Use of floating bead filters to recondition recirculating waters in warmwater aquaculture production systems

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Abstract

Floating bead filters (FBFs) are expandable granular filters that display a bioclarification behavior similar to sand filters. They function as a physical filtration device (or clarifier) by removing solids, while simultaneously encouraging the growth of bacteria that remove dissolved wastes from the water through biofiltration processes. Presently, there are two classes of FBFs that exist. Hydraulic and air washed units fall into the ‘gently washed’ category, which display reduced biofilm abrasion during backwashing and must be washed at a high frequency. Conversely, propeller-washed and paddle-washed filters inflict damage to a relatively heavy biofilm during backwashing, and are considered ‘aggressively washed’. FBFs capture solids through four identifiable mechanisms: straining, settling, interception, and adsorption. In the biofiltration mode, bead filters are classified as fixed film reactors, where each bead becomes coated with a thin film of bacteria that extracts nutrients from the recirculating water as it passes through the bed. In this paper the authors first establish application categories and parameters for recirculating system use, then give criterion for the sizing of recirculating system components in tabular form. Sizing variables for FBFs are normalized to the feed application rates, and the primary method for the sizing is based on a volumetric organic loading rate. Evaluation parameter equations are also given for comparison of bioclarifier performance. These equations include volumetric TAN conversion rate (VTR), the volumetric nitrite conversion rate (VNR), and the volumetric oxygen consumption rate of the bioclarifier (OCF). © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Aquaculture recirculating systems; Floating bead filters; Nitrification

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1. Introduction

Advocates of the production of commodity aquaculture products in recirculating systems are confronted with severe economic realities. In many cases, alternate modes of production, including harvesting of natural fisheries, depress prices. The animals not only have to be sustained for extended periods, but also the growout process must be successfully repeated to maintain income. The five major processes (aeration, degasification, clarification, biofiltration, and circulation) must be implemented with components that are affordable, yet, highly reliable.

The aquaculture industry is faced with the serious technical challenge of identifying or developing a cost-effective production format that is capable of consistently producing a high quality product. This must be accomplished in the face of increasing societal concerns about water use, environmental impact, exotic species introductions, disease impacts on natural populations, migratory bird issues and coastal land use; to name a few (Malone, 1994). Traditionally, constructed recirculating systems cannot compete directly with pond production on an economic basis (Losordo and Westerman, 1994). Commercially viable recirculating systems typically exist only where exotic species regulations, weather, or market expectations are incompatible with pond production (Lutz, 1997). The cost of recirculating water-reconditioning systems must be reduced if recirculating systems are to compete directly with other production formats (ponds and net pens). This cost reduction should be made within the context of a system capable of producing good water quality reliably over extended periods of time.

Over the last decade, the unit processes required for treatment of recirculating systems have been clearly defined (Lucchetti and Gray, 1988; Huguenin and Colt, 1989; Rosenthal and Black, 1993). The four most critical treatment processes are aeration (oxygen), clarification (solids, Biochemical Oxygen Demand (BOD)), biofiltration (BOD, ammonia, nitrite), and degasification (carbon dioxide), which all are linked by means of circulation. Systems with extended hydraulic retention times must generally have an alkalinity replenishment regime to compensate for the alkalinity-consuming nitrification reaction. Additional treatment processes are denitrification (nitrate, alkalinity), ozonation (BOD, color), disinfection (pathogens), and foam fractionation (surfactants), which can be required to comply with specific production needs. The rationale for implementation, including both device selection and sizing criteria, vary widely (Parker, 1981; Kaiser and Schnitz, 1988; Losordo and Westerman, 1994; Arbiv and Van Rijn, 1995; Summerfelt, 1995; Twarowska et al., 1995; DeLosReyes and Lawson, 1996; Heinen et al., 1996). However, the ‘unit process’ approach that has been significant to the training foundation of both the environmental and aquacultural engineers, underpins the design strategy in almost every case. This strategy calls for the assembly of a treatment train consisting of a series of focused and optimized operations to meet a stated water treatment need. The unit process concept was developed in an economic reality substantially different from that confronting the recirculating systems engineer. This strategy works well in meeting the technical objectives, but has thus far failed to overcome the severe economic challenge confronting recirculating productions systems.
In this paper, the authors urge the virtual abandonment of this strategy, arguing instead that the multiple treatment objectives normally associated with a complex treatment train must be assigned to one or two treatment components. These are optimized within the context of the broader systems objectives. Failure to meet the high plateau of performance that can be achieved when a treatment train component is optimized with respect to a single objective, may be more than offset economically in both capital and operational costs by the reduction in the number of the components. Additionally, the increased stability or reliability that may result from simplification will contribute possible significant economic benefits to an industry that must maintain active systems continuously for months on end to be profitable.

