2018

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Yang Zhang
Xi'an Jiaotong University, China, People's Republic of, zhangyang008@stu.xjtu.edu.cn

Wei Chen
Xi'an Jiaotong University, China, People's Republic of, 1045442845@qq.com

Biyuan Liu
Xi'an Jiaotong University, China, People's Republic of, iliubiyuan@163.com

Jianmei Feng
Xi'an JiaoTong University, China, People's Republic of, jmfeng@mail.xjtu.edu.cn

Xueyuan Peng
Xi'an JiaoTong University, China, People's Republic of, xypeng@mail.xjtu.edu.cn

Study on the Effects of Vane Parameters on Separation Performance in an Axial Flow Cyclone Separator

Yang ZHANG[1], Wei CHEN[1], Biyuan LIU[1], Jianmei FENG[1]*, Xueyuan PENG[1]

[1]Xi'an Jiaotong University, School of Energy and Power Engineering,
Xi'an, Shaanxi, China
(86-29-82665327, 86-29-82668724, jmfeng@mail.xjtu.edu.cn)

ABSTRACT

The oil-gas cyclone separator is a key component of an oil injection compressor system for its advantages of small volume, simple structure, high separation efficiency and low pressure loss. This paper presents the investigation on the new type of axial flow cyclone separator performance under different structural parameters, including the angle of vanes, the number of vanes, the rotation angle of single vane, by numerical simulation and verification experiments. A numerical model of two-phase flow in the cyclone separator was established and the separation efficiency and pressure loss of cyclone separators were simulated. A test rig was built up and the diameter distributions of droplets at the inlet and outlet of separator were measured by a Malvern laser particle size analyzer to verify the simulation model. The results showed that the separation efficiency and pressure loss can be improved with the increase of the rotation angle of vanes; with the decrease of the outlet angle of the first stage vane and the increase of the number of vanes, the critical separated droplet diameter of separator can be lowered effectively. The results also showed that the optimum outlet angle of vanes is 22°~25° considering the separation efficiency and the pressure loss of separators.

1. INTRODUCTION

Gas-liquid cyclone separators are widely used in industrial fog removal, which has the advantages of small volume, simple structure, high separation efficiency and low pressure loss. It has a good prospect in the development of gas liquid separation equipment. It is important to study the influence of vanes' structure parameters of cyclone separators on separation efficiency.

Axial flow cyclones have been designed with the characteristics of large operation flexibility, compact structure, low resistance and high efficiency. Cuypers and Stanbridge [1-2] designed a new type of axial cyclone separator on the basis of previous research. Four side seams on the wall of cyclone cylinder were used as the drainage channel, and the second outlet of air was used to draw air and improve the efficiency of liquid drainage. Frederic Pierre [3] changed the liquid discharge performance of the cyclone by changing the mode of the side seams. However, the second stage air flow of the structure was not purified and was discharged directly from the exhaust pipe. Burgess-Manning[4] company and Swanborn[5] designed a cyclone tube with the second-stage separation air flow circulation structure, which not only improved the separation efficiency, but also excluded the use of specialized equipments to purify air of the second stage separation. The equipment is simplified with no power cycle. However, vanes in front of the second stage separation lead to the increase of the energy loss with the increasing of the resistance. Peerless increased the vane thickness and set the second stage air flow cycle on the vane. Akiyama [6-7] found a great relationship between the dust removal efficiency and the structure parameters of axial guide vane cyclone separator. The best separation length should be about three times longer than the diameter of the outer cylinder. Man [8] pointed out that the separation efficiency was mainly affected by the gas-liquid entrainment effects when the volume concentration of liquid droplet was larger in the axial cyclone separator for gas-liquid separation.

Jin [9] studied the axial flow cyclone separator separation performance experimentally with the guide vane outlet angle being 15º, 20º, 25º and 30º. The conclusion suggested that the separation efficiency was maximum when the guide vane outlet angle of cyclone separator was 25º, the separation efficiency was minimum when the angle was 15º. At the same time, she pointed out that the pressure differential between the inlet and outlet of the axial flow cyclone separator would decrease with the increase of the angle of the guide vane. R.B.Xiang etc. [10] studied the effects of height on separation performance of cyclones numerically. Flow field of cyclones with different height were obtained. Results showed that the separation efficiency would be l lowered when the cyclone got higher.

As mentioned above, previous studies focused mainly on the condition of mixture and structure of cyclone. There were few investigation on the effects of vane size, vane number of single swirler and multi stage on the flow field and separation performance of cyclone separators. In this study, several cyclone separators with different vane parameters and number were constructed. The separation performance including separation efficiency and pressure loss was determined numerically and verified experimentally.

