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Pinning and cavity in two types of cross-flow moving beds

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ABSTRACT

The pinning, cavity and pressure drop were investigated in both trapezoidal and rectangular cross-flow moving beds via a large plexiglass cold model under different operating conditions. Experimental results indicate that the pinning appears before cavity. The critical pinning/cavity superficial gas velocities of the trapezoidal bed are considerably higher than those in the rectangular bed. Namely, the trapezoidal configuration improves the operating flexibility of the moving bed. On the other hand, it also shows that the dimensions of the pinning and cavity are both enlarged when the superficial gas velocity increases. However, the size variations of the pinning and cavity are not significant with the change of the particle mass flux. Besides, most gas passes through the bed in the horizontal direction. In the operating process, there is an undesirable phenomenon called channeling in the top of bed. Based on the force balance analysis as well as the experimental results, a mathematical model of pinning is proposed. The critical pressure drops and the pinning thicknesses can be predicted by using this model.

1. Introduction

Moving bed with cross-flow has been widely used in many industrial processes due to its small pressure drop, low particle attrition, uniform fluid–solid contact and flexible solids residence time. It is reported that moving bed reactor could be employed in catalytic cracking process [1], granular drying [2], filtration [3–5] as well as biomass oil production [6]. Perhaps the most well-known application is its use in catalytic reformer process [7] in the modern petroleum refining industries.

In a moving bed, solids move downward through a vertical channel under gravity, while gas blows horizontally across the bed via vertical porous plates [8]. The cross-flow gas passing through the descending particles exerts a drag force on the solid material, which in turn increases the normal stress on the downstream porous wall, and decreases the corresponding stress on the upstream wall. The drag force exerted by the flowing gas increases the frictional stress between the particles and the downstream wall, which opposes sliding of the material near this wall. The interaction between the gas and the granular bed results in an irregular down flow of solids [9]. If the gas flow flux is large enough, the frictional force will be sufficient to support the weight of the solids and then the downward motion of solids will cease in some of the regions adjacent to the downstream wall. The bed is then said to be "pinned" by the gas flow [10,11]. When the pinning takes place, the catalysts turn out to be immobile and become completely deactivated by coking which suspends continuous operation of the reactor. On the other hand, if the gas flow flux is large enough, some particles will be detached from the upstream wall under the effect of drag force and then cavity will occur in regions adjacent to the upstream wall [12]. When the cavity occurs, the gas assumes asymmetrical distribution in the vertical direction that in severe cases can cause gas short-cut. Therefore pinning and cavity greatly restrict the operating flexibility of the cross-flow moving bed.

The first discussion on undesirable phenomena of the cross-flow moving bed in the published literature was given by Bridgwater [8], which reported that there is a limitation of the gas flux in this bed. Since then, several researchers have investigated the flow characteristics of gas [13–16] and solid [9,17–19] phases in the moving bed. Besides, relevant explanations and analysis of the pinning/cavity phenomena [12] have been reported, and several models have been developed to predict the size and critical pressure drop of the pinning [10,11,20–22] as well as the cavity [23–26]. However, the problem of the narrow operating flexibility of cross-flow moving bed has not been solved.

Several patents [27,28] have put forward novel schemes to control the pinning. However, detail experimental data, theoretical analysis and numerical model were seldom reported in these patents. On the other hand, several relevant techniques of internals [29–33], such as the flow-corrective element and the porous dividing wall, have been proposed to further increase the gas flow rate. All of these techniques indicate that the use of the flow-corrective element can suspend the formation of cavity and decreases the cavity size while reduce the critical pressure drop of pinning. Besides, the porous dividing wall can delay the occurrence of pinning while increase the pressure drop along the bed. Therefore, it is still necessary to develop a new structure to further improve the operating flexibility of the cross-flow moving bed.

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In this paper, a new moving bed, i.e. the trapezoid moving bed with a multiple-grid discharge cone was presented. The experimental results of the pinning, cavity and pressure distribution in the large cold model trapezoid bed were shown first, and then the comparison between the trapezoid moving bed and the rectangular bed was made. Furthermore, a model was established to account for the pinning behaviors in both trapezoidal and rectangular moving beds.

2. Experiments

2.1. Experimental apparatus

As shown in Fig. 1, the experimental setup was mainly made up of plexiglass for easy observation. The system mainly consists of a trapezoidal moving bed (or a rectangular moving bed), a riser and a separating tank. The moving bed was 1.3 m in height. The riser was 0.052 m in inner diameter (I.D.) and 3.4 m in height. The separating tank was 0.188 m I.D. and 1 m in height.

Fig. 2 shows the detailed structure of the investigated cross-flow moving beds. The trapezoidal bed was 0.185 m × 0.04 m in the top cross section and 0.299 m × 0.04 m in the bottom cross section. The rectangular moving bed was 0.3 m × 0.04 m in cross section. The Johnson nets as the gas flow channel were installed at the height of 0.1 m above the bottom of the bed. Its height was 1 m while the open porosity was 23.5%.

