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Numerical simulation and experimental study on a deoiling rotary hydrocyclone

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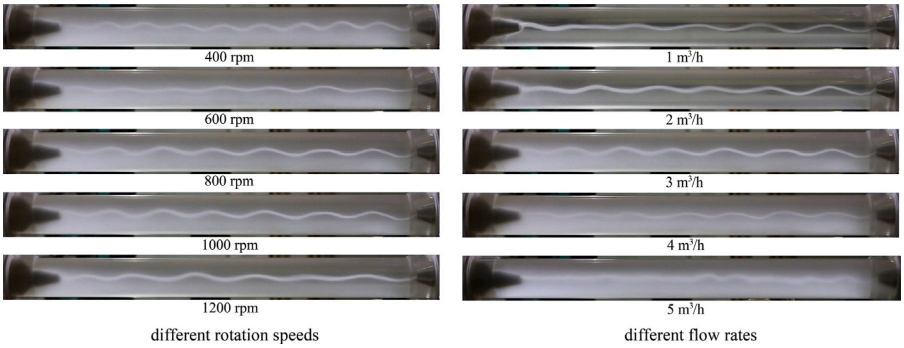
HIGHLIGHTS

- A numerical method for simulation of the flow field in RH is proposed.
- Detailed flow information from within a rotary hydrocyclone is obtained.
- The influences of rotation speed and inlet flow rate are investigated.
- An oil core phenomenon is predicted by numerical simulation and observed by experiment.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, the internal flow field and oil-water separation performance of a rotary hydrocyclone (RH) were investigated using computational fluid dynamics (CFD) simulations and experimental methods. In the numerical simulation, the turbulence was modeled by Reynolds stress model; the oil-water two-phase flow was modeled using the Algebraic Slip Mixture model; and the rotating walls were modeled by Multiple Reference Frame method. The numerical results were consistent with the experimental results. The influences of pipe wall rotation speed and inlet flow rate were also investigated. The results demonstrate that both rotation speed and flow rate have significant impacts on the velocity profile; increasing rotation speed or decreasing flow rate decrease the pressure drop and increase separation efficiency. The presence of oil core was predicted by the numerical calculations and observed in the experiment. In conclusion, the results indicate that the newly designed RH is a separator with high efficiency and wide flow rate range.

1. Introduction

Cyclones have been applied for multiphase separation for more than a century (Bradley, 2013). Cyclones were initially invented for gas-solid separation, but are currently applied for the separation of all immiscible phases: gas-liquid, gas-solid, liquid-solid, liquid-liquid, or even gas-liquid-solid mixtures. Cyclones used for the separation of particles or droplets from liquids are also known as hydrocyclones. Due to the advantages of high separation efficiency, small space requirements and low energy consumption, hydrocyclones are popularly applied in various fields such as petroleum, mineral and environmental engineering (Liu et al., 2015).

As hydrocyclones have been shown to have promising application prospects, numerous researchers have attempted to improve their performance by evaluating the effects of varying geometric and operational parameters. Various inlet designs have been tested at the inlet part of hydrocyclones. Noroozi and Hashemabadi

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(2009) found that a helical inlet can improve separation efficiency by approximately 10%; Fan et al. (2015) suggested that 30° is the optimal section angle for 35-mm mini-hydrocyclones. Ghodrat et al. (2014) and Shi et al. (2010) evaluated the effects of vortex finder dimensions on hydrocyclones through numerical simulations and found optimal parameters. The effects of cone dimension on hydrocyclone performance were also investigated in the numerical studies conducted by Saidi et al. (2013), who found that large angles increase tangential velocity but decrease efficiency. Mokni et al. (2015) showed that the pressure drop increases with increasing height (or length) of a uniflow hydrocyclone, and grade efficiency curves change significantly with length. Ghodrat et al. (2013) observed in simulations that both large and small spigot diameters may lead to poor separation performance in hydrocyclones. Silva et al. (2012) optimized the design and performance of hydrocyclones by a differential evolution technique and found the most optimal relationships of geometric parameters. Additionally, Abdollahzadeh et al. (2015) studied the influence of operational parameters such as particle shape factors, inlet velocity and feed volume concentration on the performance of hydrocyclones.

However, due to limitations inherent in conventional cyclone structure, changing geometric and operational parameters is not substantially useful in some cases. Hence, some researchers have attempted to design new cyclones based on conventional ones. Hwang et al. (2013) made certain changes to hydrocyclone inlets and top-plates, such as introducing single, dual, tetrad inlets, and different top-plates with distinct cone shapes or guide channels. The results showed that increasing the inlet number and narrowing the inlet width can effectively improve particle separation efficiency. Vieira and Barrozo (2014) designed a new hydrocyclone, termed the filtering hydrocyclone, in which the conical section of a conventional hydrocyclone was replaced by a conical filtering wall. The filtering hydrocyclone reduced Euler numbers by approximately 16% and increased efficiency by approximately 8% as compared to a conventional hydrocyclone with the same geometric parameters. Souza et al. (2015) attempted to increase the efficiency of a gas-solid cyclone by adding a post cyclone or an annular tube on the overflow duct, and the simulation results showed that the post cyclone worked well. Xu et al. (2016) improved the vortex finder structure of a guide-vane-inlet cyclone separator, leading to an increase in efficiency and decrease in the pressure drop.

