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Effect of moisture on the performance of a gas cyclone

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Abstract

Traditional gas cyclones are effective in collecting fine but not ultrafine particles. A recent proposed technology, cloud-air-purifying (CAP) shows that by introducing moisture in the cyclone, the collection efficiency for ultrafine particles can be significantly enhanced. This paper presents a numerical study to understand the effect of moisture content on the collection efficiency of fine to ultrafine particles in a gas cyclone. The multiphase (air, vapour and particles) flow in the cyclone is simulated by computational fluid dynamics (CFD) by using Fluent software. The turbulence of air flow is modelled by the Reynolds Stress Model (RSM), and the particles are modelled by Lagrangian particle tracking (LPT) model. In addition, the particle growth due to the absorption of the moisture is modelled and implemented in Fluent simulations through the user defined function (UDF). The effect of moisture content on the performance of the cyclone is studied by a series of controlled numerical experiments. The results demonstrate that the particle collection efficiency increases with the increase of super-saturation rate. Ultrafine particles can be more effectively collected because of the increase in their sizes. Moreover, three different flow patterns of particles are identified in the cyclone, which can be related to the micromechanisms of the separations of different sized particles. These studies can help improve the understanding of CAP technology.

Keywords: *Air purifying, Gas cyclone, Computational Fluid Dynamics, Condensation, Particle growth.*

1. INTRODUCTION

Gas cyclones are important devices widely used in many industry applications for removing solid particles from gas streams that. Comparing to other technologies, they provide a favourable balance between performance and cost. Collection efficiency, grade efficiency and pressure drop are the main performance characteristics of a gas cyclone(Avci and Karagoz 2003). Many studies have been conducted on the effects of various influence factors on the performance of gas cyclones, mainly for improving the collection efficiency and decreasing the pressure drop. Previously these studies were focused on the cyclone geometry and the operational condition. For example, it was found that the most advisable operation for a high collection efficiency is to guarantee the natural vortex be longer than the cyclone length (Cortes and Gil 2007), which however will be strongly influenced by inlet velocity, cyclone length, wall roughness, diameter and length of vortex finder(Qian and Zhang 2005, Cortes and Gil 2007). On the other hand, reasonably increasing solid loading can both improve the collection efficiency and decrease the pressure drop (Hoffmannc, Van Santen et al. 1992, Derksen, Sundaresan et al. 2006).
Though gas cyclones are effective in separating fine particles, with the cut-off size of 1.7 μm at which separation efficiency is 50% , they are poor at separating ultrafine particles smaller than 1 μm(Song, Pei et al. 2016). Recently, cloud-air-purifying (CAP) technology has been developed to overcome this difficulty by generating an artificial cloud environment in the cyclone where ultrafine particles can become the cloud condensation nucleus (CCN) and grow into a bigger size, similar to the formation of rain drops in natural clouds. However, it is difficult to study this process at microscopic scale by experiments, while numerical simulation based on computational fluid dynamics (CFD) provides a

cost-effective alternative. Using CFD model, Wang et al. (Wang, Xu et al. 2006) studied gas-solid flow in a cyclone separator and found that the secondary circulation flows, including short-circuiting flow, eddy flow and eccentric circumfluence can deteriorate the performance. Song et al. (Song, Pei et al. 2016) analysed the forces on the particles by CFD and demonstrated the roles of different forces will be changed with particle size.

In this paper, the multiphase flow is simulated by CFD commercial software FLUENT with the condensations of moisture on particles considered. The air turbulence flow is modelled by Reynolds Stress Model (RSM) which can improve the solution accuracy (Wang, Xu et al. 2006). Particle motion is tracked by Lagrangian particle tracking model (LPT). In particular, the particle growth based on the vapour condensation is implemented in FLUENT through user defined function (UDF). The effect of moisture on the particle growth and cyclone separation performance is investigated and the flow patterns of the uncollected particles are divided into similar three flow patterns identified in the secondary circulation. These analyses improve our microsocial understanding on the effect of moisture on the collection efficiency of the gas cyclone, and can help optimize CAP technology.

