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Designing vortex finder structure for improving the particle separation efficiency of a hydrocyclone

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ABSTRACT

In this study, three types of vortex finder structures, namely Types A, B, and C, of 10-mm hydrocyclones were designed for improving particle separation efficiency. The Type A vortex finders had uniform but different thicknesses, and the Types B and C had extra conical shapes with different lengths on the outer surfaces. The velocity and pressure distributions in the hydrocyclones were simulated using computational fluid dynamics. The governing equations were coupled using the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm, and the second-order pressure-strain coupled with the Reynolds stress model was used in the simulations. When the liquid velocity distribution was simulated, particle trajectories were traced on the basis of a Lagrangian frame considering the hydrodynamic interactions between liquid and particles. Calcium carbonate particles with a density of 2800 kg/m^3 and a mean size of 17.8 μm were used as a particulate sample. The simulation methods were verified by comparing the simulation results with the experimental data measured using several selected hydrocyclones. The particle separation efficiencies observed using the different hydrocyclones were compared at an inlet velocity of 10 m/s and a split ratio of 0.6. A thicker vortex finder resulted in higher particle separation efficiency because a higher velocity is maintained in the cylindrical part, but it also resulted in reduced particle residence time and an increased pressure drop through the hydrocyclone. Installing conical structures on the outer surface of the vortex finders was beneficial for improving the particle separation efficiency and reducing the particle cut-size. The sequence of particle separation efficiency observed using the various hydrocyclones was Type C > Type B > Type A. Considering the separation efficiency, pressure drop, and particle cut-size simultaneously, Types B-II and C-II were the optimal designs.
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1. Introduction

A hydrocyclone is an apparatus commonly used for separating particles from dispersed liquid in mineral, environmental, and chemical engineering processes. When a suspension flows tangentially into a hydrocyclone, the rotational fluid flow generates a centrifugal force that is exerted on the particles. Large particles migrate toward the wall and are collected in the underflow, and small particles have a higher opportunity of migrating into the secondary vortex to flow out through the overflow. Because a hydrocyclone has the advantages of low investment, maintenance, and operating costs, it attracts not only process engineers but also academic researchers. However, the particle separation efficiency and cut-size sharpness should be further improved to effectively apply hydrocyclones to separation processes in fine chemistry. Because the performance of a hydrocyclone depends on numerous parameters such as particle size, operating conditions and geometric structures, designing a highly efficient hydrocyclone by using computational fluid dynamics (CFD) is an effective, economical, and timesaving approach.

CFD is a useful and reliable method for simulating the operating performance of hydrocyclones [1]. Cullivan et al. [2,3] have simulated the fluid velocity and pressure distributions and particle trajectories in hydrocyclones by using a second-order pressure-strain coupled with the Reynolds stress model (RSM) for turbulence. They have reported that a static asymmetric air-core was formed in the central part. Olson and Van Ommen [4] simulated the fluid velocity distributions and particle trajectories in different 250-mm hydrocyclones by using CFD incorporated with the Reynolds stress turbulent model. The deviations between their simulated results and experimental data were less than 35%. Narasimha et al. [5] adopted a standard k-ε turbulence model to simulate the fluid velocity and predict the particle cut-size in a 101-mm-diameter hydrocyclone at low solid concentrations. They observed an

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Nomenclature

D_{HC}	diameter of hydrocyclone (m)
D_{oo}	outer diameter of vortex finder (m)
d	particle diameter (m)
E	overall particle separation efficiency (%)
$f(d)$	particle size distribution frequency (%)
L_m	length of conical structure on the outer surface of vortex finder (m)
L_{VF}	length of vortex finder (m)
v_F	inlet velocity (m/s)
v_t	tangential velocity (m/s)
v_z	axial velocity (m/s)
w	thickness of vortex finder (m)
x,y,z	coordinates (m)

