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Analysis and Optimization of Flow Characteristics of Axial Flow Gas-Liquid Cyclone Separator

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Abstract

In order to study the influence of the guide vane parameters on the internal flow field and separation performance of the axial cyclone separator in a high-pressure environment, the influence mechanism of internal velocity, pressure drop, cyclone field and separation performance of the separator was analyzed by numerical simulation by changing the enveloping Angle of the blade and the number of blades. In addition, the influence of recovery impeller on the separator was compared, and the influence of flow field and particle trajectory was analyzed. From the simulation results, it can be seen that t two swirling flow fields are generated inside and outside the separator. The pressure behind the diversion cone is low, and the pressure near the wall surface is high. The velocity field is symmetrically distributed in the separator, Under the same gas inlet velocity, the separation efficiency can be improved by increasing the enveloping Angle of the guide blade and increasing the number of guide blades. Increasing the number of blades significantly improves the separation efficiency of small droplets. When the number of blades is increased to more than 9, then increasing the number of blades has a small effect on the efficiency of separation. The increase of blade wrap Angle can improve the tangential velocity and axial velocity of the separation section and thus improve the separation efficiency, but the increase of blade wrap Angle will lead to a linear increase of pressure drop .Considering comprehensively, the wrap angle of the blades should be selected between 60° and 65°, and the number of blades should be selected from 8 to 10.

Keywords

Axial-flow cyclone separator; high-pressure natural gas separation; gas-liquid two-phase flow; number of blades; blade wrap angle; separation efficiency.

1. Introduction

In order to avoid corrosion of subsequent process equipment and environmental pollution in the process of natural gas extraction and treatment, it is necessary to remove as much as possible the liquid droplets and other impurities carried in the natural gas to prevent the droplets from entering the delivery pipe [1], [2]. At present, the gas-liquid separation method is commonly used in the industry to achieve the purification of the gas or liquid phase, and the most commonly used separator types are cyclones, including axial flow separators and counter flow separators [错误!未找到引用源。，错误!未找到引用源。]. Under the same working conditions, the axial flow cyclone has the advantages of compact structure, easy parallel connection and small pressure drop compared with the counter flow cyclone. In the offshore oil and gas production process, due to the large processing capacity of natural gas, the separation equipment is often required to have a compact structure and superior performance [错误!未找到引用源。]. In summary: the axial flow cyclone separator almost meets the characteristics of the limited space of the offshore platform and the purification requirements for natural gas[错误!未找到引用源。].

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The guide vane is the core component of the axial flow cyclone separator, and its structural parameters directly affect the separation performance of the separator. According to the existing research and practical engineering experience, the exit angle of the guide vane, the number of blades, the blade wrap angle, etc. The effect of separation efficiency is the most significant. In addition, the particle diameter of the separated liquid, the gas liquid concentration, and the working pressure also have a greater impact on the liquid separation performance.

Many researchers have done related research on the influence of blade structure parameters on the performance of axial flow cyclone separators. Gao Qifeng [错误!未找到引用源。]'s research on the inner center body of the separator shows that adding the center body can improve the stability of the internal flow field. Luo Xiaoming 错误!未找到引用源。compared the influence of the outlet angle of the guide vane on the separation efficiency and pressure drop under different working conditions of a cyclone separator with a central body inside. The result showed that when the inlet gas velocity is less than 7m/s, the outlet angle is reduced. Deng Yajun [9] and others proposed a new model to simulate the internal flow field and liquid film of the axial flow cyclone separator under high pressure, and the results are in good agreement with the experimental results. However, the current researches on direct current cyclones are mostly focused on low pressure conditions and there are few studies on the separation efficiency of different particle sizes.

Based on the above reasons, in order to improve the performance of the separator, this paper studies the internal flow field of the axial flow cyclone under high pressure on the basis of the above, and respectively studies the different blade wrap angles and different blade numbers on the speed, pressure and different particle size droplets.

