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NUMERICAL STUDY OF INFLUENCE OF FEED SOLIDS CONCENTRATION ON NON-NEWTONIAN MULTIPHASE FLOW IN HYDROCYCLONES

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ABSTRACT

The main work of this paper is to conduct a numerical study of gas-liquid-solid flow in a 75mm hydrocyclone. In the numerical study, the interface between air core and liquid and the solid-liquid mixture are simulated by the mixture multiphase flow model. Considering that the engineering medium is mostly non-Newtonian fluid and the drilling fluid can be represented by power-law model, the viscosity model adopts power-law model. The validation of the numerical model is mainly to investigate the influence of the change of feed solids concentration on the inlet pressure drop, the fractional efficiency curve, the separation particle size and the water distribution of the hydrocyclone. The results showed that with the increase of solid concentration, the separation efficiency of the same particle size decreased, the separation particle size increased and the pressure drop increased. At the same time, it is observed that the distribution and variation of tangential velocity, axial velocity, inlet pressure drop and turbulent viscosity are consistent.

Key Words: Hydrocyclone, Non-Newtonian multiphase flow, Feed solids concentration

Introduction

Hydrocyclone is a common solid and liquid separation equipment. Because of its small footprint, easy operation, high separation efficiency and easy to use in series and parallel, it is commonly used in petroleum, mining, medicine and food processing industries. The main use of the difference between the density difference between solid-liquid two-phase centrifugal force to produce different sizes and then proceed to solid-liquid separation. Although the structure of the hydrocyclone is simple and has no power components, the flow field inside the hydrocyclone is a very complicated rotational turbulent flow field. The turbulent flow field includes the formation and dynamic stability of air column, the interaction between liquid-solid and solid-solid, the settlement of discrete phase under centrifugal force and the change due to the rheological property of non-Newtonian fluid. These phenomena cause the turbulent flow field inside the hydrocyclone to be difficult to describe accurately [1].

In recent years, the study of the internal flow field of the hydrocyclone is mainly non-invasive and invasive. Non-invasive method refers to the use of imaging velocimetry in the hydrocyclone, Doppler laser velocimetry (LDV) and high speed motion analyzer (HSMA) and other non-invasive equipment without interfering with the flow field to obtain internal flow field information method. Such as Kesall [2] using the speed of light microscopy system, Knowles et al [3] use imaging velocimetry systems, Hsieh [4], Chine et al. [5], Fisher et al. [6] used LDV and Wang et al. [7] using HSMA. These people have proposed the distribution of axial and tangential velocity in the hydrocyclone. The invasive method is to insert the intrusion type of the resistance wire, the Pitot tube and the porous pressure probe into the hydrocyclone directly to obtain the information of the internal flow field. Such as Chu et al [8] measured the pressure distribution inside the hydrocyclone using a resistance wire strain gauge, Yoshioka et al. [9] measured the tangential velocity distribution in a hydrocyclone using a single-hole Pitottube, Brennan et al. [10] used a porous pressure probe to measure the tangential velocity and axial velocity distribution within the hydrocyclone. However, these experiments are generally measured under conditions of clear water or a volume concentration of less than 0.5%. The existing measurement techniques still cannot directly measure the flow field distribution in the non-Newtonian fluid at higher concentrations.

Some scholars have found that when the volume of solids in the slurry exceeds 0.5%, the interaction between particles and particles cannot be ignored. In industrial applications, the volume content of solids in the pulp is generally more than 0.5% and the pulp is mostly non-Newtonian fluid so there are some differences with Newtonian fluid obtained results. In the solid control system, the drilling fluid viscosity is mostly power law model. Therefore, in the simulation that is to consider the non-Newtonian fluid viscosity model, but also consider the solid content of the feed content.

1. Simulation method

2.1 Simulation step

The simulation of non-Newtonian turbulent flow field in hydrocyclone is very complicated. If the simulation of the flow field is carried out directly, the simulation process is difficult to converge due to too much interaction. Thus, the simulation process is divided into the following steps. Firstly, the free interface between the mud and the air column and the velocity field and pressure field distribution of the gas-liquid two phases were described by using theReynolds stress model (RSM) and mixture model. Secondly, we add the particles to be simulated and then use the mixture model to simulate the mixed multiphase flow including particle motion and obtain the production parameters such as the grading curve and the separation particle size.

1.2 mathematical model

There are several numerical models for describing the internal flow field of a hydrocyclone: the VOF model describing the gas-liquid interface, the RSM model describing the anisotropic turbulence, the mixture model describing the multiphase flow field and the LPT model describing the particle trajectory. These models in the previous study has been more detailed description [11,12]. In order to avoid the transformation between multi-models and the advantages and disadvantages of the three multiphase flow models [13], combined with previous experience. In this numerical simulation experiment, the mixed multi-phase flow model was selected. The turbulence model was RSM. The non-Newtonian fluid viscosity model was adopted power law model and the concentration of the dispersed phase was mainly considered as the main factor affecting the pulp viscosity. According to He et al [14] at room temperature with limestone particles as the dispersed phase of the experimental data obtained, the use of volume concentration of 10% and 20% were simulated and the simulation results and low concentration simulation results were compared.

