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Design for a Low-Pressure Hydrocyclone with Application for Fecal Solid Removal Using Polystyrene Particles

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The separation performances for thirty different dimensions of a low-pressure hydrocyclone (LPH) were tested in order to obtain an optimum dimension scale for fecal solid removal from an aquaculture system. The geometric variables were considered on two inlet diameters (Di: 30 and 50 mm), five overflow diameters (Do: 30, 50, 60, 70 and 100 mm), and three cylinder lengths (Lc: 250, 345 and 442 mm), while the cylinder diameter (Dc) of 335 mm, underflow diameter (Du) of 50 mm and cone angle (θ) of 68° were kept constant. A small size for carp feces was regarded as the target for the removal of solids. Spherical polystyrene particles (1.1-1.3 mm dia., ρ_s = 1.05 g/cm^3), which demonstrate a similar settling velocity and specific gravity to the carp feces, were used as feed. The separation performance was tested in the range of 330 to 1200 ml/s of the inflow rate. Experimental results using ANCOVA and the Tukey test (α=0.05) demonstrated that the separation performances of LPH were significantly affected ($P<0.05$) by fi, Di and Do. In contrast, there was no significant Lc effect ($P>0.05$) on the separation performances. The maximum separation performance was detected at dimension combinations of 30 mm of inflow diameter (Di), 50, 60 and 70 mm of overflow diameter (Do), 345 mm of cylinder length (Lc). The dimension proportions were 0.09, 1.03, 0.15-0.21 and 0.15 for Di/Dc, Lc/Dc, Do/Dc and Du/Dc, respectively.

Keywords: Low-pressure hydrocyclone (LPH), Separation performance, Solid-liquid separation, Fecal solid removal

Introduction

Due to their simple structure, small volume, low cost, easy operation, low maintenance and large capacity, hydrocyclones have become an important technique for solid-liquid separation (Chen et al., 2000; Chu et al., 2000; Chu et al., 2002a). Although hydrocyclones are very simple to build and use, their separation phenomena are still not properly understood. This inhibits their wider use in commercial products. According to Chen et al. (2000), the separation performance of hydrocyclones is structure-sensitive. To attain a satisfactory separation performance, a number of researchers have investigated their geometric parameters (Chu et al., 2002a; Chu et al., 2002b) and dimension scales (Medronho and Svarovsky, 1984; Chu et al., 2000). Numerical predictions for hydrocyclone liquid flow (Dyakowski and Williams, 1995; Rovinsky, 1995; Dai et al., 1999a; Dai et al., 1999b; Romero and Sampaio, 1999) and performance (Flinthoff et al., 1987; Hou et al., 1998; Frachon and Cilliers, 1999; Nageswararao, 1999a; Nageswararao, 1999b; Nowakowski et al., 2000; Deventer et al., 2003) have also been studied. To date, however, no separation theory has been proposed capable of a full and reliable description of hydrocyclone performance for modeling and practical scale up work (Firth, 2003). This is probably due to the lack of a simple procedure for an empirical, experience-based hydrocyclone design. According to Chen et al. (2000), the hydrocyclone separation performance is affected by the dimension scales of its cylinder length, its cylinder diameter, its inflow diameter, and its overflow and underflow diameters. However, there has been little data published on the geometric parameters and proportions of hydrocyclones in the treatment of aquaculture solid waste. Most of the well-known hydrocyclones, such as the Bradly (Antunes and Medronho, 1992), the Rietema (Medronho and Svarovsky, 1984), and the Krebs and Demco 4H models (Coelho and Medronho, 1992) operate with higher pressures and smaller dimension scales. For this reason, it is extremely difficult to use

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these types of hydrocyclones directly for fecal solid removal from an aquaculture system.

The aim of this study was to discover the optimum geometric dimensions for a low-pressure hydrocyclone (LPH) for fecal solid removal from an aquaculture system. Using polystyrene particles exhibiting similar densities and settling velocities as a substitute for the feces of young common carp, the study tested the separation performances for 30 different dimension combinations.

