

Design and evaluate a drum screen filter driven by undershot waterwheel for aquaculture recirculating systems

Samir Ahmad Ali*

Agricultural Engineering Department, Faculty of Agriculture, Banha University, P.O. Box 13736, Egypt

ARTICLE INFO

Article history:

Received 6 February 2012

Accepted 16 October 2012

Keywords:

Undershot

Waterwheel

Recirculating system

Design drum filter

ABSTRACT

Micro-screen rotating drum filters are an alternative to sand filtration especially when excessive waste water is a concern. The filtering process of drum screen filters is very simple, yet very efficient and reliable due to their overall design and operation. Drum filters are designed with few moving parts to ensure a long life with low operating/maintenance costs.

Micro-screening essentially captures particles on a screen fabric while letting the water pass. This paper describes a design of two an industrial-scale drum screen filters driven by undershot wheel and its performance installed in recirculating aquaculture system culturing tilapia at El-Nenaia fish farm. These filters are consisted of a woven metal mesh of 100 μm . The design criteria for solids loading rate in the influent water is 10 $\text{kg m}^{-2} \text{min}^{-1}$.

The results indicate that the design parameters of the filter such as surface area and rotation speed were affected by the water flow rate, where the surface area and drum speed ranged from 1.58 to 27.87 m^2 , and 1.05 to 8.40, respectively. The results also indicated that the efficiency of filter decreased during the first two months compared to the last two months of fish growth period, with an average $34.22 \pm 8.85\%$ during the first 60 days and an average $52.41 \pm 16.77\%$ during the last period. Using water wheels for driving the screen filter is very important in saving energy, where the filter with such dimensions needs 1.0 hp for driving it, which represents 18.0 kW daily.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Water quality maintenance in recirculating aquaculture systems (RAS) is focused on the detoxification of nitrogenous wastes, oxygenation, removal of suspended solids and controlling the accumulation of organic compounds. Once the system's oxygen requirement, which includes that needed for fish respiration and microbial processes, is met, nitrogenous wastes, primarily management and removal of solids is one key process in an RAS. In recirculating finfish systems the main particulate waste materials are feces, uneaten feed, decaying fish, and tank and pipes biofilm slough (Chen et al., 1993; Patterson and Watts, 2003). Since the adverse effects of solids on recirculating systems were recognized, research on solids removal has been recommended by many investigators (Brinkera et al., 2005; Summerfelt and Penne, 2005; Davidson and Summerfelt, 2005; Steicke et al., 2007; Merino et al., 2007; Bai, 2007; Timmons and Ebeling, 2007; Sandu et al., 2008; Pfeiffer et al., 2008; Couturier et al., 2009; d'Orbcastel et al., 2009). Solids that are not removed from the RAS have

numerous consequences for the fish in the system and system components. The presence of suspended solids in recirculating finfish aquaculture systems can cause damage to fish gills, increase biochemical oxygen demand, reduce biofilter nitrification, and increase ammonia in the system (Chapman et al., 1987; Bergheim et al., 1998; Wong, 2001; Zhu and Chen, 2001). The solids found in RAS operations vary in size and settling properties and have an effect in the design and operation of the solid removal mechanisms (Merino et al., 2007). All recirculating aquaculture systems utilize processes to remove waste solids, oxidize ammonia and nitrite-N, and aerate and/or oxygenate the water. Methods or processes that improve solids removal also improve water quality, which can potentially enhance production and certain operating costs. However, selection of the best treatment system for a particular aquaculture operation is difficult, given the variety of processes available, and the lack of uniform methodology for evaluation of water treatment effectiveness and economic accounting and other practical considerations (Bai, 2007; Timmons and Ebeling, 2007).

The effective management of solids in aquaculture is one of the major obstacles to the continued development of the aquaculture industry (Piedrahita and Giovannini, 1989) and is often considered the most critical process to manage in aquaculture systems (Summerfelt, 1996).

* Tel.: +20 13 2467 034; fax: +20 13 2467 786.

