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Article

Design of Closed Seawater Recirculating Aquaculture System for Korean Rockfish *Sebastes schlegeli* Culture

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Abstract : Recirculating aquaculture system (RAS) consists of different treatment compartments that maintain water quality within the ranges commonly recommended for fish cultures. However, common RASs still exert considerable environmental impact since concentrations of organic matter and nutrients in their effluents are high. Compared with the traditional RAS, the model RAS developed here use a sedimentation basin for digestion purposes and then use the released volatile organic matter to stimulate a denitrification process. Different treatment compartments for solids, total ammonia nitrogen, and nitrate removal have been reviewed. This paper provides the basic information on designing different treatment compartments as well as the engineering criteria in closed seawater RAS, consisting of circular tanks for fish cultures; dual drain systems, sedimentation basins and foam fractionators for removal of solids; nitrification biofilters for TAN removal; denitrification biofilters for nitrate removal; and aerators for aeration. The main purpose is to outline a common procedure in designing of closed RAS for marine fish culture with an emphasis on easy management and low expense, as well as reduction of the environmental impact.

Key words : recirculating aquaculture system, nitrification, denitrification, solid removal of solids

1. Introduction

Aquaculture has been the fastest growing food-producing sector in the world, with an annual growth rate of almost 10% between 1984 and 1995 (FAO 1997). Decreased capture and increased demands for seafood have led to the quick development of marine aquaculture systems. However, the marine aquaculture system can only be successful if it is cost effective, socially responsive, ecologically sustainable, and scientifically sound (Davis and Arnold 1998). The outbreak of disease and increased concern about environmental impacts of aquaculture encouraged the development of recirculating aquaculture systems (RAS). Compared with the traditional aquaculture systems, RAS has many advantages, including reduced requirements for appropriate water resources, complete environmental control, and the availability of quality controlled products (Van Gorder 1994).

The most critical treatment processes for a recirculating aquaculture system are aeration (supplying oxygen), clarification (solids removal), biofiltration (ammonia, nitrite, and BOD removal) and degasification (carbon dioxide removal), which are all linked by means of circulation (Malone and Beecher 2000). Usually, aeration and degasification can be conducted simultaneously in one operation unit such as a low head oxygen contactor, packed column oxygenator, U-tube system or simply an air blower (Watten and Todd Beck 1985; Dwyer and Peterson 1993; Wagner *et al.* 1995; Vinci *et al.* 1997). In RAS, ammonia and solids removal are of critical importance.

Many recirculating aquaculture systems have been developed (Chen *et al.* 1989; Menasveta *et al.* 1989, 1991, 2001; Millamena *et al.* 1991; Heinen *et al.* 1996; Twarowska *et al.* 1997; Davis and Arnold 1998; Greiner and Timmons

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1998; Singh *et al.* 1999; Lorsodo *et al.* 2000; Ridha and Cruz 2001) and these systems maintained good water quality for fish or shrimp cultures. Still, these systems can exert considerable environmental impact since high concentrations of organic matter and nutrients are found in their effluents. Though nitrate is generally considered nontoxic to fish (Bromage *et al.* 1988), high nitrate levels are reported to have an impact growth rates (Muir 1982). Hrubec *et al.* (1996) found that prolonged exposure to elevated levels of nitrate may decrease immune response, induce hematological and biochemical changes which are indicative of a pathologic response, and may increase mortality. In terms of total nitrogen management another biological process, denitrification, must be included (Spotte, 1979). The development of an integrated nitrogen removal system that includes nitrification and denitrification processes is essential to the advent of commercial biosecure aquaculture systems (Lee 1995; Lee *et al.* 2000). Success of a truly closed, recirculating design will allow the fish culture system to be located in any area where seawater could be transported or artificial seawater made.

Closed seawater recirculating systems for shrimp culture have been developed (Millamena *et al.*, 1991). In this system, external carbon sources were used to mediate denitrification. Recently, Shnel *et al.* (2002) evaluated the performance of a zero-discharge tilapia recirculating system featuring an anoxic treatment stage, where sludge was biologically digested and nitrate was reduced to nitrogen gas, eliminating the requirement of external carbon sources. The technical feasibility of zero-discharge recirculating aquaculture systems incorporating denitrifiers fed with endogenously produced carbon has been studied by many researchers (Kaiser and Schmitz 1988; van Rijn and Rivera 1990; Arbiv and van Rijn 1994; Schuster and Steltz 1998).

