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Recirculating Aquaculture Tank Production Systems

A Review of Current Design Practice

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Recirculating systems provide an alternative production method when temperature, salinity, disease, water supply, land availability, or exotic species /environmental regulations prevent more cost effective alternatives. A recirculating aquaculture system (RAS) can also be used to support traditional pond or net pen culture through broodstock or fingerling production. Recirculating systems have been widely used in research laboratories and universities across the country, but commercial use has been limited to relatively high value products. See SRAC Publication No. 456, *A Spreadsheet Tool for the Economic Analysis of a Recirculation System* for a discussion of the economics associated with recirculating aquaculture systems.

The science and engineering of recirculating systems is well developed. The details of recirculating technologies have been exhaustively covered by Timmons and Ebeling (2007). This fact sheet summarizes the principal technological approaches being used in current commercial designs that may range in size from a few hundred gallons to nearly 100,000 gallons (1 to 400 m^3).

The technologies that support tank based culture must address five key issues; clarification, biofiltration, circulation, aerations, and degassing. Solids must be removed from the recirculating system through a clarification process. Dissolved organics and ammonia are then removed through a biofiltration process. The system must provide for circulation between the tank and filtration components. And finally, dissolved gases (oxygen and carbon dioxide) must be brought back into balance by aeration and degasification processes. These five processes are essential to RAS success and should be viewed as links in a chain, the weakest link controlling the overall RAS capacity to hold or produce fish. Failure to address any of these five issues will ultimately lead to the downfall of any commercial RAS venture.

Once these core treatment needs are addressed, many recirculating systems are enhanced by the addition of secondary technologies. For example, broodstock conditioning systems are generally supported by a sophisticated heating and cooling system. They are also often supplemented with an UV disinfection system that protects the valuable breeders from disease. Some RAS are also equipped with foam fractionation systems that control foaming agents and help remove fine solids that can accumulate in systems with long water reuse.

Tanks

Sizing of fish tanks is based upon the density of fish, the primary controller of system stability. The fish density also ultimately controls the feed application rate. A very low fish density (<⅛ pound of fish per gallon or <15 kg/m^3) is commonly used for broodstock and display applications where the stock is considered extremely valuable. Fingerling, baitfish, and ornamental fish applications are typically sized with moderate loading (<¼ pound of fish per gallon or <30 kg/m^3). Higher fish densities are com-

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mon in the production (growout) of food fish. A half a pound of fish per gallon is a widely accepted design number. Densities of about 1 pound per gallon (120 kg/m^3) of water can be achieved, but, often display unstable water quality and are thus more prone to disease and growth issues. There are three common tank shapes (Fig. 1).

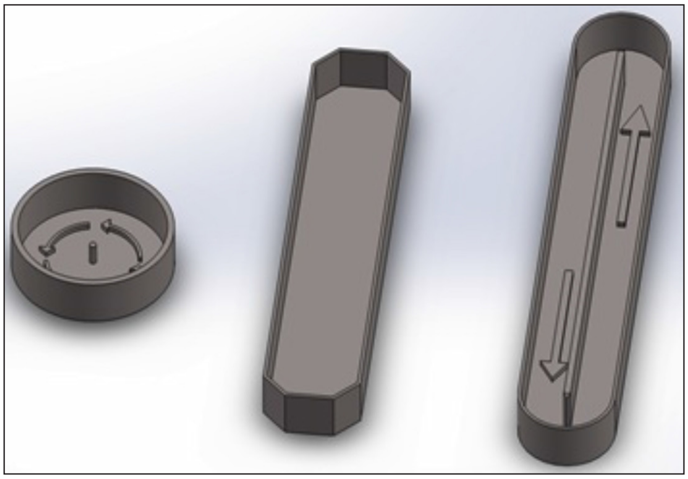

Figure 1: Common tank shapes.

Circular tanks

The dominance of circular tanks in the RAS industry stems from their inherent structural and hydrodynamic nature. Circular designs dominate broodstock and fingerling applications. Many growout facilities use circular tanks. The walls of a circular tank are maintained in tension by water pressure. In essence, the walls are self-supporting. This allows circular tanks to be constructed out of relatively thin polyethylene plastic or sturdier fiberglass materials. The hydrodynamics of a circular tank facilitate the rapid removal of suspended solids.

A circular tank with a center drain is naturally good at solids removal. Evan a small circulation will tend to accumulate solids in the center where radial velocities are the lowest. Solids removal from a circular tank can be enhanced by center sloping bottoms or by centering a dual drain system while optimizing the tank depth to diameter ratios.

