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Separation Performance of a Low-pressure Hydrocyclone for Suspended Solids in a Recirculating Aquaculture System

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The separation performance of a low-pressure hydrocyclone (LPH) was evaluated for suspended-solids removal in a recirculating aquaculture system (RAS). The dimensions of the LPH were 335 mm cylinder diameter, 575 mm cylinder height, 60 mm overflow diameter, 50 mm underflow diameter, and 68° cone angle. The inflow rate varied (400, 600, 800, and 1,000 mL s^{-1}) with 25%, 25%, 20%, and 10% of bypass (R_f), respectively. The maximum total separation efficiency (*Et*) and reduced separation efficiency (*E't*) for suspended solids from the effluent of the second settlement tank (before biofiltration) were 58.9% and 45.2%, respectively, at an inflow rate of 600 mL s^{-1} and 25% of R_f. The maximum *Et* and *E't* for suspended solids from the water supply channel (after biofiltration) were 24.4% and 16%, respectively, at an inflow rate of 1,000 mL s^{-1} and 10% of R_f. The maximum grade efficiency (*Ei*) was 51.6% for a 300 μm particle size at an inflow rate of 600 mL s^{-1} with 23% of R_f. The maximum reduced grade efficiency (*E'i*) was 37.6% for a 300 μm particle size at an inflow rate of 1,000 mL s^{-1} with 11% of R_f. The results indicate that the separation performance of the LPH for suspended solids removal was size selective and that maximum removal occurred at particle sizes ranging from 300 to 500 μm.

Key words: Grade separation efficiency, Low-pressure hydrocyclone, Recirculating aquaculture system (RAS), Separation efficiency, Solid removal, Suspended solids

Introduction

Suspended solids accumulation is the first limiting parameter of a recirculating aquaculture system (RAS) because of the well known adverse effects on fish through smothering of gills (Muir, 1982) and increased stress (Rosenthal et al., 1982; Klontz et al., 1985; Braaten et al., 1986), or indirectly through proliferation of pathogenic organisms (Braaten et al., 1986; Liltved and Cripps, 1999) and consumption of dissolved oxygen as the solids decay (Welch and Lindell, 1992). Thus, suspended solids should be removed from RASs as quickly as possible.

Various solids-removal techniques and systems have been recommended by many investigators (Wickins, 1980; Cripps and Bergheim, 2000; Lekang et al., 2001; Summerfelt and Penne, 2005). Removal of suspended solids is usually addressed by gravitational settling and mechanical filtration processes. However, the low settling velocity of fine particles makes gravitational removal methods impractical. Moreover, as particles become smaller, mechanical filtration requires finer media, and screen removal is more expensive due to pressure losses and more frequent backwashing (Chen and Malone, 1991). Thus, a solids separator for finer suspended solids is necessary for treating wastewater in a RAS.

Hydrocyclones of different shapes and dimensions are commonly used as solid–liquid separators for fine-solids removal in many industrial fields. Due to their simple design, low cost, ease of operation, and low maintenance, hydrocyclones have become important equipment for solid-liquid separations (Chu et al., 2000). Since the adaptation of a hydrocyclone for a fish farm by Scott and Allard (1983, 1984), no studies have examined the separation performance of high-pressure hydrocyclones in a RAS. The higher pressure and energy expenditure necessary for a hydrocyclone might diminish its wide use in RASs. Lee and Jo (2005a, b) developed a low-pressure hydrocyclone (LPH); however, data on separation

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*Corresponding author: jinhwanlee@hhu.ac.kr performance of an LPH for fine solids and suspended solids in a RAS are still lacking, even though these data are necessary for developing centrifugal separators to enhance separation efficiency.

The objectives of this study were to determine the separation performance of a LPH for suspended solids in culture water from a RAS and its effect on the size distribution of the removed particles and to suggest design information for centrifugal separators.

Materials and Methods

Low-pressure hydrocyclone and operating variables

The structure of the LPH used in this study is described in Lee and Jo (2005a, b). The dimensions of the LPH used were 335 mm cylinder diameter, 575 mm cylinder length, 30 mm inflow diameter, 60 mm overflow diameter, 50 mm underflow diameter, and 68° cone angle.

Operating variations for the bypass ratios (R_f) of 25%, 25%, 20%, and 10% and inflow rates of 400, 600, 800, and 1,000 mL/s, respectively, were as described by Lee (2004).

