

Research Article

Study on the Flow of Particle Agglomerates in Desulfurization Tower

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Abstract: In order to study the flow feature of particle agglomerates in a desulfurization tower, a three-dimensional numerical simulation of the gas-solid two phase flow in the tower is carried out by use of the LES model and the cohesive particles kinetics theory. Based on the experimental model of the internal circulation multistage spray desulfurization tower, the simulation successfully captures the key flow features in a desulfurization tower, find that: agglomerates forming a stable fluidization and stable internal circulation in the tower, present a typical ring-nuclear flow distribution trend. And the effects of the inlet gas velocity and inlet mass flux to the internal circulation are also analyzed.

Keywords: Agglomerates, cohesive particles, desulfurization tower, numerical simulation

INTRODUCTION

Particle agglomerations refers to part of the particles gather into agglomerations due to interactions of particles with the gas or other particles, which consequently move and react as a whole in the two-phase flow (Zhou, 2003). The particle agglomerations is a typical characteristic in the gas-solid flows, especially in dense flow of the circulating fluidized bed. Few particles flow in a state of single particle just in the top of the tower, the reaction with SO₂ between particle agglomerates and single particle is quite different (Liu and Liu, 2004). The flow characteristic of particle agglomeration would affect the gas-solid two-phase distribution and movement, heat and mass transfer rate and the wear of particles with the wall in the circulating fluidized bed directly. Therefore, the study of particle agglomerates flow characteristic in gas-solid circulating fluidized bed is an important topic that research dynamics of the gas-solid circulating fluidized bed. Yonemura *et al.* (1993) researched particles flow of the gas-solid two-phase in a vertical pipe and the generation and development of particle agglomerates in the circulating fluidized bed by the Direct Simulation Monte Carlo (DSMC). Liu and Xu (2004) researched the particle agglomerates flow in the circulating fluidized bed by the DSMC method.

Nowadays, in order to increase the absorbent recycling ratio, the majority of international and domestic installation designs of the circulating fluidized bed flue gas desulfurization systems include the external desulfurization ash recycling equipment.

In this study, we report that the multistage spouting fluidized flue gas desulfurization technology can

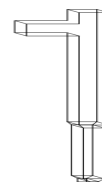


Fig. 1: Physical structure of the tower

further increase the effective utilization rate of the desulfurization catalyst, increase the desulfurization rate, reduce the equipment and operation costs and enhance the loading adaptability of the desulfurization tower. A stable uniform internal circulation formed in the multistage spouting desulfurization tower because of it is special internal structural unit and the variable cross-section area, it reduce the heat loss of the particles in the external circulation and also alleviate the load of the external circulation device (Gao *et al.*, 2007).

In this study, a three-dimensional numerical study of the flow feature of particle agglomerates in an internal circulation multistage spray desulfurization tower is carried out by use of the LES model and the cohesive particles kinetics theory. Particle agglomerates velocity distribution and particle agglomerates concentration distribution at different heights in the two-stage tower, the effects of the inlet gas velocity and inlet mass flux to the internal circulation are determined.

PHYSICAL MODEL

The model is setted up according to Gao (2007) experimental model, as shown in Fig. 1. The

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desulfurization tower is a two-stage tower, the total height is 3.5 m, the cross-section area of the level one tower is 160 mm×160 mm, the cross-section area of the level two tower is 240 mm×240 mm, the middle segment is a inverted vertebral with the inclination angle of 60°, the cross-section area of outlet is 240 mm×240 mm, as shown in Fig. 1.

MATHEMATICAL MODEL

The numerical simulations are carried out for simulating the gas-solid two-phase flow in the multistage spouting desulfurization tower by LES model for the gas flow and the cohesive particles kinetics theory for the particles after comparing various numerical simulation model, this model takes into account the particle collisions, viscous force, pulse and other factors comprehensively, so that this model is more suit for the gas-solid two-phase flow characteristics of ultra-fine particles and the simulation results are more accurate (Zheng, 2008). The model equations are as follows:

Gas mass equation:

$$\frac{\partial}{\partial t}(\rho_g \varepsilon_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{u}_g) = 0 \quad (1)$$

Solid mass equation:

$$\frac{\partial}{\partial t}(\rho_s \varepsilon_s) + \nabla \cdot (\varepsilon_s \rho_s \vec{u}_s) = 0 \quad (2)$$

