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Numerical Simulation Study on Separation Performance of Cyclone Separator Based on Fluent

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Abstract

Cyclone separator is mainly used for the separation of a small number of solid particles and droplets contained in the gas medium. The single-tube type cyclone separator is widely used in the oil and gas industry, food processing and biological science because of its simple structure, easy processing and high separation efficiency. Different applications and operating conditions on the separation performance of cyclone separator is not the same, through computational fluid analysis, USES the Fluent software the numerical simulation study on the internal flow field in cyclone separator, using two-way DPM model of fluid-solid coupling method for different size of particles in cyclone separator under different air inlet velocity of movement. The gas-solid separation efficiency was calculated by calculating the number of incident particles and escaping particles. The separation efficiency under a certain inlet velocity is in an exponential polynomial relationship with the particle size, and the separation efficiency under a certain inlet velocity of a certain particle size is in a logarithmic polynomial relationship within a certain range.. When the inlet air velocity exceeds a certain value, the number of back mixing particles increases and the length of stay in the cyclone separator increases, resulting in an increase in the amount of erosion and wear in the separator.

Keywords

Cyclone separator; numerical simulation; gas-solid separation; Inlet velocity.

1. Introduction

Because of its simple structure, easy processing and high separation efficiency, the single-pipe cut-in cyclone separator is widely used in the field of natural gas wellhead sand removal. The structure of the cyclone separator mainly includes an intake pipe, a column section, a cone section, a sealing plate, an overflow pipe, and a solid discharge pipe, as shown in Figure 1.

The gas to be separated enters the cyclone separator from the inlet pipe at a certain initial velocity. Under the action of the cylinder wall, The gas changes from linear motion to rotary motion, Spiral downward under the influence of pressure. In the process of gas swirling, under the action of centrifugal force, solid particles and liquid droplets with high density will overcome the resistance of air flow and move to the wall of the cylinder, Driven by gravity and rotating fluid, it is discharged from the sand discharge port. After the descending airflow reaches a certain position of the cone section, it turns back upwards in the same direction of rotation, spirals upward inside the downward airflow, and is finally discharged by the overflow pipe.

In 1996, the cyclone separator was formally used for wellhead desanding. The gas capacity of this separator 30×10^5 m^3/d. The concentration of grit treated is 2.85kg/m^3. Its separation efficiency for gravel above 15μm is between 95% and 98%. The gas well cyclone separation device developed by PetroChina has a processing gas volume of 5～15×10^4 m^3/d. Its removal rate of sand particles larger than 54μm is more than 90%. The ultra-high pressure cyclone sand

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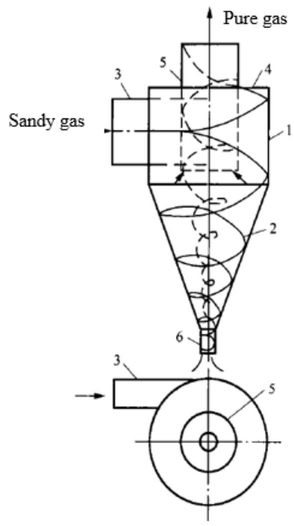
removal device developed by a domestic unit has the function of multi-phase separation of oil, gas, water and sand, Its maximum processing gas volume is 99×10^4 m^3/d. The graded particle size is 0.1mm[1].



1.Column 2.Cone 3.Intake pipe 4.Seal plate 5.Overflow pipe 6. Sand discharge pipe

Fig.1 Schematic diagram of cyclone separator structure

Lu Wei of Wuhan University of Technology and others use Fluent software, used RSM to simulate and analyze the internal flow field of the spiral inlet cyclone. Zha Wenwei and others used the RNG K-Ɛ calculation control model to analyze the internal flow field of the cyclone at the tangential entrance, analyzed the internal flow field of the cyclone separator under different structural parameters. Wan Xiaojun and others from Jiangxi Agricultural Machinery Research Institute used the Reynolds Stress Transport Model (RSMT) to simulate and analyze the internal flow field of the volute inlet cyclone separator[2-7]. The analysis and research on cyclone separators at home and abroad mainly focus on the realization method of the simulation analysis of the internal flow field of the cyclone separator and the influence of structural parameters on the separation efficiency of particles with specific sizes. However, the inlet velocity and particle size of the cyclone separator used to evaluate the separation performance in different application conditions are not the same. Therefore, it is necessary to further study the corresponding relationship between intake speed, particle size and separation efficiency.

