This is not a peer-reviewed paper.
Paper Number: 01-6081
An ASAE Meeting Presentation

Title: **Demonstration of the Use of Natural Fiber Filters and Airlift Pumps in Recirculation Aquaculture Systems**

Authors:

Dr. Von L. Byrd, P.E.
USDA Forest Service Forest Products Laboratory
1 Giffort Pinchot Dr.
Madison, WI 53706
Tel: 608.231.9485
E-mail: vbyrd@fs.fed.us

Dr. Douglas J. Reinemann
Associate Professor, Department of Biological Systems Engineering
University of Wisconsin
460 Henry Mall
Madison, WI 53706
Tel: 608.262.0223
E-mail: djreinem@facstaff.wisc.edu.

Dr. Jeffrey A. Malison, Director
UW Aquaculture Program
University of Wisconsin
Rm 123A, Babcock Hall
Madison, WI 53706
Tel: 608.263.1242.
E-mail: jmalison@facstaff.wisc.edu

Jeshua Hansen
Undergraduate Research Assistant
University of Wisconsin
460 Henry Mall
Madison, WI 53706
Tel: 608-262-5062

Mark E. Raabe, P.E.
University of Wisconsin
460 Henry Mall
Madison, WI 53706
Telephone: 608.262.5062
Fax: 608.231.9262
E-mail: meraabe@facstaff.wisc.edu

James Han
USDA Forest Service Forest Products Laboratory
1 Gifford Pinchot Dr.
Madison, WI 53706
Tel: 608.231.9423
E-mail: jhan@fs.fed.us

Written for presentation at the
2001 ASAE Annual International Meeting
Sponsored by ASAE
Sacramento Convention Center
Sacramento, California, USA
July 30-August 1, 2001

Table of Contents

Abstract

Filters made of juniper fiber and sphagnum moss were developed and used for the removal of suspended solids and as a media for biological filtration. Estimates were made of the capacity for these filters to remove suspended solids and for biological filtration. These filters have from 400 to 7000 times more surface area per unit volume than plastic media and sand filters respectively. This large surface area per unit volume contributes to the excellent performance of fiber filters at removing fine suspended solids from the culture system as well as makes a superior substrate for the organisms that perform biological filtration

Test results at both the bench scale and with this pilot scale system indicate that plant fibers perform very well for this application. The use of plant fiber filters overcomes one of the major problems of conventional solids removal and biological filtration media. The fiber filters appear to do a superior job of removing suspended solids and have a large surface area as a substrate for the bacteria that perform biological filtration. Removal of suspended solids has been a persistent problem in aquaculture systems because the solids are very fine and buoyant. The properties of these suspended solids make them difficult to remove. The accumulation of suspended solids is the main limiting factor in the capacity of commercial recirculation aquaculture systems. Bacteria that attach to some filter media, traditionally rock, sand, or plastic perform biological filtration. At some point the bacteria/slime layer sloughs off the filter media and adds to the suspended solid load in the system. The major advantage of these low-cost plant fiber-based filters is that they can be easily and inexpensively be removed and replaced as they begin to foul. This replacement removed the accumulated suspended solids as well as the accumulated bacteria from the system. The sequential removal of filters will also help to stabilize the bacteria populations in the filtration system.

The performance of the airlift pumps has been documented and was found to compare well with the theoretical model developed by Reinemann and Timmons (1989). The model can be used with confidence for the design of commercial scale facilities. Our experimental system used approximately 22% of the energy of typical state-of-the-art commercial aquaculture facilities currently being used in Wisconsin.

Keywords: airlift pumps, aquaculture, autotrophs, biofiltration, biofouling, energy, fibers, heterotrophs, lignocellulosics, recirculation, biofouling, sedimentation, Yellow Perch

Introduction

Increased demand for fish and seafood together with dwindling stocks of most of the major ocean fisheries, has spurred the growth of intensive fish culture. Regionally, yellow perch aquaculture is expanding in the Great Lakes region due to consistently high demand coupled with the decline in wild stocks from the Great Lakes. Over the next twenty years, aquaculture is anticipated to be the highest growth sector within the agriculture sector.

The most common culture method for producing fish in the Midwest is open pond culture. Pond culture relies on the natural water treatment processes occurring in large ponds and considerable water recharge from fresh sources and waste discharge. As production becomes more intensive and/or environmental regulations on discharge water become more stringent, water treatment and recirculation systems will have to be developed to continue to expand production. Water recirculation systems are advantageous because they provide a controlled environment to optimize growth, provide a continuous supply of fish, provide protection from predators and disease, and are not land intensive. Furthermore, water recirculation systems are flexible. They can be located near or within urban areas, where labor and markets exist. Recirculation systems also conserve water; thus, they can be located in areas where available supplies of fresh water are limited.