Experimental RAS

Filtered water from a water supply channel is introduced to circular rearing tanks, and a fraction of the effluent water from the rearing tanks runs through a central bottom drain pipe to the first settlement tank and then to a second settlement tank in consecutive order. Most solids precipitate in the first settlement tank; hence, the fine and floatable solids flow into the second settlement tank. Effluent water from the second settlement tank flows into the biofilter. The main water flow from the side drain of the rearing tank is also pumped into the biofilter. Biofiltered water from sand and submerged filters flows into the water supply channel and then flows into the rearing tank. The overall schematic diagram of the experimental system is shown in Fig. 1.

Inflow water was taken from the second settlement tank (before biofiltration) and the water supply channel (after biofiltration). To determine the size distributions of suspended solids, sample water was taken from the inflow and two product streams: the overflow and underflow of the LPH.

Separation performance of the LPH

Total separation efficiency (Et) was estimated using eq. 1. Reduced separation efficiency ($E't$) was calculated using eq. 2.

$$Et = \frac{M_u}{M_o + M_u}, \qquad \text{(eq. 1)}$$

where M_o is the feed amount in overflow, and M_u is the feed amount in underflow.

$$E't = \frac{Et - R_f}{1 - R_f}, \qquad \text{(eq. 2)}$$

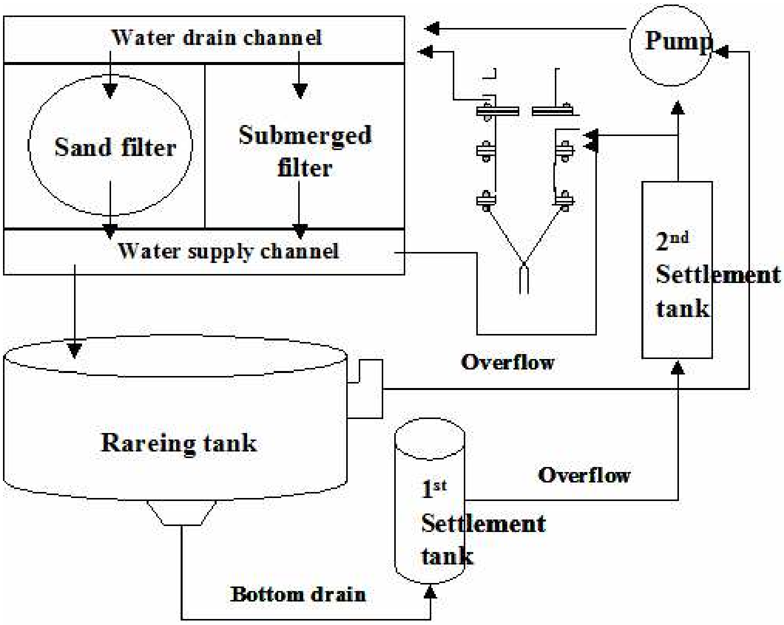

Fig. 1. Diagram of experimental system.

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

Grade-separation efficiency (*Ei*) and reduced grade-separation efficiency (*E'i*) were determined as described in Svarovsky and Thew (1992).

Statistics

A one-way analysis of variance was used to detect significant differences. When significant differences were found, Duncan's multiple range test was performed to test the differences in the means using SAS version 9.1 (SAS Institute Inc., Cary, NC, USA).

Results

Separation performance of the LPH for suspended solids from the second settlement tank (before biofiltration)

For all operating variations, total separation efficiency (*Et*) for suspended solids from the second settlement tank ranged from 40 to 59%, and the highest (59%) and lowest (40%) *Et* values occurred at inflow rates of 600 and 1,000 mL s^{-1}, respectively. The reduced separation efficiency (*E't*) ranged from 29 to 45%; and the highest *E't* value (45%) occurred at an inflow rate of 600 mL s^{-1}, and the lowest (29%) at an inflow rate of 800 mL s^{-1} (Fig. 2). Both the *Et* and *E't* were significantly higher ($P<0.01$) at 600 mL s^{-1} and an R_f of 25% than under other operating variations ($P<0.01$).