The purpose of the present study is to provide some basic design criteria in designing closed seawater RAS for Korean rockfish culture based on existing information. Korean rockfish is commonly cultured and commercially important in Korea. Various aspects of different treatment compartments have been reviewed and a model lab-scale closed RAS has been developed. The principal compartments of the model RAS include: a sedimentation basin and a foam fractionator for solids removal; styrofoam bead filters for TAN and nitrite nitrogen (NO_2-N) removal; a sand filter for nitrate removal; a circular tank for fish culture; an air blower for aeration; and a heating system for preventing temperatures from dropping to excessively low levels. It should be noted that although a variety of commercially viable designs and technologies exist, the present design is based on the concept that the system should be constructed at low cost and operated easily.

2. Design of the different compartments

Culture tank

Geometry, water velocity, and flow patterns are particularly important design considerations in designing a fish culture tank. Culture tank design has a dominating influence on the use of water resources, feed input, stock management, and waste discharge (Summerfelt *et al.* 2000). Circular tanks have been widely used because circular tanks have many advantages: they can provide a uniform culture environment and can be operated under a wide range of rotational velocities; they can be used to rapidly concentrate and remove solids that tend to settle; they allow for good feed and fish distribution and visual observation of waste feed to enable satiation feeding (Timmons and Summerfelt 1997; Timmons *et al.* 1998). A circular tank with a diameter of 110 cm and a depth of 80 cm (volume, 0.75 m^3) was selected as the culture tank in the model RAS. The bottom of the tank has a slight slope from the base of the sidewall to the central drain pool.

Once the shape of the tank is determined, the water distribution device and the velocity of the water rotating in the circular tank become the crucial factors for determining the tank's self-cleaning capacity. Usually, a combination of horizontal and vertical branches achieves uniform mixing in the culture tank (Skybakmoen 1993). The rotational velocity in the tank can be controlled by either the size and number of orifices used, or the inflow rate. The inflow pipe with orifices drilled on it was vertically positioned near the culture tank wall as shown in Fig. 1. The diameter and orifice varied according to the size of culture tank and the desired rotational velocity as well as the inlet water

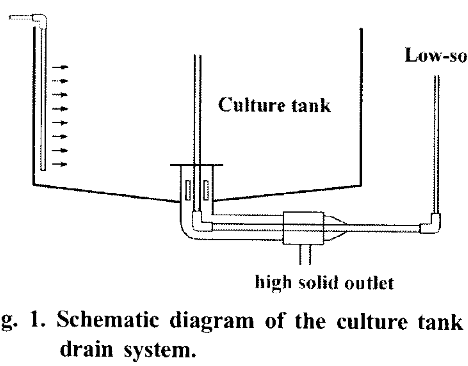

Fig. 1. Schematic diagram of the culture tank and dual-drain system.

volume. Losordo and Westers (1994) reported that rotational water velocity of 0.5-2.0 times fish body length per second is optimal to maintaining fish health, muscle tone, and respiration. For driving solids to the central drain, the velocity should be greater than approximately 15-30 cm/sec (Burrows and Chenoweth 1970; Mäkinen *et al.* 1988). The rotational velocity in the present experiment was set at around 20 cm/sec at circumference and adjusted accordingly later. In the model RAS, the diameter of the orifice is 6 mm and totally 30 orifices were equally spaced along the inflow pipe (diameter, 30 mm). A bypass with valve was used to adjust the water flow rate to the culture tank. The total area of the orifice should usually be equal or slightly greater than the cross area of the inlet pipe. In any case, it is difficult to accurately define the size and number of orifices. However, using a somewhat larger size and more numbers would never hurt.

