Optimizing Production by Continuous Loading of Recirculating Systems

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From:
Proceedings from the Engineering Aspects of Intensive Aquaculture Symposium
Northeast Regional Agricultural Engineering Service
Cornell University, Ithaca, NY
April 4-6, 1991

Introduction

The advantages recognized as characteristic of recirculating aquaculture systems have been well documented for many years (Liao and Mayo 1974; Losordo 1991). The significant water resource requirements and appropriate climatic conditions required of traditional fish culture systems are virtually eliminated. A properly designed recirculating aquaculture system can be placed almost anywhere, and produce a quality-controlled product continuously throughout the year. However, with the actual implementation of various systems, the strict prerequisites inherent in hardware and technology development, as well as the processing and marketing demands required to achieve economic viability, are becoming more clearly defined (Losordo et al. 1989).

Also, with the escalation of debate concerning recirculating technologies, it has become necessary to more carefully define the terminology that is used to describe the processes involved. Recirculating aquaculture can describe the reuse of water in semi-closed systems, such as raceways or flow-through tank systems, in which no water quality control technologies are employed except water exchange. A number describing percent recirculation in these cases can simply denote the amount of water that is reused on a single pass via pumping, thereby increasing the volume of water available, but still resulting in several new tank or raceway volumes of water each day. A value of 90% recirculation provided for a 1000 gpm flow-through facility would still describe the use of 100 gpm of new water, or 144,000 gallons/day.

When describing percent recirculation in a /closed-system", the number used, (by definition remaining above 90%). will describe the average percentage of the total water volume within the system which is used on a daily basis. In a 50,000 gallon facility, a 90% closed-system would employ 10% make-up water or only 5000 gallons of new water daily. In these systems, increasing the quality of the hardware and technologies used to maximize the recirculation efficiency to levels nearing 100% is often required. This is not to minimize water usage, but to provide for solid waste management and to reduce the amount of heat lost in the effluents (Kugelman and Van Gorder 1991).

In order for any form of aquaculture to be economically viable, it is necessary to integrate the aquatic resources or technologies with the appropriate marketing strategies. For recirculating systems, these strategies must take advantage of the specific benefits afforded to the product. These include the availability of the fish as an absolutely fresh product (alive or fresh dead), certified as unpolluted, and available continuously throughout the year. These are “value added" aspects which, considering the higher expenses involved with recirculating techniques, must result in a more highly priced product in order to provide an economically viable alternative to traditional aquaculture. These advantages must be offered as incentives to various niche markets willing to pay a higher price (Buck 1991).

State-of-the-Art

Various methods have been employed by the industry to provide for water quality control with closed-systems at several scales of production. Because of the complexities involved, there isn't just one particular cost-effective system to be developed. Every system will differ in many ways from others, in the design of the hardware, and the use of its technologies. In evaluating any recirculating aquaculture system, the production capacity will be determined by the limitations of its weakest component. With recirculating systems there are dozens of design requirements, all of which must be carefully integrated to operate efficiently. And efficiency is the final word in the successful operation of a recirculating system.

While the scale of production is extremely important in determining what components are appropriate to a particular design, commercial systems of any size cannot use many of the off-the-shelf items that have, in the past, often been characterized as effective. The use of swimming pool sand filters for solids removal and/or biofiltration, or sewage treatment and aquarium industry hardware, is seldom appropriate for fish culture. In fact, it is necessary to integrate components designed specifically for each water quality control requirements with the co-developed management techniques. The development of these systems is expensive, and is therefore often carried out on a pilot scale that is too limited to make objective projections. The result has been the design of many "paper systems", which have usually failed when implemented.

System Components

Optimizing production by continuous loading involves the maintenance of high levels of feeding at all times. The control of water quality continuously under these heavy-loading conditions requires the use of appropriately designed hardware. And the careful integration of this hardware with co-developed management technologies is also necessary.