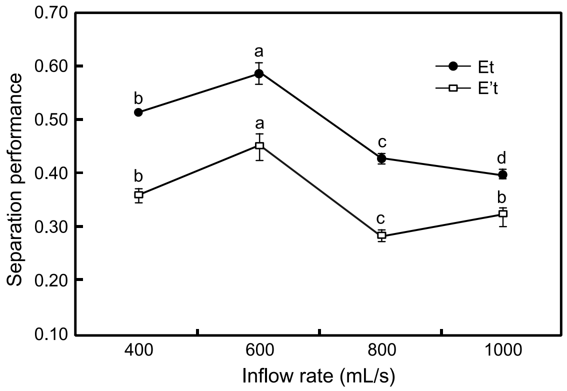

Fig. 2. Separation performance of low-pressure hydrocyclone (LPH) for suspended solids in 2nd settlement tank according to the different operating variation. Different letters are significantly different ($P<0.01$).

Separation performance of the LPH for suspended solids from the water supply channel (after biofiltration)

Total separation efficiency (*Et*) for suspended solids from the water supply channel ranged from 20.7 to 24.4%, and the highest (24.4%) and the lowest (20.7%) *Et* values occurred at inflow rates of 1,000 and 600 mL s^{-1}, respectively (Fig. 3). The reduced separation efficiency (*E't*) ranged from 0 to 16%; the highest *E't* value (16%) occurred at an inflow rate of 1,000 mL s^{-1}, and the lowest occurred at inflow rates of 400 and 600 mL s^{-1}. Both the *Et* and *E't* were significantly higher ($P<0.01$) at an inflow rate of 1,000 mL s^{-1} and 10% of R_f than under the other variations.

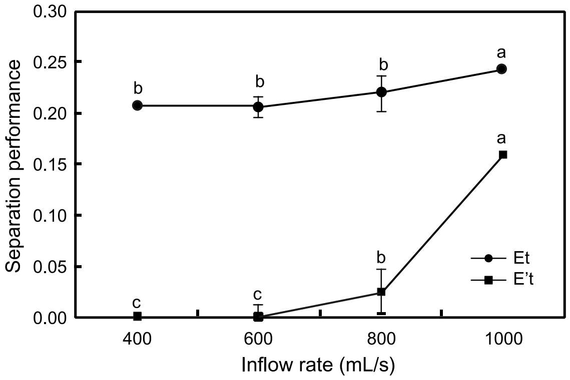

Fig. 3. Separation performance of LPH for suspended solids in water supply channel according to the different operating variation. Different letters are significantly different ($P<0.01$).

Grade-separation efficiency (*Ei*) and reduced grade-separation efficiency (*E'i*) for suspended solids from the water supply channel (after biofiltration)

Particle size distribution of suspended solids from the water supply channel is shown in Fig. 4. The size distribution of suspended solids from the water supply channel (after biofiltration) ranged from 1 to 2500 µm. The cumulative percentage of particle sizes to approximately 150 µm was 10.5%, and that to approximately 600 and 1,300 µm was 65 and 98%, respectively.

Grade efficiency (*Ei*) and reduced grade efficiency (*E'i*) for suspended solids from the water supply channel are shown in Fig. 5. The highest values for both *Ei* and *E'i* occurred with small particle sizes ranging from 200 to 600 µm, and the higher values were concentrated at an approximate particle size of 400 µm. The *Ei* value decreased with sizes larger than 1,000 µm, and no reduced grade efficiencies were expected with particles greater than 750 µm.

For the fine particles ranging from 1 to 100 µm,

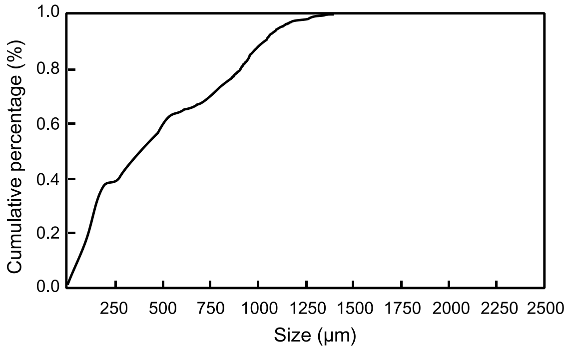

Fig. 4. Size distribution of suspended solids in the water from the water supply channel.

