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Design of a Low-Pressure Hydrocyclone with Application for Fine Settleable Solid Removal Using Substitute Polystyrene Particles

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By testing the separation performance for a fine settleable solid removal system in an aquaculture system using polystyrene particles as an experimental substitute, the optimal geometric dimensions for a Low-Pressure Hydrocyclone (LPH) were obtained. The design approach for the LPH took into consideration two inflow diameters (Di: 30, 50 mm), three overflow diameters (Do: 60, 70, 100 mm) and four cylinder lengths (Lc: 250, 345, 442, 575 mm), while the cylinder diameter (Dc) at 335 mm, the underflow diameter (Du) at 50 mm and the cone angle (θ) at 68° were kept constant. The separation performances of 19 different dimension combinations of LPH were tested, ranging from 300 to 1200 ml/sec of inflow rate using substitute polystyrene particles (0.4-0.7 mm dia., ρ_s=1.05 g/cm^3). These polystyrene particles exhibit a similar density and settling velocity to the fine fecal debris of the common carp. The total separation efficiency for the inflow rate ranged from a high of 97% to a low of 20%. Experimental results obtained by ANCOVA and the Tukey test (α=0.05) showed that the separation performances of the LPH were significantly affected ($P<0.05$) by the fi, Di, Do and Lc. The maximum separation performance was detected at a dimension combination of 30 mm of inflow diameter (Di), 60 mm of overflow diameter (Do), 442 and 575 mm of cylinder length (Lc). The dimension proportions were 0.09, 1.32-1.72, 0.18 and 0.15 for Di/Dc, Lc/Dc, Do/Dc and Du/Dc respectively.

Keywords: Low-Pressure Hydrocyclone (LPH), Separation performance, Solid-liquid separation, Fine settleable 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., 2002). Hydrocyclones require significantly less space than conventional settling basins, providing a product with a manageable concentrate that can easily be piped away for further processing or disposal. Because of these advantages, the hydrocyclone separation technique has been widely used in the fields of mineral engineering (Mukherjee et al., 2003), environmental engineering (Pisano et al., 1990), and run-off treatment (Puprasert et al., 2004). However, to date, an understanding of the exact dimensions and operating variables for successful use of hydrocyclones in aquaculture waste treatment has been lacking. The thing that has to be considered for aquaculture wastewater treatment is the characteristics of the wastewater, the large quantity of wastewater and its very dilute concentration (Cripps and Kelly, 1996). In addition, aquaculture workers must understand the specific gravity of waste solid to water (Lee, 2004). Lee and Jo (2005) have developed a low-pressure hydrocyclone for the separation of fecal solids. This has a settling velocity ranging from 0.72 to 1.81 cm/s. This size for the target fecal solids is smaller than those obtained in other studies which employ hydrodynamics for aquaculture waste removal (Backhurst and Harker, 1989; Cripps and Bergheim, 2000; Summerfelt and Timmons, 2000). However, as the target particle size decreases, the successful utilization of hyrodcyclones for high performance requires a more sensitive calibration of dimensions and operating variables. In consequence, the objective of this study is to discover the optimum dimensions for a low-pressure hydrocyclone (LPH) for use in the removal of fine settleable solids from an aquaculture system.

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Materials and Methods

Design approach and experiment procedure

The design approach and empirical investigation was described by Lee and Jo (2005), while an LPH basal drawing of LPH experimental system was depicted by Lee and Jo