1.3 Simulation conditions

Using the experimental data reported by Hsieh [4] as the simulation parameters, the hydrocyclone used for the simulation and the set operating conditions are consistent with those of the Hsieh experiment. The structure and grid are shown in Table 1 and Fig.1. The circular inlet of the hydrocyclone is converted into a square inlet according to the equal area method. In order to facilitate the grid division, is divided into five parts, the calculation area consists of 97410 hexahedral mesh.

Table 1 The structure of hydrocyclone

Structural parameters	value
Diameter of cylindrical section	75mm
Diameter of inlet	25mm
Diameter of vortex	25mm
Diameter of apex	12.5mm
Length of cylindrical section	75mm
Diameter of cone section	50mm
Included angle	20°

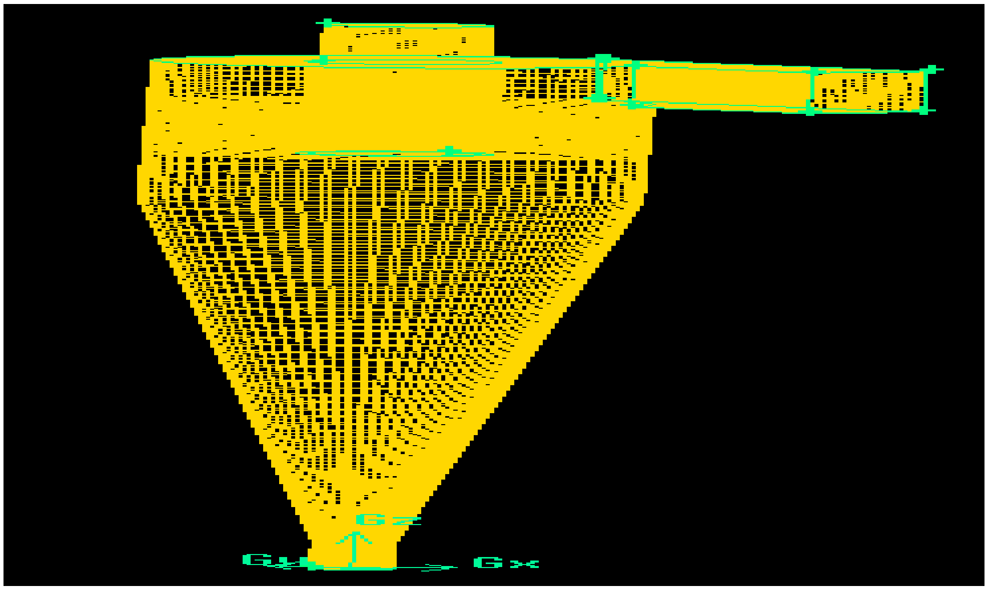


Fig. 1 The grid diagram of hydrocyclone

First, the applicability of numerical simulation method is verified by Hsieh experiment. The water is fed at a rate of 2.28 m / s. After the flow field reaches the dynamic stability, the velocity field and the pressure field of the clear water are verified, and then the water and limestone particles are fed at a rate of 2.28 m / s at the same time. In the feed process, the volume concentration of limestone particles is 4%, the density of water is 998kg / m³ and and the density of limestone is 2700kg / m³. The particle size distribution of limestone particles is shown in Table 2.

Secondly, we compare the results of the non - Newtonian fluid with power - law model and the simulation results of high volume concentration. Analyze the difference between the results and the simulated results of water validation. At this point, the volume of limestone particles in the process of concentration were 20% and 40% and the viscosity model is $\tau = 0.25\dot{\gamma}^{0.73}$, the remaining conditions are the same as above.

The boundary condition of inlet is the speed inlet, the boundary condition of outlet is the pressure outlet and the outlet pressure is set to zero. In the calculation process, pressure-velocity coupling algorithm is adopted SIMPLE, PRESTO! Pressure interpolation method is used and other discretization equations are adopted in the second-order upwind scheme. Using the unsteady calculation method, the time step is set to 0.001s and the mass flow of the downflow, overflow and inlet is monitored. When the three reached a steady state and the mass flow of the fluctuation of less than 4%, to determine the internal flow field has been stable.

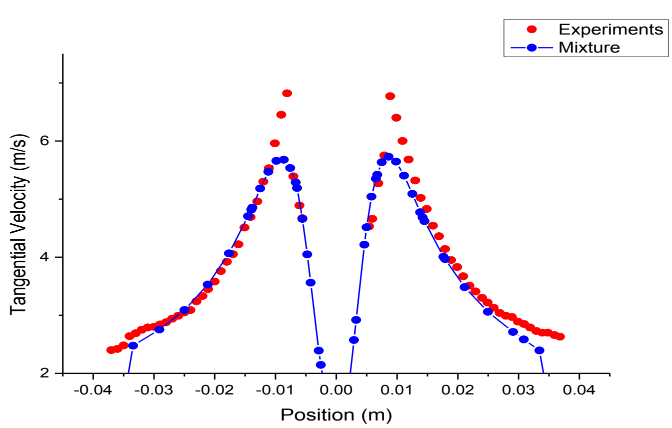
Table 2 The particle size distribution of limestone particles

