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EFFECT OF A PERIPHERAL GAS SUPPLY ON THE HYDRODYNAMICS OF A SPOUTING BED

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The results of experimental investigations of the resistance of a pyramidal spouting bed with a peripheral gas supply are discussed, including the rates at the beginning and end of the process of spouting and material entrainment from an apparatus. Data is generalized in the form of dimensionless relations.

Spouting bed apparatuses are finding increasing use for carrying out many heat and mass transfer processes in heterogeneous systems, in particular, drying and heat treatment of disperse materials [1–3]. One way to enhance heat and mass transfer in a spouting bed is jet supply of a portion of a heat carrier into an almost idle peripheral zone. In [4, 5] results of investigations are presented for a spouting bed in an apparatus having the shape of a truncated rectangular pyramid in which, apart from the gas entering from below, an additional gas flux is supplied parallel to the walls of the apparatus through four holes. Compared to familiar cylindrical-conical apparatuses [1–3], this design of the apparatus makes it possible to enhance heat and mass transfer in the bed and increase the concentration of particles in the fountain and the gas flow rate through the apparatus without increasing the entrainment of the material. A more detailed description of the design can be found elsewhere [5].

The present work concerns the conditions for formation of a spouting bed in an apparatus of the indicated design and the region of stable existence of such a bed.

The state of the bed from the time of gas supply to that of massive entrainment of the material was analyzed using curves of spouting, i.e., relations describing the dependence of the pressure drop in the bed on the gas velocity in a lower cross section of the apparatus. Such a curve contains the following typical parameters: the maximum and operating pressure drops ΔP_m and ΔP_{op}; the velocity at the beginning and end of spouting V_b, V_e [1–3]. Actually, each of these parameters for a specific material depends on three factors: peripheral gas flow rate L_p; initial height of the bed H_0; ratio of the inlet section diameter for the lower gas flow to the equivalent diameter of the separation zone d_0/D. The indicated dependences for tangential supply of the lower gas flow to the bed were found by the method of experiment planning using Box's matrix with the properties of uniformity and rotatability. The geometric dimensions of the apparatus varied within the following ranges: the side of the separation zone section $a = 0.1-0.22$ m; the diameter of the lower inlet pipe branch $d_0 = 0.02-0.04$ m; the height of the pyramidal portion $h_p = 0.135-0.21$ m; the angle of inclination of the pyramid sides to the vertical $a = 22.5^o$; the total area of the nozzles for the injection of the peripheral gas flow $S = 0.7\cdot10^{-4}-6\cdot10^{-4}$ m^2. The model material used was millet. In the experiments the gas pressure was measured immediately above the inlet hole for the lower flux and somewhat above the bed of the material. The factors were varied within the following ranges: $0.0028 < L_p < 0.0222$; $0.1 < H_0 < 0.18$; $0.111 < d_0/D < 0.223$. In accordance with the well known procedure, the factors were normalized as $L_p \to X_1$, $H_0 \to X_2$, $d_0/D \to X_3$, where $1 \le X_i \le -1$, $i = 1, 2, 3$. The functions for ΔP_m, ΔP_{op}, V_b, and V_e were sought in the form of a second-order polynomial for three factors:

$$Y = A + C_1X_1X_2 + C_2X_1X_3 + C_3X_2X_3 + \sum_{i=1}^{3} (B_iX_i + D_iX_i^2) , \quad (1)$$

where Y corresponds to ΔP_m, ΔP_{op}, V_b, and V_e; A, B_i, C_i, D_i are regression coefficients, whose values are listed in Table 1.