(2005). In the present experiment, two experiments were conducted using 19 different LPH dimension combinations (Table 1). In a first experiment, 18 different LPH dimensions, which had demonstrated previously good performances using larger feed particles (diameter 1.1-1.3 mm) (Lee and Jo, 2005), were re-evaluated using smaller feed particles. After the optimum dimensions for the Di and the Do were settled on, the effects of a greatly lengthened cylinder (575 mm of Lc) were tested. In the second experiment, this cylinder length was then compared with 250, 345 and 442 mm of Lc. The test feed material was spherical polystyrene particles (ρ_s=1.05 g/cm^3, diameter 0.4-0.7 mm). The settling velocity of theses particles is similar to that of the fine fecal debris of young carp, and the specific gravity of this material is similar to those of feces (ρ_s=1.061 g/cm^3) and suspended solids (ρ_s=1.072 g/cm^3) (Lee, 2004). The experimental procedure mostly followed Lee and Jo (2005), but the feed particles were mixed with 4 L of water and added into the feed slurry tower. This feed slurry was then fed into the LPH. During the feeding process, the feed slurry was vigorously stirred to keep the feed condensation constant. All these procedures were then duplicated. The total and reduced separation efficiencies were determined using the equations in Lee and Jo (2005). The separation performance for the dimension combinations of each LPH was then evaluated according to an inflow rate, which ranged from 300 to 1200 ml/s.

Abbreviated description for the LPH dimension combinations

The geometric parameters and dimension variables for the 19 different LPH dimension combinations are presented in Table 1. To offer a specific example of the abbreviation used: Di30XL-60 is used to represent 30 mm of inflow diameter (Di), 575 mm XL-type cylinder length (Lc), 60 mm of overflow diameter (Do), 50 mm of underflow diameter (Du), 335 mm of cylinder diameter (Dc) and 68° of cone angle.

Statistical analysis

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

Results

The total and reduced separation efficiencies for the 19 different geometric LPH dimensions according to the inflow rate are shown in Figs. 1-7, with the covariance analysis results (ANCOVA) and the Tukey test shown in Table 2. ANCOVA shows that the inflow rate factors (fi), the inflow diameter (Di), the overflow diameter (Do) and the cylinder length (Lc) were all individually significant ($P<0.05$). The reduced separation efficiencies (*E'ts*) were slightly lower than the total separation efficiencies (*Ets*). Nevertheless, the basic trends were the same. The LPH separation performances were significantly affected ($P=0.0001$) by the inflow diameter (Di). The interactions of the Di with the Do, the Di with the Lc, and the Di with the fi were also all significant ($P<0.05$). According to the Tukey test, the separation performances for dimension combinations using 30 mm of inflow diameter (Di30 series) were significantly higher ($P<0.05$) than were those using dimension combinations of 50 mm inflow diameter (Di50 series). The differences of the *Ets* between the Di30 series and the Di50 series ranged from a high of 52% to a low of 20%. Different curve patterns for the separation performances of the Di30 series and the Di50

Table 1. Geometric parameters and dimensions for each low-pressure hydrocyclone (LPH)

Inflow diameter (Di)	Overflow diameter (Do)	Cylinder length (Lc)			
		S-type (250 mm)	M-type (345 mm)	L-type (442 mm)	XL-type (575 mm)
30	60	Di30S-60	Di30M-60	Di30L-60	Di30XL-60
	70	Di30S-70	Di30M-70	Di30L-70	
	100	Di30S-100	Di30M-100	Di30L-100	
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°.

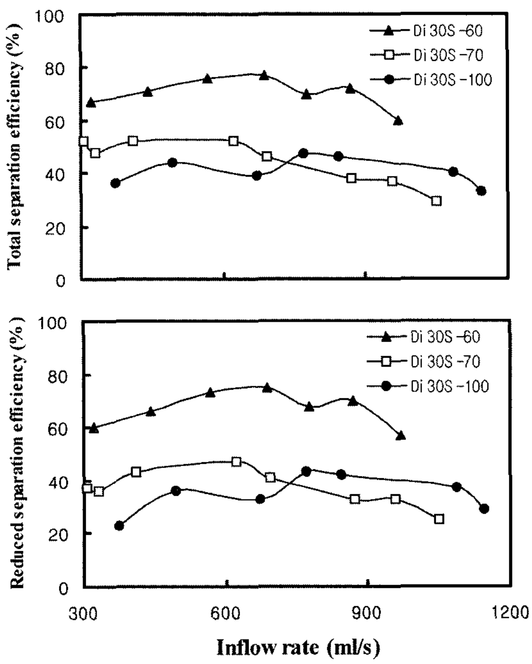

Fig. 1. Total and reduced separation efficiency for a low-pressure hydrocyclone (LPH) of 30 mm inflow diameter, three overflow diameters (60, 70, 100 mm) and 250 mm S-type cylinder length for substitute polystyrene particles (dia. 0.4-0.7 mm, ρ_s=1.05) according to inflow rate.

