Numerical Study of the "End of the Vortex" Phenomenon in a Hydrocyclone Separator

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Abstract. The single-phase flow field in a hydrocyclone was studied numerically using the LES turbulence model. The hydrocyclone geometry and flow conditions are in accordance with previous experimental work. An important phenomenon in cyclone operation, the "end of the vortex," observed in experiments was reproduced in the simulations, where the vortex end deviated from the vortex axis and bent to the wall of the hydrocyclone body. As the vortex end attached to the wall, its rotation (precession) was visualized by monitoring the motion of the low-pressure spot caused by the vortex core on the wall.

Keywords: hydrocyclones, computational fluid dynamics, large eddy simulation, end of the vortex
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INTRODUCTION

Reverse-flow cyclones have been used extensively for phase separations in a wide range of applications. The constructions of cyclones are fairly simple, generally categorized in two types: cylinder-on-cone design and swirl tubes [1]. The action of a cyclone is: The mixture enters the cyclone through the inlets which are constructed to cause the mixture to swirl along the inner wall and toward the dense phase outlet, i.e. the underflow outlet as shown in Figure 1 (a). The denser phase is flung onto the wall because of rotation and transported to the underflow outlet, while the lighter phase turns its axial direction, forming an inner vortex, and leaves the cyclone through the overflow outlet, also called the vortex finder. When the continuous phase is a liquid, cyclones are referred to as hydrocyclones, this is the focus of this study.

Despite their apparently simple construction, the flow fields inside are complex, so that significant research efforts have been focused on experimental and numerical studies of cyclones. However, limited by observation techniques, some detrimental phenomena, like the "end of the vortex" [1], are less studied. Recently particle tracks in a hydrocyclone were studied with high temporal and spatial resolutions [2] using the PEPT (positron emission particle tracking) technique, showing the likely presence of the "end of the vortex" and its strong effect on the particle flow. It is therefore desired to further investigate the flow pattern in this type of cyclone and to obtain a detailed understanding of this phenomenon. One approach to achieve this is computational fluid dynamics (CFD) simulations.

A number of CFD simulations have been performed to explore the capability of CFD in predicting the flow pattern, pressure drop, and separation efficiency of hydrocyclones of various geometries and under a range of operation conditions (see e.g. [3]), where one challenge is to employ a proper turbulence model to correctly mimic the effect of the turbulence in the strongly swirling, confined flows. For instance, the standard $k-\varepsilon$ turbulence model has been known to be unsuitable for highly swirling flows, giving velocity profiles in cyclones very different from those obtained in experiments. Hsieh and Rajamani [4] used a modified Prandtl mixing-length model to predict velocity profiles, which agree well with measurements using laser Doppler velocimetry (LDV).

The use of large eddy simulation (LES) turbulence model has been a break-through in CFD [5]. Based on space-filtered equations, LES solves the time-dependent Navier-Stokes equations for the mean flow and the largest eddies, while the effects of smaller eddies are modelled by using a relatively simple subgrid-scale (SGS) model, to a large extent avoiding the empiricism inherent in classical turbulence modelling. Previously, LES was considered too costly, but as computer hardware improves rapidly, LES is used increasingly. Lim et al. [6] studied the flow patterns in a hydrocyclone experimentally and computationally using particle image velocimetry (PIV) and LES turbulence model, respectively, showing good qualitative agreements between velocity vector fields. Recently, flow behaviours in gas swirl tubes were successfully simulated using LES, agreeing very well with experimental measurements [7].

In this present work, CFD simulations using LES were carried out to study the formation of the "end of the vortex" in a hydrocyclone as observed in experimental work of Chang et al. [2].

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MODEL DESCRIPTION

CFD models were built to comply with the configuration of the hydrocyclone used in the above-mentioned PEPT experiments in Ref. [2]. Figure 1 (b) and (c) show the dimensions of the hydrocyclone and grid configuration. As pointed out by Derksen [8], in order to realistically model the flow in cyclones, the solid collection chamber needs to be included. "Trimmed mesh" was deployed, which generates a nearly regular mesh in the interior and a precisely fitting mesh at the walls. The dimension of a cubic cell was 1.2 mm. The total number of cells was 331745.

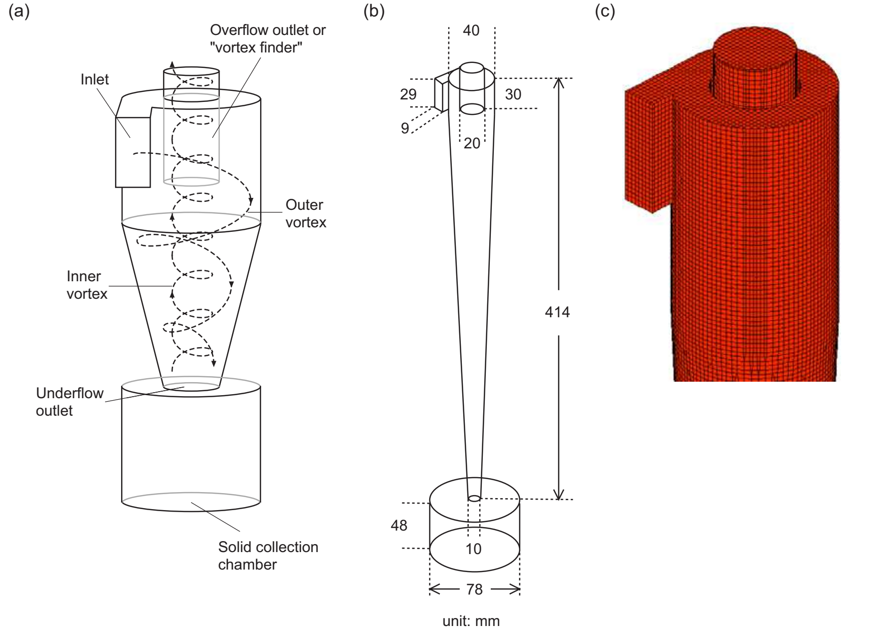

FIGURE 1. (a) Schematic cyclone separator with cylinder-on-cone design equipped with a solid collection chamber, (b) The hydrocyclone dimensions and (c) Grid configuration used in this study.