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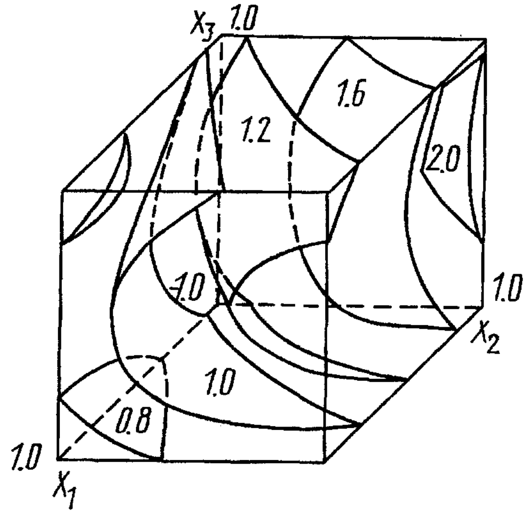
TABLE 1. Values of Regression Coefficients

Parameters	A	B_1	B_2	B_3	C_1	C_2	C_3	D_1	D_2	D_3
ΔP_m, kPa	1.36	−0.33	0.29	0.06	−0.11	0	0.05	0.12	−0.09	−0.25
ΔP_{op}, kPa	0.92	0	0.2	0.06	0	−0.02	0	−0.13	0.02	−0.07
V_b, m/sec	5.07	−3.57	1.82	−3.95	−1.98	1.77	−1.13	2.16	0	1.22
V_e, m/sec	9.73	−3.81	0	−5.44	−0.68	1.73	−0.56	3.11	0.62	0.74



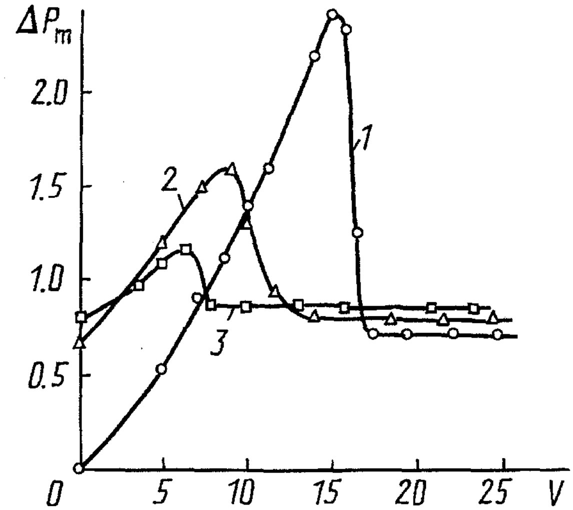


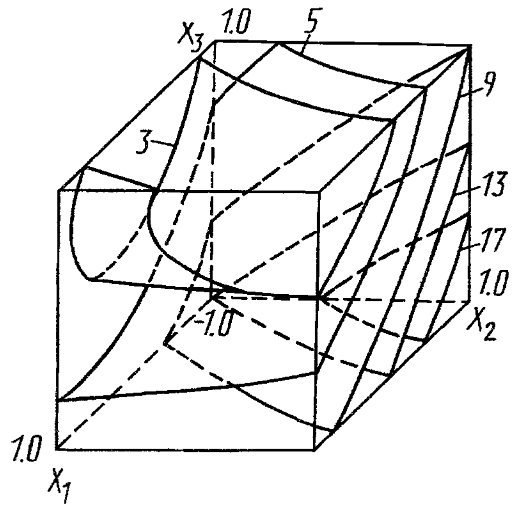
Fig. 1. Relationships for the maximum resistance of a bed. Figures at the surfaces are values of ΔP_m.

Fig. 2. Curves a spouting (azophos): H_0 = 0.13 m, d_0 = 0.03 m, a = 0.22 m, d_p = 1.74 mm, ρ = 1650 kg/m^3; 1) L_p = 0; 2) $1.67\cdot10^{-2}$ m^3/sec; 3) $2.33\cdot10^{-2}$. ΔP_m, kPa; V, m/sec.

Experimental data were processed on a computer. The significance of the coefficients was checked by the Student number. The adequacy of the resulting equations for the experiment was evaluated by the Fisher number, whose tabulated value was determined for the significance level 0.05 and the number of degrees of freedom $f_1 = mN$ and $f_2 = N - N_{sig}$, where $N = 14$ is the number of experiments; N_{sig} is the number of significant coefficients. Comparison showed that the hypothesis of the adequacy of the regression equations for the experiment is not refuted.