Particle size/μm	Solid volume concentration/%
35.50	2.99
25.10	4.4475
17.74	4.935
12.55	3.2625
8.87	2.275
6.27	2.18
4.43	1.7
3.13	3.21

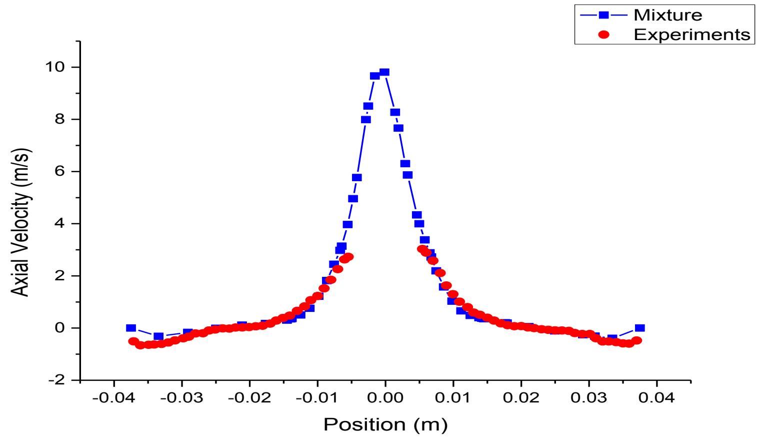
2. results and analysis

3.1 Model validation

First, the axial velocity and tangential velocity distribution of the flow field is verified after the feed. Figure 2 compares the experimental and numerical simulations of the velocity in the case of water. It can be seen from the figure to use the mixture model to obtain the simulated value and the experimental value in the axial velocity distribution has a good fit. In the comparison of the distribution of tangential velocity, the maximum value of the tangential velocity of the simulated value is slightly smaller than the maximum value of the tangential velocity of the experimental value, but its overall trend has good agreement.



(a) Simulated and measured values of tangential velocity



(b) Simulated and measured values of axial velocity

Fig. 2 The comparison between the measured value of the tangential speed (a) and the axis speed (b) and the simulated value

After verifying the reliability of the water flow field, the difference of the simulated value of the fractional efficiency curve of the hydrocyclone (Fig. 3), the inlet pressure drop and the amount of water split to underflow and the measured value of these project are further verified when the limestone particles are fed at a volume concentration of 4% (Table 3). It can be seen from Fig. 3 that the simulation value of the classification efficiency curve of the hydrocyclone is consistent with the trend of the measured value. When the particle diameter is less than 5 microns, the analog value is higher than the measured value; when the particle diameter is greater than 5 microns, the analog value is lower than the measured value. From the comparison of the measured value and the simulated value of the hydrocyclone in Table 3, it can be seen that the prediction of the inlet pressure drop is more accurate, the error value is only 3.9% and the error value of the separation particle size and water distribution is about 10%. This indicates that the simulation results still have a reference value. Therefore, it can be considered that the mixture multi-phase flow model and the power law of the non-Newtonian fluid model can be used to further study the hydrocyclone and have some reference value.

Table 3 Comparison of Measured and Simulated Values of Hydrocyclones

	Inlet pressure drop(pa)	Prediction error(%)	Amount of water split to underflow (%)	Prediction error(%)	Cut size d_{50} (μm)	Prediction error(%)
Experiments	46700	(-)	4.9	(-)	17.74	(-)

Mixture model	44889	3.9	5.4	10.2	19.5	9.9

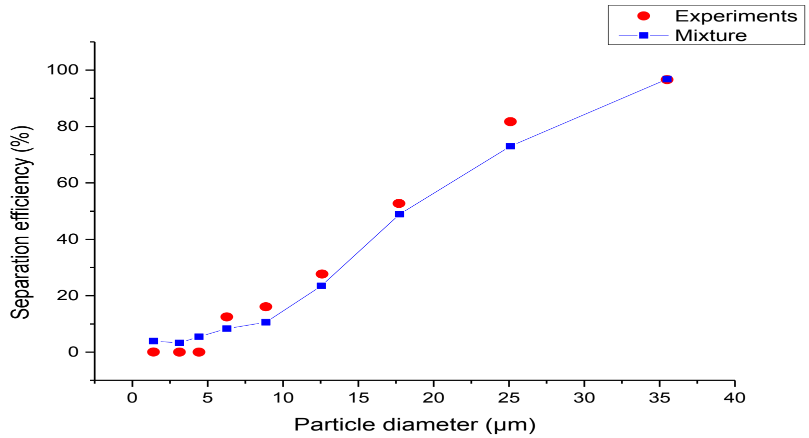


Fig.3 The classification efficiency curve of hydrocyclone

2.2 Effect of feed solid concentration

Because in the field operation, the solid concentration of the feed is generally higher than 10%, and the experimental data obtained from the laboratory do not match. Therefore, the main study of this paper is to take the solid volume concentration of 10% and 20% were simulated. Simultaneously with the verified simulation data, where the experimental conditions are the same as before.

