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The Effect of Interparticle Forces on Fluidization Regimes in the Magnetized Fluidized Beds

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Abstract−This paper investigated the influence of interparticle forces on the quality of fluidization in a magnetically stabilized fluidized bed (MSFB), where we can "artificially" create interparticle forces (F_{attr}) of any magnitude by applying an external magnetic field to ferromagnetic particles. A theoretical model was proposed which predicts the transition point from a homogeneous to a heterogeneous fluidization as a function of the magnitude of the interparticle force and other physical characteristics of both particles and fluids that are usually observed in fluidization (ρ_p, ρ_f, μ, d_p, ε). The concept of the elastic wave velocity, U_e, and the continuity wave velocity, U_ε, was introduced. In particular, the interparticle force manipulated by an externally applied magnetic field was taken into account in addition to a general consideration of a conventional fluidized bed. Bubbles form in a bed when the continuity wave velocity becomes faster than the elastic wave velocity. The simulation demonstrated the proposed model could predict the transition point of fluidization regime with reasonable accuracy.

Key words : Fluidization, Elastic and Continuity Wave Velocities, Magnetization of Particles

INTRODUCTION

Interparticle force plays an important role in fluidization of very small particles. When interparticle forces are of the same order of magnitude as other forces involved in fluidization of solids, such as gravity, drag, and buoyancy forces, one often encounters difficulties which are qualitatively described as poor fluidizability. According to the Geldart's classification of powders, a solid particle belonging to the group C is classified as a nonfluidizable particle. There is a genuine need to study the role of interparticle forces and to be able to predict more accurately the quality of fluidization (fluidizability) of fine powders.

More effective and economic fluidization can be achieved by using smaller sized particles in many fluidized bed applications. Good fluidization, unfortunately, may not be achieved if the particle size is smaller than a specific diameter. Based on previous works [Ciborowski and Wlodarski, 1962; Baerns, 1966; Donsi' and Massimilla, 1973; Donsi' et al., 1975; Rietema, 1973; Rietema and Piepers, 1990; Massimilla and Donsi', 1976; Geldart and Abrahamsen, 1978; Molerus, 1982; Overbeek, 1984; Seville and Clift, 1984; Jaraiz et al., 1992], the relative magnitude of interparticle forces, i.e., capillary forces, van der Waals forces, and electrostatic forces, becomes dominant compared to the magnitude of the gravitational force of a single particle as particle size decreases. As a result, a bed falls into channeling or channeling and bubbling rather than being homogeneously fluidized.

We acknowledge that the interparticle force itself and its effect on fluidizability must be studied in more detail. In order to accomplish this task we create 'artificial' interparticle forces by applying a magnetic field into a bed. The magnetization of particles produces attraction forces among particles. This force can be adjusted easily by controlling the magnetic field intensity. Therefore, one can characterize the fluidization mode based on the magnitude of the generated interparticle force.

DEVELOPMENT OF THEORETICAL MODEL

1. Interparticle Force Existing between Particles in the Magnetically Fluidized Bed

The magnetization of ferri- and ferro-magnetic particles is much greater than the magnetization of para- and dia-magnetic materials. Because of this magnetic property, ferri- and ferromagnetic materials have a number of industrial applications. The magnetization hysteresis curve of ferromagnetic particles is a good example to characterize the magnetization of these materials with regard to the applied magnetic field. The explanation of these magnetic properties can be found easily in many references [Chen, 1977; Barrett and Tetelman, 1973; Griffiths, 1981; Stanley and Gabriel, 1982].

Magnetized particles behave like magnetic dipoles. We assumed that the intensity of an induced magnetic field, **B**, is uniform throughout a bed. Since particle size, shape, and material are the same, the magnetic dipole moment of each particle was considered to be same. The potential energy acting between two magnetic dipoles was defined as $-\mathbf{mB}$. When there are two magnetic dipoles they interact with each other due to a magnetic field. The magnetic field intensity exerted on one dipole by the other depends on the distance between them. Fig.

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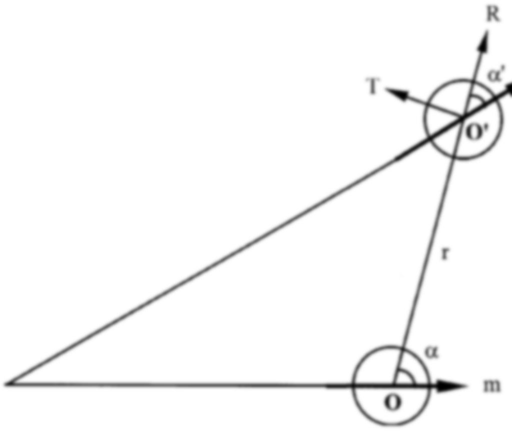

Fig. 1. Interacting force between two magnetic dipoles of moments m and m'.

1 illustrates the configuration of two dipoles having different magnetic polar axes at a constant induction of magnetic field.

