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ABSTRACT

The high-speed swirling flow field in the cyclone oil-gas separator will cause the breakup of oil droplets, thus reducing the separation efficiency. In this paper, the performance of an oil-gas cyclone separator was investigated through both numerical simulations and experiments with considering the breakup of oil droplets in oil-gas cyclone separators. The gas flow field was simulated using the RSM turbulence model and the trajectory of the oil droplets was calculated by the Discrete Phase Model(DPM).The breakup of oil droplets was simulated by TAB model and the wall boundary of oil droplets was treated as Reflect boundary. Meanwhile, the separation efficiency was measured and the Malvern Particle Size Analyzer was applied to get the droplets diameter distribution at the inlet and exit of the oil-gas cyclone separators to verify the simulation model. The results showed that the separation efficiency was influenced significantly by the breakup of oil droplets, especially for the high inlet velocity. The simulation results based on the presented model were in good agreement with the experimental data.

Key Words: Oil-gas Cyclone Separator, Numerical Simulation, Discrete Phase Model, Breakup of Oil Droplets, Separation Efficiency

1. INTRODUCTION

The cyclone separator has been widely used on account of its simple geometry and little maintenance. The separation efficiency of the oil-gas separator is one of the most important indexes in oil injected compressor systems.

A considerable amount of research existed on cyclone performance by computational fluid dynamics (CFD). Almost all of these studies focused on the flow field in the cyclone chamber and the Reynolds Stress Modeling of turbulence (RSM) which base on the Reynolds Averaged Navier-Stokes equations (RANS) has been widely accepted. Gronald(2011) compared the finite volume RANS model and two LES approaches and pointed that unsteady RANS-based simulations on a relatively coarse grid can provide reasonable and industrially relevant results with limited computational effort. Slack (2000) used RSM simulating the flow field in a conventional high efficiency Stairmand cyclone, and the result showed consistent agreement compared with Laser Droplet Anemometry measurements. Hoekstra and others (1999) reported on reported reasonable agreement with experimental data, when the anisotropic RSM was applied. The successful application of the RSM turbulence model for different studies in cyclone separators has been reported by many researches. For example, Azadi (2010) investigated the cyclone size on its performance and the swirling field were simulated by RSM.; Khairy and Elsayed (2011) studied the effect of inlet dimensions the cyclone size on its performance and the swirling field were also simulated by RSM.

Besides, there are many investigations on the particle motions in the swirling flow in a cyclone separator by using the Lagrangian discrete phase model (DPM). Matsuzaki (2006) studied the particle motions in swirling flows in a cyclone by using a large eddy simulation(LES)and predicted the performance for particle separation from the result of the particle tracing.

Actually, the high-speed swirling flow field in the cyclone separator will cause the break up of oil droplets that effect the performance of the cyclone separator. But all articles mentioned above did not study the effect of the breakup of oil droplets on the performances in the cyclone separators.

In previous study, the models for the breakup of droplets in high-speed flow field have been established and these models have been used in simulation fields, for example spray. Shan (2007) used TAB droplet breakup model to solution precursor plasma spray and indicated that droplet breakup play an important role in determining the final particle size and velocity distribution on the substrate.

In this article, a 3D model was developed and the experimental system was established for the purpose of studying the effect of the breakup of oil droplets to the performance of oil-gas cyclone separators. RSM was used to simulate the gas flow field and the trajectory of the oil droplets was described by DPM. The breakup of the oil droplets was calculated by TAB model.

2. MATHMATICAL MODELS

2.1 Cyclone separator

Fig 1 shows the schematic view of the cyclone separator in this article. This is the familiar cyclone model in oil injected compressor systems .It has a swirl chamber with a diametric of 65mm(D=65mm)and the other parameters of the cyclone separator was showed in table 1. The oil-gas mixture enters though the top of the swirl chamber in the tangential direction and is exhausted through the central channel with a diametric of d， which is installed inside the top of swirl chamber by the depth of h. The side splitter is floating to change the depth of the swirl chamber which is signed as H.