Figure 4 shows the grading efficiency curves for different solid volume concentrations. As can be seen from the figure, as the particle diameter increases, the trend of the classification efficiency curve is still increasing, but the growth rate is reduced. With the increase in the volume of the feed particles, the separation efficiency is reduced under the same particle diameter. When the particle volume fraction reaches 20%, the maximum reduction rate of separation efficiency is 76.6% at the same particle diameter and the particle diameter at this time is 17.74μm,which indicates that the separation particle size decreases as the volume of the feed particles increases. At the same time, it can be seen that when the particle size is larger than 6.27μm, the reduction rate of separation efficiency is more than 50% with the increase of the volume of feed particles but when the particle size is less than 6.27μm, with the increase of the volume of the feed particles, the reduction rate of separation efficiency is below 10%. This indicates that the increase in the volume fraction of the feed particles mainly affects the separation efficiency of particles with a particle diameter of 10 μm or more for a 75 mm hydrocyclone. This is due to the increase in the volume of the feed particles, which is mainly in the main separation zone when moving in the swirling force field, and thus the increase of the concentration of the feed particles has an important influence on it. Particles with a diameter of

10 μm or less are mainly discharged directly from the spill through the internal swirling flow, so that the increase of the concentration of the feed particles has little effect on it. At the same time, it can be observed from the grading efficiency curve that the separation particle size is increasing as the inlet particle concentration increases.

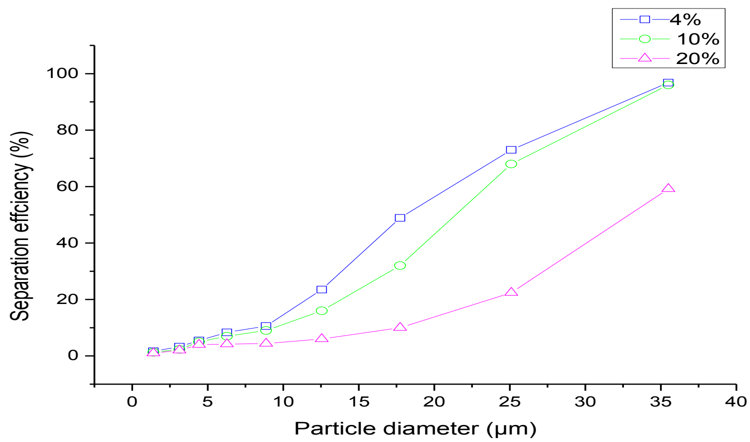
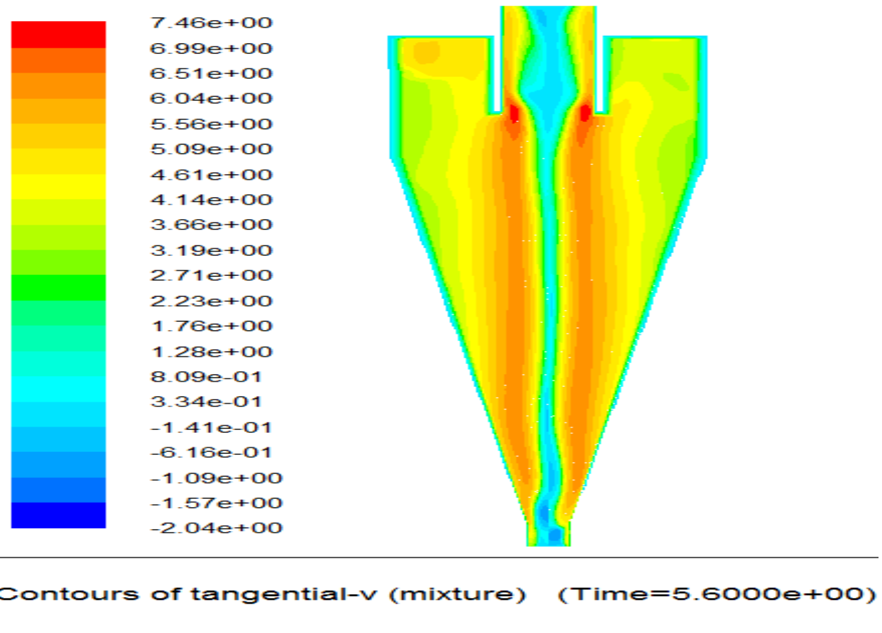


Fig. 4 Grading efficiency curves for different solid volume concentrations

Table 4 shows the inlet pressure drop of the hydrocyclone for different feed particle concentrations. As can be seen from the table, as the particle concentration increases, the inlet pressure drop also increases. This is because as the inlet particle concentration increases, the tangential velocity increases (Fig. 5), the turbulence intensity increases and energy consumption increases, which makes the inlet pressure drop increases. Figure 6 shows the axial velocity profile at different feed particle concentrations. It can be observed that the axial velocity increases as the concentration of the feed particles increases, consistenting with changes in inlet pressure and tangential velocity. At the same time, it is apparent that there is a short circuit flow and a circulating flow above the top of the hydrocyclone. Figure 6 can also be more clearly see the existence of zero-speed envelope surface, easy to distinguish between internal and external swirling flow. The shape of the zero-speed envelope is the conical part of the conical section, and the cylindrical section is shaped like a cylinder.