2. Background

The floating bead filters (FBFs) are expandable granular filters that display a bioclarification behavior similar to sand filters. However, they are specifically designed and managed to enhance their biofiltration capabilities while avoiding the caking problems that plague traditional down flow sand filters when faced with high organic loadings. They function as a physical filtration device (or clarifier) by removing solids, while simultaneously encouraging the growth of desirable bacteria that remove dissolved wastes from the water through the biofiltration process (Malone et al., 1993). FBFs are resistant to biofouling and generally require little water to backwash. Specific surface area of the small (2–3 mm), spherical polyethylene beads typically used for the filtration bed is moderate (1150–1475 m² m⁻³) (Malone et al., 1993). Hull shapes of the floating bead filters vary widely.

The FBFs are operated in the filtration mode most of the time. As the recirculating water passes through the packed bed, suspended solids are captured and the biofiltration processes are active. Periodic cleaning of the bead bed is accomplished by mechanical (Malone, 1992, 1995; Malone et al., 1993, 1998; DeLosReyes et al., 1997b), hydraulic (Wimberly, 1990), or pneumatic (Cooley, 1979; Malone, 1993) means. The objective of the backwashing step is to release solids and excessive biofloc from the beads, thus, restoring hydraulic conductivity. Sludge is removed with or without the benefit of settling, allowing re-initiation of another bioclarification cycle. Floating bead filters should not be confused with dynamic bed filters (Junius and Junius, 1996; Greiner and Timmons, 1998) that may also utilize plastic media and display some bioclarifier attributes. FBFs for the purpose of this paper are assumed to display two distinct modes of functional operation; a packed mode and an expanded or backwashing mode.

2.1. Clarification performance

FBFs capture solids through four identifiable mechanisms, which include strain-
ing, settling, interception, and adsorption. With the exception of adsorption, the solids capture mechanisms are physical in nature and are common to all types of granular media filters. On a single pass basis, they provide almost complete removal of suspended solids above 50 μm and 40–50% removal of fine solids (< 10 μm). In a multi-pass recirculating mode, bead filters provide complete clarification (Ahmed, 1996). They are fully capable of maintaining almost display quality turbidities (< 1 NTU) even in the presence of high loading. Clarification efficiency is rarely an issue for a recirculating bioclarifier application, allowing focus on biofiltration performance.

2.2. Biofiltration performance

In the biofiltration mode, bead filters are classified as fixed film reactors. Each bead becomes coated with a thin film of bacteria that extract nutrients from the recirculating water as it passes through the bed. Heterotrophic and nitrifying bacteria co-exist in the filter. The heterotrophic bacteria oxidize organic carbon, and most species have a higher specific growth rate and higher yield coefficients than the autotrophic nitrifiers do (Metcalf and Eddy, 1991; Henze et al., 1997). In almost every case, the heterotrophic bacteria dominate the biofilm defining the conditions the autotrophic nitrifiers must encounter (Bovendeur et al., 1990; Manem and Rittmann, 1992).

Organic enrichment encourages heterotrophic bacteria growth which compete with the nitrifiers for space and potentially limiting nutrients such as oxygen (Matsuda et al., 1988; Zhang et al., 1995). This phenomenon is not unique to bead filters. Studies by Bovendeur et al. (1990) with trickling filters and Figueroa and Silverstein (1992) with rotating biological contactors both associate increasing BOD levels with declining rates of nitrification. The FBFs recirculating clarification function leads to the interstitial accumulation of organically-rich solids. This condition is controlled in a FBF by backwashing, which removes solids and abrades excessive biofilm.