E-mail address: samir.ali@fagr.bu.edu.eg

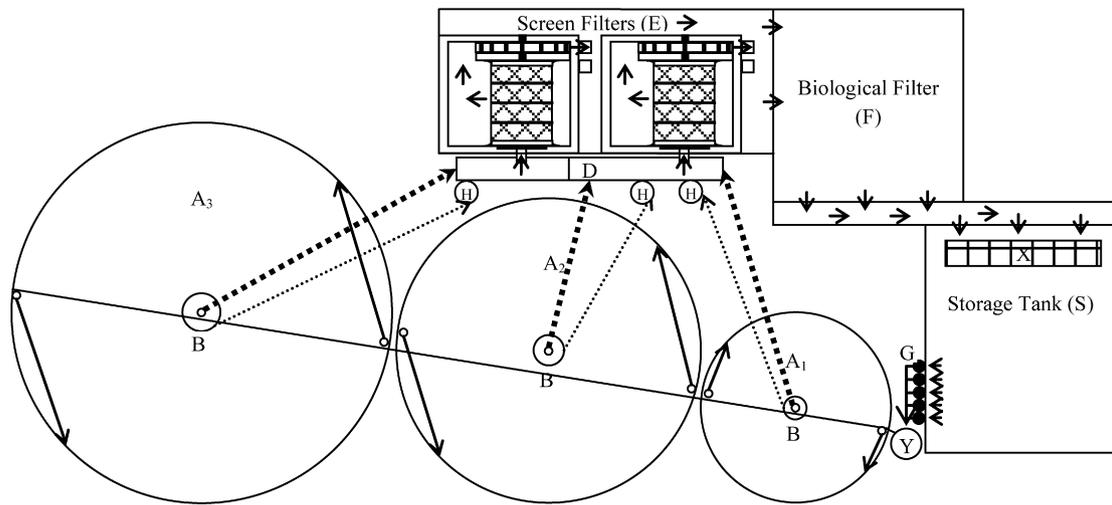


Fig. 1. Sketch of the water recycle system. Fish tank, A; particle trap, B; hydro cyclone H; channel collector, D; screen filter, E; biological filter, F; storage tank, S; pumps, G; heat exchanger, X; down flow oxygen contactor, Y.

Feed input into the system controls the production of solids and particulate matter (feces and uneaten feed). Solids and particulate matter are the major sources of carbonaceous oxygen demand and nutrient input into the water, especially if they degrade within the system. The feed portion is not assimilated by the fish excreted as an organic waste (fecal solids) and the uneaten feed consume dissolved oxygen and generate total ammonia nitrogen (TAN) when broken down by bacteria within the system (Timmons and Ebeling, 2007).

Microscreening is very common in the potable and wastewater industries where a woven metal mesh or fabric of 15–200 μm may be attached to the periphery of a rotating drum typically 1.0–3.3 m diameter and 0.6–5.1 m long. Flow enters in the center and is radially filtered through the drum mesh. The drum rotates and the solids retained on the screen are removed in a section by back-flushing with the previously filtered water. A separate launder takes the back-flush suspension off for further processing. Rotation speed usually varies from 20 to 120 s, and flow rates of up to 3900 $\text{m}^3 \text{h}^{-1}$ for single unit are claimed (Anon., 1993). Rotational speed usually fixed (4.6–26 m min^{-1} , tangentially) (Patterson, 2001).

Rotating microscreens are an alternative to primary sedimentation (Tchobanoglous and Burton, 1991) and so have been more commonly installed at farms in recent years. These usually comprise a fine mesh screen (often 60–200 mm pore size) in the form of a rotating drum or disc through which the wastewater is passed. Particles held back on the mesh are backwashed or scraped, to a waste collection trough. Rotating microscreens are especially suited to applications where blockage is likely (Wheaton, 1977), and so are used in fish farms because of the large flow of wastewater which must pass through the screen and the small screen pore size which is required to separate out the solids.

Several workers (Lilved and Hansen, 1990; Bergheim et al., 1991, 1993a,b; Ulgenes, 1992) have tested the treatment efficiency of a commercially available Unik disc microscreen. Similar to the drum screen results, treatment efficiency estimates using this unit vary considerably, both due to variations in effluent quality and characteristics, and with the pore size of the screens chosen. Ulgenes (1992) testing 250- and 120-mm pore screens together achieved a wide range of SS removal efficiencies of 16–94%, whilst Bergheim et al. (1991) achieved an average 40% suspended dry matter (SDM) removal using 35 and 60-mm pore size screens.

The capacity of a drum screen is proportional to its length and its diameter, while the capacity of a disc screen is limited by the diameter (Wheaton, 1977). Drum microscreens are therefore not

as capacity limited as disc screens. In practice however, at high flow rates, such as those in aquaculture applications, several disc or drum units are operated in parallel. This also allows for a unit to be out of operation, for repair or maintenance.

The main aim of this work is to design and evaluate a microscreen rotating filter driven by undershot waterwheel for aquaculture recirculating systems to remove solids with less power consumption.

2. Materials and methods

2.1. Design objectives

The intended design of drum screen filter is to serve a commercial recirculating aquaculture system, which was described by Ali et al. (2006) (Fig. 1). Water exiting the culture tanks A1, A2 and A3 (20 m^3 , 50 m^3 and 75 m^3 , respectively) flowed through two industrial drum screenfilter (E) (1.35 m diameter, 1.85 m long) and was then directed through two industrial scale rotating biological contactor (RBC) unit (Fig. 2). The treated water was passed through heat exchanger, and then pumped through downflow oxygenation system before reentering the culture tank through vertical manifold pipes. Each RBC unit was constructed and positioned with the central axis perpendicular to the treatment flow (Fig. 2). The two drum screen filters were equally sized (1.35 m diameter, 1.85 m long). The drum screen filters were operated at 40% submergence.

