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Performance evaluation of a uniflow mini-hydrocyclone for removing fine heavy metal particles from water

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ABSTRACT

This paper presents the separation performance and liquid flow characteristics of a miniaturized uniflow hydrocyclone in removing micron and sub-micron heavy metal particles from water. This new laboratory hydrocyclone is designed based on the idea of improving the separation efficiency besides the simplifying of geometry and fluid flow. Furthermore, the hydrocyclone device is downscaled to enhance the separation of the fine particles. Instead of traditional hydrocylones, there is only one swirling flow of liquid and both outlet ports are in the same direction. Small values of Eu number disclose low energy requirement in this arrangement. The effects of feed flow rate and solid content were studied. The results show good separation efficiency ranging from 0.69 to 0.9 for varying flow rate of 15 to 45 ml/s. There is a point at which the highest separation performance is obtained besides satisfying energy consumption, determined as high-performance point of separation. Also, experiments with varying solid content from 0.1 to 4 g/l disclose that the solid content has a slight effect on separation performance, below 3 g/l but it may causes significant changes, above that solids concentration.

1. Introduction

Hydrocyclones offer advantages such as low maintenance cost, simple design, less space requirement, high capacity and high separation efficiency for industry. These devices have applications in the chemical, food, mining and oil industries (Yang et al., 2010). Hydrocyclones can be used for thickening, dewatering, classification and desliming (Cullivan et al., 2004; Delgadillo and Rajamani, 2005). This simple, useful devise has novel industrial applications, such as separation of heavy metals from products or waste (Sierra et al., 2010; Anderson et al., 1999).

Micron and sub-micron sized particles dispersed in industrial wastewater raise serious concerns about environmental health, especially for heavy metal pollutants. Studies on water and wastewater treatment (Rastogi et al., 2008; Yurdem et al., 2010; Bader, 2005) have shown that hydrocylones can be a reliable solution for this problem and has several advantages over other methods. Several studies have researched the optimization, redesign and performance of hydrocyclones. There has been great interest in the development of hydrocylone applications in the last two decades.

Despite the simple geometry of hydrocyclones, the inside flow is very complex and affects hydrocylone performance strongly (Dyakowski and Williams, 1993). There are complex interconnected flows inside the hydrocylones, including short circuits and upward and downward swirling flow. The air core inside a typical hydrocylone is strongly affected by construction parameters (apex, vortex finder and main body diameters, length of cylindrical and conical sections) and operational conditions (feed flow rate, temperature, fluctuations) that create defects in the process and making separation performance unsatisfactory (Liu et al., 2008).

Numerous works have examined structural optimization of hydrocyclones (Chu et al., 2000; Yang et al., 2011; Zhao et al., 2008). Finer particles can be separated using mini hydrocylones (with decreased

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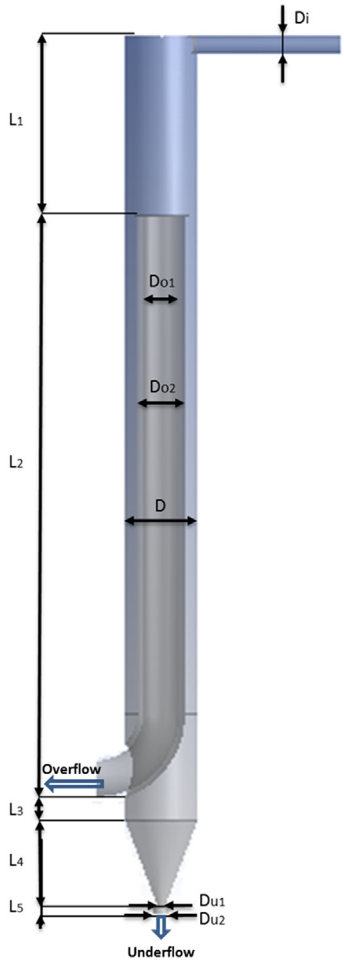
Nomenclature