Rectangular tanks

From an engineering perspective, the other extreme in tank design is rectangular. These tanks are often seen with a 45 degree bevel providing some rounding of the tank corners (Fig. 1). The rectangular tank is prone to poor solids movement. But, rectangular tanks are about 20 percent more efficient in floor space utilization and are more easily harvested than circular tanks. The inherent structural weakness of a square or rectangular design can be overcome by careful engineering when tanks are fabricated out of concrete or fiberglass. Earth reinforcement by partial burial can also alleviate most structural concerns presented by a rectangular tank design. As a result rectangular tanks are widely used in ornamental fish, baitfish, soft crab, and tilapia industries.

Solids movement in any rectangular tank requires consideration. Serious water quality problems can occur if solids accumulate in the bottom of a long rectangular tank. Water movement induced by recirculating water or aeration systems can be used to accelerate solids movement to the clarifier. In the ornamental fish industry, a secondary species (typically a *Plecostomus* or *Aeneus* catfish) is often used as a sweeper under mid or top water fish to move solids. In the case of tilapia, the high density of fish tends to re-suspend solids facilitating their movement.

Raceway Tanks

Raceway tanks blend the advantages of the circular and rectangular tanks and are most often seen in marine culture. A third wall is centered along the tanks length to facilitate controlled circulation of water. This circulation is highly effective at movement of solids with natural collection points occurring just downstream of the center panel ends. The rounded ends are generally compatible with quick moving species that have difficulty navigating sharp corners. Although raceway tanks would appear to be the perfect compromise between circular and rectangular, the third wall adds cost and can interfere with the ease of harvesting.

Circulation

The RAS is connected by water recirculating from the tank through the filtration loop. Recirculation flow rates vary among design strategies with 5 to 10 gallons per minute per pound of daily feed ration (42 to 84 lpm/kg/d) being typical. Generally, the water pump or air blower that drives the circulation loop is the major source of RAS energy consumption. Failure of the circulation system leads to a rapid deterioration in RAS tank water quality, thus, the method selected must be cost effective and reliable. Three common type of pumping systems are centrifugal, axial flow and airlift pumps.

Centrifugal pumps

Typically, a centrifugal pump is used to circulate RAS waters. These pumps operate from the thrust generated when water in the pump head is spun at high speed. The design of most centrifugal pumps is optimized for moderate to high pressure operation. In most cases, the pump will be placed outside the tank, but in some smaller systems a submersible pump may be used. Centrifugal pumps are readily available for virtually any flow range and salinity. In most RAS applications, a centrifugal pump with high flow and low lift capacity is favored to minimize energy consumption. Older RAS designs were based upon recirculation pressures of the order of 25 feet (8 m), whereas, most modern RAS designs target recirculating pressure of about 10 feet (3 m).

Axial flow pumps

Axial flow pumps are used on larger scale RASs because they have better pumping efficiencies than centrifugal pumps under low lift conditions (<10 feet or 3 m). Axial flow pumps are driven by a propeller mounted on a motor shaft within a vertical pipe. These pumps are robust and highly resistant to clogging. In recirculating applications, the propeller is submerged so pumping can be initiated without priming. Axial pumps tend to be more expensive than the more common centrifugal pump, and are rarely used unless the system recirculation rates reach several hundred gallons per minute (>2,500 lpm). In these larger systems, lower operation costs may offset higher initial capital expense.

Airlifts

Figure 2: A large airlift.

Airlift pumps operate off the density difference between column of water and a column of air/water mixture. Driven by an external air blower the airlift pump physically consists of a vertical segment of PVC pipe with an air injection port. Airlift pumps (Fig. 2) are capable of moving large volumes of water at extremely low lifts. Large diameter airlifts (>8 inches or 20 cm) have recirculation capabilities of several hundred gallons per minute (2,000 to 3,000 lpm), with lifts <18 inches (46 cm). The air injected to move the water also aerates and degasifies circulating water, thus, airlift systems are viewed as highly energy efficient as compared to most pumped systems. However, the height water can be lifted by an airlift is limited, so careful attention must be given to head loss as the system is being designed.

Aeration (oxygen addition)

The aeration process deals with the transfer of oxygen into the water. Oxygen is a relatively rare component in in water with 10 ppm being considered a high concentration. Most warm water recirculating systems operate with an oxygen level in the range of 5 to 6 parts per million; whereas, cooler recirculating systems can operate above 8 parts per million. Both the fish and bacteria rapidly consume oxygen. Under high loads, the RAS aeration system must be capable of replacing all oxygen in the system every 20 to 30 minutes at peak feeding rates.

The aeration component of the RAS design must be infallible. Even a short term interference with aeration capabilities can lead to complete loss of fish. Virtually all large scale production facilities have an aeration backup system in the form of a backup electrical generator, liquid oxygen tanks, or a mechanical blower. Alarm systems with auto-dialers supplement the backup system. Response times for re-establishing power or blower capacity need to be less than 20 minutes.