Materials and Methods

Design approach and experimental equipment

A low-pressure hydrocyclone (LPH) was developed that was capable of being operated with a lower pressure drop for aquaculture wastewater treatment. In operating the LPH, we considered water level differences for the creation of the necessary hydraulic pressure in the feed slurry tower up to 55 cm. This is within the acceptable ranges of water level differences in the IBK system (Intensive Bio-Production Korea, Kim and Jo, 1998). Fig. 1 shows the schematic drawing for the basal LPH used in the experiment. Thirty different LPH dimension combinations were tested (Table 1). The geometric variables were considered on two inlet diameters (Di: 30 and 50 mm), five overflow diameters (Do: 30, 50, 60, 70 and 100 mm), and three cylinder lengths (Lc: 250, 345 and 442 mm), while the cylinder diameter (Dc: 335 mm), the underflow diameter (Du: 50 mm) and the cone angle (θ: 68°) were all kept constant.

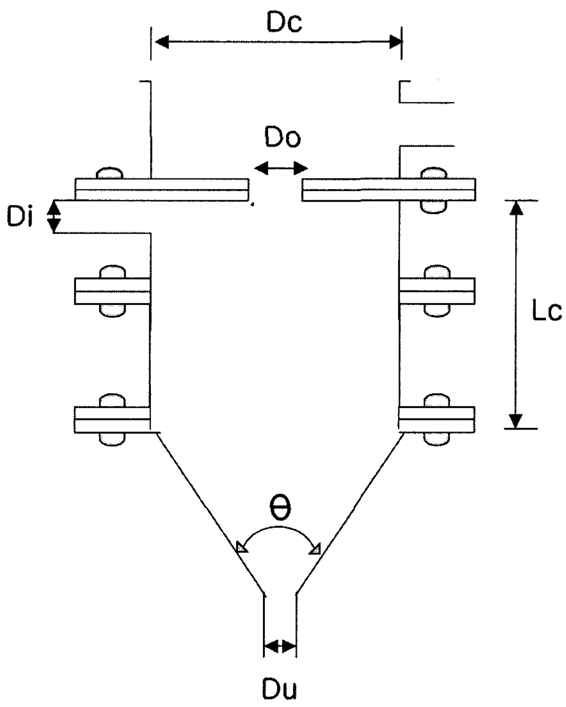

Fig. 1. Schematic configuration of low-pressure hydrocyclone (LPH); Dc, cylinder diameter; Di, inflow diameter; Do, overflow diameter; Du, underflow diameter; Lc, cylinder length; θ, cone angle.

These geometric parameter dimensions were derived from previous research (Table 2) as well as practical experience. Each of these parts was constructed of acryl to make optical observation possible for the liquid and feed particle flow patterns. We considered the comprehensive effects of the geometric dimension scale on the performance efficiency according to a differentiated inflow rate, which ranged from 330 to 1200 ml/s.

Table 1. Geometric parameters and dimensions for each apparatus of LPH

Inflow diameter (Di)	Overflow diameter (Do)	Cylinder length (Lc) S-type (250 mm)	M-type (345 mm)	L-type (442 mm)
	30	Di30S-30	Di30M-30	Di30L-30
	50	Di30S-50	Di30M-50	Di30L-50
30	60	Di30S-60	Di30M-60	Di30L-60
	70	Di30S-70	Di30M-70	Di30L-70
	100	Di30S-100	Di30M-100	Di30L-100
	30	Di50S-30	Di50M-30	Di50L-30
	50	Di50S-50	Di50M-50	Di50L-50
50	60	Di50S-60	Di50M-60	Di50L-60
	70	Di50S-70	Di50M-70	Di50L-70
	100	Di50S-100	Di50M-100	Di50L-100

All dimension combinations have the same underflow diameter (Du) of 50 mm, with a cylinder diameter of 335 mm and a cone angle of 68°.

Table 2. Geometric proportions and ranges of the hydrocyclone in other researches

Experimenter	Geometric proportion*			Reference
	Di/Dc	Do/Dc	Du/Dc	
Bradley	0.14	0.2	0.07-0.13	Castilho and Medronho (2000) Coelho and Medronho (2001)
Coelho	0.14-0.28	0.2-0.34	0.04-0.28	Coelho and Medronho (1992)
Lynch et al.	0.2-0.25	0.27-0.52	0.13-0.25	Coelho and Medronho (1992)
Plitt	0.15-0.3	0.12-0.4	0.06-0.4	Coelho and Medronho (1992)
Rietema	0.28	0.34	0.09-0.28	Castilho and Medronho (2000) Coelho and Medronho (2001)

*Di, inflow diameter; Dc, cylinder diameter; Do, overflow diameter; Du, underflow diameter.