2. Theoretical model and numerical simulation

2.1. Turbulence model

For the cyclone separator, the pressure and temperature change very little during the separation process, so the gas flow in the cyclone separator is assumed to be incompressible. Many researchers use the Reynolds Stress Model (RSM) to predict the flow model of the cyclone separator and prove that it can provide accurate predictions [10], so this paper uses RSM for turbulence simulation.

The continuity and Reynolds average Navier-Stokes equations as follows：

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

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

Where ρ stands for density, kg/m^3, u stands for speed, m/s; x stands for position length, m; subscripts i, j, and k stand for the three directions of the Cartesian coordinate system; μ stands for dynamic viscosity, Pa·s; $\bar{u}$ is the average speed, m/s; $\bar{u}$ is the fluctuation speed.

$\rho\overline{u_{\iota'}u_{J'}}$ Solve in the RSM transportation equation as follows：

$$\frac{\partial}{\partial t}\left(\rho\overline{u_{\iota'}u_{J'}}\right)+\frac{\partial}{\partial x_k}\left(-\rho u_k\overline{u_{\iota'}u_{J'}}\right)=D_{T,ij}+P_{ij}+\varepsilon_{ij}+\varphi_{ij}+S \tag{3}$$

Turbulence diffusion term:

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$$D_{T,ij} = -\frac{\partial}{\partial x_k}\left[\overline{\rho u_i' u_i' u_k'} + \overline{p\left(\delta_{kj} u_i' + \delta_{ik} u_j'\right)}\right] \tag{4}$$

Pressure strain item:

$$\varphi_{ij} = \overline{\mathrm{p}\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_i'}{\partial x_i}\right)} \tag{5}$$

Viscous dissipation rate:

$$\varepsilon_{ij} = -2\rho v \overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_i'}{\partial x_k}} \tag{6}$$

Where δ is the Kronecker factor and p is the pressure.

2.2. Geometric model

Figure 1 is a schematic diagram of the axial flow guide vane type cyclone separator, Figure 1a is a traditional axial flow guide vane type cyclone separator, mainly composed of air inlet, guide vane, guide cone, separation cylinder, exhaust pipe and drainage part composition. The natural gas-water mixture uniformly enters the separator through the inlet, and then rotates under the action of the guide vane. Due to the density difference between the gas and the liquid, the droplets are more easily separated from the center and thrown to the wall and near the wall, and some of the droplets follow.The inner wall flows out through the liquid outlet, and a part of the liquid droplets adhere to the wall surface and form a liquid film. Other liquids flow out as the gas enters the gas outflow pipe.

Figure 1b is an improvement based on Youfei Tang [11]'s new axial flow separator. A recovery blade is set inside the exhaust pipe. Under the action of the recovery blade, the gas moves back to the axial movement for subsequent secondary separation or utilization.

