

Fluidization characteristics of magnetic particles and determination of stable fluidization zone in magnetically fluidized bed

Wang Yinghui¹ Gui Keting² Shi Mingheng²

(¹School of Energy and Power Engineering, Jiangsu University, Zhenjiang 212013, China)

(²School of Energy and Environment, Southeast University, Nanjing 210096, China)

Abstract: To determine and calculate the stable fluidization zone in a magnetically fluidized bed, the fluidization characteristics of magnetic particles are investigated. Four kinds of magnetic particles with different average diameters, ranging from 231 to 512 μm , are fluidized in the presence of magnetic fields with specified values of the intensity in the range of zero to 7 330 A/m, and the particle fluidization curves are plotted. For marking the stable fluidization zone in the curves, the minimum bubbling velocities of particles are measured by the pressure-drop fluctuation. Based on the fluidization curves, the influences of the average particle diameter and magnetic field intensity on the zone are analyzed and discussed. A correlation to determine the stable fluidization zone is derived from the experimental data, using three dimensionless numbers, i. e., the ratio of magnetic potential to gravity potential, the Reynolds number and the Archimedes number. Compared with available data reported, it is shown that the correlation is more simplified to predict relative parameters for the bed operating in the state of stable fluidization under reasonable conditions.

Key words: magnetically fluidized bed; fluidization characteristics; stable fluidization; minimum bubbling gas velocity; pressure-drop fluctuation

The gas-solid fluidized bed is widely used in a variety of applications related to petrochemical, energy and pharmaceutical industries making use of its advantages. However, it is restricted to applications related to other fields due to its disadvantages, such as bubbles, gas bypassing and loss of particles by elutriation and entrainment. The magnetically fluidized bed (MFB) utilizes the external magnetic field to control the movement of magnetic particles, and can remedy these shortcomings to a large extent. Thus, it is promising in the applications to biological separation, chemical reaction, environmental protection and so on. For example, protein and hydrocarbon were separated from a compound solution, using special magnetic particles that can absorb these organic materials effectively by means of the MFB^[1-2]. By immobilizing enzymes on the fine magnetic particles, it can improve not only the stability and activity of the enzyme, but also the mass transfer coefficient^[3-4]. And it is found that the magnetically stabilized fluidized bed (MSFB) may be quite efficient in cleaning aerosols in air-flow^[5-6].

It is crucial to determine the stable fluidization

zone for the industrial MFB applications. However, effective ways are lacking to ensure the bed in the state of stable fluidization as a result of no direct and convenient criteria. In this paper, on the basis of the experimental research on the fluidization characteristics of magnetic particles in the MFB, a correlation between the stable fluidization zone and three factors (the ratio of magnetic potential to gravity potential Er , Reynolds number Re and Archimedes number Ar) is proposed, which can be conveniently used to determine the stable fluidization zone, and it is believed that it is helpful for MFB applications.

1 Experiments

The experimental facility primarily consists of an air supply system, a fluidized bed, a magnetic field generator and a series of measurement instruments, as schematically shown in Fig. 1. The bed is a 5 mm thick transparent Plexiglas pipe with an inner diameter of 100 mm, a length of 800 mm. It is advised to set up a calming section with a perforated air distributor plate to guarantee the airflow through the bed to be more stable and uniform. The ratio of opening holes in the air distributor plate is suggested to be about 10% to avoid too much bed pressure drop. The uniform magnetic field is generated by a set of modified Helmholtz coils with DC power (current range: 0 to 5 A). Each coil comprises a 262 mm inner diameter, a 312

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Biographies: Wang Yinghui (1968—), male, doctor, wyh@ujs.edu.cn; Gui Keting (1957—), male, doctor, professor, ktgui@seu.edu.cn.

mm outer diameter and a 70 mm width, and two coils are placed at a distance of 170 mm from each other. In the experiments, the magnetic field intensity is measured by the gaussmeter, and the gas velocity is calculated from rotameter readings. The bed pressure drop is read from the digital meter of the pressure-drop sensor. In addition, the power of the induced fan is 5 kW, leading to an airflow flux of $0.98 \text{ m}^3/\text{min}$. Some physical properties of the particles are given in Tab. 1.

