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Original Research Paper

Characteristic gas velocity and fluidization quality evaluation of vibrated dense medium fluidized bed for fine coal separation

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ABSTRACT

In order to remove incombustible impurity minerals, a vibrated dense medium fluidized bed (VDMFB) can be adopted for fine coal dry separation, while Geldart B magnetite powder can serve as the medium. The influence of vibration on characteristic gas velocity in flow pattern transition stage was experimentally investigated at a vibration amplitude range of 0.5–4 mm and frequency range of 5–35 Hz. The experimental results demonstrate that at a low frequency (f < 10 Hz), the vibration effect results in a denser bed and a slightly smaller initial fluidization gas velocity. As the vibration frequency increases to a level similar to the bed's natural frequency, the minimum fluidization gas velocity reduces sharply. The minimum fluidization gas velocity correlation in the VDMFB is obtained by means of theoretical deduction and experimental data fitting. Furthermore, a method is proposed for evaluating the effects of vibration on improving fluidization quality. Based on that, using the coal separation probable error $E_p \leqslant 0.1$ as the evaluation index, a suitable effective operating gas velocity range for coal separation under different vibration parameters is determined. The ratio of the boundary operating gas velocity to U_{mfc} is 0.67–2.28. Thus, a uniform and stable fluidization environment is provided for dry fine coal separation.

1. Introduction

The vibrated fluidized bed (VFB) is extensively used in various fields, such as the chemical industry, energy production, environmental protection, food processing and pharmaceutical production, as it can strengthen particle movement, increase the gas–solid contact rate, improve fluidization quality, and achieve fluidization of fine cohesive particles [1,2]. A great deal of research has been conducted in both basic and industrial applications to design and operate the VFB successfully. The influence of the vibration parameters, bed structure, and particle properties on the basic hydrodynamic behavior of the bed is significant as a critical issue in the design and development of the VFB [3,4]. Rahul and Mujumdar [5] proposed a generalized $\Delta P - U$ relation curve and discovered that the significant difference in pressure drop curves between the VFB and conventional fluidized bed (CFB) was the result of a smooth transition occurring over a wide operating gas velocity range in the VFB pressure drop curve. Various researchers considered that the introduction of vibration reduces the bed pressure drop and minimum fluidization gas velocity. Thus, the bed uniformity is improved. Jinescu [6] assumed that the particle rising time was equal to its landing time and proposed a semi-empirical, semi-theory calculation formula for minimum fluidized gas velocity (U_{mfv}). Nevertheless, it is difficult to predict U_{mfv} in operation based on this calculation formula, as it is challenging to measure the collision coefficient and particle rising time. Based on their own experimental data, Mushtaev [7], Rahul [3], Erdész [8], Chen [9], and Jin [10] summarized the different empirical correlations of U_{mfv}, involving Geldart A, B, C, and D particles [11]. However, the abovementioned empirical formulas are suitable only for operation parameters set by the researchers in question, and there is no general theoretical formula for the prediction of U_{mfv}. The structure, height, and diameter of the bed are the basic factors that affect fluidization in the VFB. Barletta [12] used a high-speed dynamic camera to track the bed height fluctuation and found that the vibration energy was weakened with an increasing bed height. Furthermore, when the vibration intensity was too high, the bed surface fluctuated severely, and a double bed surface was formed. Rao [13] indicated that an increase in the height–diameter ratio of the bed would increase the frictional resistance of the bed wall to the particles, thereby increasing the minimum fluidization gas velocity. Mawatari [14] pointed out that a larger particle size results in a more evident vibration effect on reducing the initial

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Nomenclature

A	vibration amplitude, m
d_p	particle diameter, m
$\overline{d_p}$	average equivalent diameter of equal specific surface area, m
f	vibration frequency, Hz
F_v	driving force of the vibration to the bed, N
F_{bw}	friction between the bed wall and particles, N
g	gravitational acceleration, m/s^2
Δh	height of the measured region, m
H_{mf}	bed height at the minimum fluidization gas velocity, m
$I_{u,v}, I_{u,c}$	bed density uniformity index of VDMFB and CFB
K	vibration intensity, the ratio of the maximum vibration acceleration to the gravitational acceleration
m	volume fraction of the emulsion phase
M_p	total mass of the bed, kg
$\Delta P_i, \Delta P_b, \Delta P_v, \Delta P_c$	differential pressure, Pa
R_{imp}	fluidization quality improvement index
S	cross-sectional area of the bed, m^2
U	operating gas velocity, m/s
$U_{mfc}, U_{mf\,v}, U_{mf\,v,cal}, U_{mf\,v,exp}$	minimum fluidization gas velocity, m/s
V_e, V_{bu}	volume of emulsion phase and bubble phase, m^3
ρ_{bt}	bulk density of materials, kg/m^3
$\rho_i, \rho_p, \rho_g, \rho_{bu}, \rho_e, \overline{\rho_b}$	density of measurement point, magnetite powder, gas, bubble, emulsion phase and bed, kg/m^3
ε_{mf}	bed voidage at initial fluidization
μ	dynamic viscosity of fluid, Pa·s