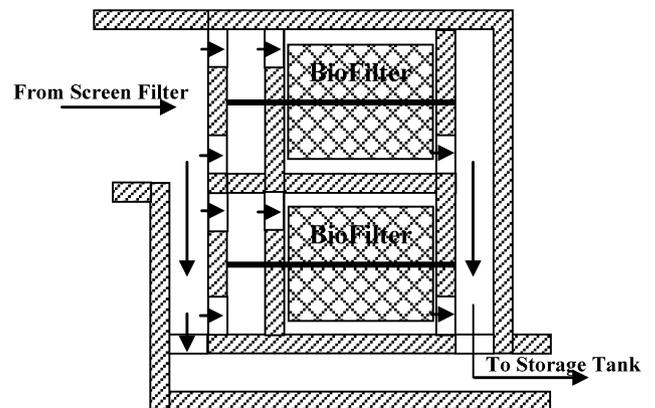


Fig. 2. Layout of rotating biological contactor (RBC) filter.

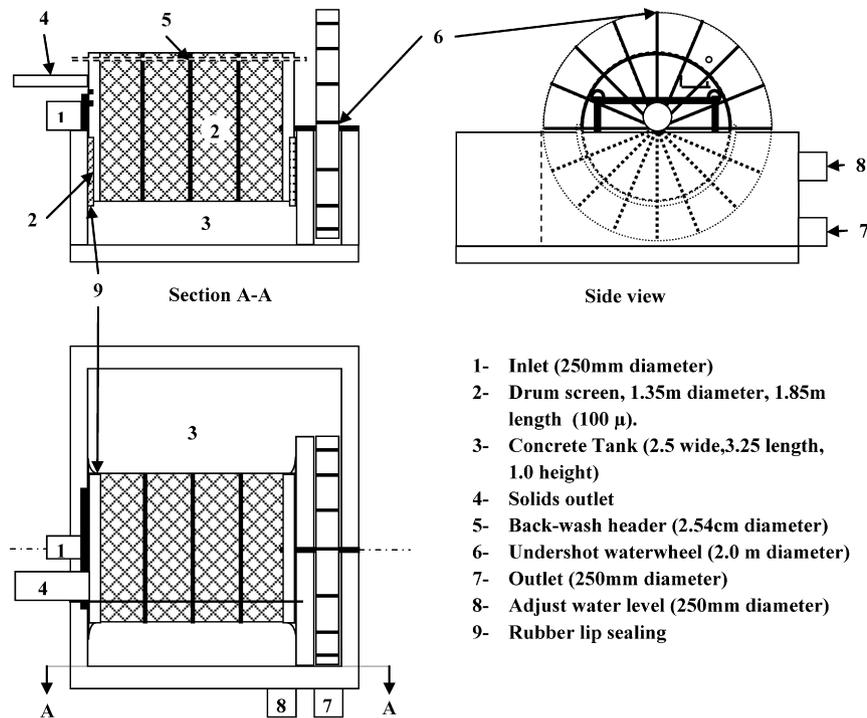


Fig. 3. Layout of drum screen filter.

These filters are consisted of a woven metal mesh 100 μ m. Flow enters in the center and is radially filtered through the drum mesh. The drum rotates and the solids retained on the screen are removed in a section by back-flushing with the previously filtered water. A separate launder takes the back-flush suspension off for further processing. Rotation speed usually varies from 3 to 6 rpm, and flow rates of up to 130 $\text{m}^3 \text{h}^{-1}$ for single unit are claimed (Fig. 3).

2.2. Drum screen filter design and manufacture

2.2.1. Drum screen design

Six factors are considered important in the hydraulic design of a microscreen: maximum flow rate, allowable head losses, porosity of the medium, effective submerged surface area, drum speed and characteristics of the feed (Rushton et al., 2000).

The design procedure for microscreens is detailed in the following steps (US Army, 1978).

2.2.1.1. Input data.

- (a) Wastewater flow:
 1. Average flow, l min^{-1}
 2. Peak flow, l min^{-1}
- (b) Suspended solids concentration, mg l^{-1} .
- (c) Effluent requirements, mg l^{-1} .

2.2.1.2. Design parameters.

- (a) Head loss across microscreen, m, $\cong 0.0152$ m water.
- (b) Initial resistance of clean filter fabric, in m, at a given temperature and standard flow conditions. Manufacturer's requirements.
- (c) Filterability index of influent measured on fabric in use (volume of water obtained per unit head loss when passed at a standard rate through a unit area of standard filter). From laboratory study.

- (d) Speed of strainer (number of square meter of effective fabric entering water in given time), $\text{m}^2 \text{min}^{-1}$ (1.3–2.4 $\text{m}^2 \text{m}^{-1}$ in $^{-1}$).
- (f) Constants: $m = 0.0267$; $n = 0.1337$.