The following assumptions in this article are made in this model:

1.The flow field is stable and incompressible;

2.The oil droplets were regarded as a spherical particles and the deflection of them were ignored;

3.The heat transfer in this article was ignored;

4.The Magnus force which was far less than saffman force was ignored.

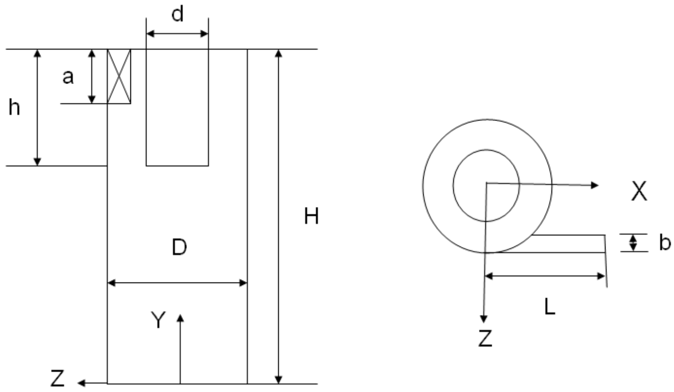

Fig.1 Schematic view of the cyclone separator

Table 1 The geometrical dimension of the tested cyclone separators in this article

Dimension	Parameter(mm)	Dimension/D
Cyclone diameter D	65	1
Cyclone height H	195	3
Cylinder diameter d	32	0.5
Cylinder height h	100	1.538
Inlet height a	30	
Inlet width b	8	
Inlet length L	60	

2.2 The gas flow field

In this paper, the Reynolds Stress Modeling of turbulence (RSM) was chose to describe the swirling flow in the cyclone separator. The details including governing equations and supplementary equations of this model can be found in the reference written by Safikhani (2010).

2.3 Oil droplets

The governing equation of the oil droplets in the flow field is given as follows:

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x \tag{1}$$

Where u and u_p are the velocities of the gas and the oil droplet; ρ and ρ_p are the densities of the gas and the oil droplet; g_x is the acceleration of gravity; F_D is the digestion stress of unit quality and F_x is the additional force that are given by:

$$F_D = \frac{18\mu}{\rho_p d_p^{\ 2}} \cdot \frac{C_D \mathrm{Re}}{24} \tag{2}$$

$$F_x = \frac{2Kv^{1/2}\rho d_{ij}}{\rho_p d_p (d_{lk} d_{kl})^{1/4}} (\vec{u} - \overrightarrow{u_p}) \tag{3}$$

Where μ is the dynamic viscosity of the gas; d_p is the radii of the oil droplet; K=2.594; d_{ij} is the deformation tensor; v is the dynamical viscosity; Re_{rp} is the relative Reynolds number of the droplet and C_D is the drag coefficient that are calculated as follows:

$$\mathrm{R}e_{rp} = \frac{\rho d_p |u_p - u|}{\mu} \tag{4}$$

$$C_D = a_1 + \frac{a_2}{\mathrm{Re}_{rp}} + \frac{a_3}{\mathrm{Re}_{rp}} \tag{5}$$

where a1、a2 and a3 are constants among some special Reynolds number range indicated by Morsi(1972).
The velocity of the oil droplet can be predicted by integrating equation over discrete time steps. Further integration of the velocity yields displacement and thereby the trajectory of the oil droplet $x = \int u_{p1} dt$, $y = \int u_{p2} dt$, $z = \int u_{p3} dt$ .When the trajectory equations are solved by integration over discrete time steps, the gas velocity is the mean gas-phase velocity.

2.4 Droplet breakup

The breakup of single oil droplet exists in the swirling flow field due to the effect of pneumatic pressure, shear stress and turbulent disturbance. The Taylor analogy breakup(TAB) developed by O'Rourke(1987) is the most widely used models on the breakup of single oil droplet. Droplet breakup in this model was considered by:

$$F - kx - d_p \frac{d_x}{d_t} = m_p \frac{d^2 x}{dt^2} \tag{6}$$

Where F is the external force of droplets, x is the displacement of the droplet equator from its spherical (undisturbed) position.