2. NUMERICAL SIMULATION

2.1 Physical model

The geometrical details of the separator carried out in this paper are presented in **Figure 1**. The water-gas mixture entered axially through the inlet, and rotated through the first stage swirler. Due to the centrifugal force, droplets moving to the wall were separated, and the remaining droplets following the gas went through the second stage swirler to be separated furtherly. At last, the pure gas was discharged from the separator through the gas outlet.

In order to study the influence of the first vane outlet angle, the number of vanes, the rotation angle of vane, and the inlet and outlet angles of two stage vanes, several cyclone separators with different structural parameters were performed and the main parameters are shown in **Table 1** and **Figure 1**.

Table 1: Dimensions of swirler

Dimension of swirler	Range of parameters					
1st β ($\alpha = 90°$)	10°	15°	20°	22°	26°	30°
2nd α ($\beta = 25°$)	50°	60°	70°			
2nd β ($\alpha = 60°$)	10°	15°	20°	25°	30°	35°
Number of vane	10	15	20	25		
1st θ	14°	18°	22°	26°		

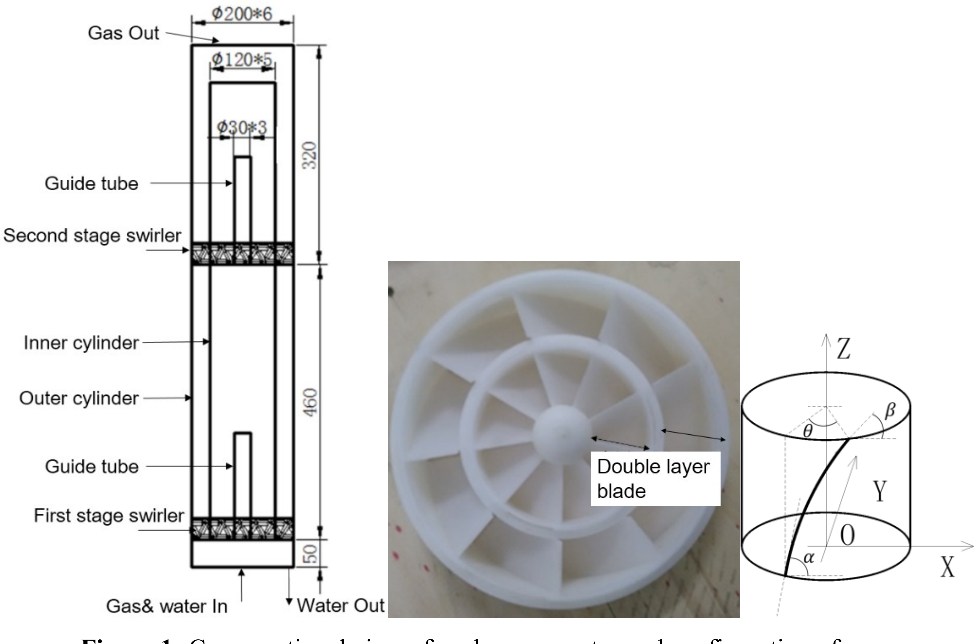


Figure 1: Cross sectional view of cyclone separator and configuration of vane

2.2 Numerical model

For the swirling flow in the cyclone separators, the suitable turbulence model was proved to be the RSM model (Reynolds Stress Model) in the preceding work of our research group. The flow field characteristics in the axial flow cyclone separator were similarly strong to the swirling flow, so the RSM model was employed as the turbulence model to study the effects of vane parameters on the performance of separator. The details of control equations can be found in the article.

The water-air two phase flow in the separator was simulated by the Eulerian-Lagrangian approach and the droplet motion was tracked using the discrete phase model (DPM), as the volume fraction of liquid in the mixture flow was far less than 10%.

2.3 Grid and boundary condition

As is shown in **Figure 2**, the model of S-a separator was divided into several parts and meshed separately. The separation efficiency and static pressure loss were compared when the grid quantities were 396407、1461180 and 1968023. The results showed that the difference of separation efficiency and pressure loss under the maximum grid quantity and the minimum grid quantity was less than 5%. Considering the complexity of the three-dimensional flow, cells of 1461180 were generated to mesh the separator for performing the simulation.