Gas momentum conservation equation:

$$\begin{aligned} \frac{\partial}{\partial t}(\varepsilon_g \rho_g \vec{u}_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{u}_g \vec{u}_g) \\ = -\varepsilon_g \nabla p + \nabla \cdot \tau_g + \varepsilon_g \rho_g \mathbf{g} - \beta(u_g - u_s) \end{aligned} \quad (3)$$

where, \mathbf{g} is the stress tensor of gas phase:

$$\tau_g = \varepsilon_g \mu_g [\nabla \vec{u}_g + \nabla \vec{u}_g^T] - \frac{2}{3} \varepsilon_g \mu_g \nabla \cdot \vec{u}_g \quad (4)$$

$$\mu_g = \mu_{g,l} + \rho_g (0.1\Delta)^2 (\tau_g : \tau_g) \quad (5)$$

$$\Delta = (\Delta x \Delta y \Delta z)^{1/3} \quad (6)$$

The momentum conservation equation of particles phase is:

$$\begin{aligned} \frac{\partial}{\partial t}(\varepsilon_s \rho_s \vec{u}_s) + \nabla \cdot (\varepsilon_s \rho_s \vec{u}_s \vec{u}_s) \\ = -\nabla \cdot (T_k + T_c) + \varepsilon_s \rho_s \mathbf{g} + \beta(u_g - u_s) \end{aligned} \quad (7)$$

where, β is interphase drag coefficient.

Dynamic stress and collisions stress of particles:

$$T_k = \varepsilon_s \rho_s \theta_{gran} I \quad (8)$$

$$T_c = p_s I - 2\varepsilon_s \mu_{s0} \left[S + \frac{5}{6} (\nabla \cdot \vec{u}_s) I \right] \quad (9)$$

$$S_{ij} = \frac{1}{2} (W_{ij} + W_{ji}) - \frac{1}{3} (\nabla \cdot \vec{u}_s) \delta_{ij} \quad (10)$$

$$p_s = p_{s0} (1 + \xi_p(R_c)) \quad (11)$$

$$\mu_s = \mu_{s0} (1 + \xi_v(R_c)) \quad (12)$$

$$R_c = \sqrt{\frac{E_c}{e^2 m \theta_{gran}}} \quad (13)$$

$$\xi_p(R_c) = \frac{e}{1+e} (e^{-R_c^2} - 1) \quad (14)$$

While $n = 1$,

$$\begin{aligned} \xi_s(R_c) = \frac{e}{1+e} \left[e^{-R_c^2} \left(1 + \frac{R_c^2}{2} - \frac{R_c^4}{32} \right) + \left(\frac{R_c^4}{4} - \frac{R_c^6}{16} \right) \ln R_c \right. \\ \left. + \frac{R_c^8}{32} - \left(\frac{\gamma}{32} + \frac{1}{8} \right) R_c^6 + \frac{\gamma}{8} R_c^4 - 1 \right] \end{aligned} \quad (15)$$

$$p_{s0} = 2(1+e) \varepsilon_s^2 \rho_s g_0 \theta_{gran} \quad (16)$$

$$\mu_{s0} = \frac{4}{5} \varepsilon_s \rho_s g_0 \sigma (1+e) \sqrt{\frac{\theta_{gran}}{\pi}} \quad (17)$$

where, σ is the particle agglomerates diameter
Pulsating energy conservation equation of particles:

$$\begin{aligned} \frac{\partial}{\partial t} \left[\varepsilon_s \rho_s \left(\frac{3\theta_{gran}}{2} \right) \right] + \nabla \cdot \left[\varepsilon_s \rho_s \vec{u}_s \left(\frac{3\theta_{gran}}{2} \right) \right] \\ = -\nabla \cdot (q_k + q_c) - (T_k + T_c) : \nabla \vec{u}_s \\ + N_c \left(\frac{1}{2} m C^2 \right) + \varepsilon_s \rho_s (\vec{f}_{drag} \cdot \vec{C}) \end{aligned} \quad (18)$$

where,

$$q_c = q_{c1} + q_{c2} \quad (19)$$

While $n = 1$,

$$\begin{aligned} q_{c1} = -\frac{224}{3} \varepsilon_s g_0 \rho_s \varepsilon_s \sqrt{\frac{\theta_{gran}}{\pi}} \left\{ 1 + e \left[e^{-R_c^2} \left(1 + \frac{1}{7} R_c^2 \right. \right. \right. \\ \left. \left. - \frac{1}{28} R_c^4 + \frac{3}{448} R_c^6 \right) + \left(\frac{3}{224} R_c^8 - \frac{1}{28} R_c^6 \right) \ln R_c \right. \right. \\ \left. \left. - \frac{\gamma}{56} R_c^6 + \left(\frac{1}{56} + \frac{3\gamma}{448} \right) R_c^8 - \frac{3}{448} R_c^{10} \right] \right\} \end{aligned} \quad (20)$$