To date, the design of equipment to accomplish this, and the evaluation of such equipment, has usually taken place independently for each unit process (biofiltration, clarification, aeration, pH control, etc.). However, to be effective, the design of the hardware and management technologies which control each unit process must be integrated with those controlling all other unit processes. The following describes the general design characteristics of the individual components associated with the maintenance of water quality and equacultural productivity within a recirculating system.

Tanks

The culture tanks are perhaps the first and most obvious component considered for recirculating systems. The tanks must be self-cleaning (therefore usually circular or oval), with angled floors to effluent ports, using dynamic flow characteristics for efficient removal of the culture water and waste products to the filter components. The volume of water in the tanks must correspond to the rate of flow through the filter components (for suitable retention time and number of daily passes). Other considerations include the anticipated density of the fish, smoothness of tank walls, am of cleaning, access to the fish, and finally cost.

Biofilters

Usually considered the heart of the system, the biofilter component must remove the ammonia produced by the fish. There must be adequate surface area for the growth of nitrifying bacteria, and the filter must not clog with fish wastes or the sloughing bacterial growth. The filter media must also have the necessary characteristics to be continuously self-cleaning.

The effectiveness of the biofilter will also depend on … the amount of oxygen available to the bacteria; the flow rate of the water through the filter; the concentration of ammonia coming in contact with the media over time; the mechanical reliability; the energy requirements of the filter; and the initial cost (Wheaton at al. 1990).

Clarifiers

Removal of particulates (mainly fish feces) from the water on a continuous basis is one of the most problematic of all system design requisites (Chen and Malone 1991). The settleable solids must be removed from the tank, removed from the flow of water and concentrated, and removed from the clarifier itself on a frequent basis, to preclude the breakdown of these wastes. The clarifier must be integrated with the tank, the biofilter, and pumping components to provide the appropriate retention times required. At least a daily removal of the concentrated solids must be accomplished.

Suspended solids must be removed to reduce biological oxygen demand (BOD), maintain clarity, and provide an optimal environment for the fish. Several species of fish will demonstrate reduced respiratory efficiency, and suffer potential gill damage and secondary disease problems from excessive suspended solids levels. These solids can be removed by foam fractionation (Chen at al. 1989) or screen filtration (Makinen at al. 1988). The potential for fine screen filtration depends on the ability to preclude clogging, and the energy efficiency of the process.

Dissolved solids result in the coloration of the water, reducing visibility and possibly productivity. Those solids include a BOD component, as well as an accumulation of various metabolites, such as hormones, that may reduce growth rates. The only effective way to remove these is by using ozone for oxidation of this component (Wheaton, 1977).

Aeration/Oxygenation

Mechanical aeration, sparging of air bubbles, and the use of air-lift designs for pumping can be incorporated in a variety of appropriate designs. Consideration must be given to accomplishing the desired aeration, and secondly to the energy efficiency. All aeration considerations must relate directly to the anticipated feeding levels, and to the temperature of the water. In super-intensive recirculating aquaculture systems, which are necessary for most commercial levels of production, pure-oxygen injection systems are required to maintain adequate and stable dissolved oxygen levels (Colt and Watten 1988).

The use of pure oxygen allows for the maintenance of saturated or even super-saturated levels of DO in the water. Several methods can be used to dissolve the oxygen into the water, including U-tubes (Watten and Beek 1985), high-pressure spargers with micro-bubbles (deep water systems) (Severson at al. 1987), or inverted cone oxygen-injection chambers (Speece et al. 1971). The design specifications require that the necessary volume of oxygen super-saturated water is efficiently provided to the culture tank to maintain the prescribed dissolved oxygen levels upon dilution. The efficiency is related to the percentage of pure oxygen which is dissolved without being lost to the atmosphere, and to the cost of the oxygen and electricity involved in the process. The system design must relate to the tank size, shape and volume, the temperature of the water, the levels of feeding, the cost of the equipment and the availability and cost of oxygen.