The magnetic field intensity generated by a magnetic dipole of moment **m** at a point apart from O by r is

$$\mathbf{B}=\frac{\mu_0}{4\pi}\left(\frac{3\mathbf{m}\cdot\mathbf{r}}{r^5}\mathbf{r}-\frac{\mathbf{m}}{r^3}\right) \tag{1}$$

Therefore, the potential energy, M, of magnetic dipole of moment **m'** is :

$$M=-\mathbf{m}'\cdot\mathbf{B}=\frac{\mu_0}{4\pi}\left(\frac{1}{r^3}\mathbf{m}\cdot\mathbf{m}'-\frac{3}{r^5}\mathbf{m}\cdot\mathbf{r}\mathbf{m}'\cdot\mathbf{r}\right)$$

$$=\frac{\mu_0\mathbf{m}\mathbf{m}'}{4\pi}(\sin\alpha\sin\alpha'-2\cos\alpha\cos\alpha') \tag{2}$$

The interacting force between two dipoles can be obtained by differentiating the obtained potential energy with repect to the distance between two dipoles, r.

$$F_{attr}=\frac{\partial M}{\partial r}=-\frac{3\mu_0\mathbf{m}\mathbf{m}'}{4\pi r^4}(\sin\alpha\sin\alpha'-2\cos\alpha\cos\alpha') \tag{3}$$

The distance between two dipoles can be formulated as a function of the bed porosity. We considered that μ_0, **m**, and **m'** were constant under the constant magnetic field intensity.

2. Model of the Deformation Velocity in a Magnetically Stabilized Bed (MSB)

It is well known that the incipient fluidization of an MSFB does not show any difference from a conventional fluidized bed with the increase of fluidization velocity. However, there is a difference when fluid velocity is decreasing from the bubbling point. In an MSFB, the pressure drop starts decreasing at a fluid velocity higher than the minimum fluidization velocity. The hysteresis of pressure drop curve has been observed by several investigators [Siegell, 1988; Saxena and Shrivastava, 1990; Casal et al., 1991; Cohen and Chi, 1991; Chetty et al., 1991].

Under the influence of a constant magnetic field, the arrangement of particles becomes pretty much chain-like because of the magnetization of particles. The order of the rearrangement of magnetized particles gets higher during fluidization and defluidization. Casal et al. [1984] observed that the height of the bed changed while their bed was fluidized and defluidized from zero velocity to the bubbling velocity. They finally obtained the maximum reordering of particles under a constant magnetic field. Under this condition, particle movement was strictly restricted and the bed behaved like a fixed bed. All of particles were aligning themselves along magnetic field lines. We defined a bed under this situation as a magnetically stabilized bed (MSB). The characteristics of an MSB compared with a conventional fluidized bed and a fixed bed are categorized in Table 1. The agglomeration of particles in an MSB can be a good example for understanding the behavior of Geldart's class C particles. The strength of the magnetic attraction forces depends on the particle array together with the distance between particles, whereas the interparticle forces of class C particles depend on the distance only. These differences have to be reflected in the investigation of the interparticle force whether an MSFB or a conventional fluidized bed is studied. The magnetic attraction force acts as an additional factor which has to be overcome by drag force in order to achieve fluidization of a bed. A more appreciable and accurate model is required to explain these behaviors. No appropriate model, however, has been developed yet. Therefore, we proposed a theoretical model to explain the effect of magnetic interparticle force on fluidization quality in an MSFB.

Table 1. Physical features of gas-solid contacting systems [Lucchesi et al., 1979]

Characteristics	Bubbling fluid bed	Stable fluid bed	Fixed bed
Constant Pressure vs. Flow Rate	Yes	Yes	No
Constant Pressure vs. Particle Size	Yes	Yes	No
Continuous Solid Throughout	Yet	Yes	No
Gas Bypassing Prevented	No	Yes	Yes
Attrition Prevented	No	Yes	Yes
Solids Backmixing Prevented	No	Yes	Yes
Traps Particles at Low ΔP	No	Yes	Yes

Particles filled in an MSFB were assumed to be uniform-sized and spherical. The wall effect was considered to be negligible since the ratio of the diameter of a particle to the diameter of a bed was small enough. The whole volume of particles remained constant. We assumed that the applied magnetic field intensity was uniform throughout the bed. Magnetization should be kept lower than the saturation magnetization of the particles. The arrangement of particles was considered to be the same shape throughout the bed. We assumed that the arrangement of particles in an MSB could be fitted in a cubical geometry. A single cube consists of one body-centered particle and eight particles on the corners of the cube. The particle arrangement in an MSB is illustrated in Fig. 2. The cubical arrangement of particles in a conventional fluidized bed has been a reasonable assumption in previous works [Zenz and Othmer, 1960; Foscolo et al., 1985].

While the fluid velocity increases in an MSB, the particles will remain stationary. The drag force produced by the fluid has to overcome both the weight of a particle and the magnetic interparticle force which keeps the particle from moving away. As soon as the drag force overcomes both the gra-

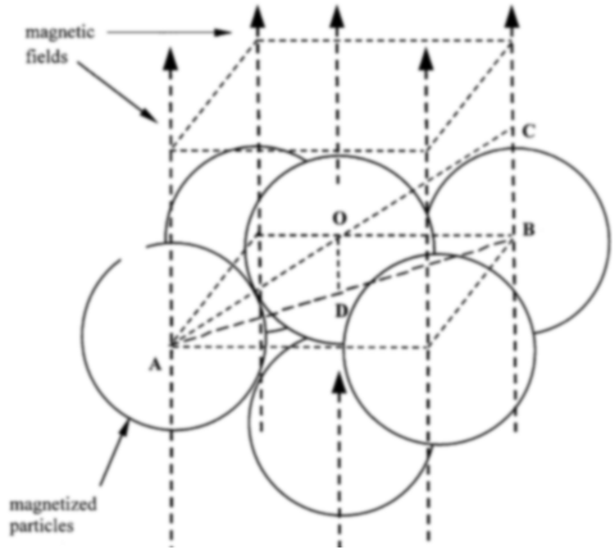

Fig. 2. Configuration of particles in a stabilized bed.

vitational force of a particle and the magnetic interparticle force all together the bed will be fluidized.