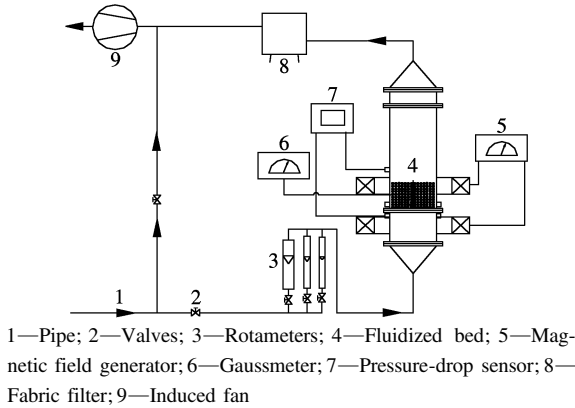


Fig. 1 Schematic diagram of the experimental facility

Tab. 1 Physical properties of magnetic particles

Diameter $d_p/\mu\text{m}$	Density $\rho_p/(\text{kg}\cdot\text{m}^{-3})$	Bed voidage ε	Minimum fluidized gas velocity $U_{mf}/(\text{m}\cdot\text{s}^{-1})$
231	5 340	0. 403	0. 25
275	5 420	0. 412	0. 29
362	5 440	0. 416	0. 34
512	5 620	0. 419	0. 62

It should be noted that the relationships, such as the bed pressure drop Δp versus the superficial gas velocity U_g and the magnetic field intensity H versus the current I , have been obtained in the empty bed experiments before particles have been introduced.

In all the experiments, the minimum fluidized gas velocity U_{mf} and the minimum bubbling gas velocity U_{mb} of the magnetic particles are detected by Δp fluctuations. When the particles fluidized, Δp can be written as

$$\Delta p = \frac{G}{A} = g(\rho_p - \rho_g)(1 - \varepsilon)L \quad (1)$$

where G denotes the weight of the particles, A the bed cross-sectional area, and L the bed height.

In the MFB, when the fluidized bed presents bubbling fluidization, bed voidage ε is a transient variable, which leads obviously to transient Δp fluctuations. But once the bed is in the state of stable fluidization, ε will be almost a constant because the particles are distributed uniformly in the bed, leading to basically stable Δp . In the experiments, the readings by the pressure-drop sensor reflect Δp variations. There-

fore, U_{mf} and U_{mb} are detected. Hence, the stable fluidization zone is determined by the range from U_{mf} to U_{mb} in this study.

2 Results and Discussion

2.1 Fluidization characteristics of magnetic particles in MFB

In the experiments, the magnetic particles of four different sizes, as listed in Tab. 1, are taken to be fluidized in the bed at specified H values (ranging from 0 to 7 330 A/m). The fluidization curves under some conditions for the small and big particles are plotted in Fig. 2 and Fig. 3, showing the relations between Δp and U_g . There are the same trends for the particles of medium diameter ($d_p = 275$ and $362 \mu\text{m}$, not shown here).

Taking Fig. 2(c) for an example, the horizontal line shows the theoretical bed pressure drop calculated by Eq. (1). At first, Δp increases linearly with increasing U_g , then Δp increases a little arcuatedly when U_g is over U_{mf} , and at the same time, the increment decreases, which coincides with the reports by Saxena and Shrivastava^[7]. In this state, Δp does not change with time, showing that the bed presents a state of stable fluidization. Increasing U_g to 0.52 m/s , Δp drops below the theoretical value, fluctuating with time dramatically, showing that the bed steps into a state of bubbling fluidization, so the minimum bubbling velocity U_{mb} is taken as 0.52 m/s . Increasing U_g further, Δp keeps fluctuating with time quite frequently, and the bed still presents bubbling fluidization. From this time, decreasing U_g to U_{mb} gradually, Δp almost decreases linearly with U_g till Δp is 0. Therefore, there is a stable zone in the MFB, from U_{mf} to U_{mb} , shown as the range between the two dash lines in Fig. 2 and Fig. 3.