Table 1: Parameters for the simulation

Particle shape	Sphere	Primary particle size	5 μm
Inlet particle concentration	0.05 kg/s	Inlet velocity	4.5 m/s
Density of particle	2500 kg/m ³	Superficial density of particle	790 kg/m ³
Temperature	300 K	Bed height	3.5 m
Particle-to-wall restitution coefficient	0.5	Particle-to-particle restitution coefficient	0.5
Time step	0.0001 s	Total time	30 s

$$q_{c2} = -\frac{14}{15} \varepsilon_s g_0 \rho_s \varepsilon_s \sigma \sqrt{\frac{\theta_{gran}}{\pi}} [W_{ij} + W_{ji} + (\nabla \cdot \bar{u}_s) I] \left\{ 1 + \frac{30}{7} e \left[\frac{1}{10} \sqrt{\pi} e^{-R_c^2} + \frac{2}{15} \sqrt{\pi} \left[e^{-R_c^2} \left(1 + \frac{1}{4} R_c^2 - \frac{1}{16} R_c^4 + \frac{3}{256} R_c^6 \right) + \left(\frac{1}{16} R_c^6 + \frac{3}{128} R_c^8 \right) \ln R_c + \frac{\gamma}{32} R_c^6 + \left(\frac{3\gamma}{256} - \frac{1}{32} \right) R_c^8 - \frac{3}{256} R_c^{10} \right] \right\} \right. \quad (21)$$

Gas-solid interphase force:

$$\beta = \frac{3C_d \varepsilon_s \rho_g |\bar{u}_g - \bar{u}_s|}{4\sigma} \varepsilon_g^{-2.65} \quad (22)$$

$$C_d = 24(1 + 0.15 \text{Re}^{0.687}) / \text{Re} \quad \text{Re} \leq 1000 \quad (23)$$

$$C_d = 0.44 \quad \text{Re} > 1000 \quad (24)$$

$$\text{Re} = \rho_g \varepsilon_g \sigma |\bar{u}_g - \bar{u}_s| / \mu_g \quad (25)$$

Boundary conditions and parameters: The concentration and velocity of both gas and particles are set at the tower inlet. However, only the pressure is set at the tower outlet. No particles within the absorption tower before simulating, just clean air is full of the whole tower. The gas phase flow as a no-slip style near the wall, however, for the particle phase, just only the centripetal velocity is determined to zero near the wall, the boundary conditions of the tangential velocity (Antonio *et al.*, 1998) are as follows:

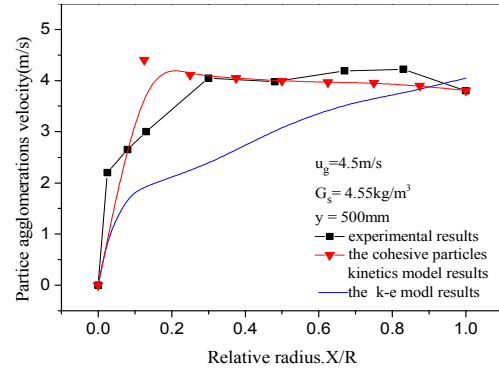
$$v_{t,w} = -\frac{\sigma}{(1-\varepsilon_g)^{1/3}} \frac{\partial v_{s,w}}{\partial n} + \left(\frac{A}{\rho_s \sigma^{1/3}} \right)^{1/2} (1-\varepsilon_g) \quad (26)$$

where, A is the Hamaker constant

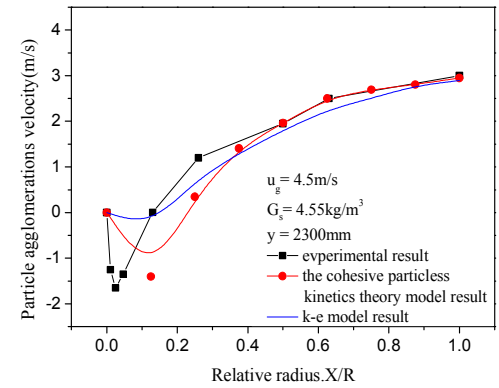
In the numerical simulation, particles are selected as ultrafine particle of fly ash. Parameters, such as the particle size and density etc, are set as shown in Table 1:

RESULTS AND DISCUSSION

Agglomerates axial velocity distribution: Figure 2 reports the difference of agglomerates axial velocity at



(a) The level one tower



(b) The level two tower

Fig. 2: Agglomerates axial velocity profiles at different depths y, for experiment and simulation

different heights in desulfurization tower between simulation results and Gao Jian-min PDA experimental values as well as its simulation results simulated by the k-ε model. As it can be seen, the simulated results of this study is agreement with the experimental better than the simulation results simulated by the k-ε model, this may be result from: the LES model used in the gas simulation is more realistic than the k-ε model; Furthermore, the k-ε model not consider the agglomerate effect, the physical characteristics of the agglomerate and the impact of gas-solid flow caused by collisions among agglomerates. As well as, the viscous particle kinetics method used in this study takes a comprehensive consideration on the impact of the agglomerates. The simulation results is agreement with the experimental results very well, but some numerical deviations still exist, this may be because of ignoring of the deviation caused by the collisions among agglomerates.