Blown Air

The most basic of aeration techniques is blowing air through a submerged air stone that disperses a fine stream of bubbles through the water at a pressure typically between 48 and 70 inches (1.2 to 1.8 m). Air pressure is generated by a linear air pump (<10 cubic feet per minute or 280 lpm), a rotary vane pump (10 to 200 cubic feet per minute or 280 to 5600 lpm) or rotary lobe pumps (>100 cubic feet per minute or >2800 lpm). As a rule of thumb, 3 cubic feet per minute of air is required for each pound of daily food ration (187 lpm/kg/day) under commercial growout conditions (Sastry et al., 1999; Malone and Beecher, 2000). Blown air is an aeration technique of choice for smaller RAS, the simplicity of the operation overwhelmingly drives the choice. Blown air systems are also widely used for commercial production of tilapia where the system's ability to simultaneously strip carbon dioxide is considered a benefit.

Aerating with Diffuser Hose: Porous stones or hard plastic air diffusers have been traditionally used to deliver air in the form of small bubbles to enhance oxygen transfer rates. All air delivery devices are subject to physical clogging as scale (calcium carbonate) occurs adjacent to the bubble formation as carbon dioxide stripping locally raises the pH. The diffuser hose is flexible and easily cleaned by hand; whereas, air stones must be routinely soaked in muriatic acid to dissolve scale. Thus, labor savings are encouraging increasing the use of diffuser hose in blown air systems. The length of diffuser hose must be compatible with the air delivery requirements. Forcing excessive amounts of air through a diffuser hose (or air stone) will increase the aeration rate but will cause excessive backpressures on the air blower.

Aerating with Airlifts: An airlift is also a blown air aeration device that is about 80 percent efficient when used in open tank aeration. Airlifts can provide all aeration needed for broodstock and fingerling systems where the fish density is less than a ¼ pound per gallon (30 kg/m^3/day). For growout systems, airlifts provide about half the oxygen demands for a RAS at full density (½ pound per gallon or 60 kg/m^3/day). Airlift systems utilize about 4 cubic feet per minute of air per pound of daily feed ration (249 lpm/kg/day). About half of the air is dedicated to the airlift operation and the rest is used to drive the diffuser hoses in the tank. Airlift systems are generally operated without any water pumps, and thus, save on energy and capital investment.

Blown Air Aeration Issues: Conservatively, air should not be injected deeper than about 5 feet (1.5 m) into a tank. Air injection at depths greater than 5 feet can cause an increase in the total dissolved gas pressure leading to gas bubble diseases in the fish. The critical depth of injection varies with altitude; higher altitude locations are more sensitive to this issue. Likewise, atmospheric air should never be injected to a U-tube or pressurized packed bed as supersaturation of nitrogen gas will cause similar problems.

Surface aerator

Surface aerators have a motor driven propeller that is mounted (floated) so the propeller turns upward throwing a cascade of water. A common feature in pond culture, surface aerators are usually used to supplement blown air systems during periods of peak loading or high temperature. Surface aerators are also reasonably effective at stripping carbon dioxide, provided the building is well ventilated.

Figure 3: A surface aerator supplementing RAS aeration during peak loading in a green water tilapia system.

Water spray heads or nozzles can provide aeration levels similar to that of small mechanical aerators. Small bait or soft crab tanks can be effectively aerated with one or two inclined nozzles. Aeration is achieved by oxygen entering the droplets and diffusing from the bubbles into the tank. However, this type of aeration is rarely used in larger scale commercial fish production.

An open packed column is also a reasonably effective aeration device. A packed column consists of column 3 to 6 feet (0.9 to 1.8 m) tall loosely filled with large and porous media. Water is re-aerated as the water cascades downward. The cascading effect can bring oxygen levels to near saturation in a 3 to 4 feet (0.9 to 1.2 m) fall. Smaller media have a tendency to biofoul (clog with bacteria) and generally display poor oxygen exchange.

Pure oxygen

The highest rate of oxygen transfer is accomplished using pure oxygen with pressurized delivery systems. Pure oxygen is available in compressed or a refrigerated liquid form. The compressed form is often used as an oxygen backup for smaller systems. Compressed oxygen has an unlimited storage life and can be reliably activated in case of power failures. Refrigerated liquid oxygen is in insulated tanks that slowly gain heat and are therefore perishable. As the tank warms up liquid oxygen is converted to gas that creates pressure that can assure delivery without power. Many large commercial systems use pure oxygen delivery systems to supply or supplement oxygen while providing backup aeration. Refrigerated RAS pure oxygen tanks must be routinely recharged by trucks. Delivery costs are controlled by the distance to the nearest industrial source.