C	Particle concentration ($g\,l^{-1}$)
D, Do1, Do2, Du1, Du2	Characteristic diameter of different sections of hydrocyclone (mm)
d_j	Particle diameter (μm)
d_{50}	Cut size (μm)
E	Total separation efficiency
Eu	Euler number
$f_i(d_j)$, $f_u(d_j)$	Mass fraction of particles with size ‘d_j’ in inlet and underflow
G	Grade efficiency
$H_{30/90}$	Sharpness of separation
L1, L2, L3, L4, L5	Characteristic height of different sections of hydrocyclone (mm)
m_i, m_u	Liquid mass flow rate of inlet and underflow ($kg\,s^{-1}$)
$(m_i)_{d_j}$, $(m_u)_{d_j}$	Inlet and underflow mass flow rate of particle of size ‘d_j’ ($kg\,s^{-1}$)
ΔP	Pressure drop (Pa)
Q_i, Q_u	Volumetric flow rate of inlet and underflow ($m^3\,s^{-1}$)
Re	Reynolds number
R_f	Split ratio
v	Characteristic velocity of liquid ($m\,s^{-1}$)
X50	Mean particle size (μm)

Greek letters

ρ	Liquid density ($kg\,m^3$)
μ	Liquid viscosity (Pa s)



L1 (mm)	25.00
L2 (mm)	72.00
L3 (mm)	2.50
L4 (mm)	12.50
L5 (mm)	1.00
D (mm)	10.00
Do1 (mm)	5.00
Do2 (mm)	6.60
Du1(mm)	1.00
Du2 (mm)	2.15
Di (mm)	2.90

Fig. 1 – Schematic view and dimensions of the laboratory uniflow mini-hydrocyclone.

diameters), but these face challenges in the complexity of flow and related phenomena along with the fishhook effect (Wang and Yu, 2010; Yang et al., 2013a; Niazi et al., 2017). Generally, simple geometry and provision of adequate centrifugal force for separation are the important issues in the structural design of hydrocylones.

The outlets at the two sides of a typical hydrocyclone cause development of reverse flows. A novel hydrocyclone called a uniflow was introduced by Mokni et al. (2015) and has a simple design and shows good separation performance. In this new design, both outlet pipes are in the same direction relative to the entrance of the inlet pipe and generates only one swirling flow. Many numerical and experimental studies have been done on reverse-flow hydrocylones and several models have been provided to predict separation performance. Most of these studies were done to better separate performance by considering geometrical parameters (Hwang et al., 2013) and operational conditions (Murthy and Bhaskar, 2012).

Uniflow cyclones have been the subject of experimental and numerical studies. This swirling flow can be provided by different geometrical schemes such as an axial inlet with swirl generator (Xiong et al., 2014; Valdez et al., 2015; Wu et al., 2016) and tangential inlet designs (Ogawa and Suzuki, 2001; Gauthier et al., 1990; Mokni et al., 2009a,b; Tan, 2008). Decreasing a hydrocyclone's size is known to effectively increase the separation of fine particles (Yang et al., 2013a). These have been labeled miniaturized hydrocylones, or mini-hydrocyclones.

The current study was undertaken to evaluate the performance of a uniflow mini-hydrocyclone and experimentally measure its ability for solid–liquid separation. Despite the similarity between a gas cyclone and liquid cyclone (hydrocyclone), there is a great difference in fluid flow dynamics and separation performance due to the dramatic differences in the density and viscosity of the continuous phases. Experimental studies on uniflow gas cyclones are numerous, but only three numerical studies exist on uniflow hydrocylones (Mokni et al., 2015, 2009a,b) and do not provide satisfying data for further practical applications. The newly-proposed hydrocyclone requires experimental studies to allow exact characterization, especially in small dimensions that have not been previously addressed. The aim of the current study is to probe the operation of a mini-uniflow hydrocyclone at laboratory scale in terms of energy consumption, flow split and separation performance. The effects of inlet velocity and solid content have also been considered.

2. Materials and methods

The present work consists of an experimental study on a novel uniflow mini-hydrocyclone. The basic design of this hydrocyclone comes from that by Mokni et al. (2009a), which was a redesign based on the uniflow cyclones proposed by Gauthier et al. (1990). A numerical study has been done to optimize the geometry of a uniflow hydrocyclone (Mokni et al., 2015). The configuration of the hydrocyclone in the present study corresponds to that having the best separation performance, but is 30 times smaller. Fig. 1 shows schematic views with the characteristic dimensions of the studied mini-hydrocyclone.

The mini-hydrocyclone in the experimental work was a glass handmade laboratory model with a diameter of 10 mm and a total height of 113 mm. Fig. 2 shows the products denoted as usual hydrocylones, a purified product called overflow and a concentrated product called underflow.