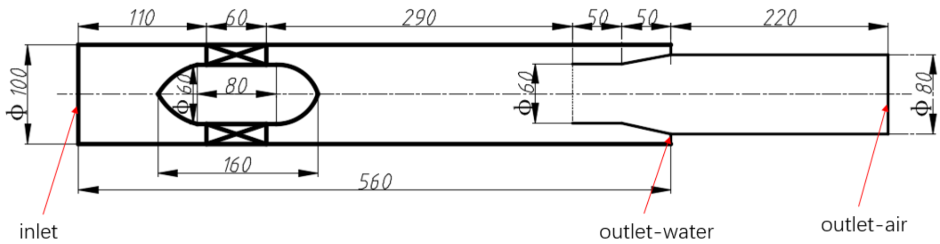

Fig 1a Without recovery blade

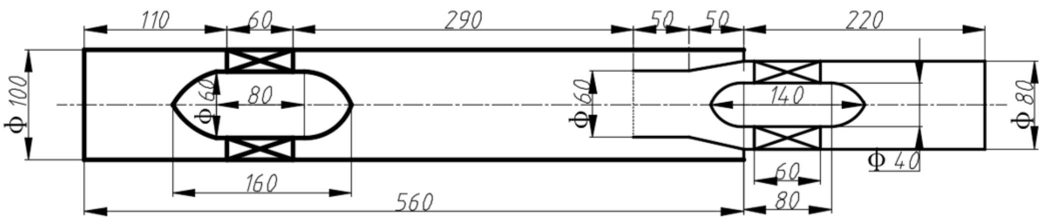

Figure 1b With recovery blades

Fig.1 Schematic diagram of the axial flow guide vane cyclone separator

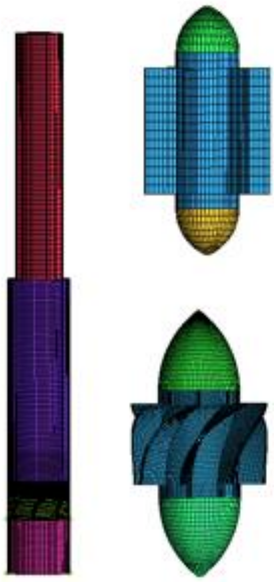

Fig.2 Mesh division

2.3. Calculation model and boundary conditions

This paper mainly studies the gas-liquid two-phase flow in an axial cyclone separator, and the continuous phase gas phase is the mainstream. The droplets are uniformly distributed in the gas phase, and the droplets and the gas are coupled with each other. Numerical simulation uses computational fluid dynamics software Fluent, uses ICEM software to divide the fluid domain with a hexahedral structured mesh, and refines the mesh near the wall. By adjusting the number of grid nodes, it is verified that the results of the numerical simulation have nothing to do with the number of grids. As shown in Figure 2, the number of grids are 858516, 556748, and 351332, respectively. The simulation results of the above three grid numbers on the axial velocity and the tangential velocity are shown in Figure 3. The simulation results of the three grid numbers at Z=310mm have good consistency. To ensure the correctness and accuracy of the simulation results Save time Select 556,748 grids for simulation analysis.

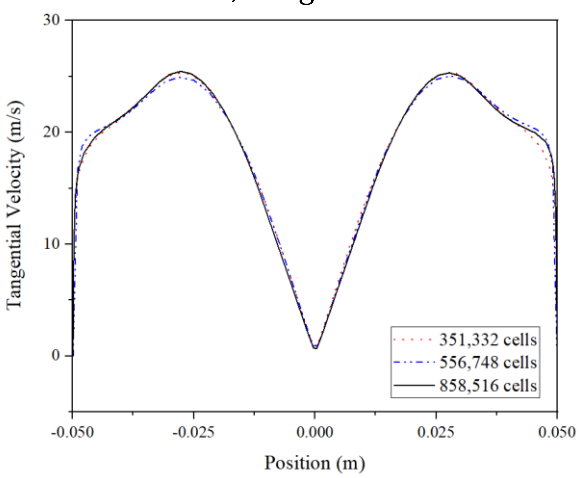

Figure 3a Tangential velocity

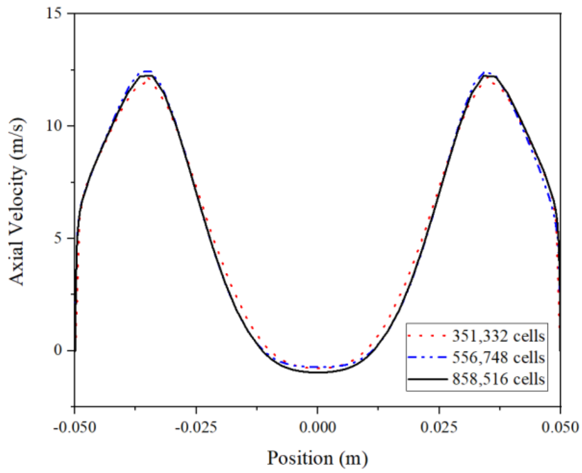

Figure 3b Axial velocity

Fig.3 Comparison of tangential and axial velocity simulation results with different mesh numbers