Removal compartments for solids

Solids generation, characteristics and impacts

The solids in aquaculture systems are mainly composed of uneaten feed particles, feces, and bacteria consortia. Decomposition of these solids can lead to consumption of oxygen and release of inorganic nutrients. The impacts identified also include direct damage to fish gills and mechanical clogging of biofilters (Liao and Mayor 1974; Spotte 1979; Chapman *et al.* 1987). So, removing solids from the culture water becomes another key factor, along with TAN removal, determining the success or failure of a RAS. Also, many environmental regulatory agencies have considered the solids load as one of the main criteria for evaluating aquaculture systems.

The quantity of solids produced in a RAS can be evaluated by considering the feces production, uneaten feed, and bacterial biomass. Some investigations have been done for several species (Liao and Mayor 1974; Malone *et al.* 1990; Wimberley 1990) and an average value of around 30% of the feed applied is commonly recognized. Since no detailed information about the feces production of Korean rockfish is available, the total solids production is assumed to be 30% of the feed applied here.

The generated solids can be divided into two categories: settleable solids and non-settleable solids. In the designed model RAS, concentration of solids in culture tank water is controlled by the combinations of dual-drain system, sedimentation basin, foam fractionators, and biofilters.

Solids removal technologies

Many technologies have been developed for the removal of solids in aquaculture systems. Introduction of a dual drain system has made the in-tank separation possible and subsequently improves the efficiency of subsequent treatment. The dual drain system will be discussed in detail in the section to follow. The high solids outlet water from a dual drain system should be treated further for solids separation and many systems have been developed for removing solids from aquaculture systems, including sedimentation basins, microscreens, hydrocyclones, constructed wetlands, foam fractionators, etc. (Wheaton 1977; Henderson and Bromage 1988; Chen *et al.* 1993; Schwartz and Boyd 1995; Summerfelt *et al.* 1999). Among them, sedimentation is the simplest. Sedimentation basins require little energy input, are cheap to construct and easy to manage. So, they have been the most common solids removal methods used not only in the municipal wastewater treatment system, but also in many aquaculture systems (Jones *et al.* 2001; Shnel *et al.* 2002). Stechey and Trudell (1990a) found that properly designed and operated settling systems could achieve solids removal efficiencies approaching 90%. However, sedimentation is usually believed to be ineffective for fine suspended solids removal (Chen *et al.* 1994). Another disadvantage is the low hydraulic loading rate required for effective solids removal. Microscreens such as triangle filters (Mäkinen *et al.* 1988) and rotating microscreens (Libey 1993) can reduce solids to as low as 5 mg/*l* (EPA 1975). However, they require low hydraulic loading and frequent backwashing, especially when using a fine mesh screen. Hydrocyclones, which employ the principal of centrifugal sedimentation, has limited application in aquaculture systems due to poor removal of fine particles and the need for a large pump to maintain flows with high headloss (Chen *et al.* 1994). Compared with the sedimentation basin, microscreen and hydrocyclones should be carefully managed by trained people. Foam fractionators have been widely investigated in aquaculture systems (Chen 1991; Peng 2003) and they are usually considered effective for removing fine solids. So, a combination of foam fractionator with other treatment processes may assure better removal of both suspended and dissolved solids.

In-tank solids separation with dual-drain system

The structure of the central drain system plays a key role in controlling the solids removal, especially the separation of solids within culture tank. The dual-drain system has the potential to improve solids removal within recirculating systems (Losordo *et al.* 1995) and enables the majority of solids to be removed in a relatively small flow, exiting the tank through one outlet, while the majority flow with low solids concentration through another outlet (Summerfelt *et al.* 2000). A dual drain system has long been used in Korea (Kim and Jo 1977; Kim 1980).

In the model closed RAS, a modified dual drain system was constructed with two concentric pipes (Fig. 1). The inner pipe had a diameter of 3 cm and a height of 70 cm and was connected to the outside standpipe with low-solids outlet. The outer pipe had a diameter of 50 mm and a height of 20 cm. Six vertical perforated slots (1.5 cm by 15 cm) were evenly spaced along the pipe. Slots were used rather than round holes since slots are easier to wash, provide greater open area, and do not clog as readily as round holes (Piper *et al.* 1982; Sedgwick 1985; Pankratz 1995). The high solids outlet was connected to the sedimentation basin.

