Computational simulation of the effects of vortex finder diameter on the air core in a hydrocyclone separator

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Abstract

Air core is inherent to the solid-liquid hydrocyclone, the air core dimension plays a significant role in the separation efficiency. However, the formation mechanism of the air core in hydrocyclone has not arrived at an agreement. To further understand the flow behaviour of air core in hydrocyclones, in this paper, the volume of fluid (VOF) multiphase model and the Reynolds Stress Model (RSM) were adopted in this study to simulate the flow fields inside a hydrocyclone. The effect of the varying vortex finder diameter on the formation and development of air core was analysed, and the generation and development of the air core were investigated. The results showed that air core could be generated in shorter time and more stable state with larger vortex finder diameter. In addition, the diameter of the air core increased with the vortex finder diameter.

Keywords: hydrocyclone; computational fluid dynamics; VOF multiphase; diameter of vortex finder; air core

1 Introduction

The hydrocyclone is widely used in the mineral, chemical, oil processing industries, because of its high capacity, low maintenance, low operating costs, the design and operational simplicity, and the small physical size of the device. Since 1950, a large number of literatures about the hydrocyclone have been published, including empirical and semi-empirical equations for predicting the equipment performance, mathematical models describing flow distributions [1-5]. After many years of application, the outstanding merits of hydrocyclone have been well acknowledged in increasing application areas. With the development of computational fluid dynamics (CFD), simulation of the flow field inside hydrocyclone has been widely promoted. By using Reynolds stress model (RSM) and volume of fluid (VOF) model, Wang B [6] numerically simulated the gas-liquid two-phase flow inside hydrocyclone. Gupta R et al. [7] studied the development of air core and its influences on the flow filed in hydrocyclone. S. M. Mousavian et al. [8] compared the k-ε model, the Reynolds stress model, and the Reynolds stress model with the VOF model for simulating the air core flow fields. Air core is inherent to the solid-liquid hydrocyclone, plays a significant part in the classification efficiency in the hydrocyclone. Till now, the formation mechanism of the air core in hydrocyclone has not arrived at an agreement [9]. To further understand the flow behavior of air core in hydrocyclone, multiphase flow model and RSM model were adopted in this study to predict the flow distribution and formation mechanism of air core inside a hydrocyclone. In this paper, the effect of the varying vortex finder diameter on the formation and development of air core was analysed, and the generation and development of the air core were investigated. The results showed that air core could be generated in shorter time and more stable state with larger vortex finder diameter. In addition, the diameter of the air core increased with the vortex finder diameter.

2 Numerical model and its boundary conditions

2.1 GEOMETRY AND MESH

The structural parameters and diagram of the geometrical model are as shown in Table 1 and Figure 1. The diameters of tubes for the feed inlet, overflow, underflow and main body of the hydrocyclone are16.7, (25, 35, 40, 50), 20, 100mm, respectively. Mesh independence analysis were discussed with mesh size 75000, 10000,125000 and 200000. The results showed that numerical results were independent of the total number of computational cells. In the rest of this paper, we took into account the accuracy of numerical results and the computational time, the total computational domain used hexahedron structure grids, including about 125000 cells for computational domain, and the grids at the centre axis and the surrounding surface were refined (Figure 2).

2.2 BOUNDARY CONDITIONS AND CONTROL PARAMETERS

RSM turbulence model was used in consideration of the turbulence characteristics of high-speed rotation inside the hydrocyclone. Meanwhile, taking the hydrocyclone's inherent multi-phase flow feature into consideration, VOF model was used due to its suitability regarding to gas-liquid two-phase flow. The principal phase was set as water in the VOF model, and the secondary phase was air. The hydrocyclone inlet was set as velocity inlet, and the feeding velocity was assumed to be constant with a magnitude of 6 m/s. The volume fractions of water and air were set as 1 and 0, respectively. The fluid velocity was set perpendicularity to

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the entry section and pointing to internal side. Both the overflow and the underflow outlets were defined based on pressure, and they connect to the atmosphere (zero gauge pressure). The air backflow ratios at both the overflow and underflow ports were set as 1, i.e. air was the only reverse current. No-slip boundary conditions were applied on all walls, and near-wall treatment was applied to the wall using standard wall functions. The computational CFD code FLUENT 6.3 (Fluent Inc., USA) was utilized to solve the continuity equation and Navier-Stokes equation and boundary conditions. This model adopted pressure-based implicit transient three-dimensional solvers. The control parameters were solved by using pressure-velocity coupling SIMPLE method. A pressure-discretization set of simulations was performed with the pressure staggered option (PRESTO), which works well for high-speed rotation flows. The momentum discretization format was carried out with a higher-order quadratic upwind interpolation (QUICK) spatial scheme. Geometric reconstructive discretization format was used for determining the two-phase volume fractions. First-order upwind format was used for determining the turbulence energy, turbulence dissipation rate and Reynolds stress discretization scheme. Initially, the hydrocyclone was filled with air, i.e. the air volume fraction inside the hydrocyclone was 1. The termination criterion for the computational accuracy was set as maximum relative residual errors of 10^{-5}, unsteady computational method was used, and time increment was defined as 0.0001 s.