2. Simulation Model Establishment

2.1. Fluid Domain Model Establishment

Establish a fluid calculation domain model based on the cyclone separator of a certain company. The design pressure of the cyclone separator is 3.5Mpa. The inner diameter of the column section is 304.84mm and the height is 350mm. The height of the cone section is 600mm. The intake pipe has a height of 150mm and a width of 60mm, flush with the top surface of the column section. The inner diameter of the overflow pipe is 154.08mm, and the length of the part extending into the column section is 180mm. The inner diameter of the drainage pipe is 102.26mm and the length is 300mm.

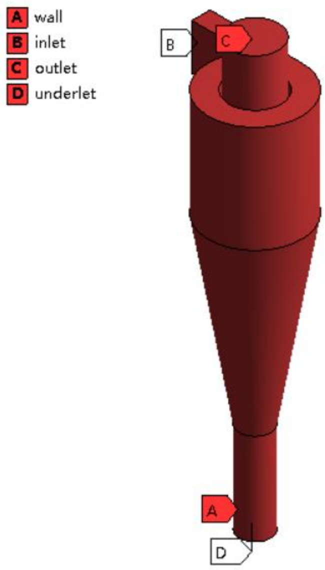


Fig. 2 Computational domain model of flow field in cyclone separator

2.2. Fluid Domain Meshing

ICEM CFD is used to mesh the computational domain model, and the tetrahedral structure mesh is used for meshing. In order to ensure the adaptability of the grid in the fluid calculation process, the tetrahedral grid is adapted to the hexahedral structure before the iterative calculation. After verification of grid independence, the number of grid nodes is finally determined to be 47,330, the number of grids is 239,300, and the average quality of the grid is 0.88775. The division result is shown in Figure 3.

Fig.3 Computational grid model

2.3. Parameter and Boundary Condition Setting

2.3.1. Physical parameters of fluid media

Set the physical property parameters of the fluid medium according to the gas gathering station's gas quality measurement report. The gas density is set to 0.71Kg/m^3, and the dynamic viscosity is 1.17e-5 Pa•s. The solid particle phase is quartz sand, the density is set to 2850 Kg/m^3, and the solid mass flow rate is 0.0105 Kg/s.

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2.3.2. Turbulence model

Considering that the flow field in the cyclone separator is highly complicated, the flow state is considered to be turbulent in the calculation. At present, the RNG k-Ɛ model, Reynolds stress model and LES large eddy model are commonly used in the simulation research of the cyclone separator flow field to simulate the internal flow field of the cyclone separator. The calculation results of the large eddy model are the closest to the real situation[8]. On the premise of ensuring the calculation accuracy, the Reynolds stress turbulence model is selected for continuous phase simulation calculation in order to save calculation resources， The control equation is as follows:

Continuity equation:

$$\frac{\partial V_i}{\partial x_i}=0 \tag{1}$$

Momentum equation:

$$\rho V_j\frac{\partial V_i}{\partial x_i}=\rho g_i-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}[\mu(\frac{\partial V_i}{\partial x_j}+\frac{\partial V_j}{\partial x_i})]-\frac{\partial}{\partial x_j}(\rho\overline{V_i^{'}V_j^{'}}) \tag{2}$$

Reynolds stress transport equation:

$$V_k\frac{\partial}{\partial x_k}(\overline{V_i^{'}V_j^{'}})=P_{ij}+\Phi_{ij}+\frac{\partial}{\partial x_k}[(v+\frac{v_t}{\sigma_\kappa})\frac{\partial}{\partial x_k}(\overline{V_i^{'}V_j^{'}})]-\frac{2}{3}\varepsilon\delta_{ij} \tag{3}$$

$$P_{ij}=-\rho(\overline{V_i^{'}V_k^{'}}\frac{\partial V_j}{\partial x_k}+\overline{V_j^{'}V_k^{'}}\frac{\partial V_i}{\partial x_k}) \tag{4}$$

$$\Phi_{ij}=-C_1\frac{\varepsilon}{k}(\overline{V_i^{'}V_j^{'}}-\frac{2}{3}k\delta_{ij})\ -C_2(P_{ij}-\frac{1}{3}P_{kk}\delta_{ij}) \tag{5}$$