The main force between particles in an MSFB acts in the vertical direction. This characteristic of magnetic attraction force contributes to the formation of chain-like arrangement of particles. Therefore, we can depict the magnetic interparticle forces as elastic strings interlinking particles with certain elasticity. The strength of the elasticity is inversely proportional to the distance between particles. If the drag force increases to overcome this elastic force together with the effective weight of the particle, the particle agglomerate will be deformed by taking particles away from the agglomerate. It is important to understand the fact that the attraction force has zero-sum effect on an individual particle. In other words, a particle is attracted upward and downward simultaneously by particles placed above and below. The strengths of these attraction forces acting on a particle are equivalent since particles are equally magnetized. Therefore, the net magnetic forces which pull a particle downward and upward have a null effect. This equilibrium condition is valid for all particles in an MSB except particles on the top layer of the bed. Particles on the top layer do not have any particles sitting above them; therefore, these particles have a magnetic attraction force which pulls them downward only. In order to fluidize these particles, i.e. to detach them from the agglomerate, the drag force should be the same as the sum of the effective weight of a particle itself and the magnetic interparticle force which keeps the particle from moving away. The fluidization velocity which causes the detachment of particles of the top layer of the bed is termed as a deformation velocity of an MSB. As soon as particles on the top of the agglomerate are detached the resultant effect will be immediately transferred to particles lower layer. We can consider, therefore, that the separation of particles eventually occurs at the same time. Accordingly, the magnetic interparticle forces may be considered as an implicit force which seemingly pulls particles down.

When the pressure drop becomes equivalent to the weight of a bed but the bed is still not homogeneously fluidized, this

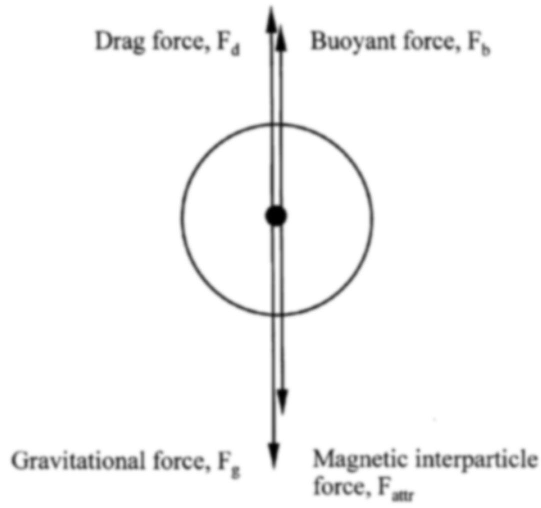

Fig. 3. Force balance acting around a single particle.

implies that the magnetic interparticle forces are so strong that the whole bed may be levitated through the bed column at higher fluidization velocity [Kirko and Filippv, 1960; Filippov, 1960; Katz and Sears, 1969; Rosensweig, 1979a, b; Siegell, 1982, 1987, 1988; Saxena and Shrivastava, 1990, 1991].

For the incipient bed expansion in an MSB, the force balance around a single particle including magnetic interparticle force is illustrated in Fig. 3. The force balance can be formulated as follows:

$$\begin{bmatrix}\text{Drag}\\ \text{Force}\end{bmatrix}+\begin{bmatrix}\text{Buoyant}\\ \text{Force}\end{bmatrix}=\begin{bmatrix}\text{Magnetic}\\ \text{Interparticular}\\ \text{Force}\end{bmatrix}+\begin{bmatrix}\text{Gravitational}\\ \text{Force}\end{bmatrix} \tag{4}$$

Based on Eq. (4), we can determine the interparticle force acting on a single particle just measuring fluidization velocity and bed porosity at the incipient fluidization, which is the deformation point. The fluidization velocity at the deformation point is defined as a deformation velocity.

The total rate of energy dissipation can be expressed in terms of the overall pressure drop and the total drag force on particles. This relation is given:

$$\Delta P = F_D/A \tag{5}$$

The drag force acting around a single particle is:

$$F_d=\frac{F_D}{N}=\frac{\pi d_p^3 A\Delta P}{6V_p} \tag{6}$$

To obtain the drag force required for detaching particles from the top layer of the bed, the Ergun equation that fits well throughout whole flow regimes can be applied.

$$\Delta P=\frac{\rho_f U_s^2 h}{d_p}\frac{1-\varepsilon}{\varepsilon^3}\left(150\frac{1-\varepsilon}{d_p\rho_f U_s/\mu}+1.75\right) \tag{7}$$

Substituting Eq. (7) into Eq. (6) yields the final expression for the drag force acting on a single particle applicable for the initial stage of the bed expansion:

$$F_d=\frac{\pi d_p^2\rho_f U_s^2}{6\varepsilon^3}\left(150\frac{1-\varepsilon}{d_p\rho_f U_s/\mu}+1.75\right) \tag{8}$$

