Influence of Blade Outlet Angles on Separation Performance of Guide Vane Type Axial Flow Cyclone Tube

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Abstract: The influences of the internal and external outlet angles on separation performance and flow field are compared and analyzed. Two arc functions are employed for controlling the internal and external angles. The separation process in the cyclone tube is calculated by using two-fluid model based on the Eulerian-Eulerian method. The results show that the structure with the internal outlet angle smaller than the external one is more beneficial to the separation performance. It is found that the small internal angle can help increase the swirl number, while the small external angle can help increase the friction coefficient. Several groups of numerical simulations are conducted for the air intake unit of the gas turbine in practice. When the internal outlet angle is 35° and the external outlet angle is 40°, the blade has sufficient cyclone strength and the separation rate of particles with diameters of 10—100 μm is between 70%—98%. The small blade angle is more conducive to the separation of fine particles, leading to violent collision of large particles on the outer wall and reduction of separation efficiency. In addition, reducing the external angle is conducive to the discharge of large particles.

Key words: axial flow; blade parameters; outlet angles; separation performance

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0 Introduction

For the gas turbine intake units, the frequency of replacing the filter screens of fiber material will cost a lot of resources[1-2]. Thus, setting a pre-filter is necessary. Existing dust removal technology can be divided into: Filtering technology, electrostatic dust removal technology, wet dust removal technology and mechanical dust removal technology[3-5]. The cyclone separator is a kind of mechanical separation technology. Thanks to its adaptability to harsh environments, high separation efficiency and low pressure drop, it has been widely used in dust removal. The multicyclone separator can effectively remove lager particles, and has been extensively used as primary filters for trucks, working machines, and military vehicles running in higher dust-concentration environment[6-7]. Thus, taking the axial flow cyclone separator as the pre-filter in the gas turbine air inlet can save the cost.

The structural parameters of the cyclone tubes and gas flow conditions are the main factors affecting the overall performance (pressure drop ΔP, separation efficiency φ)[8-10]. Mao et al.[11] studied the size and shape of the axial flow cyclone separator, and it shows that the cyclone tube with a circular blade shape and the 40°-outlet angle is the most appropriate choice. Besides, the variance analysis of separation efficiency was carried out, and the results illustrated that the blade shape and the outlet angle both have great influence on the performance. Meanwhile, Luan et al.[12] and Gopalakrishnan et al.[13] reported that the number of blades, the blade angle and the blade length have great influences on the resistance characteristics and filtration efficiency of the axial cyclone tube. Tang et al.[14] also investigated the blade outlet angle and blade numbers. They highlighted that blade was one of the most influen-

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tial factors on cyclone flow and performance. It is hitherto known that structual studies have not divided the blade outlet angles into the internal and the external ones. But changing these two angles has the possibility to enhance the performance of the cyclone tube.

In axial cyclone separators, the centrifugal force is imparted on the gas-solid mixture as a result of the guide blades on the vortex generators. This force, pushing the solid particles towards the external wall of the cyclone, is concerned with the structures. Besides, the axial cyclone separator exhibits a single vortex, and the trajectory of the particles is controlled by the swirl situation. The theory of particle separation is simple, and the swirl flow field and vortex situations in cyclone tube are intricate. It is burdensome to investigate them only using experiments.

For CFD simulations, Hosseini[15], Safikhani et al.[16], Mao et al.[11], and Gopalakrishnan et al.[17] used the Eulerian-Lagrangian method to analyze the gas-solid field in the cyclone separators and the particle trajectory. Besides, the Eulerian-Eulerian method can also describe the particle isolation and distribution with the volume fraction in the flow field. Kartushinsky et al.[18] used the two-fluid model and particle dynamics to analyze the gas-solid flow characteristics of the horizontal pipe, and revealed the movement law of the particle phase in the pipe. Meier et al.[19] said that the Eulerian-Eulerian approach, despite its assumptions, can be used to introduce the solid effects in the simulation of the gas-solid flow in cyclones and predict the efficiency collection grades of cyclones. Luciano et al.[20] evaluated a fully automated methodology enhancing the cyclone separators in series, with a multi-objective optimization method and Eulerian-Eulerian approach simultaneously minimizing the pressure drop and maximizing the efficiency. Elshorbagy et al.[21] illustrated the flow features in hydro-cyclone by employing the Eulerian-Eulerian approach. His study indicated that with the increase of the volume fraction, the static pressure increased, the axial velocity decreased, the radial velocity decreases, and the tangential velocity was almost unaltered. Zhang et al.[22] investigated the flow characteristics of the gas-solid in a short-contact cyclone reactor by adopting the Eulerian-Eulerian computational fluid dynamics model with the kinetic theory of granular flow.

