\ 6 - 25;\ 7 - 40$$

It was established that discharge of a jet in a bubble regime lessens the quality of fluidization and increases the fluctuation of the bed height, whereas in the jet and local-spouting modes the opposite effect occurs [3]. The improvement of the quality of fluidization in local-spouting and jet modes, as the experimental investigation showed, as in consequence of the predominant injection by the outflowing jet of the discrete phase of the fluidized bed (gas bubbles) with their subsequent bursting in the jet stream and formation of a localized zone of intense contact with the solid phase.

The high frequency of cycles of jet development in the jet mode and in the local-spouting mode not only gives rise to a stable position of the boundaries of the gas stream in the bed but also, as an investigation showed, lends constancy in time and complete reproducibility to the value of the local velocity in the mixing zone, measured by the pneumometric method. The Pitot–Prandtl tube was kept at the measurement points for 3 min, so that the averaging period exceeded the main period of change of the picture of the flow by about three orders. The amplitude of fluctuations of the liquid column in the micromanometer proved to be commensurable with the amplitude of fluctuations during measurement of the velocity in a drowned jet, and the characteristics of jet propagation in the jet (when $X_s/H_w > 1.0$) and local-spouting modes coincide completely. Consequently, a jet flow in local-spouting and jet modes can be regarded as quasi-steady with constant maximum parameters of the gas stream.

An experimental investigation (by the pneumometric method) of the velocity and pressure fields in the boundary layer of vertical unbounded jets in a local-spouting mode showed that a circular jet developing in a fluidized bed, as is the case for a drowned jet [4, 5], is characterized by the existence over the length of the turbulent boundary layer of three regions with different laws of variation of velocity: initial, transitional, and principal. The length of the initial section and abscissa of the transitional section can be determined (to within 10%) by the empirical equations we obtained

$$X_i/X_m = 0{,}32, \tag{4}$$

$$X_t/X_m = 0{,}60. \tag{5}$$

In approximate calculations we can take

$$X_i \approx d_0, \tag{6}$$

$$X_t \approx 1.9 d_0. \tag{7}$$

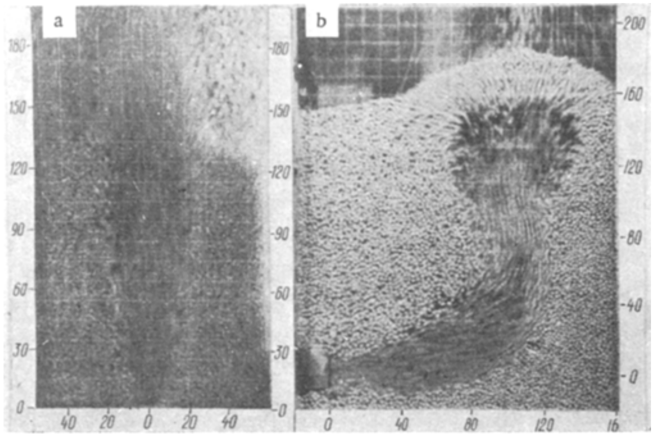

Fig. 4. Gas jet stream in fluidized bed: a) vertical jet; b) horizontal jet.

The velocity profiles of the gas in the sections of the principal region of the jet are described (Fig. 3) by symmetric dome-shaped curves and do not depend on the longitudinal pressure gradient, which is characteristic also for a drowned jet [4]. On the boundary of the jet the curve of the change of velocity passes (see Fig. 3) through the minimum when coupled with the profile of the fluidized bed. The gas velocity on the axis of the principal region of the jet decreases continuously with an increase of distance from the nozzle. In this case, on the first half of the principal region there is a marked drop of the axial velocity (to $\bar{U}_m = U_m/U_0 = 0.4$–$0.3$), after which the rate of change of velocity slows. The length of the jet is greater longitudinally than transversely, and a considerably greater velocity gradient is observed in the latter direction.