Natural Fibers and Solids Removal

One of the major limiting factors of recirculation aquaculture systems is the buildup of suspended solids in the culture water. The main sources of suspended solids in aquaculture systems are fecal matter produced by fish, wasted feed, and bacteria sloughing off filter media and other submerged surfaces. These suspended solids must be removed from a recirculation system to maintain optimum growing conditions. Large particles (down to 70-100 microns) made up mainly of feces can be removed using sedimentation or settling systems. Fish culture systems also produce a large quantity of buoyant particles between approximately 30-100 microns that cannot be removed effectively with sedimentation. High concentrations of suspended solids result in irritation of the fish gills and possible disease. In typical commercial yellow perch culture systems, maximum growth rates are achieved at approximately 20 pounds of feed per day per 12,000 gallons (Paragon Aquaculture, personal correspondence). If additional feed is applied, the fish begin to eat less.

Commercial secondary sedimentation systems typically consist of sand or rotating drum filters. The disadvantage of sand filters, however, is the high energy required to move the water through the filter. Fine sediment accumulates on the surface, thereby reducing the porosity of the sand filter. Periodic backwashing is required to maintain proper flow, which requires both additional energy as well as water. As the daily feed rate increases, the frequency of cleaning also increases.

The pilot study conducted by the project team observed that the natural fiber -- also called lignocellulosics -- filters used for biofiltration also acted as a secondary filtration system. Suspend solids were removed as a result of the high surface area of the lignocellulosic fibers combined with the sticky nature of the feces. The design of the filtration system employed multiple filters such that when the first filter became plugged with sediment, water could simply by-pass the first filter and then flow through the second filter. This system allowed continued water treatment with interruption. At the same time, it greatly reduces the energy requirement for removal of fine sediment.

Natural Fibers and Biofiltration

Ammonia is the primary nitrogenous waste product of fish (in contrast to mammals, which excrete urea). It is also emitted during decomposition of the fish feces. The un-ionized form of ammonia is highly toxic to fish; thus, waste treatment systems must accompany recirculation aquaculture systems to regulate ammonia concentrations within safe levels. Most recirculation systems use biofilters of various designs. Biofiltration relies on the simultaneous culture of two strains of autotrophic bacteria to oxidize ammonia to nitrate. Water recirculation systems using biofiltration represent a delicate compromise in which good growing conditions need to be maintained for both the fish and the bacteria in the same environmental system. This compromise usually limits the efficiency of raising fish in water recirculation systems.

Air Lift Pumps

Recirculation aquaculture is energy intensive because water must move continuously through the system to remove wastes and replace oxygen. The standard method of moving water is the use of a centrifugal pump. An alternative pumping system is the airlift pump, which uses the buoyancy produced by entrained air bubbles to lift water. Studies by Reinemann (1987), Turk et al (1991) and others indicate that use of the airlift pump is substantially more energy efficient for moving water under low-head conditions than centrifugal pumps. The economic benefits of the airlift pump are further increased when the electrical requirements for aeration, carbon dioxide removal and foam fractionation are considered. The airlift pump does all of these simultaneously, whereas separate component systems are required when standard pumps are used. Energy usage for a combination pumping and aeration are approximately one-third the cost of a conventional pumping system (Reinemann et al., 1987).

The airlift pump has other important benefits to the aquaculturist. Capital costs are significantly less than that for standard electrical (i.e., centrifugal) pumps. The simplicity in its design – there are no moving parts – means that maintenance costs are also low.

Despite the fact that the existing body of research indicates that the airlift pump is under most instances the preferred system for recirculation aquaculture, the aquaculture industry is generally biased against investment in culture systems employing the airlift pump. The reasons for this are lack of awareness of its inherent advantages, lack of available systems that employ the airlift pump, and performance deficiencies in instances where they are used. The simplicity in its design – made mostly from PVC pipe – makes it less profitable to market relative to standard electrical pumps. Most of the major supply catalogs for the aquaculture industry do not market airlift pumps. Furthermore, companies that sell package aquaculture systems typically use electrical pumps. The majority of recirculation aquaculture systems are not designed to take advantage of the efficiencies of the airlift pump. Changes in hydraulic grade line through the system are typically too great. This is done as a cost saving measure (when using centrifugal pumps) to avoid the use of multiple pumps. Conversely, multiple airlift pumps are not a significant cost consideration; they are actually necessary to maintain the hydraulic grade line within the optimal range of the airlift pump. Furthermore, where airlifts are employed, the design of the airlift typically employed does not maximize its performance capabilities. For instance, the flow rate is typically less than optimum because the lift is either too high or the pipe diameter-to-rise is too large. Hydraulic efficiency is also reduced when obstructions such as air stones are placed in the airlift tubes.