The aim of this study is to investigate the effects of the vane parameters on the performance and swirl flow. Herein the effect of internal and external outlet angles is discussed. The air is set as the gas phase, and the quartz is set as the particle phase. The kinetic model of granular based on Eulerian-Eulerian method is used to predict the separation. Further, the numerical simulation results of an axial-flow cyclone separator are compared with the experimental results to verify the accuracy of the numerical model.

1 Simulation

1.1 Numerical model

The swirl situations in the axial cyclone tubes, despite the simple structure, are complex. Therefore, the CFD simulations are run to study the separation process. Firstly, the key issue is the selection of a suitable turbulence model to predict complex swirl flow in the pipelines. Then, by providing information on all stress components and including precise terms of cyclonic effects in its stress transfer equation, the Reynolds stress model (RSM) can capture most physical phenomena[23]. Besides, it shows the predominant performance in calculating the strong swirl flows. The continuity and Reynolds Average Navier-Stokes equations can be expressed as

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

$$\frac{\partial}{\partial t}(\rho \boldsymbol{u}_i)+\frac{\partial}{\partial \boldsymbol{x}_i}(\rho \boldsymbol{u}_i \boldsymbol{u}_j)=-\frac{\partial \rho}{\partial \boldsymbol{x}_i}+\frac{\partial}{\partial \boldsymbol{x}_j}\left[\mu\left(\frac{\partial \boldsymbol{u}_j}{\partial \boldsymbol{x}_j}+\frac{\partial \boldsymbol{u}_j}{\partial \boldsymbol{x}_i}\right)\right]+\frac{\partial}{\partial \boldsymbol{x}_j}\left(-\rho \overline{\boldsymbol{u}_i' \boldsymbol{u}_j'}\right) \tag{2}$$

where subscripts "i" and "j" represent the directions of the Cartesian coordinate system. ρ represents the density (unit: kg/m^3); $\boldsymbol{u}$ the velocity (unit: m/s); x the positional length (unit: m); μ the dynamic viscosity (unit: Pa·s); $\bar{\boldsymbol{u}}$ the mean velocity (uint: m/s); here, $\boldsymbol{u}_i=\bar{\boldsymbol{u}}_i+\boldsymbol{u}_i'$, $\boldsymbol{u}_i'$ and $\boldsymbol{u}_j'$ are the fluctuating velocities (unit: m/s).

For the gas solid-field, the two-fluid model based on kinetic particle theory is used to calculate the particle isolation. This model takes the discrete phases as the quasi-continuum, and the distributions of the two phases are described based on the volume fraction[24]. And it is coupled with the transport equation model of turbulent kinetic energy of particles. Meanwhile, it considers the interaction between particles, turbulent pulsation of particles and turbulent interaction between gas-solid phases. The continuity, momentum equations for gas phase and the constitutive relations

$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla \cdot (\alpha_g \rho_g \boldsymbol{v}_g) = 0 \tag{3}$$

$$\frac{\partial}{\partial t}(\alpha_s \rho_s \boldsymbol{v}_s) + \nabla \cdot (\alpha_s \rho_s \boldsymbol{v}_s \boldsymbol{v}_s) = -\alpha_s \nabla p_g + \nabla \cdot \boldsymbol{\tau}_s + \beta(\boldsymbol{v}_g - \boldsymbol{v}_s) + \alpha_s \rho_s \boldsymbol{g} \tag{4}$$

$$\boldsymbol{\tau}_g = \alpha_g \mu_{g,\text{eff}} [\nabla \boldsymbol{v}_g + (\nabla \boldsymbol{v}_g)^{\mathrm{T}}] + \alpha_g \left(\lambda_g - \frac{2}{3}\mu_{g,\text{eff}}\right)(\nabla \cdot \boldsymbol{v}_g) \boldsymbol{I} \tag{5}$$

where the subscript "g" denotes the gas term and "s" the particle term. α is the volume fraction, ρ the density (unit: kg/m^3), β the drag coefficient of flow, v the velocity (unit: m/s), $\boldsymbol{g}$ the specific gravity force (unit: m/s^2), $\boldsymbol{\tau}$ the shear stress, p the pressure of flow (unit: Pa), $\mu_{g,\text{eff}}$ the effective gas phase viscosity, and $\boldsymbol{I}$ the unit tensor.

