Analysis of vortex flow in a cyclone separators based on the energy gradient theory

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Abstract: Numerical simulation is carried out for the tangential inlet cyclone separator with different dimensionless parameter (the ratio of cone-tip diameter and cylinder diameter d/D is 0.342, 0.355, 0.368, 0.382 and 0.395). Then, the stability of the vortex flow in the separator is analyzed with the energy gradient theory. The governing equation is the Reynolds-average Navier-Stokes equations with Reynolds Stress Model (RSM). The finite volume method is employed to simulate the flow and the velocity, pressure, separation efficiency and the turbulent intensity are obtained. Results show that the location of the maximum tangential velocity is near the axis, and the highest outer vortex tangential velocity is achieved at the dimensionless rate of 0.355. When the d/D=0.355, the tangential velocity distribution in the outer vortex is the most close to velocity distribution characteristics of free vortex. The free vortex distribution has the best stability from the energy gradient theory which may be the reason why optimal performance can be achieved at d/D=0.355. To achieve high efficiency and low pressure drop for the device studied, d/D=0.355 is the optimal dimensionless diameter ratio.

1. Introduction
Cyclone separator is one of the most important industrial dust collectors with a lot of advantages, such as simple structure, low cost of operation and medium energy loss.

In order to improve the separation performance of cyclone separator, many researchers have put forward various feasible methods. Cao et al [1] carried out numerical investigation on the inner flow in cyclone separator, and found that reducing the inlet section area, the vortex finder diameter and the cone-tip diameter can make the tangential velocity increase, but simultaneously causing the pressure drop to rise. Qian et al [2] found that the cyclone separator attached a vertical tube can avoid the re-entrainment effectively and improve the separation efficiency. Khairy’s [3] research showed that the pressure drop decreases with the increases of cylinder height, but its influence would reduce if the ratio between cylinder height and cylinder diameter is more than 1.8.

In this paper, using three-dimensional numerical simulation method, an analysis of the effects of cone-tip diameter on the flow field, pressure drop and separation efficiency of the cyclone separator, has been carried out to find out the optimal value of cone-tip diameter. According to the structure of combined

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vortex, the energy gradient theory [4-10] is employed to study influencing mechanism of cone-tip diameter.

2. Numerical Simulation
The governing equations are based on the Reynolds-averaged Navier-Stokes (RANS) equation. For increasing the accuracy of numerical simulation, the Reynolds Stress Model (RSM) is used, which solves a transport equation for each component of Reynolds stress. What’s more, the energy gradient method is applied to analyze stability of the structure of vortex.

2.1. Geometric model and boundary condition
Figure 1 is the geometric diagram of the cyclone separator, in which detail parameters can be seen from Table 1. In this paper, numerical simulation is carried out for cyclone separators with tangential inlet for various different cone-tip diameters. Five sets of diameter are employed as shown in Table 2.

| Table 1. Geometry parameters of cyclone separator.\[11\] | Table 2. Dimensionless ratio of d/D. |
|---|---|
| \(a/D\) | \(b/D\) | \(D_e/D\) | \(H/D\) | \(h/D\) | \(S/D\) | \(D/mm\) | \(d/mm\) | \(d/D\) |
| 0.5 | 0.2 | 0.337 | 4 | 1.5 | 0.5 | 65 | 0.342 |
| 67.5 | 0.355 |
| 70 | 0.368 |
| 72.5 | 0.382 |
| 75 | 0.395 |

The cyclone separator has been divided into four regions: inlet, rotary, outlet and tube cone sections using Multi-Block grid technique. Unstructured grids are used for inlet region, but structured grids are employed for others regions. A series of numerical tests show that the total amount of grids used in this study is enough to accurate simulate the flow in the cyclone separator.

The boundary conditions are as follows. The velocity at inlet is given and that at outlet is extrapolated. On the wall boundaries, non-slip condition is used for the three velocity components. When considering two-phase flow, the inlet and outlet surface are defined as “escape” boundary condition. The bottom wall is defined as “trap”, while others are defined as “reflect.”