A set of second-order surfaces gives a fairly good idea about the character of the dependence of the parameters on controlled factors. Graphical dependences for ΔP_m are presented in Fig. 1, from which it is seen that the maximum peak of the pressure drop is observed in the absence of a peripheral gas flux, whereas with an increase in it from 0.0028 to 0.022 m^3/sec it decreases by about a factor of 2. This is due to the increase in the kinetic energy of peripheral jets, which bring about loosening and partial suspension of the bed. The most intense decrease in the pressure peak is observed up to the value $X_1 = 0.5$, which corresponds to $K = 0.65$. Thus, the energy barrier that appears when a fixed bed changes to the mode of spouting is lowered. The same effects are also typical of a bed of azophos particles in the case of unswirled supply of the lower gas flux, as is evident from the curves of Fig. 2. Another factor that, as known, exerts a substantial effect on the value of ΔP_m is the initial height of the bed, with the growth of which ΔP_m increases.

With an increase in L_p the working resistance of the bed increases somewhat due to the fluidization of a portion of the peripheral zone by the wall jets and the increase in the concentration of particles in the fountain, but with all this it remains smaller than the fluidized bed resistance $\Delta P = g(\rho - \rho_g)(1 - \varepsilon)H_0$ at the same values



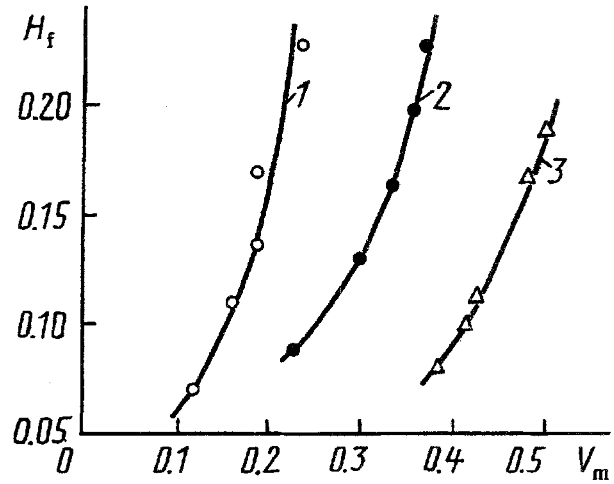


Fig. 3. Relationships for the velocity of the beginning of spouting. Figures at the surfaces are values of V_b.

Fig. 4. Dependence of the height of the fountain on the gas velocity (material: glass beads): $d_p = 1.0$ mm, $\rho = 2500$ kg/m^3; 1) $K = 0$; 2) 0.5; 3) 0.65. H_f, m; V_m, m/sec.

of H_0. It is evident that ΔP_{op} increases with an increase in H_0. The factor X_3 in the range investigated leads to an insignificant increase in ΔP_{op}. From Fig. 3 it is seen that the velocity of the beginning of spouting decreases with an increase in X_1 and X_3. An increase in the bed height leads to an increase in V_b. It is known that gas supply to a spouting bed is limited by the velocity of the end of spouting, exceeding of which causes mass entrainment of material from the apparatus. In the present case, the velocity of the end of spouting calculated in the separation zone section increases significantly. Thus, in the given apparatus it is possible to arrange a bed at a much higher (by about a factor of 2) overall gas flow rate through the apparatus compared to a conical spouting bed. It is known that the investigated parameters ΔP_m, ΔP_{op}, and V_b depend strongly on the characteristics of the particles (size, density, shape, state of the surface, etc.). Therefore, experimental data obtained with different materials were generalized (glass beads: $d_p = 1.0$ mm, $\rho = 2500$ kg/m^3, $\rho_b = 1500$ kg/m^3; miller: 1.86, 1500, 900; azophos: 1.47, 1650, 990; polyvinyl alcohol: 0.3, 1200, 300; fluoroplastic: 9.0, 2400, 1100, where d_p is the equivalent diameter of the particles; ρ is the material density; ρ_b is the bulk density of the material). In this case, the lower gas flux was supplied to the apparatus from below upward without being swirled.