The dimensionless velocity profiles $[U/U_m = f(y/y_c)]$ and curves of the dimensionless axial velocity $[\bar{U}_m = f_1(X/X_c)]$ are affine. The universal profile of the dimensionless gas velocity in the principal region of the jet, as from Fig. 3, is satisfactorily approximated practically over the entire thickness of the boundary layer, as also in the case of a drowned jet [4], by the Schlichting equation

$$\frac{U}{U_m} = \left[1 - \left(\frac{y}{b}\right)^{1,5}\right]^2 \quad \left(\text{when} \frac{y_c}{b} = 0.44\right), \tag{8}$$

which agrees with the experimental data in [1]. Some deviations of the Schlichting profile are observed only on the boundary of the boundary layer, which indicates different values of turbulent friction in the gas and gas–solid-particles zones and consequently different laws of change of the gas velocity in the indicated zones. As shown by an analysis of the experimental data, in the gas zone the profile of the dimensionless excess velocity is approximated most satisfactorily over the entire width of the boundary layer by the equation

$$\frac{U - U_b}{U_m - U_b} = 1 - \left[1 - \left(1 - \frac{y}{b_s}\right)^{1.5}\right]^2 \quad \left(\text{when} \frac{y_b}{b_s} = 0.56\right), \tag{9}$$

and the velocity profile in the gas–solid-particles zone by an approximately linear dependence determined by graphical analysis by connecting (on the graph $U = U(b)$) by a straight line the points with coordinates (U_b, b_s) and $(\sim w_f/\varepsilon, b)$.

Thus the Schlichting profile for a jet in a fluidized bed is only a satisfactory approximation of two different laws of variation of velocity with respect to the zone of the principal region of the boundary layer. Refinement of this approximating profile on the boundary of the boundary layer does not lead, obviously, to a refinement of the solution of the problem of the kinematics of the jet performed in [1], since the contribution of the boundary zone of the profile to the total balance of momenta (to the integral relation of momenta) is immaterial.

The affinity of the velocity fields of the gas indicates in this case that the development of the jet in a fluidized bed occurs analogously to a drowned jet but in the presence of different turbulence of the flow.

The development of the horizontal jet, as shown by the experimental investigation, is analogous in character (see Figs. 3 and 4) to the development of a vertical jet, except for the velocity profile of the gas in the gas–solid-particles zone and the range as a consequence of curving of the stream. In a horizontal jet the velocity profile of the gas can be approximated roughly in the gas–solid-particles zone by a straight line passing through points with coordinates (U_b, b_s) and (0, b), and in the gas zone by Eq. (9), as likewise for the vertical jet. To determine (to within ± 10%) the range of the horizontal jet X_{hor} we obtained the following empirical equation:

$$X_{hor} = X_s/1{,}60. \qquad (10)$$

The position of the curved aerodynamic axis of the gas stream can be determined approximately by graphical analysis. For this purpose a perpendicular is erected from the end of a segment equal to the length of the horizontal region of the jet and the two mutually perpendicular straight lines formed are joined by the radius

$$r = X_{hor}/1.80. \qquad (11)$$

By analogy with the vertical jet we can take the value of the parametric criterion X_s/H_w as the characteristic of the mode of development of the horizontal jet. Then for the modes characterized above the following relations hold:

bubble mode

$$X_s/H_w < 0.8, \qquad (12)$$

jet mode

$$X_s/H_w \geqslant 0.8, \qquad (13)$$

local-spouting mode

$$0.8 \leqslant X_s/H_w \leqslant 1.15, \qquad (14)$$

$1.3 \le d_e \le 4.35$; $115 \le \rho_s \le 280$; $1.00 \le W \le 2.50$; $2U_b \le U_0 \le 310$; $2 \le d_0 \le 70$; $0.26 \le X_s/H_w \le 2.4$.

A comparison of Eqs. (14) and (3) shows that the height of the fluidized bed necessary for realization of the horizontal jet (in a local-spouting mode) is about 1.35 times less than that required for realization of vertical jet of equal initial momentum.