2.2. The energy gradient theory
In the past 10 years, Dou\textsuperscript{[4-10]} proposed an energy gradient theory with the aim to clarify the phenomenon of transition from laminar flow to turbulence. According to the theory, for a given flow, a stability criterion can be written as follows for a half-period of disturbance.

\[ F = \frac{\Delta E}{\Delta H} = \left( \frac{\partial E}{\partial n} \right) \left( \frac{\partial H}{\partial s} \right) \left( \frac{\pi}{\omega_d} \right) = \frac{2}{\pi^2} K \frac{\bar{A} \omega_d}{u} = \frac{2}{\pi^2} K \frac{v'}{u} < \text{Const} \]  

(1)

And

\[ K = \frac{\partial E / \partial n}{\partial H / \partial s} \]  

(2)

Here, \( F \) is a function of coordinates; \( K \) is a dimensionless field variable (function), \( E \) is the total mechanical energy per unit volumetric fluid, \( n \) is along the streamwise direction and \( s \) is along the transverse direction. \( H \) is the energy loss per unit volumetric fluid along the streamline for finite length. Furthermore, \( u \) is the streamwise velocity of the main flow. \( V_m = \bar{A} \omega_d \) is the amplitude of the disturbance of velocity, here, \( \bar{A} \) is the amplitude of the disturbance in the transverse direction, \( \omega_d \) is the frequency of the disturbance.

When the vertical structure is free vortex, the value of energy gradient function \( K \) equals to 0 \[4-10\]. Thus, the flow is stable since the free vortex is able to restrain or absorb the disturbance.

3. Results and Discussions

3.1. Validation of the Numerical Model

Figure 2 plots the comparison of the simulation and experimental data\textsuperscript{[12]} of tangential and axial velocities along the radius at the axial position \( z=560 \) mm for the case of \( d/D=0.382 \). The tendency of the tangential velocity distribution is consistent with the experimental data, especially the location of the maximum tangential velocity. The double vortex structure exactly shows a good conformity. On the contrary, the axial velocity distribution does not accord well with the experimental data. The possible source for this difference may come from that the influences of the wall boundary layer and the unstable vortex in the region.

![Figure 2](image)

\textbf{Figure 2.} Comparison of the simulation and experimental velocity at the axial position \( Z=560 \) mm. (figure (a) and (b) show the comparisons of the tangential velocity and axial velocity respectively.

In order to check the accuracy of numerical simulation, the comparison of static pressure between numerical result and theoretical value is examined. A theoretical equation of static pressure distribution in the free vortex, based on the \textit{Gas-solid Separation Theory and Technology}\textsuperscript{[13]}, is
where, $\rho_k$ is the density of the fluid, $p_k$ is the pressure near the wall, $p$ is the pressure of optional position and $n$ is the velocity distribution index which is calculated by using the empirical equation developed by Alanander, see the reference [13]. The comparison of the static pressure obtained from the simulation and theory expressed by equation 3 can be seen from figure 3.

The above comparison results show that the numerical simulation employed in this paper is reliable.

3.2. Tangential velocity analysis

In the cyclone separator, the working principle is based on that particles can be separated from the gas due to density difference between them under the action of the tangential velocity. Thus, the role of tangential velocity is very important.

Figure 4 shows the comparison of the tangential velocity at $Z=360$, $Z=560$ and $Z=645$ (mm) in the X=0 plane with different value of $d/D$. From the figure 4, the maximum tangential velocity causes the inner flow exhibiting a combined vortex structure, i.e., inner and outer flow (quasi-forced vortex and quasi-free vortex) [14]. In the inner vortex, the tangential velocity increases with the increasing of the radius near the axis, after reaching its peak the tangential velocity decreases gradually in outer vortex. It is noted that the outer vortex is the main separation zone, so wider range of outer vortex will help the separation. Higher tangential velocity in the outer vortex facilitates the particle motion to the wall of the cyclone separator. As is given in figure 4, for $d/D=0.355$, the location of the maximum tangential velocity is closest to the axis, and the outer vortex tangential velocity is higher than other $d/D$ cases.

Figure 4. Tangential velocity distribution with different magnitude of the $d/D$ at three axial stations (a) $Z=360$ mm, (b) $Z=560$ mm and (c) $Z=645$ mm.