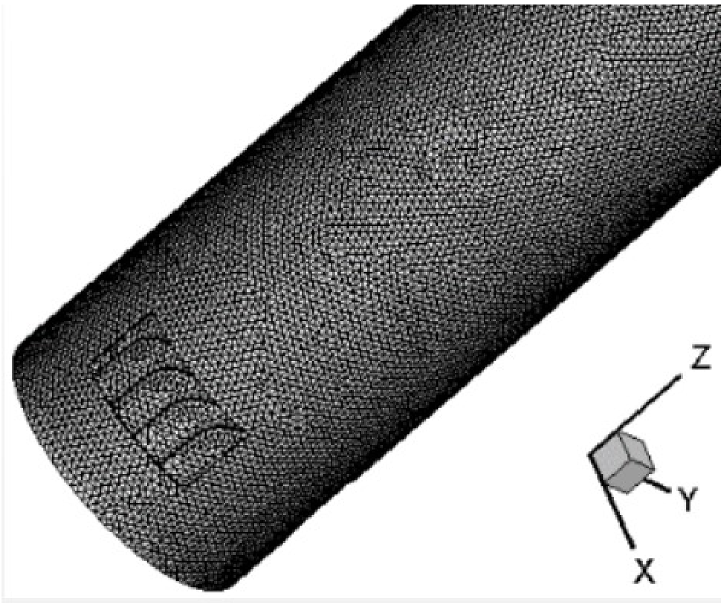


Figure 2: Mesh of cyclone separator

For the gas-phase flow field, the constant velocity inlet and pressure outlet boundary were used, and the wall was regarded as a no-slip boundary. For the water droplets phase, the constant velocity inlet same as the gas velocity was set. The outlet was defined as "escape", meaning that once the water droplets came to the outlet, they were free. The walls were defined as trap boundaries, meaning that once the water droplets came to the wall, they were separated from the mixture.

3. VALIDATION EXPERIMENT

3.1 Experimental system

The test rig for measuring the separation efficiency of the cyclone separator was built up, as is shown in **Figure 3**. The diameter distribution of the water droplets was measured using a similar method to the one introduced in the literature [12]. A four-way observation tube was installed at the inlet and outlet of the cyclone separator, and high-purity nitrogen was injected between the optical glass and the main flow during the test to ensure the purity of the optical glass, thus ensuring that the Malvern laser particle size analyzer could function normally.

The separation performance of cyclone separators was decided by separation efficiency and pressure loss. The separation efficiency was defined as the ratio of the volume concentration of the droplets was separated from the water-gas mixture to that in the mixture before separation

$$\eta_{sep} = \frac{C_{1,i} - C_{1,o}}{C_{1,i}} \quad (1)$$

Where, $C_{1,i}$ and $C_{1,o}$ are the volume concentration of water droplets at the inlet and outlet of the separator, respectively.