Recently, settled solids have been reportedly concentrated in 5-20% of the total flow that leaves the bottom center drain of circular culture tanks when the remainder of the flow leaving the tank is withdrawn through pipes above the bottom drain or part-way up the tank's side wall (Mäkinen *et al.* 1988; Eikebrokk and Ulgenes 1993; Lunde *et al.* 1997; Timmons and Summerfelt 1997). The turnover rate of the culture tank is set at 1 hour, which equals the total flow rate of 600 L/hour. So, the higher solids outlet rates should be around 30-120 L/hour.

Sedimentation basin

Selection of the best treatment system for solids removal is difficult given the variety of processes available, lack of a uniform methodology for evaluation of the effectiveness, and an accounting of the economic and practical considerations. Form the point of view of easy management, a sedimentation basin could be the best choice (Lekang *et al.* 2000, 2001). Besides, a sedimentation basin can be alternatively used as an algae or bivalve culture unit (Wang 2003) or can be installed with other treatment units, such as a combination of a sedimentation basin with a lamella settler (Lekang *et al.* 2001). For compensation of the turbulence caused by a scour in the sedimentation basin, it is better to increase the surface area of the sedimentation basin. Also, the inflow stream should be introduced evenly to the cross-section of the sedimentation basin. A weir was used at the inflow section to ensure the even distribution of inlet water and also to reduce the inlet velocity (Fig. 2). Similarly, another weir was used before the outflow pipe to assure a uniform discharge rate and baffles were used inside the sedimentation basin to enhance settling of solids.

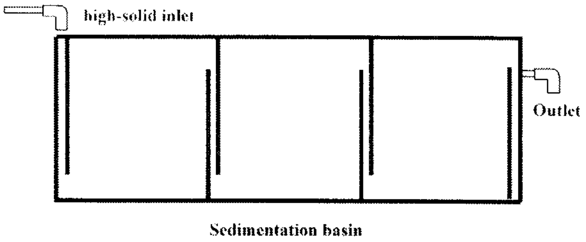

Fig. 2. Schematic diagram of the sedimentation basin.

The key factor for designing sedimentation basins is the volumetric flow rate per unit surface area of the basin and the most important is that the flow rate through the sedimentation basin should be slow enough to ensure the settling of solids. Stechey and Trudell (1990b) found that the appropriate overflow rate for design of the sedimentation basin in an intensive salmonid aquaculture system typically ranges between 40-80 $m^3/m^2 \cdot$ day and at this overflow rate, approximately 65%-85% of total suspended solids (TSS) would be removed. McLaughlin (1981) and Mudrak (1981) reported that a greater ratio than 80% of total solids were removed at a designed overflow rate of between 21.4 and 120 $m^3/m^2 \cdot$ day. Parjala (1984) recommended a maximum horizontal flow rate of 2-5 cm/sec in aquaculture sedimentation basins. So, rectangular basins with a flow direction along the long side was used here to ensure the settling of solids and a reduction of the scouring effect. A relatively low overflow rate of around 5 $m^3/m^2 \cdot$ day is selected as the designed value, since in the model RAS the sedimentation basin not only serves the pupose of removing solids, but also serves for digestion of organic matter. A relatively small sedimentation basin should also be considered in the present design. The volumetric flow rate through the basin is set at around 100 L/hour, which is in the range of 30-120 L/hour for the high solids outlet flow calculated above. Though the sedimentation of solids is independent of basin depth, very shallow basins would induce excessive scouring. The height of the basin is set at 60 cm, which is similar to that used by Shnel *et al.* (2002). The surface area of the sedimentation basin is calculated as follows (Chen *et al.* 1994):

$$A = \frac{Q}{V} = \frac{100 \times 24 \div 1000}{5} = 0.48\ m^2$$

Where: A, surface area of the basin; V, overflow rate (m^3/day); Q, volumetric flow rate through the basin ($m^3/m^2 \cdot$ day). The dimension of the sedimentation basin is eventually set at a 1.2 m length, a 0.4 m width , with a depth of 0.6 m.

