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Cold Model Experimental Research on Particle Velocity Distribution in Gas-Solid Circulating Fluidized Bed for Methanol-to-Olefins Process

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***Abstract*—**Radial profiles of particle velocities were investigated in a 6.1m high methanol-to-olefins cold model experimental device using a TSI laser Doppler velocimeter. The effect of axial height on flow development was not obvious in fully developed region under the same operating condition. Superficial gas velocity and solid circulating rate had significant influence on particle velocity in the center region of the riser. Besides, comparisons among rising, descending and average particle velocity were conducted. The particle average velocity was similar to the rising particle velocity and higher than the descending particle velocity in radial locations except the wall region of riser.

***Keywords*—**Circulating fluidized bed, laser doppler velocimeter, particle velocity, radial profile.

I. INTRODUCTION

OLEFINS including ethylene and propylene are basic raw materials of modern chemical industry and important part of the petrochemical industry. Traditionally, naphtha cracking method is used to produce ethylene and propylene. The synthesis of ethylene, propylene and other olefins via methanol from syngas provides an additional route for the production of olefins, which is considered to be the most hopeful new process to replace the petroleum route process.

In order to facilitate the removal of heat and regeneration of sintered catalyst, circulating fluidized beds (CFB) are often used for the continuous operation of the reaction-regeneration process. Analysis on gas-solid flow structure in riser reactor is significant for appropriate industrial design. Industrial processes want a shorter and a more uniform catalyst residence time which is determined by solid distribution in the riser reactors, since coke deposition easily deactivates the catalysts resulting in a decrease of selectivity in methanol-to-olefins (MTO) process. The solid distribution has a significant impact on the gas-solids contacting efficiency, heat and mass transfer, and conversion and selectivity of the chemical reaction [1]. Therefore, the study for movement of gas and particles in CFB reactor is of importance for continuous development and improvement of the MTO process.

So far, many studies have been carried out on particle motion in CFB risers [2]-[6]. Studies show that particles accelerate in the bottom of the riser at first, and then stabilize in the full developed region along axial direction. Particle velocity is high in the center and low in the wall region of the riser [7]-[9]. However, solids concentration in the center is always lower than in the wall region of the riser [9]-[13]. What's more, [14] investigated the fluidizing behaviors of powders in group A, B, C, and D. Besides, the influences of riser diameter on the axial and radial profiles of solid holdup/particle velocity/solid flux and flow development were researched by [1], [15], [16].

Although there have been some studies on CFB risers, there is still a lack of experimental data, especially on particle velocity. The laser Doppler velocimeter (LDV) is an advanced non-intrusive measuring equipment for particle velocity. However, this measurement technique can only be used at sufficiently dilute suspension. Measurement has been hampered by the appearance of more than one particle in the collecting volume of the beams. In addition, signal-to–noise ratio of Doppler signal gets worse with its penetration distance into the gas-solid suspension [17], [18]. The air and solid velocities in horizontal and vertical pipes were studied by [17], [18] using the LDV. The radial solids velocity profiles in a fine particle (36μ) riser were studied using a LDV system [19]. Besides, [20] using an improved LDV successfully measured local particle velocity and particle velocity fluctuation in a high density riser with solids fraction up to 0.21.

In order to gain a better understanding of the hydrodynamic behaviors in riser of MTO pilot plant, this study was carried out to gain radial and axial profiles of particle velocity under low solids circulation rate by a LDV system.

II. EXPERIMENT

Fig. 1 shows a schematic diagram of the experimental equipment, which consists of (A) air supply system; (B) 3-D LDV system; (C) MTO large-scale cold model experimental apparatus.

MTO large-scale cold model was made of Plexiglas, which consists of riser reactor with a 0.15-m in diameter (expanding part was 0.2m) and the height of 4.9m (expanding part was 0.7m), stripping section, catalyst regenerator, precipitator and

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feed tank. A branched pipe distributor (Fig. 2) made of stainless steel pipe and equipped with downward nozzles was installed at the height of 0.2m. Above the gas distributor, a perforated plate (Fig. 3) includes 208 holes with 2mm in diameter was installed to obtain a more uniform distribution of the gas.