The effective weight of particle, F_e, proposed by Foscolo and Gibilaro [1984] is commonly expressed as follows :

$$F_e=\frac{\pi d_p^3}{6}(\rho_p-\rho_f)g\varepsilon \quad (9)$$

The interparticle forces acting on a particle, F_{attr}, can be obtained from the difference between the drag force exerted on a particle of the top layer of the bed and the effective weight of particles.

$$F_{attr}=F_d-F_e \quad (10)$$

When Eq. (8) and Eq. (9) are substituted into Eq. (10) the interparticle force becomes

$$F_{attr}=\frac{\pi d_p^2\rho_f U_d^2}{6\varepsilon^3}\left(150\frac{1-\varepsilon}{d_p\rho_f U_d/\mu}+1.75\right)-\frac{\pi d_p^3}{6}(\rho_p-\rho_f)g\varepsilon \quad (11)$$

The deformation velocity, U_d, is explicitly embedded in Eq. (11) in a quadratic form.

3. Model to Predict the Transition Point from a Homogeneous to a Heterogeneous Fluidization Regime

One of the main purposes of this study is to develop an explicit model to predict the transition point from a homogeneous to a heterogeneous fluidization in an MSFB. A flowing substance becomes unstable when the continuity wave velocity surpasses the elastic wave velocity [Wallis, 1969]. The unstability of a flowing medium commonly indicates a bubble formation in a fluidized bed. This criterion has been applied to predict bubbling points in conventional fluidized beds. However, interparticle forces have been usually neglected. Few works have been done on MSFBs where interparticle forces become dominant. Only Foscolo et al. [1985] included the interparticle forces in their modified model for the prediction of a transition point in MSFBs.

The strength of magnetic interparticle forces drastically decreases in an expanded bed operating in a particulate regime. The expansion of the bed can be directly interpreted as the increase of distance between particles. The extension of the distance between particles will result in a decrease of the interparticle force and a decrease of the elastic wave velocity simultaneously.

If the fluidization velocity increases over the deformation velocity, a bed will be transformed from stabilized condition into an aggregate fluidization through a particulate fluidization. Now, the transition point is defined as a condition where the fluidization of an MSFB transforms from a homogeneous to a heterogeneous fluidization. An MSFB transformed to a homogeneous or heterogeneous fluidization mode is defined as a magnetically fluidized bed (MFB). The occurrence of the transition point varies with the magnetic field intensity. If the magnetic field intensity increases, the interparticle force will become stronger. Therefore, the increase of the interparticle force affects the fluidization of a bed and increases the elastic wave velocity at the same time. The increase of the elastic wave velocity contributes to the improvement of the stability of fluidization. Hence, we will consider that the stability of fluidization can be improved by 'artificially' created interparticle force.

We assumed that particles in an MFB are uniformly fluidized and the configuration of particles is a cubical arrangement shown in Fig. 4. Let the line segment AO be the distance between the centered particle within the cube and a particle located on a corner of the cube. Letting BC be the length of one side of the cube, λ, gives us the length between point A and C in terms of λ. The distance between the centered particle and particles located on the corner of the cube is :

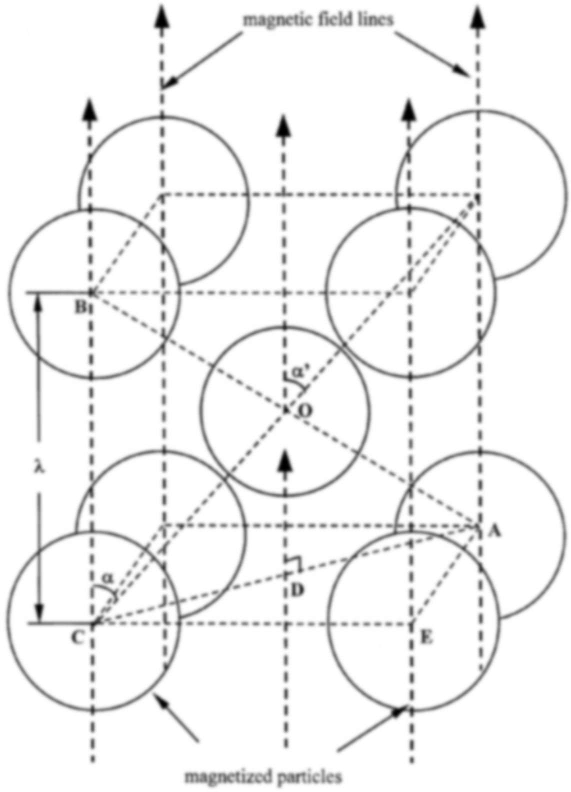

Fig. 4. Configuration of particles in a particulate fluidization regime.

$$AO=\frac{\lambda\sqrt{3}}{2} \quad (12)$$

The total volume of particles included in a cube is equivalent to the volume of two particles. If we assume that the whole bed consists of the combination of these cubes, the bed porosity can be represented with the porosity of a single cube.

$$\varepsilon=1-\frac{\text{total volume of particles within cube}}{\text{single cube volume}}=1-\frac{\pi d_p^3}{3\lambda^3}$$

