Normal Reynolds Stress and Solid Diffusivity of Solid Particles in Circulating–turbulent Fluidized Bed System Using CFD Simulation

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***Abstract*—The solid particle flow pattern is one of the important quantitatively system mixing parameters for designing and operating of fluidized bed system. In this study, the solid dispersion pattern in novel circulating–turbulent fluidized bed flow pattern is explored using computational fluid dynamics simulation, comparing to the neighbor conventional flow patterns. The objective is to investigate the effect of fluidization velocity on the normal Reynolds stress and solid diffusivity of solid particles. From the results, the solid particle flow patterns depended on fluidization velocities. Regarding the contour of solid volume fraction, it found that the solid particle behavior in novel circulating–turbulent fluidized bed flow regime had high solid particle uniformly distributed in the system both in the axial and radial system directions. In addition, the circulating–turbulent fluidization regime showed the constant normal Reynolds stress and solid diffusivity coefficient.**

***Index Terms*—CFD, fluidization, hydrodynamics, normal Reynolds stress, solid diffusivity**

I. Introduction

Fluidized bed reactor is frequently used reactor in industry. There are many industrial processes using the fluidized bed reactor such as coal combustion, electricity generation and chemical production processes [1]. For the concept of fluidization, when the fluid is fed into the bottom of fluidized bed reactor, it then contacts with solid particles and causes the solid particles to move as a fluid. The solid flow pattern is changed with the increasing of fluidization velocity. Difference solid flow patterns, including fixed bed, bubbling, turbulent, fast fluidization and pneumatic transport, will affect the rate of heat and mass transfers [2], [3]. Therefore, the suitable solid flow pattern or behavior is important for designing and operating of fluidized bed reactor.

Nowadays, there are many research studies about the behavior of different solid flow patterns using both experimental and computational methods. Maryam *et al.* [4] investigated the solid flow pattern and solid mixing characteristics in bubbling fluidized bed. Their results were compared with the experimental data presented by Leverman *et al.* [5]. The increasing of the fluidization velocity increased solid diffusivity coefficient and solid dispersion coefficient. This is because the bubble size is larger. Hosseini *et al.* [6] studied the solids hold–up distribution and circulation patterns in various conventional gas–solid fluidized beds using open computational fluid dynamics source code. The increasing of fluidization velocity leads to the low solids hold–up in the central region and high solid particle accumulation in the near wall region due to the system backflow. Besides the conventional flow regimes, Haiyan and Zhu [7] explored the flow structure in a novel circulating–turbulent fluidized bed flow pattern. The characteristic of novel flow pattern is the combination of the advantages of turbulent and fast fluidization fluidized bed flow pattern. The high–density and homogenous solids distribution in the circulating–turbulent fluidized bed flow pattern leads to the higher gas–solid particle contact efficiency. Qiang *et al.* [8] and Chalermsinsuwan *et al.* [9] compared the novel circulating–turbulent fluidized bed flow pattern with the other conventional flow patterns. According to the results, the circulating–turbulent fluidized bed flow pattern had both similarities and differences with the other conventional flow patterns. The probability density distribution curve in novel flow pattern showed different peak patterns comparing to the other flow patterns. Qiang *et al.* [10] studied the contact efficiency in the novel circulating–turbulent fluidized bed regime by using fiber optic probe and carbon dioxide (CO_2) tracer injection. The results found that obtained contact efficiency was high in this novel flow pattern.

In this study, the solid particle distribution, the normal Reynolds stresses and the solid particle dispersion behavior in novel circulating–turbulent fluidized bed regime are explored using computational fluid dynamics simulation, comparing to the neighbor conventional regimes. The main objective is to investigate the effect of fluidization velocity on the normal Reynolds stress and solid diffusivity of solid particles which are the important quantitatively system mixing parameters. This knowledge will help engineer and scientist to design and operate better for this type of fluidized bed system.

Manuscript received April 20, 2016; revised October 30, 2016.

doi: 10.18178/ijmerr.5.4.260-263

II. METHODOLOGY

A. Computational Model

The simplified schematic drawing of the fluidized bed system is shown in Fig. 1. The system was sketched by using computer–aided design program, GAMBIT and simulated by using computational fluid dynamics simulation program, ANSYS FLUENT. The computational model in two–dimensional Cartesian coordinate system had 8,000 computation cells. The simulation time was 40 s. The gas was entered to the system at the bottom and exited at the top while the solid particles was circulated inside the system.

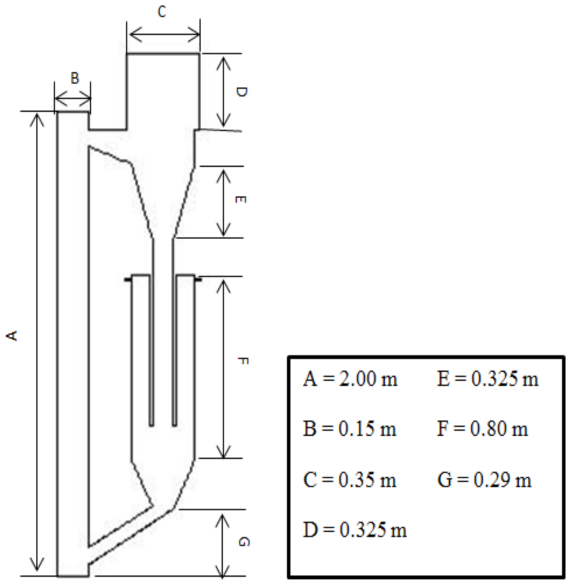

Figure 1. Simplified schematic drawing of fluidized bed system.