$$\begin{cases} \dfrac{F}{m_p} = C_F \dfrac{\rho u_0^2}{\rho_p r_p} \\ \dfrac{k}{m_p} = C_k \dfrac{\sigma}{\rho_p r_p^3} \\ \dfrac{d}{m_p} = C_d \dfrac{\mu_p}{\rho_p r_p^2} \end{cases} \tag{7}$$

Where m_p is the mass of the droplet; r_p is radii of the droplet undisturbed; σ is the surface tension of the droplet; μ_P is the dynamic viscosity of the droplet; C_F=1/3; C_k=8; C_d=5.
If x>C_b (C_b=1/2),the droplet will break. The energy of the large droplets is equal to the energy of all sub-droplets after the droplet breakup. The Energy of the large droplet included surface energy ,vibration and torsional

deformation energy. The surface energy of the droplet was given by:

$$E_{surf} = 4\pi r_p^2 \sigma \tag{8}$$

and the vibration and torsional deformation energy was calculated by:

$$E_{osc} = K\frac{\pi}{5}\rho_p r_p^5 \left[(\frac{dy}{dt})^2 + \omega^2 y^2 \right] \tag{9}$$

Where $y = \frac{C_b}{r_p}$;K=10/3;

Therefore, the energy of the large droplet can be described as following:

$$E_{parent} = E_{surf} + E_{osc} \tag{10}$$

The energy of the sub-droplet after collision can be calculated by:

$$E_{child} = 4\pi 2\sigma \frac{r_p}{r_{p32}} + \frac{\pi}{6}\rho_p r_p{}^5 (\frac{dy}{dt})^2 \tag{11}$$

Based on the conservation of energy, the average distribution of sauter distribution was given by:

$$r_{p32} = \frac{r_p}{1 + \frac{8Ky^2}{20} + \frac{\rho_p r_p{}^3 (dy/dt)^2}{\sigma}(\frac{dy}{dt})^2} \tag{12}$$

Where $r_{p32} = 0.7 r_{p\max}$ and r_{pmax} is the of the maximum of the droplet radius distribution .The velocity of the sub-droplet was calculated as following:

$$u_{normal} = C_v C_b r_p \frac{dy}{dt} \tag{13}$$

where $C_v = 1$.

2.5 Boundary Conditions

At the solution cyclone separator inlet and outlet, inlet velocity, outlet pressure, droplet size distribution is determined based on the experiment observation. During the calculation, if a droplet hits the wall, the Reflect boundary condition applies, which Means that if the droplet can not escape the separator, it is separated. If a droplet crosses the inlet and outlet, the ESCAPE boundary condition applies, which reports that the droplet has escaped when it encounters the boundary and trajectory calculation is also terminated.

3. NUMERICAL SIMULATION

3.1 Numerical Technique

Fig 3 shows the computational grid in the cyclone separator with the mesh of 794112 cells. The whole computational domain is meshed using hexahedral elements. The grids are fine at the zone near wall and vortex finder while the grids are sparse at the zone away from the wall.

The RSM model was employed to simulated the gas phase flow field and the Discrete Phase Model (DPM) was adopted to track the oil droplets trajectory together with the TAB model for considering the effect of droplets breakup.

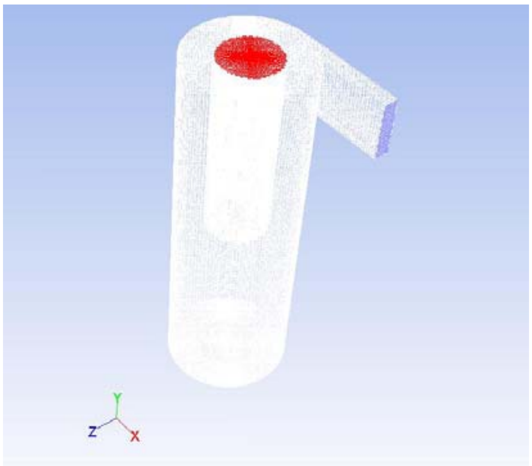

Fig.3 The computational grid for the cyclone separator

3.2 Calculating Conditions

The inlet velocity of the gas and the droplet are defined 9.3,10.5,12,14.1m/s while the outlet pressure of the gas are 0.6,0.7,0.8,0.9MPa.