2. METHOD DESCRIPTION

2.1 CFD model description

The governing equations for an incompressible fluid can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial \rho}{\partial x_i} + \frac{\partial \rho}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}(-\rho\overline{u_i' u_j'}) \tag{2}$$

Here the turbulence flow is modelled by Reynolds stress model (RSM). The velocity components are decomposed into the mean $\overline{u_i}$ and fluctuating u_i' (i=1, 2, 3) components, which are related by:

$$u_i = \overline{u_i} + u_i' \tag{3}$$

where the Reynold stress term $-\rho\overline{u_i' u_j'}$ includes the turbulence item, which must be modelled to solve Eq 2.

The transport equations for Reynold stress term-- $\rho\overline{u_i' u_j'}$ in the RSM are:

$$\frac{\partial}{\partial t}\left(\rho\overline{u_i' u_j'}\right) + \frac{\partial}{\partial x_k}\left(\rho u_k \overline{u_i' u_j'}\right) = D_{T,ij} + P_{ij} + \emptyset_{ij} + \varepsilon_{ij} \tag{4}$$

where the two terms at the left side are local time derivative of stress and convective transport term respectively, and the four terms at the right side are turbulent diffusion, stress production, pressure strain term, dissipation respectively.

LPT model is used to describe the particle motion in cyclone separator. Note that model ignores the effect of particle on the flow and collision between individual particles while particle flow is treated as dilute flow. The momentum equation of particles in the cyclone can be expressed as:

$$\frac{du_{p_i}}{dt} = F_k\left(\bar{u}_i + u'_i - u_{p_i}\right) - g \tag{5}$$

where F_k is momentum transport coefficient between fluid and particle, i (i=1,2,3) represents three dimensions.

The condensational growth of particle is due to the phase transition from vapour to liquid. The condensation rate is governed by mass fluxes on the surface of particle which takes temperature, vapour pressure, saturation, diffusion rate and thermal conductivity into account(Kulmala, Majerowicz et al. 1989, Kulmala 1993). The mass flux equation is given as follows:

$$I_c = -4\pi r \frac{S_v-1}{\frac{RT_\infty}{M_v D_c p_{ve}[1+(S+1)p_{ve}(T_\infty)/2p]}+\frac{L^2 M_v}{RKT_\infty{}^2}} \tag{6}$$

The condensation particle growth is obtained from the mass flux by the following expression:

$$I_c = -\frac{dM}{dt} = -4\,\rho r^2 \frac{dr}{dt} \tag{7}$$

Combining Eqs (6) and (7), the particle radius as a function of growth time can be given by:

$$r(t) = \sqrt{\frac{2(S_v-1)t}{\frac{\rho RT_\infty}{M_v D_c p_{ve}\left[1+\frac{(S_v+1)p_{ve}}{2p}\right]}+\frac{\rho L^2 M_v}{RKT_\infty^2}}+r_0{}^2} \tag{8}$$

Table 1. List of parameters used in simulations

Parameters	Symbol	Value
Diameter of the cyclone body	*D*	200 mm
Height of the inlet	*b*	100 mm
Width of the inlet	*a*	50 mm
Vortex finder diameter	D_e	100 mm
Vortex finder length	*S*	140 mm
Length of cylindrical part	*h*	400 mm
Height of cyclone separator	*H*	800 mm
Dust hopper diameter	*B*	50 mm
Density of water	ρ	1000 kg/m^3
Gas constant	*R*	8.314
Ambient temperature	$T\infty$	298 K
Molar mass of water	M_v	0.018 kg/mol
Diffusion coefficient	D_c	0.0000215 m^2/s
Vapour pressure	p_{ve}	3160 pa
Latent heat	*L*	2260000 J/kg
Thermal conductivity	*K*	0.025 w/m·K