A FBF’s optimum nitrification performance occurs when sludge accumulation concerns are properly balanced with Mean Cell Residence Time (MCRT) considerations. This is accomplished by adjusting the backwashing intensity and frequency. Extensive experimental studies have been conducted on this aspect of bead filter management, and evaluated by a mathematical model (Golz, 1997). These studies indicate that two broad classes of FBFs exist. Hydraulic and air washed units fall into the ‘gently washed’ category. This type of washing displays reduced biofilm abrasion during backwashing and must be washed at a high frequency. Optimum performance for heavily loaded filters occurs when the filters are washed several times daily (Wimberly, 1990; Sastry et al., 1999). Conversely, propeller-washed and paddle-washed filters inflict damage to a relatively heavy biofilm during backwashing, and are considered ‘aggressively washed.’ They must be backwashed infrequently, usually every other day, to allow growth of biofilm, thus, avoiding MCRT problems (Chitta, 1993; Malone et al., 1993).
2.3. Performance indicators

The volumetric TAN conversion rate (VTR), the volumetric nitrite conversion rate (VNR), and the volumetric oxygen consumption rate of the bioclarifier (OCF) can be used as principal parameters for evaluation and comparison of bioclarifier performance. The volumetric TAN conversion rate can be obtained by using Eq. (1):

\[
VTR = K_c(TAN_i - TAN_E)Q_r/V_b
\]

where VTR = volumetric TAN conversion rate (g TAN m\(^{-3}\) day\(^{-1}\)); \(Q_r\) = flow rate through the filter (l min\(^{-1}\)); \(K_c\) = conversion factor of 1.44; TAN\(_i\) = influent ammonia concentration (mg N l\(^{-1}\)); TAN\(_E\) = effluent ammonia concentration (mg N l\(^{-1}\)); \(V_b\) = total volume of bead media (m\(^3\)).

The actual level of nitrification occurring in the filter may be higher because TAN is a by-product of heterotrophic breakdown of nitrogen-rich organic compounds and biofloc. Despite its limitations, VTR allows the relationship between design and management parameters to be more closely examined.

The volumetric nitrite conversion rate (VNR in g NO\(_2\)-N m\(^{-3}\) day\(^{-1}\)) is defined by Eq. (2):

\[
VNR = VTR + K_c(NO_2i - NO_2E)Q_r/V_b
\]

where NO\(_2i\) = influent nitrite concentration (mg N l\(^{-1}\)) and NO\(_2E\) = effluent nitrite concentration (mg N l\(^{-1}\)).

As this equation illustrates, the readings of influent and effluent nitrite must be combined with the volumetric ammonia conversion rate to determine the level of nitrite conversion activity, since nitrite is being produced as the ammonia is converted within the bead bed. Because of this phenomenon, the apparent nitrite removal efficiency may be near zero (i.e. influent and effluent values are nearly identical), although the filter may be vigorously processing nitrite to nitrate.

The volumetric oxygen consumption rate (OCF in g O\(_2\) m\(^{-3}\) day\(^{-1}\)) is very helpful in the management of bead filters (Manthe et al., 1988). It indicates the total amount of bacterial activity within the filter, and can be obtained using Eq. (3):

\[
OCF = K_c(DO_i - DO_E)Q_r/V_b
\]

where DO\(_i\) = influent dissolved oxygen concentration (mg O\(_2\) l\(^{-1}\)) and DO\(_E\) = effluent dissolved oxygen concentration (mg O\(_2\) l\(^{-1}\)).

OCF measures the combined respiration of the nitrifying bacteria, the heterotrophic bacteria extracting soluble BOD from the water column, and the heterotrophic bacteria responsible for the breakdown of solids (sludge) held in the filter. The apparent oxygen consumption rate of the nitrifying bacteria (OCN in g O\(_2\) m\(^{-3}\) day\(^{-1}\)) can be computed directly from the volumetric conversion rates for nitrification using Eq. (4) since we can estimate the amount of oxygen required for nitrification from chemical equations (Golz et al., 1999):

\[
OCN = (3.47VTR + 1.09VNR) \times 0.92
\]
The factor 0.92 (unitless) corrects for oxygen assimilation during bacterial growth. The volumetric oxygen consumption rate that can be attributed to heterotrophic activity \((OCH\, \text{in}\, \text{g}\, \text{O}_2\, \text{m}^{-3}\, \text{day}^{-1})\) can then be calculated by Eq. (5):

\[
OCH = OCF - OCN
\]  

(5)

The ratio of \(OCN\) to \(OCF\) expressed as a percentage is a valuable indicator of the efficiency of a backwashing protocol. A high \(OCN\) percentage (> 50%) indicates that the nitrifying population is relatively high, i.e. the heterotrophic bacterial population has been successfully controlled without excessive loss of the nitrifying population. The \(OCN\) percentage tends to drop under lightly loaded regimes as the backwashing interval is extended allowing for more complete digestion of accumulated sludges. The nitrification capacity, however, is not adversely impacted as substrate (TAN) availability, not biofilm diffusion characteristics, limit the conversion process under these conditions.