The actual delivery of oxygen into the water is accomplished by one of several specialized devices that attempt to optimize the air-water interface and/or increase the pressure to maximize oxygen transfer efficiency.

Pressurized Packed Column: A pressurized packed column receives recirculating water at the top while upflowing pure oxygen. The oxygen exchange occurs as the water cascades through the column's media. A well-known chemical engineering solution for optimizing gas transfer, this approach is susceptible to biofouling under high loadings. An alternate design, a pressurized spray tower, has gained popularity in recent years. A biofouling resistant spray nozzle at the top the column sprays droplets through the pressurized oxygen-enriched air column creating excellent transfer characteristics.

Speece Cone: A second popular pressurized pure oxygen device is the oxygenation cone, more broadly called a "Speece Cone". The Speece cone looks like an upside-down ice cream cone. Water is injected into the neck of the cone at the top and flows downward to the outlet. Simultaneously, the pure oxygen is injected as a stream of bubbles near the middle of the column. The downward velocity of the water declines as the cone enlarges so each bubble rises until they are trapped by the increasing velocity (Fig. 4).

Figure 4: An oxygenation cone commonly used in pure oxygen systems.

Low Head Hoods: There are a number of pure oxygen delivery devices that are compatible with low lift designs. The low head aerator uses a series of cascading panels in an enclosed hood that accelerate the movement of the oxygen into the water. Another design utilizes a hood to enclose a surface agitator that throws water in an oxygen enriched atmosphere. Bubbles dragged to the deepest point of the cycle are pressurized, enhancing transfer from a pure oxygen source.

Pure Oxygen Caveats: Utilization of pure oxygen requires careful attention to details. Pure oxygen in mixture with a variety of common substances is explosive. Placement of pure oxygen storage containers should be positioned with fire hazard in mind. The placement of these units may be subject to local regulations. Although most pure oxygen systems are fully capable of raising oxygen levels above the normal saturation concentration, tank levels are generally kept below saturation to prevent the costly loss of oxygen to the atmosphere.

The use of a pure oxygen delivery system immediately implies carbon dioxide removal issues since pure oxygen aeration systems are efficient only in oxygen transfer, not carbon dioxide removal. Thus, a pure oxygen delivery system must be complemented by a similar sized carbon dioxide stripping apparatus (Summefelt et al., 2004).

The cost effectiveness of a pure oxygen delivery system is determined in a large part by the proximity of the nearest industrial source of pure oxygen. The scale of the operation can also be critical in cost calculations.

Aeration Summary

Most recirculating systems employ either a blown air or pure oxygen delivery system to assure oxygen levels are maintained. The blown air systems are generally simpler since they add oxygen and strip carbon dioxide at comparable rates. Pure oxygen systems are capable of maintaining higher dissolved oxygen conditions and may be more cost effective depending on the scale of operation and the pure oxygen delivery cost. A number of commercial blown air systems combine these technologies using a smaller pure oxygen system to supplement oxygen delivery and provide backup. This eliminates the need for a distinct carbon dioxide stripping unit.

Carbon Dioxide Removal

Degassing is similar to aeration although carbon dioxide is a highly soluble gas, whereas, oxygen is a poorly soluble gas. The earth's atmosphere is over 20 percent oxygen, yet contains only about 0.04 percent carbon dioxide. Under normal conditions, surface water will contain about 0.5 parts per million of carbon dioxide. In a poorly designed RAS, the respiration activities of both fish and bacteria produce a tremendous amount of carbon dioxide, elevating water levels to the 50 to 100 parts per million range. The high carbon dioxide level lowers pH and causes nitrifying bacteria to cease to function; resulting in a rise in nitrite or ammonia levels. Carbon dioxide is usually removed by blown air or by unpressurized packed columns.

Blown air

In blown air systems, placement of blowers outside the production building will assure that carbon dioxide levels are controlled. Most carbon dioxide problems with blown air systems occur during the winter when operators move the blowers inside to conserve heat while simultaneously, limiting building ventilation. The end result is an interior atmosphere that is enriched in carbon dioxide. Since levels are high in the building, carbon dioxide diffuses into the water. The end result is a RAS with low pH and high ammonia/nitrite levels. Operators with multiple blowers mitigate this impact by placing some blowers in the building and some outside, saving money from heating while the biofilters adapt to a moderately low pH.

Packed columns

The unpressurized packed column, or the spray tower, is widely used to strip carbon dioxide. A high rate of air (usually from outside the building) is counter-flowed against the falling water by a blower. These units are design to maximize the gas to liquid ratio, generally blowing 0.67 to 1.33 cubic feet per minute per each gallon of water passed through the column. When properly designed, these simple devices are highly effective at carbon dioxide removal.