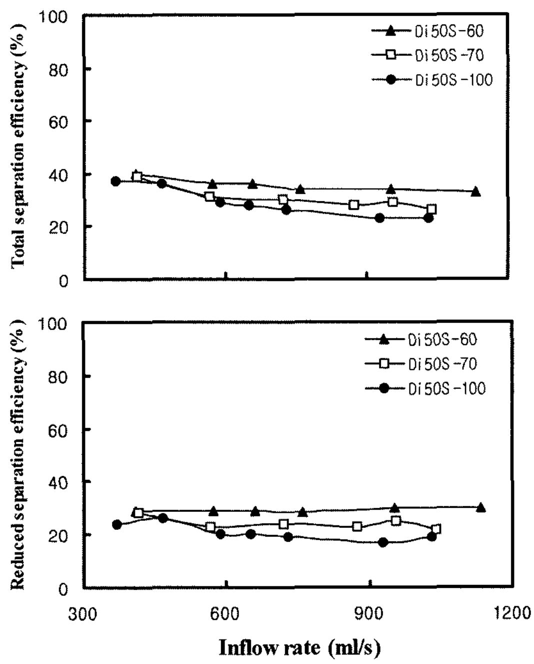

Fig. 2. Total and reduced separation efficiency for a low-pressure hydrocyclone (LPH) of 50 mm inflow diameter, three overflow diameters (60, 70, 100 mm) and 250 mm S-type cylinder length for substitute polystyrene particles (dia. 0.4-0.7 mm, ρ_s=1.05) according to inflow rate.

series were discovered according to the cylinder length (Lc) and the inflow rate. For Di30S-60, -70 and -100, the *Et*s started with the values of 67%, 48% and 36% at 322, 331 and 373 ml/s of inflow rate, respectively. As the inflow rate increased, the *Et*s were enhanced to 77%, 52% and 47% at 686, 412 and 770 ml/s of inflow rate, respectively (Fig. 1). However, at over 900 ml/s of inflow rate, the *Et*s were decreased to 60%, 29% and 40% at 969, 1051 and 1086 ml/s of inflow rate. The separation performances for the Di50S, the Di30M and the Di50M series started with higher values for the restricted inflow rate. However, as the inflow rate increased, they gradually decreased (Figs. 2-4). The Di30L series showed a similar curve pattern to that of the Di30S series. However, the values of the *Et*s of the Di30L series were significantly higher ($P<0.05$) than those for the Di30S series (Fig. 5). In other words, a dimension proportion of 0.09 for the Di/Dc showed a higher performance than that of 0.15 for the Di/Dc.

The LPH separation performances were significantly affected ($P=0.0001$) by the overflow diameter (Do). The interaction of the Do and the Lc was significant ($P<0.05$) however the interaction between the Do and the fi was not significant ($P>0.05$). The Tukey test showed that the highest separation performances were obtained at 60 mm of the over-