Foam fractionator

A sedimentation basin is not efficient for fine solids removal and aeration is a necessity in an intensive fish culture system, so a foam fractionator is used here mainly for removal of fine solids. As there is no detailed information on foam fractionator designs in aquaculture systems, the foam fractionator used in previous experiments (Peng *et al.* 2003) is used here. This foam fractionator was made of acrylic pipe with a diameter of 20 cm and a height of 120 cm. The water outlet was located near the bottom and inlet water was introduced on top of the column. This formed a counter-current flow pattern in the foam fractionator column. A 40-mm PVC elbow was installed at a 90-cm height for foam collection. An air distribution system was used, including an air blower, an air flow meter (Dwyer instruments, model RMA), and a pressure regulator. Two coarse air stones with a diameter of 3.2 cm and a length of 9 cm were used to disperse air bubbles.

Biofiltration

Ammonia production in RAS

Ammonia production in recirculating aquaculture systems mainly related to the ammonia excretion rate of the cultured species. Also, the feeding strategy, feed composition, and temperature etc. all exert some effects. Ammonia excreted by fish or produced through degradation of organic matter in aquaculture systems must be removed since ammonia is highly toxic to fish.

Meade (1985) reviewed information on ammonia production in different fish species and found ranges of 20-78.5 g/kg feed. Three out of the five production rates cited by Meade (1985) were between 31-37.4 g/kg feedday. Kim and Chin (1995) did some research on the ammonia excretion rates of juvenile Korean rockfish and reported similar results. According to the literature cited and values commonly used (Wheaton *et al.* 1994), in the case of a lack of accurate data on the ammonia excretion rate of cultured species, TAN production of 30 g/kg feed is used here. The whole system was designed to support a daily feed loading rate of 0.4 kg/day. The daily TAN production would be around 12 g.

Ammonia removal technologies

Fixed film biofilters are now commonly used in fish culture facilities since salt quickly saturates the adsorption sites and thus makes ion exchange not applicable (Hochheimer and Wheaton 1988). There are many types of fixed film nitrification biofilters and those most commonly used in aquaculture include submerged biofilters, trickling filters, biodrums, biodisks, fluidized beds, and bead filters (Wheaton *et al.* 1994). Submerged biofilters depend on water to transfer oxygen to nitrification bacteria and need energy for backwashing. Submerged bifilters usually use media with low specific surface area. Compared with submerged biofilters, trickling filters can absorb oxygen from air. However, the media in trickling filters usually have a lower specific surface area than those used in submerged biofilters. Headloss across biodrums and biodisks are usually low compared with other biofilters. The disadvantage is that they require a somewhat sophisticated mechanical control system. Fluidized bed and bead filters are relatively new and the research base on them is limited. Though backwashing is usually needed for maintaining optimal performance, they serve as both biological and mechanical filters (Wheaton *et al.* 1994). Styrofoam bead filters, which was tested previously in simulated seawater systems and showed a reasonable TAN removal ability (Peng 2003) are used for biofiltration in the model RAS in consideration of the low price, high specific surface area, and easy management of this kind of biofilter.

Nitrification styrofoam bead filter

Though ammonia production is not constant, experience has shown that an average hourly ammonia loading calculation based on daily ammonia loading is adequate to determine the potential for ammonia concentrations becoming lethal in a closed system (Wheaton *et al.* 1994). So, the effect of peak TAN concentrations was neglected here in designing the nitrification biofilter. According to the TAN conversion rates of 284 $g/m^3 \cdot day$ in styrofoam bead filters (Peng, 2003), the volume of the media needed for removal of TAN produced at the highest feed loading rate of 0.4 kg feed/day can be calculated as (Wheaton *et al.* 1994)):

$$\text{media}_{\text{volume}} = \frac{P_{TAN}}{R_{TAN}} = \frac{12\ g/day}{284\ g/m^3 \cdot day} = 0.042\ m^3$$

Where, P_{TAN}, TAN production in RAS (g/day); R_{TAN}, Daily volumetric TAN removal by nitrification biofilters ($g/m^3 \cdot day$).

The volume of biofilter media needed is about 42 L. So, two styrofoam bead filters were used in the model RAS, each containing 20 L media, instead of one to minimize the risk of failure in biofilters (Fig. 3). The dimension of biofilters and other detailed information are the same as those described by Peng *et al.* (2003).

