

Application of Microbead Filters

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Abstract

The application of floating microbead filters to aquaculture is reviewed and discussed. The microbead filter is distinctly different than the more commonly used floating bead filters that are used today. Floating bead filters work in pressured vessels and use a media that is only slightly buoyant. The required mass of beads for the volume required make the media a relatively expensive component a floating bead filter in contrast to sand or microbead media that is much less expensive on a per volume basis. Microbead filters use a polystyrene bead (microbead) that is 1 to 3 mm in diameter (floating bead filters use media approximately 3 mm in diameter, also) with a bulk density of 16 kg/m³ and a specific surface area of 3936 m²/m³ (for the 1 mm beads). This material can be obtained commercially in bulk for roughly \$4 per kg of material. Biological filters that use microbeads for their nitrifying substrate can be thought of as a trickling biofilter in terms of mechanics of operation and design. For design purposes, microbead filters can be assumed to nitrify approximately 1.2 kg of TAN per cubic meter of media per day for warm water systems with influent ammonia-nitrogen levels from 2 to 3 mg/l. For cool water applications, rates should be assumed to be 50% of warm water rates. These rates are similar to those used for fluidized sand beds. Designs and results in several applications are presented. Microbead filters have been used successfully by several commercial growers after being first introduced in the mid 1990's. Effects of capitalization for equipment and buildings upon production costs is discussed and presented in graphical form.

Keywords: biological filtration, microbead, reuse, aquaculture, capital cost recovery

Introduction

World fishery production has decreased from 101 million metric tons in the early 90's to 93 million metric tons in 2002 (FAO, 2004). Projections by FAO (2004) of world fishery production by 2010 range between 107 and 144 million tons, of which about 30 million tons will probably be reduced to fishmeal and oil for non-food use. Most of the increase in fish production is expected to come from aquaculture, which continues to supply an ever increasing amount of the world seafood supply. Nearly a third of all seafood consumed in the world today is the product of aquaculture and the industry continues to grow as consumers demand more and more seafood and wild supplies continue to dwindle.

There is consensus that aquaculture is the environmentally responsible alternative to fishing. It provides a consistent and reliable source of high quality, fresh seafood that is safe to eat, priced reasonably, and nutritious. Seafood that is produced using recirculating aquaculture system (RAS) technology is potentially the most environmentally friendly and sustainable production

system that could be used to produce this needed seafood supply. However, RAS technology is often the most expensive form of production due to the generally higher capitalization costs. A central component of any RAS system is the biological filter system that reduces toxic metabolic products to nitrate, which is fairly innocuous. This paper reviews one such technology, microbead filters, and discusses some of the economic impacts of system capitalization on costs of production.

Biological Filter Systems.

Maintaining fish in water reuse systems is dependent upon efficient biological filters (nitrifying bacteria) that oxidize the ammonia produced by the fish, which is toxic, into nitrate that is generally non-toxic. There are a large variety of biological filters in use, e.g., rotating biological contactors, trickling filters, and fluidized bed granular filters. Commercial scale production of fish on an economically competitive basis practically forces the use of some type of inexpensive granular filter due to their inherent high surface area to volume ratios for the media employed, e.g., sands that provide 10,000 m² per m³ of material as opposed to trickling media that contains 100 to 300 m² per m³. Fluidized sand beds become additionally attractive since they can be scaled to sizes that accommodate the ammonia generated from feeding high levels, e.g., 500 kg of fish feed per day into a single water reuse system that will typically have multiple fish tanks on a closed loop.

Organic nutrients result in heterotrophic bacteria growth and ammonia results in nitrogenous bacterial growth. As with all biological filters, the growth of both the heterotrophic bacteria and the nitrogenous bacteria is proportional to nutrient loads provided to the bacteria. Unfortunately, in water reuse system the organic loadings on biofilters often result in excessive heterotrophic growth, which can often result in the nitrifiers dying because of being out-competed for necessary nutrients and oxygen. Effective settleable solids removal is critical for effective biofilter operation. Even with effective settleable solids removal, there are still significant concentrations (5 to 15 mg/l) of settleable solids that will be transported to the biofilter area of the water reuse system. Granular filters have the distinct advantage of extracting fine solids from the water column, which greatly enhances water quality by reducing the turbidity of the water column in the fish tank. However, even with very low levels of settleable solids being transported into a biological filter, nitrification performance is negatively impacted. For example, Zhu and Chen (2001) demonstrated the effect of sucrose carbon on the nitrification rate of biofilters under steady-state conditions using a reactor series experimental system. They determined at carbon/nitrogen ratios from 1.0 to 2.0, which is where most RAS systems operate, there was a 70% reduction of total ammonia-nitrogen removal rate as compared to C/N ratio of 0.

Microbead filters: General Features

A microbead filter is a combination of trickling and granular type biological filters. A typical configuration of a small scale microbead filter is given in Fig. 1. Microbead filters are operated in a downflow configuration where influent water is distributed over the top of the media bed and the water then trickles down through the media and gravity flows out of the reactor vessel. The media consists of highly buoyant polystyrene beads that are 1 to 3 mm in diameter with an

overall bulk density of 16 kg/m^3 . Porosity of the media will range from 36 to 40% with newer beads being closer to 40% and acclimated beads being 36% (Greiner and Timmons, 1998). The beads are the same material that is used for disposable drinking cups. Beads are created by a steam heat treatment of a raw crystal polymer. Trade name of the bead material is Dylite™ and can be obtained from distributors of Nova Chemicals Corporation, (Calgary, Alberta Canada). Once a local user is identified, beads will cost around \$4 US per kg of material. Beads are identified as Type A, B, C, or T with average diameters of 3, 2, 1.5 and 1 mm respectively. Originally, microbead filters used Type T beads (1 mm) and more recently users seem to prefer a Type B or C. Type A should be avoided.