2.2.1.3. Design procedures. Wheaton (1977) discusses Boucher' (1947) design equation for microscreens:

- (a) The effective submerged area of the screen could be calculate using the following equation:

$$A = \frac{mQC_f e^{nIQ/40.65s}}{488.25H}$$

where A =effective area, m^2 ; $m=0.0267$; Q =total rate of flow through unit, l min^{-1} ; C_f =initial resistance of clean filter fabric, m, at a given temperature and standard flow conditions (manufacturer's requirements) (0.549 m for 23- μ m, 0.3048 m for 35- μ m screen, 0.152 m for 100- μ m screen); $n=0.1337$; I =filterability index of influent measured on fabric in use (laboratory)=0.5; S =speed of strainer, $\text{m}^2 \text{min}^{-1}$; H =head loss across microscreen, m, $\cong 0.0152$ m.

- (b) Hydraulic rate of application is calculated as follows:

$$HR = \frac{Q}{A}$$

where HR =hydraulic rate, $\text{l min}^{-1} \text{m}^{-2}$; (c) calculate solids rate of application.

$$SR = \frac{Q \times C_i}{A \times 10^6}$$

where SR =solids loading rate, $\text{kg m}^{-2} \text{min}^{-1}$; C_i =influent suspended solids, mg l^{-1} .

(c) The amount of backwash water is determined as:

$$BW = (3-6\%)(Q) \text{ where } BW = \text{backwash rate, l min}^{-1}.$$

2.2.1.4. Output data.

- (a) Effective submerged area, m^2 .
 (b) Hydraulic rate of application, $\text{l min}^{-1} \text{m}^{-2}$.
 (c) Solids rate of application, $\text{kg m}^{-2} \text{min}^{-1}$.

2.2.1.5. Design example.

(a) Calculate the effective submerged area of the screen (US Army, 1978):

$$A = \frac{mQC_f e^{n/Q/40.65s}}{488.25H}$$

where A = effective area, m^2 ; m = constant, 0.0267; Q = flow, 2050 l min^{-1} ; C_f = initial resistance, 0.152 m (100- μm fabric); n = 0.1337; I = filterability index, 0.5; S = speed of strainer, $1.85 \text{ m}^2 \text{min}^{-1}$; H = head loss across microscreen, m, 0.152 m.

$$A = \frac{0.0267 \times 2050 \times 0.152 e^{0.1337 \times 0.5 \times 2050 / 40.65 \times 1.85}}{488.25 \times 0.152} = 0.693 \text{ m}^2$$

(b) Calculate hydraulic rate of application (US Army, 1978):

$$HR = \frac{Q}{A}$$

where HR = hydraulic rate, $\text{l min}^{-1} \text{m}^{-2}$; Q = flow, 2050 l min^{-1} ; A = effective area, 0.693 m^2 :

$$HR = \frac{2050}{0.693} = 29,561 \text{ min}^{-1} \text{m}^{-2}$$

$$HR = 59,651 \text{ min}^{-1} \text{m}^{-2}.$$

Note: HR exceeds recommended limit of $264.51 \text{ min}^{-1} \text{m}^{-2}$; therefore, recalculate area using $HR = 264.51 \text{ min}^{-1} \text{m}^{-2}$.

$$A = \frac{Q}{HR} = \frac{2050}{264.5} = 7.75 \text{ m}^2$$

(c) Calculate solids rate of application (US Army, 1978):

$$SR = \frac{Q \times C_i}{A \times 10^6}$$

where SR = solids loading rate, $\text{kg m}^{-2} \text{min}^{-1}$; Q = flow rate through unit, l min^{-1} ; C_i = influent suspended solids, 10 mg/L ; A = area using, 7.75 m^2 :

$$SR = \frac{2050 \times 10}{7.75 \times 10^6} = 0.0026 \text{ kg m}^{-2} \text{min}^{-1}$$

$$SR = 0.0026 \text{ kg m}^{-2} \text{min}^{-1}.$$

Note: SR exceeds recommended limit of $0.0029 \text{ kg m}^{-2} \text{min}^{-1}$; therefore, not need recalculate area using $SR = 0.0029 \text{ kg m}^{-2} \text{min}^{-1}$.

(d) Calculate amount of backwash water (US Army, 1978)

$$BW = (3-6\%)(Q) = 0.06 \times 2050 = 1231 \text{ min}^{-1}$$

where BW = backwash rate, l min^{-1} ; % = percent, 6; Q = flow, 2050 l min^{-1} .

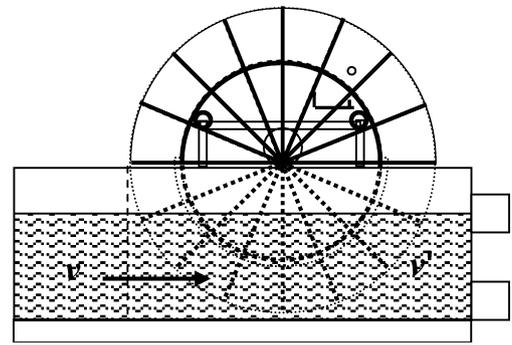


Fig. 4. Undershot waterwheel design.

Table 1

Given farm characteristics.

