Development Rationale for the Use of Marine Recirculating BioFilters to Simplify Management Strategies and Reduce Costs Associated with Marine Aquaculture Systems

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It is now generally recognized that the growing global demand for marine products has exceeded the sustainable limits of natural marine systems. The shortfall in fisheries production is now driving the development of marine aquaculture technologies on many fronts. Recirculating systems are regarded as critical components of many developmental schemes, whether as supporting systems for offshore cage culture, as broodstock and nursery facilities serving pond production sites, or as autonomous growout facilities. The recirculating format may avoid many of the land use and environmental conflicts that have been associated with pond aquaculture, especially those involving the development of marine aquaculture facilities in proximity with coastal wetlands and lowlands. Recirculating schemes are also well suited for maintenance of valuable broodstock, off-season spawning, and the production of healthy disease-free fingerlings.

This paper presents the development rationale for a new class of floating bead bioclariﬁers that have been under development for several years. These filters were developed in anticipation of an expanding interest in marine aquaculture.

Motivations

Malone and Beecher (2000) summarize design and performance characteristics for floating bead filters, which have been widely utilized over the last decade in educational, research, and commercial facilities. The criteria presented in this paper are based on the performance of propeller-washed (Malone, 1992) and bubble-washed (Malone, 1993) bead filters. The paper describes the use of floating bead filters applied to recirculating systems as bioclariﬁers that simultaneously provide both clariﬁcation and bioﬁltration
support. These floating bead filters were developed and refined with continuous feedback from the commercial sector. This feedback provided an invaluable foundation for improvements in the floating bead filters, and, slowly identified the limitations associated with the current hull designs, washing strategies, and media.

Approximately five years ago, research team members initiated an effort to develop a new class of filters that would be well suited to deal with some of the challenges that face the recirculating industry in upcoming years (Table 1).

**Table 1: Motivations stimulating the development of the Marine Recirculating Bead Filter**

<table>
<thead>
<tr>
<th>Objective</th>
<th>Means</th>
<th>Result</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Improve Nitrification Capacities</td>
<td>Modified Media</td>
<td>50 percent improvement in Volumetric Nitrification rates</td>
<td>DelosReyes et al, 1997</td>
</tr>
<tr>
<td></td>
<td>High Frequency Backwashing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce Headloss</td>
<td>Modified Media</td>
<td>Airlift operation at high loadings demonstrated</td>
<td>DelosReyes et al., 1997</td>
</tr>
<tr>
<td></td>
<td>High Frequency Backwashing</td>
<td></td>
<td>Loyless and Malone, 1998</td>
</tr>
<tr>
<td>Eliminate backwashing Waterloss</td>
<td>Internal Sludge Separation</td>
<td>No backwashing loss; losses associated with sludge removal negligible</td>
<td>Possible benefits and/or issues associated with anoxic sludge storage</td>
</tr>
<tr>
<td>Eliminate corrosion</td>
<td>Plastic or Fiberglass parts</td>
<td>Metal parts completely eliminated</td>
<td></td>
</tr>
<tr>
<td>Reduce backwashing Labor</td>
<td>Pneumatic Backwashing</td>
<td>Automated Backwashing; manual sludge removal</td>
<td>Backwash frequency control by air flow rates; sludge removal can be automated with minimal electronics</td>
</tr>
<tr>
<td>Minimize electronics</td>
<td>Pneumatic Triggers</td>
<td>No electronics timers required</td>
<td></td>
</tr>
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</table>

Of foremost concern was the economic feasibility of recirculation technologies. Although bioclarification capabilities of bead filters can be used to simplify filtration configurations, capital and operating costs remain an obstacle to widespread adoption of recirculation as a production strategy. To attack this issue the research team first sought to develop filter designs that would display elevated nitrification capacities. The
nitrification capacity controls that size of the filter used in any bioclarifier application, so, improvements in nitrification capacity would reduce the filter size, thus reducing capital costs.

Further, reduction in operating costs could be realized in some applications by utilization of airlift circulation to move water instead of water pumps. Airlift pumps rapidly lose efficiency as lift requirements increase and early bead filters were (and still are) often referred to a “pressurized” bead filters. Propeller-washed filters display their best nitrification capacity with a backwash frequency of once every two days (Malone et al. 1993). They were frequently plumbed with additional pressurized devices downstream. Thus, influent pressures in the range of 10 psi were not uncommon in practice. Airlift pumps work best with influent pressures less than 10 psi, therefore headloss has to be minimized. Conversion of bead filters to airlift operation would require substantial reconsideration of bead filter design strategies.