It is anticipated that the growth of recirculation aquaculture will provide a new market to the utility industry for electrical power. For example, based upon an energy requirement of 8 Mcal per kilogram of fish (Reinemann, 1987) and a business producing 150,000 pounds of fish per year, the expected annual energy requirement is approximately 475,000 kWh. This energy requirement is favorable to the utility industry because the majority of the electrical power used is on a continuous basis (for the operation of the pumping system). The most efficient use of this electrical power will be achieved through use of airlift pumps. If this technology is to become a standard for recirculation aquaculture, the utility industry needs to become proactive by providing information to its prospective customers. The information will be extremely valuable to the customer when planning the design of the recirculation aquaculture system.

Project Activities

The design of the pilot scale system is shown in detail in the PowerPoint presentation on the attached CD. An 800-gallon tank with a center standpipe drain is used to grow out yellow perch fingerlings. The tank has a center drain with both an outer and inner standpipe. Water enters the outer standpipe though slits in the bottom, then exits into the top of the inner standpipe. This prevents floating feed from exiting the tank. Also, in the event of a break or leak in the exterior piping network, water is maintained at the level of the inner standpipe. Treated water re-enters the tank by going up and over the lip of the tank via the airlift tubes.

The water treatment system is housed in two rectangular boxes connected in series using a 3-inch diameter PVC pipe. The boxes are constructed of plywood. Reinforcement of the edges and corners is made with 2” x 4" lumber, and five 0.5" rebar is used to provide internal support of the sidewalls. A watertight coating was applied to the inside to prevent leaks. The front half of the first box is used as a settling chamber and the back half contains filters for the removal of suspended solids. The entire second box is used solely as a biofilter.

Each filter box is equipped with an aeration system consisting of 12 air diffusers connected to a central air manifold. The air manifolds are then connected to a low-pressure air supply system. The diffusers can be used in combination with either a filter or airlift weir. Removable baffles -- consisting of 0.25-inch sheet of clear acrylic -- are located upstream of each diffuser. Airlift weirs can be placed at any of 12 locations within each filter box. Air can be introduced between each filter to reduce the head loss across the filter and for aeration. The use of air as a pumping mechanism offers unique advantages over mechanical pumping systems in intensive fish culture and numerous other applications. The high surface area of the bubbles substantially increases air / water interactions: oxygen removed by the fish and bacteria is replaced, and carbon dioxide emitted by the fish is removed. Thus, airlifts provide three essential functions that are typically performed by separate systems in commercial fish culture systems.

The wastewater moves to the first treatment box, where the first half acts as a settling tank for the large solids. The second half of the box contains four filters made of Juniper fiber. The primary role of these filters is to remove fine suspended solids. Water passed through a two-stage airlift pumping and aeration station at the end of this filter box. A chiller is mounted in the last section of this box to control water temperature (20°C).

The second filter box contains eight filters made of sphagnum moss. The primary role of these filters is as a media for biological filtration. Sphagnum moss was selected because of its large surface area and longevity in the pilot aquaculture system. Eight sphagnum moss biofilters were placed in the first system to allow inoculation of these filters with nitrosomonas and nitrobacter. The nitrosomonas bacteria, which fix ammonia to nitrite, grow much faster than nitrobacter, which fixes nitrite to nitrate. This creates a nitrite spike after the ammonia concentration has reached safe levels. Water was decanted (60% of the systems volume per day) during the period that the bacteria populations were being established on the filters.

The last section of the second filter box is also fitted with a two-stage airlift pumping and aeration station. An additional airlift pump was placed between the second filter box and the culture tank. The system was designed so that pumping could be done by either the multi-stage airlift stations in the filter boxes, by the airlifts at the return to the culture tank or a combination of these two. Aeration was also provided between each of the fiber filters to replace oxygen used by biological filtration processes. The design flow rate for the system was 1200 gal/hr or about 1.5 changes per hour.

Airlift Pumping and Aeration

The efficiency of the pumping and oxygen transfer was measured in both the airlift tubes returning water to the culture tank and in the multi-stage weirs in the filter box and compared with the theoretical model developed by Reinemann and Timmons (1989). The model was originally developed for airlift tubes. The dissolved oxygen concentration was brought down to below 1 mg/L using sodium sulfite and a zinc catalyst. Air was then supplied to the multi-stage weirs and dissolved oxygen concentration measured every 5 minutes before and after the weirs.