2.1. Materials

Heavy metals, metal oxides and metal sulfides are very in industry, especially in the refinery and petrochemical indus-

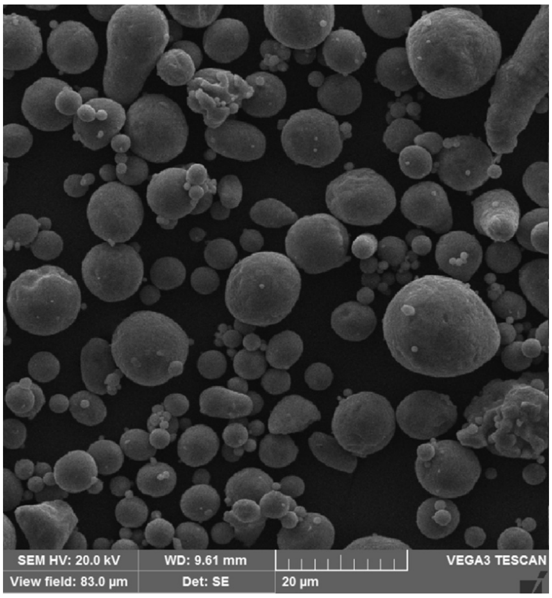


Fig. 2 – SEM image of spherical aluminum particles.

Table 1 – Properties of materials used in experiments.

Properties	Value
Particle density (kg/m^3)	2700
Mean particle size, X50, (µm)	10.6
Maximum particle size (µm)	20.1
Minimum particle size (µm)	0.1
Water density (Kg/m^3)	998.3
Water viscosity (cp)	0.89

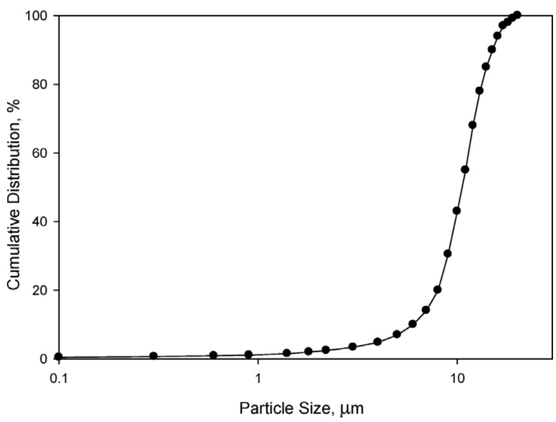


Fig. 3 – Particle size distribution of aluminum powder.

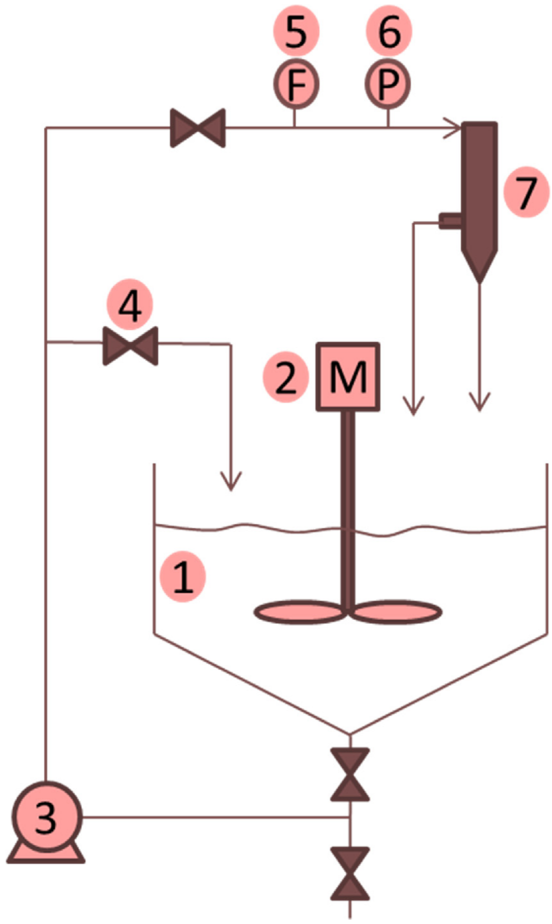


Fig. 4 – Schematic view of experimental set-up.

tries and are usually found in the wastewater. Spherical aluminum powder (Parsian; Iran) with a density of 2700 kg/m^3 was dispersed in water to simulate this condition. The powder was processed with a ball mill and classified by sieving to obtain a specific size distribution. The physical properties of the particles are presented in Table 1 and a microphotograph of the processed powder is shown in Fig. 2. The particle size distribution of the powder is presented in Fig. 3 and indicates that the particles were smaller than 20 µm with an average size of about 10 µm.

