Numerical Simulation into Agglomeration Process of Inhalable Particle in Double Gas-Jets

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Keywords: Inhalable particles; CFD ; PBM ; double jets; turbulence; agglomeration

Abstract. Inhalable particles from coal-fired plant were an important atmosphere pollutants. The removal technology has been investigated widely. A computational fluid dynamics model, coupled with population balance model (CFD-PBM), could be used to predict the particles agglomeration in turbulent flow. The calculation results suggested that double gas jet could favor the agglomeration of inhalable particles. When the jet nozzles were located asymmetrically in the opposite wall, the removal efficiency was maximum. Increasing Re number on jet exit could result in the incremental of removal efficiency. All these modeling results were similar with the experimental mass removal efficiency.

Introduction

Inhalable particles from industrial processes have a typical size of less than 10 μm. Particulate pollutions have recently gained much attention because they are considered as a serious public health concern[1]. These particles are difficult to remove by conventional separation devices. Therefore, the agglomerate of inhalable particles into larger particles becomes a new trend of dust removal technology [2-3]. In turbulence flow, inhalable particles could acquire turbulent energy from fluid to increase the collision with other particles. Turbulent agglomeration is an important agglomeration method.

In recent years, the computational fluid dynamics (CFD) method has developed rapidly and is applied widely to predict the hydrodynamic characteristics of single-phase and two-phase flows in stirred tanks[4]. In two-phase flow, the coalescence and breakup of particles or droplets could be calculated by population balance modeling (PBM). Liu etal [6] simulated the agglomeration of particles in turbulent flow using a coupled two-fluid model and PBM, and found good feasibility of the model. A combination of CFD and droplet population balance modeling(DPBM) was applied to simulate the drop size distributions and flow fields in a liquid-liquid RDC extractor [5] , and found that the modeling results were corresponding to the experimental data.

In this paper, a high gas jet was introduced into particle agglomeration chamber to form a local turbulent flow. Inhalable particles in chamber were agglomerated in the local turbulent environment. The coupling of CFD and PBM predicted the revolution of particles size. The aim of this paper was to study the effect of gas jet on the distribution and removal of inhalable particle. Simulation results were compared with experimental data obtained in our laboratory.

Numerical Simulation

Physical model. The agglomeration chamber was 2D structure with size of ϕ114×600 mm. Six jet nozzles with diameter of 2 mm were installed symmetrically on chamber. The distance was 100 mm, 200 mm and 300 mm from the upper inlet of aerosol containing inhalalble particles, respectively. Before calculation, quadrilateral elements with a grid space of 0.01mm were adopted to map the flow domain (701 cells), as depicted in Fig.1.

Mathematical model

Two-phase fluid model. The numerical simulations were based on the classic Eulerian-Eulerian "two-fluid" model, which assumed that the continuous and dispersed phase are all continuous interpenetrating into and interacting with each other in the whole domain under consideration[7]. Momentum and continuity equations are solved for each phase. Standard k-ε model is selected to calculate two-phase flow, because the particle phase concentrations is too rare to affect the flow of main phase[4].

Population balance model. Binary collision-aggregation is the dominating mode of particle aggregation, which results in the variation of particle number concentration. Population balance model can be used to predict the varying rate of particle number concentration, which is described via Eq (1):

$$\frac{\partial}{\partial t}[n(v,t)] = \frac{1}{2}\int_0^v a(v-v',v')n(v-v',t)n(v',t)dv' - \int_0^\infty a(v,v')n(v,t)n(v',t)dv' \quad (1)$$

Where $a(v,v')$ is the aggregation kernel between two particle with volumes of v and v'. $n(v,t)$ is the size distribution function. $\partial[n(v,t)]$ is the number concentration(particles per m^3) in the volume range v, $v+dv$ at time t.

Various methods can be used to solve this equation[8]. In this paper, PBM equation was solved by the discrete method.

Turbulent Aggregation Kernel. For the viscous subrange, particle collisions are influenced by the local shear within the eddy. Based on the study by Saffman and Turner, the collision rate is expressed as Eq (2).

$$a(d_i,d_j) = V_T\sqrt{\frac{8p}{15}}g\frac{(d_i+d_j)^3}{8} \quad (2)$$

Where d_i, d_j is the diameter of particle i and j, respectively. V_T is a pre-factor that takes into account the capture efficiency coefficient of turbulent collision. g is the shear rate.

Because particles are bigger than the smallest eddy in the inertial subrange, they are dragged by velocity fluctuations in the flow field. In this case, the aggregation rate is expressed using Abrahamson's model, as Eq (3)

$$a(d_i,d_j) = V_T 2^{3/2}\sqrt{p}\frac{(d_i+d_j)^2}{4}\sqrt{(U_i^2+U_j^2)} \quad (3)$$

where U_i^2 is the mean squared velocity for particle *i*.

