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Performance evaluation of a new cyclone separator – Part II simulation results ☆

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ABSTRACT

A novel vortex finder (slotted vortex finder) was designed to improve cyclone separator performance. The gas flow in axial-inlet cyclone separator with the novel vortex finder is simulated by means of Reynolds Stress Model (RSM). The computational results of the flow patterns in cyclone separator are compared with the experimental ones, and the results show that RSM offers a robust, reliable modeling option for such flows. Three dimensional gas flow simulation results indicate that the gas flow exits the separator through two pathways. One part of the gas spirals down from outer annular space to outer separation space and dust hopper, then spirals upward in the inner part of separator, and finally exits the separator. The other gas flow enters the vent pipe through the slots in vortex finder rather than entering the separation space. The simulation results show that the latter part flow accounts for 54% of the total gas flow. Diversion of gas pathways has three advantages. Firstly, the 54% of the gas–solid flows can be separated by slots due to the novel vortex finder. Secondly, the results also indicate that there are almost no short circuit flows under the inlet of the slotted vortex finder. Thirdly, the slotted vortex finder reduces the flow swirling intensity and undesired instabilities, and thus the slotted vortex finder can reduce pressure drop.

1. Introduction

The gas–solid separation technology has been used extensively in various industries over the last several decades. Reducing the environmental impacts of particles pollution requires the cyclone separating smaller particles. Thus a considerable number of experimental and theoretical investigations have been performed on the gas–solid cyclone separators to achieve higher separation efficiency [1,2].

In conventional cyclone separator, there is overflow outlet for clean gas, and the outlet is an inner tube (or so called vortex finder) which descends from the top. The density of suspended particulate phase is normally greater than that of the primary phase. Due to centrifugal force, larger particles move rapidly to the outer wall and then been collected. Smaller particles migrate more slowly, and then are captured in an upward flow and escape into the vortex finder, which reduce particle collection efficiency due to short circuit flow. Thus, the shape of exhaust will have an influence on the flow and on the separation efficiency and pressure drop of cyclone separator. Many researchers [3–13] have carried out investigations to study the effects of vortex finder geometries on cyclone separator performance, and the geometries include vortex finder diameter, length, insertion depth, off-set, etc. They proposed effective cyclone design methods. Chen [14] studied the influence of the bottom-contracted and edge-sloped vent-pipe on the separation efficiency and pressure drop, and the experimental results indicated that by changing the configuration of vent-pipe, the separation efficiency increased at the expense of increasing the cyclone pressure drop. Wang [15] made more detailed studies on the effect of vortex finder insertion depth on cyclone separation performance, and found that the separation efficiency decreases for fine particles and increases for relatively coarse particles as vortex finder insert depth decreases. Raoufi [16] designed cone-shaped vortex finders and simulated flow in cyclone separators with different cone-shaped vortex finders, indicating that tangential velocity in the inner region of the cyclone separator decreases when the cyclone vortex finder diameter increases, and this would lead to lower separation efficiency. Shi [17] studied the influence of design parameters such as different diameters, different shapes and insertion depths of a vortex finder on cylindrical cyclone oil–water separation characteristics through experiments and numerical simulations. Hesham [18] investigated the effect of vortex finder dimensions on the flow and particle separation of a tangential inlet cyclone, and made maps for the selection of the vortex finder

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diameter to obtain the maximum collection efficiency while avoiding excessive pressure drop. Elsayed [19] simulated the effect of increasing the vortex finder diameter, length and shape on the pressure drop, cut-off diameter and obtained more details about the flow field pattern, velocity profiles and found that decreasing the vortex finder diameter by 40% results in 175% increase in the Euler number and 50% decrease in the Stokes number, and doubling the vortex finder length increases both the Euler number and the Stokes number by 25%.

In summary, all previous investigations reported the effect of vortex finder geometry dimensions on gas–solid or gas–solid–liquid separator performance and flow patterns. Nevertheless, the previous studies show that changing traditional exhaust vortex finder geometries, such as diameter, length, insertion depth and shape, can improve cyclone separation efficiency with the cost of increasing the cyclone pressure drop, or reduce pressure drop with the cost of decreasing the separation efficiency. It is not easy to increase separation efficiency and decrease pressure drop at the same time by changing conventional vortex finder geometry.

In this study, a novel vortex finder is designed to improve cyclone separator performance including increasing separation efficiency and decreasing pressure drop. A computational fluid dynamics method is used to predict and evaluate the performance of axial inlet cyclone separator with the novel vortex finder. Detailed flow information is obtained to reveal how the novel vortex finder improves cyclone separator performance.