Heating//Insulation

The methods used to heat water (relating most importantly to the % recirculation previously discussed) and to conserve that heat, are vital to an energetic and economic analysis of a recirculating culture system. One choice is to heat the room air to several degrees above the desired water temperatures (taking into account evaporative cooling) and provide adequate room insulation to retain the heat economically. The second choice is to heat the water and insulate the culture tanks, as well as the room. In this case, the tanks should be covered as well. This results in a more comfortable working environment, with room temperatures maintained below water temperatures

Pumping Systems

Water must be moved through system components at prescribed rates. The main concern will be electrical costs, the efficiency of pumping, the height required to pump the water, and the elimination of potential clogging problems. Air-lift pumps should be used when possible to minimize cost and mechanical problems (Turk and Lee, 1991).

Feeding Systems

Recirculating systems require the efficient management of feed inputs to maintain a stable and continuous feeding regimen throughout a carefully controlled dial light cycle. By dispersing the computed feed levels over the entire lighted period, the negative effects of feed inputs on water quality, and subsequently the demands on all of the system design components, are mitigated. This requires the use of automatic and/or demand feeding systems. Light cycles should also be maintained at optimum levels to maximize feeding periods.

Reservoir Systems

In situations where water must be treated for removal of chlorine, or to elevate incoming water temperatures for direct administration to stocked tanks, it is necessary to employ reservoir tanks. Also, quantities of water may be required for emergency use.

Holding Systems

The value of the fish produced in closed systems is related to their freshness when delivered to market. It is often necessary to keep the fish alive while awaiting transport to preserve this freshness, or to remove any off-flavors.

Emergency Electrical Systems

There must be a provision for absolutely trustworthy back-up electrical power that will sustain all water quality parameters during power outages. There should also be automatic systems for contacting key personnel in case of emergencies.

There are many additional state-of-the-art aspects of a recirculating aquaculture system that must be specifically designed to complement all of those previously discussed. These include methods or systems for pH control, carbon dioxide removal, laboratory and field analysis of water quality, nursery and/or spawning systems for continuous fingerling availability, waste management and disposal, methodologies for year-round harvests, transport capabilities, and processing and marketing strategies.

Fundamental System Requirements

There are several aspects of design and implementation that are considered of such importance that they are obligatory to the successful operation of closed/recirculating systems:

1. Levels of water recirculation must be maintained well above 90%. (Unless there is an availability of significant volumes of heated water.)

2. Efficient and continuous removal of solid wastes is necessary, using clarification methods for settleable and suspended solids.

3. Ammonia levels must be controlled through efficient biofiltration.

4. Dissolved oxygen levels must be controlled through efficient aeration/ oxygenation systems.

5. Systems must be maintained at threshold levels of biomass loading with sustained optimal feeding inputs, and all system water quality control components must be continuously operated near threshold design limits.

6. A combination of technologies must provide for a continuous harvest capability.

It is the last two of these imperatives that will be discussed below.

Maintaining Continuous Loading

In commercial-scale recirculating aquaculture systems, the densities involved are often much higher than with most traditional methods of aquaculture, with productivity measured in hundreds of thousands of pounds per acre. However, initial and operational expenses are necessarily much higher as well. Establishing and maintaining the levels of intensive aquaculture required for these systems is more costly. Each of the design components and technologies described above are costly to develop, build and implement. The operational expenses are higher, environmentally controlled space is expensive, and the technologies require the involvement of specially trained personnel. It is therefore necessary to continually utilize all system design elements optimally.

As an example, in most pond systems, the same number of fish are stocked that will ultimately be harvested. The fish are grown out through a single warm-weather season, and increasing levels of feed are provided to the pond as the fish biomass increases. The potential loading capacity of the pond is not reached until the very end of the season.

This situation is not acceptable in recirculating systems. Considering the costs for the equipment and space, and the increased operational expenses involved with recirculating aquaculture systems, it is necessary to always maintain fish biomass at near capacity, and therefore provide continuous feeding at some threshold level. If the same number of fish are stocked in a tank system as fingerlings, as are ultimately to be harvested, they will initially receive a small fraction of the feed that will be required when they reach a harvestable size. As with pond systems, it will be several months before the system will be loaded at the rate for which it was designed. If the water quality control systems are not being utilized at or near capacity for the majority of the growth cycle, the operational expenses will be excessive, and the system will not be economically viable.