The turbulent energy dissipation rate ε is solved by the transport equation:

$$V_k\frac{\partial\varepsilon}{\partial x_k}=\frac{\partial}{\partial x_k}[(v+\frac{v_t}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x_k}]+\frac{\varepsilon}{k}(\frac{1}{2}C_{\varepsilon1}P_{kk}-C_{\varepsilon2}\varepsilon) \tag{6}$$

Where:

" g_i " is the component of gravitational acceleration along the " x_i " direction, " k " is Turbulent kinetic energy， " p " is the pressure, " P_{ij} " is the stress generating term, " P_{kk} " is the stress generating term(P_{ij})reduction， "V" is speed, " δ_{ij} " is Kronecker symbol, " ε " is Turbulent energy dissipation rate, " μ " is hydrodynamic viscosity, " v " is Kinematic viscosity, " v_t " is eddy viscosity, " ρ " is the gas density, " σ_κ " is empirical constant, " Φ_{ij} " is the stress-strain frequency, σ_ε =1.3, σ_κ =1, $C_{\varepsilon1}$=1.44, $C_{\varepsilon2}$=1.92, C_1=1.8, C_2=0.6.

2.3.3. Boundary conditions

This research focuses on the study of the influence of the cyclone separator inlet velocity on the separation efficiency of solid particles of different sizes. The inlet boundary is set as the speed inlet, and the intake speed range is 3-30m/s. The gas outlet is set as a pressure outlet, and the sand discharge port is connected with a sealed sand storage tank, which is considered as a sealed wall in the simulation calculation.

2.3.4. Fluid-structure coupling

In order to study the trajectory of solid particles in the cyclone separator, At the same time, considering that the solid phase volume fraction is less than 1%, Therefore, the DPM model is used to simulate the particle trajectory in both directions. Particles are injected into the separator perpendicular to the inlet surface, The injection speed is the same as the gas phase speed, and the particle size range is 1-15μm. When the particles move to the overflow nozzle,

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it is assumed that the particles escape with the gas without being separated. When the particles move to the solid discharge nozzle, the particles are deemed to be captured and separated. When the particles in the separator move, they are subjected to the force of the fluid, gravity and wall rebound. the force of the fluid is calculated and automatically applied to the particles during fluid-solid coupling. Gravity is a constant force, and the acceleration of gravity is $9.81m/s^2$, The normal recovery coefficient of quartz sand particles with a diameter less than 50μm and the carbon steel wall meets:

$$\varepsilon_N = 0.993 - 0.0307\alpha + 4.75\times10^{-4}\alpha^2 - 2.61\times10^{-6}\alpha^3 \tag{7}$$

The tangential recovery coefficient satisfies:

$$\varepsilon_T = 0.998 - 0.029\alpha + 6.43\times10^{-4}\alpha^2 - 3.56\times10^{-6}\alpha^3 \tag{8}$$

Where: " α " is the incident angle of the particle.

3. Calculation Results and Analysis

Through numerical calculations, Under the condition of 3-30m/s intake speed, Particles with a diameter of 1-10μm run in the cyclone separator, By counting the number of particles escaping from the overflow, The particle separation efficiency under different working conditions is calculated by the formula.

$$eff = (1-\frac{n_1}{N})\times100\% \tag{9}$$

Where: " n_1 " is the number of escaped particles, " N " is the total number of incident particles.

The separation efficiency of the cyclone separator for solid particles under various working conditions is shown in Table 1.

Tab.1 Separation efficiency statistics

Flow rate（m/s）	eff（%）									
	1μm	2μm	3μm	4μm	5μm	6μm	7μm	8μm	9μm	10μm
3	5.22	14.52	15.25	26.12	26.12	34.23	37.58	38.45	47.22	47.10
6	11.56	20.54	28.54	32.66	40.76	48.62	50.46	58.62	60.02	64.22
9	12.82	26.92	34.25	48.62	50.44	58.02	66.46	71.43	75.62	76.33
12	22.66	30.23	46.78	52.12	66.57	68.12	76.10	78.52	86.18	88.64
15	23.54	40.12	53.28	63.74	71.87	78.17	83.06	86.86	89.80	92.09
18	27.42	45.66	58.56	69.11	76.79	82.83	87.20	90.45	92.88	94.67
21	28.64	47.02	60.12	73.58	78.22	85.32	90.12	93.66	93.66	96.34
24	30.62	50.32	64.33	74.71	82.06	87.28	90.98	93.60	95.82	97.66
27	31.64	52.66	65.90	76.18	83.36	88.37	91.88	94.33	96.04	97.23
30	32.58	54.14	68.32	79.54	85.62	88.83	92.05	95.22	98.02	99.16

In order to study the separation efficiency of the cyclone separator for particles of different sizes under a specific flow rate, Select the separation efficiency of the cyclone separator for quartz gravel with a particle size of 1-10μm when the air inlet velocity is 3m/s, 12m/s, 21m/s, and 30m/s. Draw a discrete point diagram and fit it, as shown in Figure 4.