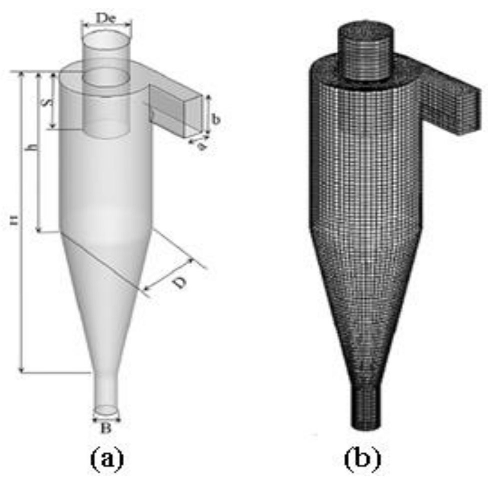

Figure 1. Schematic (a) and grid representation (c) of the simulation cyclone

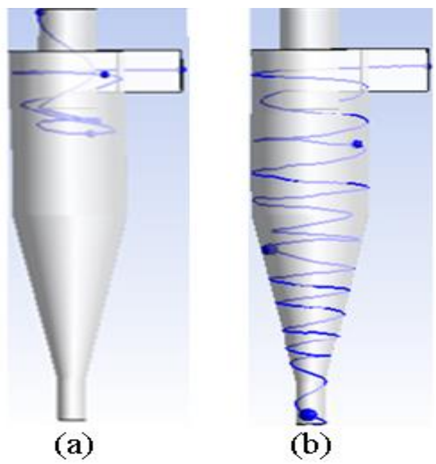

Fig 2. Trajectories of a 1µm particle in the cyclone (a) without vapour, and (b) with vapour. Spheres demonstrate particles sizes.

2.2 Simulation conditions

A typical Lapple cyclone is used in the simulations. The dimensions of the cyclone are shown in Fig 1 and Table 1. Fig 1a describes the physical parts of the gas cyclone including inlet, cyclone main body and vortex finder. Fig 1b is the computational domain, containing 232800 CFD cells.

The inlet gas and particle velocity are both 16m/s. Particles with the bulk density of 2800 kg/m^3 is injected into cyclone through inlet. The density of air is 1.225 kg/m^3. The gas viscosity is 1.7894 ×10^{-5} kg(m·s). The saturation ratio S_v in the cyclone is assumed to be uniform. The moisture content is considered by varying S_v from 1.0 to 1.2. Other parameters are listed in Table 1.

3. Results and discussion

3.1 Particle trajectory

In CAP technology, vapour condenses on the surfaces of ultrafine particles which makes individual particles grow into the appropriate size so that they can be collected using a gas cyclone. This can be captured in our CFD model. Figure 2 shows the simulated particle trajectories under two different operational conditions. The particle diameter remains constant without vapour in the dry cyclone separator as shown in Figure 2a, while Figure 2b shows that the size of the particle increases with the increase of residence time in the wet cyclone. As a result, the forces on the particle will be different, leading to different trajectories of the particle (Song, Pei et al. 2016). In the typical cases demonstrated in Figure 2, a 1μm particle will escape in the cyclone without vapour, but will be collected in the cyclone, which clearly show the effect of the moisture on the microdynamics of the particle.

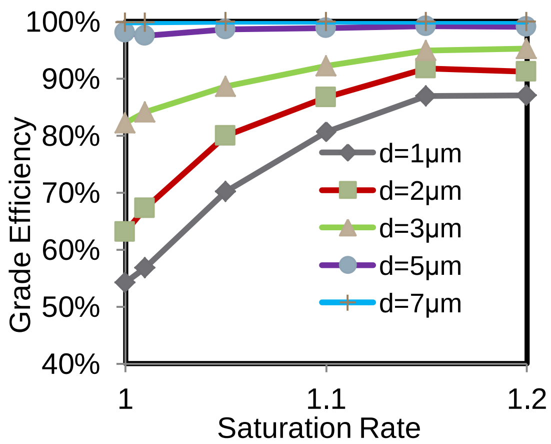

Fig 3. Collection efficiency as a function of saturation ratio for different sized particles