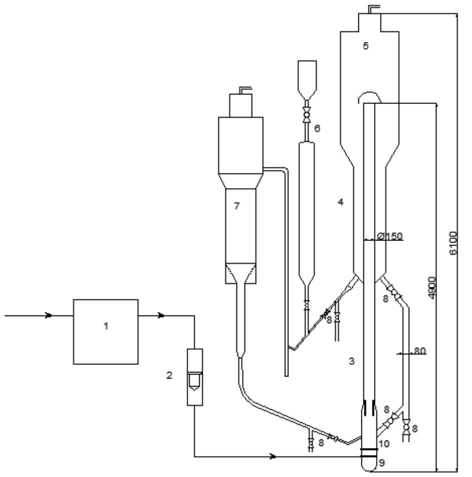

Fig. 1 Schematic diagram of the MTO cold model apparatus: 1. Air system; 2. Glass rotameter; 3. Riser reactor; 4. Stripping section; 5. Precipitator; 6. Feed tank; 7. Catalyst regenerator; 8. Ball valve; 9. Branched pipe distributor; 10. Perforated plate

The solids in riser were glass beads with a mean diameter of 89 μm and a particle density of 2400kg/m^3. Compressed air first passed through filter and freeze-dryer to remove water, oil and other impurities. After that, the gas entered the gas distributor at the bottom of the riser through a glass rotameter. The gas-solid suspension traveled up in the riser reactor. In the riser top, most of the solid particles rebounded into stripping section after hit the cap structure. The rest of the particles were settled in precipitator. A handful of solids followed with gas passed through a smooth exit into bag filter for gas-solid separation. Particles which entered the stripping section could be returned back into expanding part of riser via circulating pipe with a 0.08m in diameter. The solids flow rate can be adjusted by the ball valve used in circulating pipe. Solids circulating through the system could be accumulated in circulating pipe for a given time period to get solids circulating rate (G_s). Since this paper only studied particle velocity distribution in the riser, relevant ball valves were closed so that no particles can go into the catalyst regeneration system.

A TSI laser Doppler velocimeter (LDV) was used to measure the local particle velocity in the riser. The LDV measurement technique uses a laser to generate a coherent beam to illuminate a moving particle in the flow. This particle movement creates a Doppler shift in the light frequency directly proportional to its velocity. Without inserting any sensor into the flow, this technique provides a noncontact way of measuring velocity. The components of this LDV system mainly are: laser (5W, Argon-Ion), transmitting optics, receiving optics, detector, signal processor and data analysis system.

The particle velocity was measured on five axial levels (Z=1.67, 1.82, 1.97, 2.07, and 2.22m) and at 8 radial positions (r/R =0.00, 0.13, 0.27, 0.40, 0.53, 0.67, 0.80, and 0.93) on each level. The effects of different solids circulation rates (G_s=1.14, 2.08, and 4.21kg/(m^2·s)) and different superficial gas velocities (U_g=0.94, 1.26, 1.57, 1.89, and 2.20m/s) on the particle velocity were also investigated. At each measurement position, the sampling time was typically over 60s or the number of sampled particle reached 20000.