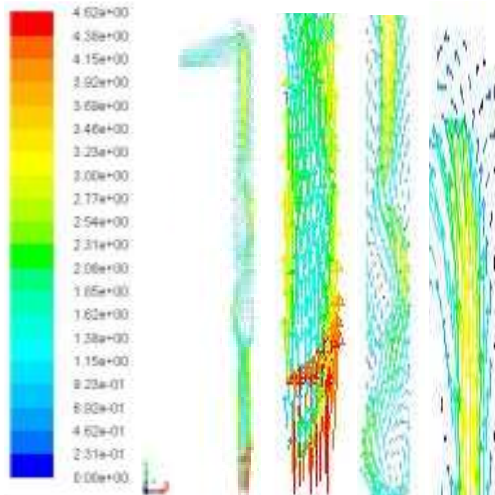


Fig. 3: Agglomerates axial velocity distribution

Figure 3 shows the agglomerates axial velocity vector distribution. As it can be seen, the agglomerates speed upward overall in the level one tower, eddy current occurs at joints two-level tower due to changing of the tower cross-section area; The agglomerates also speed upward near the center of the level two tower, however, the distribution is not as symmetrical as in the level one tower and presents the S-type flow, an obvious reflux exist at the side of the wall; The reflow at the top of tower indicates that agglomerates speed up at the top of tower with the gas entrainment effect and then flow back along the wall; At the same time, it can lead to agglomerates accumulation easily, so some appropriate measures must be take to avoid the excessive accumulation.

Figure 4a reports the agglomerates axial velocity at different depths y in the level one tower. The disturbance of the flow is very strong near venturi inlet at the bottom of the tower, the flow is diverse at

different location of the same height and shows that the velocity is higher at the side of the wall than at the center of the tower, this mainly because of the structure of the venturi inlet, as a result, disturbance exist at some places. The flow in the tower tends to be stable with increasing of height and makes regularity enhancement gradually.

Figure 4b reports the agglomerates axial velocity profile at different depths y in the level two tower. The flow is influenced by local eddy strongly at the zone near the joints two-level tower (such as $y = 1840$ mm), however, it is stable basically at other height regions, showing that agglomerates speed upward overall at the center of the tower, agglomerates are easy to be broken due to the shear force such as gravity. However, the flow is stationary almost or speed downward near the wall, showing that agglomerates flow slowly at this region, therefore it is easy to cause particle gathered to generate larger particle agglomerates.

Figure 5 reports the velocity profile of the gas at three different depths y in the two level tower. The gas velocity distribution are very similar with the agglomerates velocity distribution in Fig. 4 at the same cross-section, however, it is can be seen that the gas velocity is higher than agglomerates velocity significantly and the gas-solid slip velocity exit obviously. The gas-solid slip velocity in the usual circulating fluidized bed is very small, so the variable cross-section area of the tower contribute to increase the gas-solid slip velocity in the tower; thereby the mass transfer coefficient is increased so much. In the process of chemical reaction and the gas-liquid solid three mass transfer in the absorber tower, the flow velocity in the desulfurization tower is decided by the gas-liquid mass transfer processes because the chemical reaction is very fast.