Feed material and experiment procedure

The test feed material consisted of spherical polystyrene particles (ρ_s=1.05 g/cm^3, diameter 1.1-1.3 mm). The settling velocity of this size of particle is similar to those of the feces of young carp (avg. 15 g). The specific gravity of this material is similar to that of feces (ρ_s=1.061 g/cm^3) and suspended solids (ρ_s=1.072 g/cm^3) (Lee, 2004). Fig. 2 shows a schematic diagram of the experimental system. The volume of the holding tank was 344 liters 0.1% (v/v) of polystyrene particles were added to it. The liquid in the holding tank was pumped into the feed slurry tower, with the slurry fed tangentially through the inlet opening into the cylindrical portion of the LPH. One part of the feed stream was discharged through a circular opening pipe at the end of the conical section (underflow) and the other part was discharged out of the top of the LPH (overflow). The flow rate for the inflow and underflow were measured by the bucket-and-stopwatch-method and controlled by a set of valves. The underflow from the LPH ran into the settlement cylinder (diameter 90 mm, length 945 mm) connected to the cone spigot through a pipeline and thence returned to the holding tank. LPH overflow and underflow were filtered by a fine mesh screen to collect the polystyrene particles before their return to the holding tank. During the experiment, the slurry temperature in the holding tank was kept constant at 20°C by periodically replenishing with cool tap water. Measuring according to the inflow rate, each test was conducted for one complete holding tank turnover time.

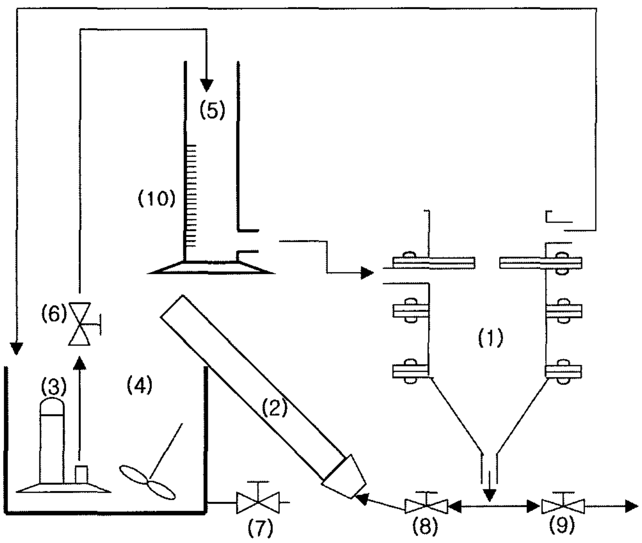

Fig. 2. Schematic diagram of the experimental apparatus; (1) hydrocyclone, (2) settlement cylinder, (3) submerged pump, (4) holding tank, (5) feed slurry tower, (6, 7, 8, and 9) valves, (10) measures.

Performance estimation

The LPH separation performance was determined by the mass separation of the feed amounts in the overflow and underflow. The feed particles in the overflow and underflow were filtered, dewatered and weighed volumetrically using the mass cylinder method. The total separation efficiency, *Et,* was calculated using the following equation:

Et (%) = Mu / (Mo + Mu) 100 (equation 1)

where, *Mo*, represents the feed amount in the overflow; *Mu*, represents the feed amount in the underflow. All these procedures were then duplicated.

In the present experiment, we wanted the flow rate of the underflow to allow for little solids to be flushed out of the settlement cylinder. For this reason, the underflow rate was set at 90-120 ml/s. The reduced separation efficiency (*E't*) was also considered in order to calibrate the effect of the bypass (*Rf*) on the separation performance. The *E't* was defined as follows:

$E't\,(\%) = \{(Et / 100 - Rf) / (1 - Rf)\}\ 100$ (equation 2)

where *Rf* represents the volume ratio of the underflow to the inflow and the *Rf* value is independent of the particle size (Frachon and Cilliers, 1999).

Abbreviated description for the LPH dimension combinations

In abbreviated form, Table 1 represents the geometric parameter and dimension combinations for 30 different LPH dimensions. To offer a specific example of the abbreviation used: Di30S-60 represents a combination of a 30 mm inflow diameter (Di), a 250 mm S-type cylinder length (Lc), and a 60 mm overflow diameter (Do), with the three fixed dimensions of a 335 mm cylinder diameter (Dc), a 50 mm of underflow diameter (Du) and a 68° cone angle.

Statistical analysis

An analysis of the covariance (ANCOVA) was conducted to detect the significance of the three factors-Di, Do and Lc-and the explanatory variable-fi (inflow rate). When a significance was discovered, a Tukey test was performed to discover the factor means differences at α=0.05 by SAS (version 6.12).