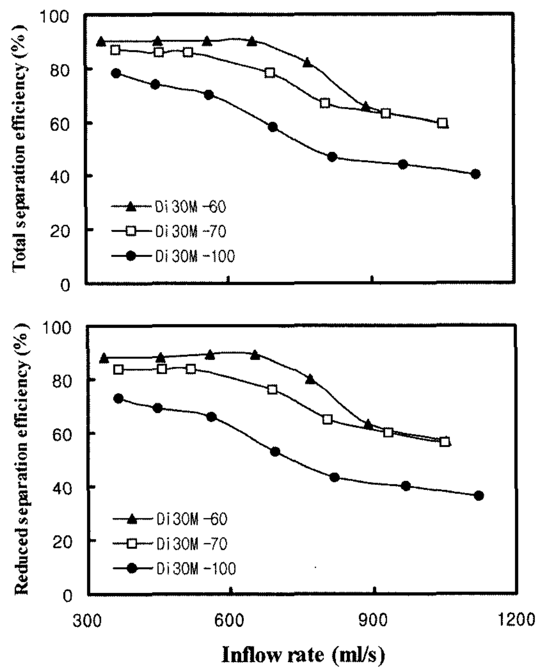

Fig. 3. Total and reduced separation efficiency for a low-pressure hydrocyclone (LPH) of 30 mm inflow diameter, three overflow diameters (60, 70, 100 mm) and 345 mm M-type cylinder length for substitute polystyrene particles (dia. 0.4-0.7 mm, ρ_s=1.05) according to inflow rate.

flow diameter (Do). For the Di30S series, the 67% *Et* of Di30S-60 at 322 ml/s of inflow rate was decreased to 48% as

Table 2. Result of analysis of covariance (ANCOVA) and Tukey test (α=0.05) in exp. 1

Source	DF	SS	Adj SS	Adj MS	F-value	P-value
fi	1	3378.8	1680.0	1680.0	42.37	0.0001
Di	1	26330.7	4355.4	4355.4	109.84	0.0001
Do	2	4890.1	770.6	385.3	9.72	0.0001
Lc	2	18010.8	1699.1	849.5	21.43	0.0001
Di*Do	4	471.0	360.4	180.2	4.54	0.013
Di*Lc	2	1560.0	1470.1	735.0	18.54	0.0001
Di*fi	1	302.5	307.5	307.5	7.75	0.006
Do*Lc	4	680.4	688.1	172.0	4.34	0.003
Do*fi	2	90.8	141.1	70.6	1.78	0.174
Lc*fi	2	1351.7	1351.7	675.8	17.04	0.0001
Error	103	4084.1	4084.1	39.7		
Total	122	61151.0				
Factor				Level		
Di		50	30			
Do		100	70	60		
Lc		250	345	442		

Di, inflow diameter; Do, overflow diameter; Lc, cylinder length; fi, inflow rate.
R^2=0.9332; DF, degrees of freedom; SS, sum of squares; MS, mean square; Adj R^2=0.9209.

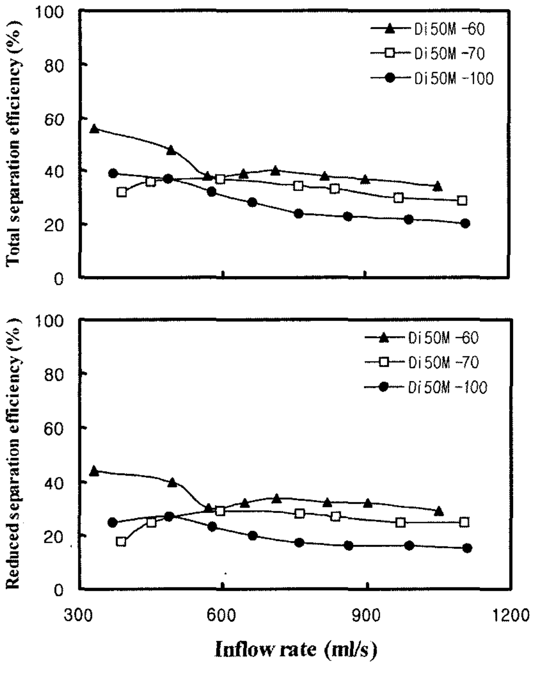

Fig. 4. Total and reduced separation efficiency for a low-pressure hydrocyclone (LPH) of 50 mm inflow diameter, three overflow diameters (60, 70, 100 mm) and 345 mm M-type cylinder length for substitute polystyrene particles (dia. 0.4-0.7 mm, ρ_s=1.05) according to inflow rate.