The length of each edge of the cube, λ, is :

$$\lambda=\sqrt[3]{\frac{\pi d_p^3}{3(1-\varepsilon)}} \quad (13)$$

The distance between the centered particle and a particle on a corner of the cube, r_d, is

$$r_d=\frac{\lambda}{2\sin(90-\alpha)}=0.87\sqrt[3]{\frac{\pi d_p^3}{3(1-\varepsilon)}} \quad (14)$$

The distance between the body-centered particle and a particle on the same vertical axis as the body-centered particle, r_s, is

$$r_s=\lambda=\sqrt[3]{\frac{\pi d_p^3}{3(1-\varepsilon)}} \quad (15)$$

The total interparticle forces acting on the body-centered particle in an MFB can be obtained as follows :

$$F_{attr}=\frac{3\ \mu_0 \mathbf{mm'}}{2\pi}\left(\frac{2}{r_d^4}+\frac{1}{r_s^4}\right)$$
$$=2.017\frac{\mu_0 \mathbf{mm'}}{d_p^4}(1-\varepsilon)^{4/3} \quad (16)$$

The continuity wave velocity in a flowing medium has been studied by several researchers [Slis et al., 1959; Wallis et al., 1969; Massey et al., 1979]. Slis et al. [1959] developed a model of the continuity wave velocity by considering the step change of the fluidizing velocity in a liquid fluidized bed of solid particles. The equation of state in a liquid-solid system proposed by Richardson-Zaki [1954] is :

$$\Phi=U_t\varepsilon^n \quad (17)$$

The continuity wave velocity obtained by Slis et al. [1959] by using Richardson-Zaki equation could be expressed in the form of :

$$U_\varepsilon=nU_t(1-\varepsilon)\varepsilon^{n-1} \quad (18)$$

The value of n in the Richardson-Zaki equation, Eq. (17), represents the characteristic of the particle and a function of Re_t and the wall effect on the bed. Rowe [1987] developed a simple relation to calculate the value of the exponent, n, as a function of the Reynolds number, Re_t, of a free settling particle.

$$n=2.35(2+0.175Re_t^{3/4})/(1+0.175Re_t^{3/4}) \quad (19)$$

For gas-solid fluidization, Foscolo et al. [1985] suggested that the Richardson-Zaki exponent, n, is reasonably applicable for the particulate gas-solid fluidization system when they compare the experimentally determined value with the calculated value of n.

A flowing substance has elastic properties and responds to a change of flow conditions in different ways. Massey [1979] suggested that the variation of pressure initiates the density variation in a flow system. When pressure is suddenly changed the flowing substance will be divided into two parts across a boundary. Ahead of the boundary, the pressure change is not adjusted yet. Behind of the boundary, the change is already adjusted. This boundary formed due to the step change of pressure was termed a pressure wave. The pressure wave will be propagating forward due to the pressure gradient. For an incompressible fluid, the rate of the wave propagation is instantaneous. For a compressible fluid, however, the propagation rates differ from each other. Wallis [1969] also suggested that the net force on a flowing substance produced by the concentration gradient generates the elastic wave. Massey [1979] obtained an expression for the elastic wave velocity :

$$U_e=\left(\frac{\delta P}{\delta\rho_f}\right)^{1/2} \quad (20)$$

In a particulate fluidization, the drag force acting on a single particle which belongs to a cross-section in a bed can be calculated as :

$$\delta F=\frac{\delta P}{N_p/A} \quad (21)$$

where N_p is the number of particles in a cross-section of a bed :

$$N_p=\frac{4(1-\varepsilon)A}{\pi d_p^2} \quad (22)$$

Combining Eq. (21) and Eq. (22) and substituting the result into Eq. (20) yields

$$U_e=\left(\frac{4(1-\varepsilon)}{\pi d_p^2}\right)^{1/2}\left(\frac{\delta F}{\delta\rho_b}\right)^{1/2} \quad (23)$$

The general expression for a drag force on a single particle in a fluidized bed, F_d, was proposed by Gibilalo et al. [1985].

$$F_d=F_{dt}\left(\frac{U_s}{U_t}\right)^{4.8/n}\varepsilon^{-3.8} \quad (24)$$

Replace F_e and F_d in Eq. (10) according to Eq. (9) and Eq. (24), respectively, to get a net force on a particle due to a pressure change

$$F=F_{dt}\left(\frac{U_s}{U_t}\right)^{4.8/n}\varepsilon^{-3.8}-\frac{\pi d_p^3}{6}(\rho_p-\rho_f)g\varepsilon \quad (25)$$

Since both the bed density and the net force on a particle are dependent on bed porosity, we can obtain the explicit form of the $\partial F/\partial\rho_b$ by differentiating both variables with respect to bed porosity,

$$\frac{\partial F}{\partial\rho_b}=4.8\frac{\pi d_p^3}{6}(\rho_p-\rho_f)g/\rho_p \quad (26)$$

When we substitute Eq. (26) into Eq. (23), we can obtain the elastic wave velocity as a function of the bed porosity only in a fluidized bed

$$U_e=\left(\frac{4(1-\varepsilon)}{\pi d_p^2}\right)^{1/2}\left(4.8\frac{\pi d_p^3}{6}\frac{g(\rho_p-\rho_f)}{\rho_p}\right)^{1/2}$$
$$=[3.2\ gd_p(\rho_p-\rho_f)(1-\varepsilon)/\rho_p]^{1/2} \quad (27)$$

The obtained elastic wave velocity, Eq. (25), does not include the interparticle force which has a dominant effect in an MSFB. According to the foregoing discussion, the magnetic interparticle forces act as implicit forces which pull particles downward. A particle is attracted upward by an upper particle but it is attracted downward by a lower particle simultaneously. Both the attracting forces exerted by upper and lower particles are the same magnitude of strength since the induced magnetic field intensity is assumed to be constant and the magnetization of all particles is the same. Therefore, the net magnetic force acting on a single particle can be null. However, there exists certain elastic force acting between two particles even though the net magnetic force acting on a single particle is null.