Table 3 The parameters and cases of the tested cyclone separator in this article

Case	A	B	C	D
Inlet velocity(m/s)	9.3	10.5	12	14.1
Outlet pressure(MPa)	0.9	0.8	0.7	0.6
Density of the gas(kg/m^3)	10.522	9.353	8.184	7.015
Viscosity of the gas(kg/m.s)	2.09e-06(353K)			
Density of the oil(kg/m^3)	830			

The density and the viscosity of the gas are related with inlet pressure, while the density of the oil droplet is 830kg/m^3. Cases of the tested cyclone separator in this article was showed in table 3.

The droplet size distribution is described by the Rosin-Rammler equation, with the mean diameter equal to 0.009999mm and the spread parameter 1.45 that were obtained by the experiment followed.

The performance for the separation of the cyclone separator is estimated by the collection rate which is calculated by the following equation:

$$\varepsilon = (1 - \frac{N_{out}}{N_{total}}) \times 100(\%) \tag{14}$$

where N_{out} is the number of droplets which flow out from the outlet and N_{total} is the total number of droplets mixed into the swirl chamber.

4. EXPERIMENTAL SETUP

To get the separation efficiency and the droplets diameter distribution at the inlet and exit of the cyclone separator, the experimental system was established and showed in Figure 5. The work fluid used in the experimental investigation presented was air. From Fig.4, it can be seen that the oil–gas mixture discharged out of the compressor first flows into the oil–gas separator and then enters into the cyclone separator. The mixture after separated by the cyclone separator flows through the oil filter and AO/AA superfine oil filter. To get the droplets diameter distribution at the inlet and exit, Malvern Particle Size Analyzers were set before and after the cyclone separator.

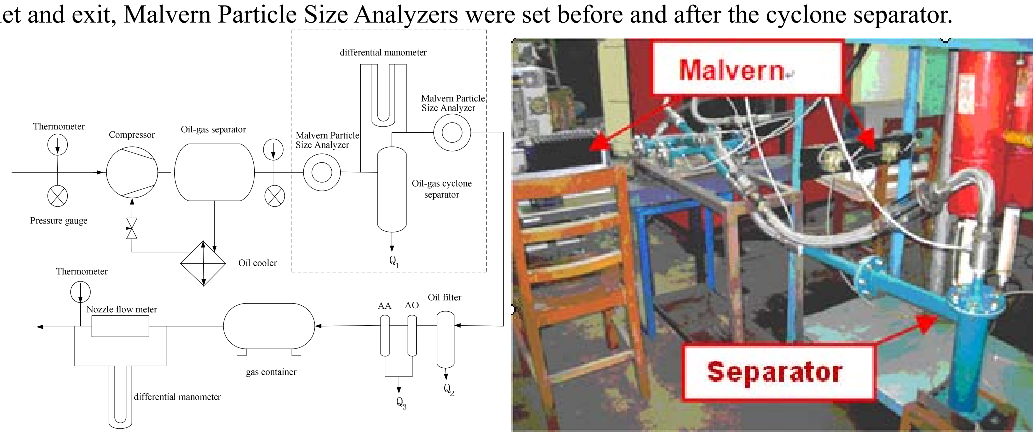

Fig.4 The experimental system

The separation efficiency was defined by ε that was calculated by the following equation.

$$\varepsilon = \frac{Q_1}{Q_1 + Q_2 + Q_3} \tag{15}$$

Where, Q_1,Q_2 and Q_3 are the oil filtrated by the cyclone separator, AO and AA superfine oil filter.

The volumetric flow rate and the speed of the compressor are 2.5m^3/min and 2900rpm. The discharge pressure ranges from 0.6MPa to 0.9MPa, whereas the inlet air temperature and pressure are 80℃ and 0.1MPa.