Characteristic	Tank (A1)	Tank (A2)	Tank (A3)
Water volume (m^3)	20	50	75
Individual fish weight (g)	35	120	250
Feed protein content (%)	40%	30%	25%
Feeding rate (kg day^{-1})	6–25	25–60	60–100
Number of fish per tank		20,000	
Water flow rate (l min^{-1})	800	1300	2050
(Water flow rate (l min^{-1}))		2100	2050

2.2.2. Conventional undershot waterwheel design

To estimate the speed of undershot waterwheels is consider Fig. 4. We assuming that wheel radius is large, so that the water flow is normal to the vanes. Thus, if the effective water wheel area is A_v , then the mass of water that presses against each vane per unit time is:

$$m = \rho A_v (v - v')$$

where $v' = \omega R \equiv cv$ is the mean water speed afterwards, ω = rotating speed, rpm; R = undershot waterwheel diameter, m.

Thus we expect $0 < c < 1$. This peaks for $c = 1/3$ (so that the waterwheel vanes move at a third of the initial water speed in the millrace) so that the maximum efficiency of the undershot waterwheel is about 30%.

Table 1 illustrates the farm characteristics which used the intended design of the drum screen filter will serve.

Operating the previous steps using the design parameters of Table 1, Table 2 shows the results upon which the filter was manufactured.

2.3. Feed management

In feeding the fish, the recommendations of feeding rates for different size groups of tilapia in tanks of Rakocy (1989) and, the

Table 2

The design results of drum screen filter.

Item	Abbreviation	Unit	Value
Peak water flow rate	Q	l min^{-1}	4150
Hydraulic rate of application	HR	$\text{l min}^{-1} \text{m}^{-2}$	2956
Solids loading rate	SR	$\text{kg m}^{-2} \text{min}^{-1}$	0.0026
Screen area using	A	m^2	7.75
Rotating speed	ω	rpm	1.05–8.40
Amount of backwash water	BW	l min^{-1}	123
Undershot waterwheel diameter	R	m	2.0
Water depth in the filter tank		m	0.8
No. of waterwheel puddles		No	16
Width of waterwheel puddle		m	0.2
Drum diameter		m	1.35
Drum length		m	1.85
No. of units (drums)		No	2

Table 3
Water quality monitoring.

Item	Before	SD	After	SD
Dissolved oxygen (mg l^{-1})	5.0	± 0.4	7.1	± 0.6
pH	6.7	± 0.4	7.7	± 0.7
Unionized ammonia (mg l^{-1})	0.0131	± 0.0027	0.0083	± 0.0027
Nitrite (mg l^{-1})	0.26	± 0.19	0.18	± 0.15
Nitrate (mg l^{-1})	4.0	± 4.56	8.4	± 8.4

recommendations of Jauncey and Ross (1982) for the feed pellets diameter were used.

2.4. Drum filter manufacture

The two units of drum screen filters were (1.35 m diameter, 1.85 m length) manufactured from stainless steel at private company for steel industry. The units were driven by undershot waterwheel to give the recommended rotating speed (3–6 rpm).

2.5. Sample collection and analysis

Water samples were collected daily at the inlet and the outlet of the screen filter for measuring suspended solids according to APHA (1998). The samples were stored in refrigeration for analysis. Unionized ammonia (NH_3), nitrite and nitrate were measured by an ion selective electrode (ORION 710). Dissolved oxygen was measured by a digital oxygen analyzer (ORION 810), provided with a dissolved oxygen prop (No. 81010). The pH was measured by the pH meter (ORION 230A), provided with pH electrodes (No. 910500).

2.6. Drum screen filter efficiency

Drum screen filter efficiency was calculated as follows:

$$\eta_f = \frac{SS_{f\text{ in}} - SS_{f\text{ out}}}{SS_{f\text{ in}}} \times 100$$

where $SS_{f\text{ in}}$ = the suspended solids at the inlet the screen filter, mg l^{-1} ; $SS_{f\text{ out}}$ = the suspended solids at the outlet the screen filter, mg l^{-1} ; η_f = the screen filter efficiency for suspended solids (%).

3. Results and discussion

3.1. Water quality monitoring

Dissolved oxygen was monitored before and after downflow oxygen contactor. pH, unionized ammonia, nitrite and nitrate were monitored before and after rotating biological contactor (RBC) during the study period; the results are summarized in Table 3. It indicate that the dissolved oxygen ranged from 4.6 to 5.4 mg l^{-1} with an average of $5.0 \pm 0.4 \text{ mg l}^{-1}$ and from 6.5 to 7.7 mg l^{-1} with an average of $7.1 \pm 0.6 \text{ mg l}^{-1}$ over the study before and after the downflow oxygen contactor, whereas water pH stayed in the range of 6.7–7.7. Unionized ammonia concentration ranged from 0.0093 to 0.018 mg l^{-1} with an average of $0.0131 \pm 0.0027 \text{ mg l}^{-1}$ and from 0.005 to 0.0135 mg l^{-1} with an average of $0.0083 \pm 0.0027 \text{ mg l}^{-1}$ over the study before and after the (RBC), respectively. Nitrite–nitrogen concentration over the same period varied from 0.05 to 0.62 mg l^{-1} with an average of $0.26 \pm 0.19 \text{ mg l}^{-1}$ and from 0.03 to 0.46 mg l^{-1} with an average of $0.18 \pm 0.15 \text{ mg l}^{-1}$ before and after the RBC, respectively. Nitrate–nitrogen concentration over the same period varied from 0.409 to 18.94 mg l^{-1} with an average of $4.0 \pm 4.56 \text{ mg l}^{-1}$ and from 1.39 to 34.93 mg l^{-1} with an average of $8.4 \pm 8.4 \text{ mg l}^{-1}$ before and after the RBC, respectively.