The continuity, momentum equations for particle phase and the constitutive relations are expressed as

$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \boldsymbol{v}_s) = 0 \tag{6}$$

$$\frac{\partial}{\partial t}(\alpha_g \rho_g \boldsymbol{v}_g) + \nabla \cdot (\alpha_g \rho_g \boldsymbol{v}_g \boldsymbol{v}_g) = -\alpha_g \nabla p_g + \nabla \cdot \boldsymbol{\tau}_g - \beta(\boldsymbol{v}_g - \boldsymbol{v}_s) + \alpha_g \rho_g \boldsymbol{g} \tag{7}$$

1.2 Definition of design parameters

Here, the blade outlet angle is divided into internal and external ones. The two angles can be changed by some geometric methods (Fig.1). Then the blade surface forming principle of guide blade is as follows: a straight line intersects a cylinder at a certain angle, and then moves along with a guide-line which is a specified curve on the cylinder. Therefore, two circular guide-lines are set to control the internal and external outlet angles, respectively, as shown in Fig.1. The guide-line equations are as follows

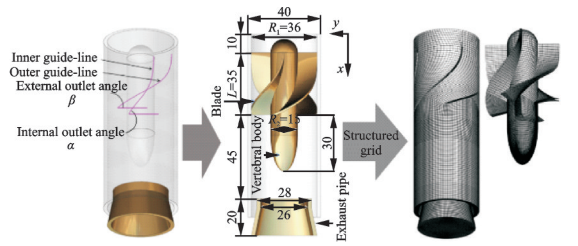


Fig.1 Definition of cyclone tube parameters and structural grid

$$y_{\text{inner}} = \psi_{\text{inner}} - \sqrt{\psi_{\text{inner}}^2 - z^2} \tag{8}$$

$$y_{\text{outer}} = \frac{R_1}{R_2}\left(\psi_{\text{outer}} - \sqrt{\psi_{\text{outer}}^2 - z^2}\right) \tag{9}$$

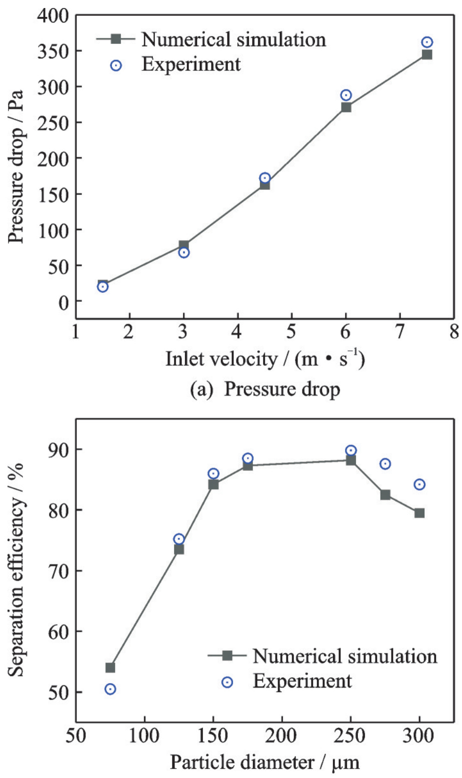
$$\psi_{\text{inner}} = \frac{L}{\cos\alpha} \tag{10}$$

$$\psi_{\text{outer}} = \frac{L}{\cos\beta} \tag{11}$$

where R_1 and R_2 are the diameters of the external and internal cylinders, respectively (unit: mm). L is the length of the blade (unit: mm), α the internal outlet angle, and β the external outlet angle.

1.3 Validation of numerical model

The accuracy of the numerical model is the basics of the analysis. Therefore, an experimental object[11] is taken as the simulation target to verify the accuracy of the CFD model. The RSM model with standard wall function is employed to simulate the steady air flow field. The pressure-velocity coupling is done with using the SIMPLEC algorithm. For pressure, the PRESTO interpolation scheme is applied. The first order upwind scheme is used for the momentum and turbulent kinetic energy. The turbulent dissipation rate uses QUICK. Then, the Euler two-fluid model is used to solve the gas-solid flow. For the air phase, let the density of 1.225 kg/m^3 and viscosity of 2.0×10^{-5} kg/m·s at the standard atmospheric pressure. When calculating the gas-solid flow, the dispersed RSM multiphase model is selected and diameter is set as 75, 120, 150, 180, 250, and 270 μm[11]. Meanwhile, the Gidaspow drag model is adopted. Then the restitution coefficient of particle-particle collision is set at 0.9. The velocity inlet and pressure outlet corresponding to the experimental conditions are adopted. And the solid particles enter the pipe at the same velocity as the air. The specularity coefficient, ranging from 0 to 1, which controls the amount of lateral momentum transfer, is set at 0.2. Fig.2 shows the agreement between results of the simulations and experiments[11]. It illustrates that the RSM can solve the pressure drop, and the two-fluid model can accurately predict the separation axial cyclone tubes.