Using the method of least squares, the following relations were obtained:

$$\frac{\Delta P_m}{\rho_b g H_0} = 0.33\,\mathrm{Ar}^{0.1}\left(\frac{H_0}{d_0}\right)^{0.16}(1+K)^{-0.57}, \tag{2}$$

$$\frac{\Delta P_{op}}{\rho_b g H_0} = 0.13\,\mathrm{Ar}^{0.12}\left(\frac{H_0}{d_0}\right)^{-0.02}(1+K)^{0.37}, \tag{3}$$

$$\mathrm{Re}_b = 3134\,\mathrm{Ar}^{0.17}\left(\frac{H_0}{D}\right)^{0.39}(1+K)^{-1.37}. \tag{4}$$

These equations were obtained in the following ranges of governing parameters: $\mathrm{Ar} = 1.27\cdot10^3 - 3.79\cdot10^5$; $H_0/d_0 = 2.2-8.5$; $H_0/D = 0.4-0.9$; $K = 0-0.8$. The mean standard error of the equations is equal to 14, 13, and 9%, respectively.

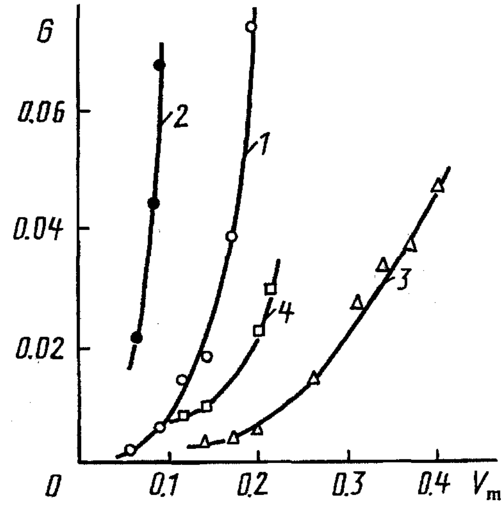


Fig. 5. Dependence of the mass rate of entrainment on the gas velocity: 1, 2) $K = 0$; 3) 0.62 (material: sand with $d_p = 0.23$ mm); 4) $K = 0.62$ (material: polyvinyl alcohol, $d_p = 0.3$ mm). The dimensions of the apparatus are the same as in Fig. 2. G, kg/(m^2·sec).

An analysis of the effect of the gas velocity in a horizontal section of the separation zone on the material entrainment from the apparatus and the height of the fountain (Figs. 4 and 5) showed that with increase in the peripheral gas flux the height of the fountain and the mass rate of entrainment decrease substantially due to equalization of the horizontal gas velocity profile. The height of the fountain is understood to be the distance of the formation of a compacted "cap" of the fountain above the bed surface. Taking into account the fact that during a number of heat and mass transfer processes their rate is limited by the amount of heat supplied, an increase of the gas phase in the spouted bed is very important. Moreover, a decrease in the entrainment of material from the apparatus reduces the load on the dust-capturing equipment.

NOTATION

d_p, diameter of the particles, m; g, free fall acceleration, m/sec^2; G, rate of material entrainment from the apparatus, kg(m^2·sec); H_0, initial height of the bed, m; H_f, height of the fountain above the bed surface, m; K, ratio between the peripheral gas flow rate and the total gas flow rate through the apparatus; L_p, total flow rate of the peripheral gas flow, m^3/sec; V_m, mean gas velocity in a horizontal section of the separation zone, m/sec; ε, bed porosity; ρ and ρ_b, actual and bulk density of the material, respectively, kg/m^3; ρ_g, gas density, kg/m^3; $\mathrm{Ar} = gd_p^3/\nu^2 \cdot (\rho - \rho_g)/\rho_g$; $\mathrm{Re}_b = d_0 V_b/\nu$.

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