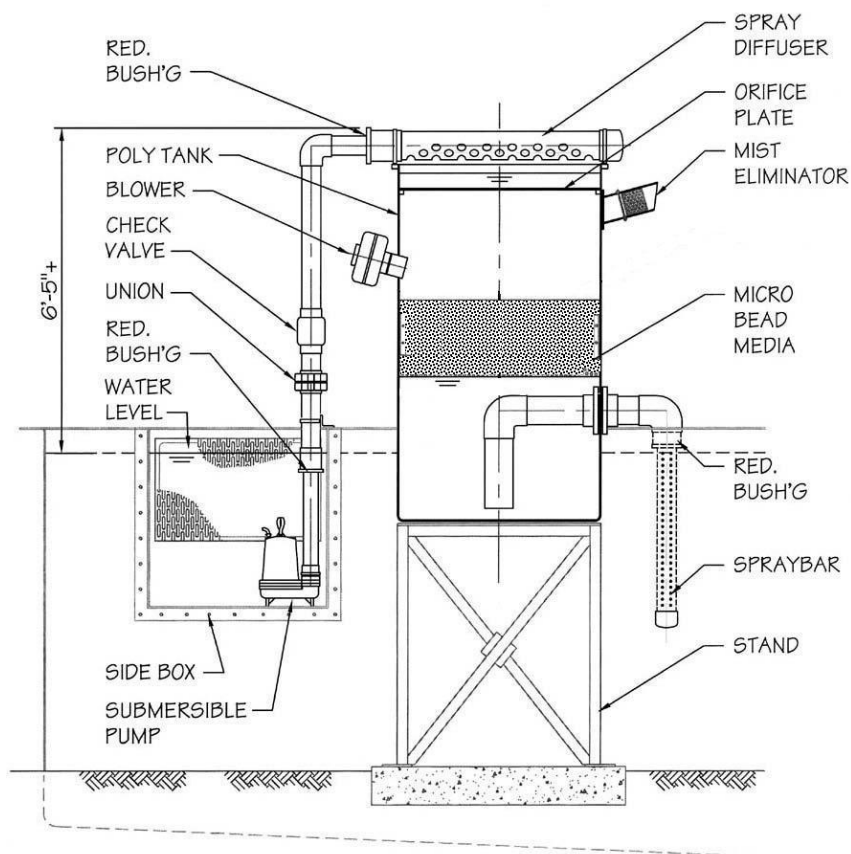


Fig. 1. Generic microbeads filter design (drawing courtesy of JLH Consulting, Courtenay, BC Canada, 2004).

The dominant design features of all microbead filters are illustrated in Fig. 1:

- Water distribution system over the top of the bead bed
- Floating bed of beads
- Adequate water depth below the floating beads (retention vessel)

Variations on microbead filters will be the manner in which the water is distributed over the beads. In Fig. 1, a spray diffuser is shown. Other applications use flooded perforated plates and create a water head of a few centimeters on top to create the water distribution. Some

applications actually use the orifice plate to "hold down" the beads and force the beads to be submerged into the retention vessel of the biofilter. Other designs intentionally create a gas space between the top of the beads and the water spray so that gas stripping can be forced. The ultimate embellishment in this arrangement is where the gas space is ventilated at 3 to 10 times the hydraulic loading rate to provide CO₂ stripping. All approaches work.

Performance Characteristics of Microbead Filters

Greiner and Timmons (1998) reported the first performance data on a microbead filter and compared its performance to a trickling filter:

$$R = k_1 C_i \quad (1)$$

$C_i < 2.5 \text{ mg/l}$

where

R	ammonia-nitrogen oxidation rate, g/m ² /d
C _i	ammonia-nitrogen influent concentration, mg/l
k ₁	0.19 for microbead filter (SE _{coeff} = 0.005, R ² = 0.93, n=11)
	1.43 for trickling filter (SE _{coeff} = 0.108, R ² = 0.58, n=11)

The reaction rate in Eq. 1 goes to zero order for ammonia concentrations above 2.5 mg/l. Nitrification rates for different water temperatures than used to develop Eq. 1 can be predicted using the relationship presented by Wortman and Wheaton (1991):

$$R_{\text{rel}} = 140 + 8.5 T(C) \quad (2)$$

where

R _{rel}	= relative ammonia removal rate per unit time
T	= water temperature, C

The above equation can be used to predict relative nitrification rates over the range of their data (7 to 35 C). For example, the nitrification rates at 10 C would only be 55% of the rates obtained at 30 C, or a 45% reduction in rate. This is less severe than the 75% reduction that would be predicted based upon Q-10 (Arrhenius relationship) effect for a 20 C drop in water temperature.

The specific surface areas for the two medias were 3,936 m²/m³ and 164 m²/m³ for the beads and the trickle media respectively. The trickle filter media was 5 cm diameter Norpak media (NSW Corporation, PO Box 2222, Roanoke, VA 24009) that had been cut into pieces 7 to 10 cm long. Using Eq. 1 and an influent ammonia concentration of 1 mg/l, the volumetric removal rate is predicted to be 0.75 and 0.23 kg TAN per m³ per day for the microbead and trickling filter respectively. For the tests conducted, the influent water had an average temperature of 26.4 °C (SD= 0.3), a dissolved oxygen greater than 5.0 mg/l, a pH of 6.7 (SD = 0.2), total suspended solids (TSS) conditions 6.4 (SD =3.6) mg/l and an alkalinity of 90 mg/l (SD= 18). The Greiner and Timmons data was based upon small scale reactors, 0.1 m³ microbead and 0.06 m³ trickle filter. Note that for typical tilapia systems that have influent ammonia-N levels of 2 to 3, the volumetric removal rate would be predicted to be 1.9 kg TAN/m³/d. Also, note that the TSS

levels in the Greiner Timmons research experiments were very low, thus maximizing nitrification performance in the biofilters.