the Do increased to 70 mm; and to 36% when it was increased to 100 mm (Fig. 1). For the Di50M series, the 38%

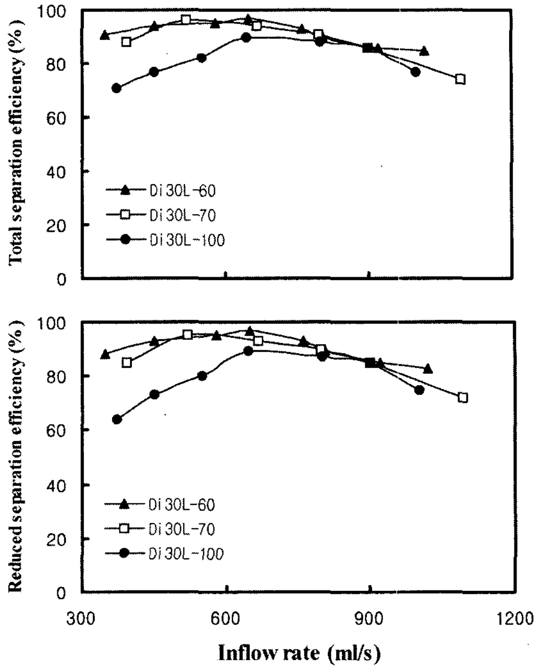

Fig. 5. Total and reduced separation efficiency for a low-pressure hydrocyclone (LPH) of 30 mm inflow diameter, three overflow diameters (60, 70, 100 mm) and 442 mm L-type cylinder length for substitute polystyrene particles (dia. 0.4-0.7 mm, ρ_s=1.05) according to inflow rate.

Et of Di50M-60 at 815 ml/s of inflow rate was decreased to 33% as the Do increased to 70 mm; and to and 23% as it was increased to 100 mm (Fig. 4). The optimum dimension of the Do showing a maximum separation performance was 60 mm, while the geometric proportions of the Do/Dc was 0.18.

The LPH separation performances were significantly affected (P=0.0001) by the cylinder length (Lc). The interaction of the Lc and the fi was also significant (P=0.0001). According to the Tukey test, the separation performances for 442 mm of Lc were significantly higher (P<0.05) than those for the other Lc dimensions. The maximum separation performances were obtained at the dimension proportions of 1.32 for Lc/Dc. As the Lc was increased, the *Et*s for the similar inflow rate decreased less according to the inflow rates. For Di30S-70, the 37% *Et* at 956 ml/s of the inflow rate rapidly decreased to 29% at 1051 ml/s of the inflow rate. However, as the Lc was increased to the M-type (Di30M-70), the 63% *Et* at 930 ml/s of the inflow rate decreased less to 59% at 1049 ml/s of the inflow rate. As the Lc increased to the L-type (Di50L-70), the 86% *Et* at 899 ml/s of the inflow rate decreased less to 74% at 1093 ml/s of the inflow rate. The results of experiment are shown in Fig. 7. According to the results of ANCOVA (Table 3), the separation performances were significantly affected (P<0.05) by the factors of the fi