TABLE 1 Main structural parameters of the hydrocyclone

Structural parameter of the hydrocyclone	Structural dimensions
Hydrocyclone diameter D (mm)	100
Vortex finder diameter of the hydrocyclone do (mm)	25, 35, 40, 50
Underflow port diameter of the hydrocyclone du (mm)	20
Feed inlet dimensions of the hydrocyclone a×b (mm)	25×12.5
Feed inlet equivalent diameter of the hydrocyclone di (mm)	16.7
Overflow pipe insertion depth of the hydrocyclone H4 (mm)	50
Thickness of the overflow pipe of the hydrocyclone S (mm)	7.5
Extension length of the overflow pipe of the hydrocyclone H5 (mm)	30
Cylinder height of the hydrocyclone H1 (mm)	90
Cone section height of the hydrocyclone H2 (mm)	227
Underflow pipe height of the hydrocyclone H3 (mm)	50

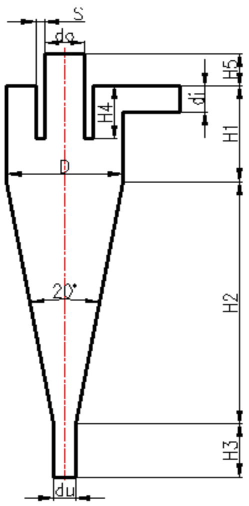


Fig.1. Structural diagram of the hydrocyclone

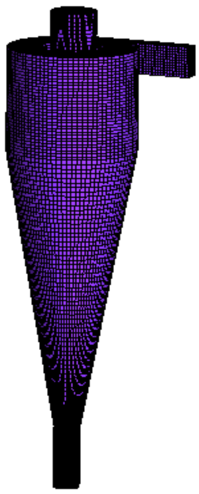


Fig.2. Mesh structure of the hydrocyclone

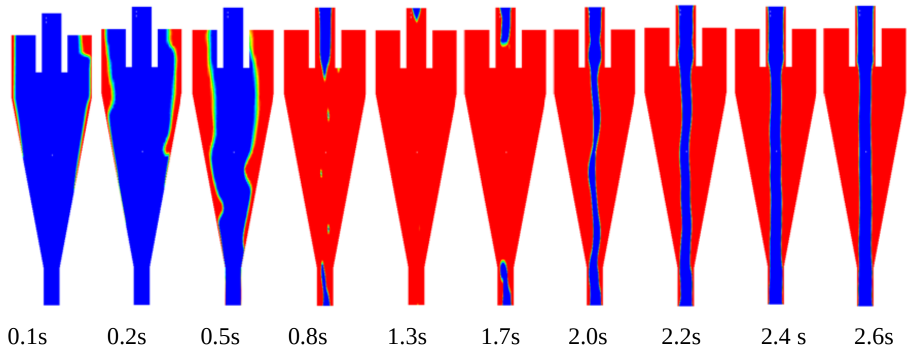
3 Simulation results and discussion

Simulation completed when all physical parameters in the flow field remained stable. Figure 3 shows the formation and development of the air core in the hydrocyclone during the startup process obtained from CFD simulations. The blue area in Figure 3 represents air, red represents water. In the initial stage, the hydrocyclone was filled with air, i.e. air volume fraction was 1. This value gradually decreased over time, correspondingly, the fluid volume fraction increased. Along with the development of the flow field, negative pressure was generated near the centre axis of the hydrocyclone. Since the outlet of the hydrocyclone was connected to atmosphere, air intake occurred at both the overflow and underflow ports, and air core firstly appeared at the bottom of the overflow outlet. Subsequently, air core at underflow and overflow outlets developed toward each other and finally interconnected.

