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Experimental study of particle separation and the fishhook effect in a mini-hydrocyclone

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ABSTRACT

The effect of inlet velocity, inlet particle size distribution, particle sphericity and particle concentration on the separation efficiency was studied with a mini-hydrocyclone of 5 mm diameter to study its performance when miniaturised. For this mini-hydrocyclone, the separation efficiency was found to increase with decreasing particle size resulting in a fishhook curve for particle diameters smaller than 15 μm. The fishhook effect was found to increase with increasing inlet velocity. The presence of large particles in the feed was found to enhance the fishhook effect supporting the hypothesis that entrainment of small particles within the wake of a large particle is the major cause of the fishhook effect. As the inlet velocity is increased, the larger particles have larger slip velocities which give rise to larger wakes that are more effective in entraining small particles, thereby enhancing the fishhook effect. Spherical particles were found to give rise to a more pronounced fishhook effect compared to non-spherical particles. A simple empirical model that accounts for the fishhook effect shows that the relative particle size and inlet velocities play a major role in effecting the fishhook effect.

1. Introduction

Hydrocyclones with $D<10$ mm are seldom used in industry although recently there has been an interest in small diameter hydrocyclones for biological and environmental applications, particularly for the separation of fine particles and cells, as well as miniaturising them for micro-device applications. This interest is due to the cut size at 50% separation efficiency (mass ratio of overflow to total flow for a particle size), the d_{50}, for a hydrocyclone decreases with decreasing hydrocyclone diameter (D); thus smaller hydrocyclones will enable finer feed streams to be fractionated (Svarovsky, 1984). A hydrocyclone with a diameter between 1 and 10 mm is defined here as a mini-hydrocyclone. Mini-hydrocyclones operate in the laminar to transition regime and provide information on the role played by the onset of turbulence on the hydrocyclone's ability to separate fine particles. An earlier numerical study of the flow field in a 5 mm mini-hydrocyclone (Zhu et al., 2012) showed that flow transition and unsteady state behaviour occurred at an inlet Reynolds number (Re_{in}) of approximately 300 leading to the onset of turbulence. An effective separation by a mini-hydrocyclone should result in a step function where coarse particles are separated to the underflow with a high efficiency followed by a sharp transition at the d_{50} value with minimal fines exiting through the underflow. This is not achieved in practice, but a typical separation efficiency curve should decrease monotonically with decreasing particle size. Zhu et al. (2012) also found that as the inlet velocity was increased, the d_{50} value decreased with a corresponding steeper separation efficiency curve.

However, experimental evidence for hydrocyclone operations has suggested that the separation efficiency of very fine particles increases with decreasing particle size below a particle size of 10 μm leading to entrainment of the fines to the hydrocyclone underflow (Pasquier and Cilliers, 2000; Majumder et al., 2003; Neesse et al., 2004; Schubert, 2004; Majumder et al., 2007). This phenomenon is known as the fishhook effect as a fishhook-shaped separation efficiency curve results in the fine particle range on a separation efficiency plot as illustrated in Fig. 1. Features of the fishhook curve include the fishhook dip (d_d) which is the particle diameter at which the minimum separation efficiency occurs, the fishhook peak (d_p) being the particle diameter at which the maximum separation efficiency occurs in the finest particle range, and the fishhook depth (h_f) being the difference in separation efficiency between the peak and the dip (Majumder et al., 2007). As the fishhook peak normally occurs at the smallest particle size measured, the fishhook depth may vary depending on the lowest cut-off size analysed. Mini-hydrocyclones are proposed to fractionate feeds in the finer particle range in micro-devices, and the fishhook effect may limit its applicability.

The fishhook effect appeared in the literature in the 1980s with evidence reported from hydrocyclone data in the minerals industry (Finch, 1983) but earlier reports originate from mechanical air

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classifiers (Beke, 1981). A short list of fishhook data for hydrocyclones found in the literature is given in Table 1. Early data on the fishhook effect are often of poor quality due to limitations in mechanical sieving with large gaps in the size fractions and poor resolution below 20 μm.

Reasons given in the literature for the existence of the fishhook effect include:

- Inaccuracies in the size analysis including poor resolution of the particle sizes and inadequate resolution of particles sizes below 38 μm (Finch, 1983; Nageswararao, 2000). Table 1 shows that for work before the 1990s, the fishhook dip was found to be above 10 μm but with the advent of laser based particle sizing, the fishhook dips are predominantly found in the 3–6 μm regime. Most of the inaccuracies in size analysis have been overcome through more precise size analysis and careful statistical analysis. Bourgeois and Majumder (2013), through a statistical analysis, ruled out the possibility of measurement error as the cause of the fishhook effect and provided arguments as to why, in certain situations, the effect has been observed to be random and sporadic.
- Different densities of the particles in the feed, particularly with complex ores and dense media effects (Finch, 1983). Rouse et al. (1987) showed that the fishhook effect still occurred for a sample of constant density pure alumina feed thus disproving this reason. Since then, most of the fishhook observations have been reported on feeds with a solid phase of constant density.
- Fines agglomerating to coarse solids (Finch, 1983; Hoffmann and Stein, 2007) and flocculation of the feed material. Gerhart (2001) (quoted by Schubert, 2004) used surface-active substances and ultrasound to prevent agglomeration and showed that the fishhook effect was still present, thus invalidating this reason as a sole cause. However, fine particles can be charged and the van der Waals forces can play a role in causing agglomeration, hence the chemistry of the particles being separated may play a significant role as the feed size distribution moves to below 10 μm.
- Entrainment of fine material in different flow regimes present in the hydrocyclone (Roldan-Villasana et al., 1993). Kraipech et al. (2005) carried out a timescale analysis and found that liquid–particle interaction played the major role in the particle interaction mechanism in most parts of the hydrocyclone except at the walls where lubrication and collisions may dominate when the solids concentration is high. Entrainment of fines with the underflow was suggested by Kelsall and Holmes (1960) and Finch (1983) modelled the entrainment component as a decreasing function of particle size but when extended to separation curves where no obvious fishhook was visible, Del Villar and Finch (1992) managed to create fishhook curves. Experimental results with a 10 mm diameter hydrocyclone by Frachon and Cilliers (1999) also showed that the fitted bypass fraction and fishhook dip were substantially higher than the water recovery to the underflow.
- Filtering effect of coarse particles on fines near the boundary layer (Austin and Klimpel, 1981; Finch, 1983). However there has not been any strong evidence of the existence of this phenomenon affecting the separation of fine particles.

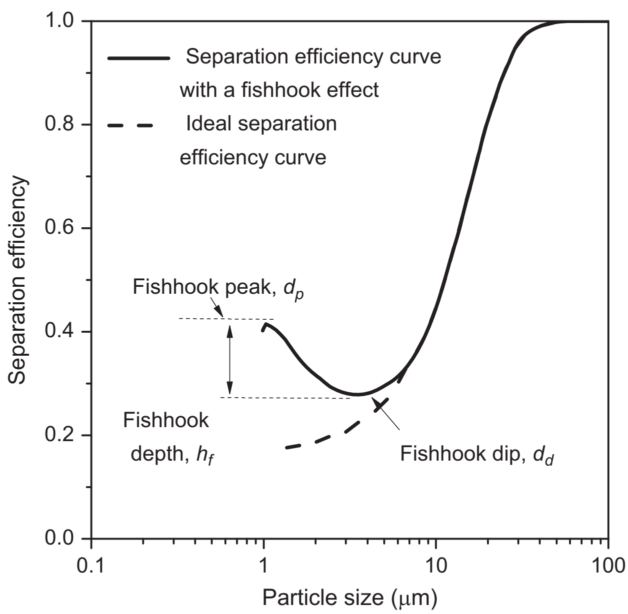

Fig. 1. The fishhook curve showing the nomenclature based on Majumder et al. (2007) with the ideal separation curve delineated by a dotted line.

Table 1
Summary of fishhook data.

Solid	Solid fraction	Solid density	Size	Cyclone diameter (mm)	Fishhook dip (μm)	Source
Zn conc. [46% Zn, 12% Fe]	0.41	N/A	71% < 75 μm	25	35	Finch (1983)
Zn conc. [8% Zn, 4% PB, 28% Fe]	0.65	N/A	30% < 38 μm	50	Not clearly delineated	Finch (1983)
Calcium silicate	1 wt%	2910 kg/m^3	d_{50} = 21 μm	44	5 – 6 μm	Lee and Williams (1993)
Silica	1.46 wt%	N/A	d_{50} = 20 μm	50	5 – 6 μm	Roldan-Villasana et al. (1993)
Silica flour	44 g/l	N/A	d_{50} = 8.5 μm	10	1.8 – 2 μm	Frachon and Cilliers (1999)
Silica flour	35 g/l	N/A	d_{50} = 8.5 μm	10	0.03 – 2 μm	Pasquier and Cilliers (2000)
Lime/water	0.6–1.4 vol%	2560 kg/m^3	d_{50} = 15 μm (est.)	100	3.4 μm	Kraipech et al. (2002)
Dust/water(I)	5.5–6.6 vol%	2820 kg/m^3	d_{50} = 20 μm (est.)	50	3.4 μm	Kraipech et al. (2002)
Glass beads/water	4.9–5.2 vol%	2500 kg/m^3	d_{50} = 3.5 μm (est.)	50	3.0 μm	Kraipech et al. (2002)
Ground quartz	1 – 4 vol%	N/A	< 50 μm [d_{50} = 9 μm] < 14 μm [d_{50} = 3.5 μm]	40	6 μm 6 μm	Neesse et al. (2004)
Quartzite	100 g/l	2650 kg/m^3	d_5 = 0.6, d_{50} = 3, d_{95} = 14 μm d_5 = 0.8, d_{50} = 11, d_{95} = 50 μm d_{95} = 5 μm	25	3.5 μm 3.5 μm None	Schubert (2004)
Clay	10% solids	2650 kg/m^3	Passing 25 μm [d_{95} ~ 15 μm]	76	None found	Udaya Bhaskar et al. (2007)
Ground magnetite	N/A	1350–1450 kg/m^3	d_{50} = 28.6 μm, passing 75 μm	76	3 – 10 μm	Majumder et al. (2007)