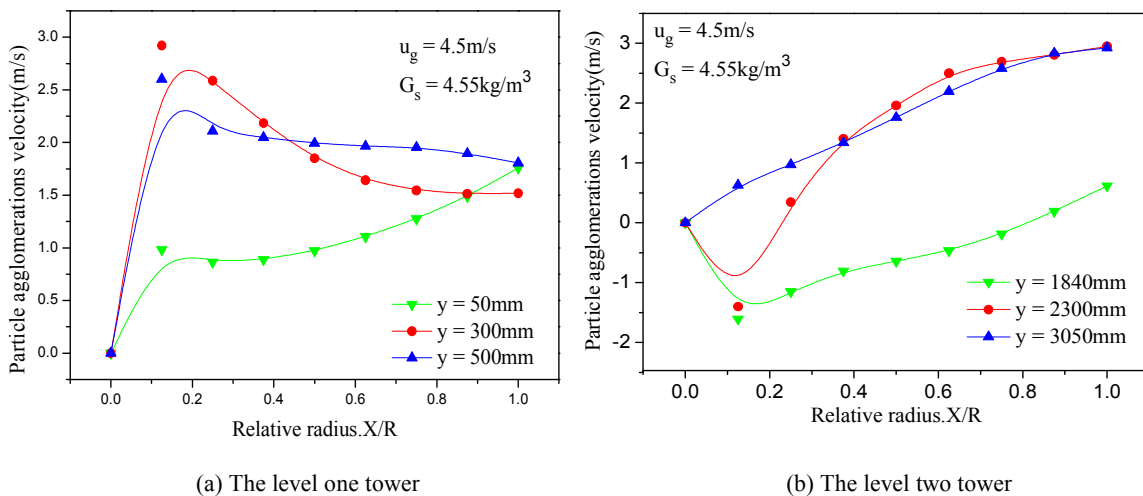


Fig. 4: Agglomerates time-averaged velocity profiles at different depths y

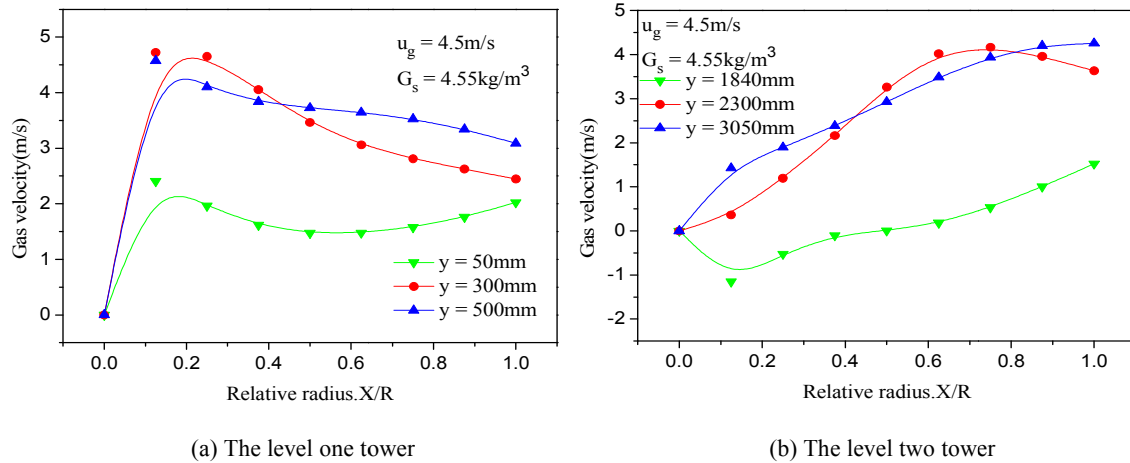


Fig. 5: Gas phase time-averaged velocity profiles at different depths y

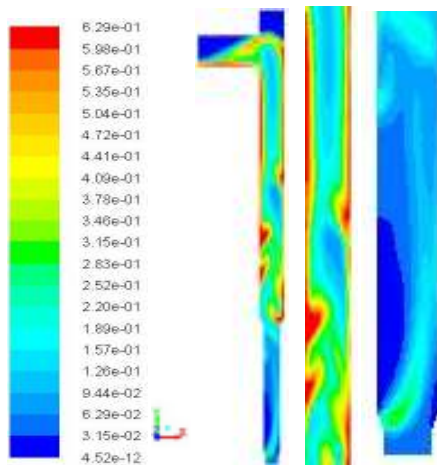


Fig. 6: Agglomerates concentration distribution

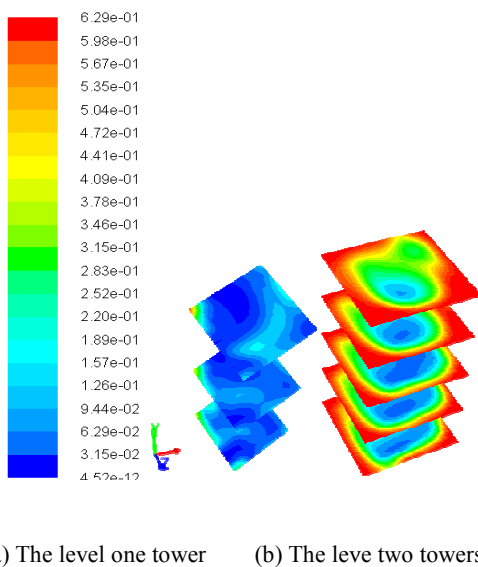


Fig. 7: Agglomerates concentration profiles, for the level one tower and the level two towers

Agglomerates radial concentration: The gas are spouted into the tower from the venturi inlet located at the bottom of the multistage spouting desulfurization tower, agglomerates speed upward in a high velocity carried by airflow, so a agglomerates high velocity spouting zone is formed and the concentration of the particle agglomerates is very low in the spouting zone, the gas has radial penetration effect while it speed upward, so that some particles and particle agglomerates permeate into the annular gap zone near the side wall of the tower from the spouting zone, particles and particle agglomerates speed downward slowly around the spouting zone in the annular gap zone.