Performance of a commercial microbead filter system provided similar performance data over an 8-year period of continuous operation. Chapman (2004, personal communication, Northern Tilapia Inc, Lindsay Ontario Canada) reported that eight microbead filters, each being 0.4 m³ in bead volume, had an average TAN removal rate of 1.2 kg TAN/m³/d. This was for a system that was fed 100 kg of 42% protein feed on a daily basis. The ammonia nitrogen (P_{TAN}) produced from 100 kg of 42% protein feed can be predicted to be 3.9 kg of TAN per day using Eq. 2 (Timmons et al., 2002):

$$P_{TAN} = \frac{F \cdot PC \cdot 0.092}{t = 1 \text{ day}} \quad (3)$$

where

F feeding level per day, kg/d
 PC protein content, decimal

The unit TAN removal rate was calculated using Eq. 2 and the known volume of microbeads. Water quality conditions were 27 C, 2.5 mg/l TAN, NO₂-N < 1.0 mg/l and TSS ~ 10 mg/l. Overall water exchange rates are 2 to 3% per day (extremely good water quality for this low of an exchange rate). The author has visited this facility multiple times over this 8-year period and the water has been very clear with a dark tea color. Fish feeding behavior is aggressive at each feeding that occurs over a 16 hour feeding periods with hourly frequency for feed distributions.

Large Scale Commercial Microbead Filters

Producing food fish on an economically competitive basis requires large production scales, e.g., greater than 500 metric tones per year. Fillet operations will require production levels exceeding 2,500 metric tons per year and preferably 5,000 metric tons per year or greater. At such scales, a key element is that the biological filter can be designed to oxidize ammonia loads resulting from the associated large daily fish feedings, e.g., daily feedings in excess of 500 to 1,000 kg feed per day, so that overall system costs can be reduced per unit of fish produced. The TAN resulting from this fish-feeding load is approximately 3% of the fish-feeding rate; a 33% protein feed will result in 3% of the feeding rate being the TAN loading rate, see Eq. 3. Warm water nitrification systems basically assimilate ammonia at a rate of 1 kg TAN per cubic meter of media per day. Thus, the mentioned 1000 kg/day fish-feeding rate would require a bio-filter with a 30 m³ media volume. Bead filters as originally developed and demonstrated successfully at such farms as Northern Tilapia were roughly a single cubic meter in bead volume or less. The first attempts at scaling microbead filters by simply making their footprint larger failed to provide a proportional increase in nitrification capacity.

A successful design modification to the original microbead filter concept that was patented by Cornell University (Patent Number 6,666,965 "Cellular microbead filter for use in water recirculating system", awarded December 23, 2003) was to subdivide a large bead bed into smaller subsections all within the same filter vessel. Large scale applications of microbead

filters using single reactor vessels has been implemented by Fingerlakes Aquaculture LLC (Groton, NY) under a license from the Cornell Research Foundation. Performance characteristics of such a system are shown in Fig. 2 (Belcher, 2003). Fingerlakes Aquaculture is a 500 metric ton per year tilapia farm. The Fingerlakes Aquaculture farm consisted of six independent production systems or pods; four of the pods employed CycloBio™ filters (Marine Biotech, Beverly, MA), and one pod was under construction during the study. Design feeding loads per production pod were approximately 270 kg of feed per day. The data shown in Fig. 2 is approximately 7 months after startup of the microbead filter, which was on Pod 5. The microbead filter had a bead depth of 21 cm, a filter bead volume of 6 m³, and used a Type B bead 1.85 mm diameter. The hydraulic loading rate of the Aquafilter was 1108 m³/m²/d (18.9 gpm/ft²). Measured performance characteristics for the Fingerlakes Aquaculture bead filter were: 1.1 kg TAN/m³/d, average influent TAN 1.9 mg/l, average system nitrite-N 0.6 mg/l, water temperature 26 C, and average feed per day into the system was 239 kg/d. Note that the nitrification rate is based upon assuming that all nitrification occurs in the biological filter. This may over-estimate substantially the actual performance of any biological filter.

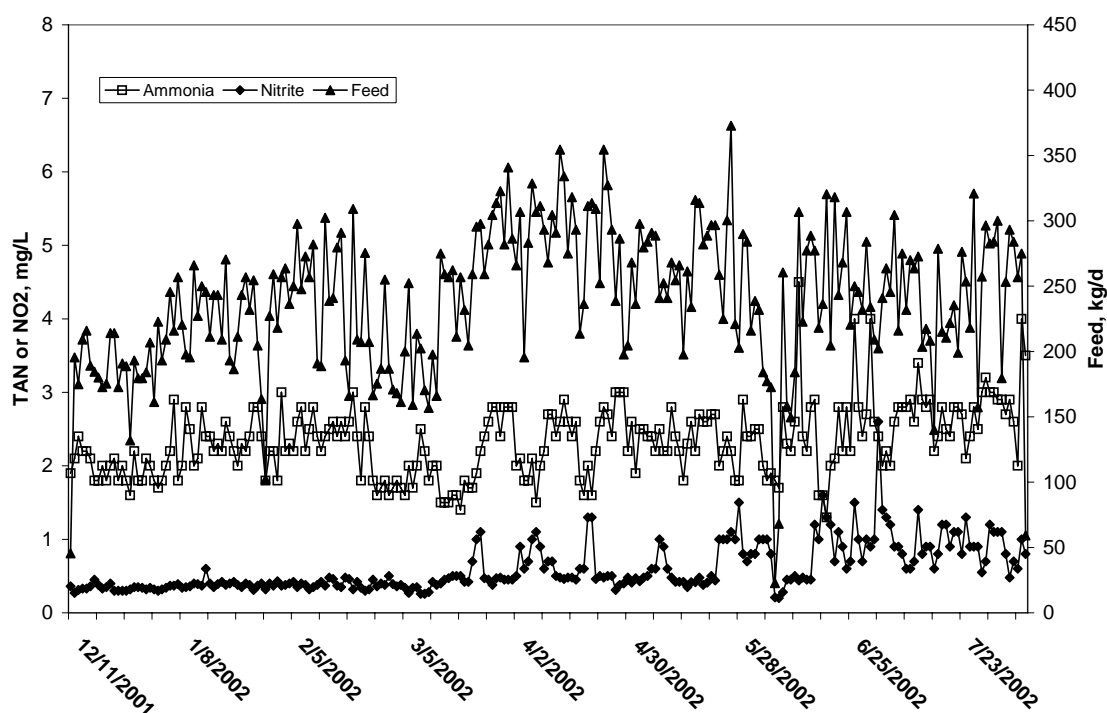


Fig. 2. Performance of a large-scale microbead filter (Belcher, 2003).