Saltwater recirculating systems are also different from freshwater systems by the corrosive nature of that culture medium. Consequently, although propeller-washed floating bead filters (Malone 1992) are capable of achieving only about two percent water loss with good management, they are unfortunately, equipped with 316 stainless steel screens and mixing apparatus which do corrode. Virtually all individuals involved with marine aquaculture can testify to this issue. The technologies and methodologies, which are currently available to address these problems, add capital and operational costs to a fledgling industry that is already under serious economic pressures.

Obtaining (mixing, hauling, pumping) and maintaining a saltwater environment at a non-coastal location is expensive. Most freshwater recirculating systems replace 3 to 10 percent of their make-up water per day (or more). A generally acceptable practice given the low cost of obtaining high quality, pathogen free freshwater commonly available in moderate quantities. However, it is expensive to operate a marine system in this range unless the facility is located in a prime coastal location. Otherwise, the practical problems of biofouling, variable salinity, high sediment loads, and disease introduction lead to significant costs for pre-treating replenishment water (Huguenin and Colt, 1989). It is not uncommon for fisheries biologists to specify pretreatment of influent waters, including solids removal to 1 micron and disinfection as standard practices for influent treatment systems. In fact, these concerns have led many to adopt artificial sea salts exclusively for their systems. Clearly, there is a need to minimize water loss due to backwashing operations.

It was also clear that there are economic advantages to automating filter backwashing. Backwashing costs can be virtually eliminated while consistency is improved. This has been addressed in recent years by the development of customized solid state controllers that have an excellent record of performance providing for automatic backwashing and sludge removal. However, the boxes and associated automated control valves represent a significant cost factor for smaller bead filters. Additionally, application of electronics to marine systems is complicated by corrosion. It is clear that sophisticated electronics will
play an important part in future marine aquaculture facilities, but their use should be clearly justified. A means of automatically backwashing with a minimum amount of electronic support was viewed as highly desirable.

**MRBF Layout**

The Marine Recirculating BioFilter (MRBF) is conceptually illustrated in Figure 1, and a summary of compartments can be found in Table 2. There are five distinct zones, which are identified by letter. The filtration bed (A) lies at the top of the filter. It is underlain typically by a diffuser screen (7) that evenly introduces the recirculating water into the filter hull. The expansion zone (B) lies beneath the bead bed. This zone receives the beads that have been displaced by air released from the pneumatic charge chamber (C). Backwash waters move from the expansion zone to the charge chamber via the chute (E). The charge chamber consists of an inverted airtight compartment that overlies the sludge storage compartment (D).

**Table 2. Description of MRBF compartments and function.**

<table>
<thead>
<tr>
<th>No.</th>
<th>Compartment</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Filtration bed</td>
<td>Provides for clarification and biofiltration of circulated waters.</td>
</tr>
<tr>
<td>2</td>
<td>Expansion Zone</td>
<td>Provides space for beads dropping down during backwashing.</td>
</tr>
<tr>
<td>3</td>
<td>Chute</td>
<td>Provides conduit for backwash waters to “discharged” charge chamber.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forms sediment trap preventing fine solids from re-entering filtration path during charge cycle.</td>
</tr>
<tr>
<td>4</td>
<td>Charge Chamber</td>
<td>Develops pneumatic charge for backwashing.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Displaces clarified backwash waters returning them to the filtration path.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Airflow determines backwash frequency.</td>
</tr>
<tr>
<td>5</td>
<td>Sludge Compartment</td>
<td>Consolidates accumulated sludge.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some sludge digestion occurs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some denitrification occurs.</td>
</tr>
</tbody>
</table>

The active components of the filter include the influent line (1) which typically injects the water under the bead through a screening/diffuser configuration (6 & 7) that is designed to minimize turbulence under the bed (A) and within the chute (E). Water exits the filter through a screen outlet (2) at the top of the static bead bed. Sludge is removed by an outlet (3) at the bottom of the sludge storage area. Air is slowly introduced into the charge chamber through a regulated input line (4) and transferred from the pneumatic charge chamber to zones A and B intermittently by a trigger device (5).
MRBF Operation

The operation of the MRBF is dominated by the filtration mode (Figure 1).