(a) Pressure drop

(b) Separation efficiency

Fig.2 Comparison of simulation and experimental results[11]

2 Results and Discussion

2.1 Study of internal and external angles

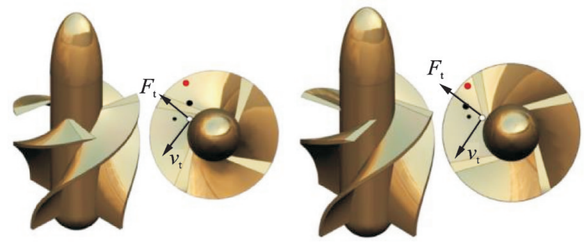
With the action of the guide blade, the particles get the rotary motions and centrifugal force. For the small blade outlet angles, they can provide the particles with greater tangential velocity[25]. Thus the centrifugal force of the particle is larger, which is defined by

$$F_t = m_z \frac{v_t^{\ 2}}{r} = \frac{1}{6}\pi\rho_p d_p^{\ 3}\frac{v_t^{\ 2}}{r} \tag{12}$$

$$v_t = v_0 / \cos\theta \tag{13}$$

where r is the radial position (unit: m), ρ_p the particle density (unit: kg/m^3), d_p the particle diameter (unit: m), v_t the tangential velocity (unit: m/s), v_0 the inlet velocity (unit: m/s), and θ the outlet angle.

In Fig.3, it suggests that the relation of internal and external outlet angles have their own effect on the isolation. For the particles close to the external wall, they can be separated without a big centrifugal force. But for particles at the internal wall, they require a larger one. Thus, these two angles will affect the centrifugal force on the particles, then they will influence the particle rebound degree at the wall.



(a) $\alpha<\beta$ (b) $\alpha>\beta$

• Particle at external wall • Particle at internal wall

Fig.3 Force condition of particles

In order to explore the influence of these two angles on the performance, a numerical investigation is carried out. In this process, a reference in which the angle is 40°-40° (α-β) is set, and the internal and external outlet angles are reduced respectively.

By comparing the simulation results in Fig.4, it can be observed that reducing α can markedly enhance the separation efficiency, but it has small effect on the pressure drop. Conversely, reducing β has little contribution to improving separation, but can increase the resistance obviously. Then, this phenomenon provides a significative evidence for the selections of design parameters. Guaranteeing α is smaller than β is necessary in the engineering application.

For rotary flow, the swirl number (S) is an important parameter to evaluate the intensity of swirls[26]. S is the ratio of the axial flux of tangential momentum to the axial flux of axial momentum, expressed by

$$S = \frac{2\int_{R_1}^{R_2} v_z v_t r^2 \mathrm{d}r}{R^3 v_{\mathrm{avg}}^2} \tag{14}$$

where v_{avg} is the average flow velocity (unit: m/s).

Fig.5 illustrates the influence of the internal and external outlet angles on the swirl number. It is