Figure 6 shows that the concentration profile of the particle agglomerates measured with the gas inlet velocity is 4.5 m/s and mass flow rate is 4.55 kg/m²s. As it can be seen, the regulation of the agglomerates flow is poor at the inlet and outlet of the absorption tower affected by the structure, however, the agglomeration flow at the other parts of the absorption tower all exhibits core-annulus flow structure distribution trend with dense agglomerations near the wall and sparse at the center of the tower. The concentration of the particle agglomerates in the level two tower is higher than in the level one tower, especially near the side of the wall. The concentration profile of the particle agglomerates shows that the concentration near the side of the wall is much higher than the center zone, this can be interpreted that particle agglomerates backflow near the side of the wall, so that a stable particles agglomerates internal circulation is format in the level two tower, this is agreement with the experimental results.

Figure 7 shows that the concentration profiles of the particle agglomerates at different cross-section areas in the two-stage tower. As it can be seen from the eight cross-section areas, compared with the level one tower,

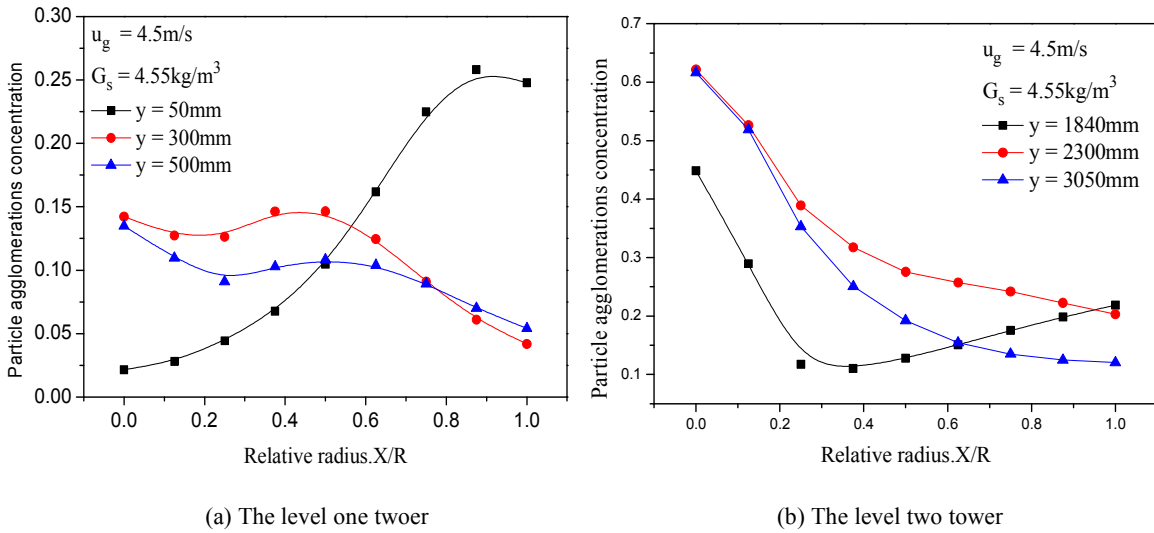


Fig. 8: Agglomerates concentration profiles at different depths y

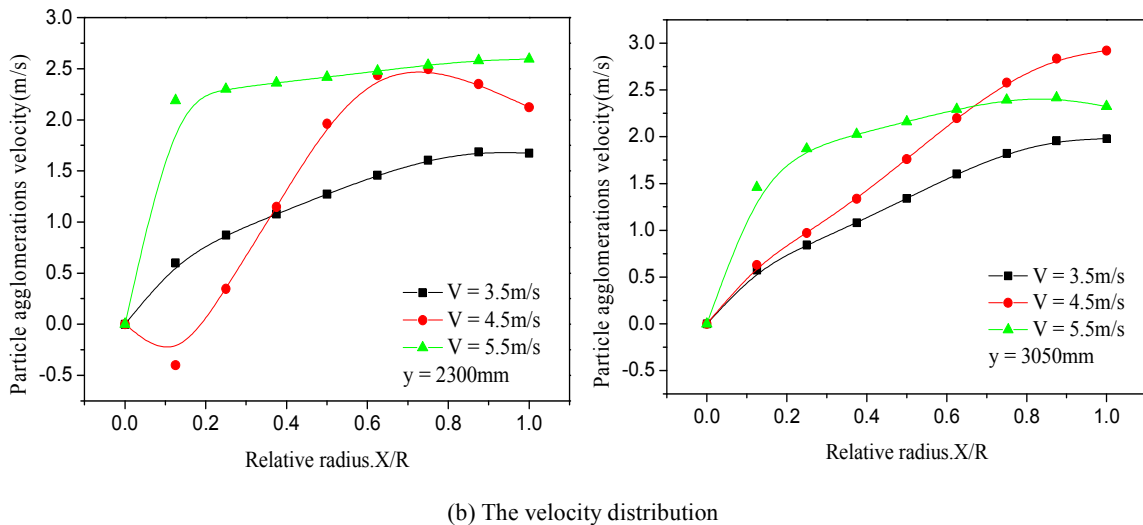
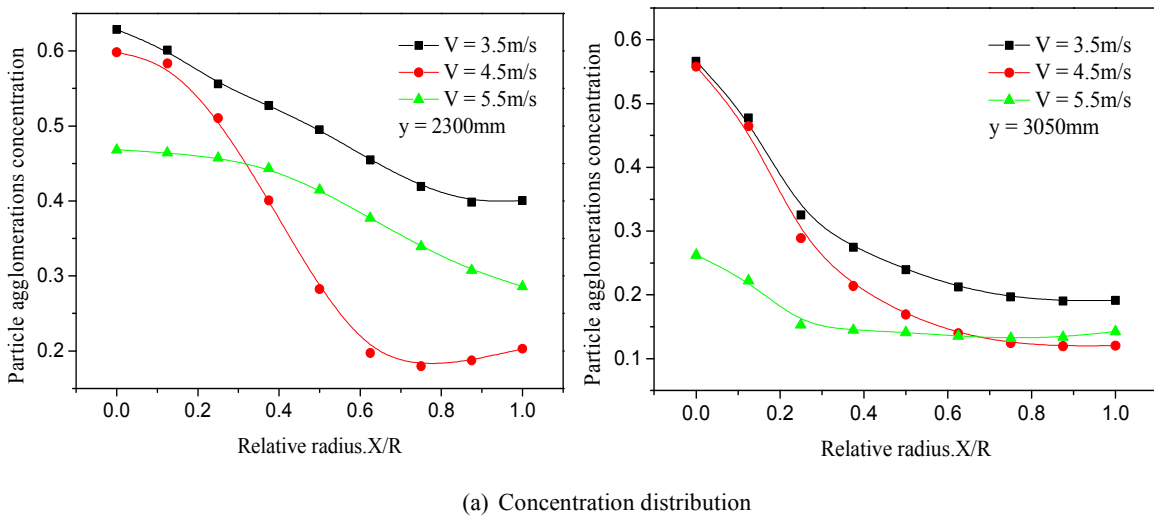


Fig. 9: Agglomerates time-averaged concentration and velocity profiles with three different gas inlet velocity