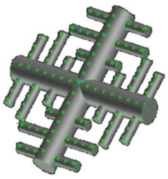

Fig. 2 Branched pipe distributor

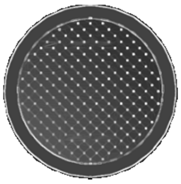

Fig. 3 Perforated plate

III. RESULTS AND DISCUSSION

A. Axial Variation of Radial Profile of Particle Velocity

Fig. 4 shows the mean particle velocities at 8 radial positions on five axial planes under five operating conditions. The superficial gas velocities were 1.57, 1.89, and 2.20m/s and the solids circulation rates were 1.14, 2.08, and 4.21kg/(m^2·s). The five operating conditions were named a, b, c, d, and e respectively. Particle velocities in the radial direction show varying degrees of core-annulus flow structure on five axial elevations under all five operating conditions. Particle velocities are higher in the center than in the wall region of the riser at all axial locations. In the middle radial region, the particle velocity profiles are relatively flat and fall rapidly to negative toward the wall, leading to a cluster of parabolic-shaped radial velocity profiles. The measuring plane is in 1.67-2.22m above riser bottom which is in the full developed region. Therefore the effects of the entrance and exit structures can be eliminated. Fig. 4 also shows that the radial profiles of particle velocity are very uniform which is consistent with the experimental phenomena of [15]. They believe that the radial profile of particle velocity is more uniform with lower solids flux. Comparing the operating conditions b, c and d, it can be found that the particle velocity in the center region of the riser increase with the superficial gas velocity. Under the same superficial gas velocity, conditions a, c and e shows that the particle velocity decreases with increasing solids circulation rate. The particle velocities on different axial levels do not change significantly under the same solids circulation rate and gas velocity. It also demonstrates that the measuring planes from 1.67m to 2.22m are in the fully developed region.

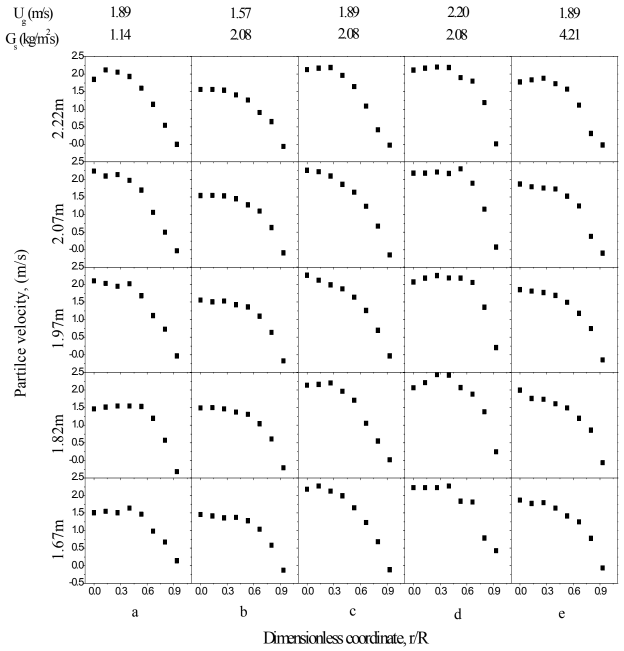

Fig. 4 Radial profiles of local particle velocity under five different operating conditions

B. *Effect of Superficial Gas Velocity on Radial Profile of Particle Velocity*

Fig. 5 shows that typical radial distributions of the time-average solid velocity. Radial profiles of particle velocity on the various axial levels under same solid circulation rate and different superficial gas velocity were displayed in Figs. 5 (a) and (b). It is clear that particle velocity at almost all r/R position increases with the superficial gas velocity on the same axial plane. This phenomenon can be explained that lager superficial gas velocity provides a larger kinetic energy, weakening the cluster formation and leading to increase of gas-solid drag force. Therefore, particles get a higher velocity under the action of gas-solid drag force. Fig. 5 also shows that the effects of superficial gas velocity on the center and the wall region of the riser are different. In the center region of the riser, particle velocity increases significantly with the superficial gas velocity. However, superficial gas velocity seems to have only a slight influence in the wall region of the riser. Fig. 6 further illustrates this phenomenon. This is mainly due to core-annulus flow structure. According to [10], the solids concentration remains low and relatively constant at the riser center throughout the riser and is lower in the center than in the wall region of the riser at all axial locations. A large number of particles are gathered in the wall region and inhibit the flow of gas. Huge amount of gas tends to go through the riser from the center of the riser where the resistance is smaller. Moreover, the wall effect also weakens the influence of superficial gas velocity. In conclusion, particle velocity in the center of riser is larger than in the wall region.