Particles were fed into the moving bed from the feed pipe and moved downward into the feed influence zone without air flow. Then they moved down to the main body of the moving bed, i.e. the gas–solid contact zone whose upstream and downstream walls were both Johnson nets. Particles left the discharge influence zone and then were returned to the separating tank by pneumatic conveying in the riser, as shown in Fig. 1. A multiple-grid discharge cone which consisted of three cones was used at the bottom of the bed, as shown in Fig. 3. The solid flow rate was controlled by a flap valve at the bottom of the particles exit pipe.

The air, supplied by an air blower, was fed into the bed from the upstream Johnson net, and then passed through the bed along the horizontal direction and left via the downstream Johnson net. Its flow rate was also controlled by a valve and measured by a Rotameter.

2.2. Experimental materials

The gas was air and the particles were supporter 3861 for catalytic reforming catalyst. The physical properties of the particles are listed in Table 1. It is noted that this type of particle has a narrow particle size distribution.

2.3. Experimental conditions

The experiment was carried out under the atmospheric pressure with ambient temperature. The superficial gas velocity with respect to the longitudinal section of the bed (1 m × 0.04 m) ranged from 0.1 m/s to 0.8 m/s in the moving bed. The particle mass flux with respect to the cross sectional of the rectangular bed (0.3 m × 0.04 m) varied between 0.51 $\text{kg}/(\text{m}^2\cdot\text{s})$ and 1.72 $\text{kg}/(\text{m}^2\cdot\text{s})$.

2.4. Experimental method

In this paper, the phenomena of pinning and cavity were observed under different operating conditions in the moving bed. A marker pen was used to record the position and geometry of the cavity/pinning on the plexiglass plate. Moreover, a digital camera was used for image analysis. The pressure distribution was measured using the 26-PC pressure sensors which were produced by the Honeywell International Corporation. The locations of the pressure taps were shown in Fig. 2.

3. Experimental results

3.1. The pressure distribution

Fig. 4 shows the pressure distributions in the trapezoidal and the rectangular beds. It suggests that the pressure almost remains unchanged along the y direction in the gas–solid contact zone under different operating conditions, which indicates that most gas flows horizontally along the x direction in the gas–solid contact zone.

In the discharge influence zone, the pressure values are similar to those in the gas–solid contact zone, which suggest that there is almost no gas leakage between the moving bed and the riser. However, there is a significant change of the pressure profile in the feed influence

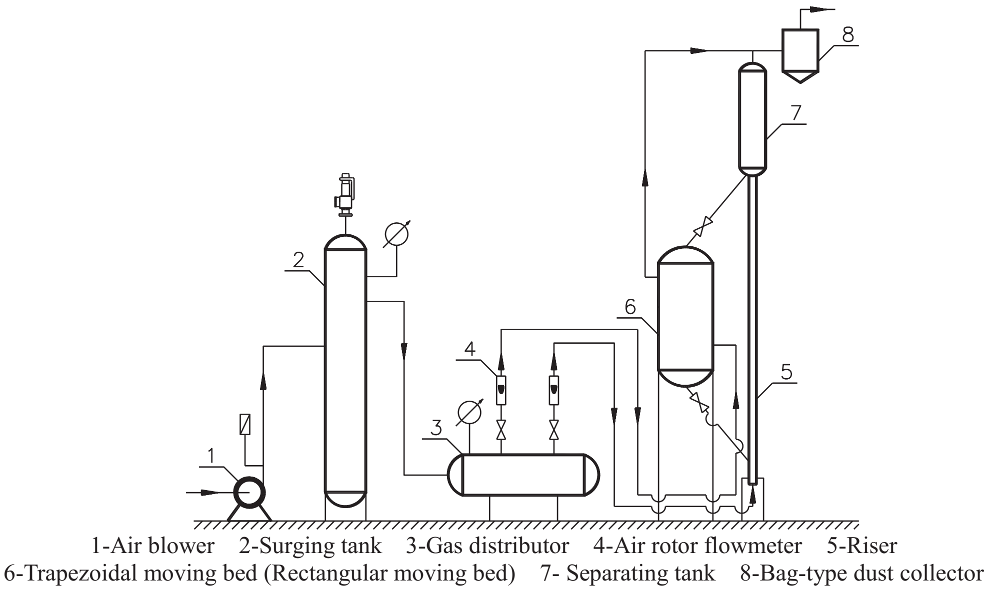

Fig. 1. Schematic diagram of the experimental setup. 1 — Air blower, 2 — Surging tank, 3 — Gas distributor, 4 — Air rotor flowmeter, 5 — Riser, 6 — Trapezoidal moving bed (Rectangular moving bed), 7 — Separating tank, and 8 — Bag-type dust collector.