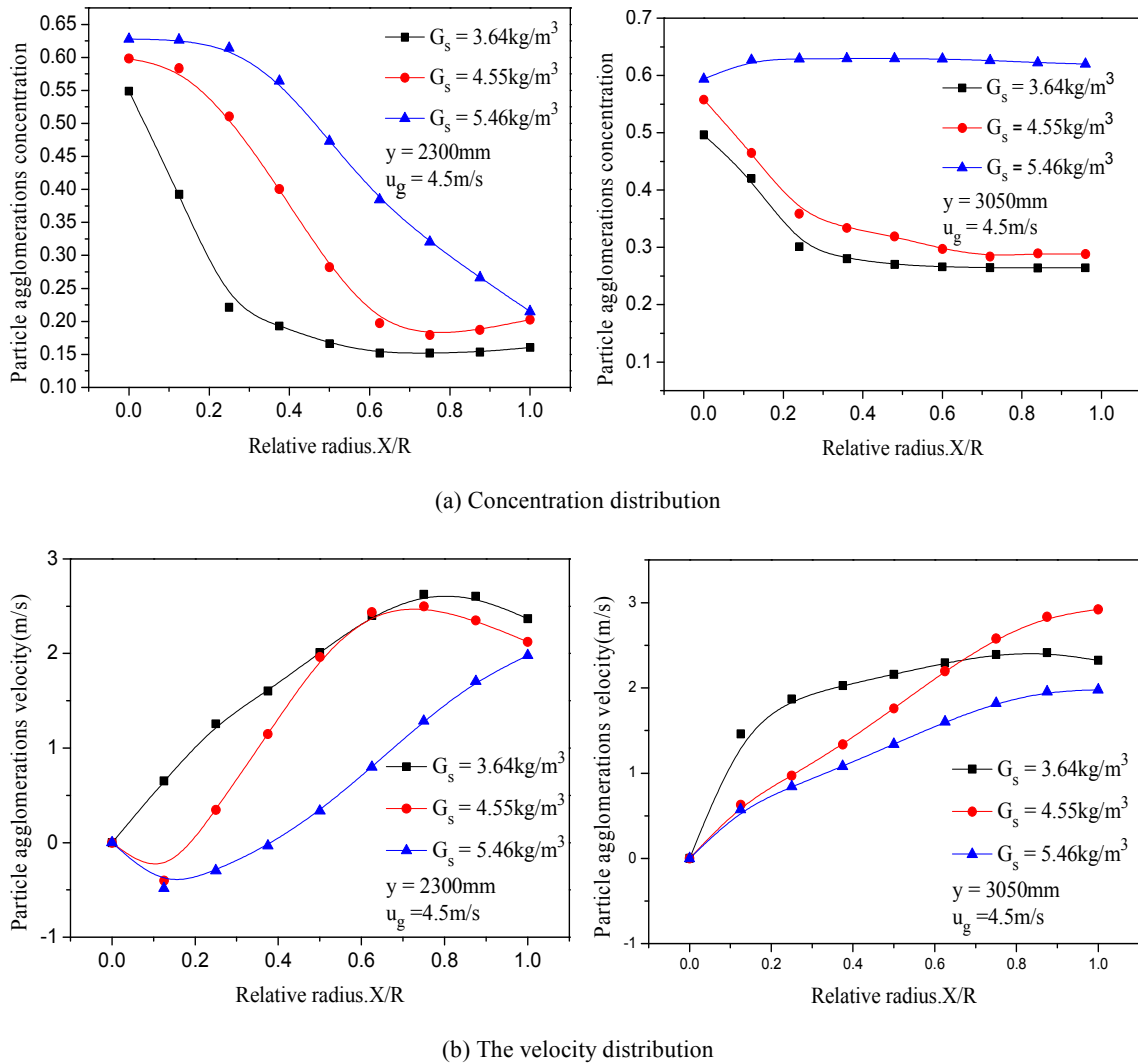


Fig. 10: Agglomerates time-averaged concentration and velocity profiles with three different inlet mass flow

the concentration of the particle agglomerates in the level two tower increase markedly, especially near the side of the wall, this indicates that a uniform stable internal circulation is formed in the level two tower.

Figure 8 reports that the concentration profiles of the particle agglomerates at three different depths y . The regularity of the particle agglomerates concentration in the level one tower is poor, it because ultrafine particles used in the study are carried by gas flow easily, so it is influenced by the intense pulsating spouted from venturi near the tower inlet strongly and lead to the regularity to be poor. Secondly, it may also be because of not considering the crushing phenomenon among particle agglomerates, so further researching discussions are needed. In the level two tower, the agglomerates concentration near the side wall is higher than at the center zone significantly, this may be because the disturbance caused by airflow is weakened.

The influence of gas inlet velocity to the flow characteristic of particles and particle agglomerates:

Figure 9 reports that the influence of gas inlet velocity to the concentration and velocity of particle agglomerates. As it can be seen, changing of the gas inlet velocity has a large impact on the particle internal circulation within the tower, high gas velocity can increase particles velocity, but also lead particles concentration reduce in the absorption tower, this is because high gas velocity strengthens the ability of the gas entrained particles and enhances the particle agglomerates velocity and will reduce the chance of particle agglomerates collide with each other, so that the concentration of particle agglomerates within tower will reduce and number of particles escaped out the tower will increase, so the reflux is more and more inconspicuous even disappears completely, that is number of internal circulation particles will reduce.