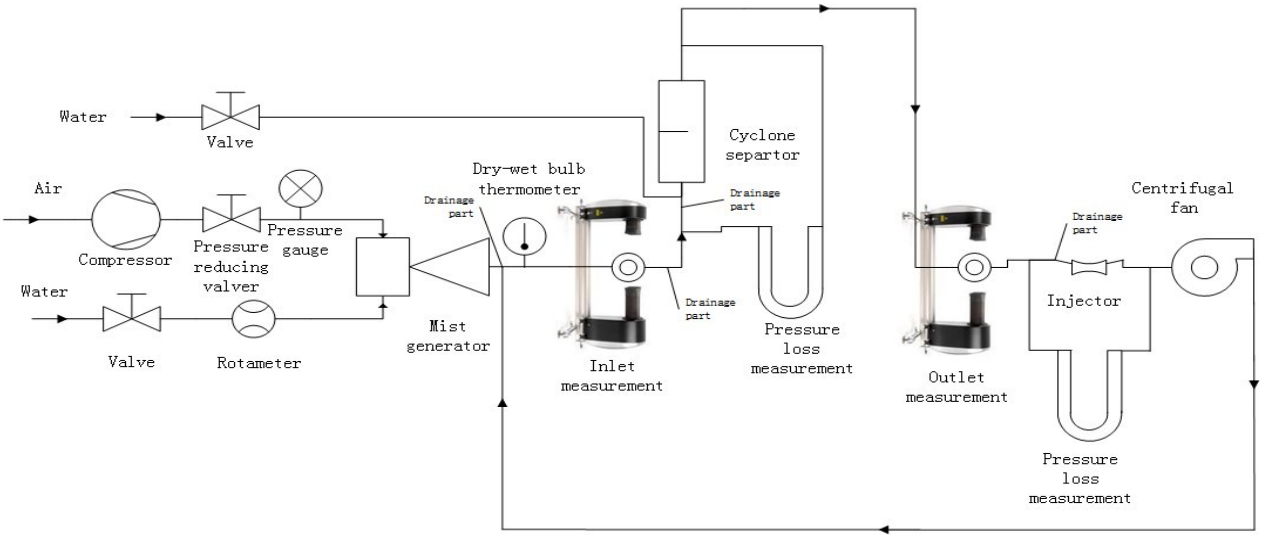


Figure 3: Schematic diagram of experimental system

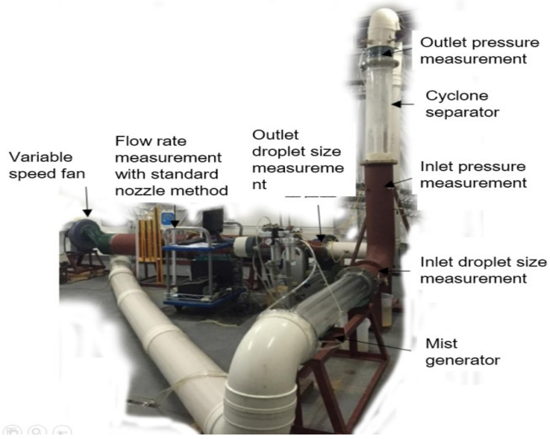


Figure 4: Photo of test rig

3.2 Structural parameters of swirlers

In order to obtain the particle size distribution of the droplets in the inlet and outlet of the separator and compare the results of CFD and experiments, one of the separators was studied numerically and experimentally in various flow rates. The structural parameters of the cyclone separator are shown in **Table 2**. The swirler pictures of S-1 separator are shown in **Figure 5**.

Table 2: The structural parameters

Name	The first stage vane	The second stage vane

	Inlet angle	Outlet angle	Inlet angle	Outlet angle
S-1	90°	22°	25°	25°

(a) The first stage swirler (b) The second stage swirler

Figure 5: Detailed view of swirler

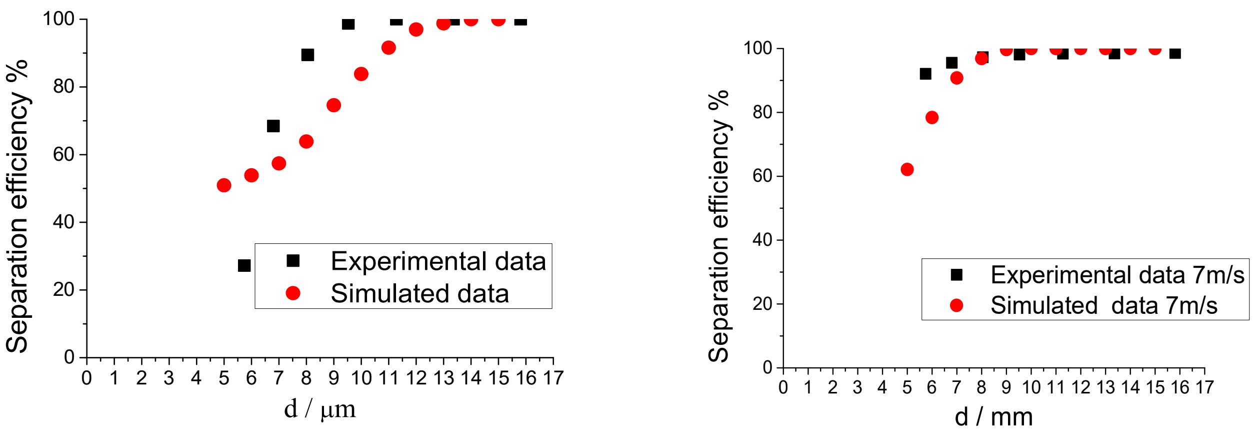
4. RESULT ANALYSIS OF NUMERICAL AND EXPERIMENTAL RESULTS

4.1 Comparison of experimental and numerical results

In order to verify the results of numerical computation, S-1 separator was studied experimentally and numerically. **Figure 6** illustrates the comparison of the simulated and experimental separation efficiency and pressure loss of S-1 separator. The experimental and simulated results show that the diameters of the water droplets can be separated completely are almost identical. The deviation of separation efficiency of droplets greater than or equal to 4um between the experimental and simulated results is smaller as the inlet velocity increases.

The deviation of separation efficiency to droplets with different diameters between the experimental and simulated results is smaller as the droplets diameter increases. The separation efficiency of experiment and simulation is consistent when the diameter of droplets is greater than 10um, with both being 100%. This is because most water droplets were thrown into the cylinder of separator under the centrifugal force.