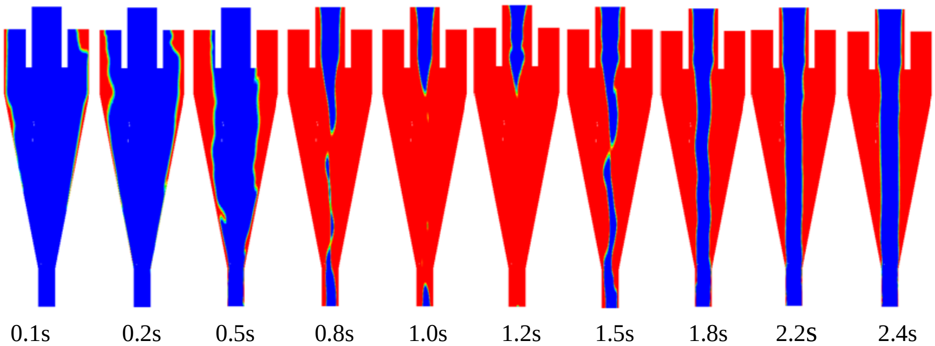
According to Figure 3, the diameter of the overflow pipe affects the air core significantly. Figure 3(a) shows the air core generating process when the diameter of the overflow pipe was set as 25 mm. It is observed that air core structure was formed in about 2.0 s, when it was still unstable at the moment. Gradually developing with its separating process, the air core reached a pseudo-stable state after about 2.6 s of operation and appeared to be in very regular shape with minimal oscillations. Figure 3(b) shows the transient development of the air core structure in the hydrocyclone when the diameter of the overflow outlet was set as 35 mm. It was observed that the air core structure stabilized after about 2.4 s of simulation, which is obviously shorter in time compared to the 25 mm-diameter-overflow hydrocyclone. Figure 3(c) shows the changing process of the air core structure when the diameter of the overflow outlet was increased to 40 mm. From this figure it can be seen that the air core structure is formed in about 1.4 s, and soon reached a steady state itself. Figure 3(d) shows the changing process of the air core structure when the diameter of the overflow pipe was set as 50 mm. It is obvious that the air core stabilized within the shortest time, which was only 1.7 s.

Overall, the diameter of the stabilized air core increased with the diameter of the overflow outlet. The results also showed that the diameter of the overflow outlet affected the air core to some extent, from its generation to stabilization: the larger diameter of the overflow pipe, the shorter time the air core needed to develop. The air core stabilized itself after about 2.6 s for a 25 mm-diameter-overflow pipe, while for the 50 mm one it stabilized after only about 1.7 s. From the perspective of the air core regularity degree, the smaller diameter of the overflow outlet, the more regular shape the air core had.

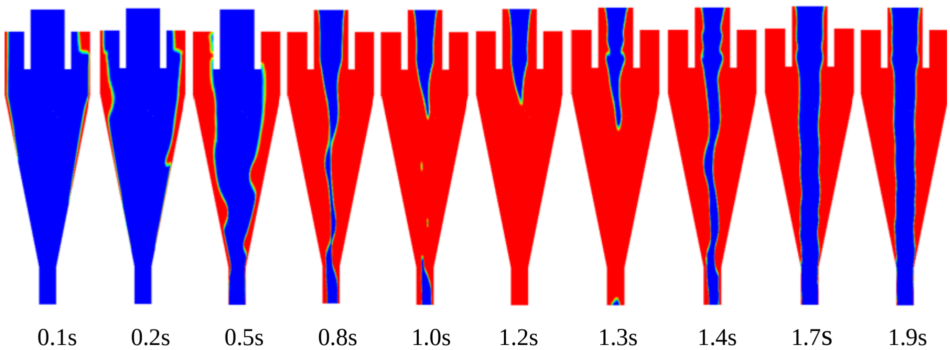
To verify that the generation of the air core is indeed contributed by both the overflow and the underflow outlets, the hydrocyclone with 35 mm-diameter-overflow was set as example as shown in Figure 4. All the parameters and setups remained the same, because the underflow port was blocked by water rather than being connected to atmosphere, and the iteration continued after the air core stabilized. Figure 4 shows that the air core exhibited instability with time, and disconnected after about 2.8s. After that, it gradually disappeared till after about 3.0s, when the air core around the underflow port totally vanished. This phenomenon was due to the disconnection to atmosphere and negative pressure in the hydrocyclone is the prerequisite of forming air core.