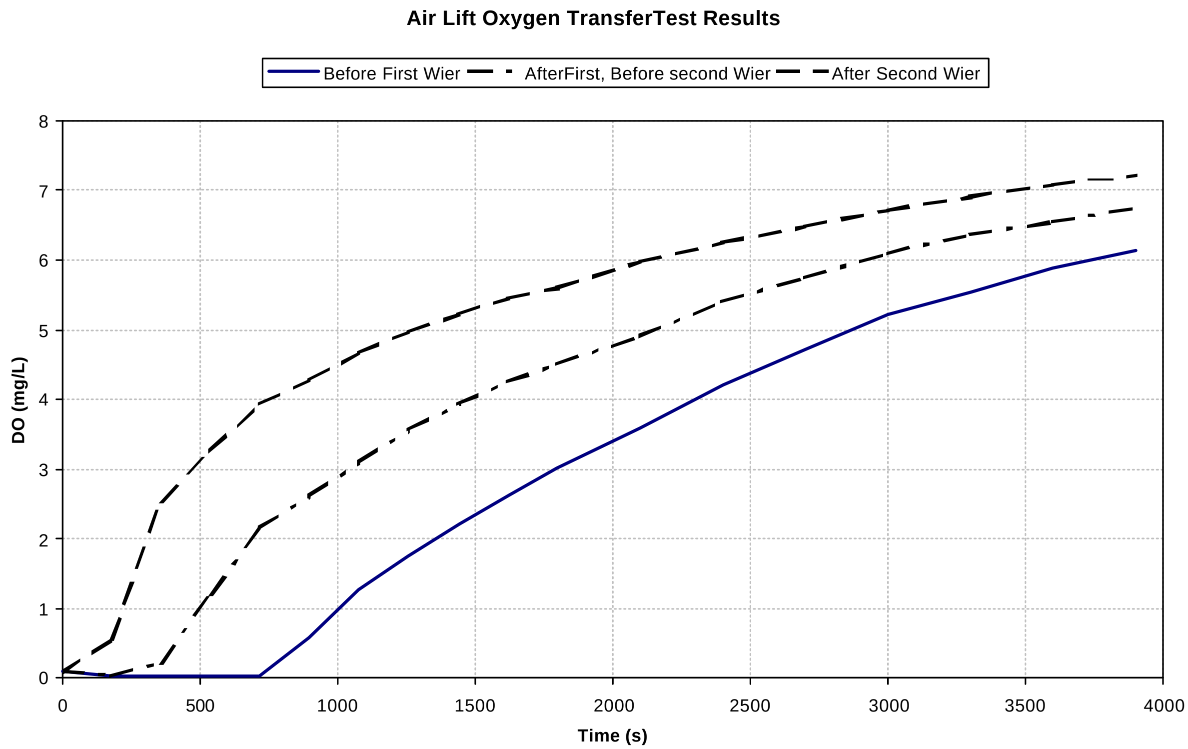


Figure 1. Comparison of Oxygen Transfer of the System Compared with Predicted Values

The airlift weirs were modeled as 20 tubes with 32-mm diameter giving the same cross sectional area as each weir. The model predicts that if the dissolved oxygen concentration at the entrance to a weir is 50% (4 mg/L) saturation, then the outlet concentration should be 65% (5.2 mg/L). The measured values match the predicted values to within the measurement accuracy of our dissolved Oxygen (DO) meter (see Figure 1). The theoretical model under-predicted the pumping capacity by about 10%, probably because of the reduced wall friction in the weirs as compared to the 20-tube model. The model can thus be used with confidence in the design of aquaculture facilities.

Fish Stocking

The system was stocked with approximately 400 yellow perch fingerlings in early June, to allow the biofilters to be inoculated with the bacteria to consume ammonia and nitrite. Fingerlings were added to bring the total in the system to about 1200 fingerlings. When the studies reported here were conducted the size of the fish ranged from 15 to 20 cm (6 to 8 inches) with and average weight of 88 grams each or total of 106 kg of fish mass being fed a rate of 1 kg of feed per day.

Suspended Solids Removal

The primary system for removing suspended solids is the juniper pre-filtration in the first stage treatment box. Juniper was chosen as the fiber for this application because:

- The Forest Products Laboratory has conducted extensive studies on this fiber.
- Juniper fiber is widely available, because small diameter timber is commonly removed from western forests as a forest management practice.
- Juniper has a long fiber; thus, mats can be easily manufactured, and
- Juniper fiber does not experience rapid biological decay due to the presence of heterotrophs.

The fine buoyant suspended solids characteristic of aquacultural waste are removed in two ways. The particles themselves are ‘sticky’ and will attach to the fiber in comes into contact with. Second, heterotrophic bacteria prefer to attach themselves to surface areas that allow them to come in contact with food sources. Therefore, the filters actually promote the growth of heterotrophic bacteria. The heterotrophs will then consume the suspended solids that accumulate on the filter. The heterotrophs will also remove dissolved solids that might ordinarily pass through the filter.

Heterotrophs convert the organic material into biomass, creating a film of slime that increasingly reduces the pores between the fibers. Eventually, the hydraulic capacity of the filter will fall below the flow rate of the pumping system. Increased frictional losses through the filter result in a reduction in the flow rate. At this point, the filter may be easily removed from the system and discarded.