Boundary Conditions. The aerosol inlet boundary was velocity condition, which was 0.217 m/s. And the outlet boundary was pressure condition. The particle density was 1838 kg/m^3, and the initial particle fraction was 1%. The simulations were unsteadily carried out to reduce the time step from 0.1 to 0.001s, using the first order implicit solver. The initial particle size was divided into nine intervals between 0.43 μm and 17 μm, which was shown in Table 1.

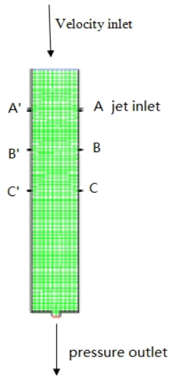

Fig. 1 Computational grid for agglomeration chamber

Table 1 Initial particle size distribution

	particle size(μm)	fraction
Bin-0	17	0.0712
Bin-1	11	0.1023
Bin-2	6.9	0.0551
Bin-3	4.3	0.1294
Bin-4	2.7	0.2971
Bin-5	1.7	0.2252
Bin-6	1.1	0.0862
Bin-7	0.68	0.0312
Bin-8	0.43	0.0024

Results and discussion

Effect of gas jet on inhalable particle distribution. In agglomeration chamber, there were drag force, van der Waals forces and gas jet among particles. In our previous experimental results[9], gas jet could reduce the mass of inhalable particles. Fig.2a showed the modeling volume fraction of particles. One could find that the volume fraction decreased obviously under the action of gas jet. Double gas jet could remove more inhalable particles, which was consistent with the experimental results [9]. As comparison, fig.2b illustrated the experimental mass distribution. One could find the medium size of inhalable particle could be reduced greatly in turbulent agglomeration process. The volume fraction could reduce to about 10% for medium size particle and to 5% for large particles. However, the mass fraction was still above 12% for medium particles. In the simulation process, the peak data of volume fraction was in size of 2.7 μm for the initial particles. After agglomeration, the maximum fraction was shifted to 4.3μm.

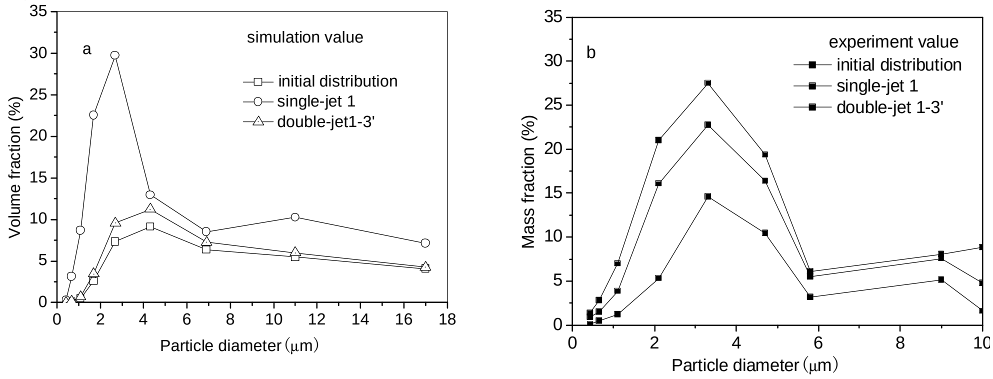

Fig. 2 Effect of gas jet on inhalable particle mass distribution

Effect of double jet site on removal efficiency of inhalable particle. Double gas jet sites could affect the structure of vertex in turbulent flow to change the collision among particles. The effect of double gas jet location on number removal efficiency of inhalable particle was shown in Fig.3a. From the figure, one could find the small particles (<2 μm) were easy to be removed in gas jet flow. The number removal efficiency exceeded 90%. However, the removal of 7 μm particles was in range of 20-60%. For large particles (⩾10 μm), the number removal efficiency was about 60% in different double gas jet flow. The number removal results were similar with the variation of mass efficiency[9]. Fig.3b showed the removal comparison of simulation and experimental data. One also found the maximum removal efficiency was acquired when the jet nozzles were located asymmetrically in the opposite wall. This result could be explained by the fact that the formation of a plurality of vortex structure between double jets and jet downstream increased the entrainment of inhalable particles in gas flow and strengthen the effective collisions between particles. However, the simulation values were higher than the experimental data. This may be due to the average density values for different size particles in calculation process.