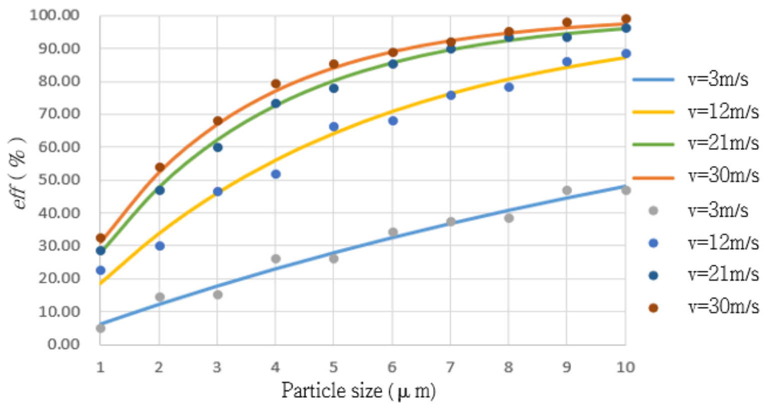


Fig. 4 Diagram of separation efficiency and particle size

An exponential polynomial function is used to fit the result data. When the air inlet velocity is 3m/s, the relationship between the separation efficiency and the solid particle size satisfies:

$$eff = (1 - e^{-0.065644d}) \times 100\% \tag{10}$$

When the inlet velocity is 12m/s, the relationship between separation efficiency and solid particle size satisfies:

$$eff = (1 - e^{-0.204632d}) \times 100\% \tag{11}$$

When the inlet velocity is 21m/s, the relationship between separation efficiency and solid particle size satisfies:

$$eff = (1 - e^{-0.323656d}) \times 100\% \tag{12}$$

When the inlet velocity is 30m/s, the relationship between separation efficiency and solid particle size satisfies:

$$eff = (1 - e^{-0.367652d}) \times 100\% \tag{13}$$

Where: "d" is the particle size, the unit is μm.

In order to study the separation efficiency of cyclones at different flow rates for particles of specific sizes, respectively select the intake speed to be 3-30m/s. The separation efficiency of the cyclone separator for quartz gravel with a particle size of 2μm, 5μm, and 8μm. Draw discrete point plots and fit, As shown in Figure 5.

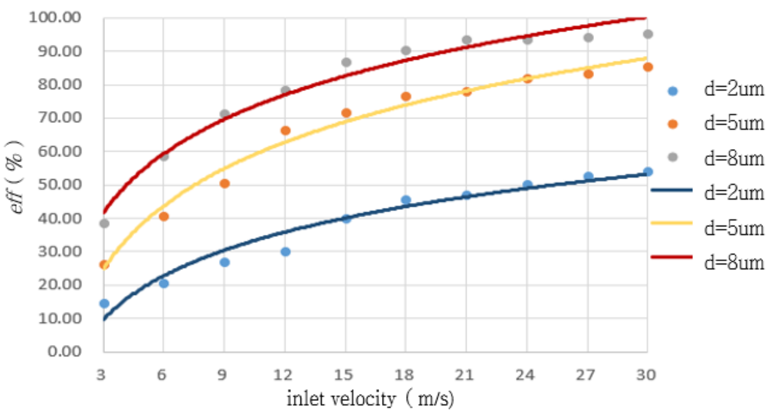


Fig.5 Diagram of separation efficiency and inlet velocity

For the quartz gravel with a particle size of 2μm, the relationship between the separation efficiency and the air inlet speed satisfies:

$$eff = 18.904\ln(d) - 11.109 \tag{14}$$

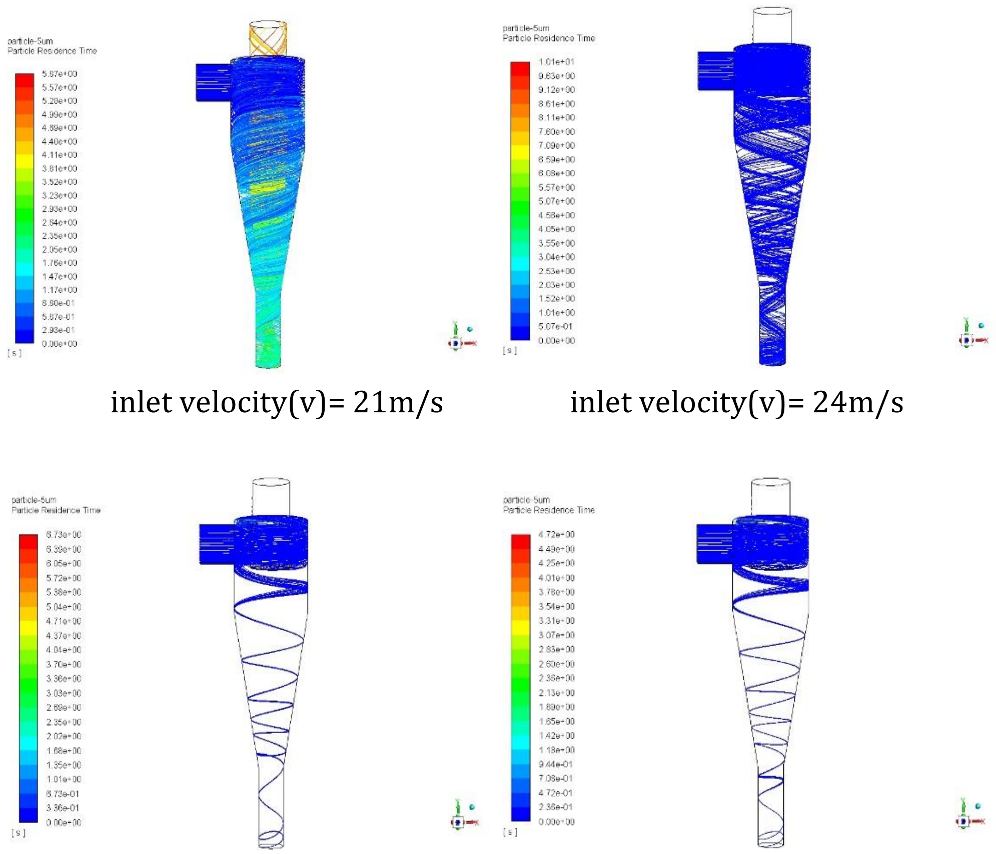
For the quartz gravel with a particle size of 5μm, the relationship between the separation efficiency and the air inlet speed satisfies:

$$eff = 27.449\ln(d) - 5.4358 \tag{15}$$

For the quartz gravel with a particle size of 8μm, the relationship between the separation efficiency and the air inlet speed satisfies:

$$eff = 29.466\ln(d) - 1.673 \tag{16}$$

When the air intake speed is greater than a certain limit, the residence time of the solid particles in the cyclone separator is significantly increased, and keeps rotating in the separator for a long time. Take 5μm quartz gravel as an example, Figure 6 shows the trajectory of solid particles in the cyclone at different inlet velocity.



inlet velocity(v)= 21m/s inlet velocity(v)= 24m/s

inlet velocity(v)= 27m/s inlet velocity(v)= 30m/s

Fig.6 Particle trajectory diagram

Under the condition that the inlet velocity does not exceed 24m/s, the sum of the number of particles escaping from the overflow port and the number of particles captured by the solid discharge port is equal to the number of incident particles. Under the condition that the air inlet velocity is greater than 24m/s, the sum of the number of particles escaping from the overflow port and the number of particles captured by the solid discharge port is less than the number of incident particles. More than 27% of the particles stay in the cyclone separator for a long time and keep rotating and moving along the center axis of the cyclone separator.

4. Summary

At a constant flow rate, the separation efficiency of the cyclone separator for solid particles increases with the increase of the particle size, and the relationship between the separation efficiency and the particle size satisfies an exponential polynomial relationship.

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When the particle size is constant and the intake velocity is less than 30m/s, the separation efficiency of the cyclone separator for solid particles increases with the increase of the intake velocity. The relationship between the separation efficiency of the cyclone separator and the intake velocity Approximately satisfy the logarithmic polynomial relationship.

The suitable intake velocity of the cyclone separator model used in this research should be less than 24m/s. When the intake velocity exceeds this value, a large amount of particles will be retained in the cyclone separator and cannot be discharged. The velocity limit is separated from the cyclone. The device structure is related.

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