Denitrification sand filter

Closed recirculating aquaculture systems where there is

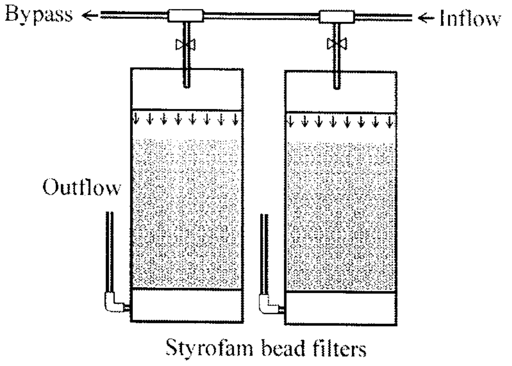

Fig. 3. Schematic diagram of the two Styrofoam bead filter used (Arrows indicate the direction of waterflow).

no significant primary productivity exhibit increasing nitrate concentrations over time. Hrubec *et al.* (1996) found that prolonged exposure to elevated levels of nitrate may decrease the immune response, induce hematological and biochemical changes, which are indicative of a pathologic response, and may increase mortality. Another problem associated with high nitrate concentrations in a fish culture system is the potential formation of nitrite in oxygen-poor zones. Discharge of effluent water is an additional problem related to nitrate-rich fish culture systems.

Most denitrification reactors employed in aquaculture systems are based on immobilization of denitrifiers on media and supply of a suitable carbon source. There are many factors including inlet DO concentrations, COD/nitrogen (C/N) ratios, and hydraulic residence time influences the performance of denitrification biofilters. Increment of denitrification efficiencies have been reported with the increase of inlet C/N ratios and hydraulic residence time (Oh *et al.* 1997; Lee *et al.* 1999). Higher inlet DO concentrations lowered denitrification efficiencies (Terai *et al.* 1987; Oh *et al.* 1997).

Various carbon sources have been used to stimulate denitrification such as methanol, acetic acid, etc. Another cheaper carbon source for denitrification is the organic carbon produced in the fish culture units through the fermentation process (Aboutboul *et al.* 1995; van Rijn *et al.* 1995; Lee *et al.* 2000). The potential use of this carbon source for nitrate and phosphorus removal has been studied by many investigators (Arbiv and van Rijn 1994; Barak and van Rijn 2000a, b, c; Shnel *et al.* 2002; Barak *et al.* 2003). Here, in the present model system, a combination of sedimentation basins for organic matter degradation and sand filters for nitrate removal using the organics produced in the sedimentation basin, were employed. Since no detailed information about the use of these denitrification biofilters in seawater RAS is available, a relatively large dimension of the denitrification sand filter was used in the model RAS when compared with that used by Shnel *et al.* (2002). The volume of the sand filter was 35 L (height, 200 cm; diameter, 15 cm) and contained 10 L of sand (Fig. 4). Size distribution of sand was in the range of 0.5-1.5 mm. The filter column was made of a PVC pipe with five sampling ports along the column and one grating was placed inside to hold the media. The sand filter was initially designed to operate in an upflow fluidized mode using a bypass to adjust the flow rate through the sand filter.

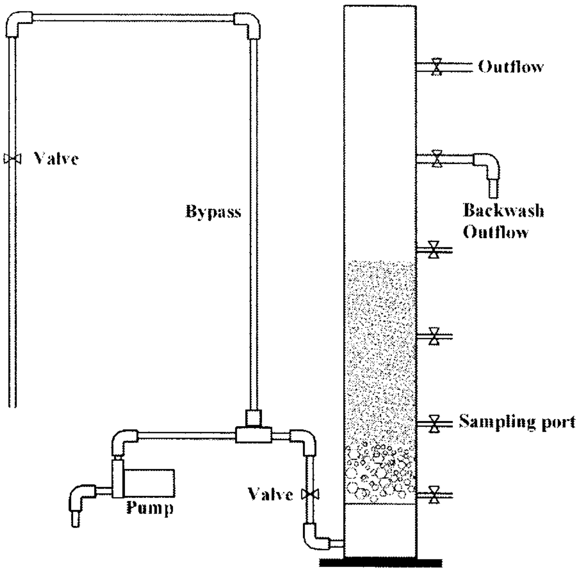

Fig. 4. Schematic diagram of the denitrification sand biofilter.