Some of the water droplets go into the water ring straightly formed in the cylinder of the separator and are separated from the water ring. Therefore, the separation efficiency of experiment is higher than that in the simulation.



(a)Separation efficiency(velocity of air is 2.9 m/s） (b) Separation efficiency(velocity of air is 7 m/s）

Figure 6: Effect of inlet velocity on separation efficiency

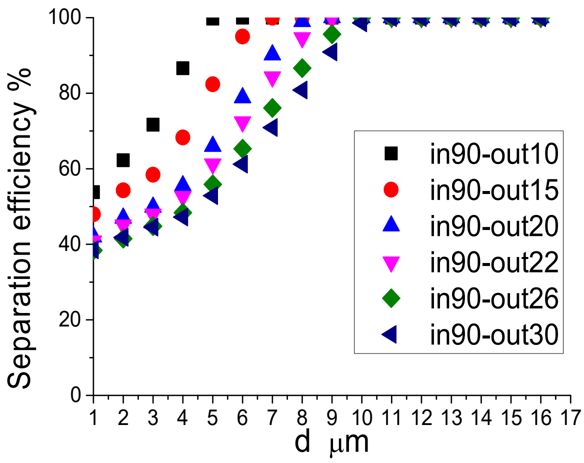
4.2 The relationships between the deviation and the diameter of droplets

There are great relationships between the deviation of separation efficiency to droplets with a same diameter between the experimental and simulated results and the diameter of droplets. The deviation is reducing with the inlet velocity and the diameter of droplets with the increase of the inlet velocity and the diameter of droplets. The maximum deviation for droplets diameter greater than 10um is -8% when the inlet velocity is 2.9m/s. The maximum deviation for droplets diameter greater than 7um is -10% when the inlet velocity is 6.3m/s.

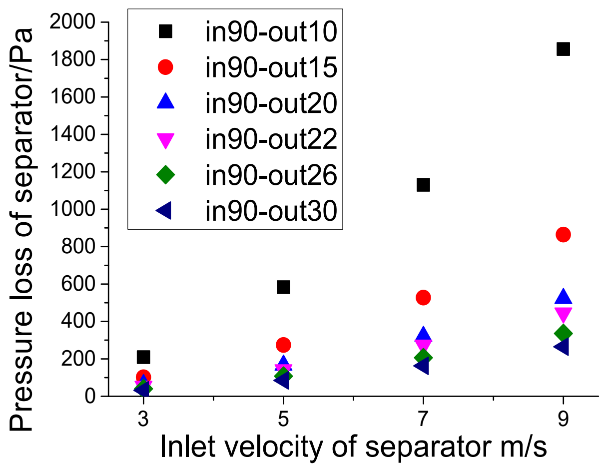
4.3 Effects of the outlet angle of the first stage vanes

The separation efficiency for the diameter range in 1~12um improves with the outlet angle of the first stage vanes with the decrease of the first stage vanes. However, the pressure loss of separator also increases.

The inlet angles α of the first stage vanes are all 90° and the outlet angles β of the first stage vanes change from 10° to 30°. The velocity of mixture increases rapidly when the outlet angle β of the first stage vanes decreases. Therefore, the centrifugal force of water droplets increases when the outlet angle β of the first stage vanes decreases. The separation efficiency of separators with larger outlet angle is higher as the water droplets under greater centrifugal force is easier to be separated. At the same time, the circumferential distance of mixture increases with the outlet angle β of the first stage vanes decreases. Therefore, the pressure loss of separators increases with the on-way resistance increases.



(a)Separation efficiency of separators(Inlet velocity 7m/s)

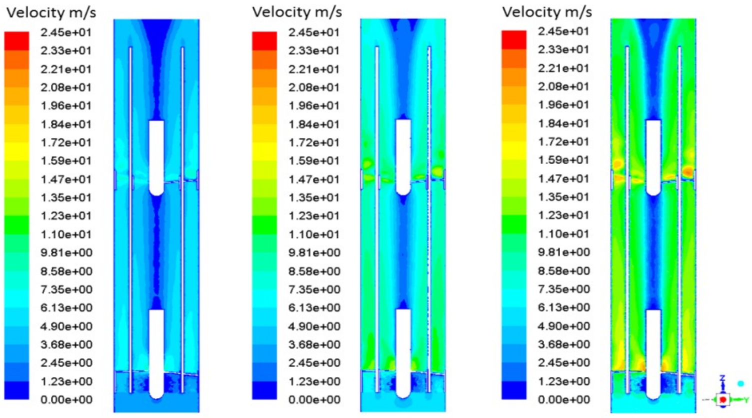


(b) Pressure loss of separators

Figure 7: Effects of outlet angle of the first stage vanes on separation performance