Results

Figs. 3-8 show the total and reduced separation efficiencies for the 30 different dimension combinations, according to a low inlet pressure range ranging from 80 to 390 g. The analysis results for the covariance and Tukey test are shown in Table 3. ANCOVA verified that the inflow rate (fi), the inflow diameter (Di) and the overflow diameter (Do) were individually significant (P<0.05). However, it also emerged that the cylinder length (Lc) was not significant (P=0.059). The tests also revealed that the reduced separation efficiency was slightly lower than the total separation efficiency. Nevertheless, the basic trends were the same. The LPH separation performances were also significantly (P=0.009) affected by the inflow diameter (Di). Moreover, the interactions of Di and Do, and Di and Lc were also significant (P=0.0001). According to the Tukey test, the separation performances of the dimension combina-

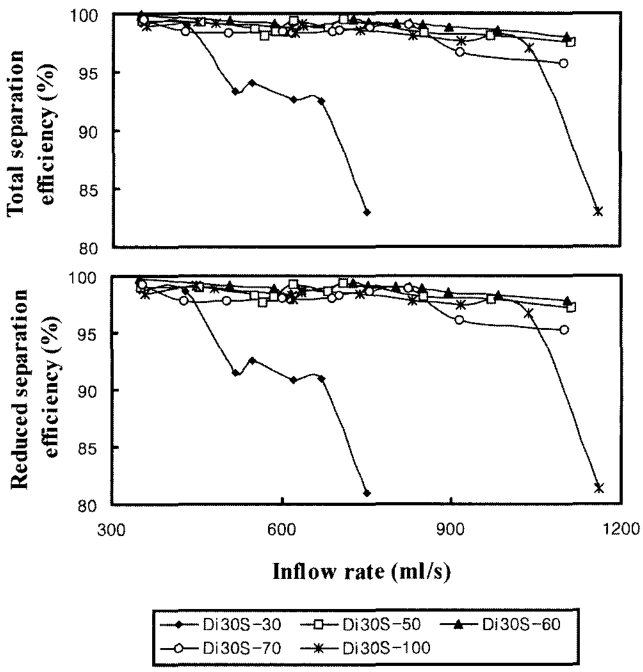

Fig. 3. Total and reduced separation efficiency for dimensions of 30 mm inflow diameter, five overflow diameters (30, 50, 60, 70, and 100 mm) and S-type (250 mm) cylinder length according to inflow rate.

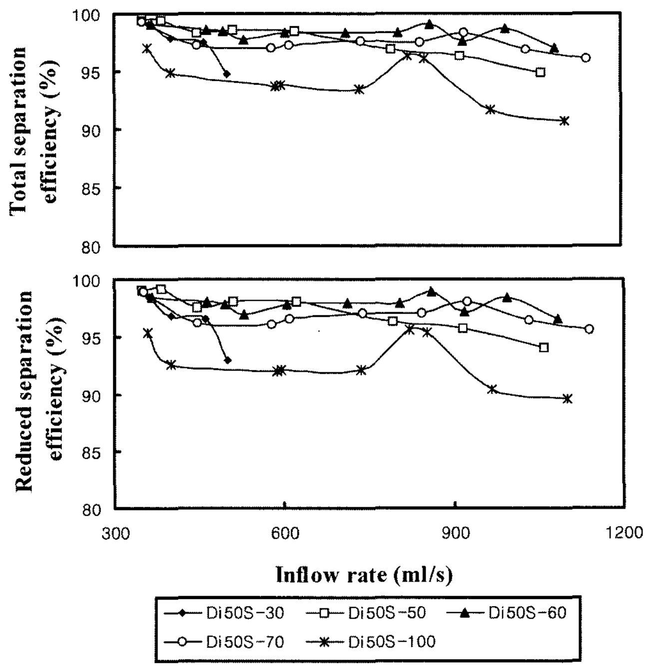

Fig. 4. Total and reduced separation efficiency for dimensions of 50 mm inflow diameter, five overflow diameters (30, 50, 60, 70, and 100 mm) and S-type (250 mm) cylinder length according to inflow rate.