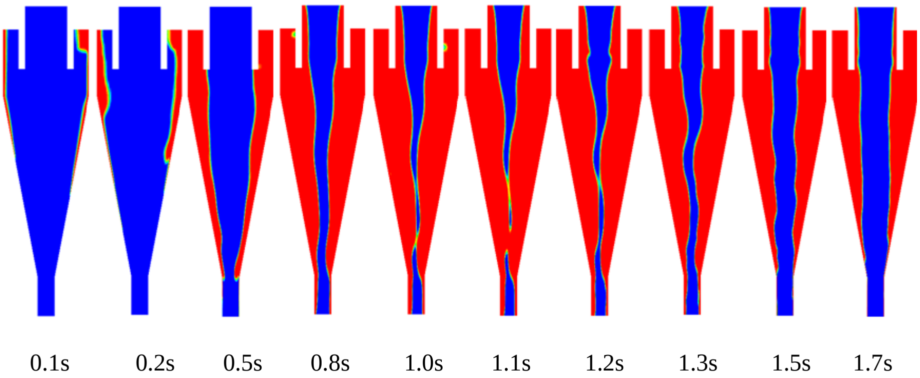
(a) Overflow pipe diameter is 25 mm



(b) Overflow pipe diameter is 35 mm



(c) Overflow pipe diameter is 40 mm



(d) Overflow pipe diameter is 50 mm

Fig.3. Effect s of overflow pipe diameter on air core

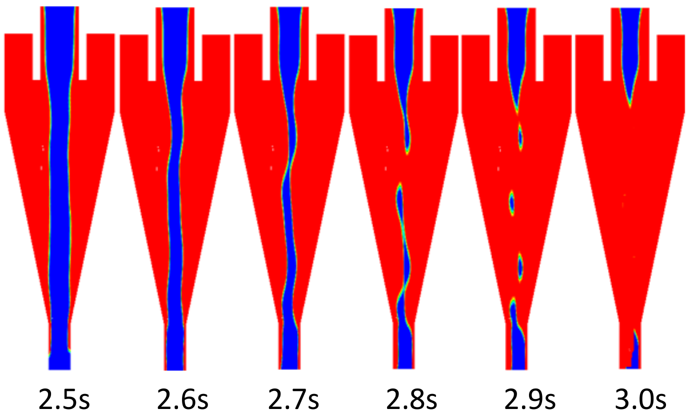


Fig.4. Efects of water-blocked underflow port on air core

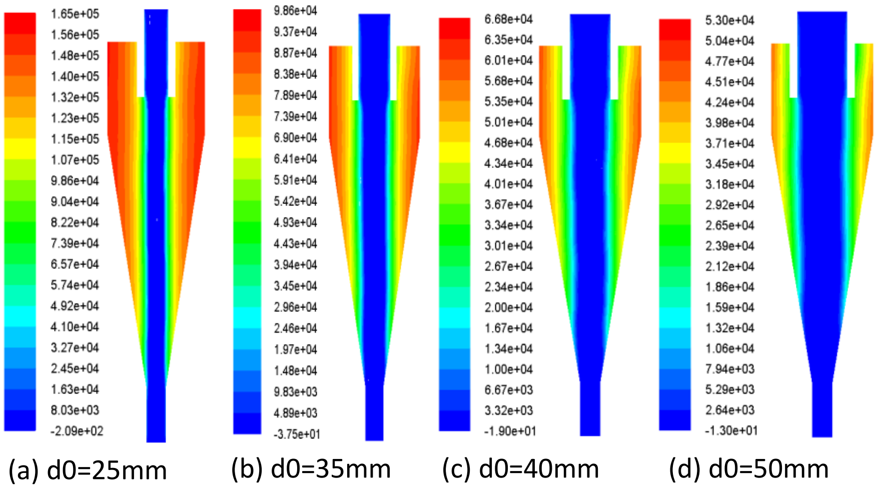


Fig. 5.Static pressure distributions in the hydrocyclone for different diameter of overflow outlet diameters

To better explain the effect of the overflow outlet on the air core, the pressure distributions inside the hydrocyclone with varying overflow outlet diameters were compared as shown in Figure 5. It is shown clearly in Figure 5 that the pressure inside the hydrocyclone was about 165000 Pa when the overflow pipe diameter is 25 mm. The pressure gradually decreased with increasing overflow pipe diameter; for example, the pressure dropped to only 53000 Pa when the overflow diameter increased to 50 mm. Estimated from these results, the larger overflow pipe diameter, the shorter time during, which negative pressure exists, i.e. the shorter time air core appears. It can also be noticed in Figure 5 that as the overflow diameter increased, larger radial area was featured by negative pressure, further proving the conclusion above: the air column diameter increases with the overflow diameter.