The influence of inlet mass flow to the flow characteristics of particles and particle agglomerates: Figure 10 shows that the influence of inlet mass flow to the concentration and velocity of particles and particle agglomerates. It can be seen that the particle agglomerates concentration will increase with the increasing inlet mass flow as inlet gas velocity is constant, especially near the side wall of the tower. The increasing mass flow promotes particles gather into agglomerates, especially near the side wall of the tower and the regularity get worse and worse; The difference of the agglomerates concentration between at the side wall and at the center is more and more inconspicuous gradually with the increasing of the bed height, lead to agglomerates accumulate throughout the whole plane.

It can be seen from Fig. 10b that the concentration of particle agglomerates will increase but velocity will reduce with increasing of inlet mass flow. This may be result from the probability that collisions among particle agglomerates strengthen with increasing of inlet mass flow and the collisions among particle agglomerates can lead energy consumpt, which reduces the ability of gas carry particle agglomerates out of the tower, so that the phenomenon above appear.

CONCLUSION

A numerical simulation was performed to the internal circulating multistage spouting desulfurization tower based on LES and the cohesive particles kinetics theory to study agglomerates flow characteristics in the gas-solid tow phase flow. The results shows that particle agglomerates have low velocity and high concentration in the level one tower but opposite in the level two tower, due to the variable tower body cross-section area and lead to particles form a stable uniform internal circulation in the level two tower; And gas-solid disturbance is enhanced, the utilization of desulfurizer is improved, gas-solid slip velocity is also increased, thereby the gas-liquid mass transfer process which determines the desulfurization rate in tower to be strengthened.

Some conclusions can be found by contrastive analysis under diverse flow conditions that: changes of the gas inlet velocity has a great impact on the flow of particles and particle agglomerates, particle circulated

concentration will reduce with increasing the gas inlet velocity; However, the particle agglomerates velocity will reduce with increasing the inlet mass flow and particles accumulate to be particle agglomerates as a result.

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