The filters were used effectively for as long as 21 days. Contact with the culture water resulted in noticeable changes in the fiber: the presence of bacterial slime, and partial decomposition by the heterotrophs. Longer periods of use may be possible; however, changing the filters every three weeks would be acceptable in a commercial-size fish culture system.
Fiber material was manufactured from chips of juniper. Chips were separated into fibers using a pressured, steam-treated, mechanical fiberizer. The gap in the mechanical plates was at 0.15 mm (0.006 inch). The fibers were dried and made into mats by Odbek Industries, Inc. using a Dan-Web, air-laid forming system. This system enables web formation of a mixture of natural bonding fibers and bonding fiber dispersed in an air stream. Fabrication is completed by passing it through a set bonding via an infrared dryer. The surface area of the fiber was estimate at 200 m2/gm based on previous research by Wetherwax et al (1971) and Caulfield (1980).

Three fiber designs were used over the course of the project period. The 'basis weight' (i.e., weight per area) of the fiber mats ranged from 300 to 600 grams per square meter. The lower basis weight was the most effective. Greater pore volume promotes greater utilization of the fiber mat, increases the useful life of the mat, and reduces rapid accumulation of sediment and biomass on the upstream face only.

Investigations currently on-going include:

- Measurement of the amount of solids captured on a given surface of a fiber filter is problematic, due to the nature of the organic solids and design of the filter apparatus. Therefore, measurements are being made of the total amount of organic solids removed by the fiber filters. The measurements are made indirectly through quantification of the amount of setteable solids being removed from the system. Measurements are being conducted over an eight-week period period.
- Measurement of the degradation and lifetime of juniper-aspen filters in the fish culture tanks by quantifying fiber weight loss and microscopic observations of filter fiber and surfaces.

These results will be included in the conference presentation of this project.

Comparison of Natural Fiber Filters with Commercial Processes for Removal of Suspended Solids

Table 1 lists various techniques that are typically used by aquaculturists to remove suspended solids from a recirculation system (Chen et al, 1991). Specific systems are listed under each technique. Performance data for each system is provided in the adjacent columns. Table 2 shows configurations of various suspended solids processes (Chen et al., 1991) and their associated problems. The following is an explanation of how natural fiber filters compare with these systems:

Head loss: High head loss is a problem in granular media filters, cartridge filters and diatomite filters. Pressure is required to push water through the filter. The pressure required to maintain a constant flow rate increases as the voids become filled with solids. In contrast, the gradient through a new fiber filter is negligible. The gradient increases as solids accumulate and voids are reduced. Filters were replaced when the gradient is in excess of one inch. Thus, natural fiber filters are compatible with the use of airlift pumps.

Biofouling: Tube settlers and other commercial systems that promote settling of suspended solids through contact with surface area, are prone to biofouling. Periodically cleaning of the surfaces is required; otherwise frictional losses will increase, resulting in reduced flow through the treatment system.

Natural fiber filters are more effective than these conventional systems because: 1) they possess a tremendous amount of surface area for solids capture; and 2) maintenance requirements are substantially less. Natural fiber filters provide an ideal environment for the growth of heterotrophs. The growth of these organisms aid in the removal of suspended and dissolved solids. Biofouling is actually encouraged as part of the treatment process. Spent filters are removed and replaced with new filters, saving time required to remove the accumulated biofilm.

Water Loss: Sedimentation tanks and granular media filters use large amounts of water for removing accumulated solids. By comparison, natural fiber filters require substantially less water for solids removal. Removal of spent natural fibers from water results in the disassociation (i.e., 'sloughing off') of a portion of the accumulated solids, particularly that portion which is not directly attached to the fiber or biofilm. In a commercial-scale system, this could be avoided by compartmentalizing groups of filters into parallel flow paths. When filters in one compartment are to be replaced, flow to the compartment could be closed and the water drained out from the bottom of the compartment. This would assure that all of the accumulated solids are removed. The water loss is minimized by the small size of the compartment. Furthermore, given the efficiency in removing suspended solids -- due to the high surface area of the fiber -- the amount of water per unit weight of solids is likely to be greater than other less water-intensive technologies; e.g., tuber settlers.

Energy Requirements: Energy is required to overcome head losses through the waste treatment system. Processes such as granular media filters and cartridge filters have high-energy requirements for suspended

Table 1. Typical techniques applied to aquacultural systems for suspended solids removal (Chen et al., 1991)