For comparison purposes with the microbead filter, performances of two CycloBio™ filters are shown in Figs. 3 (Pod 1) and 4 (Pod 4) (Belcher, 2003). These filters had been in operation for at least two years. The filters were the 3.5 m (11.5 ft) diameter and 4.9 m (16 ft) tall and were loaded with 1.8 MT of washed graded sand (0.45 – 0.55 mm) from Best Sand Company (Chardon, OH). Bed expansion for each of the biofilters averaged 40%. Fig. 4 for Pod 1 shows a very stable, textbook type performance. In contrast, the Pod 4 performance shown in Fig. 4 is

extremely erratic and plagued by high nitrite levels. This is an example of the frustration of working with biofilters. The two biofilters shown in Figs. 3 and 4 were as identical in design and operation as possible, yet performance is dramatically different between the two during this particular time frame. Overall performance characteristics are summarized in Table 1, which also includes performance of the other two CycloBio™ filters.

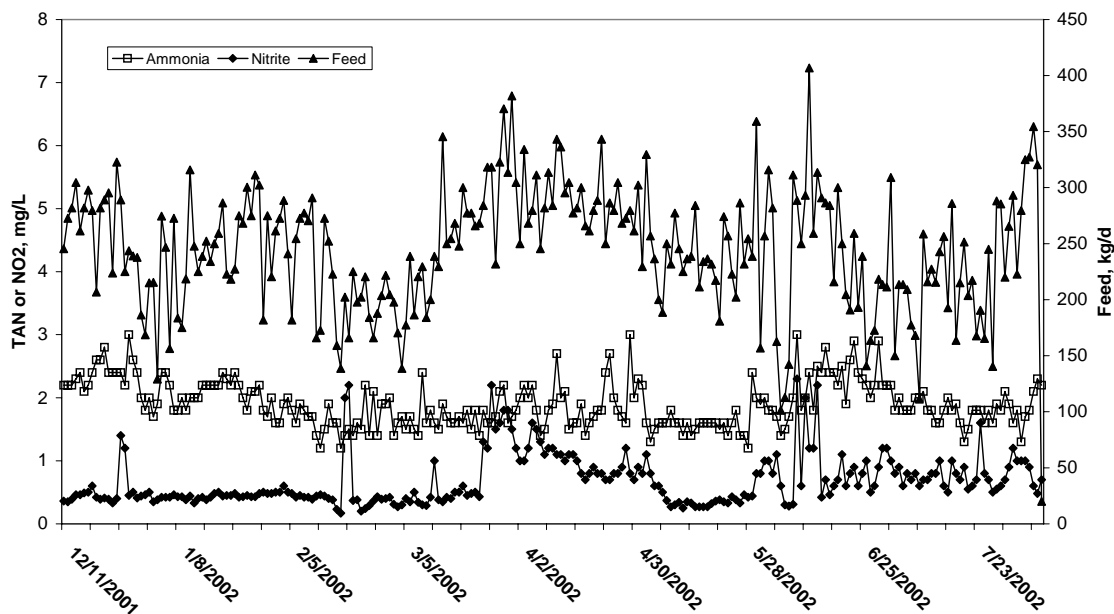


Fig. 3. Performance of a CycloBio™ filter, referred to as Pod 1 (Belcher, 2003).

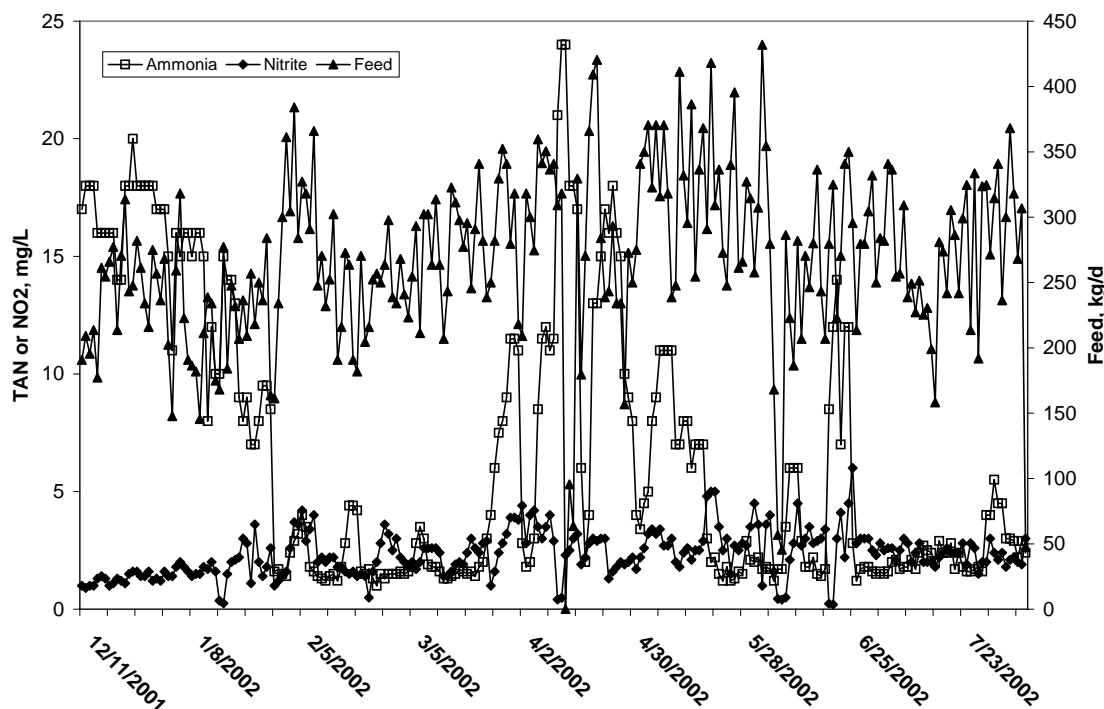


Fig. 4. Performance of a CycloBio™ filter, referred to as Pod 4 (Belcher, 2003).