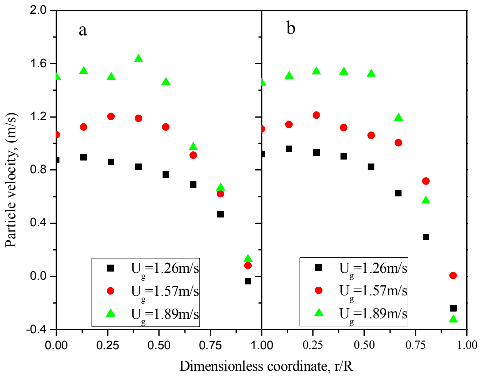

Fig. 5 Radial profiles of particle velocity under three different superficial gas velocities (a: Z=1.67m, G_s=1.14 kg/m^{2}s; b: Z=1.82m, G_s=1.14kg/m^{2}s)

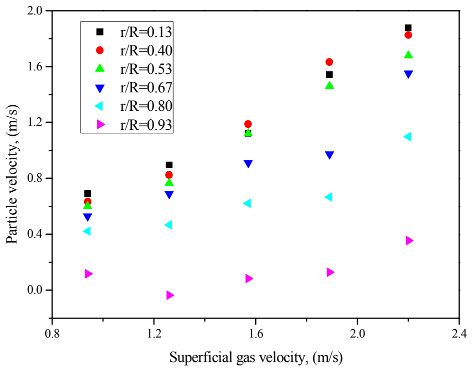

Fig. 6 Effect of superficial gas velocity on particle velocity (Z=1.67m; G_s=1.14kg/m^{2}s)

C. *Effect of Solid Circulation Rate on Radial Profile of Particle Velocity*

Fig. 7 shows the effect of solids circulation rate on particle velocity radial distribution under a constant U_g of 1.89m/s. The effect of solids circulation rate on the particle velocity radial profile is not obvious because of the low circulating rate and narrow range. It can be seen that with the increase of solids circulation rate the particle velocity in the center of riser decreases. But this trend is not significant in the wall region. The above phenomenon can be attributed to the decreases of the gas-solid drag force. The number of solids in the riser increases with the solids circulation rate and decreases the force on the particles under a constant gas velocity. Therefore, it is easy to know the reason why particle velocity decreases with increasing solids circulation rate.

D. *Axial Variation of Particle Velocity in Different Radial Positions*

Fig. 8 provides in the center region of riser (r/R=0.00-0.27) particle velocities always keep a larger stable value. In the region of r/R=0.27-0.80, the effect of axial position on the particle velocity is not obvious. Although particle velocities decrease with the increase of dimensionless diameter, they maintain a relatively constant value at the same radial position. In the wall region ($r/R \geq 0.93$), the axial position still has no significant impact on the speed. However, in this region particle velocities are below zero, which means movement direction of particle is downward. This also verifies that the flow develop first in the center region of the riser, and then gradually and progressively close to the wall as the solids pass through the riser [7]. Actually, rising and descending particles exist in any radial position, which will be discussed in the following paragraphs. Fig. 8 also shows that the particle average velocity in the wall region of the riser is negative and in the other region is positive form an inner circle, which corresponds well with the core-annulus flow structure.

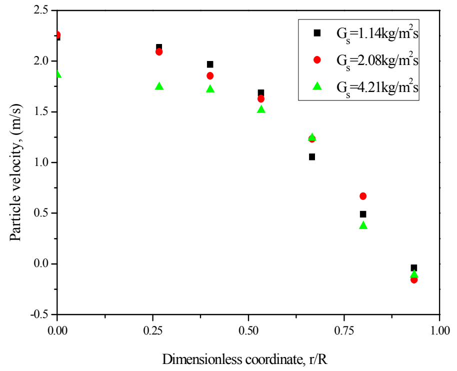

Fig. 7 Radial profiles of particle velocity under different solid circulating rates (Z=2.07m; U_g=1.89m/s)