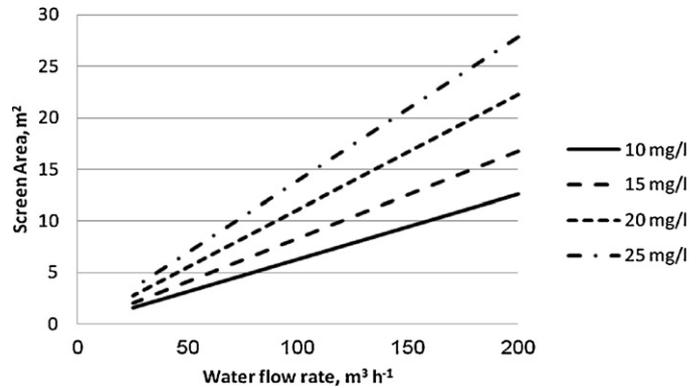


Fig. 5. Effect of water flow rate and solids concentration on screen surface area.

The data in the table indicated that water quality in the system remained excellent of tilapia production according to Boyd (1982), Lawson (1995) and Soderberg (1995) during the study.

3.2. Effect of water flow rate on design parameters of the drum screen filter

3.2.1. Screen surface area

The screen surface area of the filter was affected mainly by the water flow rate through it. Fig. 5 shows the effect of water flow rate on the screen surface area at different solids concentrations ($10\text{--}25 \text{ mg l}^{-1}$). It could be seen the required surface area of the filter increased linearly with increasing the water flow rate, were increased from 1.58 to 27.87 m^2 when the flow rate increased from 25 to $200 \text{ m}^3 \text{ h}^{-1}$ at different solids concentrations ($10\text{--}25 \text{ mg l}^{-1}$).

3.2.2. Rotation speed of the filter

Selection of the rotational speed of the drum filter and its relationship with the water flow is shown in Fig. 6. The results indicate that the drum speed increased with increasing the water flow rate, where it ranged from 1.05 to 8.40 rpm at different flow rates that ranged from 25 to $200 \text{ m}^3 \text{ h}^{-1}$. The relationship between the measured and predicted drum speeds as shown in Fig. 6 indicated that the measured drum speed was lower than the predicted values, where it ranged from 0.6 to 5.7 rpm, which is attributed to the water leakage through the undershot waterwheel puddles which is not considered during the calculation of the drum speed. The recommended drum speed of these kinds of filters ranged from 3 to 6 rpm (Patterson, 2001).

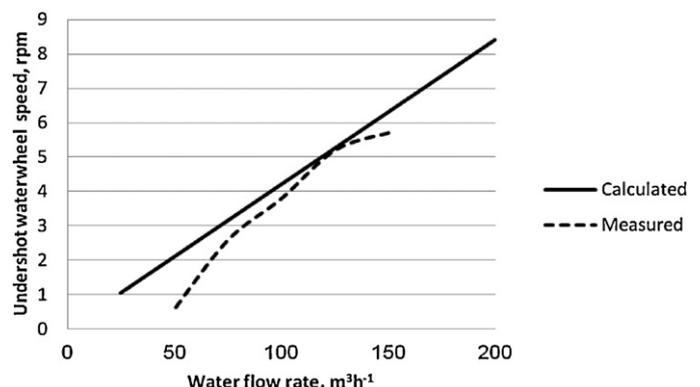


Fig. 6. Effect of water flow rate on undershot waterwheel speed.

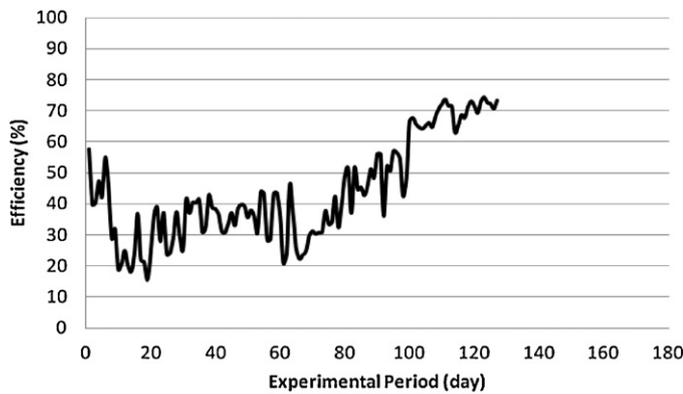


Fig. 7. The efficiency of the removal suspended solids (%).