As shown in Fig. 2(a) and Fig. 3(a), where $H = 1\,890 \text{ A/m}$, it can be clearly seen that the bed does not present stable fluidization as a result of a weaker magnetic field intensity. All the other curves, shown in Figs. 2(b) to (d) and Figs. 3(b) to (d), imply that the stable fluidization zones in MFB can be adjustable under different fluidization conditions, such as changing the diameter of particles or the magnetic field intensity. For instance, for the small particles ($d_p = 231 \mu\text{m}$), comparing Fig. 2(b) with Fig. 2(d), where H is 2 955, 5 440 A/m, respectively, U_{mb} increases from 0. 43 to 0. 69 m/s, and the ratio of U_{mb} to U_{mf} (i. e., the relative value of the stable fluidization zone) is from 1. 74 to 2. 77, enlarged about 60%. While for the large particles ($d_p = 512 \mu\text{m}$), comparing Fig. 3 (b) with Fig. 3 (d), U_{mb}/U_{mf} is just from 1. 55 to 2. 29,

enlarged about 48%. That is, the effect of the magnetic field intensity on the stable fluidization zone for

the small particles is more obvious than for large ones.

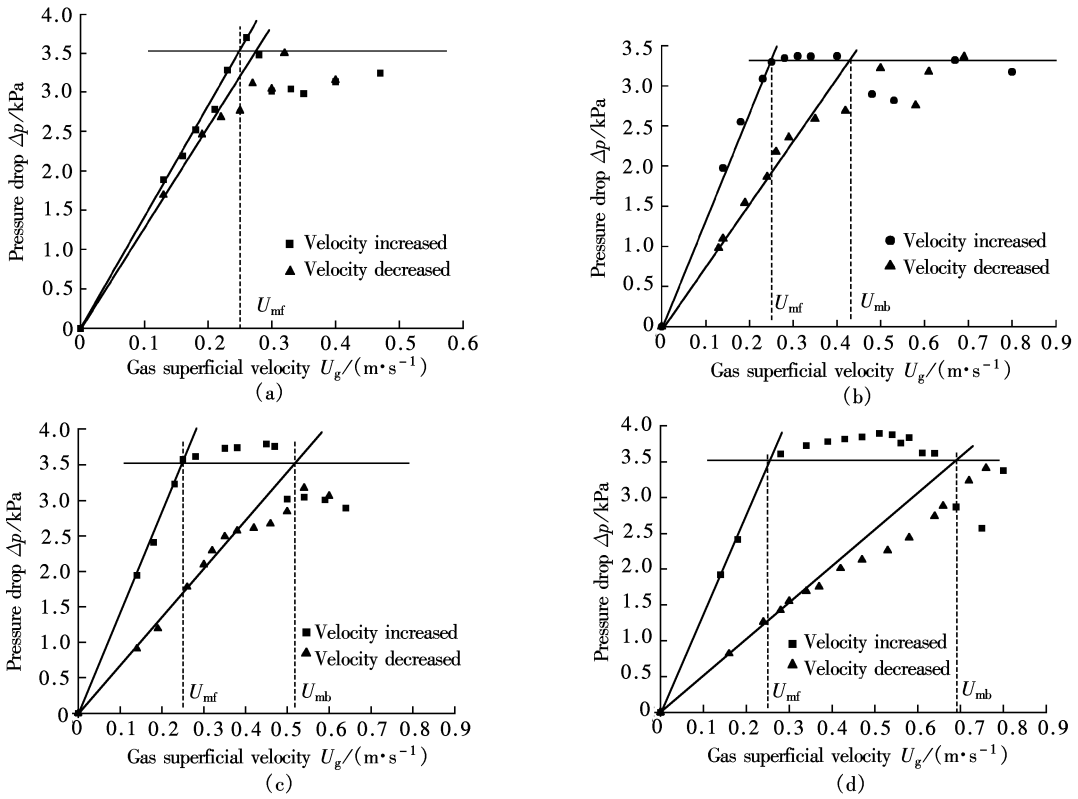


Fig. 2 Variation of bed pressure drop with gas velocity for various magnetic field intensities ($d_p = 231 \mu\text{m}$).

(a) $H = 1890 \text{ A/m}$; (b) $H = 2955 \text{ A/m}$; (c) $H = 3665 \text{ A/m}$; (d) $H = 5440 \text{ A/m}$

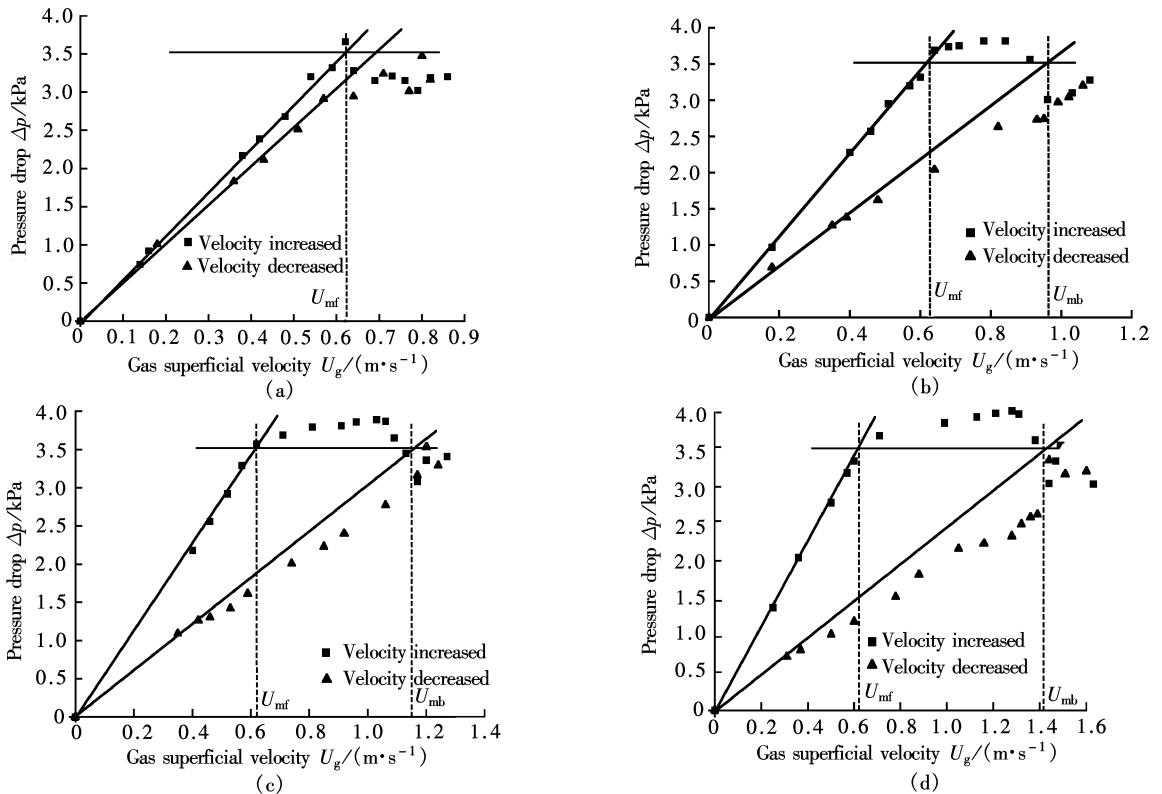


Fig. 3 Variation of bed pressure drop with gas velocity for various magnetic field intensities ($d_p = 512 \mu\text{m}$).