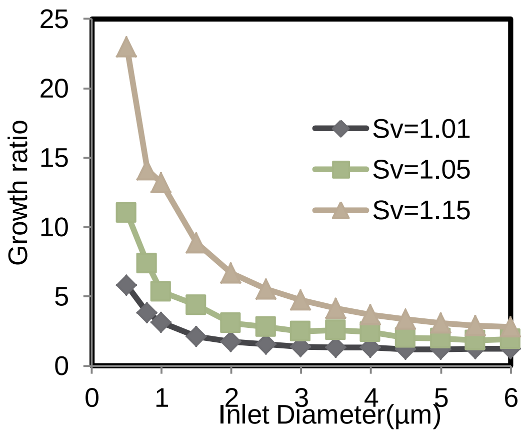

Fig 4. The effect of saturation ratio on the growth of particles of different sizes

3.2 Effect of saturation ratio on the growth of particles and collection efficiency

As shown in Fig. 2, the moisture will affect the dynamics behaviours of individual particles and hence the whole collection process. Figure 3 demonstrates the effect of saturation ratio on the collection efficiencies of different sized particles. It shows that with the increase of the saturation ratio from 1.0, the collection efficiency always increases. Note here *d* is referred to the particle size at the inlet, as the particle size will change during the process. In particular, the collection efficiency of 1 μm particles increases from 54.23% to 87.07% when the saturation ratio in the cyclone rises from 1 to 1.2. For larger particles, however, the increase of the saturation ratio is less effective in improving the collection efficiency as the growth rate of a particle will be decreased with its size, which can be seen from Eq.8. Also for these particles, because the centrifugal force of particles is larger than the drag force on them (Song, Pei et al. 2016), particles can be easily trapped by the wall even without the presence of vapour. It can also be seen that the effect of saturation ratio on the improvement of the collection efficiency is not significant after S_v>1.15. That may provide some guidance for the balance between water consumption and particle collection efficiency.

With the absorption of vapour, ultrafine particles become easier to be collected because the increase in their sizes. Figure 4 shows the effect of saturation ratio on the growth rates of particles, defined as the ratio between the diameters of particles when collected and when at inlet. From the figure it can be seen that the growth rate increases with the increase of the saturation ratio and the decrease of the inlet diameter, especially when the inlet diameter is below 2.5 μm. The growth rate of the collected particles shows that ultrafine particles with the size under 1 μm can grow into fine particles of sizes up to 15 times when saturation ratio is 1.15.