Solids removal

About half the feed consumed by fish, crustaceans, and reptiles are excreted as solids. These solids rapidly break down into fine particles that are classified by size into four categories: settable solids (>100 microns), total suspended solids (1 to 100 microns), colloids (0.1 to 1 microns), or dissolved solids. The total suspended solids (TSS) category contains a large fraction of organic material that is measured as volatile suspended solids (VSS). The VSS content is important since it promotes bacterial growth that is associated with water quality and odor problems. Solids removal methods differ in their ability to remove the different solid categories. Traditionally a clarification device is placed upstream of the biofilter to remove organically rich suspended solids (Volatile Suspended Solids or VSS). This reduces the organic load on the biofilter allowing development of healthy biofilm that is rich in nitrifiers.

Settling basins

Settling basins incorporate gravitational settling which takes advantage of the density differences between the solid particles and water. Settling tanks can be round or rectangular. The minimum water depth should be maintained above 4 feet (1.2 m). It is recommended that hydraulic retention times be maintained at 15 to 30 minutes, with basic length to width ratios for rectangular tanks of 4:1 to 8:1. Required settling times can be estimated though Imhoff cone measurements that provide site specific estimates of settling times. Perhaps the most critical tank feature is the bottom design, as there must be a means of concentrating collected sludge while limiting the re-entrainment of settled particles.

Although a powerful tool, settling basins have their limits. Despite the installation of sludge drains, organically rich settled solids tend to stick to the tank surface and many designs require regular washing to move settled waste that is not captured by the drains. Settling basins are sized by their surface area to flow ratio (overflow rate). High RAS recirculation rates demand very large settling areas, which require a lot of valuable heated floor space. Finally, settling basins are very ineffective at the removal of fine suspended solids. As water is recycled, fine organics tend to build up in the water; biofiltration efficiencies drop and the water can become cloudy. Settling basins are most appropriate for lightly loaded systems or systems with water reuse (<2 days). As such, settling basins are used more to treat facility discharges than main recirculation flows.

Rotating microscreens

A rotating microscreen uses a drum shaped structure covered with a fine mesh screen. A typical RAS microscreen will have a 20 to 60 micron mesh size that will catch all the settable solids and the larger suspended solids. The drum is periodically rotated so the screen can be counter-flowed with high pressure jets (Fig. 5). Although somewhat limited in their ability to capture fine suspended particles, rotating drum microscreens require very little floor space, do not need daily wash downs, and operate at very low recirculating heads. This is the predominate solids removal technology for larger freshwater RAS with moderate (<10 days) to low hydraulic retention times.

Figure 5: A microscreen with spray nozzles mounted in the rear of the unit.

Microscreens can generate a substantial amount of backwash waters. Some RAS address this by the use of circular tanks with a dual drain system and swirl separators to reduce the solids loads on the microscreen. Foam fractionators can complement the unit by attacking the finer suspended solids and colloids. This allows the wash interval to be lengthened so that water loss rates from the facility can be reduced.

Floating Bead Filters

Floating bead filters utilize a bed of static beads to capture solids from a recirculating flow. Solids are captured as they pass through 12 to 36 inches (30 to 90 cm) of granular plastic beads. When the bead bed fills with solids it must be backwashed. Floating bead filters are backwashed either by mechanical means (a propeller) or pneumatic means (air bubbles). Once the bed is mixed, the solids are allowed to settle so a concentrated sludge can be removed. They are highly efficient at the removal of particles down to about 30 microns on a single pass, and in the typical RAS application, will remove all suspended particles after multiple passes. Although floating bead filters support nitrification, they are often used as a clarifier supporting moving bed reactors or fluidized beds. In RAS applications, floating bead filters can be operated at relatively high flowrates (>15 gallons per minute per cubic foot or 2000 lpm/m^3) at moderate pressure losses (0.5 to 5 pounds per square inch). Propeller-washed units are available in a variety of sizes (3 to 100 cubic feet or 0.08 to 2.8 m^3). Some of the smaller "hourglass" units (0.25 to 8 cubic feet or 7 to 227 liters) operate by draining the bubbles being drawn in by the suction of the hull. The newest designs (3 to 75 cubic feet or 0.08 to 2.1 m^3) recycle their backwash water internally, virtually eliminating water loss as a clarification issue. Floating bead clarifiers are widely used in both freshwater and marine application where an extended water reuse (30 to 100 days) is desired.

Figure 6: A Propeller-washed Bead Filter.