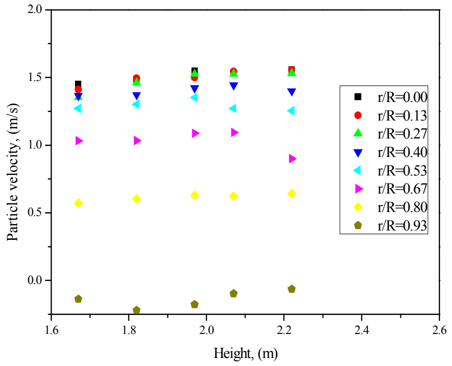

Fig. 8 Particle velocity at different radial positions along the riser (G_s=2.08kg/m^{2}s; U_g=1.57m/s)

E. Comparisons among Rising, Descending, and Average Particle Velocity

The particle average velocity with the velocity of rising particle and descending particle are compared in Fig. 9. It is clearly that the radial profile of average velocity is very similar to the velocity of rising particle except in the wall region of the riser in both operating conditions. Conversely, the velocity of descending particle is much less than average value. For most of the radial position, the velocity of rising particle is larger than descending particle, while in the wall region the relationship is reversed. The reason for this phenomenon can be found in Part B. In the center region and middle radial region particle gets larger kinetic energy to achieve high speed while in the wall region particle moves downwards under the influence of wall effect and gravity.

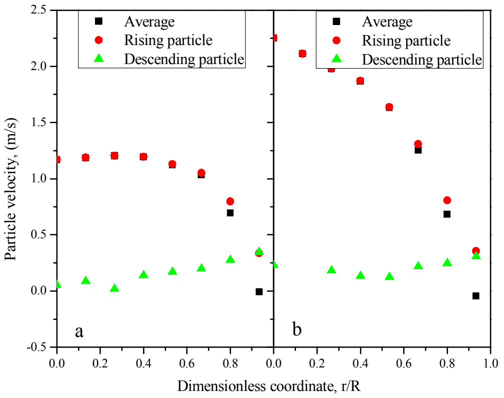

Fig. 9 Radial profiles of rising, descending and average particle velocity (a: G_s=1.14kg/m^{2}s, U_g =1.57m/s, Z=2.07m; b: G_s=2.08kg/m^{2}s, U_g=1.89 m/s, Z=1.97m)

IV. CONCLUSIONS

Numerous measurements were performed in a gas-solid circulating fluidized bed for methanol-to-olefins process to show the velocity distribution in full developed region of the riser, using a LDV at eight radial positions on five different axial levels.

Radial profiles of particle velocity are parabolic-shaped under five operating conditions. In axial measuring range, radial profiles of particle velocity are very similar under the same solid circulating rate and superficial velocity. Axial heights have little or no effect on the particle velocity in full developed region.

Superficial gas velocity and solid circulating rate remarkably influence the particle velocity in the center region of the riser. However, this effect to be small in the wall region. Particle velocity increases in the center region of the riser with the increase of superficial gas velocity and decrease of solid circulating rate. In addition, radial profile of particle velocity descends more sharply in the wall region of the riser.

Rising and descending particles exist at any radial location. The particle average velocity is similar to the rising particle velocity and far greater than the descending particle velocity at most of radial locations except the wall region where the velocity of rising particle is slightly less than descending particle.

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REFERENCES

[1] A. Yan and J. Zhu, "Scale-Up Effect of Riser Reactors (1): Axial and Radial Solids Concentration Distribution and Flow Development," *Ind. Eng. Chem. Res.*, vol. 43, pp. 5810-5819, 2004.

[2] J. J. Nieuwland, R. Meijer, J. A. M. Kuipers, and W. P. M. van Swaaij, "Measurements of solids concentration and axial solids velocity in gas-solid two-phase flows," *Powder Technol.*, vol. 87, pp. 127-139, 1996.

[3] A. S. Issangya, D. Bai, H. T. Bi, K. S. Lim, J. Zhu, and J. R. Grace, "Suspension densities in a high-density circulating fluidized bed riser," *Chem. Eng. Sci.*, vol. 54, pp. 5451-5460, 1999.