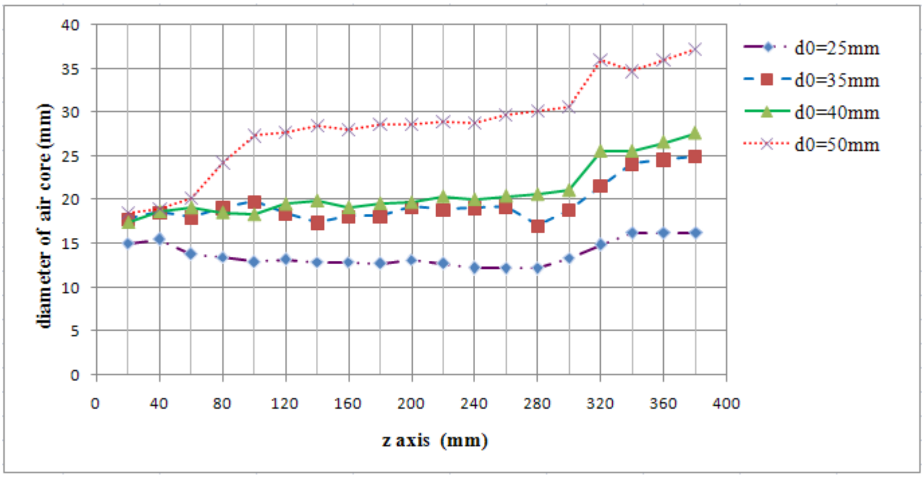


Fig.6 Diameter of air core in the hydrocyclone at z axis

In order to study the effect on the air core with different diameter of vortex finder, Figure 6 showed comparisons of the value of air core diameter with different vortex finder at various axial positions of the hydrocyclone obtained from CFD simulations. It is observed that movement rule of air core inside hydrocyclone could be divided into four parts: the first one is the underflow pipe (from z=0 to z=50mm), the air core in this part remain relatively stable, the air core diameter remain basically unchanged at z axis. At vertical position z=50mm, when the vortex finder diameter is d0=25, 35, 40, 50mm, respectively, the corresponding value of air core diameter in the hydrocyclone is 15.50, 18.57, 18.68, 18.98mm, respectively; The second part is conical section (from z=50mm to z=277mm), the results showed that the diameter of air core there are abrupt changes at the junction of the cylindrical section and conical section of the hydrocyclone. And it is also found that there is a couple of small fluctuation of the air core diameter within conical section. But the change in the rules of air core within this section was not similar. At vertical position z=227mm, when the vortex finder diameter is d0=25, 35, 40, 50mm, respectively, the corresponding diameter of air core in the hydrocyclone is 12.74, 18.89, 20.38, 28.96mm, respectively; The third part is cylindrical section (from z=227mm to z=317mm), from the Fig.6 above mentioned we can see with the z axis increasing, the diameter of the air core in various vortex finder of the hydrocyclone was increasing trend, and the tendency towards increasing in value was obvious. This phenomenon indicated that the air core movement in this section was not stable. At vertical position z=317mm, when the vortex finder diameter is d0=25, 35, 40, 50mm, respectively, the corresponding diameter of air core in the hydrocyclone is 14.92, 21.65, 25.55, 35.94mm, respectively; The fourth section is above the vortex finder insertion depth, it was found that with the z axis increasing, the diameter of the air core in various vortex finder of the hydrocyclone was increasing trend, but increased indistinctively with the increasing of z axis. At the top of vortex finder (z=380mm), the diameter of air core reached the maximum value. when the vortex finder diameter is d0=25, 35, 40, 50mm, respectively, the corresponding diameter of air core in the hydrocyclone is 16.25, 25.00, 27.61, 37.17mm, respectively

4 Conclusions

In this paper, the computational fluid dynamics (CFD) method was used to simulate the flow fields in a Φ100 mm hydrocyclone. The flow filed patterns inside the hydrocyclone was revealed and the generation and development of the air core inside the hydrocyclone were discussed. In addition, the simulation helped to improve the understanding of how the vortex finder diameter affects the air core, and the results could be used as a theoretical basis to optimize hydrocyclone design.

(1) The vortex finder diameter significantly affects the dimension and shape of the air core. As the diameter of the vortex finder increased, the diameter of the produced air core increased, and the time for the air core to stabilize became shorter.

(2) As the air core increased in diameter, the pressure-drop and the split ratio inside the hydrocyclone decreased, thus improving the separation performance.

(3) Negative pressure in the hydrocyclone is the prerequisite of air core. The axis of the air core almost superposed the hydrocyclone's. The dimension and shape of the air core changed with the flow field. Even in a stable flow field, the air core still had different dimensions at different positions of the axis. Analysis showed that this could partially because of the unstable flow field, and partially because the structure variation of the hydrocyclone itself.

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