As mentioned, to simulate the highly complex, turbulent, swirling flow field in hydrocyclones, the turbulence model needs to be carefully chosen. Since LES in other work carried out by some of the present authors has proven to give results that are highly physically realistic and is able to supply values for turbulence properties that are difficult to measure, the LES turbulence model in combination with SGS model of Smagorinsky was applied in this study using the commercial CFD package Star-CD. Transient flow calculations have to be implemented. The MARS differencing scheme was applied. The SIMPLE algorithm with temporal discretization of three-time-level implicit was used.

The fluid in the hydrocyclone in the simulations was water, of which the properties were: density 997.561 kg/m^3, molecular weight 18 kg/kmol, and molecular viscosity $8.8871 \times 10^{-4}\,\mathrm{kg/ms}$. The temperature was set 293 K.

The fluid velocities that had been used in the experimental work were prescribed at the inlet boundary. The initial condition was given as no-flow. In the experiments and the simulations, the only fluid outlet was the vortex finder. The no-slip condition was used on the wall boundary. Standard wall functions were used to handle the no-slip boundary condition at wall boundaries.

Mesh convergence tests using 775488 cells were carried out to assure the validity of solutions. The time-dependent static pressure distributions simulated under same conditions did not change significantly upon such mesh refinement.

RESULTS AND DISCUSSION

The "end of the vortex" refers to the vortex spontaneously ending at some point within the cyclone body [9]. As the phenomenon occurs, the vortex end attaches to the side wall and turns around. This is known as "vortex precession," since the orientation of the vortex axis is changing. In order to observe the vortex core, the cross-sectional static pressure distributions at an inlet fluid velocity of 4 m/s (volumetric flowrate of 3.76 m^3/hr) are displayed in Figure 2. It is obvious that the vortex core is already attached to the wall as it formed. Later on the vortex end descended, varying its axial position until gradually remaining around some steady level in the cyclone body.

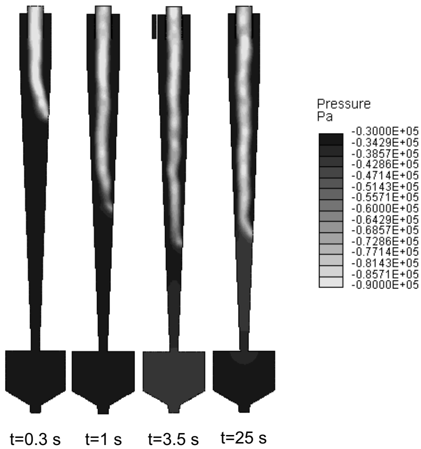

FIGURE 2. Cross-sectional contour plots of the static pressure simulated at an inlet flow rate of 4 m/s.

An important finding observed in Ref. [2] is that the tracer particle, after passing the "end of the vortex" region, continued its swirling motion, but at a much slower speed. The reason for this is that below the "end of the vortex" the particle flows in a much weaker, secondary vortex induced by the vortex core's rotation on the wall. The rotation of the vortex core is visualized in the simulations by extracting the pressure profiles on the wall as shown in Figure 3. The period of the rotation is estimated to be 14 ms, giving a frequency of 71.43 s^{-1}, which is confirmed in a long time series.

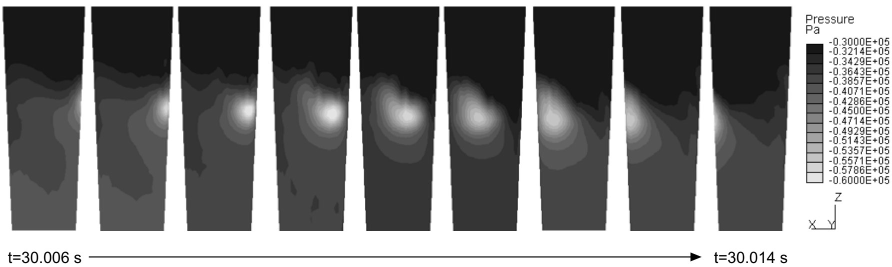

FIGURE 3. Profile plot for the pressure on the wall viewed from a fixed angle. From left to right: one graph per ms from 30.006 s to 30.014 s.

CONCLUSIONS

CFD simulations of a hydrocyclone using the LES turbulence model has been carried out to gain understanding of the "end of the vortex" phenomenon observed in experimental work of Chang et al. [2] using the PEPT technique. The numerically calculated static pressure distributions in the cross section show that the "end of the vortex" was successfully simulated, i.e. the vortex core bent from the hydrocyclone axis and attached to the wall. The axial position of attachment remained around some steady level after a few seconds of simulation. The vortex core's rotation around the inner wall was visualized and the rotation frequency was obtained by monitoring the pressure profile on the wall. The simulated flow field provides a reliable basis for further modelling of the motion of solid particles, even in the presence of the end of the vortex.

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