### 2.4. Application categories

The sizing of a FBF is facilitated by identification of three categories of application that are identified here according to a common production objective. The first is the broodstock category. Valuable broodstock are often held at low densities with oversized treatment units to assure a stress-free environment displaying excellent water quality (Watanabe et al., 1998). This category calls for levels of total ammonia nitrogen and nitrite nitrogen less than 0.3 mg N l\(^{-1}\). Low total ammonia nitrogen (TAN) and nitrite concentrations dictate operation of FBFs in a thin film mode of operation, a condition induced by low organic and nitrogen loading levels. For example, the best water quality is often demanded for shrimp maturation (Lawrence and Hunter, 1987). Eggs and fry of many species are very sensitive to water pollution (Holt and Arnold, 1983; Russo and Thurston, 1991). Similarly, display aquaria are often kept in an oligotrophic state to assure that the highest aesthetic standards are encountered.

The second, fingerling category, reflects the need for very good, but not pristine water quality demanded by many species during early stages of life. This category is also compatible with ornamental fish production where concerns about quality dictate improved water quality conditions (Ng et al., 1992; Kaiser et al., 1998). Substrate levels can be allowed to increase to a level (0.5 mg N l\(^{-1}\)) encouraging the development of a healthy biofilm that can be maintained within broad management parameters. Recirculating soft-crab (\(Callinectes sapidus\)) shedding systems (Malone and Burden, 1988b) and soft-crawfish (\(Procambarus clarkii\) and \(P.\, zonangulus\)) shedding systems (Malone and Burden, 1988a; Malone et al., 1996) are designed to display mesotrophic conditions to protect the animals as they pass through vulnerable molting processes.

The third, or growout category, describes the bulk of high-density production systems where risk and economics must be carefully balanced to achieve profitability (e.g. trout \([Salmo gairdneri ]\) — Kaiser and Schmitz, 1988; Heinen et al., 1996); tilapia \([Oreochromis niloticus]\) — Losordo and Westerman, 1994; Twarowska et al.,
1995; DeLosReyes and Lawson, 1996). For this category some deterioration in aesthetics is permitted, but water quality is held below safe levels (TAN and nitrite < 1.0 mg l\(^{-1}\)) to avoid growth inhibition and disease problems. Both organic and nitrogen loading levels are permitted to rise to a level where rapid solids accumulation rate and rapid net biofilm growth dictate careful attention to management factors.

A fourth growout category, undoubtedly, exists for the most tolerant species [e.g. carp (Cyprinus carpio) Arbiv and Van Rijn, 1995; snakehead (Channa striatus), Qin et al., 1997; Kemp’s ridley turtles (Lepidochelys kempi) Malone et al., 1990; alligators (Alligator mississippiensis) DeLosReyes et al., 1997b] that show vigorous growth under deteriorated water quality conditions. Here substrate levels may be allowed to rise to the level where heterotrophic domination limits nitrification conversion rates. Thick biofilms can induce oxygen rather than TAN diffusional limitations (Harremoes, 1982; Rogers and Klemetson, 1985; Zhang et al., 1995; Henze et al., 1997). A submerged biofiltration format may be arguably inappropriate in this category with the floating bead filter operating in a supporting clarification role. This category is not supported here, as the authors are not convinced that the category is ethically appropriate or economically justified since the rise in substrate concentrations induces little treatment advantage. These applications are best handled under the growout category where the tolerance of the species can contribute to the safety factor for the operation.

3. Sizing rationale

The primary method for the sizing (bead volume, \(V_b\)) of floating bead filters is based on a volumetric organic loading rate. This approach assumes: (1) the filter is being employed as a bioclarifier, (2) organic loading is the principal factor controlling nitrification conditions within the bioclarifier, (3) the organic/nitrogen ratio is relatively consistent across a wide spectrum of feeds, and (4) the filter is well managed to sustain nitrification. The ultimate source of organics in a recirculating system is the feed; therefore the FBF sizing criterion, \(\nu_b\), is based upon feed loading. The volume of bead media required for any application, \(V_b\), can then be determined by the rates of the peak feeding rate, \(W\), and the FBF sizing criterion, \(\nu_b\):

\[
V_b = \left[\frac{L(f)}{100}\right]\nu_b
\]

\[
V_b = W\nu_b
\]

where \(L\) = maximum weight of fish in the system (kg); \(f\) = feedrate (percent of body wt. fed \(\text{day}^{-1}\)); \(\nu_b\) = FBF sizing criterion (m\(^3\) kg\(^{-1}\) feed \(\text{day}\)); \(W\) = peak feed application rate (kg \(\text{day}^{-1}\)).