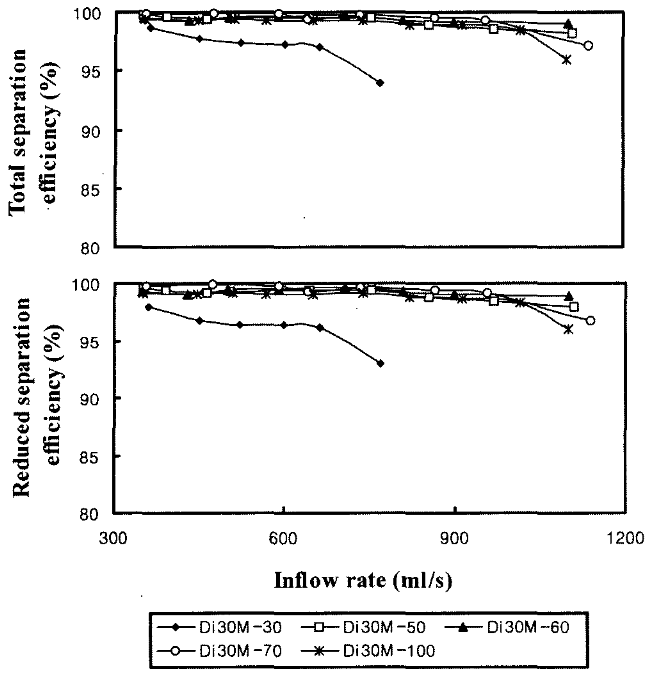

Fig. 5. Total and reduced separation efficiency for dimensions of 30 mm inflow diameter, five overflow diameters (30, 50, 60, 70, and 100 mm) and M-type (345 mm) cylinder length according to inflow rate.

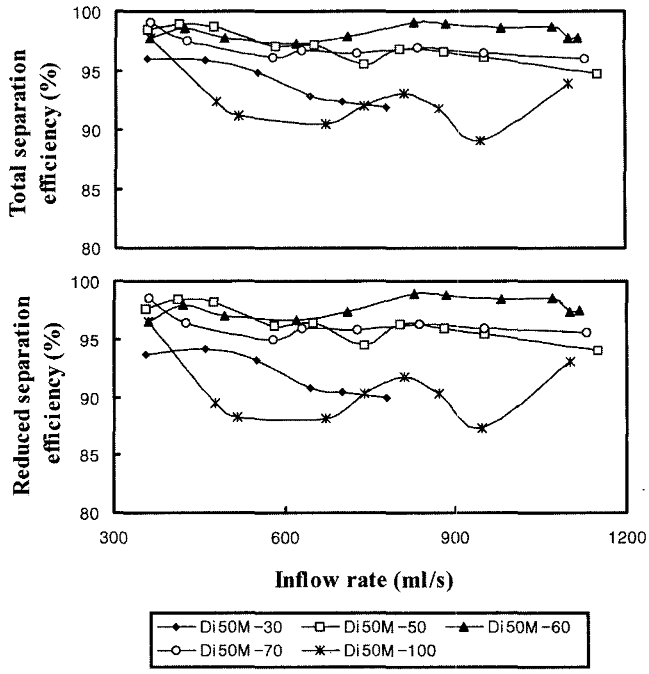

Fig. 6. Total and reduced separation efficiency for dimensions of 50 mm inflow diameter, five overflow diameters (30, 50, 60, 70, and 100 mm) and M-type (345 mm) cylinder length according to inflow rate.

tions with a 30 mm of inflow diameter (Di30 series) were significantly higher ($P<0.05$) than those of dimension combinations with a 50 mm of inflow diameter (Di50 series). This trend was more significant for the LPH dimensions with 30 and 100 mm of overflow diameter (Table 3). The separation performances in the Di50 series fluctuated according to the inflow rates (Figs. 4, 6, and 8). Most importantly, the separation performances for the Di30 series with M- and L-type of the Lc were shown to be the highest and most stable performance for all the inflow rate range (Figs. 5 and 7). For this reason, the dimension proportion with 0.09 for the Di/Dc showed a higher performance than those with 0.15 for Di/Dc.

LPH separation performances were significantly affected ($P<0.05$) by the overflow diameter (Do). The interactions of Do and Lc, and Do and fi were also significant ($P=0.0001$). The Tukey test showed that the higher separation performances were shown at 50, 60 and 70 mm of the overflow diameter (Do). This was true both in the Di30 series and the Di50 series. As the overflow diameter decreased and the inflow rate increased, the water level difference between the head

Table 3. Result of analysis of covariance (ANCOVA) and Tukey test ($\alpha=0.05$)