B. Mathematical Model

The mathematical model that used in this study consisted of three conservation equations, which were mass, momentum and fluctuating kinetic energy conservation equations, and other related constitutive equations similar to the ones employed by Chalermsinsuwan *et al.* [11]. For the constitutive equations, the kinetic theory of granular flow concept was used to explain the solid particle flow behavior. This model is developed based on the kinetic theory of gas with the modification of inelastic solid particle collision.

TABLE I. THE USED BOUNDARY AND INITIAL CONDITIONS.

Variable	Solid particle	Gas	Pressure outlet (atm)
Volume fraction (–)	0.60	0.0	1
Diameter (microns)	385	–	
Density (kg/m^3)	2,650	1.206	
Viscosity (kg/m.s)	–	0.000017	

C. Boundary and Initial Conditions

The system consisted of two inter-penetrating phases which were gas and solid particle phases. The gas phase was air and solid particles was potassium carbonate (K_2CO_3) solid particles. For the wall boundary condition, no slip condition was used for gas phase at the wall and partial slip condition was used for solid particle phase. For the initial conditions, there was solid particle phase inside the system. The other boundary and initial conditions are shown in Table I. The operating gravitational force was –9.81 m/s^2 and the operating pressure was set equal to 101,325 Pa. To analyze the solid particles behavior in the system with different flow patterns, the fluidization velocity was varied from 1.25, 1.50, 1.75 and 2.25 m/s which represent turbulent fluidized bed, circulating–turbulent fluidized bed and circulating fluidized bed flow patterns.

III. RESULTS AND DISCUSSION

A. Solid Particle Distribution (Solid Volume Fraction Distribution)

The important variable for fluidized bed system is the contacting area between gas and solid particles. In Fig. 2, the solid volume fraction was changed with different fluidization velocities. At velocity equal to 1.25 m/s, the fluidized bed system was laid in turbulent fluidized bed flow pattern or in batch operation. Therefore, it will not suitable for using in the continuous mode. When the fluidization velocity was increasing to 1.50 and 1.75 m/s, the solid particles expanded further up to the point that could be transfer or to be in the continuous mode. At this point, the system was laid in novel circulating–turbulent fluidized bed flow pattern. This novel flow pattern had high solid particle uniformly distributed in the system both in the axial and radial system directions. Considering the fluidization velocity at 2.25 m/s, the flow pattern was changed to fast fluidization flow pattern. The occurrence of core–annulus which reduced the efficiency of fluidized bed system was the major flow structure in this flow pattern.

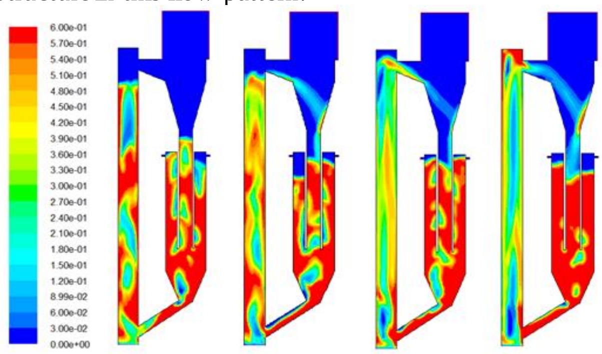

Figure 2. Contour of solid volume fraction with various fluidization velocities (1.25, 1.50, 1.75 and 2.25 m/s, respectively).

B. Normal Reynolds Stresses

The normal Reynolds stress is the additional stress due to random velocity fluctuations. The normal Reynolds stress ($\overline{v'_{s,i}v'_{s,i}}$) is calculated by Equations (1) and (2) as shown below,

$$\overline{v'_{s,i}v'_{s,i}} = \frac{1}{t}\int_{t_0}^{t_s}\left[v_{s,i}(t)-\bar{v}_{s,i}\right]\left[v_{s,i}(t)-\bar{v}_{s,i}\right]dt \quad (1)$$

$$\bar{v}_{s,i} = \frac{1}{t_s}\int_{t_0}^{t_s} v_{s,i}(t)dt \tag{2}$$

where $\bar{v}_{s,i}$ is the averaged fluctuation of hydrodynamic velocity of solid particles in *i* direction. The high normal Reynolds stress represents the high velocity fluctuations inside the system. From Fig. 3(a), the radial oscillations were high in the central region and low in the near wall region which made the high mixing in the central region and low mixing in the near wall region. From Fig. 3(b), the axial oscillations were comparable distributed throughout the system for all the fluidization velocities. This is due to the solid particles is uniformly dispersed across the system in these flow patterns. At the fluidization velocity of 1.50 and 1.75 m/s, the profile was similar and seemed likes flat profile in both the axial and radial directions which refers to the uniform mixing in all of the region. In addition, the normal Reynolds stresses was large in the direction of the flow because the velocity fluctuation was large in the direction of the flow.

