Analysis of a cylindrical cyclone separator based on the RMS data

Z W Gao\textsuperscript{1,2}, J Wang\textsuperscript{1,2}, J Y Wang\textsuperscript{1,2}, Y Mao\textsuperscript{1}, Y D Wei\textsuperscript{1,2}

\textsuperscript{1} State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China.
\textsuperscript{2} Beijing Key Laboratory of Process Fluid Filtration and Separation, Beijing 102249, China
E-mail: wangjuan@cup.edu.cn

Abstract. This study presents a flow analysis on an atypical cylindrical cyclone separator with a large ratio of length to diameter. The Phase Doppler Particle Analyzer (PDPA) is used to measure the gas flow, and the numerical simulation is carried out by using the Reynolds Average Navier-Stokes (RANS) equation, the Reynolds stress model (RSM). Since the model is validated by good agreement between the numerical results and experimental data, and then the tangential velocity is analysed from the transient flow field and dynamic performance. The results showed that the tangential velocity of the transient flow field existed a non-axisymmetric phenomenon in the cross section, which was mainly presented as asymmetric distribution of the contours. The zero location of tangential velocity value was not coincided with the geometric center, where the tangential velocity was larger near the zero location. In addition, the dynamic character of tangential velocity was high-speed pulsating, with quasi-periodic characteristic. Meanwhile, a parameter of RMS was used to identify the degree of turbulence velocity deviating from mean velocity. The RMS data showed that the flow instability gradually increased with the fluid flowing into the cyclone separator from the inlet section, until reached a peak value at the position about 2.0 times the length to diameter. And then the flow instability gradually decreased, with the fluid energy dissipated.

1. Introduction
Cyclone separator is an important equipment for gas-solid separation process. Although there is no moving parts inside, the internal flow field is a complex turbulent flow. The swirling flow is instability, where the flow frequency changes with time \cite{1}. But the distribution of flow field determines the separation performance. The instability of the swirling flow not only affects the distribution of the flow field, but also causes noise and the pressure fluctuation of the shell to form the vibration \cite{2}. Therefore, the research of flow instability in cyclone separator has a far-reaching significance for engineering.

For the flow instability of in cyclone separator, many scholars have experimentally \cite{3-5} and numerically simulated them \cite{6-8}. However, most scholars analyzed the cyclone separator, still focused on the transient flow field, while neglecting the research of dynamic change of swirling fluid and how to identify the degree of the flow instability.

Aiming to understand the flow behaviour, this work will conduct a numerical investigation of the hydrodynamics in the cyclone separator with a large ratio of length to diameter. The RSM model will be used to capture the flow. The key is focus on the understanding of the relationship between the velocity fluctuation and the flow instability. This work can provide further insight into the design and optimization, which is highly significant.
2. System description and numerical methods

2.1. Configuration of the cyclone separator

The schematic diagram of the cyclone separator was shown in Figure 1 and the parameters characterizing the structure were given in Table 1. The cylinder of the cyclone separator was 140 mm in diameter. The cyclone with a large ratio of length to diameter, which doesn’t have a section of the cone, could well reflect the flow of swirling fluid. During simulation analysis, six monitoring surfaces were considered, including \( z/D = 0.71, 2.14, 3.57, 6.43, 9.29 \) and 12.14 respectively. The horizontal plane across the bottom of the entrance was set as the reference plane, and the positive direction was upward. While the geometric center of the vortex finder was set as the origin.

![Figure 1. Dimensions of the cyclone separator.](image)

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![Figure 1. Dimensions of the cyclone separator.](image)

**Table 1. Geometry dimensions of the cyclone separator**

| Symbol | Dimensions/mm |
|--------|---------------|
| \( D \) | 140           |
| \( H \) | 1919          |
| \( De \) | 50            |
| \( a \)  | 36            |
| \( b \)  | 76            |
| \( S \)  | 1000          |
| \( L \)  | 150           |
2.2. Governing equations

Previous studies [9] have determined the Reynolds stress model (RSM) as having the greatest potential for predicting the swirling flow in cyclone separator. For incompressible fluid flow in cyclone separators, the governing equations can be expressed as:

\[ \frac{\partial \nu_i}{\partial x_i} = \rho \frac{\partial v}{\partial x_i} - \frac{\partial}{\partial x_i} \left( \mu \frac{\partial v}{\partial x_i} \right) + \rho g - \frac{\partial}{\partial x_i} \left( \rho v' \nu' \right) \]

where \( \rho, \mu \) and \( \rho g \) are pressure, density and dynamic viscosity, respectively. \( v \) and \( v' \) are the mean and fluctuating velocity. The Reynolds stress term, \( \rho v' \nu' \), represents the effect of turbulent fluctuations on the fluid flow and is modelled by using RSM in this study. The transport equation of Reynolds stress is given below:

\[ \frac{\partial}{\partial x_i} \left( \rho v_i \nu_j \right) = P_{ij} + \phi_i + \frac{\partial}{\partial x_i} \left( \mu + \frac{\rho}{\sigma_j} \frac{\partial \nu_j}{\partial x_i} \right) \left( \nu' \nu' \right) + \frac{2}{3} \rho \delta_{ij} \]

where \( P_{ij} \) is the stress production term given by

\[ P_{ij} = -\rho \left( \nu' \nu' \frac{\partial v_i}{\partial x_j} + \nu' \frac{\partial v_i}{\partial x_j} \nu' \right) \]

and \( \phi_i \) is the pressure-strain term, which is modeled by

\[ \phi_i = -C_1 \rho \frac{\varepsilon}{k} \left( \frac{\nu_i}{\nu} - \frac{2}{3} \delta_{ij} \right) - C_2 \left( P - \frac{1}{3} \rho \delta_{ij} \right) \]