Eq. (6) was developed in an environment where the average protein content of feeds was typically 35%. Variations in feed protein content are normally absorbed in the criterion’s safety factor (\(\nu_b\) values set at 67% of readily achievable peak performance). Furthermore, increasing the protein content of a feed effectively...
lowers the organic/nitrogen-loading ratio to benefit the nitrification process. However, in practice when the protein content is known to be very high, Eq. (6) is modified:

\[ V_b = \frac{L(f)v_b(P/35)}{100} \]

\[ V_b = Wv_b(P/35) \]  \hspace{1cm} (7)

where \( P \) is the protein content of the feed (%).

Peak carrying capacities for the various bead filter models discussed in this paper occur at values from 24 to 32 kg m\(^{-3}\) day\(^{-1}\) when filled with standard spherical beads. The criterion of 16 kg m\(^{-3}\) day\(^{-1}\) (Table 1) has been tested and has proven to be stable in the local commercial sector (Beecher et al., 1997; DeLosReyes et al., 1997a; Sastry et al., 1999). At this feeding level the filters can reliably provide solids capture, BOD reduction, and nitrification, while sustaining water quality conditions suitable for the growout of most food fish species. TAN and nitrite levels can be expected to remain well below 1 mg N l\(^{-1}\). Reduction of the criterion to 8 kg m\(^{-3}\) day\(^{-1}\) allows the reliable maintenance of water quality conditions demanded by the fingerling category. Finally, a loading guideline of 4 kg m\(^{-3}\) day\(^{-1}\) is used for

<table>
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<tr>
<th>Management parameters</th>
<th>Units</th>
<th>Typical operational values observed in practice</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Broodstock</td>
<td>Ornamental</td>
</tr>
<tr>
<td>Feed loading</td>
<td>kg feed m(^{-3}) media day(^{-1})</td>
<td>≤4</td>
</tr>
<tr>
<td>Design TAN</td>
<td>g TAN m(^{-3}) media day(^{-1})</td>
<td>0.3</td>
</tr>
<tr>
<td>Typical TAN</td>
<td>g TAN m(^{-3}) media day(^{-1})</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>VTR</td>
<td>g TAN m(^{-3}) media day(^{-1})</td>
<td>35–105</td>
</tr>
<tr>
<td>Design nitrite</td>
<td>g N m(^{-3}) media day(^{-1})</td>
<td>0.3</td>
</tr>
<tr>
<td>Typical nitrite</td>
<td>g N m(^{-3}) media day(^{-1})</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>VNR</td>
<td>g N m(^{-3}) media day(^{-1})</td>
<td>35–105</td>
</tr>
<tr>
<td>OCF</td>
<td>kg O(_2) m(^{-3}) media day(^{-1})</td>
<td>0.7–2.5</td>
</tr>
<tr>
<td>OCN/OCF</td>
<td>%</td>
<td>25–35</td>
</tr>
<tr>
<td>OCH/OCF</td>
<td>%</td>
<td>65–75</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>20–30</td>
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<tr>
<td>FBF effluent O(_2)</td>
<td>mg l(^{-1})</td>
<td>&gt;3.0</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg CaCO(_3) l(^{-1})</td>
<td>&gt;50</td>
</tr>
<tr>
<td>pH range</td>
<td></td>
<td>6.5–8.0</td>
</tr>
<tr>
<td>Backwash interval</td>
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<td></td>
</tr>
<tr>
<td>Aggressive wash</td>
<td>Days</td>
<td>1–7</td>
</tr>
<tr>
<td>Gentle wash</td>
<td>Days</td>
<td>1–3</td>
</tr>
</tbody>
</table>

* Values derived principally from Wimberly (1990) and Sastry et al. (1999).
breeding and broodstock maintenance programs where pristine conditions are justified by the value of the stock.

An alternate approach to sizing bead filters is in terms of volumetric nitrification capacity (Malone et al., 1993). This criterion is based on a wide spectrum of floating bead (and other) filters that are found to display areal conversion rates with a magnitude of about 300 mg TAN m\(^{-2}\) day\(^{-1}\) in recirculating systems with TAN and nitrite levels between 0.5 and 1.0 mg N l\(^{-1}\). The authors suspect that this plateau of performance reflects TAN diffusion constraints as the biofilm thickens in response to increased loading (Harremoes, 1982; Henze et al., 1997). Below a TAN concentration of about 1.0 mg N l\(^{-1}\), laboratory evidence and empirical observations indicate that conversion rates decline with TAN concentration (Chitta, 1993). Thus, observed VTR values tend to increase with the increasing TAN tolerances (0.3, 0.5 and 1.0) associated with the categories (Table 1). These VTR values can then be used in conjunction with Eq. (2) to estimate the size of the bead filter:

\[
V_b = (1 - I_s)(E_{\text{TAN}})W/VTR 
\]

where \(I_s\) = in situ nitrification fraction (unitless); \(E_{\text{TAN}}\) = TAN excretion rate in g TAN kg\(^{-1}\) feed.

