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HYDRODYNAMIC CHARACTERISTICS OF MAGNETICALLY FLUIDIZED BEDS CONSISTING OF A MIXTURE OF MAGNETIC AND NONMAGNETIC MATERIALS

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The velocity of the beginning of fluidization and the porosity of a bed were investigated for a mixture of cast-iron ($\bar{d}_p$ = 1.086 mm) and copper ($\bar{d}_p$ = 1.086 mm) particles fluidized in a homogeneous external magnetic field of an intensity of up to 5662 A/m. By analyzing the forces that act on the magnetic particles the authors obtained an expression for calculating U_{mb} in a bed consisting of a mixture of magnetic and nonmagnetic particles. The calculation results are compared with the experimental data.

It is well seen from a number of reviews (for example, [1, 2]) that reactors with magnetically fluidized beds have widespread and diverse applications. Unfortunately, the characteristics of these reactors have not been sufficiently studied, and to predict their design and operating parameters, both theoretical knowledge and experimental verification are required. The need to obtain reliable correlations to calculate the characteristic parameters is confirmed by daily practice. This investigation concerns the hydrodynamics of the bed and, in particular, has as its aim to determine experimentally and to analyze theoretically the velocity of the beginning of the bubble formation U_{mb} and the porosity of the bed m. These characteristics were measured rather thoroughly, which made it possible to perform the corresponding evaluation of analytical models proposed for their calculations.

Reliable knowledge of the values of U_{mb} is necessary for the operation of magnetically fluidized beds since their values establish the upper limit of the regime of a magnetically fluiduized bed. In [3], a semiempirical expression for the calculation of U_{mb} was proposed that is verified below based on the experimental data we obtained for a bed of a mixture of magnetic and nonmagnetic particles. In [4], when the balance of forces acting on the magnetic particle in the bed was considered, an equation was derived for the determination of U_{mb} in a magnetically fluidized bed of magnetic particles, which is also verified in this work for the correlation of experimental data that characterize a mixture of magnetic and nonmagnetic particles.

Experimental Investigations. The setup that was used to conduct the experiments is described in detail in [2]. Its main portion is a column with a fluidized bed (D_{ins} = 102 mm), the damping section's height of which is 0.21 m, whereas the height of the fluidized bed and of the superbed space is 3.5 m. A compressor system ensures the feed of filtered dry air with a maximum productivity of 8.5 m^3/min at 700 kPa and 311 K. A Helmholtz electromagnet made up of two coils with inside and outside diameters of 0.358 and 0.568 m, respectively, placed at a distance of 0.171 m from each other and designed to work at maximum voltages of 60 V and maximum currents of 15 A, creates in the bed a uniform constant magnetic field with an intensity of 27,137 A/m. The latter was measured with a self-calibrating gaussmeter with an accuracy of 0.5% of the complete scale that was connected to a perpendicular-type Hall sensor 15.24 mm in diameter and 58 mm in length. The check of the uniformity of the magnetic field yielded the following results: the deviations (mainly in the region adjacent to the wall of the column) did not exceed 1% horizontally and 5% vertically of the established magnitude.

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TABLE 1. Properties of the Particles of the Bed

Material	ρ_s	$\bar{d}_p$	μ_M	χ	Ar
Copper particles	8890	1.086	–	–	410,966
Cast-iron particles	7830	1.086	$1.884 \cdot 10^{-3}$	1500	361,965

TABLE 2. Comparison of the Experimental and Calculated Values of U_{mb}

Characteristics	H				
	0	1865	2598	4048	5662
U_{mb}, experiment	1.15	1.22	1.30	1.42	1.66
Re_{mb}, experiment	83.0	88.0	93.8	103	120
U_{mb}, calculation by (4)	–	1.25	1.30	1.41	1.55
Re_{mb}, calculation by (1)	–	90.2	93.8	102	112
U_{mb}, calculation by (14)	–	1.22	1.37	1.49	1.66
Re_{mb}, calculation by (1)	–	88.0	98.5	107	120
U_{mb}, calculation by (16)	–	1.53	1.80	2.01	2.16
Re_{mb}, calculation by (1)	–	110	130	145	156

The bed consisted of a mixture of cast-iron and copper shots in an equal mass proportion; each component had an average diameter of 1.086 mm and was a rather narrow fraction within 1.00–1.18 mm. The column was manufactured of acrylic plastic 12.5 mm thick, the inside diameter was 102 mm, and the height of the nonblown dense bed was 87 mm. The velocity U_{mb} was determined from the reverse fluidization curve ($\Delta P = f(U)$), i.e., when the gas-filtration rate decreased after the state of developed fluidization had been reached. The magnetic field intensity H varied from 0 to 5662 A/m, and the velocity U_{mb} was determined for five values of H, including the zero one, when $U_{mb} = U_{mf}$. The values of the porosity m were found by measuring ΔP of the section of the bed located between marks 6 and 66 mm over the grid as the gas-filtration rate increased and decreased. The values of m were also determined by measuring the height of the bed, and these values were compared with those obtained using ΔP-measurements for increasing and decreasing rates of gas filtration.