Pure water was used as the continuous phase in the experimental testing at 25 °C. Because temperature (viscosity) and density of the continuous phase are parameters effecting the separation performance of hydrocylones (Murthy and Bhaskar, 2012), these values were measured under experimental conditions and are presented in Table 1.

To study the effects of the solid content of waste water, suspensions with concentrations of 0.1, 1, 2, 3, 4 g/l were prepared and subjected to separation.

Fig. 4 is a schematic view of the experimental rig. The suspension of aluminum powder was prepared in a storage tank (1) and was stirred continuously (2). The hydrocyclone (7) was fed by a centrifugal pump (3) that provided feed flow rates of 0.015–0.045 kg/s (at seven levels). There was a recirculation line with an adjusting valve (4). The inlet flow rate and pressure were measured by a flow meter (5) with an accuracy of up to 0.1% and a digital pressure transmitter (6) with an accuracy of up to 0.05%, respectively.

2.2. *Experimental procedure*

2.2.1. *Single-phase experiments*

Tests were first conducted using pure water with no dispersed particles at room temperature. The inlet flow rate was the experimental variable (0.015–0.045 kg/s) used to study fluid flow behavior inside the hydrocyclone. The inlet flow rate was adjusted through the bypass pipeline. The inlet pressure was monitored and recorded during experimental testing. These tests were done to determine the energy consumption, flow split and effects of the solid content on the liquid medium. These experiments present an approximate operating domain at which the swirling flow is developed. The lowest flow rate (0.015 kg/s) was determined to be a steady swirling flow with a narrow air core.

2.2.2. *Solid–liquid separation experiments*

Next, 10 g of aluminum powder was dispersed in 10 l of water medium mixed continuously to homogenize completely and was pumped into the hydrocyclone inlet. After about 5 min, a stable condition was achieved during separation and the overflow and underflow were sampled simultaneously. The particle size distribution (PSD) of the products was determined in the wet phase using laser diffraction analysis employing Mie theory. The tests were all done in triplicate to determine uncertainty in the experiments. The collected products of the overflow and underflow were dried and weighed to determine the separation efficiency.

The experiments were done at six inlet flow rates at a constant solid concentration of 1 g/l to find the high-performance point for separation. Separation experiments were done with different concentrations at 0.1–4 g/l at the optimum feed flow rate determined previously to disclose the effects of solid content.

2.3. *Analytical methods*

The solid content of the inlet feed, overflow and underflow products was determined by weight. A Fritsch Analysette 22 particle size analyzer was utilized to determine the particle size distribution of the aluminum powder. The Mie theory of light scattering was used in laser diffraction analysis to calculate the particle size distribution assuming a volume-equivalent sphere model.

Scanning electron microscopy (SEM) was done using a set model Vega 3 (Tescan; Czech Republic) for graphical representation of particle shape and size distribution.

3. Results and discussion

The flow inside the hydrocyclone is usually characterized by dimensionless factors such as Reynolds number (Re), split ratio (R_f) and Euler number (Eu). These parameters are very important and effect the pressure drop (energy consumption) and separation performance of hydrocyclones. These factors are defined as follows:

$$Re = \frac{\rho v D}{\mu} \tag{1}$$

$$v = \frac{4Q_i}{\pi D^2} \tag{2}$$

$$R_f = \frac{Q_u}{Q_i} \tag{3}$$

$$Eu = \frac{\Delta P}{\frac{1}{2}\rho v^2} \tag{4}$$

where ρ is the liquid density, D is the hydrocyclone diameter, v is the characteristic velocity of the slurry stream with respect to the total flow rate and hydrocyclone diameter treating the hydrocyclone body as a pipe (Eq. (2)), Q_i is the total volumetric inlet flow rate, μ is the viscosity of the liquid, Q_u is the volumetric flow rate of the underflow product and ΔP is the pressure drop along the hydrocyclone.

The pressure drop in a hydrocyclone is defined as the pressure difference between the inlet and outlet (overflow and underflow streams in the case of equal outlet pressure or overflow pressure at different pressures). Overall, Eu denotes the energy consumption (or pumping energy requirement) and Re denotes the general properties of fluid flow and turbulence with respect to the fluid properties, geometry, and flow rate (Zhu et al., 2012).