The in situ nitrification fraction recognizes the effect of nitrification occurring on the sidewalls of tanks, and in particular, the systems piping configuration (Mia, 1996). A value of \(I_s\) = 0.3 is conservatively estimated, although values in excess of 50% are frequently observed. The TAN excretion rate is normally assumed to be around 30 g kg\(^{-1}\) for a 35% protein feed used to support warmwater fish (Malone et al., 1990; Wimberly, 1990). If \(E_{\text{TAN}}\) is not known for a feed with substantially different protein content, then the value of \(E_{\text{TAN}}\) can be proportionally adjusted from a known excretion rate for a similar species fed a feed with a known protein content.

The design values given are conservative with the indicated values easily achievable when the filters are managed to sustain nitrification. The values can be expected to hold for fresh and saltwater applications where the temperature is maintained between 20 and 30°C. However, the bead filter nitrification performance can vary widely (Fig. 1), and peak conversion rates are almost always associated with careful management (Wimberly, 1990; Chitta, 1993; Sastry et al., 1999). Bead filters primarily operated for clarification display nitrification performance that are largely supplemental (Mississippi Power and Light, 1991; DeLosReyes, 1995; DeLosReyes and Lawson, 1996).

4. Bioclarifier integration

Although floating bead bioclarifiers can, and often, are used in conjunction with other biofilters, it is the opinion of the authors that the most cost-effective and stable systems will be based upon simplified integrated design strategies that depend entirely on the FBF for clarification and biofiltration. Stability and transferability within the context of an industry that will most likely be implemented by individu-
als with minimal formal training are major underpins to this strategy. This philosophy leads the authors to the conclusion that simple blown air or mechanical aeration devices that inherently address carbon dioxide control best support the FBFs. When implemented with a straightforward alkalinity control program (Loyless and Malone, 1997), this approach addresses pH collapse problems that continue to be a concern in the commercial sector despite the ongoing discussion in the literature (Grace and Piedrahita, 1994; Loyless and Malone, 1998).

The warmwater criteria (Table 2) were developed in support of this strategic approach. Sizing variables are normalized to the feed application rates, $W$ (Fig. 2). These criteria have provided a technically robust foundation for a number of experimental and commercial systems. They are currently used as a guide by the principal floating bead filter manufacturer in the United States (Drennan, 1999) for a wide variety of species, feeds, and filter configurations. This simple sizing chart facilitates preliminary economic analysis and provides a sizing check for more detailed design work. It is presumed that common design practice is followed. In recognition of the variety of conditions and devices encountered, the sizing criteria includes a 33% safety factor. The stated water quality objectives, mentioned earlier, can be reasonably met with a device or rate at two-thirds of the stated value. Additional safety factors are realized from the conservative nature of the target water quality levels.

The growout system volume criterion, $v_v$, is set at 1.67 m$^3$ kg$^{-1}$ feed day to assure stability. For a 1% feedrate ($f$), this results in fish density of 60 kg m$^{-3}$ that has been proven to be stable under the rigors of commercial growout conditions (Beecher et al., 1997; DeLosReyes et al., 1997a; Sastry et al., 1999), when used with a $v_b$ in the range of 0.062 m$^3$ kg$^{-1}$ feed day. At this density, problems with low dissolved oxygen levels during feeding can be managed by feeding frequency, and acute problems with nitrite or ammonia build-up can be detected with a once a day
Table 2
Interim guidelines for the design of recirculating systems employing floating bead bioclarifiers, water pumps, and airstones