Source	DF	SS	Adj SS	Adj MS	F-value	P-value
fi	1	130.51	358.34	358.34	121.38	0.0001
Di	1	573.98	20.33	20.33	6.89	0.009
Do	4	540.78	75.23	18.81	6.37	0.0001
Lc	2	10.54	17.00	8.50	2.88	0.059
Di*Do	4	154.99	160.20	40.05	13.57	0.0001
Di*Lc	2	138.00	132.72	66.36	22.48	0.0001
Di*fi	1	13.17	10.13	10.13	3.43	0.066
Do*Lc	8	133.05	184.49	23.06	7.81	0.0001
Do*fi	4	207.46	211.37	52.84	17.90	0.0001
Lc*fi	2	35.85	35.85	17.93	6.07	0.003
Error	184	543.20	543.20	2.95		
Total	213	2481.53				

Factor	Level				
Di	50	30			
Do	30	100	70	50	60
Lc	250	442	345		

Di, inflow diameter; Do, overflow diameter; Lc, cylinder length; fi, inflow rate.
$R^2=0.7811$; DF, degrees of freedom; SS, sum of squares; MS, mean square; Adj $R^2=0.7466$.

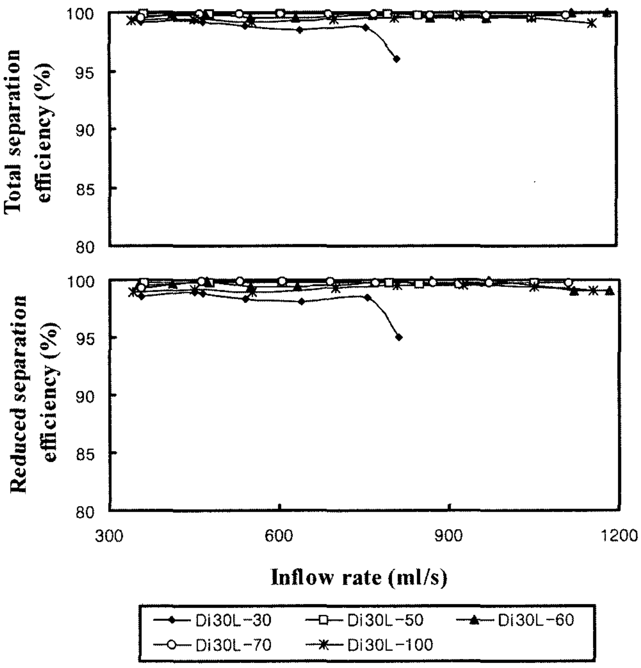

Fig. 7. Total and reduced separation efficiency for dimensions of 30 mm inflow diameter, five overflow diameters (30, 50, 60, 70, and 100 mm) and L-type (442 mm) cylinder length according to inflow rate.

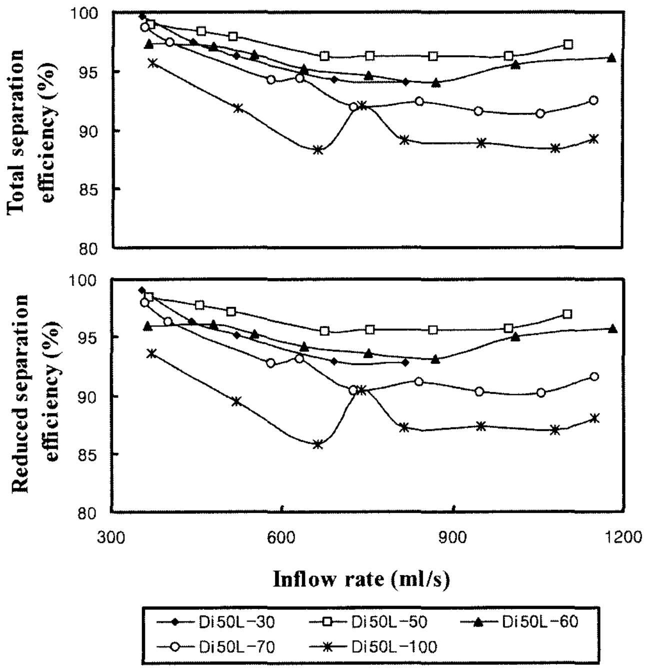

Fig. 8. Total and reduced separation efficiency for dimensions of 50 mm inflow diameter, five overflow diameters (30, 50, 60, 70, and 100 mm) and L-type (442 mm) cylinder length according to inflow rate.

of the LPH and the feed slurry tower also increased to more than 55 cm in both series. Solid flushing rates for the overflow and the g-force in the feed slurry tower in the Do30 series also rapidly increased to over 500 ml/s of the inflow rate. Most importantly, the separation performances for the dimension combinations of 50, 60 and 70 mm of Do with 30 mm of Di and M- and L-type of Lc showed the highest and most stable performance of all the inflow rate range (Figs. 5 and 7). For this reason, the optimum dimension proportions with 0.15 to 0.21 for Do/Dc showed a better performance than those with proportions under 0.09 or those with proportions over 0.30 for Do/Dc.