Greek letters

ΔP	pressure drop through hydrocyclone (Pa)
$\eta(d)$	partial separation efficiency of particles (–)
ϕ	split ratio (ratio of underflow to overflow) (–)

agreement between the simulated results and experimental data. Moreover, they indicated that an increase in the feed velocity or a reduction in the underflow conduit diameter could efficiently improve the separation sharpness. Wang and Yu [6,7] have used the RSM for simulating turbulent flow, the volume of the fluid model for defining the air–liquid two-phase interphase, and the stochastic Lagrangian model for simulating particle trajectories. They reported that the particle separation efficiency could be improved by reducing the hydrocyclone size or increasing the conical section length [6]. Reducing the vortex finder length engendered lower separation efficiency for fine particles but higher efficiency for coarse particles. A thinner vortex finder resulted in higher separation efficiency for coarse particles, but the pressure drop was also increased [7]. A hydrocyclone with a mantle-shaped vortex finder could reduce the pressure drop by 10% and increase the separation efficiency by 5%–10% for fine particles [7]. Hwang et al. [8–10] have studied the effects of a geometric structure parameter on the performance of 10-mm hydrocyclones by using *RFLOW* CFD software incorporated with the RSM. They indicated that the particle separation efficiency could be enhanced by reducing the overflow diameter, increasing the underflow diameter [8], increasing the inlet number [9], or installing a conical top-plate [9]. The optimum cone angle design on the top-plate was 30° [8]. Wang et al. [11] simulated a liquid–solid multiphase flow in a hydrocyclone by using an Euler-Euler approach and the RSM. They reported that increasing the conical height or reducing the cylindrical height improved the partial separation efficiency of particles.

Several novel hydrocyclones have been designed using numerical and experimental methods simultaneously [8–10,13,14]. Hwang et al. [9] and Nenu and Yoshida [12] have reported that a dual inlet could markedly increase the particle separation efficiency compared with the conventional single inlet at the same total feed rate and underflow ratio. Yang et al. [13] used two connected cones instead of the conventional single cone in a hydrocyclone design. The velocity and pressure distributions were simulated using *FLUENT* software incorporated with the RSM. The separation efficiency and sharpness could be improved using the double-cone designs. Instead of the conventional tangential-flow type, Wang et al. [14] designed an axial-flow type hydrocyclone by introducing a guide vane to accelerate the rotational flow. The CFD results of water flow by using *FLUENT* software with the RSM were verified with the measurements by using Laser Doppler Velocimetry.

In the current study, three types of vortex finder structures of 10-mm hydrocyclones were designed for improving the particle separation efficiency. The velocity distributions in different hydrocyclones were simulated using a segregated, steady-state, three-dimensional (3D) implicit numerical solver incorporated with the RSM, and the particle trajectories were simulated on the basis of a Lagrangian frame considering the interactions with a continuous phase. The effectiveness of thickening the vortex finder and installing conical structures on the outer surface of the vortex finder on the particle separation efficiency was examined.

2. Materials and methods

2.1. Structures of hydrocyclones

Hydrocyclones measuring 10 mm in diameter and containing different vortex finder structures were designed. Rectangular

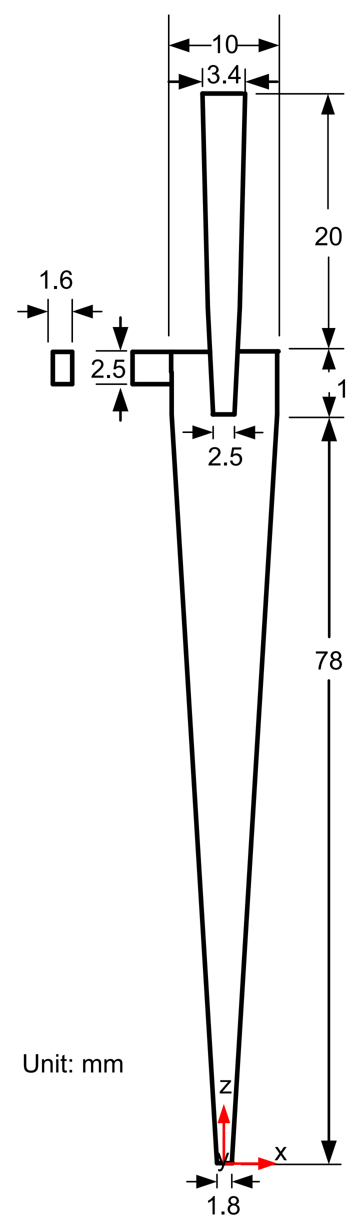

Fig. 1. Schematic diagram of the Type A-I hydrocyclone.

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