5. RESULTS AND DISCUSSION

5.1 The Trajectory of Oil Droplets in Simulation

As shown in Fig. 5, the trajectories of the oil droplets were simulated with case A, B, C and D, separately .The inlet velocity was 9.3 m/s to 14m/s and the Reynolds number reached 1.1×10^5, so the flows in these cases were treated as the turbulent flow that can be indicted from the trajectories of the oil droplets**.** The maximum residence time reduces from 0.0551 to 0.036 s as the inlet velocities of the oil droplet increases from 9.3 to 14.1m/s .Simulated separation efficiencies of the cases were obtained and showed in Fig.6.

5.2 Effect of Droplet Breakup

In order to estimate the effect of the breakup of the oil droplets, the separator efficiencies of simulations with case A, B, C and D were compared with the values obtained by experiment and simulations above. It can be seen that if the breakup of oil droplets were not considered in simulation, the separation efficiencies were almost 100%. But the separator efficiencies got by experiment were 70%-85%.While TAB model was used in simulation to described the breakup of the oil droplets, the separator efficiencies were in good agreement with the experimental data. The maximum error was less than 10% and it may be due to the low inlet velocity which reduced the collision energy. It can also be found that the separation efficiency enhanced with the velocity.

5.3 The Droplet Size Distribution

Fig.7 showed the droplet size distributions at inlet and outlet of case A and C. It can been seen that the volume percent at inlet with the diameter less than 5μm of total imports was 22.6%,the diameter between 10μm and 25μm was 51.6% and the diameter more than 25μm was 11.4%.Compared the droplet size distributions at inlets, it can be found that the droplets with the diameter more than 25μm could be separated completely and the droplets with the diameter less than 5μm were hard to be separated. It can be indicated that the level of intensity of the breakup of oil droplets in case A was not as high as in case C and the phenomenon can be explained as the inlet velocity of case A was smaller than case C.