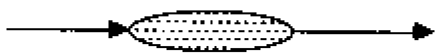
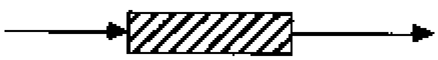
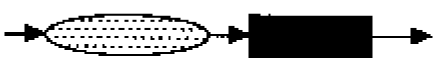
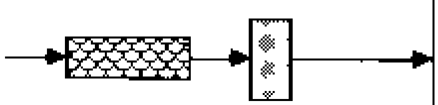
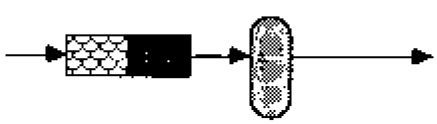
Processes	Solids Size Removed (µm)	Head Loss (m)	Hydraulic Loading (M^3/m2/day)	SS Removed (%)	Reference
Sedimentation	>100		24 - 94	40 - 60	EPA, 1975
Settling Tank			24.2 - 61.3		Liao, 1980
Tube Settler			30 - 90		Muir, 1978
GM Filter	>20[c]	0.1 - 3	176 - 429	20 - 60	Muir, 1982; EPA, 1975
Rapid Sand Filter			94 - 351	67 - 91	EPA, 1975
			285	70 - 90	Mayo, 1975
Pressure Sand Filters		2 - 20	117 - 704	50 - 95	Muir, 1982; EPA, 1975
Floating Bead Filter		0.8 - 6	1935		Wimberly, 1990
Screen	>75	Negligible	1 - 1000(gpm)		Huguenin & Colt, 1989
Coarse Screen			587 - 1760	5 - 25	EPA, 1975
Microscreen		0.01 - 0.1	176 - 587	17 - 50	EPA, 1975
Drum Filter			840 - 2180		Zeigler Bros.[a]
Triangle Filter					Makinen et al., 1988
PM Filter	>0.1		43 - 130		Muir, 1982
DE Filter	>0.1		29 - 59	>90	Muir, 1982; EPA, 1975
Cartridge Filter	1 - 10	~5	1 - 10 (gpm)		Huguenin & Colt, 1989
Hydrocyclones	1 - 75	14 - 35			Huguenin & Colt, 1989
					Wheaton, 1977
	5 - 200				Svarovsky, 1977
Other	<30				
Foam Separation			288 - 2880		Chen, 1991
Ozonation			3 - 456		Keeton Fisheries[b]

[a] Zeigler Bros. Inc., Gardners, Pennsylvania 17324

[b] Keeton Fisheries Consultants, Inc., Fort Colins, Colorado

[c] The Task Committee on Design of Wastwater Filtration Facilities, 1986

Table 2. Recommended suspended solids control processes in recirculating systems, their main problems and potential applications (Chen et al., 1991).

Process configuration	Main Problems	Potential Applications
 Plain Settling Tank (PST)	Large space, poor fine solids removal, water loss	Resistant fish (e.g. carp, tilapia), reptiles
 Tuber Settler	Limited fine solids removal, biofouling	Resistant fish Warm Water fish (e.g. catfish) at moderate density
 GM filter	Higher head loss, limited fine solids removal, water loss	Fingerlings, baitfish crustaceans, koi ponds ornamentals
 PST + GM Filters	High head loss, moderate space requirement	Fish at high density, reptiles
 GM filter + Cartrige Filter	High head loss, frequent maintenance, cartrige costs	Larvae development, broodstock, display tanks, ornamentals
 GM filter + DE Filter	Higher head loss, frequent maintenance	Larvae development, broodstock, display tanks, ornamentals

solids removal. By contrast, head losses through fiber filters are so small that they can be compensated using airlift pumps.

Maintenance: All waste treatment systems require periodic maintenance. A preferred technology for solids removal would incorporate high solids removal efficiency with minimal maintenance. Natural fiber filters are a simple technology that promotes the capture of suspended solids. Maintenance is required for periodic replacement of the filters. Potential exists for development of engineering applications of this technology that reduce labor requirements for this activity.

Cost: Commercial processes for removal of suspended solids typically have either high fixed costs (e.g., micro screen drum filters, rotating drum filters, bead filters and granular media filters) or high recurring costs (e.g., cartridge filters). By comparison, natural fiber mats can be produced inexpensively using by-product and waste fiber. The mats can be placed in simple filter cages and mounted in modular tanks. More elaborate applications are possible, resulting in greater capital investment; however, this could be offset by a reduction in recurring costs for maintenance.

Test Results

Fiber filters were arranged in series, with each filter having dimensions of 42"x24" and a thickness ranging between 6 to 12.5 mm (0.25-0.50 inches). Four filters were used in the study. The total surface area per filter is approximately 30,000 m^2; thus, the total surface area of the four fiber filters is approximately 120,000 m^2. Additional filters could be installed, however it was determined that four filters are sufficient to maintain low suspended solids. The first filter removes the majority of the solids, and the subsequent filters act as polishers. The primary function of the first filter is reduced with decreasing basis weight of the fiber, however this is offset by less frequent plugging and greater exposure of the suspended solids to all of the surface area within the filter.

The solids removal capacity and efficiency was estimated for both the juniper and sphagnum moss filters. The juniper filters were expected to remove the majority of the solids but some solids removal also occurs in the sphagnum moss filters. Tests were conducted using a water recirculation rate of 97%. The total suspended solids were measured before and after each set of filters both before feeding -- when the waste load is at its lowest -- and after feeding when the waste load is at its highest. Suspended solids concentrations during non-feeding periods range between 2-4 mg/l.