[4] D. Bai, A. S. Issangya, and J. R. Grace, "Characteristics of Gas-Fluidized Beds in Different Flow Regimes," *Ind. Eng. Chem. Res.*, vol. 38, pp. 803-811, 1999.

[5] Q. Geng, X. Zhu, Y. Liu, Y. Liu, C. Li, and X. You, "Gas–solid flow behavior and contact efficiency in a circulating-turbulent fluidized bed," *Powder Technol.*, vol. 245, pp. 134-145, 2013.

[6] Z. Q. Li, C. N. Wu, F. Wei, and Y. Jin, "Experimental study of high-density gas–solids flow in a new coupled circulating fluidized bed," *Powder Technol.*, vol. 139, pp. 214-220, 2004.

[7] J. H. Pärssinen and J. X. Zhu, "Particle velocity and flow development in a long and high-flux circulating fluidized bed riser," *Chem. Eng. Sci.*, vol. 56, pp. 5295-5303, 2001.

[8] X. Qi, H. Zhu, and J. Zhu, "Demarcation of a new circulating turbulent fluidization regime," *AIChE J.*, vol. 55, pp. 594-611, 2009.

[9] B. Wang, T. Li, Q. W. Sun, W. Y. Ying, and D. Y. Fang, "Experimental Study on Flow Behavior in a Gas-Solid Fluidized Bed for the Methanol-to-Olefins Process," *Chem. Eng. Technol.*, vol. 33, pp. 1591-1600, 2010.

[10] J. H. Pärssinen and J. X. Zhu, "Axial and radial solids distribution in a long and high-flux CFB riser," *AIChE J.*, vol. 47, pp. 2197-2205, 2001.

[11] S. W. Kim, G. Kirbas, H. Bi, C. Jim Lim, and J. R. Grace, "Flow behavior and regime transition in a high-density circulating fluidized bed riser," *Chem. Eng. Sci.*, vol. 59, pp. 3955-3963, 2004.

[12] A. S. Issangya, J. R. Grace, D. Bai, and J. Zhu, "Further measurements of flow dynamics in a high-density circulating fluidized bed riser," *Powder Technol.*, vol. 111, pp. 104-113, 2000.

[13] H. Zhu and J. Zhu, "Gas-solids flow structures in a novel circulating-turbulent fluidized bed," *AIChE J.*, vol. 54, pp. 1213-1223, 2008.

[14] D. Geldart, "Types of gas fluidization," *Powder Technol.*, vol. 7, pp. 285-292, 1973.

[15] A. Yan and J. Zhu, "Scale-up effect of riser reactors: Particle velocity and flow development," *AIChE J.*, vol. 51, pp. 2956-2964, 2005.

[16] A. Yan, J. Ball, and J. Zhu, "Scale-up effect of riser reactors (3) axial and radial solids flux distribution and flow development," *Chem. Eng. J.*, vol. 109, pp. 97-106, 2005.

[17] Y. Tsuji and Y. Morikawa, "LDV measurements of an air-solid two-phase flow in a horizontal pipe," *J. Fluid Mech.*, vol. 120, pp. 385-409, 1982.

[18] Y. Tsuji, Y. Morikawa, and H. Shiomi, "LDV measurements of an air-solid two-phase flow in a vertical pipe," *J. Fluid Mech.*, vol. 139, pp. 417-434, 1984.

[19] Y. Wang, F. Wei, Z. Wang, Y. Jin, and Y. Zhiqing, "Radial profiles of solids concentration and velocity in a very fine particle (36 μm) riser," *Powder Technol.*, vol. 96, pp. 262-266, 1998.

[20] F. Wei, H. Lin, Y. Cheng, Z. Wang, and Y. Jin, "Profiles of particle velocity and solids fraction in a high-density riser," *Powder Technol.*, vol. 100, pp. 183-189, 1998.

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