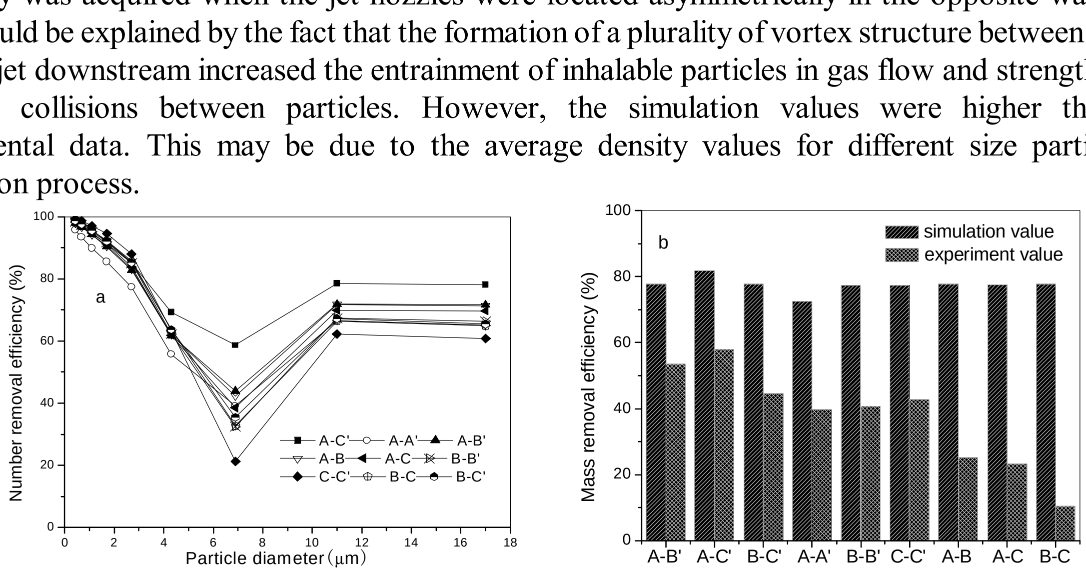

Fig. 3 Effect of double gas jet on removal efficiency of inhalable particle

Effect of Re number on jet exit of double gas jet. Effect of Re number on exit of double gas jet on removal efficiency of inhalable particle was shown in Fig.4. The number and mass removal efficiency increased with the incremental Re number on jet exit. For low Re number, the model number efficiency was less than 0% for particles of 7μm, which indicated the number concentration increased under the action of gas jet. In low Re number, the entrainments of gas jet were weak for particles, which resulted in slight agglomeration of small particles to form medium particles. The particle diameter affected the removal efficiency. For small particles (<2 μm), the calculated number removal efficiency was higher than the experimental mass removal value. This result was similar with the previous reports[10]. However, the number efficiency was consisted with the mass removal values for large particles (≥10 μm).

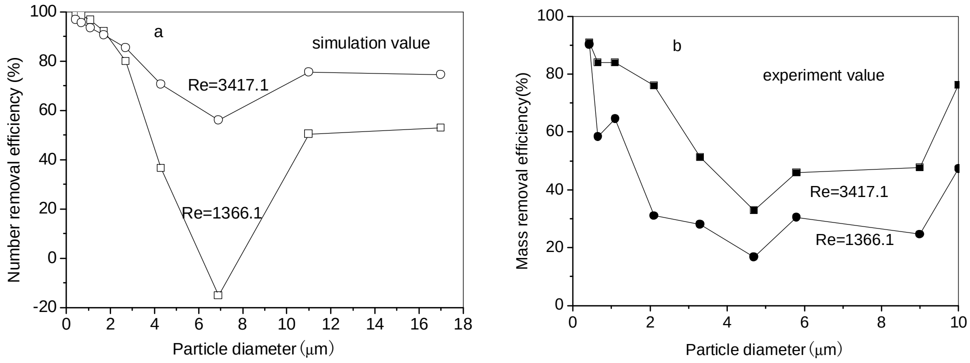

Fig. 4 Effect of Re number on exit of double gas jet on single-stage removal efficiency of inhalable particle

Conclusion

1) The volume fraction of inhalable particles decreased obviously under the action of gas jet. By comparison with single gas jet, double gas jet could remove more inhalable particles. The simulation results indicated that peak particle diameter increased from 2.7 μm to 4.3 μm.

2) The locations of jet nozzles could affect the removal of inhalable particles. The maximum removal efficiency was acquired when the jet nozzles were located asymmetrically in the opposite wall, which was consistent with the experimental data.

3) Increasing Re number on jet exit could result in the incremental of removal efficiency. For small particles (<2 μm), the calculated number removal efficiency was higher than the experimental mass removal value. The number efficiency was consisted with the mass removal values for large particles (≥10 μm).

Acknowledgment

The authors wish to acknowledge the financial support from National Natural Science Foundation of China (Contract No. 21206080) and from Postdoctoral Innovation Fund of Shandong Province (Contract No. 201203027).

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