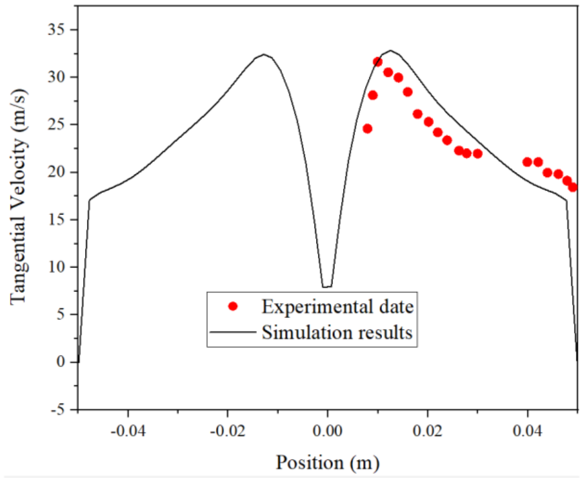

Fig.4 Comparison curve of tangential velocity simulation results and experimental results

For the simulation of gas-liquid two-phase flow, since the volume fraction of droplets in natural gas separation is less than 10%, the droplets adopt the discrete particle model (DPM), and the turbulence model adopts the Reynolds stress model (RSM). The SIMPLE algorithm is used to solve the velocity-pressure field, the momentum and turbulent flow are in the second-order upwind style, and the pressure gradient term is in the PRESTO format.

According to the actual working conditions, the speed inlet is adopted, the operating pressure is 8.5MP, the temperature is 25℃, the natural gas density under these conditions is 82.9kg/m^3, and the viscosity is 1.32×10^{-5}Pa·s [12] The outlet uses a pressure outlet, the gas outlet gauge pressure is 0, the gas outlet DPM is set to escape, and the liquid outlet DPM is set to trap. The standard wall function is used to simulate the flow near the wall. The droplets are mainly water with a density of 998.2 kg/m^3 and a viscosity of 0.001 Pa·s. The droplets and gas enter at the same speed from the inlet at the same time. The wall boundary condition adopts the non-slip boundary condition. When it collides, it is captured by the wall to form a liquid film. When it collides with other walls, the DPM option is set to reflect, assuming that the rebound recovery coefficient is equal to 1.

2.4. Model validation

Perform numerical simulation on the axial flow cyclone separator, set the gas inlet velocity to 8m/s, and use air in the gas phase. The tangential velocity at Z=310mm is simulated and the experiment measured at the corresponding position by Man Xiaowei [13] Compared with the data, the simulation value is close to the experimental result, which verifies the simulation result, as shown in Figure 4. The results show that the RSM model can accurately predict the gas-liquid flow in the separation process.

3. Calculation results and analysis

3.1. Continuous phase analysis

After the natural gas enters the cyclone, it is forced to rotate by the guide vanes. After passing the guide vanes, the gas and liquid begin to separate. The flow of the gas-liquid two-phase fluid is mainly determined by resistance, centrifugal force, and gravity. When the centrifugal force is greater than the resistance, the droplets are easily separated near the wall and discharged through the liquid outlet. Otherwise, it will be taken away by the natural gas and removed from the gas outlet. Therefore, the tangential velocity and axial velocity of the gas are the two main factors in the separation process.

The influence of different blade wrap angles on the tangential velocity is shown in Figure 5a. When the natural gas-water mixture encounters the guide vane, the airflow transforms from axial motion to rotational motion. At this time, the tangential velocity appears, which can be seen from the tangential velocity cloud chart. The velocity distribution law is basically the same at different sections. The tangential velocity increases first and then decreases from the wall to the axis, and the tangential velocity at the axis is 0m/s. The appearance of tangential velocity forms two vortices in the internal flow field of the cyclone. The velocity gradient of the external flow field is small and the velocity gradient of the internal flow field is high, so the droplets are easily separated.

Figure 5b is a cloud diagram of the axial velocity distribution under different blade wrap angles. The velocity field is symmetrically distributed. The axial velocity increases after the guide vane is accelerated, and there is a low-speed recirculation zone behind the guide cone. It can be seen from the axial velocity cloud graph that the gas outlet has a negative velocity, indicating that there is a backflow phenomenon at the outlet, and the larger the backflow area becomes, the more obvious it is with the increase of the blade wrap angle.