When pressure in a fluidized bed is changed suddenly, the energy dissipation around a single particle will be caused. This energy dissipation can be represented as the difference between the drag force produced with fluidizing fluid and the summation of the effective weight of a single particle and the magnetic interparticle force, which tend to pull down a single particle. The difference between drag force and effective weight of particle may be dependent on the bed density. The magnetic interparticle force is a function of bed porosity as well. Therefore, Eq. (23) can be modified by taking into account the effect of interparticle force in the force balance as follows :

$$U_e=\left(\frac{4(1-\varepsilon)}{\pi d_p^2}\right)^{1/2}\left(\frac{\delta F}{\delta \rho_b}-\delta F_{attr}\right)^{1/2} \tag{28}$$

Here, we have already obtained the first term in the second bracket of Eq. (28) in Eq. (26). The δF_{attr} can be expressed as follows :

$$\delta F_{attr}=\frac{\partial F_{attr}}{\partial \varepsilon}=-\frac{2.69\,\mu_0 mm'}{d_p^4}(1-\varepsilon)^{1/3} \tag{29}$$

When we plug both Eq. (26) and Eq. (29) into Eq. (28) we will get the final form of the elastic wave velocity in the form of

$$\begin{aligned} U_e &=\left(\frac{4(1-\varepsilon)}{\pi d_p^2}\right)^{1/2}\left(4.8\frac{\pi d_p^3}{6}(\rho_p-\rho_f)g/\rho_p-\delta F_{attr}\right)^{1/2} \\ &=\left(3.2gd_p(\rho_p-\rho_f)(1-\varepsilon)/\rho_p-\frac{4(1-\varepsilon)}{\pi d_p^2}\delta F_{attr}\right)^{1/2} \end{aligned} \tag{30}$$

where δF_{attr} was given in Eq. (29).

RESULTS AND DISCUSSION

The continuity wave velocity curve according to Eq. (18) in a particulate fluidization regime is shown in Fig. 5 for the case of steel shot of diameter 100 μm with air as a fluidizing fluid. The elastic wave velocity curve shown in Fig. 6 was obtained from Eq. (30) under the same condition as above. This curve depends on the diameter of particles, the intensity of a magnetic field, and the degree of magnetization of particles. The elastic wave velocity curve represents the characteristic of the elasticity of a flowing medium. Furthermore, when the interparticle force is increased the whole curve tends to move upward along the y-axis. This movement of the elastic curve corresponding to the increase of the interparticle force produces the more stable fluidization. Several investigators [Slis, 1959; Wallis, 1969; Verloop and Heertjes, 1970; Foscolo and Gibilaro, 1984; Foscolo et al., 1985; Gibilaro, 1986; Flemmer and Clark, 1987; Cox and Clark, 1991] have studied the wave velocities in order to correlate wave velocities to predict the transition point from a homogeneous to a heterogeneous fluidization mode.

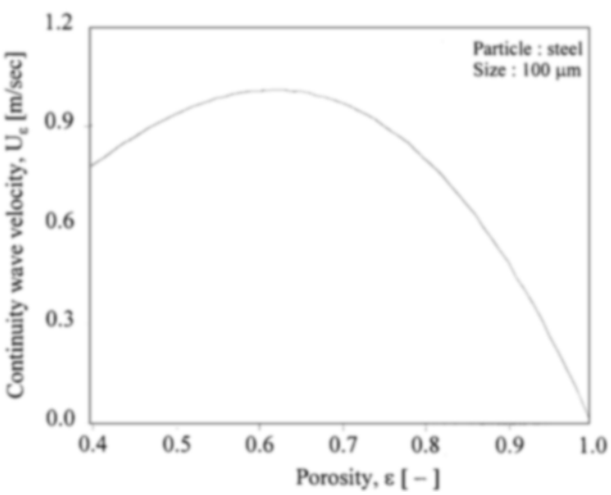

Fig. 5. Continuity wave velocity in a particulate fluidization regime according to Eq. (18).

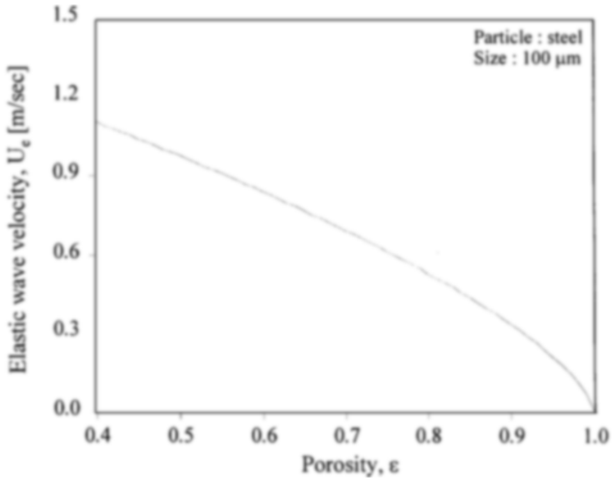

Fig. 6. Elastic wave velocity in particulate fluidization regime according to Eq. (30).