The characteristics of the cast-iron and copper particles are presented in Table 1. The experimental values of U_{mb} are given in Table 2 along with the corresponding values of Re_{mb}, calculated by the relation

$$Re_{mb} = \frac{U_{mb} \bar{d}_p \rho_f}{\mu_f} . \qquad (1)$$

The procedure of determining U_{mb} is described in [5]. The experimental values of U_{mf} do not depend on H and are constant for this bed and equal to 1.15 ± 0.01 m/sec. The values of U_{mb} increase simultaneously with H. The measurements of the pressure drop (ΔP_L) in the above two points (6 and 66 mm) with increase and decrease in the filtration rate U were used to determine the average values of porosity by the expression

$$m = 1 - \frac{\Delta P_L}{Lg (\rho_s - \rho_f)} , \qquad (2)$$

where ρ for a mixture of particles was calculated as

$$\rho_s = \left[\frac{X_{mass}}{\rho_M} + \frac{1 - X_{mass}}{\rho_N} \right]^{-1} . \qquad (3)$$

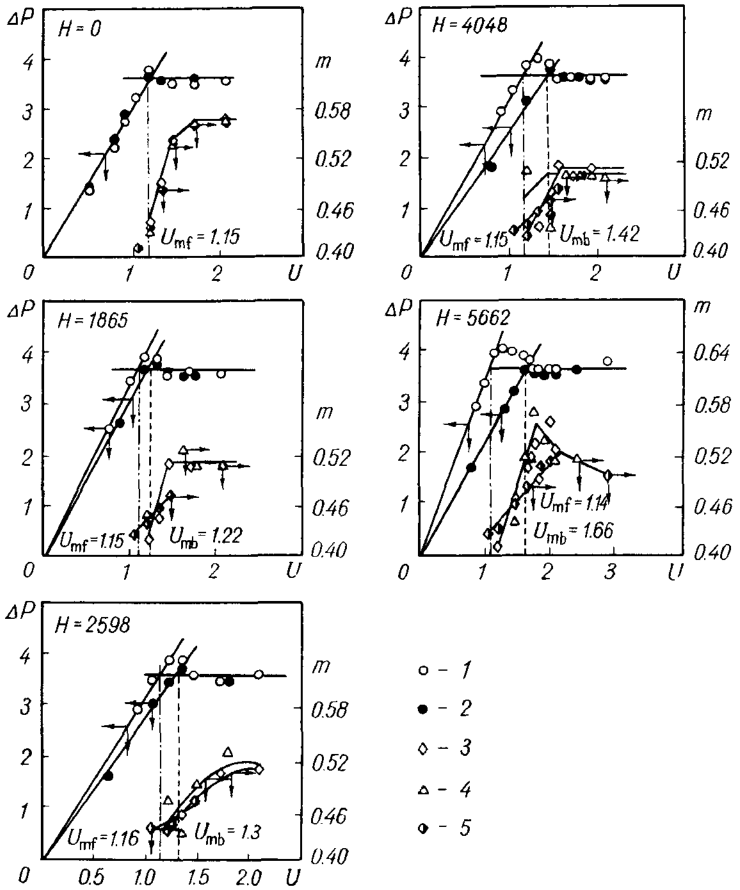

Fig. 1. Dependence of ΔP on U and H: 1) direct run; 2) reverse run; 3) from the measurements of ΔP with increase in U; 4) same with decrease in U; 5) from the measurements of L. ΔP, kPa; U, m/sec; H, A/m.