Figure 1: The basic MBRF filter has five distinct compartments

During this mode of operation the inflow of water (1) and airflow (4) is held constant. Water flowing in through the influent line (1) moves up through the filtration bed where fine solids are captured and dissolved wastes are absorbed by the biofilm coated bead surface. The rate of water inflow is high, typically ranging from 600-900 lpm/m³-beads. These high flow rates are maintained to assure adequate oxygen and ammonia transport to the bed. The air inflow rate into the charge chamber is low, in the range of 3-6 lpm/m³-beads. The trigger (5) is tuned to engage when enough air has accumulated in the charge chamber to assure a good wash of the bead bed. Optimum filter performance under heavy loading can be expected to occur with a backwash frequency in the range of 1-6 hrs. Thus, the airflow rate is simply set to assure that the critical charge chamber volume will be reached at the desired time interval. Air flows into the charge chamber, dirty backwash water is slowly displaced back up the chute and into the filtration pathway. So the air flow rate divided by the cross sectional area of the chute (E) defines the vertical velocity of the escaping water column and, inversely by Stokes law, the size of particle that can escape. Thus, the chute's cross sectional area determines the maximum rate that air can be bled into the chamber. Captured solids fall into the sludge
chamber while the clarified backwash water exits the chute and are re-filtered by the filtration bed.

The alternate mode of operation is the backwash mode (Figure 2). Backwashing occurs very rapidly, typically within 5-10 seconds. The inflow of water and air are not interrupted during backwashing. Backwash water, which accumulates in the charge chamber, is completely displaced by new air entering the pneumatic charge chamber. The trigger rapidly releases the air in the pneumatic charge chamber and the dirty wash waters drop through the chute. The trigger is then closed and another filtration cycle initiated.

Sludge is generally allowed to accumulate before it is removed through the sludge line (3). Consolidation of sludge is generally rapid, and sludge thickening and compaction usually control the maximum length of time between removal. In fish systems, problems can occur with sludge flow after a week or two.

![Diagram of MRBF](image)

**Figure 2.** Backwashing mode of the MRBF.

**Significance**

The MRBF’s pneumatic backwashing feature breaks the linkage between backwashing and waterloss. This linkage has limited optimization of backwash frequencies for a
number of years. This new freedom is likely to be a significant advancement on bead filter bioclarifier application in both the freshwater and saltwater aquaculture areas.

Wimberly (1990) and Sastry et al. (1999) demonstrated the advantages of high frequency backwashing in gently washed formats. In both of these studies “gently-washed” formats required a high frequency of washing (five to eight times daily) to maximize carrying capacities expressed in Kg-feed applied daily per cubic meter of beads (or kg/m²-day). Golz et al. (1999) attributed this to a reduction in heterotrophic competition within the filter’s biofilm (Zhang et al., 1995). Solids accumulation between the beads represents the principal food source for the heterotrophic bacteria, and rapid removal of these solids dramatically reduces their population. The fraction of bacterial activity (measured by oxygen consumption) attributed to nitrifying bacteria dramatically increases once heterotrophic growth has been inhibited and substantial improvements in nitrification capacity result.

One of the principle criticisms against the use of bead filters in the bioclarifier mode has been the recognized conflict (Malone et al. 1993) between solids accumulation and nitrification. Of course, bioclarifiers are designed to capture solids. Use of the high frequency strategy eliminates the issue of interstitial solids accumulation. Recent work in the LSU laboratory (DelosReyes et al. 1997) pushed high frequency washing to the extreme in a demonstration of airlift recirculation, and backwashing the bubble-washed filter as often as once per hour. The combination of high frequency washing and modified plastic media produced the highest sustained volumetric conversion rates (about 700 g/m³-day) that have been observed in recent floating bead bioclarifier applications.

The potential advantages of high frequency washing have been recognized for sometime (Wimberly, 1990). Full commercial implementation was at first limited by labor requirements. This obstacle has been recently been resolved (at least for larger units) by the development of control boxes. And yet, commercial implementation was still prevented in many applications by the waterloss issue. Even freshwater studies such as Sastry et al. (1999) and DelosReyes et al. (1997), had to utilize external settling tanks to recapture backwash waters to stay within the definition of a “closed” recirculation system (<10 percent exchange per day). The MRBF format’s internal solids separation capabilities will finally allow the benefits of high frequency washing to be fully examined by the commercial sector in a practical way.