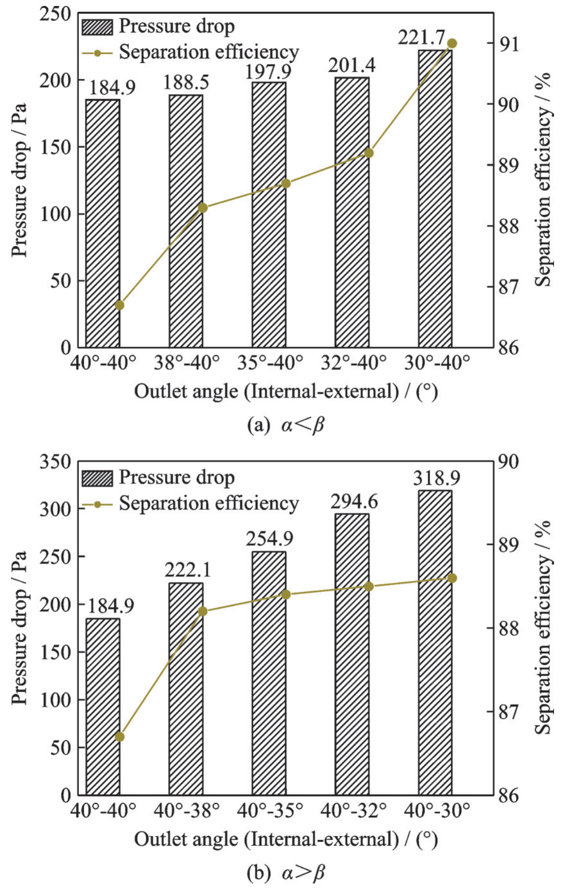


Fig.4 Effect of two outlet angles on cyclone performance

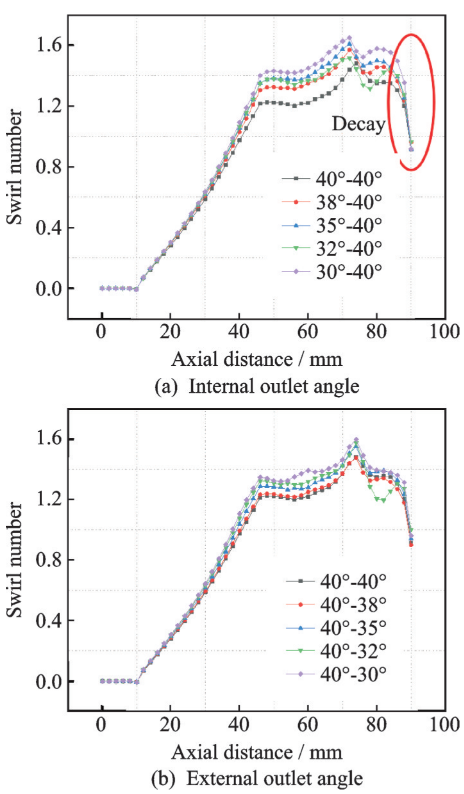


Fig.5 Swirl numbers of axial cyclone tubes

obvious that reducing the internal outlet angle is more beneficial to increasing the swirls number. And the flow with decay is more obvious in the strong swirl flow.

2.2 Performance of cyclone tubes

To show the performance of the cyclone tubes when α is smaller than β, simulation is carried out. And in this process, we let $\beta-\alpha=5°$. In Fig.6, it illustrates the influence of the guide-line outlet angles on the distribution of tangential velocity. With the increase of the angle, the tangential velocity of airflow decreases obviously. In Figs.6(a, b), the near wall velocity is reduced for rising the external angle.

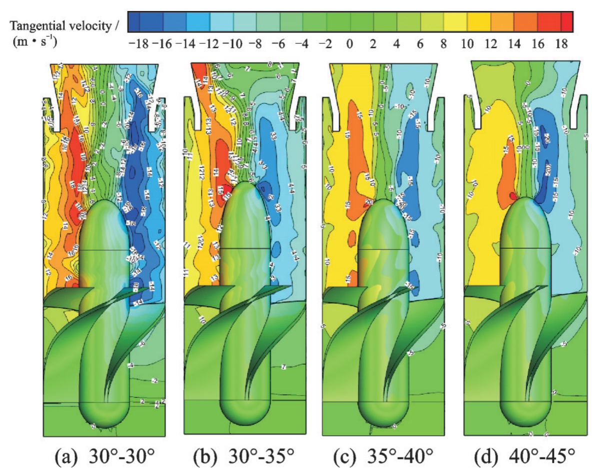


Fig.6 Nephograms of tangential velocity with different internal-external outlet angles

The swirl number expresses the ratio of the axial flux of tangential momentum to the axial flux of axial momentum, thus it gives a measure of the strength of the swirling flow. Fig.7 shows the effect of outlet angle on swirl number. As the outlet angle gradually decreases, the swirl number gradually increases, which means the swirl intensity increases. The airflow passes over the blades and becomes strong swirl ($S>0.6$). As mentioned, based on swirl number, the swirl flows are classified into weak, medium and strong swirl. If the swirl number is less than 0.3, it is usually classified as a weak swirl; if the swirl number is between 0.3 and 0.6, it is called a medium swirl; and if the swirl number is greater than 0.6, it is called a strong swirl[27]. With the swirl continue flow downstream, the axial and tangential momentum fluxes in the near wall region reduces because of the wall friction, thus causing swirl decay.