In addition, the transport equation for turbulence dissipation rate \( \varepsilon \) is expressed as

\[ \frac{\partial}{\partial x_i} \left( \rho v_i \varepsilon \right) = \frac{\partial}{\partial x_i} \left( \mu + \frac{\rho}{\sigma_j} \frac{\partial \varepsilon}{\partial x_i} \right) + \frac{\varepsilon}{k} \left( \frac{C_3}{2} \rho - C_4 \rho \varepsilon \right) \]

The following constants of RSM are used, \( C_1=1.8 \), \( C_2=0.6 \), \( C_3=1.44 \), \( C_4=1.92 \), \( \sigma_1=1 \), \( \sigma_2=1.3 \).

3. Numerical simulation

The ANSYS ICEM software was used to mesh and ensure all the structured grid for hexahedron grid. The whole computational domain was divided into 234610 elements. The simulation result of this grid domain was examined to be grid independent with three grids of different densities.

Following actual operating conditions, a constant inlet velocity at the inlet boundary surface and a constant pressure at the outlet boundary surface were used. In addition, the fluid flow was modelled using the standard wall function and no-slip boundary condition near the wall.

The governing equations mentioned above were solved by a finite volume method. These equations were discretized by the QUICK scheme, and solved by the commercial CFD code FLUENT 16.0. The SIMPLE algorithm was implemented to deal with the velocity-pressure coupling. The numerical
solution was considered converged when the scaled residuals of the continuity equation was below $1 \times 10^{-4}$ s.

4. Results and discussion

4.1. Model validation

For cyclone separator, tangential velocity and axial velocity plays a critical role in the separation process. To validate the model of this study, the numerical results of the two velocities were compared with experimental data. As shown in Figure 2, both of them were in good agreement, which indicated that the model of this study has a good prediction accuracy for the flow field distribution in cyclone separator.

![Figure 2. Comparison of simulation result and experimental data.](image)

4.2. Transient flow field analysis

Tangential velocity dominates the flow behavior in the cyclone separator, so tangential velocity was analyzed. Figure 3 shows the tangential velocity distribution. From the longitudinal section, the tangential velocity was divided into the inner and outer double-layer structure at different axial positions. Each section had a rotation center, the center and the geometric center was not completely coincide. In the process of the fluid moving, the position of the rotation center was constantly changing. And then the procession vortex core (PVC) phenomenon was formed. At this time, the movement of fluid was not periodicity, but a complex movement with a strong unsteady characteristic.

![Figure 3. Contour of tangential velocity distribution.](image)
4.3. Dynamic characteristics analysis

The gas-solid separation process in the cyclone is a dynamic continuous process. Figure 4 shows the fluctuation curve of the instantaneous tangential velocity pulsation value. In the upper part of the cylinder, the fluctuation range of tangential velocity was -8~8 m/s, due to the flow instability. With the axial downward, the fluid energy gradually dissipated, tangential velocity pulsation range gradually reduced.

![Figure 4](image)

Figure 4. Curve of tangential velocity fluctuation, r/R=0.14.

4.4. Swirling RMS analysis

Turbulence pulsating motion was irregularly random in time series. In order to study the flow instability in the cyclone, the time-averaged velocity of each section was recorded with time, and the deviation of the sample and the mean could be obtained by analyzing the standard deviation. The RMS value of the turbulence pulsating velocity of the measured point could be expressed by the following formula, which reflects the degree of velocity fluctuation.

\[
\text{RMS} = \sqrt{\frac{\sum_{i=1}^{N} (v_i - \bar{v})^2}{N}} = \sqrt{\frac{\sum_{i=1}^{N} v_i^2}{N}}
\] (7)
Where \( N \) was the number of measurements, \( \nu_i \) was the instantaneous velocity, \( \bar{\nu} \) was the mean velocity, and \( \nu'_i \) was the pulsation velocity of the measurement sample.

Before using the RMS analysis of the cyclone instability of the cyclone, it was necessary to verify the sampling independence. As shown in Figure 5, the results showed that the RMS distributions were basically the same in two sampling cases.

![Figure 5](image)

**Figure 5.** The curve of the sampling independent verification.

Figure 6 shows the distribution of RMS in cyclone separator. It could be found that the value of RMS increased from the inlet section, until reached to a peak. Which indicated that the movement of fluid from the inlet section into the cyclone separator was unsteady, and the flow instability reach a maximum in a certain position.

![Figure 6](image)

**Figure 6.** The distribution curve of RMS in cyclone separator.

5. Conclusions

By numerical simulation and experiments, this paper aimed to study the flow instability character in cyclone separator. Moreover, a cylindrical cyclone with a larger ratio of length to diameter was analyzed to describe the performance. The main conclusion could be summarized as follows:

1. The tangential velocity zero value does not coincide with the geometric center. The movement of fluid was not periodicity, but a complex movement with a strong unsteady characteristics.

2. In the upper space of the separation space, the instability of the moving fluid is larger, the turbulence pulsation is stronger and the velocity fluctuation range is larger. With the axial downward, the fluid energy gradually dissipated, the speed of pulsation gradually reduced.
Using the RMS data to analyze the degree of velocity fluctuation. The movement of fluid from the inlet section into the cyclone separator was unsteady, and the flow instability reach a maximum in a certain position.

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