Wallis [1969] proposed that a flowing substance becomes unstable when a continuity wave velocity surpasses an elastic wave velocity. According to this criterion, one can classify fluidization into three regimes.

$U_e > U_\varepsilon$ homogeneous fluidization
$U_e = U_\varepsilon$ transition from particulate to aggregate fluidization
$U_e < U_\varepsilon$ aggregate fluidization

The above criteria enable us to predict the transition point from a homogeneous to a heterogeneous fluidization regime by comparing the continuity and elastic wave velocities. As shown in Fig. 7, the elastic wave velocity increases with an increase in magnetic field intensity where the strength of the interparticle force is in the order of $F_{attr,0} < F_{attr,1} < F_{attr,2} < F_{attr,3}$.

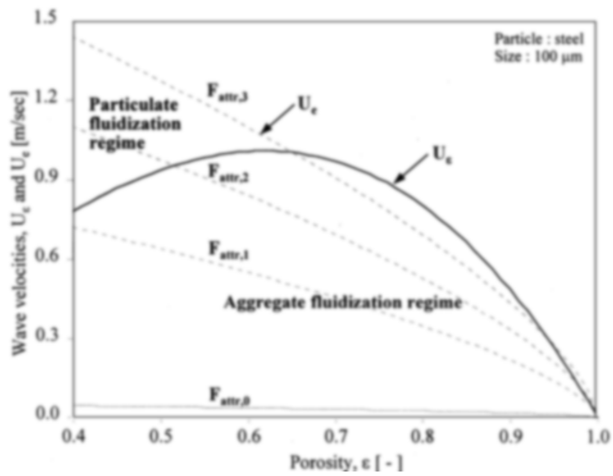

Fig. 7. Prediction of the transition point at different magnetic field intensities by a comparison of the continuity wave velocity, U_ε, (solid line) according to Eq. (18) and the elastic wave velocity, U_e, (dotted lines) given in Eq. (30).

The fluidization condition is completely unstable in the absence of a magnetic field (for the case of $F_{attr,0}$). With the increase of the magnetic field intensity from $F_{attr,0}$ up to $F_{attr,3}$ the elastic wave velocity increases accordingly. The predicted transition point of fluidization mode, as a value of bed porosity, was increased correspondingly. Particulate fluidization will be maintained as long as bed porosity is less than the value at the cross point of the elastic and continuity wave velocities. The shaded area indicates the particulate fluidization regime.

Using experimental data obtained by Saxena and Shrivastava [1990, 1991], we calculate the interparticle force at a stabilized condition and the bed porosity at transition point respectively. Based on our model for deformation point, we calculate interparticle force acting on a single particle. The magnetization of the particle does not change even when the bed is transformed from stabilized to particulate fluidization. Fig. 8 shows that the estimated interparticle force according to Eq. (10) became stronger with the increase of magnetic field intensity. It is obvious that the increase of the interparticle force is due to the increase of magnetic dipole moment of a particle. The comparison of the transition point in terms of bed porosity is shown in Fig. 9. The experimentally determined bed porosity and the predicted values of the bed porosity were plotted and the diagonal line indicates exact matching points between the predicted values and experimentally determined values. The predicted bed porosity was estimated from the model where the elastic wave and continuity wave velocities became equal. The result shown in Fig. 9 demonstrates the proposed model predicts the transition point with considerable accuracy. The discrepancy at higher bed porosity was presumably due to either channeling or/and bubbling. In these cases, we guess that a greater portion of the fluidizing fluid may pass through the formed channels or in the form of bubbles rather than passing by individual particles due to the high velocity of the fluid.

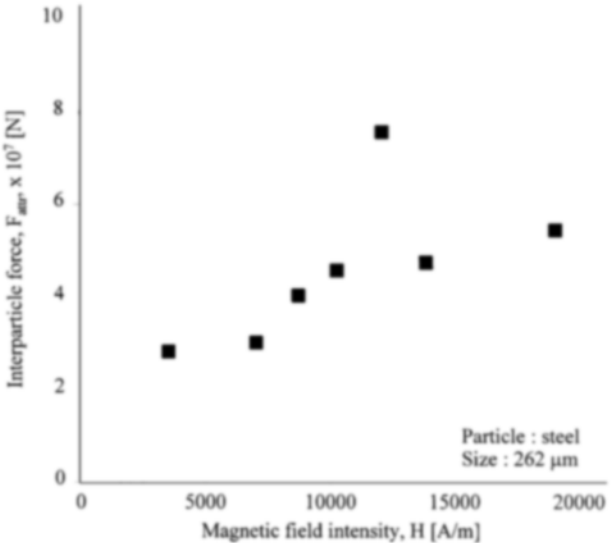

Fig. 8. Relation between interparticle force and the magnetic field intensity applied to a fluidized bed.