The average feeding level in Pod 1 (Fig. 3) during the 240 day time period was 245 Kg (540 lb) of feed per day with 80 days exceeding 316 Kg/day (700 lb/day). There are several shifts in feeding that can be observed as waves in Fig. 3. Total ammonia nitrogen concentrations were relatively stable during this time (mostly between 1.5 and 2.0 mg/l) with slightly higher concentrations occurring when higher feeding rates were being applied to the system. The average TAN concentration during this time was 1.9 mg/l. The average TAN removal rate by the Pod 1 biofilter was calculated to be 0.7 Kg TAN/m³/day with a 10% water exchange rate. Nitrite-N concentrations were relatively stable during the first half of this time, experienced a spike to approximately 1.5 mg/l during the spring of 2002 (coinciding with increased feeding), and then decreased shortly afterwards to below 1 mg/l for the remainder of the period. The average nitrite-N concentration during this period was 0.7 mg/l.

The average feed concentration in Pod 4 during 240 day time period (Fig. 4) was 268 Kg (588 lb) of feed per day with over 110 days exceeding 316 Kg/day (700 lb/day). In general, feeding levels ranged between 204 and 340 Kg/day (450 to 750 lb/day). Total ammonia nitrogen concentrations were mostly between 1.5 and 3.5 mg/l during this time period however there were several significant spikes during this time, TAN > 20 mg/l. The average TAN concentration during this sampling period was 6.6 mg/l. The average TAN removal rate by the biofilter was calculated to be 0.7 Kg TAN/m³/day with a 10% water exchange rate. Nitrite-N concentrations typically ranged between 1 and 3 mg/l during this sampling period with smaller spikes following the TAN spikes. The average nitrite-N concentration during this period was 2.3 mg/l.

All systems using the CycloBio™ filters experienced high TSS levels, e.g. in excess of 30 to 50 mg/l (estimated based upon authors' observations). The hydraulic retention times (HRTs) using the larger sands are very short and result in minimal fine solids capture by the fluidized sand bed. In contrast, using fine sands increases the HRTs and these filters are known to promote extremely high water quality conditions relative to TSS levels. Summary performance data is provided in Table 1 for the four CycloBio™ filters (Belcher, 2003) and the microbead filter for comparative purposes.

Table 1: Performance Data of CycloBio™s and a microbead filter (Pod 5) at Fingerlakes Aquaculture's Groton Facility from 12/11/01 – 8/8/02 (Belcher, 2003)

Pod System #	Pod 1	Pod 2	Pod 3	Pod 4	Pod 5 Microbead
Average Kg of feed/day to system	245	262	281	268	239
Average TAN concentration (mg/l)	1.9	3.0	2.5	6.6	1.9
Average nitrite-N concentration (mg/l)	0.7	2.3	2.4	2.3	0.6
Average TAN removal rate (Kg TAN/m ³ /day)	0.7	0.7	0.8	0.7	1.1

Coolwater Application. Microbead filters were applied to an Atlantic salmon smolt operation during the Fall of 2004 using an average hydraulic loading rate of 984 m³/m²/d (16.8 gpm/ft²). Over a 30 day period, the average feeding rate was 56 kg (45% protein feed) for two biofilters (similar to Figure 1) with a media volume per biofilter of 0.93 m³. Sodium bicarbonate was added daily at a rate of 135 kg/d, and makeup water averaged 567 lpm (150 gpm). The average removal rate was 1.25 kg TAN per m³/d with a removal efficiency per pass of 29% (SD 12%) across the filter. The water quality parameters in the fish tanks were TAN 1.2 (SD 0.9) mg/l, NO₂ 1.4 (SD 0.3) mg/l, water temperature 13.6 C, hardness 72 mg/l, pH 7.3, turbidity 11.7 mg/l, CO₂ 10 mg/l, and chloride concentrations 400 mg/l.

Carbon Dioxide Removal Using Microbead Filters

Microbead filters can be designed to include a CO₂ stripping function. This can be an advantage by reducing the overall operating costs of the system, since CO₂ removal will be a necessary component in most intensive systems. The airflow requirements for successful stripping (generally about 5 to 10 times the volumetric water flow) can be coupled with overall building ventilation requirements for minimal air exchanges to control air quality and moisture levels. Wintertime ventilation requirements will require 2 to 3 building air exchanges to maintain adequate air quality (relative humidity below 85% and CO₂ levels less than 2000 ppm; OSHA maximum 8 hr exposure is 5000 ppm, Timmons et al., 2002). The CO₂ stripping ventilation requirements will be similar to the building air exchange requirements, thus a convenient coupling of design and operational requirements. Air high in CO₂ leaving the biofilter can either be vented directly from the building or dispersed into the general airspace where the building's ventilation system will control overall air quality. Surprisingly, the choice of venting directly or through the overall building ventilation system has minimal impact on the overall heating

requirements for the operation. Venting directly can be attractive and provide opportunities for using heat exchangers to conserve heat.

In the Northern Tilapia system, the CO₂ levels in the water column are maintained between 20 to 50 mg/l by maintaining pH between 6.7 to 7.1 and alkalinities between 75 to 150 mg/l. Approximately 50% of the total flow through the microbead filters is first stripped through a 1 meter high packed column placed above the microbead filter. There is additional CO₂ removal through the bead filters but is estimated to be a small percentage of the total removal since there is no forced air movement through the gas space between the beads and the distribution plate. Without the active forced air removal in the microbead filters, one should design for an active removal mechanism. Based upon the Northern Tilapia experience, approximately 50% of the flow should be actively stripped for CO₂ removal. The degree of stripping required will be species dependent.