The ANCOVA results demonstrated that the LPH separation performances were not significantly affected ($P=0.059$) by the cylinder length (Lc). The interaction of Lc and fi was also significant ($P<0.05$). According to the Tukey test, the separation performances for 250 mm Lc and 345 mm Lc and for 345 mm Lc and 442 mm Lc were not significantly different ($P>0.05$). However, the separation performance for 345 mm Lc was slightly higher than for 442 mm Lc. Most importantly, the maximum separation performances were obtained using dimension proportions of 1.03 for Lc/Dc.

In the present experiment, the underflow diameter (Du) was 50 mm, and the dimension proportion of Du/Dc was 0.15. This is in the range of previous work (Table 2). No clogging was found in the underflow pipe.

Discussion

The polystyrene particles (ρ_s=1.05 g/cm^3) used as feed material exhibit similar settling velocities (0.72 to 1.81 cm/s) to that of the feces of young carp (Lee, 2004). Summerfelt and Timmons (2000) also used PVC cylindrical pellets (ρ_s=1.05 g/cm^3) as swirl settlers. They noted that these plastic pellets are similar in specific gravity to trout fecal matter as well as exhibiting a similar settling velocity to fecal matter (1.7-4.3 cm/s). However, in the present experiment, we required a finer substitute for the fecal matter. This is because the majority of larger fecal matter tends to settle down in the primary settlement tank basins in a recirculating aquaculture system (RAS).

Chen et al. (2000) have previously noted that poor hydrocyclone separation performance might be due to the difficulties in obtaining optimum workable dimensions for the plant operating cyclones. Many different hydocyclone geometric dimensions have been used in other fields of industry. According to Petty and Parks (2001), major diameters ranging from 10 to 30 mm for some well-known hydrocyclones have been used commercially for more than 40 years. For example, Coelho and Medronho (2001) used 7 different diameters (15-122 mm) in their experiment. These were thought to be wide enough to include most of the well-known hydrocyclone designs. For this reason, most well-known hydrocyclones have operated with small-diameter dimensions under high pressure (Table 4). After Wheaton (1977), an inlet pressure of 2500g has become acceptable for the operating of a 300 mm hydrocylone diameter. According to Rushton et al. (1996), an inlet pressure of 800g (dia. 300 mm) and 50000g (dia. 10 mm) is also common. For this reason, hydrocyclones have usually been evaluated using a higher pressure (50-150 kPa) (Asomah and Napier-Munn, 1997). In comparison with the present experiment, however, all of these values are very high. The optimum dimensions of the hydrocyclone in the present study, Di30L-60 operated with an inflow rate of 300 and 1100 ml/s with an inlet pressure of 80-390 g. for this reason, wastewater could be introduced into the separator (LPH) simply by means of the gravitational flow without using the farm's electric pump or small amounts of electricity for pumping water. This LPH hydraulic pressure, which is lower than that of the Bredly and the Rietma (Table 4), thus helps to separate fecal solids in an unbroken condition and saves on construction and management expenditure as well.

Particles experience a centrifugal force in the rotational flow field, and this is directly dependent on the tangential velocity (Statie et al., 2001). With most inflow ranges and most upper S-type cylinder length, the Di30 series achieved a higher separation performance than the Di50 series: it achieved a faster liquid tangential and axial velocity than the Di50 series. However, the Di30 series needs a much higher hydraulic pressure to treat the same mass of inflow than the Di50 series does. For similarly shaped single inlet, Castilho and Medronho (2000) and Medronho and Svarovsky (1984) have shown that the separation performance was dependent on the cyclone design, but was not affected by the relative size of the inlet orifice (Di/Dc). In the present experiment, the LPH separation performance for operating with low pressure was affected by the dimension of the inlet pipe. A 0.09 dimension proportion for the Di/Dc exhibited a better separation performance than a 0.15 Di/Dc. This Di/Dc dimension proportions are lower than those in Yuan (1992) and other previous research for high-pressure hydrocyclones (Table 2).