Biofiltration

The biofiltration process removes dissolved wastes from the water by bacterial action. Bacteria can be either grown in suspension (suspended growth) or in a fixed film attached to a physical substrate (a gravel, sand, or plastic media). The fixed film processes have proven more reliable and are most often used to support RAS water treatment objectives. However, it should be noted that there have been some notable successes with suspended growth in the production of shrimp and tilapia where the animals and bacteria are cultured in the same tank.

Perhaps the most important function of the biofilter is to remove dissolved organic material (sugars, starches, fats, proteins) that are excreted by the fish. This is a very fast and efficient process that is frequently overlooked in literature favoring the slower nitrification process. The nitrification process is the conversion of the toxic nitrogen form, ammonia, to the relatively nontoxic nitrate. A product of protein metabolism, ammonia, is excreted through the gills of fish. Ammonia buildup in combination with a slightly elevated pH will rapidly prove fatal to most fish. The nitrification process is absolutely dependent on the availability of oxygen. It is also very sensitive to water's alkalinity and pH.

Early RAS biological filter design was based upon the premise that biological filters were limited by oxygen transfer. Biofilters, such as the tricking filter or the rotating biological filter that had inherent re-aeration capabilities were favored. As solids removal and pH management improved, a second generation of designs arose under the presumption that ammonia movement into biofilms (diffusion), not oxygen, was the ultimate factor controlling biofiltration rates. Filter design began to emphasize high surface areas for bacterial attachment. Focus here is placed on these later designs (fluidized bed, bead filters, and moving bed reactors) that currently dominate US aquaculture design.

Fluidized bed

A fluidized bed is a bed of sand that is suspended by an upflowing current of water. The sand bed has very high surface area to support biofilm development. Each sand particle is suspended in the water column, gently bumping into adjacent sand grains providing a means for abrasion of excessive biofloc. Expertly designed, the fluidized bed is capable of achieving the highest volumetric conversion rates (amount of ammonia converted per unit of media). In growout systems, a coarse sand fluidized bed is capable of providing nitrification rate in the range of 1 to 2 pounds of daily feed ration per cubic foot of sand (16 to 32 kg/m^3/day). Fine sand beds are noted for their ability to maintain very low ammonia and nitrite levels (<0.2 mg/L-N).

Over the long term, fluidized sand filters have had a history of notable failures mixed with great successes based upon the designer's ability to properly match the sand size to the application. The hydraulic design of injectors under larger sand beds are too frequently underestimated resulting in piles of sand in one corner and empty space in the rest of a reactor. These concerns have been partially addressed by emerging commercial designs that spin the sand, and by detailed engineering analysis of under-drain design strategies.

Bead filters

Bead filters form the second class of biofilters. These filters use small plastic beads in a floating bed to support bacterial growth. This class of filters can be broadly divided into two subclasses. The first utilizes the floating bead bed in a static mode that is subject to intermittent backwashing. These filters are designed to act as bioclarifiers simultaneously performing the solids capture and the biofiltration function. The second employs floating beads that are continually moved. These filters are designed to provide biofiltration, although some do make contributions to RAS clarification.

Floating bead bioclarifiers: Floating bead bioclarifiers must be intermittently washed by hydraulic, pneumatic, or mechanical means. Hydraulic washing is viewed as too gentle for intermittent washing, so most bioclarifiers are either washed by air injection or propeller. These units use polyethylene beads with a diameter of about 1/8 inch or 3 millimeters. Units with beads of modified shape and subject to optimized high frequency washing (Sastry et al., 1999) are capable of supporting about the same level of nitrification as a fluidized bed (1 to 2 pounds per cubic foot per day or 16 to 32 kg/m^3/day). However, floating bead bioclarifiers are rarely employed just as biofilters, their adoption is normally dependent on their concurrent use as clarifiers, otherwise, pure biofilters are more cost effective.

Dynamic floating bead biofilters: Dynamic bead filters generally either employ ⅛ inch shaped polyethylene beads or 3⁄64 inch (1 mm) styrene beads. The beads are constantly moved, albeit sometimes at very slow rate, by either hydraulic or by air-induced circulation. Peak nitrification rates are comparable to the fluidized bed reflecting the high surface area of the small media. In particular, the styrene bead based systems are relatively inexpensive to fabricate, but these systems have an inherent tendency to biofoul so attention to hydraulic design is critical. Sizing for these units can be as high as a fluidized bed (1 to 2 pounds per cubic foot per day or 16 to 32 kg/m^3/day).

Figure 7: A Moving Bed Reactor supported by a bank of UV lights on a marine fingerling system.