Table 4 The inlet pressure drop at different feed solids concentrations

Feed solid concentration(%)	4%	10%	20%
Inlet pressure drop(pa)	44889	58644	70297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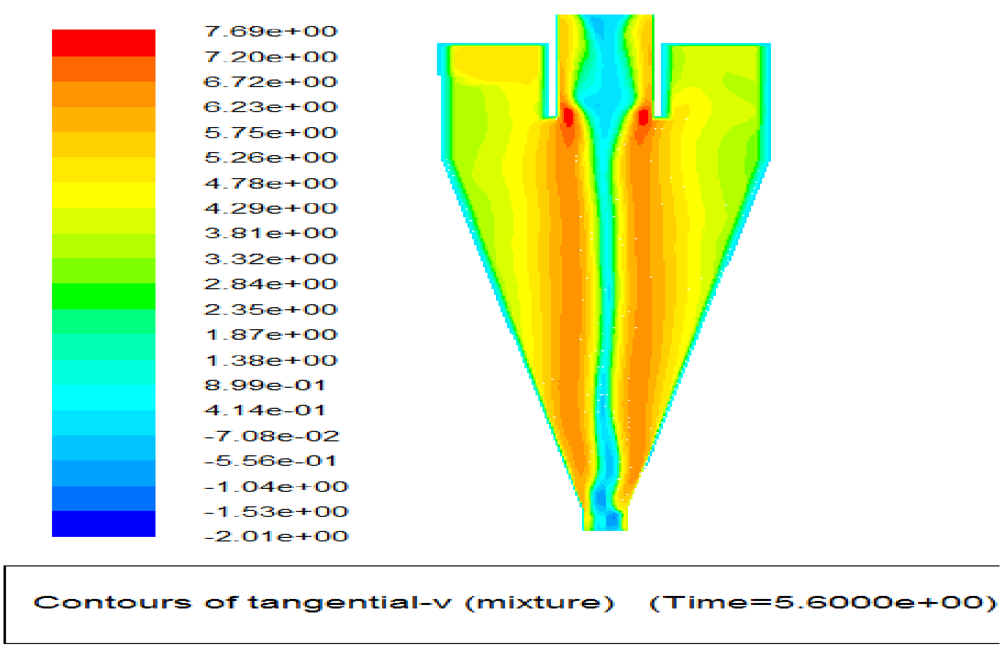
2.71e+00
2.23e+00
1.76e+00
1.28e+00
8.09e-01
3.34e-01
-1.41e-01
-6.16e-01
-1.09e+00
-1.57e+00
-2.04e+00
Contours of tangential-v (mixture) (Time=5.6000e+00)