3.3. Pressure drop and separation efficiency profiles

Pressure drop and separation efficiency are two of main performance parameters for the cyclone separators. Under the same volume fraction, the separation efficiency with various sizes of silica sand (5, 7, 9 and 11 $\mu$m) are obtained, which is shown in figure 5. With the particle diameter increase, it is can be seen that the variation of separation efficiency has the same tendency for the different $d/D$. Figure 5 reveals that the higher separation efficiency is obtained at $d/D=0.355$. Meanwhile, the pressure drop increases with the increase of the magnitude of the $d/D$ as shown in figure 5. The main reason for this phenomenon may be due to the variation of the contacting area of particles and the wall, which leads to the increase of the friction loss. In conclusion, at $d/D=0.355$, the cyclone separator achieves the highest separation efficiency and the relatively low pressure loss.
3.4. Stability analysis

The vortex structure can mainly be divided into forced vortex and free vortex in inviscid fluid, and the moment of momentum is same in every position in free vortex \[15\]. However, due to the effect of the viscosity in cyclone separator, the outer vortex is a quasi-free vortex which is divided into half free vortex region and the boundary layer region. The velocity distributions equations of free vortex and half free vortex respectively as follows:

Free vortex

\[ u_r c = c_1 \]  

Half free vortex

\[ u_r^0 c = c_2 \]  

where \( n \) is the velocity distribution index, generally \( n=0.5\text{–}0.9 \). In this paper, \( n \) is selected at 0.5; \( r \) is the radius; \( c_1 \) and \( c_2 \) are constants.

Figure 6 shows the tangential velocity distribution at \( Z=560 \text{ mm} \). From this figure, at the case of \( d/D=0.355 \), the tangential velocity distribution of real flow is the most close to the theoretical tangential velocity distribution in half free vortex and the distribution form in quasi-free vortex of real flow and free vortex is most similar.

Meanwhile, as shown in table 3, at \( d/D=0.355 \), the proportion of forced vortex in vortex structure is the least for various different structures.

![Figure 6. Tangential velocity distribution along radius.](image)

**Figure 6.** Tangential velocity distribution along radius.

![Figure 7. Comparison of turbulence intensity with different magnitude of the d/D at three axial station (a) Z=360mm,(b) Z=560mm and (c) Z=645mm.](image)

**Figure 7.** Comparison of turbulence intensity with different magnitude of the d/D at three axial station (a) Z=360mm,(b) Z=560mm and (c) Z=645mm.
According to the energy gradient theory, the free vortex is stable and has the ability to restrain disturbances. Thus, when the quasi-free vortex area becomes bigger, the turbulence intensity is lower. The tangential velocity distribution in quasi-free vortex is close to free vortex, and thus the stability of the internal flow in cyclone separator is improved. Furthermore, figure 7 shows the comparison of the turbulence intensity distribution with different structures. For figure 7(a), turbulence intensity achieves the minimum and the maximum value at $d/D=0.342$ and 0.395, respectively. However, at $d/D=0.355$, the turbulence intensity is minimum as showed in figure 7(b) and figure 7(c). Thus, the velocity distribution for $d/D=0.355$ is relatively stable. It is noted that there may also exists secondary flow (short-cut flow, vertical eddy and eccentric circulation vortex et al) besides the mainstream in cyclone separator. Moreover, Xue et al.\cite{16-17} found that whether secondary flow occurs or not has great relations to the turbulence intensity in a cyclone separator. The secondary flow will appears frequently when the turbulence intensity becomes larger, and then the flow will be of high instability.

In a word, we can obtain the conclusion that, at $d/D=0.355$, the half free vortex area is the largest and the turbulent intensity is relatively low, resulting in the flow to be most stable.

4. Conclusions
In this paper, considering the influence of dimensionless parameter $d/D$, the distributions of velocity and pressure, separation efficiency and vortex structure are studied by using numerical simulation method. Conclusions obtained are as follows:

1) At $d/D=0.355$, the location of the maximum tangential velocity is closest to the axis and tangential velocity in outer vortex is higher than others cases of geometric structures. Meanwhile, the cyclone separator achieves the highest separation efficiency and the relative small pressure drop at $d/D=0.355$. Thus, $d/D=0.355$ is the optimal dimensionless diameter ratio.

2) According to the energy gradient theory, the free vortex is stable, while the forced vortex is unstable. From the analysis for five different ratios ($d/D$), the quasi-free vortex occupies largest area at $d/D=0.355$ among the five cases. Thus, the velocity distribution for $d/D=0.355$ is most stable. This may be the reason why this case can get the optimal performance.

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