Moving bed reactors

Moving Bed Reactors (MBR) use large (¼ to ½ inch or 6 to 13 mm) plastic media and are specifically manufactured to provide protected surfaces for fixed film bacteria. The media is placed in a tank that is constantly aerated. These filters particularly have a robust design and are relatively easy to design and operate (Fig. 7). A significant amount of air must be injected into the bed to keep it moving, thus the MBRs can make significant contributions to the RAS aeration and degasification needs. The nitrification capacity of these filters tends to be only ¼ to ½ of the fluidized beds, with filters sized to support about 0.5 to 1 pound of feed ration per cubic foot of media (8 to 16 kg/m^3/day). Low cost of construction and simplicity of operation offset the lower conversion rate, making this biofilters design popular for all sizes of operation.

Additional System Components

Once the five core processes in a RAS are addressed, additional components can be added to achieve specific objectives or to compensate for particular issues that the application presents. Some of the commonly included additions are discussed below.

Heating

There are two basic strategies for heating a RAS facility: heating building air space or heating the water directly. In either case, the RAS building that receives heating must be equipped with good insulation and a good water vapor barrier assuring condensation is properly diverted away from sensitive building structures. Condensation always occurs at an interface between the warm air in the building and the cold exterior air. This condensation interface will cause a constant water drip that has been known to cause damage to many improperly designed RAS buildings.

Heating Coils: Direct heating of RAS waters is typically avoided to minimize scaling on heated lines, a problem in even moderately hard waters. Water heating is generally accomplished by polypropylene heating coils connected to a boiler or inline heating system. The heating coils are placed in a sump or in the tank itself. A thermostat in the tank turns on the boiler (typically powered by natural gas) whenever the temperature falls below a set minimum and hot water is circulated through the coils. The chemically treated heating water does not mix with the tank water, so scaling is not a problem. Heating coils are an energy efficient means for thermal input. Although installation of heating coils can complicate RAS designs, this approach should be given serious consideration.

Air Space Heating: The more common way of heating a RAS is to heat the air space above the tanks. This strategy uses readily available centralized heaters. The technology is well understood and broadly serviceable. With some consideration for the high humidity of the airspace; sizing and implementation is straight forward. However, any heating calculations should take into consideration the heat loss associated with ventilation or water cooling that may also be associated with carbon dioxide control strategies.

Greenhouses: In many southern states, greenhouses are a favored way of enclosing a RAS operation. Greenhouses are well known for their ability to gather and hold solar energy. The solar energy heats both the air and the water directly, dramatically reducing heating requirements where winter temperatures are moderate. Greenhouse technology is well developed and the criteria for heat balances are readily available. Modern plastic designs for dual layered covers enhance insulation and are not impacted by the moisture. Most greenhouses, however, have to be equipped with fans and/or swamp coolers to maintain production temperatures in the summer. Supplemental heating systems may be required for the coldest days of the winter. The heat balance for greenhouses becomes increasingly unfavorable the further the system is placed to the north.

Disinfection

Disinfection was once thought to be a required process for recirculation. However, modern design requires it only when the stock is particularly valuable or the disease threat is high. Source water control (largely groundwater) and other external disease prevention strategies have largely eliminated the need for internal disinfection. The two most common disinfection devices are UV light and ozone treatment. UV light is mostly widely used because of its ease of installation and operation. Ozone is employed in larger facilities that can support the cost of its installation and operation by a technically trained staff.

UV lights: The principle internal disinfection device is UV light. These lights emit a light spectrum concentrated in the UV wave lengths that are deadly to microorganisms. Disinfection rates are typically proportional to light intensity, which is related to the wattage of the bulb used and the flow rate treated. Sizing criteria for bacterial or algal kill percentages are well published. If properly sized UV lights are used, they are effective with only a few issues. First, UV light penetration into water is controlled by clarity; relatively clear RAS waters are required to assure effectiveness. Secondly, UV light bulbs have a limited effective life (typically several months) so the process is effective only if the bulbs are routinely replaced.

One notable RAS area where disinfection is widely used is broodstock maturation (artificial conditioning of adult fish for spawning). The fish in this case must be maintained, often for months, and the breeding outcomes are of often critical to a RAS facilities operation. Marine species are particularly sensitive to diseases, many of which can penetrate quarantine strategies. Given the overall cost of these operations most are installed with an internal UV disinfection treatment unit. Virtually all shrimp maturation systems are internally treated with UV as part of the protocol to control the spread of critical bacterial and viral diseases through the larvae.

Ozone: The second, less common internal disinfection option is ozone. Ozone is a form of oxygen that is a very powerful oxidant, similar but more powerful than chlorine in its action. It is generated by a number of devices, with the corona discharge designs generally being recognized as the most powerful. Corona discharge ozone generator performance is controlled by the oxygen content of air fed into it. The humidity of the air is critical to the unit's longevity. So gases fed into corona discharge units are normally oxygen-enriched and are passed through an air drying unit.