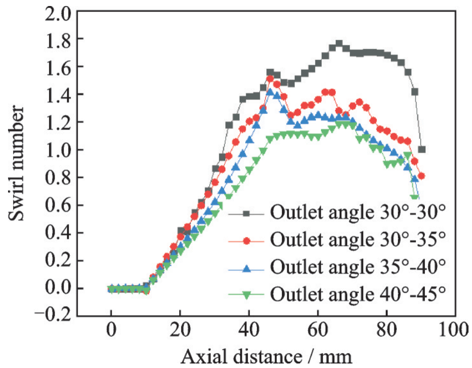


Fig.7 Swirl number of different outlet angles

Fig.8 shows the effect of blade outlet angle on the pressure drop. It is obvious that the pressure at the blade decreases most rapidly. The maximum total static pressure drop is 349.79 Pa. And the blade-pressure-drop of 30°-30° cyclone tube is the greatest: 240.21 Pa. Besides, it can be seen that the smaller blade outlet angle bring the more pressure drop. And compared with weak swirl, the stronger swirl has the greater friction loss at the wall surface, so it has larger axial and radial pressure drops.

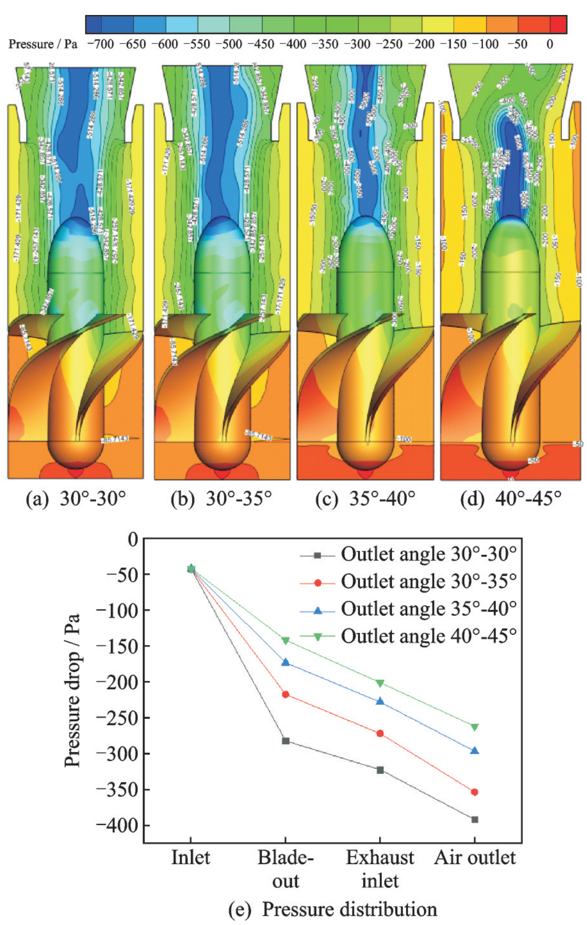


Fig.8 Pressure with different internal and external outlet angles

The friction factor is defined by

$$f=\left(\frac{\Delta p}{\rho W_{\text{avg}}^{2}}\right)\left(\frac{2d_0}{l}\right) \tag{15}$$

where d_0 is the equivalent diameter; W_{avg} the average velocity, which is calculated from flow rate and pipe cross area, and l the flow length[26].

Fig.9 illustrates the relationship between outlet angle and friction factor. It can be found that the value of friction factor at the blade is the greatest. And it is easy to know that the smaller blade outlet angle is, the greater friction factor will be. Combined with the static pressure at different locations of the guide vane axial flow cyclone tube, it can be found a pattern that the greater the friction factor, the faster the pressure drop. As Rocha et al.[26] said that the greater the cyclone strength, the greater the friction coefficient, and the greater the pressure drop.