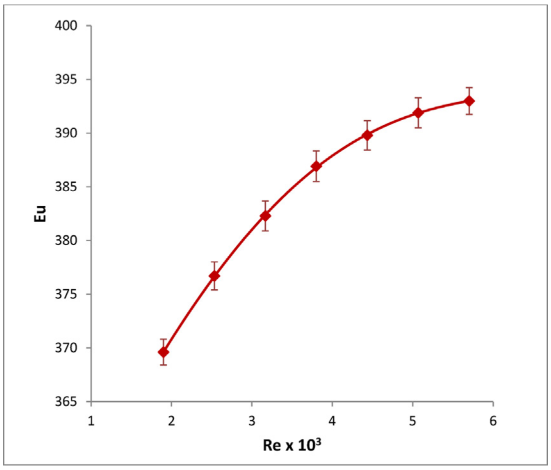


Fig. 5 – Variation of Eu number with Reynolds number of fluid flow.

3.1. *Effects of Reynolds number*

The separation performance was studied in terms of energy loss (pressure drop), split ratio, total and grade efficiency considering the effects of Re, which is known to be the most important parameter in cyclonic separation (Yang et al., 2013b).

3.1.1. *Pressure drop*

Fig. 5 shows the variation in Eu versus the Re of the water flow. The figure shows that Eu increased as Re increased. In other words, increasing the inlet flow rate (throughput) increased the pressure drop (energy loss). Reciprocally, it can be stated that a higher throughput results from an increase in the pressure drop. As this figure shows, Eu increased sharply at low Re values, but this increase flattened gradually with a further increase in Re.

3.1.2. *Split ratio*

As stated, R_f denotes the ratio of total inlet flow that comes out as underflow product. The split ratio is a major parameter in hydrocyclone separation performance. Logically, an increase in R_f increases the solid discharge with the underflow, but also leads to more liquid discharge. In some applications, additional liquid is a disadvantage (in dewatering); hence, R_f must be considered, optimized and controlled for different hydrocyclone uses. As both outlets were discharged into the atmosphere and no control valve was used on the outlet pipes, R_f varied during testing.

The split ratio values obtained at different Re values are presented in Fig. 6 for single phase tests. The figure shows that an increase in Re increased the flow split to the underflow, in contrast to the case of the reverse flow in the hydrocyclone (Murthy and Bhaskar, 2012). In other words, a stronger swirling flow formed as the inlet velocity increased, which led to a sharper pressure gradient in the radial direction. This pressure gradient drives the fluids toward the central zone. The air core enters from the underflow port strengthened because of the negative pressure in the central zone, which prevents the liquid from coming out through the underflow. For uniflow hydrocylones, the air core spreads from the overflow and its

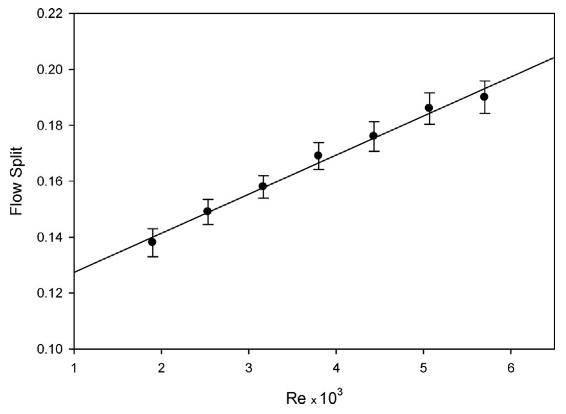


Fig. 6 – Variation of flow split with Reynolds number.

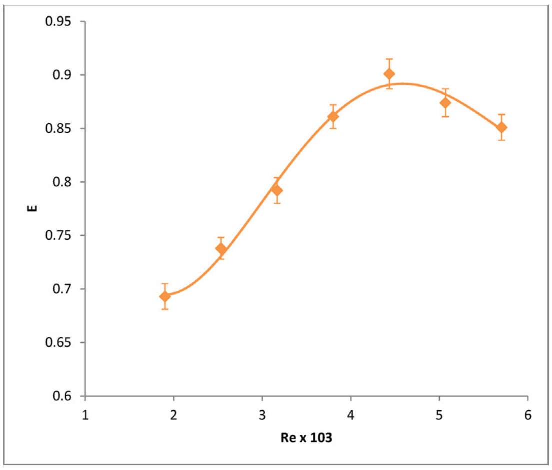


Fig. 7 – Results of separation efficiency, E, at different Reynolds numbers.

diameter grows as the inlet velocity increases and the subsequent stronger radial pressure gradient. This backflow of air sucked from the overflow port hindered the exit of the liquid through the overflow. A thicker air core formed at higher Re values from the decreased pressure in the central zone caused by higher tangential velocity, which allowed the liquid to exit through the underflow port.