Aeration and degasification

Oxygen should be supplied to an intensive aquaculture system since dissolved oxygen is typically the first water quality variable to limit production. Many kinds of equipment, including pure oxygen contact systems and air water contactors have been developed. Carbon dioxide is one of the important considerations in intensive aquaculture systems. Carbon dioxide may lower pH to stressful levels, suffocate animals even in the presence of oxygen, and reduce the efficiency of biological filters (Grace and Piedrahita 1994). Grace and Piedrahita (1993, 1994) and Summerfelt (1993) have reviewed and reported criteria for carbon dioxide stripper design within aquaculture systems.

Totally two air blowers were used in the present design, one for foam fractionators and the other one for aeration in the water sump and fish culture tank. No special degasification device was employed because the dimension of the system was small and foam fractionation and aeration were provided.

pH control

The equilibrium of many of the chemical parameters important in aquaculture, especially the equilibrium of ammonia and carbonic acid systems, is controlled by pH (Summerfelt 1996). Changing the system pH only 1 unit changes the corresponding equilibrium carbon dioxide and ammonia concentrations 10 fold. Chemical treatment can be used to maintain pH that will minimize the potential toxic effects of ammonia and carbon dioxide in RAS. Sodium bicarbonate is commonly used to maintain system pH levels.

3. System layout and comparison with traditional RAS

The schematic diagram of the designed system consisting of a circular culture tank, two nitrification bead filters, a denitrification sand filter, a sedimentation basin, a foam fractionator, a water sump, and pumps is shown in Fig. 5. Low solids outlet water is let to two bead filters through a standpipe before going to the water sump. The hydraulic loading rate is set around 100 m^3/m^2 filter in the top surface areaday for each styrofoam filter based on the experimental results obtained by Peng (2003). The excess outlet water directly falls to the water sump. From the sump, water is pumped back to the culture tank. The flow rate to the culture tank is controlled by a bypass system and excess water flows to the foam fractionator. High solids outlet water from the culture tank is led to the sedimentation basin. The denitrification sand filter is connected to the sedimentation basin. The excess water from the sedimentation basin overflows to the water sump.

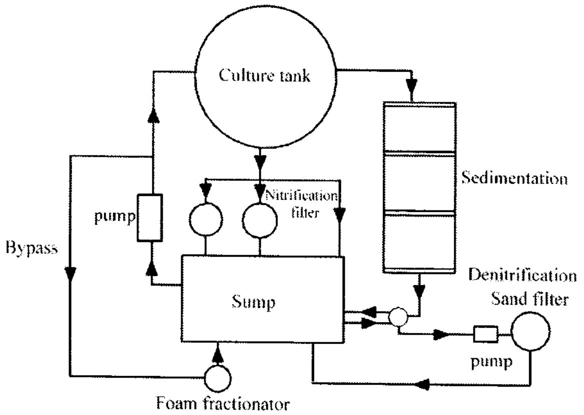

Fig. 5. Schematic diagram of the seawater recirculating aquaculture system. Arrows indicate the direction of water flow.

Traditional RAS without a denitrification unit will usually experience high NO_3-N concentrations in culture water and releasing NO_3-N rich water will induce environmental problems. Another problem associated with high nitrate concentrations in a fish culture system is the potential for nitrite formation in oxygen-poor zones as mentioned previously. Even in RAS featured with a denitrification unit, but using external carbon sources for stimulating denitrification, high additional capital and operating costs will be involved. So, developing zero discharge RAS using internal carbon sources to stimulate the denitrification process is promising. Zero discharge freshwater RASs have been developed by a number of investigators (Schmitz-Schlang and Moskwa 1992; Shnel *et al.* 2002) and the performance of these systems has proved the technical feasibility of this kind of system.

In conclusion, the technologies described here consist of the common yet effective unit processes available to recirculating systems design with emphasis on easy management and low expense when considering the large investments and high operating expense related to other production technologies. The concept, criteria, and relationships provided here would give some basic information in designing closed recirculating aquaculture systems. However, the small-scale system designed here makes direct application of this methodology to large- scale recieculating system design questionable and performance of this system should be evaluated.

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