A review of the literature indicates that the suspended solids concentrations produced in the culture tank do not approach levels that have been shown to cause adverse health conditions in fish. Alabaster and Lloyd (1982) state that for inland fisheries, suspended solids concentrations less than 25 mg/l do not have harmful effects. FIFAC (1980) states that total suspended solids concentrations below 15 mg/l are safe for recirculation systems. However, Muir (1982) states that a limit of 20-40 mg/l is appropriate. Evidence cited by Chapman et al. (1987) states that the concentration depends upon the particular species and the distribution of particle size. Further tests are required at solids concentrations approaching this range in concentrations, in order to determine more precisely the effectiveness of the fiber filters. However, based on these tests the filters performed extremely.

The general level of solids in the system and the gradient of suspended solids across the filters were generally too low to give an accurate estimate of removal rates. Higher levels of solids were created by stirring the settled solids in the sedimentation chamber. This resulted in a solids concentration of 10.0 mg/l entering the juniper filters and 1.9 mg/l leaving these filters. This corresponds to a solids removal rate of over 850 gm/day. Another method of estimating the solids removal is a mass balance assuming that 1 kg of feed will produce 300 to 600 grams of suspended solids (Chen et al., 1991). If the suspended solids concentration in the system is not increasing the solids are being removed by settling and by the fiber filters. The maximum feeding rate achieved with this pilot system was 1.0 kg/day. The solids removed by settling were estimated at 10%, leaving approximately 200-500 gm/day removed by the filters. The filtration system is capable of peak removal rates of over 800 gm/day and overall removal rates of 200 – 500 gm per day but it is clear that we have not reached the maximum capacity of the filters. Further testing will be performed at higher daily feeding rates.

Biofiltration and Energy Efficiency

Sphagnum moss was selected as the primary media for biofiltration because of its high specific surface area (relative to synthetic biofiltration media and even juniper fiber) and its resistance to biological decay. The generally accepted design criteria for the capacity of aquacultural biological filtration systems is the amount of ammonia removed per surface area of media (Speece, 1973, Wheaton 1977, Wheaton 1991). The specific surface areas of juniper and sphagnum moss were estimated to be 200 m^2 per gram of dry leaf matter or 3.8 million m^2 per cubic meter. This is a conservative estimate as the surface area of sphagnum moss is generally thought to be higher than that for fiberized wood, however, the surface area of both media decreases over time due to biological decomposition. This compares quite favorably with conventional biofilter media as follows:

	Surface area per unit volume	
	m^2/m^3	(ft^2/ft^3)
Fiber Filters	3,800,000	(1,140,000)
Sand	1500 – 10,000	(450- 3000)
Gravel	130 – 1300	(40 – 400)
Plastic Media	530	(160)

A biological filter made of plant fiber can be contained in a much smaller volume than conventional biofilter media thus, reducing the cost of the water treatment system. Our objective is to produce fiber filters that can be economically be removed and replaced when fouled.

The carrying capacity of a recirculation system can be calculated in a number of ways, depending on the limiting waste treatment process. A useful way of characterizing systems is the total amount of feed that can be added to the system per day. Feed is either ingested by the fish resulting fish waste or passes uneaten into the treatment system and imposes treatment demand directly. The maximum feeding rate will determine the maximum number and size of fish that can be supported in the system, and the growth rate of the fish. The estimated feeding capacity and ammonia removal capacities for several types of biofilters, calculated using the methods presented by Wheaton (1991), are as follows;

	Kg feed per m^3 of media
Single Pass submerged gravel filter	3.3
Single Pass Bio-drum	6.0

These loading rates are not achieved in practice because of the accumulation of suspended solids in the culture system. As reported by Wheaton et al (1991), the design techniques for biofilters are imprecise because of the lack of accurate data and lack of understanding of dynamics of various surface mechanisms. To illustrate these points, data from 'state-of-the-art' recirculation system used in Wisconsin given below are 0.27 kg feed/day/m^3 a full order of magnitude below the design value.

The energy intensity of recirculation aquaculture systems can vary considerably. The analysis presented here compares the energy use for pumping and aeration. Other energy uses such as for lighting, heating and cooling and other incidental uses in a building, are not presented but would not be different between conventional and fiber based systems. Relevant system parameters and estimates of the energy used by a local aquaculturist using a typical commercial recirculation system, are presented below along with the same performance data for the experimental fiber filter/airlift system.

Commercial Recirculation System Parameters

Culture Volume	33,000 Liters
Stocking rate	450 kg of fish
Maximum feeding rate	7.2 kg/day
Solids Removal	In-tank settling, rotating screen and foam fractionation
Biofilter - plastic media	27 m^3 volume, 4320 m^2 area
Biofilter capacity	0.27 kg feed/day/m^3 or 1.7 gm feed /day/m^2
Aeration Blower	1.5 kW
Circulation Pump	2.0 kW
Energy Use	0.49 kW/ kg feed/day

Experimental Recirculation System Parameters

Culture Volume	2800 Liters
Stocking rate	106 kg of fish
Maximum feeding rate	1 kg/day
Solids Removal	Fiber filters 120,000 m^2
Biofilter	Sphagnum Moss 240,000 m^2
Biofilter capacity	10 kg feed/day/m^3 or 2.8 mg feed/day/m^2
Pumping and Aeration Blower	0.11 kW
Energy Use	0.11 kW/ kg feed/day or 22% of conventional system.