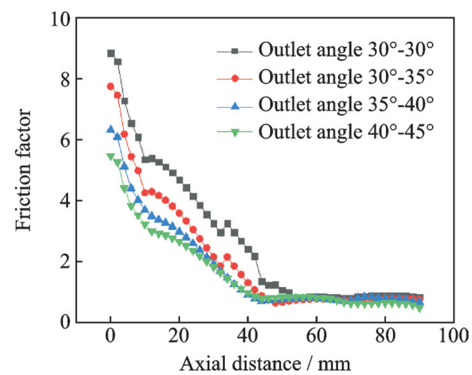


Fig.9 Friction factor of the guide vane axial flow cyclone tube with different blade parameters

Herein the analysis of the applicability to different particles is carried on. When the inlet velocity is 5 m/s, with different particle sizes, the separation efficiency of the cyclone tube is obtained by CFD method. As shown in Fig.10, for the small particle size (10—30 μm), smaller blade outlet angle results in higher separation efficiency. Besides, the bigger particle is, the greater centrifugal force is, and the collision with the external wall is more violent. Thus for the large particle size (50—100 μm), small blade outlet angle will result in lower separation efficiency. By comparing 30°-30° with 30°-35° tubes, it can be seen that decreasing the external angle slightly reduces the separation efficiency of the small particles, but it greatly improves isolation of the large particles.

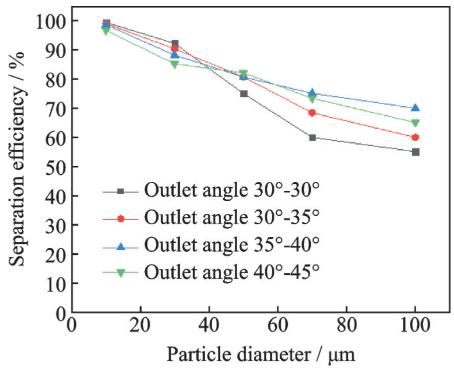


Fig.10 Separation efficiency of guide vane axial flow cyclone tube with different blade parameters

3 Conclusions

The axial flow cyclone separator can meet the requirements of the first stage separator of gas turbine. In this paper, the accuracy of the simulation model is verified by the experimental results. The effects of the internal and the external outlet angles on separation are analyzed.

The structure with the internal outlet angle smaller than the external one's is more beneficial to the separation performance. With the decrease of the blade outlet angle, the friction factor of the blade increases gradually. When the outlet angle is 40°-45°, the friction factor of the cyclone is the smallest. And this minimum value is from 0.7 to 5.2. Considering the pressure drop and the separation efficiency, the cyclone tube with a blade outlet angle in 35°-40° has the best separation performance. And its separation efficiency is 70%—98% when the particle size is 10—100 μm.

References

[1] SUTHERLAND K. Air filtration in industry: Gas turbine intake air filtration[J]. Filtration and Separation, 2008, 42(1/2): 20-23.

[2] MIKHAYLOV V E, KHOMENOK L A, SHERAPOV V V. Problems in creation of modern air inlet filters of power gas turbine plants in Russia and methods of their solving[J]. Thermal Engineering, 2016, 63(8): 529-535.

[3] BOJDO N, FILIPPONE A. Comparative study of helicopter engine particle separators[J]. Journal of Aircraft, 2014, 51(3): 1030-1042.

[4] WANG Yao. Overview of downhole spray dust removal technology[J]. IOP Conference Series: Earth and Environmental Science, 2020, 558(3): 42-52.

[5] CALISKAN M E, KARAGOZ I, SURMEN A A. An experimental investigation into the particle classification capability of a novel cyclone separator[J]. Separation and Purification Technology, 2019 (209): 908-913.

[6] DZIUBAKA T, BĄKAŁAA L, KARCZEWSKIA M, et al. Numerical research on vortex tube separator for special vehicle engine inlet air filter[J]. Separation and Purification Technology, 2020(237): 116463.

[7] DZIUBAK T. Performance characteristics of air intake pleated panel filters for internal combustion engines in a two-stage configuration[J]. Aerosol Science and Technology, 2018, 52 (11): 1293-1307.

[8] KOU Jie, CHEN Yi, WU Junqiang. Numerical study and optimization of liquid-liquid flow in cyclone pipe[J]. Chemical Engineering and Processing, 2020 (147): 107725.

[9] ZHONG X, DU H Y, ZHU S J, et al. Effects of numbers of parallel micro-cyclone separators on separation performance[J]. Journal of Chemical Engineering of Chinese Universities, 2019, 33(3): 548-556.

[10] KARAGOZ S A, ATAKAN I A. Performance analysis of axial and reverse flow cyclone separators[J]. Chemical Engineering and Processing, 2019 (144): 107630.

[11] MAO Yanqin, PU Wenhao, ZHANG Hao, et al. Orthogonal experimental design of an axial flow cyclone separator[J]. Chemical Engineering and Processing: Process Intensification, 2019(144): 107645.