This situation can be dealt with in several ways:

Culture tanks utilizing individual or centralized water quality control systems can be designed to maintain several size classes of fish, with the stocking of additional fingerlings attending the harvest of fully grown fish. Biomass and feeding levels would therefore not be reduced below threshold levels following harvests.

Many culture tanks, each with varying size classes of fish, can utilize centralized water quality control systems designed to maintain water quality within all tanks. The additive feeding levels, and the subsequent demands on the control systems of the total population of fish, are thereby not excessively reduced by the total or partial harvest of any single tank.

Multiple tank complements with individual or centralized water quality control systems can utilize a system of density manipulation to maintain threshold levels of productivity in each tank. This requires that a significant population of small fish is initially stocked in a tank. As the biomass of the fish and the subsequent feeding levels approach the capacity of the associated water quality control systems, the fish population is periodically sub-divided to additional tank systems, thus maintaining the biomass loading at acceptable levels in each. This way, relatively constant and efficient use is made of all tanks and water quality control systems.

The last of these scenarios is employed by Fresh-Culture Systems, Inc. (Patent Number 4,913,093), and involves the use of multiples of 16 production tanks, with de-centralized water quality control systems. The design employs three manipulations of fish density within overlapping 6-month growth cycles. The management system will also provide for the continuous availability of harvests throughout the year.

There are a number of philosophies underlying the selection of this process for maintaining continuous loading and harvesting:

The use of multiple tanks with individual water quality control capabilities provides for the isolation of each system from others (decentralized technique). Any water quality, disease, management or hardware problems are usually completely isolated to a single production unit.

The necessary integration of appropriate system components can be accomplished without relying on off-the-shelf hardware, often designed for non-aquacultural purposes. Individual water quality control requirements can be met with custom engineering appropriate to the scale of the individual tank systems. Example: The sizing of such filters as rotating biological contactors; for the totality of a commercial system's demands requires the use of units that are constrained by certain associated limitations. These include the use of sewage treatment units or proportionately sized designs with the same problematic gearmotors, chain drives, shafts and pillow blocks, and the increased energy requirements. Such units will suffer from the many related malfunctions.

Pumping requirements for circulating all water from multiple locations through a centralized water quality control center involves much greater expense and risk than carefully engineered individual tank systems. Also, to provide for continuous harvest capabilities, it is still necessary to manage multiple culture units with harvestable-sized fish populations, or use partial harvests. To manage these and the various additional production levels will require many tanks and probably multiple water quality control systems,

The design of the water quality control systems must be integrated with the methodology for the maintenance of continuous loading. Examples:

- Round tanks are required for optimal management of solid wastes. However, these tanks do not lend themselves to the maintenance of several size classes of fish within the same tank

- Oxygen injection systems using U-tubes require the mixing of the highly super-saturated water into large volumes of tank water. Therefore, this will require the mixing of all system water, either into various tank locations, or into individual very large tanks. This reduces the potential for the isolation of water quality, disease or stress problems.

- Maintaining mixed-size populations within the same tank requires the use of partitioning, which is difficult in round tanks, or the mixing of sizes within the tanks (not possible with some cannibalistic species). Such mixing will exacerbate the variability within size classes of stocks and the stunting of some percentage of the fish populations. Larger, more aggressive, fish will usually get the food. It will also require the use of graders to remove harvest-sized fish on a continual basis, resulting in more stress to the fish than with periodic manipulations of a fraction of the population. In order to maintain good water quality, it is as important to manage the bacterial populations growing on the biofilters as it is to manage the fish populations. This is simplified with numerous tanks requiring moderate loading levels, each with a properly scaled biofilter. Multiple tanks of tremendous additive volume and production capacity being serviced by a single bank of biofilters, are more dangerous to maintain and to integrate with all other water quality control systems.