3.3. The drum filter efficiency

The efficiency of the drum filter was determined by measuring the suspended solids concentration in the water entering and leaving the drum. Since the drum was continuously rotated and the backwash water was always on, this provided a convenient means of measuring drum efficiency. The data presented in Fig. 7 shows the efficiency of the drum filter. It could be seen that the efficiency of filter decreased during the first two months compared to the last two months of fish growth period, with an average $34.22 \pm 8.85\%$ during the first 60 days and an average $52.41 \pm 16.77\%$ during the last period. This could be due to that the efficiency is greatly dependent inversely on the suspended solids entering the filter. These solids are affected by the rate and shape of feeds and the rate of feces of fish. At the early age of fish, feeds are added as a powder, which causes more loss in the water before filtering. By the time, feeds are served to the fish as pellets which decrease the loss of particles in the water which in turn increase the efficiency of the filter. These results are in agreement with those obtained d'Orbcastel et al. (2009) whose found that the suspended solids efficiency of $40 \pm 18.5\%$.

4. Conclusions

A micro-screen drum filter was designed and evaluated within a recirculating aquaculture system. The drum surface area and rotating speed were mainly affected by the water flow rate through the system, the screen surface area of the filter ranged from 1.58 to 27.87 m² at different water flow rate (25–200 m³ h⁻¹), meanwhile, the designed drum rotation speed ranged from 1.05 to 8.40 rpm at previous flow rate. The results also indicated that the efficiency of filter decreased during the first two months compared to the last two months of fish growth period, with an average $34.22 \pm 8.85\%$ during the first 60 days and an average $52.41 \pm 16.77\%$ during the last period. Using water wheels for driving a screen filter is very important in saving energy, where the filter with our dimensions need 1.0 hp for driving it, which needs 18.0 kW daily.

Acknowledgement

The financial support of this work from Eng. Ahmad Gharieb, the owner of El-Nenaia Company (One of Gharieb Group), Egypt. The author is highly acknowledged.

References

Ali, S.A., El-Haddad, Z.A., Ghareib, A., 2006. Design and management of El-Nenaia fish farm: as a recirculating aquaculture system. *Misr Journal of Agricultural Engineering* 23 (2), 396–408.

Anon., 1993. *Filtration and Separation* 30, 289.

APHA, 1998. *Standard Methods for Examination of Water and Wastewater*, American Public Health Association, American Water Works Association, Water Pollution Control Federation Washington, DC.

Bai, C., 2007. President's column. *World Aquatic Magazine* 38 (4), 3.

Bergheim, A., Kristiansen, R., Kelly, L.A., 1993a. Treatment and utilization of sludge from land based farms for salmon. In: Wang, J.-W. (Ed.), *Techniques for Modern Aquaculture*. Proceedings of an Aquaculture Engineering Conference. 21–23 June 1993, Spokane, WA, American Society of Agricultural Engineers, St. Joseph, MI, pp. 486–495.

Bergheim, A., Cripps, S., Litved, H., 1998. A system for the treatment of sludge from land-based fish farms. *Aquatic Living Resources* 11, 279–287.

Bergheim, A., Sanni, S., Indrevik, G., Hølland, P., 1993b. Sludge removal from salmonid tank effluent using rotating microsieves. *Aquacultural Engineering* 12, 97–109.

Bergheim, A., Tyvold, T., Seymour, E.A., 1991. Effluent loadings and sludge removal from landbased salmon farming tanks. In: *Proceedings of Aquaculture Europe'91: Aquaculture and the Environment International Aquaculture Conference*, Dublin, Ireland, 10–12 June 1991, EAS Special Publ. 14. EAS, Bredene, Belgium, p. 27.

Boucher, P.L., 1947. A new measure of filterability of fluids with application to water engineering. *ICE Journal (British)* 27 (4), 415–446.

Boyd, C.E., 1982. *Water Quality Management for Pond Fish Culture*. Elsevier, Amsterdam.

Brinkera, A., Schröder, H.G., Röscha, R., 2005. A high-resolution technique to size suspended solids in flow-through fish farms. *Aquacultural Engineering* 32 (4), 325–341.

Chapman, P.E., Popham, J.D., Griffin, J., Michaelson, J., 1987. Differentiation of physical from chemical toxicity in solid waste fish bioassay. *Water, Air, and Soil Pollution* 33, 295–309.

Chen, S., Timmons, M.B., Aneshansley, D.J., Bisogni, J.J., 1993. Suspended solids characteristics from recirculating aquaculture systems and design implications. *Aquaculture* 112, 143–155.

Couturier, M., Trofimenkoff, T., Buil, J.U., Conroy, J., 2009. Solids removal at a recirculating salmon-smolt farm. *Aquacultural Engineering* 41 (3), 71–77.

d'Orbcastel, R.E., Blancheton, J.P., Belaud, A., 2009. Water quality and rainbow trout performance in a Danish Model Farm recirculating system: comparison with a flow through system. *Aquacultural Engineering* 40 (2), 135–143.