The feeding capacity per volume of filter media is about 37 greater for fiber filters than for commonly used plastic media. However, the feeding capacity per unit area of fiber filter is 600 times less for these fiber filters than for the plastic media. This explains the excellent solids removal capacity of the fiber filters and also indicates that we have not yet optimized the use of fiber surface from biological treatment.

Conclusions

This project demonstrates the following:

1. Natural fiber filters and airlift pumps are simple technologies that are suitable for recirculation aquaculture systems.
2. Natural fiber filter mats can be used to reduce accumulation of suspended organic particles. Further study is necessary to quantify the interaction between an organic solid and the surface of natural fiber, and to determine the optimum use of natural fibers for application to commercial systems.
3. Future research in the design of fiber mats for suspended solids removal should focus on three areas:
   a) analysis of mat designs with a basis weight below 300 gm/ m^2 and with various thicknesses;
   b) use of biodegradable binding agents, allowing decomposition and recycling of the entire mat; and
   c) use of natural fibers other than juniper.

   Fiber filter mats having larger voids and greater thickness are likely to have greater capacity for removing suspended solids. Biodegradable binding agents should be investigated to determine their effectiveness over the life of the filter. Spent filters could then be composted and used for fertilizer and as a soil conditioner.

4. Sphagnum moss may be used as a replacement for conventional biofiltration media. Further study is necessary to determine if less expensive alternative fibers may be used, based upon their natural resistance to bacterial decomposition or through modification techniques.
5. Airlift pumps perform more cost-effectively than conventional electric pumps. The experimental system used only 22% of the energy required in a conventional recirculation system (employing one electrical pump). The main contributors to this lower energy requirement are: 1) combination of aeration and pumping tasks using airlift technology: 2) the low head loss through the treatment system made possible by the use of fiber filters, and, 3) the excellent performance of fiber filters as a solids removal system and biofiltration media.

Acknowledgements

Michael Becker of Odbek Industries, Inc. manufactured the filter fiber mats used in the project. He also provided valuable assistance in the design of the mats. Dr. Peter Bilkey of AgriSearch International, Inc. provided the sphagnum moss used in the project.

This project is indebted to the many tradesmen employed at the USDA Forest Products Laboratory. It was through their support and dedication that the recirculation system was constructed, and that many technical problems encountered were resolved.

References

Alabaster, J.S., and Lloyd, R. 1982. Water quality criteria for freshwater fish, second edition, London, Butterworth.

Caulfield, D.F. 1980. Interactions at the Cellulose-water Interface. Paper Science and Technolo9gy – the Cutting Edge. Pp. 70-88. The Institute of Paper Chemistry. Appleton, WI.

Chapman, P.E., Popham, J.D., Griffin, J. and Michaelson, J. 1987. Differentiation of physical from chemical toxicity in solid waste fish bioassay, *Water, Air, and Soil Pollution*, Vol. 33, pp. 295-308.

Chen, S., and Malone, R.F. 1991. Suspended solids control in recirculating aquaculture systems. Proceedings from the Aquaculture Symposium. Cornell University. Ithaca, New York. April 4-6, 1991.

FIFAC. 1980. Symposium on new developments in the utilization of heated effluent and recirculation systems for intensive aquaculture, EIFAC, 11th Session, Stavanger, Norway, May 28-30th.

Reinemann, D.J., 1987. A Theoretical and Experimental Study of Airlift Pumping and Aeration with Reference to Aquacultural Applications. Ph.D. Thesis, Cornell University.

Reinemann, D.J. and M.B. Timmons, 1989. Predicting Oxygen Transfer and Total Dissolved Gas Pressure in Airlift Pumping. Aquacultural Engineering, Vol. 8, pp. 29-46.

Speece, R.E. 1973. Trout Metabolism Characteristics and the Rational Design of Nitrification Facilities for Water Reuse in Hatcheries. Department of Civil Engineering. University of Texas at Austin.

Wheatherwax, R.C., and Caulfield, D.F., 1971. Cellulose Aerogels: and Improved Method for Preparing a Highly Expanded Form of Dry Cellulose. Technical Association of the Pulp and Paper Industry (TAPPI). Vol. 54, No. 6.

Wheaton, F.W. 1977. Aquaculture Engineering. A volume in Ocean Engineering. John Wiley & Sons, Inc.

Wheaton, F.W., J.N. Hochheimer, G.E. Kaiser, and M.J. Kranes, 1991. Principles of Biological Filtration. Proceedings from the Aquaculture Symposium. Cornell University. Ithaca, New York. April 4-6, 1991.