The values of m obtained are also presented in Fig. 1. Measurements of the bed height made it possible to find m, as U changed, by using the formula

$$M = AL_b (1 - m) \rho_s . \tag{4}$$

The values of m obtained from (2) and (4) are in agreement at $H = 0$ (see the figure). The values of m, determined using the data on ΔP as a function of U, were always higher with its decrease than with its increase, since when the air-filtration rate decreased the magnetic particles retained (to a certain extent) their structure formed at higher values of U. As U increased, the values of m calculated by formula (4) were greater than those obtained by formula (2) in the region of the magnetically stabilized bed ($U > U_{mb}$). This is explained to a great extent by possible errors in the measurement of the bed's height that result from the fact that in the magnetically stabilized region, as the bed expands, the particles predominantly move upward in the wall zone, creating, as it were, a concave surface at the upper base, which hinders the determination of the true height.

Processing, Discussion, and Generalization of the Experimental Results. In [3], it is proposed to determine U_{mb} using the following expression:

$$U_{mb} = U_{mf} + 0.0015 (\nu/\bar{d}_p) \, \mathrm{Ar}^{0.81} E_R^{0.59} , \tag{5}$$

where

$$\bar{d}_{\mathrm{p}} = \left[(X_{\mathrm{mass}}/\bar{d}_{\mathrm{pM}}) + \left\{(1 - X_{\mathrm{mass}})/\bar{d}_{\mathrm{pN}}\right\}\right]^{-1} \tag{6}$$

and

$$\mathrm{Ar} = g\bar{d}_{\mathrm{p}}^{3}\,(\rho_{\mathrm{s}} - \rho_{\mathrm{f}})/\rho_{\mathrm{f}}\nu^{2}\,. \tag{7}$$

The average diameter of the particles in the bed of magnetic and nonmagnetic materials can be calculated from the relation

$$\bar{d}_{\mathrm{p}} = 1/\Sigma\,(X_i/\bar{d}_{\mathrm{p}i})\,. \tag{8}$$

The dimensionless quantity E_{R}, which is the ratio of the density of the potential magnetic energy of the bed to the density of the potential gravitational energy of the particle, is determined by the formula

$$E_{\mathrm{R}} = (3/2)\,\mu_{\mathrm{b}}H^{2}/g\bar{d}_{\mathrm{pM}}\,\rho_{\mathrm{M}}\,, \tag{9}$$

where

$$\mu_{\mathrm{b}} = m\mu_0 + (1 - m)\,\mu_0 \exp(0.03\mu_{\mathrm{M}}\,HX_{\mathrm{mass}})\,. \tag{10}$$

The values of U_{mb} obtained from expression (5) using (3) and (6)-(10) are given in Table 2 and, as is seen, agree well with the experimental data.

The authors [4] suggest that the induced dipole moments in the bed of magnetic particles caused by an external magnetic field with intensity H create around themselves nonuniform magnetic fields of a substantial, at least at high H, magnitude. Apart from the action of the resultant magnetic field, the particles also experience the forces of magnetic interaction with each other. Thus, when making up a balance of forces acting on the magnetic particle in the bed, apart from the gravitational, lift, and frictional forces, forces caused by an external magnetic field must also be taken into account. Considering that at a rate of gas filtration equal to U_{mb} to the resultant force must be equal to 0, the authors [4] obtained the relation

$$\mathrm{Re}_{\mathrm{mb}}^{2} + 85.71\,(1 - m_{\mathrm{mb}})\,\mathrm{Re}_{\mathrm{mb}} - \mathrm{Ar}\,(m_{\mathrm{mb}}^{3}/1.75)\,(1 - E_{\mathrm{M}}) = 0\,, \tag{11}$$

where

$$E_{\mathrm{M}} = 4kE_{\mathrm{rp}}\,[1 + 4.80\,(k_1/k)\,\chi\,(1 - m_{\mathrm{mb}})^{2/3}] \tag{12}$$

and

$$E_{\mathrm{rp}} = 3\mu_0 MH/2g\bar{d}_{\mathrm{pM}}\,\rho_{\mathrm{M}}\,. \tag{13}$$

From the point of view of the physical meaning, E_{rp} is a ratio of the density of the potential magnetic energy of the particle to the density of its potential gravitational energy. The solution to Eq. (11) is the expression

$$\mathrm{Re}_{\mathrm{mb}} = 42.86\,(1 - m_{\mathrm{mb}})\left\{[1 + 0.000311m_{\mathrm{mb}}^{3}\,\mathrm{Ar}\,(1 - m_{\mathrm{mb}})^{-2}\,(1 - E_{\mathrm{M}})]^{1/2} - 1\right\}. \tag{14}$$

The constants k and k_1 can be determined experimentally if U_{mb} is known at two values of H. In [4] it is showed that these constants do not depend on the size of the particles, and good agreement of the calculated (using expression (14)) and experimental values is demonstrated on six series of data on fluidization of iron shot with average diameters in the range of 0.262–1.416 mm that belong to four groups of researchers.

