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Influences of different operating parameters and gas/solid properties in rectangular cross-flow moving bed

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ABSTRACT

Under different operating parameters and gas/solid physical properties, the pressure drop distribution, the cavity and pinning phenomena in the rectangular cross-flow moving bed are investigated by the Eulerian two-fluid & the kinetic theory of granular flow models with single variable method. The simulation results are validated by the experimental data. The particle force equations are built to explain the occurrence mechanisms of the cavity and pinning phenomena. For describing the pressure drop distribution more explicitly, the bed average pressure drop and the radial uneven index of pressure drop (*UI*) are introduced. In addition, the combined body force is introduced to explain the influences of different parameters and properties on the cavity and pinning phenomena. The relative deformation of particle group is also applied to analyze the cavity/pinning sizes under different particle packing properties.

1. Introduction

Nowadays, the cross-flow moving bed is widely used in many industry processes including drying [1], filtration [2], heat exchange [3] and naphtha reforming [4]. Compared with other beds (e.g. the fixed bed, the fluidized bed, the concurrent and the counter-current moving bed), the cross-flow moving bed has many distinct advantages such as high process capacity, low pressure drop, flexible solid residence time, comparatively constant resistance as well as uniform gas-solid contact. However, it also has some shortcomings including the appearance of the gas axial dispersion (the end effect), the cavity and the pinning phenomena. This will suspend the continuous operation of the bed [5,6]. Thus, the two-phase flow in the cross-flow moving bed needs to be deeply investigated.

In addition, it is reported that these disadvantages (e.g. the cavity [7–9] size, the pinning [8,10–14] thickness, the gas axial dispersion) closely relate to the pressure drop distribution. The cavity and the pinning phenomena occur only when the pressure drop is high enough. However, the bed average pressure drop ($\overline{\Delta p}$) [15] rather than the pressure drop distribution is mainly discussed in the published literature. However, it is virtually difficult to determine the cavity/pinning sizes and/or quantify the gas axial dispersion via the bed average pressure drop. The bed average pressure drop cannot reflect the pressure drop distribution clearly. Compared with the bed average pressure drop, the local pressure drop varies considerably in the cavity and the pinning zones. The gas uniformity is badly affected by the gas axial dispersion. Thus, the position/size of the cavity/pinning and/or the quantification of the gas axial dispersion can be determined according to the pressure drop distribution rather than the bed average pressure drop. For instance, Wang et al. [16] verified that the pressure drop distribution can reflect the gas-solid flow pattern, the cavity and the pinning phenomena. Therefore, the pressure drop distribution is the most important factor in the cross-flow moving bed. It is necessary to introduce the radial uneven index of pressure drop (*UI*) to describe the pressure drop distribution more thoroughly.

Ergun equation [15] is put forward to calculate the pressure drop of the fixed bed. It considers both the kinetic and the viscous energy losses. The equation has been widely used to compute the pressure drop in the fixed bed by the theoretical and simulation methods [17–19]. The gas-solid flow pattern has been investigated by many researchers such as Chen et al. [7], Zhao et al. [20], Zhang et al. [21] and Tao et al. [22] via experimental method in the cross-flow moving bed. It turns out that, the pressure drop of the cross-flow moving bed presents quite similar profiles to that of the fixed bed. This is attributed to the small solid flux and large solid holdup in the moving bed. Thus, the Ergun equation is used directly [23] or modified slightly [24] to estimate the pressure drop of the cross-flow moving bed. Many simulation software (FLUENT [16,19,25–27], Barracuda [28], mathematical model [23], finite element method [29], et al.) also used the Ergun equation to compute the pressure drop when the solid holdup is sufficiently high. As a result, the Ergun equation is widely used to calculate the pressure drop of the fixed and the moving beds. Therefore, all parameters in the Ergun

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equation, which consists of the gas density, the gas superficial velocity, the gas dynamic viscosity, the particle diameter and the solid holdup, undoubtedly have influences on the pressure drop distribution of the cross-flow moving bed. On the other hand, other operating parameters and gas/solid physical properties (e.g. the solid flux, the solid seal height, the particle density, the particle internal friction angle and the particle packing properties), which are not considered in the Ergun equation, may also affect the pressure drop distribution of the cross-flow moving bed. These parameters and properties also need to be studied.

Limited by the experimental conditions, previous experimental studies mainly focused on the influences of the operating parameters, the structural optimization [2,10,26,28,30–33] as well as a few particle physical properties [22,34] on the gas-solid flow pattern in the cross-flow moving bed. However, it is hard to adopt the single variable method in experiment, which is used to determine the effect of individual parameter or property on the gas-solid flow pattern in the cross-flow moving bed. Although the classical theory formulas such as the Ergun equation give us the bed average pressure drop under different conditions via theoretical method; the pressure drop distribution, the cavity and the pinning phenomena cannot be computed by the Ergun equation directly. The exploration is worthy to be carried on via the simulation method [16]..