For the Fingerlakes Aquaculture microbead system, there was no active CO₂ removal other than what was provided by the spraying the biofilter influent water onto the top of the bead bed. However, this was an uncovered bed and there was good air movement, although not forced, around the top of the bead bed. The average pH for the data shown in Fig. 2 was 6.7 and the average alkalinity was 111 mg/l. Using the pH-alkalinity-CO₂ relationships presented by Timmons et al. (2002), the dissolved CO₂ can be predicted to be approximately 48 mg/l. While this level of CO₂ may be satisfactory (marginal) for tilapia, other fish species that are more sensitive to CO₂ would require more complete CO₂ stripping. Stripping after a biofilter provides greater potential for stripping CO₂ since the water will be higher in CO₂ since the nitrification process produces CO₂.

Other Design Considerations for Microbead Filters

Coolwater Applications. The data presented in this paper has been from warm water, tilapia applications. Microbead filters are equally applicable to coolwater applications, but adjustments should be made according to Eq. 3 to lower the predicted nitrification rate. Microbead filters have been installed into multiple salmonid operations in the last year. For example, at the USDA-ARS National Center for Cool and Cold Water Aquaculture (NCCCWA, Kearneysville, WV), a research-scale recirculating aquaculture system was installed and used to rear rainbow trout. The system is comprised of 34- 1.2 m dia. tanks connected to a central drain system. Water is recirculated through the system at a rate of 1500 lpm (400 gpm), with approximately 1320 lpm (350 gpm) returning to the tanks. Biofiltration was accomplished using a micro-bead filter using a polystyrene bead (1 - 1.5 mm dia) with a footprint of 2.1x1.8 m (7x6 ft) broken into two sections so that either section could be loaded independently. A 0.6 m (24 inch) bead depth was used. The hydraulic loading rate used was 1110 m³/m²/d (19 gpm/ft²). The temperature for the system was maintained at 12.5 C. No operational problems were observed (personal communication, Dr. Brian Brazil, 2004), however, the required hydraulic loading was approximately twice for the microbead filter (if both sections were operated) than what was required for the rest of the system.

Reports from commercial users are positive. However, adjustments need to be made for design applications. For warmwater applications and influent ammonia levels of 2 to 3 mg/l, the

reported data indicates a safe value for design purposes is 1.2 to 1.9 kg TAN per day per m³ of media. Adjusting nitrification rate from 30 C to 10 C using Eq. 3 predicts a 45% reduction in rate. Coolwater systems are generally for species that require higher water quality standards than tilapia systems, e.g., lower suspended solids and ammonia levels at or below 1 mg/l. Nitrification rates can be assumed to be proportional to influent ammonia levels over a range of 0 to 2.5 or 3 (Greiner and Timmons 1998; and Ebeling, 2000). Combining temperature effects and expected lower ammonia levels, a design value of 0.6 kg TAN per day per m³ could be assumed for design purposes for coolwater applications.

Hydraulic Loading. The hydraulic loading of any biofilter is often a critical design parameter. For fluidized sand beds (FSB's), the hydraulic loading determines the amount of bed expansion and ensures full mixing of the sand column; the design principles of fluidized sand beds are well reviewed by Summerfelt and Cleasby (1996). In microbead filters, the hydraulic loading rate is less critical than for FSB's, yet it is still a very important design criteria. Greiner and Timmons (1998) reported a range of 424 to 837 m³/m²/d (7.2 to 14.3 gpm/ft²). The Northern Tilapia Inc farm used a rate of 1056 m³/m²/d (18 gpm/ft²) while Fingerlakes Aquaculture's large-scale bed uses a slightly higher loading rate of 1108 m³/m²/d (18.9 gpm/ft²). We currently recommend minimum loading rates of 1290 m³/m²/d (22 gpm/ft²). The bead bed will not act like a FSB in terms of seeing the media being well mixed. The bead bed almost appears to be a static mass, but when loaded at the higher loading rates, one will observe movement of beads from the upper portion of the bed into the lower portions. To some degree, the bead bed acts like a slowly eroding sand castle, where outer portions of the bed bead column finally fall away from the walls back into the main portion of the bed where they are then re-mixed with other beads. This constant yet slow turnover of beads in the bed is what provides the overall volumetric nitrification of roughly 1 kg TAN per day per cubic meter of bead volume.

Bed Expansion, Loss of Beads, and Bead Depth. A microbead is operated in a down flow mode. The beads because of their high buoyancy effectively float on top of the water column with minimal submergence. During operation, Greiner and Timmons (1998) reported bed expansions of 3 cm (for new beads) and 8 to 9 cm for acclimated beads with fully developed biofilms. These expansions were independent of bead bed depth.

Some operations have noted a loss of beads from the biofilter vessel. Loss of beads is obvious, since the beads reappear somewhere else in the system floating on top of the water column. Most bead loss is observed with new beads, which will have some small percentage of undersized beads that can be hydraulically flushed from the bio filter vessel. It is extremely important to maintain at least 60 cm of water depth separation between the bottom of the bead bed that is "floating" on the water column and the invert of the pipe or outlet port. Note in Fig. 1 how the outlet pipe is elbowed downward to provide much of this separation difference. Some thought should also be given to how to minimize any turbulence or mixing action on the solids that might settle in the biofilter vessel. Generally, providing some means to gravity discharge the vessel to remove any collected solids should strongly be considered. Regardless of how efficient the solids removal system is for the overall system, any vessel with retention time will collect solids. A microbead vessel is no different.

Smaller beads are also more subject to flushing out of the biofilter vessel since the biofilm on a smaller bead has more of an impact on the beads relative buoyancy than a larger bead. For this reason, we currently favor a Type B or C bead with diameters of 1.5 to 2.0 mm, as opposed to the Type T bead with a diameter of 1.0 mm.

