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Effectiveness of a hydrocyclone in separating particles suspended in power law fluids

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ABSTRACT

This study evaluated the separation of particles suspended in power law fluids by applying a 10 mm hydrocyclone. Al_2O_3 particles were added to an aqueous polyacrylic acid solution to prepare 0.1 vol% suspensions with different flow behaviors. The effects of operating conditions, such as the inlet velocity, pressure drop, split ratio, and fluid flow behavior, on the fluid velocity distribution, particle trajectory, and particle separation efficiency were studied. The study applied a simulation in which the governing equations were coupled using the SIMPLE algorithm; the Reynolds stress model served as a turbulence model. The distributions of the fluid velocity and pressure were simulated using a segregated, steady-state, three-dimensional implicit numerical solver provided by *ANSYS* 15.0 software. The tangential velocity increased with the flow behavior index, n, at a fixed inlet velocity and split ratio. This effect was attributed to a lower molecular viscosity. The particle trajectories were simulated using a Lagrangian frame. The particle migration in the cylindrical part of the hydrocyclone dominated the particle separation efficiency. A reduction in the fluid n-value engendered a higher effective viscosity and lower tangential velocity, which caused fewer particle rotations and lower centrifugal effects, consequently lowering the opportunity for particles to collect in the underflow. The separation efficiency increased with the inlet velocity and particle size because of a higher centrifugal effect, but the influence of the inlet velocity was extremely small for a low fluid n-value. The total separation efficiency increased by approximately 40% as the n-value increased from 0.51 to 1.00. The simulated particle separation efficiency was highly consistent with experimental data. This verified the reliability of the simulation method and the validity of this method for understanding the effects of fluid flow behavior on particle separation performance.

1. Introduction

In recent years, hydrocyclones have been increasingly used in chemical engineering, mineral, and materials manufacturing processes for separating particles from liquid dispersion media. Particles are separated mainly by the centrifugal force generated by the rotational flow of the liquid. Coarser particles move faster toward the walls, migrate into the primary vortex, and flow out through the underflow, compared with finer particles. By contrast, lower centrifugal forces are exerted on finer particles; hence, finer particles are more likely to migrate into the secondary vortex and flow out through the overflow. Using a hydrocyclone for particle-liquid separation has several advantages, such as low initial and maintenance costs, flexible capacity expansion, and easy system control and operation; therefore, this apparatus attracts not only academic researchers but also process engineers.

The performance of a hydrocyclone depends largely on its geometric structure and operating conditions. The complex phenomena occurring in hydrocyclones cause various difficulties in the design of efficient hydrocyclones and in the determination of optimal operating conditions. Hwang et al. [1] proposed separation mechanisms for describing a typical curve of partial separation efficiency. They reported that the separation efficiency of coarse particles was mainly determined by the centrifugal effect, whereas the underflow and diffusion effects played major roles in the separation efficiency of fine particles. In recent years, numerous efforts have sought to modify hydrocyclone structures and improve separation efficiency. For instance, Nenu and Yoshida [2] and Hwang et al. [3] have demonstrated numerically and experimentally that a dual inlet was more efficient for particle separation and had a more symmetric fluid flow than a single inlet. The particle cut size can be drastically reduced by using a dual-inlet hydrocyclone. Although conventional hydrocyclones have single cones, Yang et al. [4] innovated a hydrocyclone with two cones connected in series. Their numerical results revealed that a wide first cone angle led to a low fluid split ratio and high separation efficiency. A small cone angle variation between the cones improved the particle cut-size sharpness. Wang and Wang

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[5] installed a plastic rod in a 25 mm hydrocyclone and experimentally studied the effect on the pressure drop reduction. The drag reduction increased with the radial position of the rod, and their optimal rod-to-hydrocyclone size ratio was 0.068. Hwang et al. [3,6] have installed conical top plates in a 20 mm hydrocyclone to improve particle separation efficiency levels. These conical top plates effectively reduced the circulation flow near the outer surface of vortex finder and increased the centrifugal effect near the hydrocyclone wall. They determined the optimal angle of the conical top plate to be 30°, at which the cut size was reduced by 12% compared with a conventional flat-plate type.

In recent decades, substantial computational progress has enabled rapid developments in the study of hydrocyclone performance through computational fluid dynamics (CFD) [3,7]. The distributions of pressure and velocity in various hydrocyclones have been simulated numerically; several researchers have simulated fluid velocities and pressure distributions using the Reynolds stress model (RSM) and have simulated particle trajectories using a stochastic Lagrangian scheme [4,8–11]. A static asymmetrical air core has been observed in the central part of a hydrocyclone [8,9]. Wang and Yu [10] reported that the dimensions of the cylindrical part of a hydrocyclone were not essential factors affecting separation performance, and that the particle separation efficiency could be enhanced remarkably by reducing the hydrocyclone diameter or increasing the conical section length. Hwang et al. [12] examined the influence of hydrocyclone structural parameters on the performance of 10 mm hydrocyclones by using *RFLOW* software. They indicated that the particle separation efficiency was improved by reducing the overflow diameter or increasing the underflow diameter. Hwang et al. [13] designed various vortex finder structures of 10 mm hydrocyclone for improving the particle separation efficiency. They found that a thicker vortex finder resulted in higher particle separation efficiency. Hwang et al. [14] used two identical 10 mm hydrocyclone connected in series for improving particle separation efficiency. The results showed that installing a second hydrocyclone in series and operating it at a high split ratio were the optimal conditions for particle separation efficiency and energy saving. An Euler–Euler three-dimensional (3D) approach and RSM have been adopted to simulate liquid–solid flows in hydrocyclones [15,16]. The simulated results demonstrated that increasing the conical length or reducing the cylindrical length enhanced the particle separation efficiency [15]. Yang et al. [11] studied the effects of particle arrangements at the inlet of a hydrocyclone on the separation efficiency of fine particles. They determined that the separation efficiency was as high as 83% for particles with an average size of 0.53 μm when the particle size was increased from the wall to the inside of the inlet, and that short-circuit flows were eliminated by an opposite particle arrangement.

