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Development of a novel high-efficiency dynamic hydrocyclone for oil–water separation

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ABSTRACT

A dynamic hydrocyclone (DH) is a high-efficiency separator, but the oil core dispersion phenomenon was observed when the split ratio was small in the experiment. The separated oil mixed with water again and the separation failed in that case. To overcome these deficiencies and improve the performance, a novel reverse-flow DH (RDH) was designed by the inspiration of conventional hydrocyclones. The performances of the DH and RDH were investigated both experimentally and numerically. The results showed that in RDH, air bubbles and oil droplets were discharged quickly from the oil outlet, and the influence of the interferences was diminished. Thus the oil core dispersion phenomenon was avoided, and separation performance was improved. The results of numerical simulations were largely consistent with the experimental results. Furthermore, the flow field analyses indicated that the residence times of the oil droplets in two DHs are similar, while the tangential velocity in the RDH was larger than that in the DH, which leads to a higher separation efficiency.

1. Introduction

A hydrocyclone is a separator that uses physical methods to separate immiscible gases, droplets, and solid particles from liquids. Hydrocyclones are more environmentally friendly compared with separators that use other methods, such as chemical and biological ones. Furthermore, hydrocyclones can provide considerable centrifugal force which is several dozen times of gravity with a reasonably small size, leading to a relatively high efficiency. Therefore, hydrocylones have been widely applied in a variety of industrial fields, such as chemical (Cao et al., 2016; Xu et al., 2016), mineral (Zhang et al., 2017), petroleum (Rocha et al., 2017), environmental (Liu et al., 2017; Ni et al., 2016), aquacultural (Lee, 2015) and food (Altieri et al., 2015) engineering.

The density difference in liquid–liquid mixtures is smaller than that in gas-liquid and solid-liquid types. Therefore, liquid–liquid separation is considerably more difficult. However, since being first proposed in 1950s (Simkin and Olney, 1956), the liquid–liquid hydrocyclone (LLHC) has been greatly improved and widely used (Bai et al., 2011; Cao et al., 2016; Huang et al., 2017; Motin and Bénard, 2017; Shi and Xu, 2015). However, most of these hydrocyclones were developed from the classical structure proposed by Thew (1986), which had several limits inherent in its operating principles, such as the necessitating high pressure inlets to achieve a sufficient acceleration field, droplet break-up in the inlet jets at high velocity, and a loss of efficiency at low flow rate (Gay et al., 1987). Thus, Gay et al. (1987) designed a new hydrocyclone called rotary hydrocylone or dynamic hydrocylone (DH). Compared with conventional settling tanks or static cyclones, DH offers a large flexibility in flow rate and oil concentration in the treated water, a lower inlet pressure requirement, a higher separation efficiency and better adaptability to changing field operating conditions. The concept of "dynamic" is relative to conventional hydrocyclones, which have no moving parts. The flow in a DH is made to spin by vanes and/or the shell of the separation chamber which are driven by a motor; thus, the swirl intensity is irrelevant to inlet velocity or pressure.

The improved performance and operating experience of DHs were confirmed by Triponey et al. (1992) and the advantages over conventional static hydrocylones were verified in the field test by Jones (1993). The relationships between operating parameters, such as flow rate, outer shell rotation speed, and split ratio with pressure drop and efficiency were later studied by Zhao et al. (2007). The performance of a DH used for dewatering was investigated by Lv et al. (2009), whose results showed that the application of the DH in thin oil dewatering is

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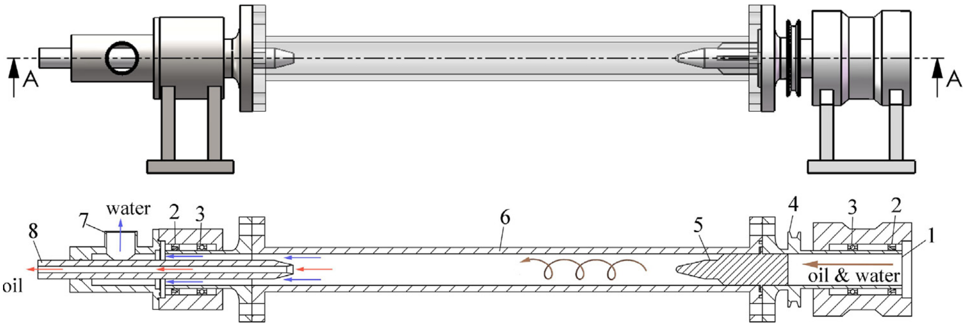

Fig. 1 – Original structure of the DH: (1) inlet; (2) sealing; (3) bearing; (4) belt pulley; (5) guide vanes and central body; (6) rotating shell; (7) water outlet; (8) oil outlet.