Bead depths in microbead filters are limited to around 50 cm. It is unclear why, but the limited depth requirement is probably related to eventual channeling of water flow as the water trickles through the bead column. As the bed depth is increased, the opportunity for water channeling increases. Hence, the need to either limit bed depth or to provide some type of additional mixing or stirring of the bed.

Nitrification Efficiency. The percent removal of ammonia across a biological filter or efficiency is mostly dependent upon the hydraulic retention time across the media. Fluidized sand beds with fine sands and long vessel retention times will remove almost all the ammonia of the entering water. Conversely, fluidized sand biofilters using large sands will have somewhat proportionally less efficiency. The removal rate is the product of mass flow and change in concentration. In effect, the efficiency is not as important as the rate of ammonia mass removal. A microbead filter will have a very short retention time through the bead column and as a result the efficiency of removal will not be high. The authors recommend using 20% as a design value for removal per pass through the bed. Data supplied by Northern Tilapia indicates an efficiency of removal of 20% while the data supplied by Fingerlakes Aquaculture had an average efficiency of removal of 11%. The bead depth in the Northern Tilapia system was 0.45 m versus 0.21 m for the Fingerlakes Aquaculture bead filter. Nitrification efficiency is similar to the ratio of bead depths. Greiner and Timmons (1998) reported a 9% removal efficiency for a bed depth of 9 cm and a bead volume of 12 l. Shallow bed depths do not contribute to high removal efficiency.

Operating Expense. The microbead filter used by Fingerlakes Aquaculture (Belcher, 2003) was designed to treat the ammonia resulting from up to 300 Kg (660 lb) of feed per day or approximately 100 metric tons per year of fish growth at feed conversion ratio of 1.1. While capitalization costs of a microbead filter should be one of the least expensive biological filters to install, e.g., similar to large scale fluidized sand beds, the greatest savings associated with microbead filters are in operating costs. Specifically, by using a low head, low profile microbead design, and significant savings in pumping costs are realized. In the case for Fingerlakes Aquaculture, a total of 27 horsepower was required to operate the entire microbead filter system (biofiltration, solids separation and oxygenation) pumping 15,100 lpm (4000 gpm) compared to the 41 HP required to operate the CycloBio™ system for these same unit processes pumping 11,400 lpm (3000 gpm). A system operating on a 27 HP continuous draw will consume the following electrical energy (kWh) in a year:

$$27\text{HP} \cdot \frac{0.74\text{kW}}{\text{HP}} \cdot 24 \frac{\text{h}}{\text{day}} \cdot 365 \frac{\text{day}}{\text{year}} = 177,000 \frac{\text{kWh}}{\text{year}}$$

Expressing this on a per unit of fish produced from a 100 metric ton per year system yields an operating cost for electrical pumping of 1.8 kWh per kg of fish produced for the microbead filter and 2.7 kWh/kg for the CycloBio™ system or 33% less energy costs. Summerfelt et al. (2004) reported that CycloBio™ systems reduced overall operating pressure by 19 to 23% compared to

a conventional fluidized sand bed. Thus, a microbead filter compared to a traditional fluidized sand bed system will use roughly only 50% of the operating cost for pumping.

Scale of Production

RAS produced seafood must lower current production costs to compete successfully against other commodity type seafoods and against the other meat choices. Salmon farms produce 1,000 to 2,000 metric tons per site. Catfish farms are similar in production capacity. RAS farms will also need to be similarly scaled and need to focus on improved productivity per unit worker. Labor savings obtained from converting from outdoor production to indoor farming was a primary factor that drove the poultry industry to confinement housing. The productivity per unit worker in the broiler industry has increased from 95 metric tons of broilers per year in 1951 (Watt Publishing, 1951) to 950 metric tons per year in 1991 (Perry, 1991) and is now 1,480 metric tons per year per full-time worker (Cunningham, 2003). The current labor productivity for indoor broiler production is roughly 15 times more productive than the current 100 ton/yr per worker for large scale indoor tilapia farms (500 tons per year) and still 7 times that of the best current salmon farms that produce 130 to 200 tons per worker year.

Ultimately, indoor RAS fish production has two distinct advantages over poultry production: better feed conversion efficiency and higher productivity per unit area of building. The yearly meat output per unit floor area from a large-scale tilapia farm is approximately 150 to 250 kg/m², depending upon floor coverage utilization and tank depth, compared to 122 kg/m² from a broiler house. Broiler production has feed conversion efficiencies of approximately 2.00 (2.09 bird weight, feed to gain ratio on feed energy levels of 3,170 kcal/kg and protein levels of 19.5%), while tilapia conversions range from 1.1 to 1.4 for feed energy levels of approximately 2,500 kcal/kg and high protein contents, e.g., greater than 38%.

US broiler production is based upon vertical integration with the broiler grower being the contract farmer. The farmer owns the building, provides husbandry, and pays the majority of the utilities. Total capitalization or investment for a broiler building and equipment is \$0.42 per kg of yearly broiler production capacity (Cunningham, 2003); capital recovery costs will be from 0.06 to 0.09 per kg of broiler produced. For these services and capital investment, the farmer is paid \$0.11 per kg of broiler produced (Cunningham, 2003). All costs associated with building ownership, depreciation of capital equipment, labor and utilities (electric and water and generally about 50% of the fuel heating costs) are borne by the farmer. Broiler contracts are based upon 15 year bank loans and the same equipment and building depreciation periods used for the RAS analysis in this paper (7 years on equipment and 10 years on buildings). A broiler grower reaps most of the financial benefit once the building has been fully depreciated and the bank loan has been paid off.