**MBRF Evaluations**

Development of filters consistent with the MBRF is being attacked on a broad front. Although a single filter configuration has been used as an illustration in this paper, no fewer than 30 drawings have been generated as the general concept has moved to commercial production. Several prototypes have been fabricated and subject to long term evaluations. Highlights of the evaluation program are described below.
A formal evaluation program is being conducted under the auspices of a Department of Commerce Small Business Innovative Research Grant (Drennan, 1997a). This program is focusing on the collection of sustained performance data in support of the marine warmwater growout, recirculating category (Delos Reyes and Malone, 1997). This study is providing documentation of the MBRF format performance on three red drum (Sciaenops ocellatus) fingerling growout units. This study is currently in its third iteration. The two initial filter configurations were constructed in-house and tested. Data from this work has shown that the nitrification rate can be significantly increase by a high rate of backwashing, up to 18 times per day in some cases. These have been replaced by a commercially manufactured prototype. These early studies have provided proof of concept data. But, the specific configurations tested were not able to achieve high performance levels desired because of design problems. The findings from these, however, have dictated a number of essential structural modifications in the current configuration that is currently being stress tested. Three additional low profile MBRF units have been placed in other commercial/research saltwater facilities for evaluations under the same DOC-SBIR grant. These are located in New Hampshire, Alabama and Texas.

A second research effort is employing two distinctly different filters in the MRBF format in support of warm, freshwater growout (Drennan 1997b). This study is supported the USDA Small Business Innovative Research Program. Focus here was placed on maximizing nitrification rates using reformed-floating beads. After two years of study, the system was re-configured with two screenless concentric filters (MRBF’s) with modified and tubular media. These filters are being evaluated against a propeller-washed filter with modified media in an attempt to set a new carrying capacity recommendation.

Three low profile MBRF format filters are being utilized in the research facilities at Louisiana State University. Two of these have been under use for over a year supporting a red drum breeding program under Louisiana Sea Grant College Program Funding. A third is being used to support a marine greenhouse pond configuration currently being evaluated for thermal behavior at the LSU Ben Hur Aquaculture Farm. The Louisiana Board of Regents is currently funding this research. These units have all been installed in airlift formats. Data is currently being collected to document filter nitrification behavior in response to varying temperature regimes presented by the refrigerated indoor conditioning units and the manipulated environment of the greenhouse pond.

Finally, several filters of the MBRF screenless concentric design have been subjected to testing over the last three years. Most of these tests utilized units with volumes of about 0.1 m³ although the largest unit has a bead bed of 0.7 m³. The smaller units have been used to support a range of activities from high-density tilapia growout to filtration of ornamental koi ponds. Early designs suffered from inadequate air pump selection, and were primarily installed to verify long term pneumatic trigger stability. This area of concern has since been addressed and the team now has what we believe is a very robust filter design. The large unit has been placed in three large-scale facilities providing the research team with direct commercial feedback.
MBRF Findings

Filters in the MBRF format have been under laboratory and field testing for the last three years. The introduction of this new technology has been associated with a rapid learning curve for all those involved.

Several dramatically different hull configurations have been tested. A number of these have displayed weaknesses that preclude their commercial introduction. The screenless concentric MBRF units are currently considered very favorably and this configuration will likely be dominant in early commercial production with no fewer than four models being positioned for commercial introduction during the 2000 year. A large-scale, low profile airlift design is currently undergoing final evaluation in a number of locations as well. These early testing programs have raised a number of issues.

First, many trigger designs that have been evaluated, and several have shown to be extremely reliable. Clogging and/or biofouling of pneumatic trigger components are the primary issues of concern. It was anticipated that many filters, particularly airlift configurations, would be buried, thus, reliable performance over a period of years will be demanded of trigger configurations. Although common sense will dictate that triggers in early commercial designs be accessible, trigger failure is not expected. The triggers are now delivering consistent backwashes every few hours, for months with only intermittent adjustments on the air delivery valve.