In conclusion, some attempts are made in this paper to solve the above problems. Firstly, both the bed average pressure drop ($\overline{\Delta p}$) and the radial uneven index of pressure drop (*UI*) are considered. Secondly, all of the operating parameters and the gas/solid physical properties mentioned above are studied individually by the single variable method. Thirdly, the Fluent 6.3.26 is used to simulate the gas-solid flow pattern in the rectangular cross-flow moving bed by the Eulerian two-fluid model & the kinetic theory of granular flow models. The simulation method makes the single variable method achievable compared with the experimental studies. Moreover, in order to better understand the gas-solid flow pattern in the rectangular cross-flow moving bed, the occurrence mechanisms of the cavity and the pinning phenomena are analyzed by building the particle force equations. Meanwhile, the influence mechanisms of different parameters and properties on the cavity and the pinning phenomena are also explained by numerical simulation and theoretical analysis.

2. Rectangular cross-flow moving bed

Fig. 1 shows the investigated rectangular cross-flow moving bed. It is 1.3 m in height. The cross section of the moving bed is 0.3 × 0.04 m. Only the gas and solid phases are contained in the bed. The gas phase is the air with atmospheric pressure and room temperature. The solid phase is the supporter 3861 for catalytic reforming catalyst. The solid phase is fed into the bed from the top of the moving bed, then moves downward slowly to the bottom of the bed for discharge. On the other hand, the gas phase flows through the bed horizontally from the gas distribution channel to the gas collection channel. As illustrated in Fig. 1, the bed is divided into three parts: the feed influence zone, the gas-solid contact zone and the discharge influence zone. The division is made in that the pressure drop maintains high values only in the gas-solid contact zone [14]. The Johnson net, which is 1 m in height, prevents the solid phase from leaving the bed. However, the gas phase is allowed to pass through it. The porosity of the Johnson net is 23.5% and then its resistance for the gas phase is neglected.

The cavity and the pinning phenomena are recorded by a digital camera; while the pressure drop distribution is obtained by measuring the pressure drop in 14 points [14], which is also shown in Fig. 1.

3. Simulation

In this paper, the rectangular cross-flow moving bed is the fully scaled modeled by the GAMBIT 2.4.6 software. As shown in Fig. 2, the structured hexagonal meshes are applied in the model. In addition, the rectangular cross-flow moving bed is simulated by the Eulerian two-fluid and the kinetic theory of granular flow (KTGF) models, which are given in Fluent 6.3.26 software. The governing equations are listed in Table 1. The Johnson net is simulated by the porous model to make sure that only the gas phase can pass through it. The laminar equation is used because the Reynolds number ranges from 0 to 309 in this paper. Based on the experimental results [10,16], both the cavity and the pinning phenomena appear under the condition shown in Table 2. This condition is noted by a *REFERENCE CASE* in this paper.

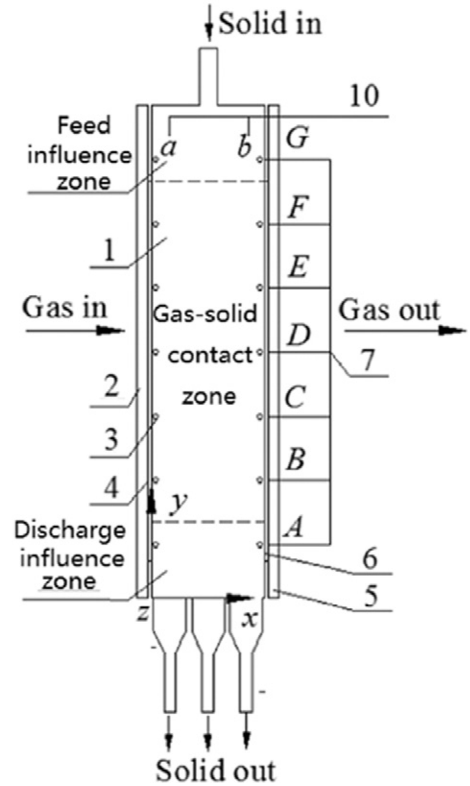

Fig. 1. Schematic diagram of the rectangular cross-flow moving bed. 1—Gas distribution channel, 2—pressure measurement points (14 points), 3—Johnson net (upstream), 4—gas collection channel, 5—Johnson net (downstream), 6—seven axial positions (y/H) of pressure measurement points: *A*—0.11, *B*—0.24, *C*—0.37, *D*—0.5, *E*—0.63, *F*—0.76, *G*—0.89, 7—two horizontal positions (x/L) of pressure measurement points: *a*—0.04, *b*—0.96.

4. Theoretical methods

4.1. Single variable method

In this paper, the single variable method is used to determine how individual parameter or property affects the pressure drop distribution while other parameters and properties remain unchanged. According to Table 2, the parameters studied here including the operating parameters (the gas superficial velocity, the solid flux and the solid seal height) and the gas/solid physical properties (the gas density, the gas dynamic viscosity, the particle density, the particle mean diameter, the particle internal friction angle, the particle initial holdup, the particle friction packing limit and the particle packing limit). In addition, individual operating parameter or gas/solid physical property is chosen in a reasonable range according to similar experimental conditions in published literature. Consequentially, its influences on the pressure drop distribution, the cavity and the pinning phenomena are discussed here.