(a) 4%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3.32e+00
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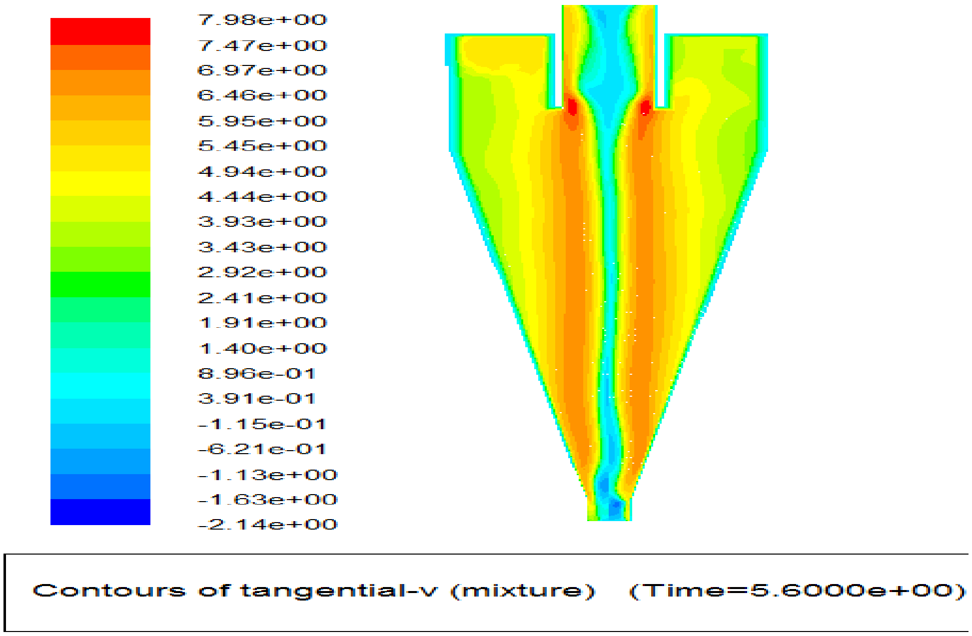
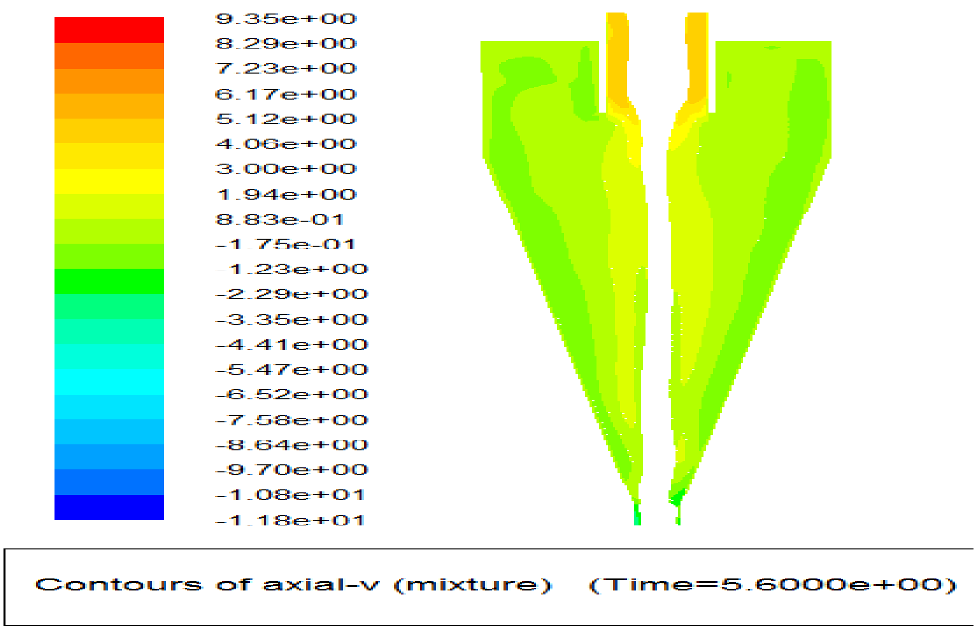
2.35e+00
1.87e+00
1.38e+00
8.99e-01
4.14e-01
-7.08e-02
-5.56e-01
-1.04e+00
-1.53e+00
-2.01e+00
Contours of tangential-v (mixture) (Time=5.6000e+00)