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Broodstock systems</th>
<th>Ornamental and fingerlings</th>
<th>Growout applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System volume (m$^3$ water kg$^{-1}$ feed day)</td>
<td>$v_s$</td>
<td>6.66</td>
<td>3.33</td>
</tr>
<tr>
<td>Bead volume (m$^3$ beads kg$^{-1}$ feed day)</td>
<td>$v_b$</td>
<td>0.250</td>
<td>0.125</td>
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<tr>
<td>Circulation rate (l min$^{-1}$ kg$^{-1}$ feed day)</td>
<td>$q_r$</td>
<td>208</td>
<td>83</td>
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<tr>
<td>Air for airstones (l min$^{-1}$ kg$^{-1}$ feed day)</td>
<td>$g_a$</td>
<td>375</td>
<td>375</td>
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<tr>
<td>NaHCO$_3$ dose (g kg$^{-1}$ feed)</td>
<td>$b_a$</td>
<td>242</td>
<td>242</td>
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<tr>
<td>Water replacement (l kg$^{-1}$ feed)</td>
<td>$q_r$</td>
<td>600</td>
<td>204</td>
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<tr>
<td><strong>Common system descriptors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish density (kg fish m$^{-3}$ water)</td>
<td>$100/(v_i 	imes f)</td>
<td>15^e</td>
<td>10$^e$</td>
</tr>
<tr>
<td>System hydraulic residence time (HRT in days)</td>
<td>$1000 v_i/q_i$</td>
<td>11</td>
<td>16</td>
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<tr>
<td>Tank turnover (min)</td>
<td>$1000 v_i/q_i$</td>
<td>32</td>
<td>40</td>
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<tr>
<td>Cumulative feed burden (mg l$^{-1}$)</td>
<td>$10^6 q_i$</td>
<td>1667</td>
<td>4902</td>
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<tr>
<td>Nitrate accumulation (mg N l$^{-1}$)</td>
<td>$30 000/q_i$</td>
<td>50</td>
<td>147</td>
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<tr>
<td>Mixing constraint (mg TAN l$^{-1}$)</td>
<td>$14.58/q_r$</td>
<td>0.07</td>
<td>0.18</td>
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<td><strong>Filter design parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen delivery (g O$_2$ kg$^{-1}$ feed)$^f$</td>
<td>$5.76 q_i$</td>
<td>1198</td>
<td>478</td>
</tr>
<tr>
<td>Oxygen delivery (O$_2$ m$^{-3}$ beads day$^{-1}$)$^f$</td>
<td>$5.76 q_i/v_b$</td>
<td>4792</td>
<td>3825</td>
</tr>
<tr>
<td>FBF TAN loading (g m$^{-3}$ beads day$^{-1}$)$^f$</td>
<td>$21/v_b$</td>
<td>84</td>
<td>168</td>
</tr>
<tr>
<td>FBF feed loading (kg feed m$^{-3}$ beads day$^{-1}$)$^f$</td>
<td>$1000/v_b$</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>FBF hydraulic loading (l min$^{-1}$ m$^{-3}$ beads)$^f$</td>
<td>$q_i/v_b$</td>
<td>832</td>
<td>664</td>
</tr>
</tbody>
</table>

$^a$ Assumes $I_s = 0.3$.
$^b$ Assumes $E_{TAN} = 30$ g TAN kg$^{-1}$ feed.
$^c$ Assumes 4 mg O$_2$ l$^{-1}$ drop.
$^d$ Neglects in-situ denitrification.
$^e$ Assumes $f = 1\%$.
$^f$ Assumes $f = 3\%$. 

inspection or monitoring. At 50 l min\(^{-1}\) kg\(^{-1}\) feed day, the recirculating rate constant, \(q_r\), assures oxygen delivery to the biofilter (Manthe et al., 1988; Sastry et al., 1999). The air delivery rate to the airstones, \(g_a\), is set at 187 l min\(^{-1}\) kg\(^{-1}\) feed day, which balances the need for aeration with carbon dioxide stripping (Loyless and Malone, 1998). Ion balance is normally addressed by sodium bicarbonate addition at a rate (\(b_a = 242 \text{ g kg}^{-1} \text{ feed}\)) that approximately replaces alkalinity lost due to the nitrification processes (Loyless and Malone, 1997). A flushing rate of \(q_f\) at 68 l kg\(^{-1}\) feed or HRT at about 25 days slowly replaces the recirculating waters, thus, avoiding problems with ion build-up (nitrate).