2. Numerical simulations

2.1. Turbulence model

The separator's working process contains complicated three dimensional strong swirling flows and two-phase separation movement, making the flowing law very complex. So it is very difficult to predict the internal flow status through experiments and analytical methods. In recent years, the rapid development of numerical calculation technique promotes the study on properties of separator. CFD has a great potential to predict the flow field characteristics and particle trajectories inside the cyclone as well as the pressure drop [20], and the use of numerical simulations to predict the performance of the cyclone has received much attention [21–24,19].

Reynolds Stress Model (RSM) or the RNG k-e turbulence models appears to be the most preferred choice when calculating the flow pattern and particles trajectories in cyclones and hydrocyclones [25–35]. The RSM is naturally suitable for calculating the average properties of swirling flows as it is capable of handling anisotropic effects, which suggested that the corresponding numerical results obtained by RSM are comparable with experimental measurements. This has been extensively demonstrated [36].

2.2. Gas–solid two-phase flow model

The Discrete Phase Model (DPM) is Fluent is adopted to calculate the solids concentration distribution. And the particles governing equations in X-direction can be expressed as:

$$\frac{dx_p}{dt} = u_p$$

$$\frac{du_p}{dt} = F_D\left(u_g - \grave{u}_g - u_p\right) - g$$

Similar equations can be written for the other two directions, where p, g stands for the particles and gas phase, respectively. $\grave{u}_g$ is the fluctuation velocity components. F_D stands the relaxation time of particles.

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D Re_p}{24}$$

Re_p and C_D are the particle Reynolds number and the drag coefficient, and the empirical correlations between Re_p and C_D were proposed by Schiller and Naumann [37].

Forces such as Saffman's, Basset and virtual force have been neglected, since the particles material density is nearly 1000 times the gas density.

2.3. Geometry and grid division

The schematic diagram of the cyclone separator with the main dimensions is plotted in Fig. 1. The cyclone separator consists of an axial guide vane, annular space, separation space, dust hopper and vortex finder. The diameter of the cyclone is 250 mm. The diameter and thickness of the exhaust pipe are 154 mm and 7 mm, respectively. A novel vortex finder was designed, named slotted vortex finder (SVF, as shown in Fig. 1(a)). There are 20 slots on the slotted vortex finder, connecting flow fields in vent pipe and annular space. The ratio of slots area to vortex-finder-inlet area is 2.7. The structure of slots was specially designed and the most important thing is that the direction of the slots differs from that of swirling flow in annular space. To examine the effects of slotted vortex finders, the conventional shape vortex finder (CVF) was adopted, as shown in Fig. 1(b). The dimensions of the CVF are the same with the ones of the SVF, but there are no slots on the CVF.

In this study, multi-block structured hexahedral grids were generated in the entire domain of the cyclone as shown in Fig. 2, and the grids are parallel to the flow direction. The mesh independent analysis of the axial-inlet cyclone has been conducted in this study. And the SVF separator mesh design of 397,632 nodes and CVF separator mesh design of 358,272 nodes have been chosen for performing simulation of the axial-inlet separators.

2.4. Boundary conditions and simulation strategy

A "velocity inlet" boundary condition was used at the cyclone inlet, and the inlet velocity was 23 m/s (flow rate 2400 m^3/h). The boundary condition at the outlet was set as Outflow. Outflow condition assumes the fully developed flow at the outlet section. No-slip conditions are set at the wall. For the grid nodes near the wall, the wall function was applied. The air density of 1.225 kg/m^3 and the viscosity of 1.7894×10^{-5} kg/m s were defined in this study. The solid particles density was 2700 kg/m^3, and inlet solids concentration was 1 g/m^3. The median particle diameter is approximately 10 μm, and the Maximum particle size is 39 μm and the Minimum particle size is 1 μm.

The SIMPLEC pressure–velocity coupling and Presto pressure interpolation scheme were employed as suggested by Shukla [38]. The solution of cyclone simulation was started by running the steady solver using RSTM technique, and then the unsteady option was enabled and a fixed time step size of 2×10^{-5} s was employed. The solution converged at each time step with preset scaled residuals of 1×10^{-5} as convergence criterion for all solution variables and total flow time is 6 s.

2.5. Validations

The comparisons of simulation and experimental results are illustrated in Fig. 3. The results include dimensionless tangential and axial velocity profiles at s section Z = 490 mm. The results of simulated mean axial and tangential velocity profiles show consistent agreement with the measurements. The simulation gives good predictions, demonstrating that the unsteady RSM Model can predict the gas flow distribution in the cyclone separator well.