4.4 Effects of inlet angle of the second stage vanes

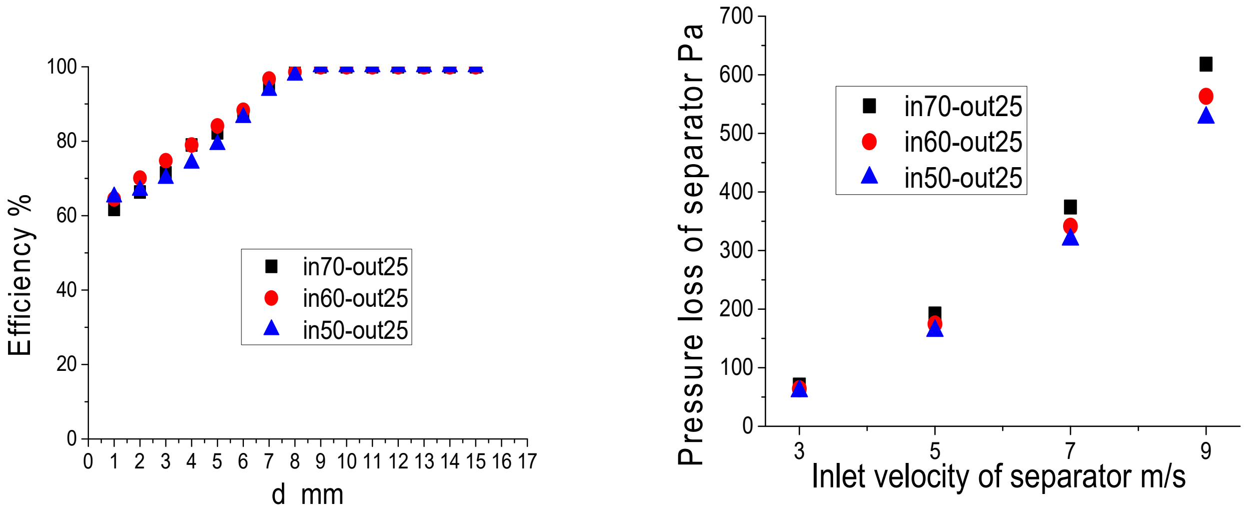
The results of the first stage separation indicate that the droplets with diameter greater or equal to 14um can be separated completely when the inlet velocity is 3m/s. The droplets with the diameter of 14um can move to the maximum height of 550mm. Therefore, plane Z=550mm is selected to observe the velocity angle (the angle with the Z axis) of gas: the outer ring of the second stage vanes（35°～44°）, the inner ring of the second stage vanes（17°～27°）. To study the influence of inlet angle of the second stage vanes, the axial position of the second swirler in the separator is initially set at 550mm. The outlet angle (the angle with the XOY plane) of the second vanes is initially set at 25° and the inlet angle (the angle with the XOY plane) of the second vanes is initially set at 50°、60°、70° respectively.



(a) 2.7m/s (b)5.0m/s (c)7.0m/s

Figure 8 : The velocity field distribution under different inlet velocity (X=0mm)

The separation efficiency gets the highest when the inlet angle of the second stage vanes is 60° under the inlet velocity being 3～9m/s, as is shown in **Figure 9** (For example, in70-out25 means the inlet angle of the second stage vane is 70°and the outlet angle of the second stage vane is 25°). Its pressure loss is in between the angle being 70° and 50°. The pressure loss and separation efficiency get the lowest when the angle is 50°. However, there is little difference of the separation efficiency when the angle is 50° and 70°. Therefore, the separation efficiency is higher when the inlet angle of the second stage vanes is consistent with the angle of the air flowing in separator. At the same time, the pressure loss can be reduced. It's bad to improve the separation efficiency and reduce the pressure loss of separator when the inlet angle of the second stage vanes is not consistent with the angle of the air flowing.