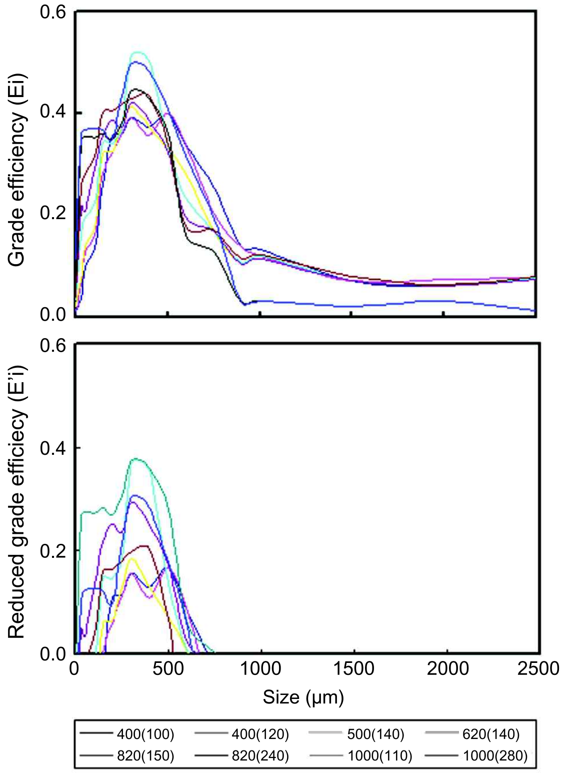

Fig. 5. Grade and reduced grade efficiency curves of suspended solids in the water from the water supply channel according to the inflow rates and bypass ratio. The numbers in parenthesis refer to underflow rates

the *Ei*s increased as inflow rate and R_f increased. For the particle sizes ranging from 150 to 200 μm, the highest *Ei* occurred at an inflow rate of 820 mL s^{-1} with 19% and 30% of R_f. For the coarse particles ranging in size from 500 to 1,000 μm, the *Ei*s increased as inflow rate and R_f decreased. The *Ei* increased with an increase in the R_f values, but the *E'i* decreased when R_f increased. Thus, the increased *E'i* for all operating variations was obtained at the higher inflow rate with a lower R_f.

Discussion

Since Scott and Allard (1983, 1984) reported the performance of a hydrocyclone as a prefilter in conjunction with a microscreen filter for treating aquaculture wastewater, limited data on fine suspended solid separation by hydrocyclones have been reported. Although tank hydrodynamic studies for suspended particle movement (Backhurst and Harker, 1989; Summerfelt and Timmons, 2000) and self-cleaning of tanks (Watten and Beck, 1987; Westers, 1991; Cripps and Poxton, 1992; Yoo et al., 1995; Twarowska et al., 1997) have been investigated, these studies only considered the removal of settleable feces and feed wastes. In the present study, the suspended solid particle sizes ranged in size from 1 to 2,500 μm. However, most were smaller than 1,300 μm. The LPH showed good size-selective separation performance for the fine suspended solids ranging from 300 to 500 μm. According to Scott and Allard (1984), particle sizes from 200 to 300 μm were most effectively removed by the LPH. These separation performances are very comparable to more recent centrifugal separators used in aquaculture systems.

In the United States and Europe, another type of centrifugal separator, called a swirl separator, is commonly used in intensive fish culture systems. Swirl separators are usually designed to treat large quantities of wastewater. However, this larger capacity is insufficient to produce the necessary centrifugal force for separating finer particles. Thus, high-pressure hydrocyclones are usually operated with pressures ranging from 50 to 276 kPa to separate particles with densities greater than 2 g cm^{-3} (Medronho and Thew, 1984; Antunes and Medronho, 1992; Coelho and Medronho, 1992; Nageswararao, 1992) and sizes smaller than 212 μm (Hou et al., 1998; Tavares et al., 2002). However, the LPH was designed to separate both larger (floatable fecal solids and feed waste) and finer solid particle sizes (suspended solids) (Lee, 2004). Due to the need for numerous stepwise procedures to design a centrifugal separator, not much information is available on the effective dimensions and operating variables for LPHs. Thus, the data on the dimensions and operating variables of the LPH used here will contribute to further development of centrifugal separators for RASs.