(b) 10%

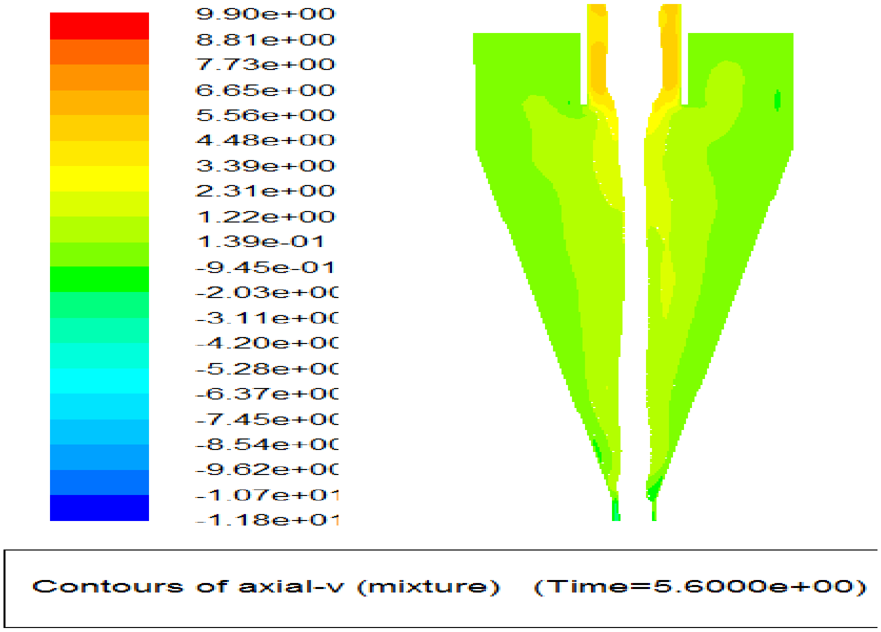


(c) 20%

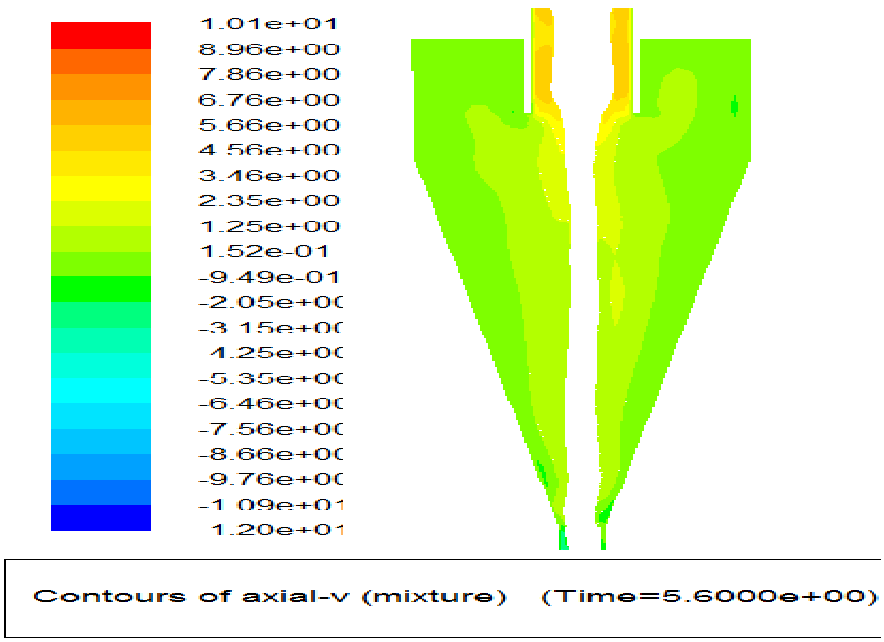
Fig. 5 The tangential velocity profile at different solid concentrations (a) 4% (b) 10% (c) 20%



(a) 4%



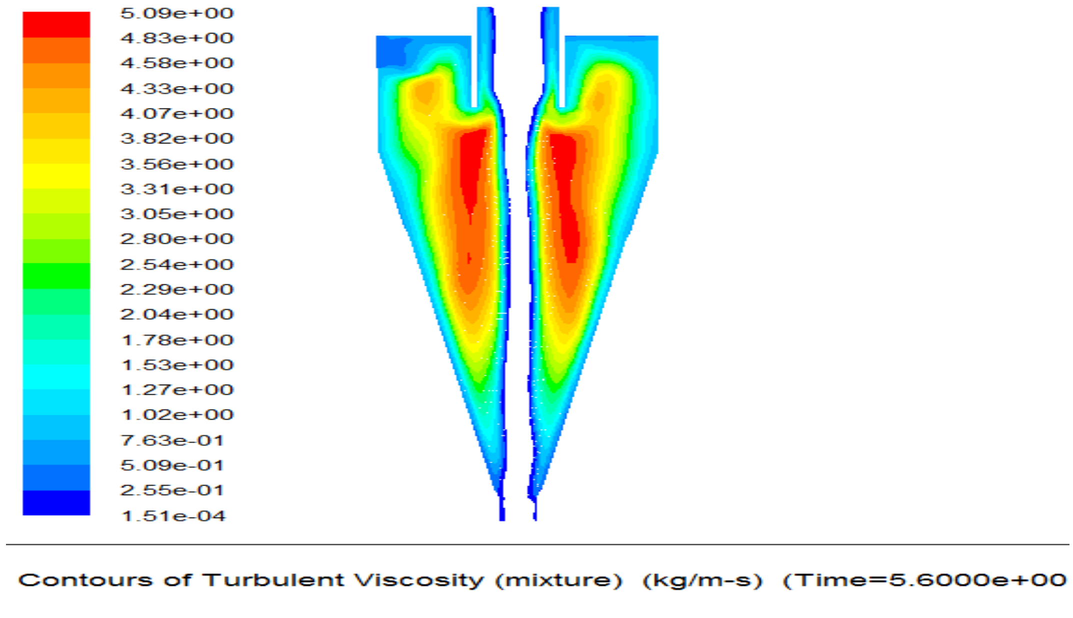
(b) 10%



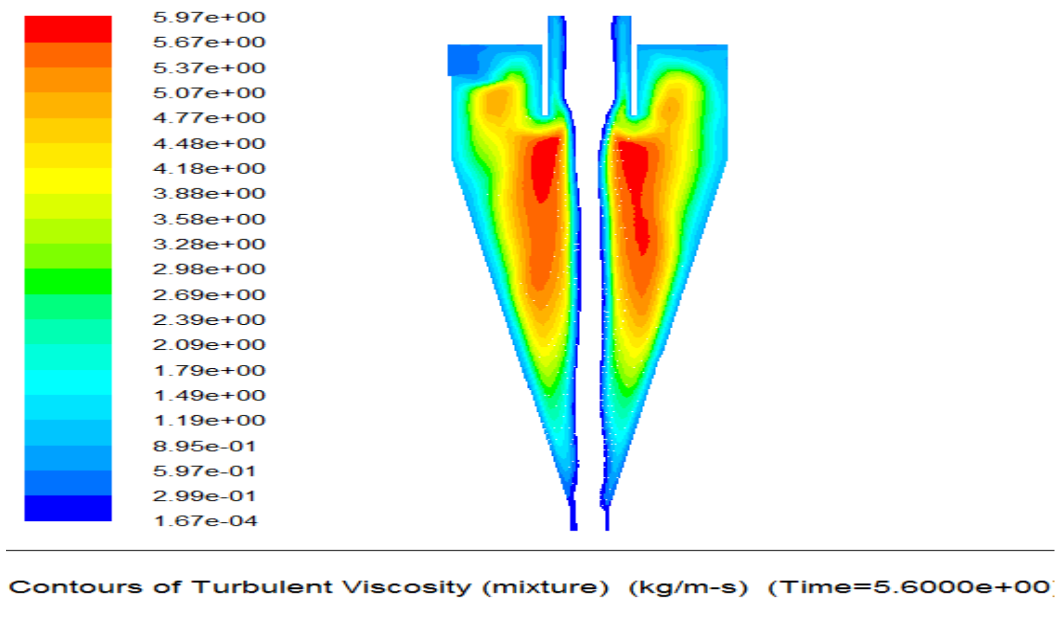
(c) 20%

Fig. 6 The axial velocity profile at different solid concentrations (a) 4% (b) 10% (c) 20%