3.1.3. *Total Separation efficiency*

The separation performance of a cyclone was evaluated using separation efficiency factor, *E*, which represents the fraction of total inlet solid that is separated and exits with the heavy product. The separation efficiency of a hydrocyclone is defined as the ratio of the solid contained in the heavy product (underflow) to the total amount of solid entering the hydrocyclone. Separation efficiency can be determined as:

$$E = \frac{m_u}{m_i} \tag{5}$$

where m_i and m_u are the input and output solid mass flow rate with the underflow product, respectively.

Centrifugal force is the key factor of cyclonic separation and is generated by swirling flow. Low inlet velocity values result in inadequate swirl and centrifugal force for separation. Increasing the inlet velocity (feed flow rate) provides sufficient centrifugal force but usually increases pressure loss and may cause disturbances in the swirling flow and separation (Yang et al., 2013b). It is thus necessary to find the optimum feed flow rate.

Fig. 7 shows the variation in separation efficiency versus Re (feed flow rate) at a constant solid concentration of 1 g/l. As shown, a low inlet flow rate resulted in low separation efficiency because of the inefficient centrifugal force driving the particles toward the wall. Increasing Re from 1900 to 4450 increased the separation efficiency, but Re values above 4450 (inlet flow rate of 0.035 kg/s) led to a decrease in separation efficiency with an increase in Re. A higher inlet flow rate provided a stronger centrifugal force and a greater split ratio, both of which increased the amount of exhaust particles from the underflow port. Decreasing the separation efficiency at high flow rate zone (Re > 4450) results either from a decrease in the residence time of particles inside the hydrocyclone or development of the air core and liquid streams, as in short-circuit and mantle flows in reverse-flow hydrocylones. Consequently, the turbulence increased inside the hydrocyclone, which disturbed the orderly motion of the particles (Gutierrez et al., 2000; Schwerzler, 2005).

3.1.4. *High-performance zone for separation*

Figs. 5 and 7 show the variation in *E* and Eu versus Re, respectively. As shown, when Re was small, the mini-hydrocyclone did not provide effective separation, but resulted in the lowest energy consumption (low pressure drop). At very high Re values, the highest energy consumption was observed along with inadequate separation efficiency. A zone appeared at which the maximum separation efficiency and satisfactory pressure loss were obtained. An Eu of about 390 and *E* of about 0.9 were obtained for Re values of 4000–5000. Considering this result, the feed flow rate was set to 35 ml/s, at which the highest separation efficiency was achieved for the rest of the study.

3.1.5. *Grade efficiency*

Grade efficiency is defined as the separation efficiency of each size grade of solid particles or the rate of solid recovery reported for every size grade of the particles. Grade efficiency can be determined for the size grade *j*, denoted as d_j ($j = 1, 2, \ldots, n$), as follows:

$$G\left(d_j\right) = \frac{(m_u)_{d_j}}{(m_i)_{d_j}} = \frac{m_u f_u\left(d_j\right)}{m_i f_i(d_j)} \tag{6}$$

where $G\left(d_j\right)$ is the separation efficiency of the particles of size d_j, $(m_u)_{d_j}$ and $(m_u)_{d_j}$ are the mass flow rates of the underflow outlet and feed inlet solid particles of size d_j, respectively, $f_u\left(d_j\right)$ and $f_i\left(d_j\right)$ are the mass fraction of particles of size d_i in the underflow outlet and feed inlet, respectively.

The grade efficiency demonstrates separation and classification in more detail and may be affected by the particle size distribution, feed flow rate, solid content and viscosity in a cyclonic separation. The important factors when studying the grade efficiency are cut size (d_{50}) and sharpness of separation ($H_{30/90}$). The former refers to the particle size at which the grade efficiency is 0.5 and the latter denotes the ratio of the particle size at which the grade efficiency is 30% of that at which the grade efficiency is 90%. In other words, $H_{30/90}$ represents the classification ability of the hydrocyclone.