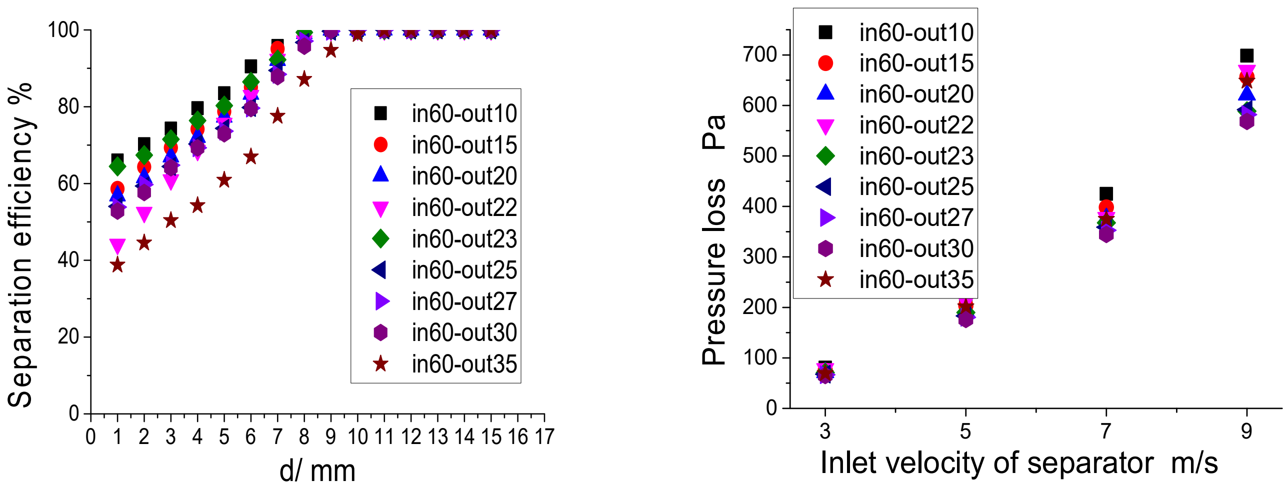
(a)Separation efficiency of separators(Inlet velocity 5m/s) (b) Pressure loss of separators

Figure 9 : Effects of inlet angle of the second stage vanes on separation performance

4.5 Effects of outlet angle of the second stage vanes

The inlet angle of the second stage vanes is 60°, and the outlet angles are set at 10°、15°、20°、22°、23°、25°、27°、30°、35° respectively. The distance between the first stage swirler and the two stage swirler is 550mm. The inl et angle of the first stage vane is 90° and the outlet angle is 22°. There are 25 vanes in a swirler. Other structural par ameters remain unchanged.

As is shown in **Figure 10** (a), the separation efficiency is from high to low with the outlet angle of the second vane changed with the order of 10°、23°、15°、20°、25°、27°、30°、22°、35°. The pressure loss of separator is influenced by the outlet angle of the second vane greatly, which is shown in **Figure 10** (b). Considering the separation efficiency and the pressure loss of the separator, the outlet angle of the second stage vane should be chosen at 23°.



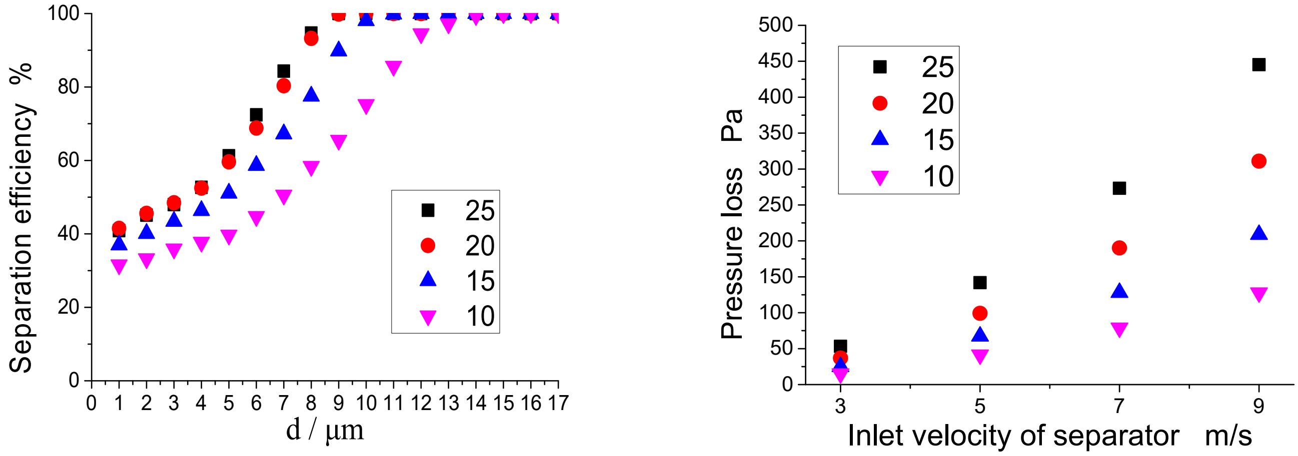
(a) Separation efficiency of separators (Inlet velocity 5m/s) (b) Pressure loss of separators