feasible. Li et al. (2008) studied a new type of DH, namely, a compound hydrocyclone, and deduced the calculation formula for the pressure drop and production ability. Furthermore, the effects of the pressure parameters, inlet flow rate and concentration fluctuations on the separation performance of a novel DH were investigated numerically (Chen et al., 2015; Ge and Chen, 2016). These studies have showed that DH is a promising alternative for the separation process in the chemical and petroleum industries. As a result, DH has been applied in various fields in recent years. A novel DH was developed for subsea separation of oil, water and gas, and it is a significant component of subsea boosting and processing systems (Skiftesvik and Svaeren, 2000). Chen et al. (2012) proposed a new DH with three outlets for oil–water separation in deep water, which has the advantages of both controllable rotation of the whirling cylinder and continuing separation of the oil–water mixed transitional layer. Ma et al. (2010) and Cheng (2016) each designed a DH for ship-born water treatment system and achieved satisfactory performance.

However, there remain deficiencies in the DH with conventional structure. Because the DH contains a motor and moving parts (vanes and a rotating shell), vibration is inevitable in the separation process, which is harmful for separation. Lv et al. (2010) and Zhao et al. (2007) both mentioned that vibration may affect the oil core in the DH, and even cause the failure of the oil–water separation. In our experiment, the vibration phenomenon also occurred, and oil core dispersion was observed when the split ratio was small. Thus, in this paper, we proposed a novel DH, namely, a reverse-flow dynamic hydrocyclone (RDH), to diminish the dispersion of the oil core and to improve the separation performance. The design idea and process of the RDH were introduced, and experiments were performed to compare the separation effect of the RDH with that of the DH. In addition, numerical simulations were also conducted to analyze the flow fields in two DHs, throwing light on how could the RDH improve the separation performance.

2. Original structure and deficiencies

The original structure of the DH is shown in Fig. 1. The DH has an axial inlet, and the mixture of water and oil is pumped from each tank as the feed stream to the inlet. The DH has several moving parts, namely the rotating shell and guide vanes. These parts are driven by a motor through a belt and pulley. The oil–water stream is rotated by the guide vanes and rotating shell. Thus, under centrifugal force, the oil droplets move to the center and are separated from the water. The original design is a uniflow hydrocyclone, which means that the oil outlet or overflow outlet is on the other side of the inlet, and the flow goes straight through the hydrocyclone and does not go in reverse, as shown in Fig. 1.

However, in the experiment to determine the performance of the DH, we observed several deficiencies in the original design. There were several sources of interference that may disturb the separation in the DH and even make the separation fail. One was the vibration caused by the moving parts and the motor, and another was the air bubbles or air core, which are common in hydrocyclones (Zou et al., 2016). Due to these interferences, the separation of the original DH seemed to be unstable. As shown in Fig. 2, when the split ratio was too small, the oil droplets gathered in the center of the separation chamber and were dispersed again. Because the dispersed oil droplets in the water may make the flow murky, we can infer the oil distribution from the transparency of the flow. The white ribbon is the gathered oil, or so-called “oil core” (Liu et al., 2012; Zhao et al., 2017). It can be seen that the oil core was formed after the guide vanes, but in the long path to the oil outlet, the oil core was dispersed again. Around the outlet, the oil and water were completely mixed. Furthermore, the oil concentration measurement showed that the DH could not separate oil and water at all under these circumstances.

3. Development of the novel DH

During the experiment, we noticed that the dispersion of the oil core occurred in the later half of the separation chamber, though the oil droplets had been gathered in the front half, as shown in Fig. 2. Inspired by the reverse flow hydrocyclone, we changed the oil outlet to be on the side of the inlet, as shown in Fig. 3. Thus, the gathered oil behind the guide vanes could be discharged with the reverse flow from the oil outlet. The air bubbles which disturb the separation field would also be discharged. Therefore, the oil core would not stretch too long and the dispersion could be avoided. As a result, a more stable oil core would be achieved.

The novel DH was modified from the original structure, on which only the inlet, outlet and the guide vanes were changed. A new central body was designed on which a hole was bored in the center. A thin tube was placed into the hole to act as the “vortex finder”. The oil outlet at the other side of the inlet was removed. Thus, the oil droplets gathered in the center would be discharged from the tube at the same side as the inlet. As a result, a reverse flow appeared in the center of the separation section, as shown in Fig. 3. The characteristic dimensions are also shown in Fig. 3 and Table 1.

Table 1 – The characteristic dimensions of the RDH as defined in Fig. 3.

Geometrical properties	Dimension (mm)
Diameter, D	50
Total length of rotating shell, L	800
Length of shorter side of vanes, L1	90
Length of longer side of vanes, L2	100
Diameter of the central body of vanes, Dc	30
Diameter of oil outlet, d	10