The character of the development of an annular jet in the principal region is determined by the laws governing the development of a circular jet flowing out into the bed with a velocity of equivalent momentum, determined by the equation

$$U_{eq} = U_{an}\sqrt{1 - \frac{d^2}{d_0^2}}. \qquad (15)$$

Thus the results of our experimental investigation confirm the automodel nature of the development of vertical and horizontal gas jets in a fluidized bed (in a jet mode) in a wide range of variation of the bed and jet parameters ($5600 \le Re_0 \le 310{,}000$; $62.3 \le Re_f \le 512$; $19.8 \cdot 10^4 \le Ar \le 313 \cdot 10^4$). The quantitative similarity between the propagation characteristics of the vertical and horizontal jets (within the gas stream) indicates that the velocity of the fluidizing agent flowing with it has a negligibly small effect on the development of the vertical jet in comparison with the effect of the airborne suspension as a whole. The discharge of the vertical and horizontal jets constitutes the same gas-jet development process in a fluidized bed as it does in a specific medium of different density.

The specificity of the medium is governed by the possibility of exchange of light fractions through the wall of the boundary surface of the stream and the presence of zones with a different intensity of quenching turbulent velocity fluctuations, which leads (when $\rho_s \gg \rho_g$) to the formation of a convergent stream and to its subsequent separation with the initiation of a bubble [1, 2]. Therefore, we consider the method of investigating the mechanism of development of a gas jet and formation and growth of a bubble in a fluidized bed on a model liquid–gas system [6] to be insufficiently founded. In these systems, for identity of end effects (formation of a bubble) the intermediate phase of its initiation and growth can be considerably different.

NOTATION

U_0, U_{an}, U_{eq}	are the initial discharge velocity of a circular, annular, and equivalent (in momentum) jet;
U, U_m	are the radial velocity in a given section and along the axis of the jet;
U_b	is the velocity at the boundary of the gas stream;
ρ_g, ρ_s	is the density of the fluidizing agent (jet) and solid particles;
y, b, b_s, y_n	are the current radius (ordinate), the half-width of boundary layer of jet and gas stream, the ordinate of the point (in the same section) at which the velocity is half that on the axis;
X, X_n, X_s, X_{hor}, X_1, Xt	are the distance along the axis from the nozzle edge to a given section of the jet (abscissa), to the point where the velocity is $U_0/2$, the maximum length of gas stream, the range of the horizontal jet, the length of initial region of jet, and the abscissa of the transitional section;
$d_0(r_0)$, d, D	are the initial diameter (radius) of the circular jet (outside diameter (radius) of annular jet and diameter (radius) of equivalent (in momentum) jets), the inside diameter of annular jet, and the diameter of apparatus;
$f_b = 1/\tau$	is the frequency of the cycles of development of the jet (initiation of bubble);
d_e	is the equivalent diameter of particles of the bed;
w_f, w_0	are the working and critical initial velocities of fluidization;
$W = w_f/w_0$,	is the fluidization number;
ε	is the average porosity of the bed;
H_w	is the working height of bed above nozzle (vertical jet) and above axis of nozzle (horizontal jet);
ν	is the kinematic viscosity of fluidizing agent (jet);
H_0	is the height of stationary bed;
$Re_0 = U_0 d_0/\nu$, $Re_f = w_f d_e/\nu$, $Ar = g d_e^3 \rho_s - \rho_g/\nu^2 \rho_g$	are the Reynolds and Archimedean numbers.

LITERATURE CITED

1. N. A. Shakhov, Doctoral Dissertation [in Russian], MIKhM, Moscow (1966).
2. N. A. Shakhova, Inzh.-Fiz. Zh. 14, No. 1 (1968).
3. G. A. Minaev and N. A. Shakhova, Trudy MIKhM, Moscow, 2, 57-60 (1968).
4. G. N. Abramovich, Theory of Turbulent Jets [in Russian], Fizmatgiz, Moscow (1960).
5. J. O. Hinze, Turbulence. An Introduction to Its Mechanism and Theory, McGraw–Hill, New York (1959).
6. Kumar Rajinder, Chem. Tech., 19, No. 2, 733-737 (1967).