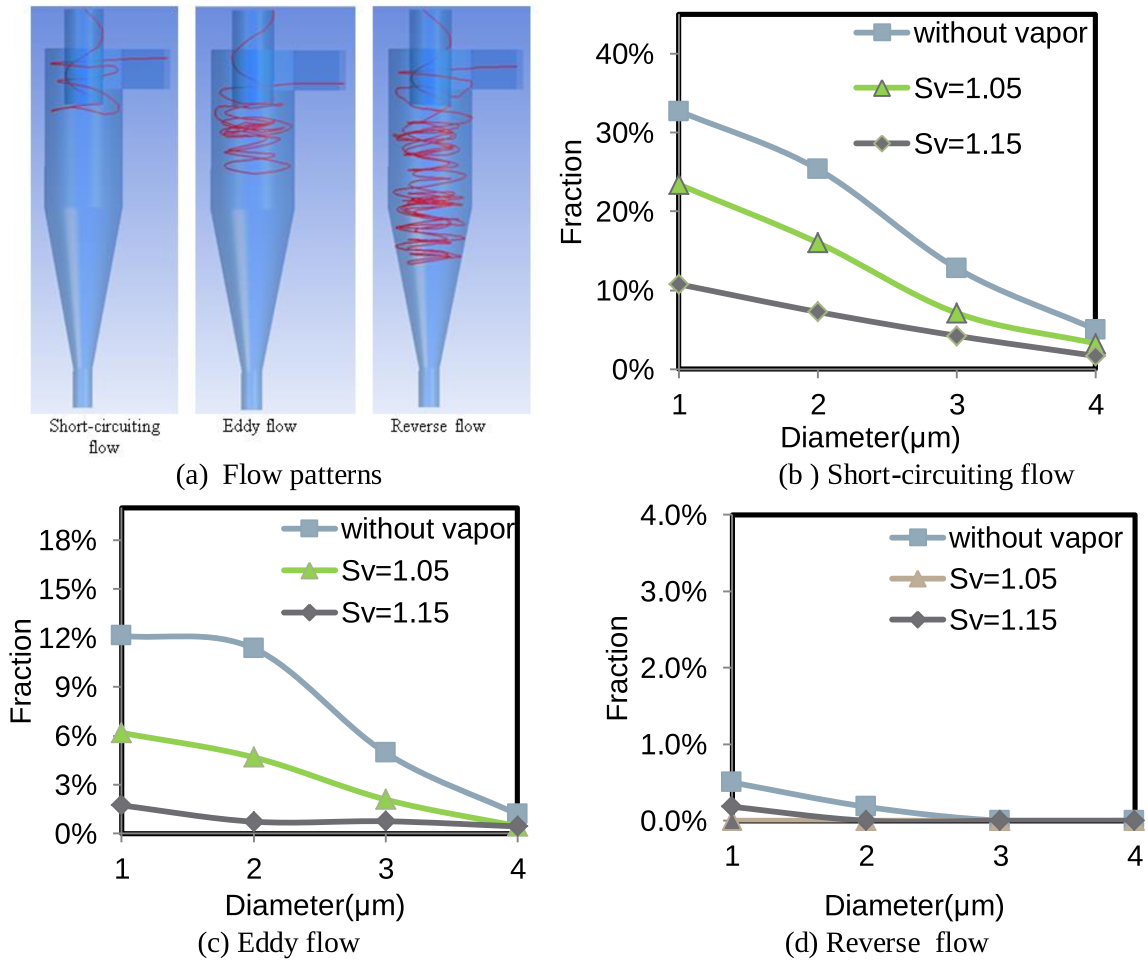

Fig 5. Schematic of three flow patterns and the effect of saturation ratio on the fraction distribution of flow patterns

3.3 Effect of saturation ratio on the particle flow patterns in the cyclone

Particle motion is governed by the gas flow in the cyclone. Generally, the trajectories of the particles escaping from the top of the cyclone can be divided into three patterns, which are demonstrated in Fig. 5 (a). They are closely linked to the secondary circulation of the air as previously found, thus they are also called as short-circuiting flow, eddy flow and reverse flow (Wang, Xu et al. 2006). For each uncollected particle, its deepest position in the cyclone is extracted. If such a particle has not reached 0.06m below the vortex finder, it is regarded as in the short-circuiting flow; if it has gone down this level but never into the conic part of the cyclone, it is regarded as in the Eddy flow; otherwise it is considered to be in the reverse flow. In our simulations, the escaped particles are divided into these three flow patterns, which can give a better understanding on how the particles escape from the collection. The effect of moisture content on the fraction of particles following the three flow patterns are shown in Fig. 5 (b), (c) and (d) respectively. It can be seen that most uncollected particles are through short-circuiting flow and eddy flow rather than reverse flow. With the increase of S_v, the fraction of escaped particles by short-circuiting flow and eddy flow decreases significantly. The decrease is more significant for smaller particles, which should be due to the growth of these particles. The fraction distribution can provide guidance on how to improve the collection, such as to cut the short-circuiting flow by changing the geometry of the vortex finder.

4. Conclusion

By CFD simulations with condensations of water vapour on particles considered, we have studied the effect of moisture content on the performance of a gas cyclone. The presence of moisture content can help improve the collection efficiency. The increase of saturation ratio will improve the grade efficiency for all sized particles, especially for ultrafine particles. However, after S_v reaches a certain value, the further increase of the moisture content will not increase the efficiency much.

The simulations clear demonstrate that due to the condensation, ultrafine particles increase their sizes in the cyclone, which lead to the changes of their trajectories. The effect of moisture content on the growth rates of different sized particles are quantified, which can be linked to the increase of the collection efficiency. Moreover, different flow patterns of uncollected particles are analyzed. It is shown that moisture can weaken the effect of short-circuiting flow and eddy flow significantly and help increase the collection efficiency.

The established CFD model has shown to be an effective way to understand the micromechanisms of the effect of moisture on the performance of a gas cyclone used in CAP technology, which can guide the design, control and optimization of this innovative air purifying technology.

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