(a) $H = 1890 \text{ A/m}$; (b) $H = 2955 \text{ A/m}$; (c) $H = 3665 \text{ A/m}$; (d) $H = 5440 \text{ A/m}$

From Fig. 2 and Fig. 3, it can also be found that Δp exceeds the theoretical value when the bed presents stable fluidization, and Δp increases a little with increasing H . This is mainly because the cohesive forces between the particles are more strengthened as H is increasing, and the resistance of the airflow becomes larger. Consequently, the pressure loss is increasing. In addition, the bed pressure drops are much below the theoretical value while U_g is decreasing and Δp is also less than the values while U_g is increasing. The reason is that the bed structures are badly destroyed when a large number of bubbles occur in the bed, channels are formed, and the channels can provide passages for air shortcircuits; hence, the pressure loss is less accordingly.

2.2 Determination of stable fluidization zone in MFB

To determine the zone of stable fluidization in the MFB, Arnaldos et al.^[8] gave an empirical equation to calculate U_{mb} , but the equation shows that U_{mb} mostly depended on the magnetic field intensity, and it cannot reflect the influences of the diameter and density of the magnetic particles, so its availability is restricted. Recently, Ganzha and Saxena^[9] derived an equation to describe the state of minimum bubbling fluidization,

$$Re_{mb}^2 + 85.71(1 - \varepsilon_{mb})Re_{mb} - Ar \frac{\varepsilon_{mb}^3}{1.75} \cdot (1 - 4kEr[1 + 4.80 \frac{k}{k_1} \chi(1 - \varepsilon_{mb})^{\frac{2}{3}}]) = 0 \quad (2)$$

where $E_r = 3\mu_0 MH/2gd_p\rho_p$ is the ratio of magnetic potential to gravity potential, M is induced particle magnetization, μ_0 is permeability of free space; χ is magnetic susceptibility; k and k_1 are constant; $Re_{mb} = U_{mb}d_p/\nu_g$ is the Reynolds number in the state of minimum bubbling fluidized; $Ar = gd_p^3(\rho_p - \rho_g)/\rho_g\nu_g^2$ is the Archimedes number.

From Eq. (3), the stable fluidization zone can be given by the Reynolds number Re_{mb} , which is corresponding to the state of minimum bubbling fluidization, but it is complicated to calculate Re_{mb} , and it is not convenient to provide the operational parameters in the MFB. In order to reveal the relationships of all the factors influencing the stable fluidization zone, an effective way is to take the method of dimensionless analysis. Besides Er , Re and Ar , as mentioned in Eq. (2), $(U_{mb} - U_{mf})/U_{mf}$ is introduced, and it is also a dimensionless number, reflecting the relative values of the stable zone. Taking $(U_{mb} - U_{mf})/U_{mf}$ as ordinate, Er as abscissa, the relationships can be seen in Fig. 4. It can be found that there seems to be a power func-

tion between $(U_{mb} - U_{mf})/U_{mf}$ and Er . Suppose that the relationship is

$$\frac{U_{mb} - U_{mf}}{U_{mf}} = CRe_{mf}^i Ar^j Er^k \quad (3)$$

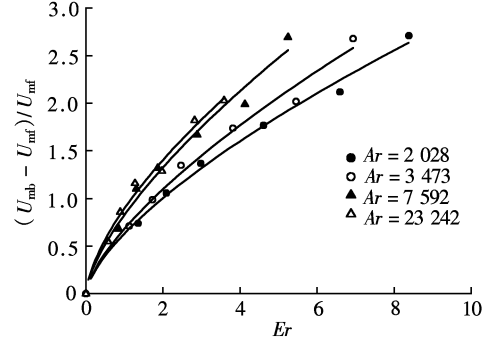


Fig. 4 Variation of $(U_{mb} - U_{mf})/U_{mf}$ as a function of Er for different values of Ar