Fig. 8 presents the grade efficiency curves for different values of Re. As this figure shows, increasing the Re number increased the grade efficiency of all size grades to the high efficiency zone (inlet flow rate of about 35 ml/s and the split ratio of 18.5%). In the high-performance condition, the cut size and $H_{30/90}$ were 4.5 μm and 26%, respectively. Beyond this point,

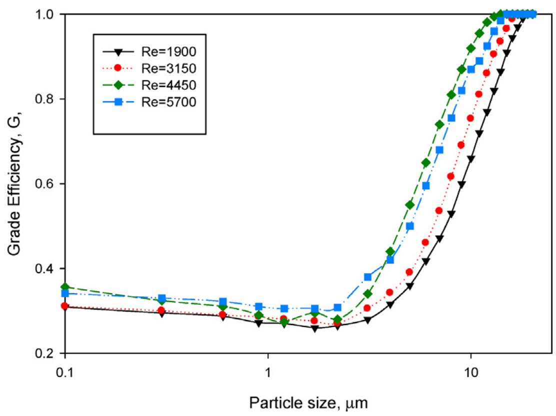


Fig. 8 – Effect of Reynolds number (flow rate) on grade efficiency curve, with a solid concentration of C = 1 g/L.

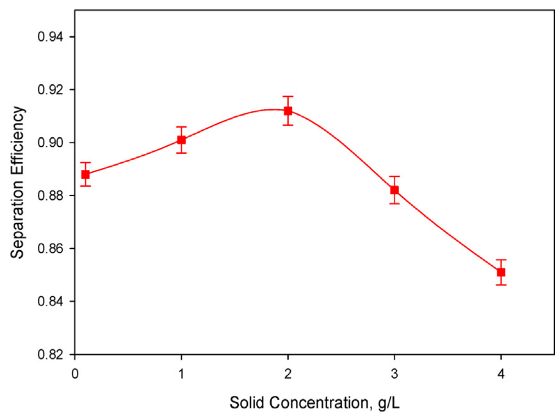


Fig. 10 – Effect of solid concentration on total separation efficiency.

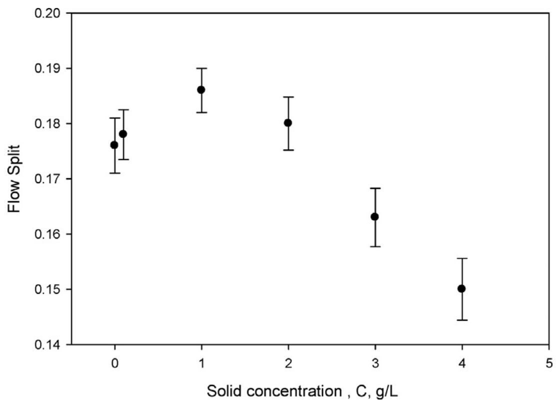


Fig. 9 – Effect of solid concentration on split ratio.

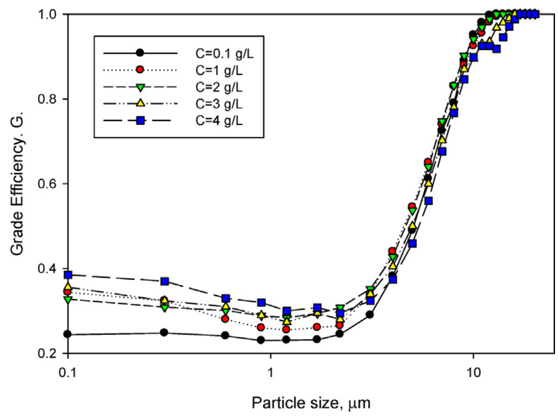


Fig. 11 – Effect of solid concentration on grade efficiency curve, at Re = 4450.

the grade efficiency curve declined for almost all grade sizes, which is consistent with the results presented in Fig. 7. Overall, the sharpness of separation and the cut size values increased as the inlet flow rate increased up to 35 ml/s and then subsided with a further increase in flow rate. In all tests, particles larger than 18 μm separated completely and increasing the feed flow resulted in complete separation of finer particles so that, in the high efficiency zone, particles larger than 12 μm separated entirely.

A relatively minor sign of the fishhook phenomenon can be observed at 0.1–3 μm in the performance curves. The fishhook effect has been studied and reported by several researchers (Zhu and Liow, 2014). These observations are not fully consistent with the numerical study of Mokni et al. (2015) in which separation efficiency appears to be overpredicted. The results indicate the effective performance of this uniflow hydrocyclone occurs in small dimensions. The high separation performance of uniflow hydrocylones can meet the industrial requirements in solid–liquid separations, especially in the pretreatment of wastewater containing heavy metal particles.

3.2. *Effects of solid concentration*

The solid content is a parameter effecting separation quality and flow features inside the hydrocylones. The effects of solid concentration were studied in terms of the split ratio and separation efficiency.