Often, the economic viability of a project depends on the acquisition of inexpensive space, such as barns or old factory buildings. It is seldom possible to require or afford the excavation necessary for such water quality systems as multiple U-tubes, below-grade settling systems, or angled tank floors as designated for the very large units carrying all size grades of fish, or large multiple tank units coupled with centralized water quality control.

Also, the required movement of significant proportions of the fish population provides an opportunity to assess the size and health of the fish, determine the success of the previous growth cycle, and adjust feed levels accordingly.

For these reasons, multiple-tank density manipulation systems have been designed as described, by Fresh-Culture Systems, Inc. The potentially adverse consequences of density manipulations are minimized by proper management techniques, and the use of appropriate hardware. The stress of handling the fish is reduced by the harvesting techniques. This includes the use of customized hardware to accomplish the move quickly, without subjecting the fish to rough handling, while maintaining optimal water quality and proper conditioning.

The use of the density manipulation system results in an increase in the production capacity of a 16-tank system by 2.3 X per year. The system provides for the harvest of eight tanks every six weeks (8.7 times per year).

This system also results in the maintenance of substantial feeding levels within each tank at all times. Three density manipulations provide for the initial stocking of four times as many fish as could normally be sustained. And having four size classes of fish being cultured at all times, and eight tanks available for harvest every six weeks in combination with holding systems, results in the continuous availability of market-sized fish.

Guidelines for Implementation

Initially, a tank is stocked with the appropriate number and size of fingerlings that will, following six weeks of intensive culture at maximum feeding rates, approach the relatively fixed capacity of the growing environment to maintain water quality. At that time, half of the fish are moved to a previously harvested tank. Also at that time, another single tank is stocked with the initial number of fingerlings.

This is followed by another six weeks of intensive feeding, a subsequent density manipulation from each of the two equally stocked tanks and the second fingerling tank to three additional units, and the stocking of another tank of fingerlings. A third sub-division will result in the equal apportionment of the originally stocked fish within eight tanks, and the subsequent stockings similarly divided in the other seven tanks.

When in full operation, fifteen tanks will include one tank of fingerlings stocked at a predetermined density. Two tanks will be maintained at half, four at a quarter, and eight at an eighth of this original density. Every six weeks, eight tanks are harvested, seven are sub-divided and one is restocked with fingerlings. The 16th tank is an extension of the nursery tanks, providing for the maintenance of large numbers of fingerlings for continuous stocking.

Operational Results

The described techniques were developed and tested over several years in full scale systems operated by Fresh-Culture Systems, Inc., using tilapia, striped bass, hybrid striped bass, catfish, carp, yellow perch, coho salmon and trout. The culture systems and density manipulation technologies have now been implemented successfully in commercial culture systems for several years.

By incorporating appropriate handling methods, losses accrued during or following the movement of fish are negligible. The techniques are not excessively management intensive, and result in a much more realistic and economically viable system than all other alternatives tested. However, the potential of this system for maintaining continuous loading and harvestable levels of fish is completely dependent on the integrated development of closed-system hardware and technologies for water quality control, and proper aquacultural management techniques. The use of several multiples of the 16-tank design provides for the up-scaling of the system on the same or different site locations.

Summary

Recirculating aquaculture systems provide many advantages towards environmentally controlled production of finfish throughout the year, removing the normal climatic and water resource restrictions. However, the systems are expensive, usually require costly indoor space, and have continuous and substantial operational requirements beyond traditional methods. Because of the initial and operational costs of the complex water quality control systems, it is imperative that they function at near capacity at all times. The basis for determining the operational capacity of any system for growing fish is the average level of feeding that can be maintained. This will, in turn, determine the design parameters of all of the filtration and aeration equipment. Therefore, any significant fluctuation from an optimal average feeding level will reduce the operational efficiency of the system below economically acceptable levels.

The described system for maintaining an acceptable threshold level of average feeding has been tested and employed for several years, and is effective. However, to achieve and maintain this effectiveness requires not only the multiple tank / density manipulation protocols. It also requires the use of integrated hardware and technologies for all levels of water quality control, fish and feed management, the availability of water reservoir, nursery and holding systems, and the employment of many energy conservation techniques.

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