Davidson, J., Summerfelt, S.T., 2005. Solids removal from a coldwater recirculating system—comparison of a swirl separator and a radial-flow settler. *Aquacultural Engineering* 33 (1), 47–61.

Jauncey, K., Ross, B., 1982. *A Guide to Tilapia Feeds and Feeding*. Institute of Aquaculture, University of Sterling, Scotland, p. 111.

Liltved, H., Hansen, B.R., 1990. Screening as a method for removal of parasites from inlet water to fish farms. *Aquacultural Engineering* 9, 209–215.

Lawson, T.B., 1995. *Fundamental of Aquacultural Engineering*. Elsevier Scientific Publishers, Amsterdam.

Merino, G.E., Piedrahita, R.H., Conklin, D.E., 2007. Settling characteristics of solids settled in a recirculating system for California halibut (*Paralichthys californicus*) culture. *Aquacultural Engineering* 37 (2), 79–88.

Patterson, R.N., 2001. *Micro-particles in recirculating aquaculture systems*. Ph.D. Thesis. Dalhousie University, Halifax, Nova Scotia.

Patterson, R.N., Watts, K., 2003. Micro-particles in recirculating aquaculture systems: microscopic examination of particles. *Aquacultural Engineering* 28 (2), 115–130.

Pfeiffer, J.T., Osborn, A., Davis, M., 2008. Particle sieve analysis for determining solids removal efficiency of water treatment components in a recirculating aquaculture system. *Aquacultural Engineering* 39 (1), 24–29.

Piedrahita, R.H., Giovannini, P., 1989. *Diel aquaculture models: listings, descriptions and operating instructions*. Technical Committee Meeting 1989, PD/A CRSP, Davis, CA, 50 pp.

Rakocy, J.E., 1989. Tank culture of tilapia in the biology and culture of tilapia. In: Pullin, R.S.V., Lowe, R.H. (Eds.), *McConnell-ICLARM Conference Proceedings 7 International Center for Living Aquatic Resources Management*. Manila, the Philippines.

Rushton, A., Ward, A.S., Holdich, R.D., 2000. *Solid-Liquid Filtration and Separation Technology*, 2nd edition, WILEY-VCH Verlag GmbH, D-69469 Weinheim (Federal Republic of Germany), p. 249.

Sandu, S., Brazil, B., Hallerman, E., 2008. Efficacy of a pilot-scale wastewater treatment plant upon a commercial aquaculture effluent. I. Solids and carbonaceous compounds. *Aquacultural Engineering* 39 (2), 78–90.

Soderberg, R.W., 1995. *Flowing Water in Fish Culture*. Lewis Publishers, Boca Raton, FL.

Steicke, C., Jegatheesan, V., Zeng, C., 2007. Mechanical mode floating medium filters for recirculating system in aquaculture for higher solids retention and lower freshwater usage. *Bioresource Technology* 98 (17), 3375–3383.

Summerfelt, R.C., Penne, C.R., 2005. Solids removal in a recirculating aquaculture system where the majority of flow bypasses the microscreen filter. *Aquacultural Engineering* 33 (2), 214–224.

Summerfelt, S.T., 1996. Engineering design of modular and scaleable recirculating systems containing circular tank, microscreen filters, fluidized-sand biofilters, cascade aerators, and low head or u-tube oxygenators. In: *Successes and Failures in Commercial Recirculating Aquaculture*, Editors Northeast Regional Agricultural Engineering Service (NRAES). NRAES-98, 1, pp. 217–244.

Tchobanoglous, G., Burton, F.L., 1991. *Wastewater Engineering: Treatment Disposal and Reuse*, 3rd ed. McGraw-Hill, New York, p. 1334.

- Timmons, M.B., Ebeling, J.M., 2007. *Recirculating Aquaculture*. Cayuga Aqua Ventures, Ithaca, NY.
- Ulgens, Y., 1992. Undersøkelse av utslippsmengder, renseutstyr og slambehandlings-metoder ved settefiskanlegg. Delrapport III: Renseeffekt og driftserfaring med UNIK hjulfilter type 1200. SINTEF NHL Report No. STF60 A92100. SINTEF, Trondheim, Norway, 25 pp (in orwegian).
- US Army, 1978. *Engineering and Design – Design of Wastewater Treatment Facilities Major Systems*, Engineering Manual No. 1110-2-501, U.S. Army, Washington, DC.
- Wheaton, F.W., 1977. *Aquacultural Engineering*. Wiley, Chichester, UK.
- Wong, K., 2001. Enhanced solids removal for aquaculture raceways. Doctoral Dissertation. Biological and Agricultural Engineering, University of California, Davis, CA.
- Zhu, S., Chen, C., 2001. Effects of organic carbon on nitrification rate in fixed film biofilters. *Aquacultural Engineering* 25 (1), 1–13.