3.2.1. *Split ratio*

Fig. 9 shows the effect of solid concentration on the split ratio R_f at a Re of 4450. During the experiments, it was found that the presence of a small amount of particles in the liquid and an increase in the particle concentration up to 1 g/l increased the R_f gradually. Beyond this value, increasing the solid content had an adverse effect and decreased R_f. This can be explained by the small size of underflow outlet port, where the solid concentration was substantially higher and caused resistance to the liquid flow exiting through the underflow outlet, resulting in a lower R_f.

3.2.2. *Total separation efficiency*

Fig. 10 shows the effects of solid content on the total separation efficiency of the uniflow mini-hydrocyclone at an Re of 4450. As shown, separation efficiency increased from 0.88 to 0.91 with an increase in the solid concentration from 0.1 to 2 g/l. A further increase in solid concentration decreased the separation efficiency. The decrease in separation efficiency with an increase in the solid content from 2 to 4 g/l can be explained by the friction drag force exerted on the fluid flow by the particles, which is known as the braking effect, and led to dissipation of swirling flow (Hoffmann et al., 2002). The braking effect was negligible for dilute suspensions but was a significant factor for concentrated suspensions, especially for solid concentrations of more than 2 g/l.

3.2.3. *Grade efficiency*

Fig. 11 shows the effects of solid content on the configuration of the grade efficiency curve at an Re value of 4450. The separation curves show no major changes and the separation trends are similar. Fig. 9 shows that separation efficiency increased with as the solid content increased up to a certain value and then decreased with a further increase in the solid content.

As Fig. 11 shows, an increase in the concentration of the finest fraction of particles (particle size of 0.1–3 μm) resulted in higher grade efficiency. An increase in the solid content from 0.1 to 2 g/l could be related to the slight increase in the water split (Fig. 9), which then carries more fine particles to the underflow product. At higher concentrations, there were more large particles in suspension, which likely dragged more small particles into the underflow, through different mechanisms (e.g. aggregation of large particles or drag from the wake flow of large particles) (Kraipech et al., 2005; Zhu et al., 1994; Yao et al., 2009).

The separation efficiency of the particles 3–10 μm showed negligible dependence on the solid content, so that the grade efficiency curves are similar in the middle zone. On the other hand, grade efficiency of the largest particle fraction (particle sizes larger than 10 μm) decreased with an increase in solid content. The performance curve is deformed in this region for solid contents of 3 and 4 g/l. This can be attributed to the overload of particles in the wall vicinity that caused a barrier for separation of coarse particles, known as the hindered settling effect. This effect arises from a steep velocity gradient in adjacent wall due to the high concentration of solid particles, resulting in increased fluid flow drag force on the particles toward the center (Helland et al., 2007).

Generally, a lower concentration of solid particles results in a relatively sharper grade efficiency curve (higher values of $H_{30/90}$), which improves classification performance. The cut size, d_{50}, increased with an average increase in the solid concentration, which resulted in worse classification performance. Fig. 11 indicates that particles larger than 12 μm in size could be separated thoroughly using the uniflow mini-hydrocyclone at low concentrations.

4. Conclusion

A uniflow mini-hydrocyclone with a diameter of 10 mm was tested experimentally in the laboratory. The experiments were done to evaluate separation performance and pressure drop. These parameters were measured for different feed flow rates and solid contents. The results showed that the miniature uniflow mini-hydrocyclone has good potential for separation of micron and sub-micron particles in water and wastewater treatment.

This experimental study revealed that the uniflow hydrocyclone is highly energy-efficient because of its simple geometry and the elimination of reverse swirling flows. Satisfactory separation performance was observed in efficiency evaluation. Increasing the feed flow gradually increased the pressure drop and Eu value. Moreover, increasing the inlet flow rate increased the separation efficiency (from 69.3 to 90.1) up to a certain point, beyond which separation efficiency decreased.

The experiments in the solid content range of 0.1–4 g/l disclosed that an increase in the solid concentration up to 2 g/l increased the separation efficiency, but that a further increase in solid concentration decreased the separation efficiency. Furthermore, the solid content affected the grade efficiency curves, especially for the finest (0.1–3 μm) and the largest (10–20 μm) particles. Overall, classification performance was enhanced with an increase in the feed flow rate and decreased with an increase in the solid concentration in the study range.

The current work is the first experimental study on uniflow hydrocyclones. Further study is required in experimental and numerical forms for comprehensive understanding of the flow patterns, particle motion and separation performance of uniflow hydrocylones at the mini and large scale.

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