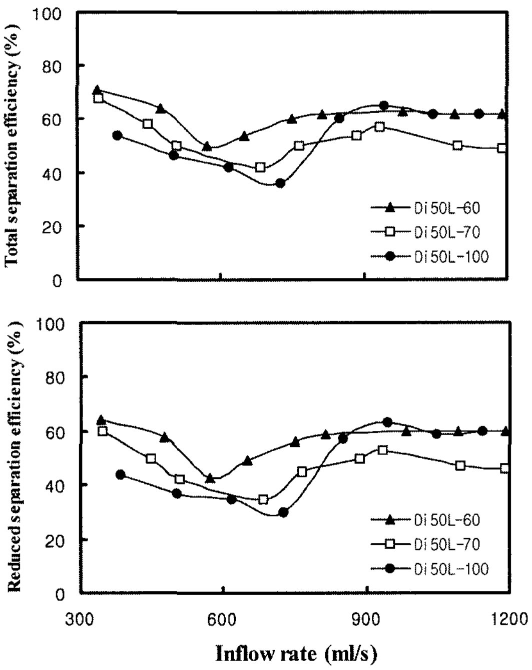

Fig. 6. Total and reduced separation efficiency for a low-pressure hydrocyclone (LPH) of 50 mm inflow diameter, three overflow diameters (60, 70, 100 mm) and 442 mm L-type cylinder length for substitute polystyrene particles (dia. 0.4-0.7 mm, ρ_s=1.05) according to inflow rate.

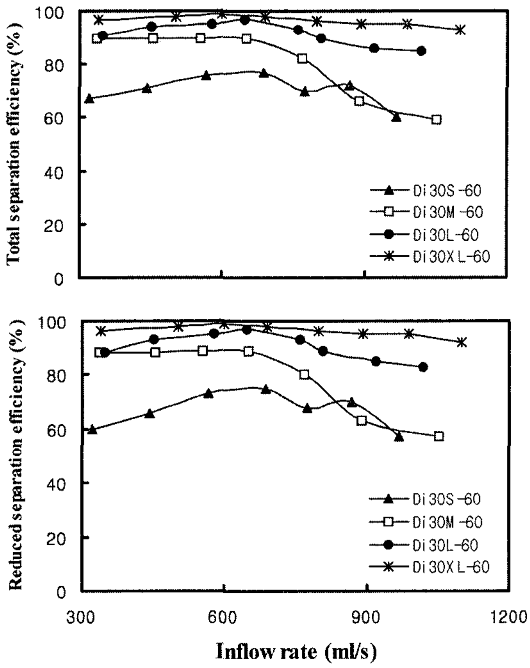

Fig. 7. Total and reduced separation efficiency for a low-pressure hydrocyclone (LPH) of 30 mm inflow diameter, 60 mm overflow diameter and four cylinder length (250 S-, 345 M-, 442 L-, 575 mm XL-type) for substitute polystyrene particles (dia. 0.4-0.7 mm, ρ_s=1.05) according to inflow rate.

and the Lc. The separation performances of 575 mm of Lc were slightly higher than those for 442 mm of Lc according to the inflow rate (Fig. 7). However, there were no significant differences found in the Tukey test at α=0.05. This may have been caused by the significant interaction (P=0.002) of the Lc and the fi. Evaluating according to the inflow rates, the highest separation performances were distributed in the middle range of inflow rate, especially at around 600 ml/s (Fig. 7). These were 77%, 90%, 97% and 99% for the S-, M-, L- and XL-type at 686, 651, 648 and 598 ml/s of the inflow

Table 3. Result of analysis of covariance (ANCOVA) and Tukey test (α=0.05) in exp. 2

Source	DF	SS	Adj SS	Adj MS	F-value	P-value
fi	1	244.29	497.55	497.55	23.93	0.0001
Lc	3	3201.93	524.26	174.75	8.41	0.001
Lc*fi	3	435.64	435.64	145.21	6.99	0.002
Error	22	457.35	457.35	20.79		
Total	29	4339.20				
Factor				Level		
Lc		250	345	442	575	

Lc, cylinder length; fi, inflow rate.
R^2=0.8946; DF, degrees of freedom; SS, sum of squares; MS, mean square; Adj R^2=0.8611.

rate. The optimum dimensions for the Lc showing a maximum separation performance were 442 mm and 575 mm, while the geometric proportions of the Lc/Dc were 1.32-1.72.