The case of magnetic fluidization of mixtures of magnetic and nonmagnetic materials appears to be more complicated. At the same time, assuming that the nonmagnetic particles in this case can be considered as additional porosity, i.e., by replacing m_{mb} in (12) with the seemingly effective porosity m'_{mb} determined as

$$m'_{\mathrm{mb}} = (1 - m_{\mathrm{mb}})\,(1 - X_{\mathrm{V}}) + m_{\mathrm{mb}}\,, \tag{15}$$

one can obtain E_{M}, and then $\mathrm{Re}_{\mathrm{mb}}$, too, from (14).

The verification of the legitimacy of this approach was carried out experimentally.

The constants k and k_1 were found using experimentally obtained values of U_{mb}, corresponding to H, equal to 1.865 and 5.662 A/m. Their values $k = -0.0046$ and $k_1 = 1.645 \cdot 10^{-6}$ then served to obtain the calculated values of U_{mb} presented in Table 2 that were compared with the experimental data. As is seen from the table, the agreement is satisfactory.

The importance of taking into account the forces of magnetic interaction when calculating U_{mb} of fluidized mixtures of magnetic and nonmagnetic particles is also confirmed by the fact that without such an account the disagreements between the experimental values and the values calculated by the Ergun equation

$$\mathrm{Re}_{\mathrm{mb}} = 42.86\,(1 - m_{\mathrm{mb}}) \left\{ [1 + 0.000311 m_{\mathrm{mb}}^3\,\mathrm{Ar}\,(1 - m_{\mathrm{mb}})^{-2}]^{1/2} - 1 \right\}, \tag{16}$$

where m_{mb} is the experimental values, turned out to be within 25–42%, i.e., above the possible error in the experiments (Table 2).

NOTATION

A, cross-sectional area of the bed, m^2; Ar, Archimedes number; $\bar{d}_{\mathrm{p}}$, average diameter of the particles, m; $\bar{d}_{\mathrm{p}i}$, average diameter of the particles remaining between two sieves of neighboring numbers, m; $\bar{d}_{\mathrm{pM}}$, average diameter of the magnetic particles, m; $\bar{d}_{\mathrm{pN}}$, average diameter of the nonmagnetic particles, m; E, dimensionless quantity determined by relation (12); E_{R}, dimensionless number that determined the ratio of the potential-energy densities (9); E_{rp}, dimensionless ratio of the densities of potential energy of the particle (13); g, gravitational acceleration, m/sec^2; H, magnetic-field intensity, A/m; k and k_1, dimensionless constants; L_{b}, height of the bed; M, mass of the particle layer, kg; $\mathrm{Re}_{\mathrm{mb}}$, Reynolds number at $U = U_{\mathrm{mb}}$; U, filtration rate of the gas, m/sec; U_{mb}, velocity of the beginning of bubble formation, m/sec; U_{mf}, velocity of the beginning of fluidization, m/sec; X_i, dimensional mass fraction of the fractional size $d_{\mathrm{p}i}$; X_{mass}, dimensionless mass fraction of the magnetic particles in the bed; X_V, dimensionless volume fraction of the magnetic particles in the bed; ΔP, pressure difference in the bed, N/m^2; ΔP_L, pressure difference in the section of the bed of height L, N/m^2; m, dimensionless porosity of the bed; m_{mb}, dimensionless porosity of the bed at U_{mb}; m'_{mb}, dimensionless effective porosity of the bed, Eq. (15); μ_{b}, magnetic permeability of the bed, N/m; μ_{f}, viscosity, N·sec/m^2; μ_{M}, magnetic permeability of the material of magnetic particles, N/m; μ_0, magnetic permeability of the vacuum, N/m; ν, kinematic viscosity of the gas, m^2/sec; ρ_{f}, density of the gas, kg/m^3; ρ_{M}, density of the magnetic particles, kg/m^3; ρ_{N}, density of the nonmagnetic particles, kg/m^3; ρ_{s}, density of the solid phase, kg/m^3; χ, dimensionless magnetic susceptibility. Subscripts: p, particle; pi, ith particle; pM, magnetic particle; pN, nonmagnetic particle; R, rp, energy ratio of the particle; b, bed; mb, beginning of bubble formation; mf, beginning of fluidization; mass, mass; V, volume; L, height difference; f, gaseous phase; s, solid phase; 0, referring to vacuum.

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