Water from the water supply channel (after biofiltration) contained mostly fine suspended solids, and water from the second settlement tank (before biofiltration) contained mostly larger suspended solids. The size distributions of the suspended solids from the second settlement tank were also very wide and variable because these solids included unsettled feces and fine feed waste. Therefore, it was difficult to determine the size and grade efficiency. The physical characteristics of aquaculture solid waste, such as size and specific gravity, vary according to the characteristics of the feed, fish species and size, and system structure. Thus, the densities of aquaculture solid waste (1.01 to 1.2 g cm^{-3}) and settling velocity (0.01 to 3.91 cm s^{-1}) of aquaculture solid wastes show a wide range (Summerfelt, 1998; Wong and Piedrahita, 2000; Patterson et al., 2003). However, suspended solids from aquaculture waste show a trend such that although particle numbers are greatest at the lower end of the size range, total particle volume is usually greatest at the upper end of the size range (Chen et al., 1993; Cripps, 1993).

The performance of hydrocyclones is usually size-dependent, and the grade-separation efficiency varies with particle size. In the present study, total separation efficiency (*Et*) for suspended solids in the water supply channel (after filtration) were highest (24.4%) at an inflow rate of 1,000 mL s^{-1} with 10% of R_f. The suspended-solid size distributions in the water supply channel ranged from 1 to 2,500 µm. The size distributions of the underflow for all operating conditions were concentrated in a range from 1 to 1,000 µm. The cut-point, known as the d_{50}, corresponds to the particle size with a 50-50 chance of reporting to the underflow or overflow. The d_{50} ranged from approximately 300 to 400 µm at 620 mL s^{-1} of inflow rate with 23% of R_f.

The effect of bypass (R_f) and inflow rate on the grade and the reduced grade efficiencies according to the different feed material varied slightly. The results of the *Ei* and *E'i* partition curves indicated that the separation performance of the LPH for specific feed materials was strongly dependent on the operating variables. This means that the LPH can be operated for a target particle size distribution with slight changes in operating conditions.

Suspended solids in intensive aquaculture systems originate predominantly from feed (Cripps 1993), and a common loading level for suspended solids in a fish farming system is 0.4 to 8.4 mg L^{-1} (Han et al., 1996). In the present experiment, the loading level of suspended solids in the second settlement tank ranged from 1.7 to 2.0 mg L^{-1}, and that in the water supply channel ranged from 2.2 to 2.5 mg L^{-1}. However, the recommended limit for sus-pended solid concentrations in a recirculating system is less than 15 mg L^{-1} (FIFAC, 1980; Timmons et al., 1987; Chen, 1991). According to Chu et al. (2002a, b), when particle density or particle size increases, the absolute radial velocity of the solid particles decreases. For this reason, a higher *Ei* occurred at a lower inflow rate of 400 mL s^{-1}for the coarse particles ranging from 500 to 1,000 µm. The increased inflow rate will cause an increase in the velocity of the overflow, so larger particles will be easily flushed out.

According to Thompson and Galvin (1997), coarse particles are easier to settle than fine ones at the proper radial velocity. This is the general partition curve pattern for experiments conducted with a serial particle size distribution and feed materials with a higher specific gravity. However, the partition curves in the present experiment were not a monotonic increasing pattern. As the inflow rate increased, the volume of finer particles in the underflow increased. Thus, it is likely that most fine particles found in the underflow were entrained through underflow and fractionated from the coarse particles in the spigot cylinder. However, coarse particles, which are formed from bacteria, are easily fractionated and flushed out.

The highest grade and reduced grade efficiencies were concentrated on a specific particle size for the limited number of operating conditions and showed a specific separation performance pattern. This is a common separation performance characteristic of long-cylinder hydrocyclones (Svarovsky and Thew, 1992), and this pattern of separation is similar to the present results.

According to Summerfelt (1998), suspended-solids removal efficiency across microscreen filters ranges from 22 to 70% for the majority of pore sizes (60-100 µm) within a RAS. Scott and Allard (1983) demonstrated that a hydrocyclone removed approximately 56% of the net dry solids circulating in the system, increased the efficiency of the microscreen filter to 97% removal of suspended solids, and lengthened the required backwash periods for the biological filter from 4 days to 3 weeks. From the results of the present work, the LPH performance ranged from 24 to 59% according to particle size and operating conditions. This performance was relatively high compared with other suspended-solids separators. Additional separation performance data on *Et*, *E't*, *Ei*, and *E'i* for the operation conditions are necessary to develop and enhance the use of centrifugal separators.

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