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# Numerical study on the relationship between high sharpness and configurations of the vortex finder of a hydrocyclone by central composite design

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## HIGHLIGHTS

- A new parameter of evaluation of separation sharpness has been proposed.
- A model has been established to optimize the sharpness with different configurations.
- Effects of configurations of vortex finder on separation sharpness was evaluated.
- The magnitude of the effects of the configurations on sharpness was investigated.
- High sharpness was achieved with the optimal configurations of vortex finder.

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## ABSTRACT

High separation sharpness of hydrocyclones has attracted much interest with its classification becoming increasingly popular. It is well known that the separation process in hydrocyclones is always accompanied by low sharpness. Therefore, the coarse particles escape by the overflow, and the fine particles are collected through the underflow. This paper presents a numerical study of the effects of the configurations of vortex finder on the separation sharpness of a hydrocyclone. A regression model for the effect of the configurations of vortex finder on the separation sharpness was developed by the application of central composite design. The results show that among the configurations of vortex finder, the effects of the parameters on the separation sharpness follow the order: the diameter (highest) > vortex finder length > the thickness (lowest). A high separation sharpness can be achieved by an appropriate range of the diameter and vortex finder length. According to the fitted regression model, the predicted results of separation sharpness is found to be in satisfactory agreement with the observed data, and an optimal configuration is proposed for the vortex finder to achieve a higher separation sharpness. Based on this result, titanium was recycled from acid leaching tailings using a hydrocyclone with a high sharpness during titanium dioxide production through the optimization of vortex finder.

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## 1. Introduction

Hydrocyclones are widely used to separate particulates from liquids in many industries because of the advantages such as high operational reliability, low production and maintenance costs, and well adaptability to harsh conditions. Until now, the applications of hydrocyclones cover broad areas in chemical engineering, petrochemical engineering, environmental engineering, minerals engineering, and biochemical engineering. Because of the high acceleration condition created by the rotational entrance of feed suspension, large particles are separated through the underflow because of the great centrifugal force. In contrast, small particles migrate into the overflow and flow out of the hydrocyclone with most of the fluid. Because of the increasing specific demands, the design of a high-performance hydrocyclone has attracted much attention.

In recent years, as a useful method, computational fluid dynamics (CFD) has been increasingly applied to model diverse flow modules such as gas–solid bubbling fluidization [1], gas–liquid–solid reaction systems [2,3], liquid–solid sedimentation [4]. Because of a better understanding of velocity profiles and multiphase hydro-

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**Nomenclature**

| | | | |
|---|---|---|---|
| $\Phi$ | diameter of body (mm) | $E_o$ | index of separation efficiency of fine particles (%) |
| $D_i$ | diameter of inlet (mm) | $A$ | the amount of particles smaller than 25 micron separated by the overflow |
| $D_o$ | diameter of vortex finder (mm) | | |
| $D_u$ | diameter of spigot (mm) | $C$ | the amount of particles smaller than 25 micron separated by the underflow |
| $L_v$ | length of vortex finder (mm) | | |
| $V_t$ | thickness of vortex finder (mm) | $E_u$ | index of separation efficiency of coarse particles (%) |
| $L_c$ | length of cylindrical part (mm) | $B$ | the amount of particles larger than 25 micron separated by the underflow |
| $\alpha$ | included angle (°) | | |
| $k$ | number of CCD factors | $D$ | the amount of particles larger than 25 micron separated by the overflow |
| $\beta_i$ | coefficients of linear terms | | |
| $\beta_{ii}$ | coefficients of squared terms | | |
| $\beta_{ij}$ | coefficients of interaction terms | | |
| $K$ | index of separation sharpness (%) | | |

dynamics in these processes provided by CFD, some detailed optimization suggestions for improving the performance were proposed [5–7]. Taking advantage of the mathematical modeling of flow behavior in hydrocyclones based on CFD, several attempts have been made to enhance the performance of hydrocyclones by a series of structural modifications. Hwang et al. [8] studied the effects of inlet size, number of inlets, and top-plate types of novel hydrocyclones on particle separation systematically, and some suggestions in favor of fine particle separation were made. The Qian research group [9] described the comprehensive effects of structural configuration on the partial separation efficiency of hydrocyclones. Some favorable structures of hydrocyclones were recommended for the high-efficiency separation of small particles. Wang et al. [10] focused on the interrelationships between different body dimensions and the flow field in hydrocyclones. According to the numerical results, the cylindrical section of hydrocyclones played an inessential role in collecting particles. Moreover, many authors [11–13] reached a consensus that the flow field in hydrocyclones must maintain a stable state to achieve high performance over a long period. To achieve the goal of stable conditions, diverse structural optimization schemes were introduced to reduce the turbulent flow conditions of hydrocyclones [14–16].

Specifically, the effects of vortex finder configurations on the performance of hydrocyclones have been extensively studied. The Wang research group [17] carried out experiments to analyze the mechanism of vortex finder parameters on the performance of mini-hydrocyclones by phase Doppler particle analyzer (PDPA). The parameters of vortex finder were optimized for improving the light dispersed phase separation. The Wang research group [18] studied the flow conditions and performance of a hydrocyclone with different geometries of vortex finder systematically by numerical simulation. However, the magnitude of the effects of the configurations of vortex finder on separation performance was not evaluated. Hsu [19] proposed that the ratio of the vortex finder diameter to the hydrocyclone diameter might be a factor influencing the short circuit flow; however, the result was not validated. Martínez [20] demonstrated that the highest efficient length of vortex finder is 10% of the total length of hydrocyclones; nevertheless, this conclusion has certain limitations when it is applied in practice. However, to date, comprehensive studies of precise separation in hydrocyclones with different configurations of vortex finder have not been reported.

It is well known that the separation process in common hydrocyclones is always accompanied by some inherent disadvantages [21–23] such as low separation efficiency and unsatisfactory separation sharpness, because of their complex multiphase flow field [24,25]. The insufficient separation efficiency and low separation sharpness lead to subsequent retreatment, causing additional costs and material waste.

In the production process of titanium dioxide, some titanium-containing ores after the unit operation of acid leaching are discarded because of the incomplete reaction, wasting mineral resources and leading to environmental issues. Furthermore, until now, the separation of unreacted titanium from the acid leaching tailings by hydrocyclones is also accompanied with the problem of low sharpness, leading to slight recycling of titanium and loss of significant amounts of ores discarded as tailing. By analyzing the components of these acid hydrolysis residues, the particles larger than 25 micron were intended to be recycled as much as possible by the spigot, because of the presence of high amounts of unreacted titanium. Moreover, the rest of the materials composed of mostly impurities should be separated through vortex finder. Therefore, the separation sharpness in hydrocyclones should be ensured to separate the small particles (smaller than 25 micron) through vortex finder, and the rest of the particles (larger than 25 micron) are collected by spigot.

The objective of this study is to understand the effects of the structural modifications of vortex finder on the precision of particulate separation in hydrocyclones by analyzing the system of titanium recovery in acid leaching tailings. Numerical investigations were carried out systematically according to central composite design (CCD). As a result, the true functional relationships between the three structural variables of vortex finder, namely, the length, the diameter and the thickness, and the separation sharpness were established. The results are useful to design vortex finder for high separation sharpness, and good performance of hydrocyclone was achieved by response surface methodology for the high recovery of titanium.

## 2. Methodologies

### *2.1. Computational fluid dynamics*

#### *2.1.1. Simulation models*

Because of the complex multiphase flow in hydrocyclones, it is important to apply appropriate models to describe the fluid dynamics of each phase. For an incompressible fluid flow, the governing equations of continuity and balance of momentum can be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

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