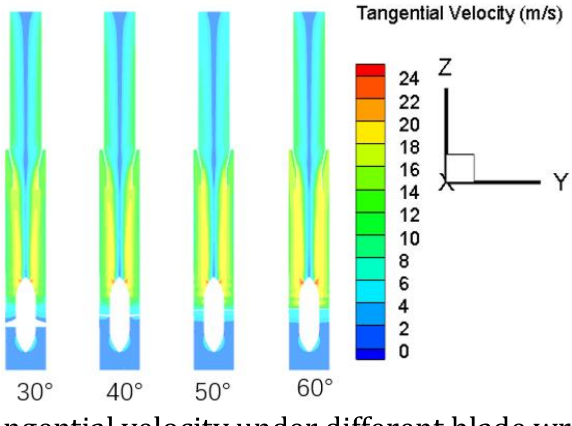

Fig.5a Tangential velocity under different blade wrap angles

Figure 6 is the velocity distribution diagram of the tangential velocity and axial velocity under different blade wrap angles at Z=300mm. From the velocity distribution diagram, it can be seen that the velocity distribution law under different blade wrap angles is basically the same, and the tangential velocity is a typical Rankine The “vortex” distribution is consistent with the experimental results of Jin Xianghong et al. The internal forced vortex and the external free vortex [14]. Increasing the wrap angle increases the fluid staying time in the guide vane, and the tangential velocity and axial velocity of the fluid after being accelerated by the guide vane increase at the same time, while the maximum tangential velocity and axial velocity approach the wall. The increase of the tangential velocity increases the centrifugal force of the liquid, which promotes the liquid to enter the annular liquid removal area and improves the separation efficiency.

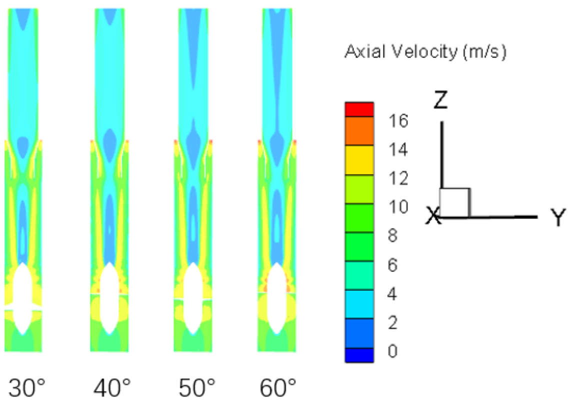

Fig.5b Axial velocity cloud diagram under different wrap angles

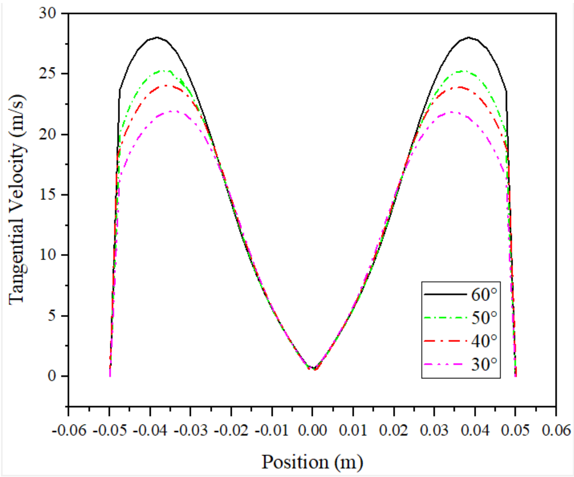

Fig.6a The influence of blade wrap angle on tangential velocity distribution (Z=300mm)

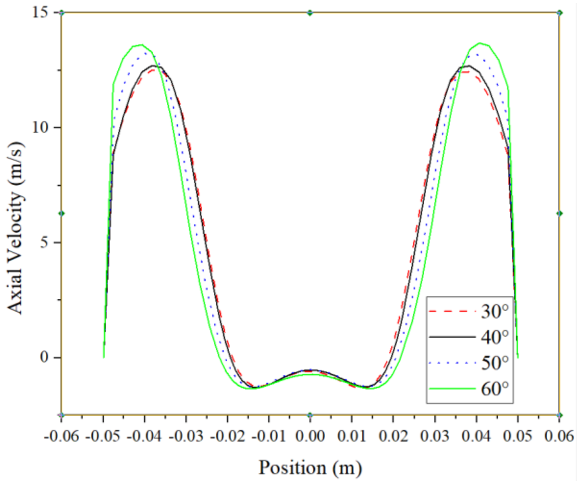

Fig.6b The influence of blade wrap angle on axial velocity distribution (Z=300mm)