According to Gupta et al. (1984), high efficiency cyclones tend to have a smaller inlet area with a smaller ratio for Di/Do and a larger Dc with a ratio of Dc/Do>2. In the present experiment, geometric dimensions of Di30L-50, -60, and -70 have values of 0.6, 0.5, and 0.43 respectively for the Di/Do and 6.70, 5.58, and 4.79 respectively for the Dc/Do. These LPH Dc/Do values are somewhat higher than those for hydrocyclones in previous work (Table 2).

The overflow diameter (Do) is related to the overflow product. The separation efficiency was optically observed for the inner solids swirling diameter (SSDi) in the upward flow of the cylindrical part of the LPH. When the SSDi is smaller than the overflow diameter, the overflow product start to increase. For this reason, when the SSDi is located near the Do, the overflow product will easily be increased according to the overflow rate. In the present experiment, the velocity of the inner and outer helical flow could not be determined. By optical observation, as the inflow rate increased, the velocities of both the inner and the outer helical flow also increased. This introduces a different axial velocity to the inner and outer helical flow.

The separation performances for 345 mm of Lc were higher than for 250 mm of Lc and 442 mm of Lc. Chu et al. (2000) observed that a reduced separation efficiency increased according to the increase in the length of the cylindrical parts, which indicated that the centrifugal sedimentation in the cylindrical parts made a remarkable contribution to the hydrocyclone separation process. They also noted that the best choice for the hydrocyclone cylindrical length to achieve a high sepa-

Table 4. Range of hydrocyclone diameters, operating conditions and feed materials used in other works

Hydrocyclone	Dc (mm)	ΔP (kPa)	Cv (%)	Feed sp	ρ_s (g/cm^3)	Reference
Bradley	15-60	69-276	1-10	$CaCO_3$ Barite	2.45 3.75	Antunes and Medronho (1992)
Rietema	22-88	69-276	1-10	$CaCO_3$	2.78	Medronho and Svarovsky (1984)
Krebs	102-508	50-150	13-70	Limestone		Nageswararao (1999b)
DEMCO4H	12.2	69-172	1-10	Barite	3.75	Coelho and Medronho (1992)

Dc, cylinder diameter; Cv, feed concentration.

ration sharpness was 1.6 times the cylinder diameter (1.6Dc). This is much higher than that of the present experiment (1.03Dc).

In previous studies, the underflow diameter has not been observed to be a serious dimension parameter on the hydrocyclone separation performance (Chu et al., 2000). It seems likely that an underflow diameter of 50 mm will not create clogging and that the dimension proportion (0.15Dc) is also in the range of previous research (Table 2). The feed particles moving up and down in the underflow pipe were optically observed. They either settle down or float upward due to the central vortex flow. It is thus likely that the separation performance is influenced by the turbulence of the inner helical flow. Chu et al. (2000) improved the separation efficiency by some partial structural modification using a central insertion. This decreased the effect of the inner helical flow and reduced particle entrainment by the inner upward helical flow. Chu et al. (2002a) also improved the performance of the hydrocyclone by positively controlling the turbulence structure inside the hydrocyclone using a winged core. However, in the present experiment, no structural modification, accessories, or decant chamber capacity was required. To reduce the operating variations, the underflow rates were set at 90-120 ml/s. These underflow flow rates were determined from the optical observation of feed particle movement in the settlement chamber. With these underflow rates, the flushing overflow rate was 1.88 cm/s, and the feed particles were not flushed out from the settlement chamber. However, with variation to the inflow rate, the volume ratio of the underflow to inflow (*Rf*) can be manipulated. For this reason, the effect of *Rf* on the separation performance was observed according to the inflow rate. In the operating of the LPH, the underflow rate decreased with an increasing inflow rate and an overflow rate for the same valve operation. Frachon and Cilliers (1999) also found a simultaneous decrease in the recovery of water through underflow when the inlet pressure was increased. However, they noted that the solid concentration of the underflow was also increased. For this reason, the cone angle was decided to minimize the total height of the separator and the construction expenditure.

From the above results, the maximum separation performance for the LPH for a wide range of inflow rates (330 to 1200 ml/s) was detected at dimension combinations of Di30M-50, -60, and -70 series. This was achieved using 30 mm of inflow diameter (Di), 50, 60 and 70 mm of overflow diameter (Do), 345 mm of cylinder length (Lc), and 50 mm of underflow diameter (Du) and using dimension proportions of 0.09, 1.03, 0.15-0.21 and 0.15 for Di/Dc, Lc/Dc, Do/Dc and Du/Dc, respectively.

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