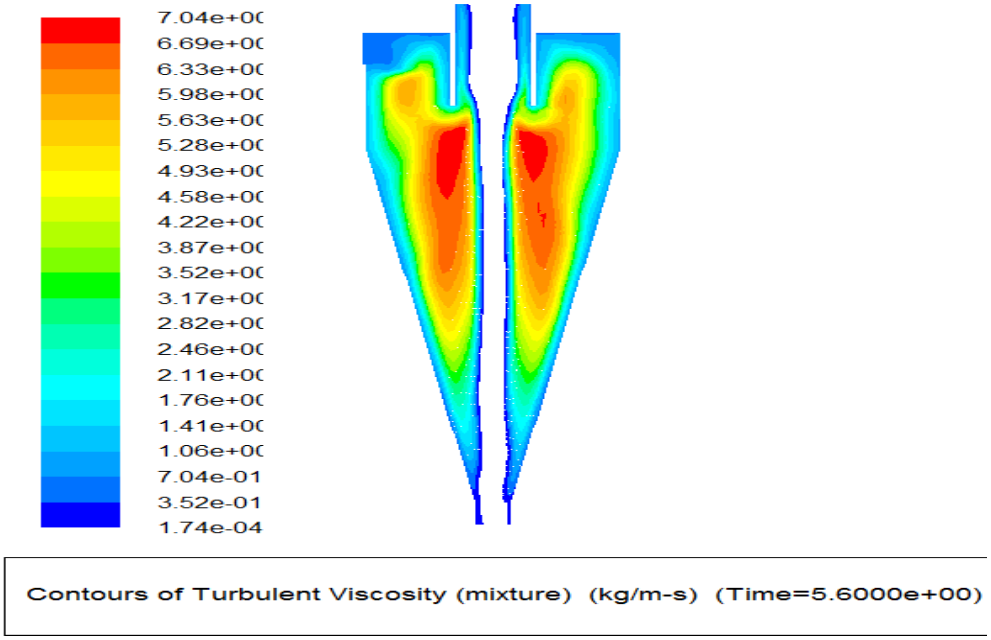
It is observed from Fig. 7 that the turbulence viscosity is also increasing as the concentration of the feed particles increases. Compared with the axial velocity profile, it can be found that the turbulence viscosity is larger under the zero velocity envelope and the turbulence viscosity is smaller than that of the zero velocity envelope. This is due to the fact that the radial velocity of the fluid is mostly inwardly in the main separation zone. At this time, the lighter particles move inward with the fluid and the degree of collision between particles-particles and the particles-fluid increases, thereby increasing the turbulence viscosity there.



(a) 4%



(b) 10%



(c) 20%

Fig. 7 Turbulent Viscosity Profile of Different Solid Concentrations (a) 4% (b) 10% (c) 20%

3. Conclusion

In this paper, when the hydrocyclone is numerically simulated, RSM is used for gas-liquid-solid three-phase, because of the strong turbulent flow field inside the anisotropy. Taking into account the calculation time and the calculation accuracy, the interface of the air and liquid and the liquid - solid mixture are simulated by the mixture multiphase flow model. Considering that the engineering medium is mostly non-Newtonian fluid and the drilling fluid can be represented by the power law model so the viscosity model adopts the power law model.

First, it can be confirmed that the mixture model is feasible for numerical simulations of hydrocyclones. Secondly, with the increase of the solid concentration of the feedstock, the separation efficiency of the same particle size is reduced but the separation efficiency of the particles mainly affecting the particle diameter of 10 μm or more is mainly affected. Because of the increase in the volume of the feed particles, the particles in the swirling force field are mainly in the main separation zone and the particles below 10μm have little effect because they flow out mainly from the overflow port. With the increase of the feed solid concentration, the tangential velocity increases, the turbulence intensity increases and the energy consumption increases, which lead to the inlet pressure drop increases. As the solid concentration increases, the separation particle size increases. Finally, the distribution and variation of tangential velocity, axial velocity, inlet pressure drop and turbulent viscosity are consistent.

The flow field of the hydrocyclone in the actual work is very complicated. In this paper, the flow field in its motion is simplified by the known mathematical model, which is inevitably deviated from the actual working condition. Since only a few samples are selected for the simulation process, the results are of some reference value and further numerical simulation is needed if more accurate changes are needed.

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