3.2. The effect of the recovery blade on the separator

As mentioned above, because the airflow in the axial flow separator is in a rotating state, the airflow moves along the guide cone for a certain distance and then leaves the guide cone, forming a low-pressure zone at the shaft center and generating two vortices inside and outside, reducing the flow field stability. Especially for the influence of pressure drop, in order to facilitate the secondary separation and reduce the pressure drop loss, a recovery impeller can be installed in the gas discharge pipe to restore the rotating airflow to linear motion, as shown in Figure 7, the backflow phenomenon of the gas outlet disappears after the recovery impeller is added. The gas is restored to axial movement from rotational movement.

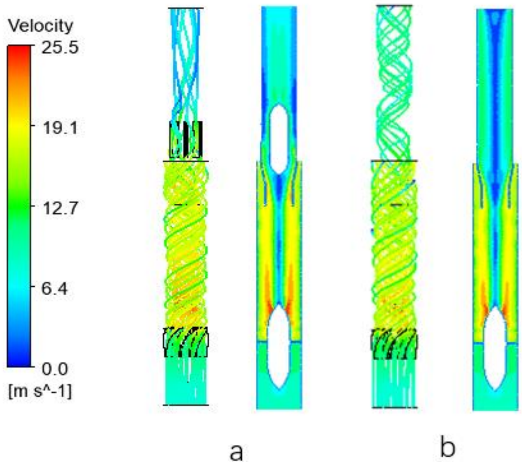

Fig.7 Streamline distribution diagram of two structures

Figure 8 is a pressure distribution cloud diagram of different sections of a separator with a recovery blade. It can be seen that under the action of the guide vane, the pressure gradually increases from the shaft center to the inner wall of the separator, and negative pressure appears at the shaft center; the airflow has a large pressure value and uniform distribution before passing through the guide vane, and the pressure in each section of the separation section does not change much. , The negative pressure zone at the center disappears after hitting the guide cone of the recovery blade.

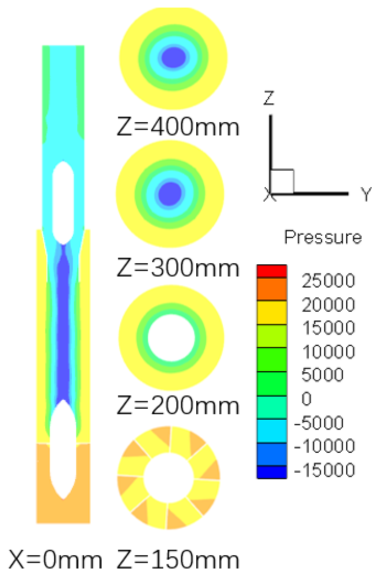

Fig 8 Distribution of pressure cloud diagrams of different sections of the separator (unit: Pa)

3.3. Discrete phase analysis

After the droplets are accelerated by the impeller, the droplets of different particle diameters are dispersed in different areas. Figure 9 shows the particle distribution of different cross-sections. It can be seen that the particles of various diameters are mixed together just after the gas is accelerated by the impeller. Separately, the larger diameter droplets begin to approach the tube wall, the smaller diameter particles are in the middle, and the droplets of different diameters are further separated under the action of the tangential velocity, and the smaller diameter droplets are distributed in the Near the core, the gas escapes from the gas outlet, and the larger diameter liquid is mostly near the pipe wall or captured by the pipe wall to form a liquid film, which is separated from the liquid outlet under the push of the gas flow.