Figure 10 : Effects of outlet angle of the second stage vanes on separation performance

4.6 Effects of vanes' number

The one stage separation structure is used to study the influence of the number of vanes on the separation performance of the separator. The inlet angle of the vanes is 90°and the outlet angle of the vanes is 22°. The number of vanes is 25, 20, 15 and 10 respectively. The simulation results are shown in **Figure 11** (25 means the vanes number of single swirler is 25 in **Figure 11**) .

The separation efficiency can be improved with the increase of vanes number under a constant inlet velocity, which can also reduce the critical separated droplet diameter of separator. However, the pressure loss of separator increases at the same time.

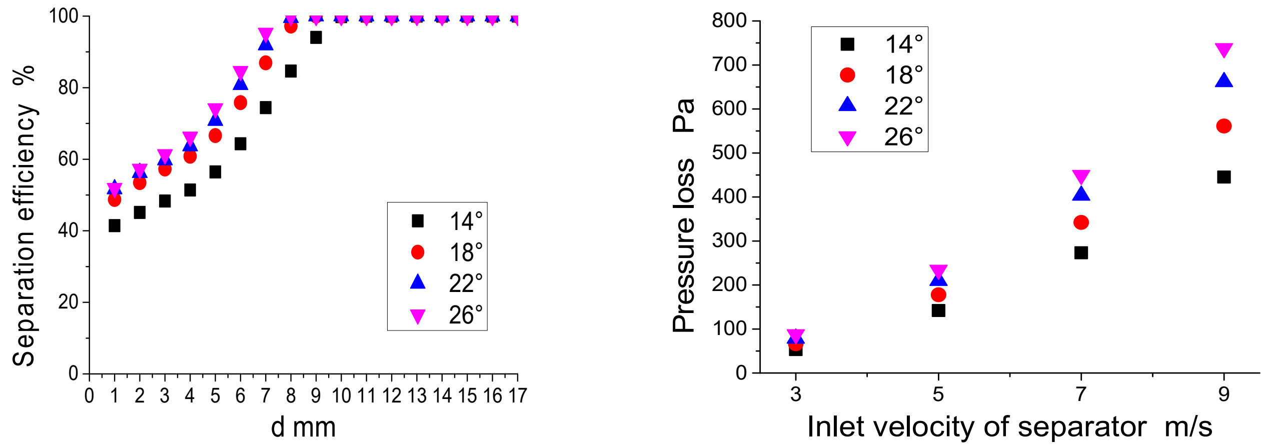


(a)Separation efficiency of separators (Inlet velocity 7m/s) (b) Pressure loss of separators

Figure 11: Effects of vanes' number on separation performance

4.7 Effects of rotation angle of a single vane

The rotating angles of single vane are 14°, 18°, 22° and 26°, which are shown in **Figure 12**. They are studied by simulation. It is found that the separation efficiency improves with the increase of vanes' rotation angle. But the pressure loss increases, too. The separation efficiency of droplets greater than 10um can be separated completely when the rotation angle is 18°, 22° and 26°. The separation efficiency of droplets greater than 10um is 90% when the rotation angle is 14°. The separation efficiency of droplets greater than 1um is greater than 40% under all of the separators.



(a) Separation efficiency of separators (Inlet velocity 5m/s) (b) Pressure loss of separators

Figure 12: Effect of rotation angle on separator performance

5. CONCLUSIONS

The two-phase flow simulation model in the water-gas cyclone separator was built up using the Euler-Lagrange method. The distribution of the gas flow field, the separation efficiency and pressure loss of separator were obtained.

The simulation results were verified by experiments.

There are water rings in the top of the separator cylinder when the speed of air is greater than 5m/s. The water ring has a great influence on the inlet and outlet pressure loss and separation efficiency of the separator, which is also an important reason for the deviation between the simulation and the experimental results.

The optimum outlet angle of vanes is 22°~25° considering the separation efficiency and the pressure loss of separators. The height of separator can be reduced effectively and the separation efficiency can be improved with the increase of the rotation angle of vanes, while the pressure loss of separator can be improved, too. With the decrease of the outlet angle of the first stage vane and the increase of the number of vanes, the critical separated droplet diameter of separator can be lowered effectively.

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