The \(v_t\) criterion is increased to 3.33 m\(^3\) kg\(^{-1}\) feed day\(^{-1}\) to provide additional stability for fingerlings and ornamentals whose quality maybe adversely impacted by water quality fluctuations. The drop in substrate concentrations (TAN and nitrite-N) increases the importance of mixing constraints (as opposed to oxygen transport) so the FBF hydraulic loading, \(q_r/v_{lb}\), are held at a level similar to the growout criteria. The resulting \(q_r\) of 83 l min\(^{-1}\) kg\(^{-1}\) feed day also facilitates nitrification within the biofilter by helping to maintain the interstitial TAN levels within the bead bed. The air delivery rate, \(g_a\), is increased moderately to 375 l min\(^{-1}\) kg\(^{-1}\) feed day eliminating concerns about oxygen or carbon dioxide management. The flushing rate is raised moderately to 204 l kg\(^{-1}\) feed (a HRT of about 16 days) limiting steady state nitrate accumulations to about 150 mg N l\(^{-1}\). The alkalinity addition rate remains at 242 g kg\(^{-1}\) feed although this value is reduced in areas of the country with source waters high in alkalinity.

The third design category, the broodstock category, is established for applications that demand the utmost stability and pristine water quality. Both the bead
filter and tank volume criteria are increased, although in practice the latter is most often increased even further by previously defined breeding or maturation protocols. The recirculation rate remains important as TAN transport clearly limits the filter’s nitrification capacity. The flushing rate is increased to 600 l kg\(^{-1}\) feed lowering the HRT to 11 days and the steady state nitrate level to 50 mg N l\(^{-1}\). Aeration and sodium bicarbonate addition rates remain the same as mentioned earlier in the fingerling category.

5. Discussion

The warmwater bioclarifier system criteria are functionally robust and fully suitable for application in the commercial environment that exists today in the United States. Although competitive with other technological approaches, the criteria described in the design categories above have not been fully and economically optimized. Three areas for further cost reductions include (1) reduction in the capital cost of biofilter units, (2) reduction in pumping costs associated with water recirculating, and (3) refinement of alkalinity adjustment strategies. These issues are actively being addressed through ongoing research efforts.

The utilization of alternate floating media that display a degree of biofilm protection and increase bed porosity is showing promise in addressing the first two concerns cited above. These new media facilitate operation under a high frequency washing regime (Sastry et al., 1999) that improves carrying capacities. Operational headloss that occurs through the bead bed are also dramatically reduced permitting the use of low head airlift pumps and cost-effective, non-pressurized hulls. The use of airlift pumps as an energy saving tool is well documented (Wheaton, 1977; Spotte, 1979; Castro and Zielinski, 1980; Bronikowski and McCormick, 1983; Reinemann and Timmons, 1989; Turk and Lee, 1991). An airlift criteria is currently undergoing evaluation (DeLosReyes et al., 1997a) and with commercial feedback it should evolve into an alternate and more cost-effective criteria for some applications.

The alkalinity adjustment approach has proven to be safe and easy to manage, but the requirements for sodium bicarbonate addition have proven to be substantial and contribute about 6% to the cost of operating services in the authors’ economic projections for commodity fish such as tilapia. The use of a less expensive, more caustic additive such as lime or sodium hydroxide (Weaver, 1999) may warrant consideration in future criteria.

Finally, increasing interest in marine applications has raised concerns about the flushing rate associated with the criteria. Inland marine systems can face significant costs obtaining salt, and particularly in arid regions, face environmental obstacles for disposal of saline waters. Nitrate accumulations are expected to limit the degree of water reuse in many marine applications (Whitson et al., 1993). The use of a denitrification unit in future marine recirculating criteria may be needed. The cost of the denitrification units would be partially offset by the elimination of the alkalinity replenishment requirement (Kaiser and Schmitz, 1988; Nijhof and Bovendeur, 1990; Van Rijn and Rivera, 1990; Van Rijn, 1996).
Definition of criteria for coldwater applications (10–20°C) continues to be an issue with the authors, reflecting their commercial experience in the southern United States. Current commercial sizing practice is to simply reduce $v_b$ by 50% for the selected category of application in recognition of the general reduction in bacterial kinetics associated with cooler waters (Knowles et al., 1965; Srna and Baggaley, 1975; Sharma and Alhert, 1977; Wortman and Wheaton, 1991). This approach works, but is probably overly conservative since the bacterial consortium and the nitrifying bacteria density in the biofilm undoubtedly change. Further research is needed in this area.

The authors continue to advocate a stepwise simplification of supporting processes to assure stability and economic viability of production systems. In the near future, recirculating systems can be expected to serve a growing role in support of extensive (pond) production as they contribute to the production of disease-free fingerlings, over wintering of warmwater broodstock, and purging of off-flavor (Malone, 1994). Eventually, if the systems can be adequately simplified and economically optimized, recirculating systems may compete directly as an economically viable alternative to extensive grow out systems.

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