Once generated, ozone may be dosed through a packed column. More commonly, ozone is dosed with a simple venturi that uses the energy from the pump to draw the air into the recirculating line as fine bubbles. Ozone is rapidly absorbed by most recirculating waters destroying dissolved organics first then killing bacteria, viruses, and ultimately protozoan organisms. Effective disinfection requires that ozone residual is maintained for some seconds. The residual ozone is difficult to maintain in a growout situation where fine solids and waste are likely to react with the ozone before it can effectively attack the disease causing microorganisms. Conversely, over dosing can cause damage to the fish, so many ozone treatment units are followed by an ozone neutralization step, such as, an activated carbon column. Unintentional releases into the tank can damage or kill fish and crustaceans. Additionally, care must be taken in marine systems to avoid the formation of toxic byproducts, such as bromates.

Installation and operation of an ozone treatment process can be complicated and costly. Ozone treatments are normally associated with larger RAS with trained technical staff. That being said, ozone is a very effective polishing device and will make large differences in the RAS water quality. Its removal of organics will be evidenced in clear-looking water, reduced organic content, and enhanced biofilter nitrification rates.

Figure 8: RAS treatment does not have to be complex. This marine fingerling system is supported by a floating bead clarifier and a set of airlifts.

Source water disinfection: Any surface water that may be a source of disease should be disinfected. Rigorous chlorination, ozone treatment, and/or repeated UV treatment are all utilized to pretreat water coming into a RAS. This is most often seen in marine fish systems where the absence of a suitable groundwater source forces the use of surface waters sources. A disinfection process of incoming waters usually not required for RAS operation as long as the replenishment water is taken from a disease-free source, such as a groundwater or chlorinated domestic water supply.

Foam Fractionation

Foam fractionation is a technique used to remove surfactants from RAS waters. Surfactants are chemicals that have a molecular end that is hydrophobic forcing the chemicals to the air-water interface. These surfactants can cause RAS foaming problems. Surfactants are formed as part of the protein degradation process so it is not uncommon to hear a foam fractionator referred to as a “protein skimmer”. The foam fractionation process also strips fine solids and some dissolved organics from the water. In freshwater the effectiveness of a foam fractionator is usually limited by the availability of surfactants. Foaming action is also effectively suppressed by fish oil found in many feeds. As a result, the performance of many freshwater foam fractionators is erratic, and water quality benefits can be marginal. The technology works better in saltwater. In saltwater small bubbles are easily formed and foam production is dependable. Foam fractionators are more widely accepted in marine applications ranging from ornamental to food fish production.

Foam can be controlled with a simple foam fractionator design. A basic foam fractionator consists of a section of PVC pipe with an air stone. The process can be improved by inducing a counter-flow between the water and the bubbles. The most elegant commercial designs are fabricated out of clear acrylic columns that are several feet high. These units are capable of contributing to the removal of fine solids and refractory organic from the RAS waters.

Integrated Treatment

To the novice, RAS design can appear complicated. Yet, robust RAS designs can be as simple as a tank, a pump, a few spray heads, and a bioclarifier. All the technologies described here have proven track records and can be combined in a variety of ways to form a viable RAS. Always be sure that the five core processes: 1) circulation, 2) clarification, 3) biofiltration, 4) aeration, and 5) carbon dioxide stripping are addressed. All components in an RAS must be sized to handle the same fish (feed) loading. Table 1 presents just a few of the large variety of RAS configurations that have worked successfully. In a typical design exercise, the holding capacity of the system (pounds of fish) is defined, the peak daily feed ration is calculated, and then all components are sized to support the peak daily feed load. A prudent designer will then multiple a uniform safety factor (for example 1.5) across all the major component sizing calculations.

With a little knowledge, it is relatively easy to develop an RAS system that will produce fish. It is considerably

Table 1: Illustrative RAS Core Treatment Configurations.

Type	Circulation	Clarifier	Biofilter	Aeration	CO$_2$ Removal
Marine Fingerling	Airlift	Bead Filter		In tank aeration and airlifts	
Cool water Growout	Axial Flow Pumps	Microscreen	Moving Bed Reactor	Pure Oxygen by hooded agitation	Moving Bed Reactor
Warmwater Growout	Centrifugal Pumps	Bead filter	Moving Bed Reactor	In tank aeration	
Coldwater Growout	Centrifugal Pumps	Microscreen	Fluidized Sand Bed	Pure Oxygen Speece Cone	Packed Column
Marine Broodstock	Centrifugal Pumps	Bead Filter	Fluidized Sand Bed	Packed Column	

more difficult to configure a RAS business that makes money. When you make the transition from hobby or bench scale to commercial, seek professionals for help or review of your RAS design. Cost effectiveness between RAS design varies widely.

Suggested Readings

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