Virtually all backwashing failures have been associated with pressurized filter configurations operated with relatively low backwash intervals (1-2 per day). These failures are caused by inadequate air pump selection. Air pumps (2-6 psi) and blowers (1-2 psi) commonly used in aquaculture applications have shutoff pressures below the most commonly used water pumps (10-30 psi). Air must be delivered to the pneumatic chamber at the same pressure as the water. With a clean open bed, pressures below the filtration bed are low. A number of inexpensive aquarium pumps can deliver an adequate supply of air. However, when backwash frequencies are low, or system loading is heavy, transition pressure build-ups have a tendency to occur. If these pressures exceed the shutoff pressure of the air delivery system, failure is assured since the beds resistance to water flow only increases without washing. Careful attention to air pump selection eliminates this problem. This problem cannot occur if the shutoff pressure for the air pump is higher than that of the water pump.

The research team has also observed that setting precise backwash intervals with the pneumatic charge chamber is difficult. The varying hull pressures not only impact the rate of delivery, but also, compresses air already in the charge chamber. Since each filter pressurizes at a slightly different rate, it is difficult to precisely set backflush frequencies without some trial and error adjustment. Use of air delivery and pressure gauges can practically eliminate this problem for commercial applications since the filter’s nitrification response appears to be insensitive to small variations in backwash.
frequencies. The triggering mechanisms may have to be modified to facilitate experimental applications that demand reproducibility.

Concerns have been raised in some sectors about the internal storage of sludge in the MRBF sludge chamber. This remains a controversial issue and one that is worthy of further consideration. The default position is to let the sludge accumulate in the internal storage chamber until it is convenient for removal. Convenience quickly translates into high sludge residence times (days to weeks). Accumulated sludge rapidly compresses and decays. It does not interfere with the backwashing of the filter. Researchers have observed volatile suspended solids reductions of 30 percent during the first 24 hours under warmwater conditions (Chen et al., 1997). Extended holding of sludge then is not only more convenient, but also reduces waterloss as a very thick stabilized sludge can be produced. However, this sludge decay is progressing largely in an anoxic environment.

Valid concerns can then be raised about the possibility of deposited sludge producing toxic anaerobic bi-products. Of particular concern are sulfide compounds. Sulfide compounds are known to be toxic at some level to a variety of aquatic organisms. There is no doubt that thick accumulations of the organically rich aquaculture solids will rapidly induce low redox potentials allowing sulfide production. Clearly, if there are concerns about sulfide sensitivity, sludge removable frequencies should be increased. This can be accomplished automatically in an airlift or pumped system for a few hundred dollars using simple controllers and an automated ball valve.

However, there are advocates of extending sludge retention times in recirculating systems. They argue that some form of anaerobic decay is essential to realistically close the recirculating system (Arbib and van Rijn, 1995, Whitson et al., 1993). The degree of control required to safely accomplish the benefits however, is more heavily debated (Lee, 1993; 1994). Certainly, even at this early date it is becoming apparent that the sludge storage chamber in the MRBF format rapidly becomes an anaerobic reactor. Using current bioclarifier design recommendations for warmwater growout conditions (Malone and Beecher 2000) and a modest backwash frequency of 6 times per day, the entire system’s water volume is cycled through the sludge chamber every 4 days before returning to the system. It is not surprising therefore, that no nitrate accumulations have been observed in both marine broodstock and fingerling growout systems that were included in the early testing programs. The cyclically charged sludge storage chamber is potentially a powerful water quality modifier. Inherent protection for the system is provided by the high dilution (about 200:1) that occurs when the charge chamber waters are re-introduced to the filtration pathway. Additionally, it must be assumed that these low levels of anoxic/anaerobic are subject to microbial attack as they pass through the overlying filtration bed. Early users of the MRBF technology, however, should be cognizant of this issue and realize that any degree of sludge retention can be facilitated in the MRBF format.
Summary

After nearly four years of development and two years of evaluations and refinements the first commercial filters following the MRBF format are being introduced. The MBRF format features an internal pneumatic charge and sludge chamber combination that effectively eliminates the linkage between backwashing and waterloss for floating bead bioclariers. Early commercial units will utilize the stacked concentric design. These designs are relatively aggressive washers and have performed well during almost three years of testing. It will be followed shortly by a low profile configuration designed to support airlift applications. These units are expected to facilitate a thorough commercial evaluation of recently developed high frequency washing strategies. Care needs to be taken in the selection of air pumps delivering air to the pneumatic charge chamber so that the circulating water pump does not exceed the shutoff pressure of the air pump. Careful attention should be given to the management of sludge if potential benefits are to be realized without suffering adverse effects of anaerobic by-products such as sulfide that could be potentially introduced.

References