Furthermore, on the basis of the experimental data, using the mathematical method of multi-analysis, Eq. (2) can be derived as

$$\frac{U_{mb} - U_{mf}}{U_{mf}} = 0.0012 Re_{mf}^{-0.9678} Ar^{0.9237} Er^{0.7011} \quad (4)$$

where $H = 0$ to 7330 A/m, $d_p = 213$ to 512 μm , $\rho_p = 5340$ to 5620 kg/m^3 . Eq. (4) shows that the stable zone increases with increasing Ar and Er , but decreases with increasing Re_{mf} , corresponding to the state of minimum fluidization. Compared to Eq. (2), Eq. (4) is more simplified and convenient to determine the stable fluidization zone in the MFB.

Fig. 5 shows the comparison of experimental data and calculated values from Eq. (4). It can be seen that the coincidence is good, and the error is less than 8%. In addition, the values calculated by Eq. (4) are basically consistent with the data of Ganzha and Saxena^[9].

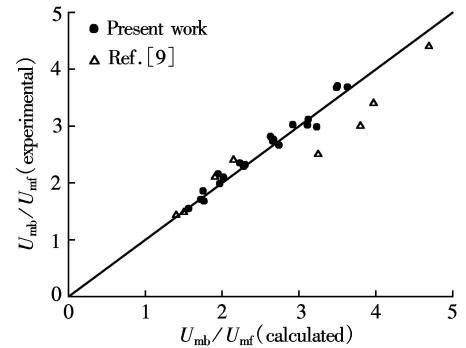


Fig. 5 Calculated vs. experimental values of U_{mb}/U_{mf}

3 Conclusion

On the basis of the fluidization experiments of the magnetic particles in the MFB, the fluidization curves have been plotted, and after analyzing the flu-

idization characteristics of the magnetic particles, some conclusions can be drawn. First, the stable fluidization zone in the MFB varies with the particles' diameter d_p and the magnetic field intensity H . It increases as H increases, while decreasing as d_p increases. Secondly, when H is not strong enough, such as when H is at 1 890 A/m, the stable fluidization zone cannot exist in the MFB. Thirdly, the bed pressure drops are above the theoretical values when the bed presents stable fluidization while the gas velocity U_g is increasing, but below the theoretical value while U_g is decreasing. Finally, a correlation to determine the stable fluidization zone in the MFB is derived, and it is easier to predict relative parameters for the bed operating in a state of stable fluidization under reasonable conditions.

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磁流化床铁磁颗粒的流化特性与磁稳区的确定

王迎慧¹ 归柯庭² 施明恒²

(¹ 江苏大学能源与动力工程学院, 镇江 212013)

(² 东南大学能源与环境学院, 南京 210096)

摘要:针对磁流化床可实现磁稳流化的特点,提出了一种确定和计算磁稳流化区域的方法.通过对4种不同粒径的铁磁颗粒(其平均粒径范围231~512 μm)进行流态化实验研究,得到铁磁颗粒分别在磁场强度为0~7 330 A/m时的流化曲线.实验中采用压降波动的方法测定最小鼓泡流化速度,进而确定磁稳流化区域的范围.基于铁磁颗粒的流化曲线,分析得到铁磁颗粒的流化特性,讨论了颗粒粒径、磁场强度对磁稳流化区域的影响;运用多元回归的方法得到磁稳流化区域与磁重势能比、阿基米德数以及雷诺数之间的实验关联式.与已有的研究相比,此式较为简单,具有较好的适用性,据此式可以方便地给出磁流化床磁稳流化状态运行时的合理参数.

关键词:磁流化床;流化特性;稳定流化;最小鼓泡流化速度;压降波动

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