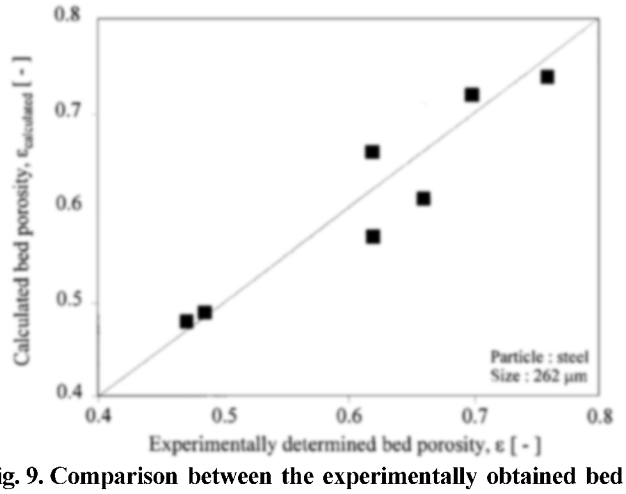

Fig. 9. Comparison between the experimentally obtained bed porosity and the predicted bed porosity from the proposed model.

CONCLUSIONS

According to this study on a theoretical model to predict the transition point from a homogeneous to a heterogeneous fluidization regime under the influence of an externally applied magnetic field in fluidized bed we conclude the following.

1. The interparticle force generated by the magnetization of particles is the main reason for the different behavior of fluidized particles in MSFBs. Based on Fig. 8, we observe that the calculated interparticle force becomes stronger as the applied magnetic field intensity increases.
2. The magnetic interparticle force can improve the stability of fluidization. Fig. 7 illustrates that the bed porosity at the transition point of the fluidization regime increases with increasing magnetic interparticle force. This implies that stable fluidization can be retained up to a higher fluidization velocity by increasing interparticle force mediated by the externally applied magnetic field.
3. The interparticle force on the fluidization of particles (i.e., Geldart's class C fine powders) may have two different effects. First, the interparticle force acts as a positive factor to make a bed fluidized when the interparticle force is moderately strong. Second, the interparticle force may be considered as a negative factor restricting fluidization of the bed when the interparticle force is overwhelmingly strong. Previously observed bed levitation may correspond to this case. Therefore, the current model will be valid within proper strength of magnetic field intensity.
4. The deformation velocity where the transition of fluidization regime from stabilized to particulate fluidization took place was explicitly embedded in the model. One may attempt to estimate the deformation velocity using the proposed model equations once the physical properties of particles and fluidizing fluid together with magnetic field strength applied to a bed are acquired.
5. According to the foregoing theoretical development, the transition from a homogeneous to a heterogeneous fluidization regime occurs where the continuity wave velocity exceeds the elastic wave velocity. The proposed model incorporated the interparticle force generated by the magnetic field externally ap-

plied to a fluidized bed. Shown in Fig. 9, the model demonstrated that the model could predict the transition point with accuracy.

NOMENCLATURE

A : cross-sectional area of a cylindrical bed [m^2]
B : vector of the magnetic flux density [N/m]
d_p : diameter of a spherical particle [μm]
F : net force acting on a single particle [N]
F_{attr} : interparticle forces acting on a single particle by surrounding particles [N]
F_d : drag force exerted on a single particle [N]
F_{dt} : drag force on an unhindered particle settling at terminal velocity [N]
F_D : overall drag force exerted on particles in a bed [N]
F_e : gravitational force produced by the effective weight of a particle in a bed [N]
g : gravitational acceleration [m/sec^2]
h : bed height [m]
m, m' : vectors of magnetic dipole moments [A·m^2]
M : potential energy at distance r from charge q [J]
n : Richardson-Zaki exponent [-]
N : number of particles in a fluidized bed [particles]
N_p : number of particles in a cross-section of a bed [particles]
P : pressure [N/m^2]
r : distance between two particles or two magnetic dipoles [m]
r : vector of the line connecting two particles or two magnetic dipoles
r_d : distance between a body-centered particle and a particle at a corner of a cube [m]
Re_t : Reynolds number at the terminal velocity of particle, $\rho_f U_t d_p/\mu$ [-]
r_s : distance between a body-centered particle and vertically located particles [m]
U_d : deformation velocity which causes the transformation of a magnetically stabilized bed from stabilized to particulate or aggregate fluidized condition [m/sec]
U_e : elastic wave velocity in a bed•[m/sec]
U_s : superficial fluid velocity [m/sec]
U_t : terminal velocity of a particle through unhindered fluid [m/sec]
U_ε : continuity wave velocity in a bed [m/sec]
V_p : total volume of particles in a bed [m^3]

Greek Letters

α, α' : angles between axis of magnetization of a particle and the line connecting centers of two particles or magnetic dipoles [°]
ε : instantaneous bed porosity [-]
μ : viscosity of fluid [N·sec/m^2]
μ_0 : magnetic permeability of a fluid [H/m]
λ : length of one side of a cube [m]
ρ_b : density of bed, $\rho_f+(1-\varepsilon)\rho_p$ [kg/m^3]
ρ_f : density of fluid [kg/m^3]
ρ_p : density of particle [kg/m^3]
Φ : volumetric flow rate of liquid per unit area of empty bed [m^3/sec]

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