In contrast to the low capital costs of broiler production, capital costs in fish production systems are much higher. Currently, the most cost competitive systems being reported have equipment costs in the \$1.00 to \$2.00 range per kg of yearly production capacity and building costs will add an additional \$25 to \$150 per m² of building floor area provided or an additional \$0.16 to \$0.94 when expressed on a per kg of yearly production capacity. The impact of these investment costs on capital recovery cost per unit of fish produced are demonstrated in Fig. 5, assuming a fish rearing tank depth of 2 m, a floor utilization of 40% (percentage of floor that is covered by

rearing tanks, excludes biofilters, settling systems, etc), and an interest rate of 8%. Capital costs are shown over a range of building and equipment costs. The capital cost recovery is calculated as follows:

$$A = P \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (4)$$

where

A = Annual cost, \$/yr

P = Investment, \$

i = annual interest rate, decimal

n = number of years for cost recovery, integer

As shown in Fig. 5, producing food fish in RAS's will require continued improvements in the cost efficiency of the equipment and building systems if these capital recovery costs are to become comparable to those associated with broiler production, e.g., \$0.06 to 0.09 per kg of broiler produced. For RAS production, a realistic target over the next 10 years is to reduce the capital recovery costs to \$0.15 per kg of fish produced. This could be achieved if for example the equipment capital investment costs were \$0.53 per kg of yearly production capacity (\$0.10/kg capital recovery cost) and building costs were \$50 per m² (\$0.05/kg capital recovery cost), using an 8% interest rate and capital recovery periods of 7 years for equipment and 10 years for buildings (same assumptions used to develop Fig. 5). Most of the cost improvements will need to come in the equipment area and some improvements in building costs, since insulated buildings are currently installed in the broiler industry for the price noted. Uninsulated buildings can be installed for the \$50 per m² cost noted currently.

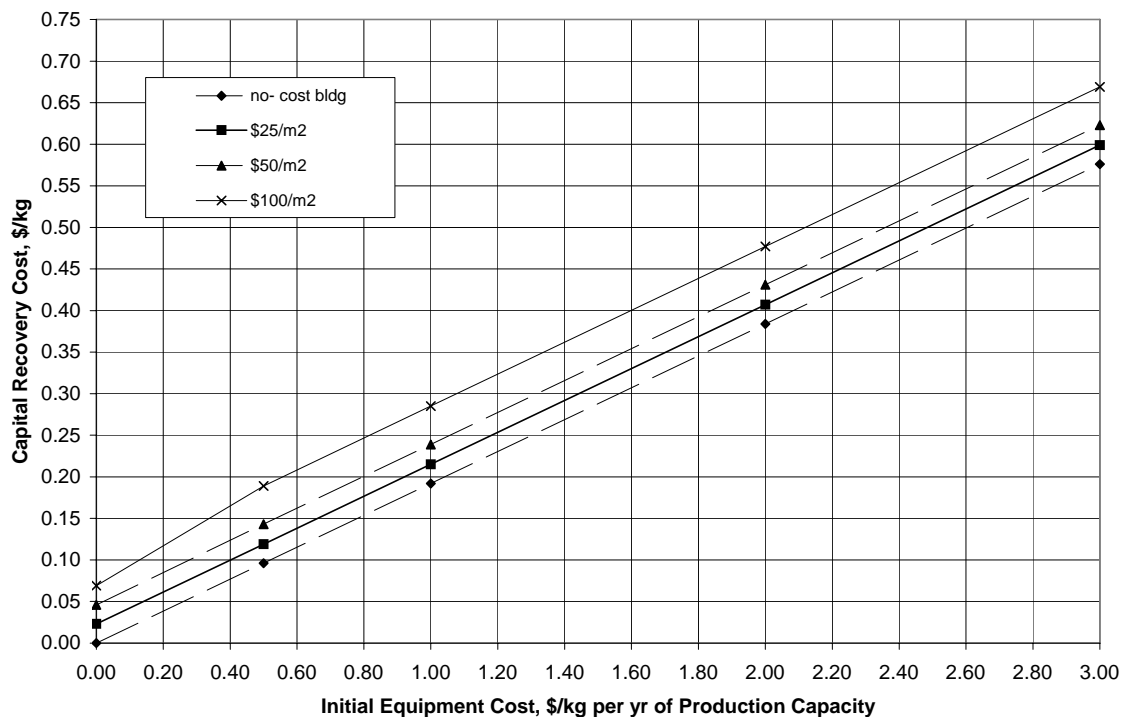


Fig. 5. Capital recovery costs as affected by combined capitalization costs for building and equipment (for a tank depth of 2 m, floor utilization of 40%, and interest rate of 8%).

Summary and Conclusions

The application of floating microbead filters to aquaculture are reviewed and discussed. The microbead filter is distinctly different than the more commonly used floating bead filters that are widely used today. Floating bead filters work in pressured vessels and use a media that is only slightly buoyant, thus the media is a relatively expensive component of the overall filter design. In contrast, microbead filters use a polystyrene bead (microbead) that is 1 to 3 mm in diameter with a bulk density of 16 kg/m³ and a specific surface area of 3936 m²/m³ (for the 1 mm beads). This material can be obtained commercially in bulk for roughly \$4 per kg of material. Microbead filters are considered a low-cost design alternative similar to fluidized sand filters because of their ability to be scaled to large production systems. A key advantage of microbead filters is that their cost of operation will be approximately 50% of a fluidized sand bed due to the ability to use low head high volume pumps for their operation. For design purposes, microbead filters can be assumed to nitrify approximately 1.2 kg of TAN per cubic meter of media per day for warm water systems with influent ammonia-nitrogen levels from 2 to 3 mg/l. For cool water applications, rates should be assumed to be 50% of warm water rates. These rates are similar for design purposes with fluidized sand beds. Microbead filters will have low nitrification efficiencies of 10 to 20% primarily because of the low hydraulic retention time within the bead bed volume. Bead filters are limited in depth to approximately 50 cm; this will increase the required footprint of the biofilter as compared to a fluidized sand bed that can be made several meters tall.

Effects of capitalization for equipment and buildings upon production costs is discussed and presented in graphical form. RAS produced seafood remains compromised by the high capitalization costs. Producing food fish in RAS's will require continued improvements in the cost efficiency of the equipment and building systems if capital recovery costs are to become comparable to those associated with broiler production, e.g., \$0.06 to 0.09 per kg of broiler produced. Most of the cost improvements will need to come in the equipment area and some improvements in building costs.

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