Subscripts

b	bed
bu	bubble
c	conventional fluidized bed
cal	calculated value
e	emulsion phase
exp	experimental value
g	gas
mf	minimum fluidization parameter
p	particle
v	vibrated dense medium fluidized bed (VDMFB)

Box–Behnken RSM experiment

A	operating gas velocity, m/s
B	vibration amplitude, mm
C	vibration frequency, Hz

bed pressure drop. This may occur because the number of large particle layers is reduced at the same static bed height. According to Rahul and Mujumdar's research [3], it appears that the vibration impact is damped out more effectively by non-spherical particles, which possess a larger area of contact with neighboring particles. For certain cohesive particles, such as wet particles containing 6–25% moisture and Geldart A particles that are fluidized with difficulty in CFB, Marring [15] and Sande [16] determined the vibration intensity required for effective fluidization with the unconfined yield strength of lightly consolidated powder batches.

Based on the application of VFB in the chemical industry, pharmaceutical industry, food processing, and other fields [17–20], the majority of studies on vibration fluidization have been aimed solely at fluidized particles. Because a uniform, stable gas–solid fluidized environment can be formed in the VFB by fluidizing particles, it can be considered for beneficiating materials with a larger particle size by density. In order to solve the problem of high water resource consumption during the coal cleaning process [21,22], some researchers [23–27] applied a dry coal preparation program based on the air dense medium fluidized bed (ADMFB), adopting Geldart B magnetite powder as the medium. This method provided a new method for dry coal cleaning. However, the ADMFB technique only exhibits an efficient separation effect for >6 mm coal. Several researchers, such as Wang [28,29], Luo [30], Liu [31], and Jin [32], introduced vibration into the ADMFB to form a VDMFB, separating <6 mm fine coal and coke slag to achieve useful component enrichment. These authors explained the mechanism by which vibration energy weakened the influence of bubbles and proposed the viewpoint that the vibration energy passed through the quasi-elastic and quasi-continuous bed in a class of elastic waves. Furthermore, they provided an optimization scheme for operation and bed structure parameters to achieve a uniform, stable fluidized environment that can realize efficient beneficiation for fine coal under specific parameters with a probable error E_p below 0.1 g/cm^3. Macpherson [33] used sand as a heavy medium and separated <8 mm coal in a vibrated reflux classifier with an E_p of 0.07 g/cm^3.

Thus far, research on VDMFB for coal separation is somewhat limited, and previous studies have mainly qualitatively explored the influence of operating parameters on fluidization and separation [34], but have rarely offered definite quantitative conclusions and correlations that can be adopted for predicting characteristic gas velocity and evaluating fluidization quality. As a result of the complexity of vibration fluidization and experimental condition limitations, different researchers have obtained varying results for similar problems, with some even contradicting one another. As an example, the studies of Yoshida [35] and Chen [9] demonstrated that the introduction of vibration reduced the minimum fluidization gas velocity. On the contrary, Rahul and Mujumdar [3] indicated that the correlation between the minimum fluidization gas velocity and vibration was not absolute. Obviously, many of the research results relevant to the VFB are applicable only to the range of operating conditions defined by the researchers [36]. A great deal of previous research concerning the VFB for other uses is not suitable for the VDMFB; therefore, it is necessary to carry out an in-depth investigation of the hydrodynamic characteristics of the VDMFB. In this study, the authors focus on certain characteristic parameters that can represent the bed fluidization behavior, including the fluidization curve, minimum fluidization gas velocity, and evaluation method for fluidization quality. Furthermore, attention was paid to establishing the corresponding correlations to predict characteristic gas velocity and fine coal separation behavior in the VDMFB.

2. Experimental

2.1. Apparatus and materials

The typical apparatus used in the experiments are schematized in Fig. 1. The pre-gas distribution chamber, gas distributor, and fluidization chamber are connected to the electro-dynamic shaker with bolts to form a VDMFB, which creates a periodic vertical harmonic motion under the shaker driving. The adjustable vibration parameters of the shaker include vibration amplitude (0–10 mm)

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