However, the most significant change in hydrocyclone design should be the development of mechanisms to establish swirling flow. Hydrocyclones were initially designed with a tangential inlet to establish swirling flow (Fig. 1a); the swirling intensity can be varied by changing the cross section of the tangential inlet, and this form is the currently most commonly used. Later, axial flow cyclones were proposed in which swirling flow is maintained by guide vanes (Fig. 1b); the swirling intensity can be changed by varying the deflection angle of the guide vanes, the radial position of the vanes, and the cross section of the annular ring in which the vanes are mounted (Dirgo and Leith, 1986). However, both methods for swirling face a disadvantage stemming from the tangential velocity being closely related to the flow rate. If the flow rate is very low, the tangential velocity may be insufficient to separate the mixture; if the flow rate is too high, disturbance and the pressure drop may increase. Hence, Gay et al. (1987) designed a new type of hydrocyclone, termed a rotary hydrocyclone (RH) or dynamic hydrocyclone. RH has guide vanes and a cylindrical separation section that are both driven by an electric motor (Fig. 1c). Thereby, the tangential velocity in RHs is less sensitive to flow rate and can be controlled by the motor. RH is mainly used for liquid-liquid separation, because the density difference in a liquid-liquid mixture is much smaller than those in gas-solid or liquid-solid mixtures and more difficult to separate. Moreover, RH can provide sufficient and flexible swirling intensity. Jones (1993) compared the performance of conventional hydrocyclones and RHs in an operating oil field, and the results showed that RHs performed better and could remove smaller oil droplets from water. Furthermore, RHs operated more efficiently at lower inlet pressures than conventional hydrocyclones. Ren et al. (2007) also compared the flow fields of conventional and rotary hydrocyclones. The results showed that flow field distribution in RHs is optimized and centrifugal force is enhanced. Chen et al. (2012) studied a novel RH that contains three outlets: one for separated water, one for the oil-water mixture, and one for oil. The results showed that the RH was highly efficient and adaptable to environmental pressure changes. Chen et al. (2015) investigated the effects of the pressure drop on the separation efficiency and the split ratio of a novel RH through numerical simulation. The results showed that pressure parameters had a significant influence on RH performance and that the optimal value for the pressure drop ratio was approximately 1.3. Guo and Deng (2013) investigated oil droplet breakage and emulsification in RHs, and analyzed the forces lead to droplet breakages and the breakdown locations of oil droplet.

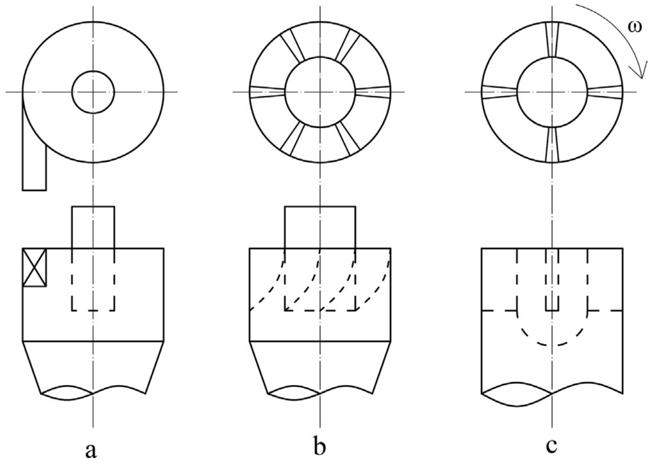

Fig. 1. Different ways to establish swirling flow.

The literature review shows that most recent studies on hydrocyclones were performed using computational fluid dynamics (CFD), which has proven to be a useful tool for predicting the flow pattern in hydrocyclones. And compared with conventional hydrocyclones, studies on RHs are considerably less abundant and less adequate. The flow pattern in RHs has not yet been deeply investigated. Therefore, the present study aims to elucidate the detailed flow information within a newly design RH by CFD simulations, introduce an appropriate numerical method for simulation of the RH, and demonstrate the oil distribution and separation performance of the RH. The velocity and pressure distribution were predicted by numerical simulation, whereas the oil distribution, pressure drop and separation efficiency were verified through experimentation. The experimental results show agreement with the calculations.

2. Structure and advantages

2.1. The geometric structure

The novel rotary hydrocyclone investigated in this study is designed for deoiling. The structural diagram of the RH is shown in Fig. 2. The main difference between the novel RH and a static hydrocyclone is that fluid enters the RH from an axial inlet, and is rotated by synchronous rotating guide vanes and a pipe (separation chamber wall) driven by a motor. Under the centrifugal force