C. *Solid Diffusivity*

The solid diffusivity (*d*) is an important indicator for quantifying the solid particle mixing. The first solid diffusivity was defined by Gidaspow [12].

$$d = \frac{1}{3\sqrt{\pi}}\frac{\sqrt{\Theta d_p}}{\varepsilon_s} \tag{3}$$

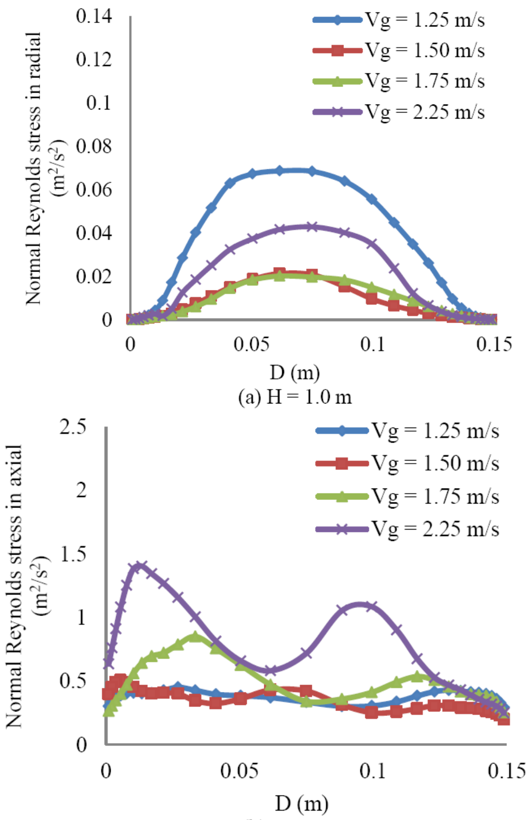

Figure 3. Radial distributions of the computed normal (a) radial and (b) axial Reynolds stresses at four different fluidization velocities.

The small solid diffusivity coefficient results in the well dispersed of solid particles. Fig. 4 shows the almost constant solid diffusivity coefficient across the system at four different fluidization velocities. However, the solid diffusivity coefficient in the top of the system with fluidization velocity of 1.25 m/s was rising rapidly. This can be attributed to occurrence of bubble bursting in the top system region. Also, the main solid particle quantity cannot move to that section because the system is batch operation. According to the results, the solid diffusivity coefficient with the gas inlet velocity of 1.50 and 1.75 m/s or the circulating–turbulent fluidized bed flow pattern showed the constant solid diffusivity coefficient comparing to the neighbor fluidization flow regimes. Therefore, the mixing in the system will be uniformly distributed throughout the system. Designing and operating the reactor in this flow pattern then will be good for occurring the chemical reaction.

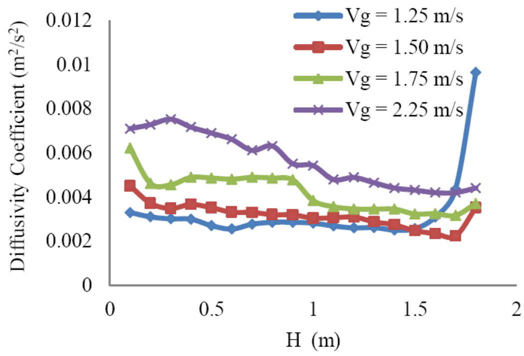

Figure 4. Solid diffusivity coefficient across the system at four different fluidization velocities.

IV. Conclusion

In this study, the objective is to investigate the effect of fluidization velocity on the normal Reynolds stress and solid diffusivity of solid particles which are the important quantitatively system mixing parameters. From the results, the solid particle flow patterns depended on fluidization velocities. Regarding the contour of solid volume fraction, it found that the solid particle behavior in novel circulating–turbulent fluidized bed had high solid particle uniformly distributed in the system both in the axial and radial system directions.

In addition, the circulating–turbulent fluidization flow regime showed the constant normal Reynolds stresses and solid diffusivity coefficient. Thus, the mixing in the system will be uniformly distributed throughout the system in this novel flow pattern. From all the obtained results, the future work is recommended to apply this novel circulating–turbulent fluidization flow regime to capture CO_2 comparing with the conventional flow regimes.

Notation

d_p diameter of solid particle (m)

D diameter of system (m)

H height of system (m)

t time (s)

v velocity (m/s)

Greek letters

ε_S solid volume fraction (–)

Θ granular temperature (m^2/s^2)

Subscripts

i direction in Cartesian coordinate

g gas phase

s solid phase

ACKNOWLEDGMENT

This study was financially supported by the Scholarship from the Graduate School, Chulalongkorn University to commemorate the 72nd anniversary of his Majesty King Bhumibol Aduladej, the 90th Anniversary of Chulalongkorn University Fund, the Ratchadaphiseksomphot Endowment Fund of Chulalongkorn University (CU-58-059-CC) and the Faculty of Science, Chulalongkorn University (GF 58 08 23 01).

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