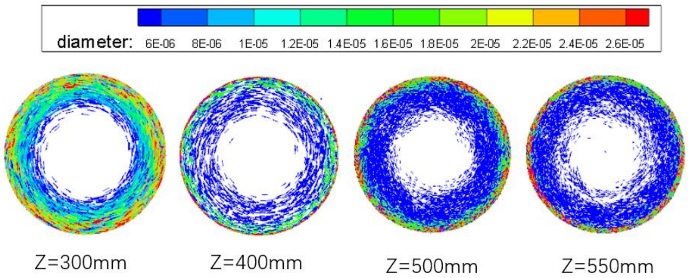

Fig 9 Droplet distribution diagrams of different cross-sections

4. Conclusion

(1) Increasing the wrap angle of the blade can increase the tangential velocity and radial velocity of the gas in the separation zone, and improve the separation efficiency of the separator; when the wrap angle of the blade is greater than 50°, increasing the wrap angle can significantly improve the separation efficiency of droplets

(2)Increasing the number of blades and increasing the blade wrap angle will cause the pressure drop to increase, and the blade wrap angle and the number of blades should not be too large when the pressure drop is required under the condition of meeting the separation efficiency.

(3) Restoring the impeller can convert the rotating motion of the gas in the exhaust pipe into linear motion, which can well reduce the turbulent kinetic energy, reduce the pressure drop, and use the secondary separation and utilization.

References:

[1]. Bybee Karen. Revolutionizing Offshore Production by In-Line Separation Technology[J]. Journal of Petroleum Technology, 2010, 62(12):74-75.

[2]. Lian Lingjun,Wang Wei,Xu Wei,et al.Numerical simulation of 3-D turbulent flows of plug discharge tunnel[J].Journal of Sichuan University(Engineering Science Edition),2011,43

[3]. Cai Lu,Sun Zhiqian,Zhu Liyun,Wang Hanxiang,Wang Zhenbo. Application research progress of gas-liquid cyclone separation technology[J]. China Petroleum Machinery. 2021,49(01):102-109.

[4]. Li Wenjing. Numerical simulation of natural gas swirling gas-liquid separator[D]. China University of Petroleum, 2009.

[5]. Han Chuanjun,Chen Fei,Yang Xue,Zhang Jie. Effects of blade′s parameters on performance for guide vane cyclone tube [J].Journal of Machinery Design,2015,32(08):72-77.

[6]. Liu Shuai,Wang Jianjun,Guo Ying,Liu Yongfei. Performance and Structure Optimization of a Multi-Tube Axial Flow Cyclone Separator [J]. Journal of Chemical Engineering of Chinese Universities. 2018,32(05):1042-1053.

[7]. Gao Qifeng,Yang Donghai,He Limin.Structural analysis and optimization of the uniflow cyclone separator[J]. China Petroleum Machinery,2019,47(02):103-109.

[8]. Luo Xiaoming, Gao Qifeng, Liu Meng et al. Separation characteristics of axial flow gas-liquid cyclone separator[J]. Acta Petrolei Sinica (Petroleum Processing Section), 2020, Vol. 36(3): 592-599.

[9]. Deng Yajun. Study on the numerical method and separation characteristics of axail flow cyclone.China University of Petroleum (Beijing)).

[10]. S. Bernardo,M. Mori,A.P. Peres,R.P. Dionísio. 3-D computational fluid dynamics for gas and gas-particle flows in a cyclone with different inlet section angles[J]. Powder Technology,2005,162(3).

[11]. Youfei Tang et al. Numerical analysis of separation performance of an axial-flow cyclone for supercritical CO 2 -water separation in CO 2 plume geothermal systems[J]. Separation and Purification Technology, 2020, 248
[12]. Long, Huang, et al. Numerical analysis of a novel gas-liquid pre-separation cyclone[J]. Separation & Purification Technology, 2018.
[13]. Man Xiaowei.Experimental research on the new type axial flow cyclone [D]. China University of Petroleum, 2011.
[14]. Jin Xianghong,Jin Youhai,Wang Jianjun,Wang Zhenbo.Numerical simulation of gas-phase flow field in an axial flow type gas-liquid cyclone separator[J] Journal of Chemical Engineering of Chinese Universities 2009,23(05):748-755.

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