Discussion

Polystyrene particles (ρ_s=1.05 g/cm^3) used as feed material exhibit a similar settling velocity (0.21 to 0.43 cm/s) to that of the fine debris of the feces of young carp. This size is much finer than that used in previous work (Lee and Jo, 2005). However, most research on the removal of aquaculture solid waste by hydrodynamics in a tank have considered bigger feces size and feed wastes (Watten and Beck, 1987; Backhurst and Harker, 1989; Westers, 1991; Cripps and Poxton, 1992; Yoo et al., 1995; Twarowska et al., 1997; Cripps and Bergheim, 2000; Summerfelt and Timmons, 2000). Scott and Allard (1983; 1984) have shown the possibility of using hydrocyclones in aquaculture wastewater treatment as a pre-filter in conjunction with a micro-screen filter. However, their system operated at high pressure. The LPH geometric dimensions evaluated in the present experiment were taken from other research (Coelho and Medronho, 1992; Castilho and Medronho, 2000) and were practically considered in order to operate a low pressure hydrocyclone. The inlet pressure was kept under 390 g. In comparison with other research, this value is very low (Wheaton, 1977; Asomah and Napier-Munn, 1997). With an inflow rate range of 300 to 1200 ml/s, the hydraulic water level difference for the Di30XL-60 was kept to a range of 55.5 to 11.5 cm. This will help to collect the fragile fecal solid and the fine waste solids in an unbroken condition and save on construction and operating expenditure.

According to Lee and Jo (2005), a maximum LPH separation performance (100%) for large particles (diameter 1.1-1.3 mm) was achieved for a wide rage of inflow rates and dimension combinations. However, in the present study, the maximum separation performance (97%) for the small particles (diameter 0.4-0.7 mm) was achieved with a narrower inflow rate range (at around 600 ml/s) and dimension combinations. For the same LPH dimensions, the separation performances for the small polystyrene particles in the present experiment were lower than were those for the large polystyrene particles reported in the previous study (Lee and Jo, 2005). The total separation efficiencies (*Ets*) ranged from a high of 97% to a low of 20%. The effects of the inlet diameter (Di) on the separation performance was more significant than in the previous study (Lee and Jo, 2005). This contrasts with Medronho and Svarovsky (1984) who showed no relative size effect for the inlet orifice (Di/Dc) on performance. That said, the separation performances for the Di30 series were significantly higher ($P<0.05$) than were those of the Di50 series, with the separation performance curves for the Di30 series fluctuating more than those of the Di50 series. This is possibly the result of the wide LPH inlet velocity range for the Di30 series in comparison with that of the Di50 series.

Particles experience a centrifugal force in a rotational flow field. This is directly dependent on tangential velocity (Statie et al., 2001). For the separation of finer feed particles, a much higher tangential velocity has to be engendered by the inflow velocity. However, in this experiment, this was compensated for by increasing of the cylinder length for similar inflow rates. To achieve a high separation performance for fine solids, a much longer cylinder length was utilized in comparison with previous research with a similar inlet pressure (Lee and Jo, 2005). Chu et al. (2000) noted that the best choice for the hydrocyclone cylindrical length to achieve a high separation rate was 1.6 times the cylinder diameter (1.6Dc). This is in the range of the results of the present experiment (1.32-1.72Dc). After Gupta et al. (1984), high efficiency cyclones have tended to have a smaller inlet area, with a smaller ratio of Di/Do and a larger Dc, usually with a ratio of Dc/Do>2. In the present experiment, the Di30XL-60, which showed the best separation performance, had geometric proportions of 0.5 of the Di/Do and 5.58 of the Dc/Do. According to Chu et al. (2002), the underflow diameter is not a serious dimension parameter for hydrocyclone separation performance. The underflow diameter and cone angle in the present study followed Lee and Jo (2005). For this reason, the results indicate that the LPH optimum dimensions for obtaining a maximum separation performance for fine solid removal were: 30 mm inflow diameter, 442 mm and 575 mm cylinder length, and 60 mm overflow diameter at 50 mm underflow diameter, 335 mm cylinder diameter and 68 cone angle. Their dimension proportions were 0.09 of the Di/Dc, 1.32-1.72 of the Lc/Dc, 0.18 of the Do/Dc and 0.15 of the Du/Dc.

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