[12] LUAN Yigang, SUN Haiou. Effect of blade numbers on pressure drop of axial cyclone separators by CFD[J]. Applied Mechanics and Materials, 2011(55/56/57): 343-347.

[13] GOPALAKRISHNAN B, PRAKASH K A. Numerical analysis of multiphase flow through axial vortex tube cyclone separators[C]//Proceedings of E3S Web of Conferences. [S.l.]: [s.n.], 2019(128): 6-10.

[14] TANG Youfei, QIAO Zongliang, CAO Yue, 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): 116999.

[15] HOSSEINI E. Performance assessment of a square cyclone influenced by inlet section modifications[J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2020, 42(10): 515.

[16] SAFIKHANI H, ALLAHDADI S. The effect of magnetic field on the performance of new design cyclone separators[J]. Advanced Powder Technology,

2020, 31(6): 2541-2554.

[17] GOPALAKRISHNAN B, PRAKASH K A. Numerical study on pressure drop and filtration efficiency of gas-solid flow through axial cyclone separators[J]. International Journal of Advances in Engineering Sciences and Applied Mathematics, 2019, 11 (4): 280-287.

[18] KARTUSHINSKY A, MICHAELIDES E E. Particle-laden gas flow in horizontal channels with collision effects[J]. Powder Technology, 2006, 168 (2): 89-103.

[19] MEIER H F, MORI M. Gas-solid flow in cyclones: The Eulerian-Eulerian approach[J]. Computers and Chemical Engineering, 1998, 22 (1): 641-644.

[20] LUCIANO R D, SILVA B L, ROSA L M, et al. Multi-objective optimization of cyclone separators in series based on computational fluid dynamics[J]. Powder Technology, 2018(325): 452-466.

[21] ELSHORBAGY K, ABDELRAZEK A. Effect of volume fraction on the performance and separation efficiency of a de-oiling hydrocyclone[J]. Leonardo CFD Letters, 2013, 5(4): 153-164.

[22] ZHANG Yuchun, WANG Zhenbo, JIN Youhai, Simulation and experiment of gas-solid flow field in short-contact cyclone reactors[J]. Chemical Engineering Research and Design, 2013, 91(9): 1768-1776.

[23] WANG J, PRIESTMAN G H, TIPPETTS J R. Modelling of strongly swirling flows in a complex geometry using unstructured meshes[J]. Int J Numer Meth Heat Fluid Flow, 2006, 16(8): 910-926.

[24] ZHAO Yunhua, LU Bing, ZHONG Yingjie. Euler-Euler modeling of a gas-solid bubbling fluidized bed with kinetic theory of rough particles[J]. J Chemical Engineering Science, 2013(104): 767-779.

[25] AKIRA O, TETZUYA I, HIDEKI S. Estimation of the collection efficiency of the axial flow cyclone dust collector with the fixed guide vanes[J]. Therm Sci, 1997(6): 58-65.

[26] ROCHA A D, BANNWART A C, GANZAROLLI M M. Numerical and experimental study of an axially induced swirling pipe flow[J]. International Journal of Heat and Fluid Flow, 2015(53): 81-90.

[27] GANESAN V. Recirculation and turbulence studies in an isothermal model of a gas turbine combustor chamber[D]. Chennai, India: Indian Institute of Technology Madras, 1974.

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Author contributions Mr. **XING Xiaolong** designed the study. Mr. **YANG Yu** wrote the manuscript. Prof. **PU Wenhao** contributed data for the damage detection part. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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叶片出口角对导叶型轴流旋流管分离性能的影响

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摘要：为分析内外出口角对分离性能和流场的影响，采用两圆弧函数控制内角和外角，运用欧拉-欧拉法二流体模型计算了旋流管内的分离过程。计算结果表明，内出口角小于外出口角的结构更有利于分离性能。小内侧出口角有利于提高旋流数，小外侧出口角有利于提高摩擦系数。针对燃气轮机进气机组的实际应用，给出了相应数值模拟结果。当内出口角为35°，外出口角为40°时，叶片具有足够的旋流强度，粒径为10～100 μm的颗粒分离率在70%～98%之间。虽然小叶片角度更有利于细小颗粒的分离，但却使大颗粒在外侧壁面碰撞激烈，降低分离效率。此外，减小外侧角更有利于大颗粒排出。

关键词：轴流；叶片参数；出口角；分离性能