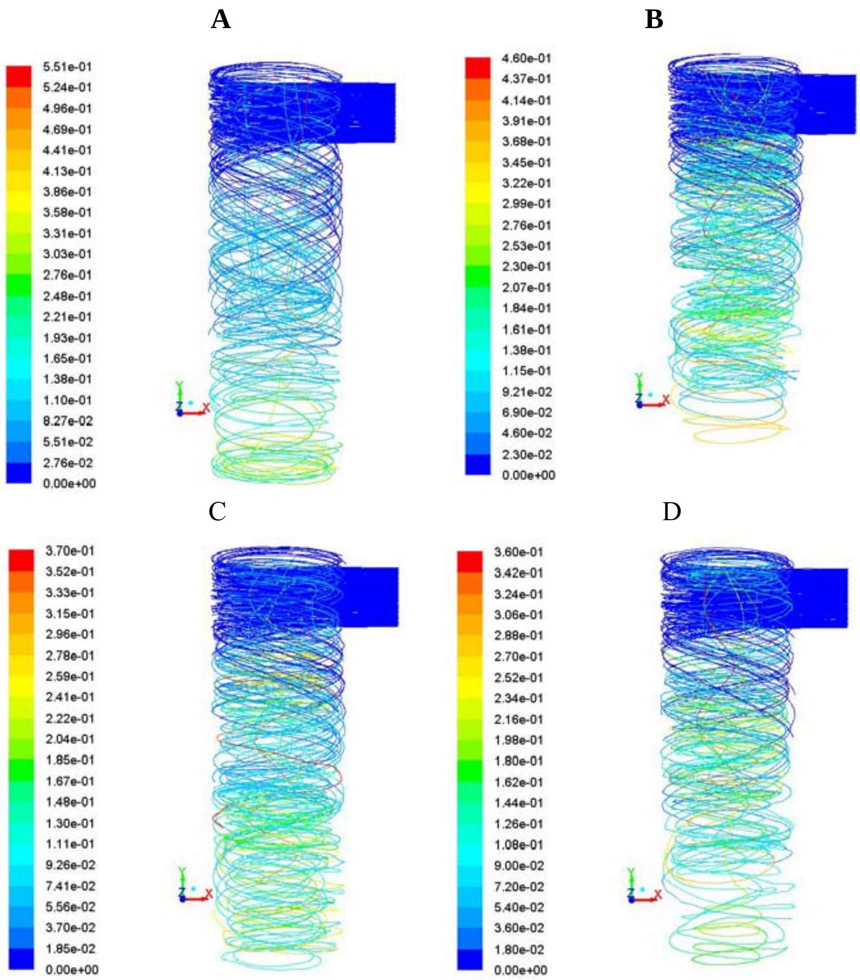

Fig.5 The trajectory of the oil droplets in simulation

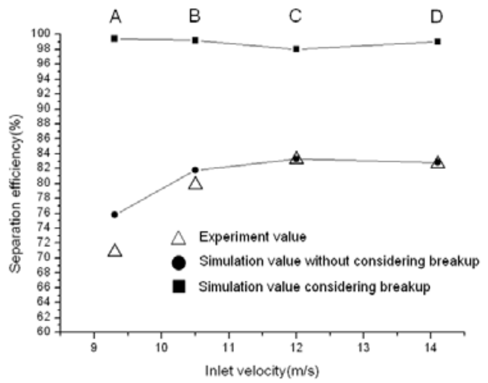

Fig.6 Compared of the separation efficiencies by experiment and simulation

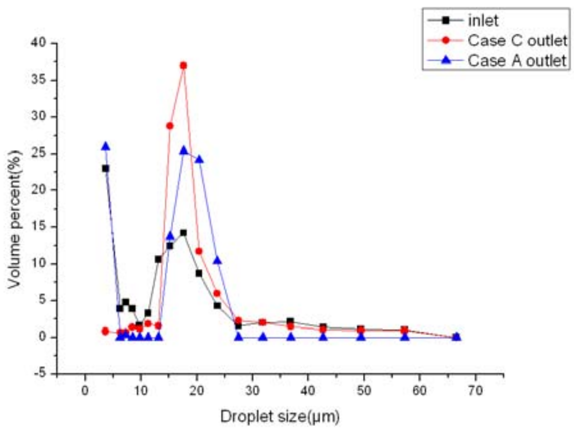

Fig.7 The droplet size distribution at inlet and outlet

5.3 Conclusions

A numerical simulation taking the droplets breakup into account of oil–gas cyclone separator and experimental investigation were carried out in this paper. By simulating and testing the separator efficiency of the separator, the influence of the breakup of oil droplets on separation performance was analysed.

- Both the experimental data and simulation results showed that the breakup of oil droplets which influenced the separator efficiency existed in cyclone separators due to the high speed swirling flow field. The simulation results based on model considering the breakup of the oil droplets were in good agreement with the experimental data.
- The velocity at inlet of separator played an important role in the separator efficiency, because it determined the tangential velocity and then caused the breakup of the oil droplets, particularly at high inlet velocity.
- Further investigation on different structures of cyclone separator and what about the mechanism of the oil droplet breakup are required to understand how best to design the separator.

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NOMENCLATURE

a	inlet height	(mm)
b	inlet width	(mm)
C_D	drag coefficient	
D	cyclone diameter	(mm)
d	cylinder diameter	(mm)
d_{ij}	deformation tensor	
d_P	oil droplet radii	(m)
E_{surf}	oil droplet surface energy	(J)
E_{osc}	vibration and torsional deformation energy	(J)
E_{parent}	large droplet energy	(J)
E_{child}	sub-droplet energy	(J)
F_χ	additional force	(N)
F_D	digestion stress of unit quality	(N)
g_x	gravity acceleration	(m/s^{-2})
H	cyclone height	(mm)
h	cylinder height	(mm)
L	inlet length	(mm)
m_p	oil droplet mass	(kg)
R	gyration radii of the droplet	(m)
Re	gas Reynolds number	
Re_p	oil droplet Reynolds number	
Re_{rp}	relative Reynolds number	
r_p	oil droplet radii	(m)
u	gas velocity	(m/s)
u_P	oil droplet velocity	(m/s)
u_{normal}	sub-droplet velocity	(m/s)
ρ	gas density	(kg/m^3)
ρ_P	oil droplet density	(kg/m^3)
ε	separation efficiency	
ν	dynamical viscosity	(m^2/s)
μ	gas viscosity	(pa•s)
μ_P	oil droplet viscosity	(pa•s）

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