A review of previous hydrocyclone studies revealed that numerous researchers have considered separation efficiency improvements for particles suspended in water media. The separation of fine particles from non-Newtonian dispersion media is often applied in polymer manufacturing and fine chemical processes. Tavares et al. [17] investigated classification of a feed material containing a large proportion of ultrafines in hydrocyclone under varying rheological conditions. Yang et al. [18] carried out the numerical simulation about non-Newtonian rheology effect on hydrocyclone flow field. The result showed that non-Newtonian rheology has a great effect on tangential velocity. Understanding particle separation performance under such conditions is essential to extend the applications of hydrocyclones. Therefore, the current study evaluated the performance of a 10 mm hydrocyclone in separating particles suspended in power law fluids. Given that this study's focus is to understand the effects of operating conditions, such as the inlet velocity, pressure drop, split ratio, and fluid flow behavior, on the fluid velocity distribution, particle trajectory, and particle separation efficiency is subsequently investigated. The flow behavior indices and particle separation efficiency levels were determined numerically and experimentally. The velocity distributions in the hydrocyclone for various fluid behaviors were simulated using a 3D implicit numerical solver provided by *ANSYS* software. Particle trajectories were simulated using a Lagrangian frame and were used for calculating the particle separation efficiency levels. The separation efficiencies of particles suspended in various *n*-value fluids and under various operating conditions were also simulated and compared with experimental data.

2. Hydrocyclone dimensions and numerical methods

A 10 mm diameter hydrocyclone (Japan Chemical Engineering & Machinery Co., Osaka, Japan) was used for separating particles suspended in power law fluids. The structure of the hydrocyclone was similar to the authors' previous work [13]. The cylindrical part of the hydrocyclone had a length of 10 mm and a diameter of 10 mm, and it connected to a conical part having a length of 78 mm. The inner diameters for underflow and overflow were 2.0 and 2.5 mm, respectively. A vortex finder was installed into the cylindrical part at a depth of 10 mm. A rectangular inlet with a width of 2.5 mm and height of 1.6 mm was connected tangentially to the top cylindrical part. In the simulation, a Cartesian coordinate system was selected. The origin was located at the center of the underflow outlet plane. Fluid flowed into the hydrocyclone from the inlets in the –*x*- direction and flowed out from the overflow and underflow in the *z*- and –*z*- directions, respectively.

The *ANSYS* 15.0 CFD software package was used for simulating fluid flows and particle migrations in the hydrocyclone. In the pretreatment process, the hydrocyclone geometry and 3D meshes were established using *Gambit* 2.4 software. An unstructured Tet/Hybrid mesh type was used, and denser meshes were created near the walls, inlet, underflow, and overflow. The mesh sizes were approximately 1.6×10^5, and the orthogonalities of grid lines, aspect ratio, and connectivity of grids were autochecked. In the numerical process, the fluid velocity and pressure were simulated using a segregated, steady-state, 3D implicit numerical solver. The governing equations of material and momentum balances were coupled using the SIMPLE algorithm. The RSM was applied as a turbulence model. The difference between Newtonian and non-Newtonian fluid is according to the viscosity changed with the shear rate. The related parameters of viscosity of non-Newtonian power law model fluid can be set in the viscosity parameters setting of non-Newtonian power law. Nonslip conditions were selected on all solid walls. The other boundary conditions included uniform velocity at the inlet and flow rate weightings of the underflow and overflow. The criteria of convergence were set as the residuals of continuity and velocity being below 10^{-5}.

The properties of fluids and particles were set equal to the properties of those fluids and particles used in the physical experiments. Particles at the inlet were simulated as a uniform distribution. The particle trajectories were simulated using a Lagrangian frame by considering their interactions with neighboring fluids at a dilute particle concentration of 0.1 vol%. The particle separation efficiency was evaluated according to the mass fraction of particles collected into the underflow.

3. Materials and experimental methods

Polyacrylic acid (PAA) (Sigma-Aldrich; CAS No.: 9003-01-4; USA) was used for preparing power law dispersion media. Its mean molecular weight was 450 kDa. For a power law fluid, the molecular viscosity is a function of the shear rate at a given temperature and can be expressed as follows:

$$\mu = K\dot{\gamma}^{n-1} \tag{1}$$

where $\dot{\gamma}$ is the shear rate, and K and n are the fluid consistency index and flow behavior index, respectively. PAA was dissolved in deionized water (density = 998.2 kg/m^3) to prepare power law fluids; the relationships between PAA concentration and the indices of flow behavior at 293 K are summarized in Table 1. The PAA aqueous solutions were shear-