VII. GAS MANAGEMENT IN INTENSIVE AQUACULTURE

INTRODUCTION

The following gases may have to be managed or controlled in intensive aquaculture; oxygen, ozone, nitrogen, hydrogen sulfide, and carbon dioxide. Oxygen ($O_2$) must be added to the water in the culture tank and, either is taken from the ambient air (aeration) or from a pure or high purity source (oxygenation). If ozone ($O_3$) is used, it too is either produced from air or from pure oxygen. Because ozone is toxic to fish, it may have to be removed from the water as well. Nitrogen gas ($N_2$) can cause the bends in fish, i.e., create gas bubbles in the blood, when present in rearing water under supersaturated conditions. Nitrogen supersaturation is not uncommon in groundwater; it can occur when water temperature is increased, and sometimes is caused by air leaks in pumps. Low level supersaturation can cause chronic gas bubble disease (gas bubble trauma) while high concentrations can lead to high mortalities in a very short period of time.

Carbon dioxide too, can be present in groundwater. Limestone, for instance, can be a reservoir of carbon dioxide. As has been discussed, living organisms that use oxygen (fish and nitrifying bacteria on biofilters) also generate carbon dioxide in large amounts. Because much oxygen is utilized in intensive fish culture, carbon dioxide must be managed in such systems.

OXYGENATION

Because air contains only 21% oxygen and about 78% nitrogen, the maximum safe limit of aeration is to 100% saturation. Going beyond this will result in supersaturated nitrogen levels and may result in gas bubble disease, potentially causing acute mortalities. Continuous exposure to a total gas pressure (TGP) even slightly over 100% saturation can cause gas trauma. Dissolved oxygen can be above 100% saturation without exceeding 100% TGP, provided nitrogen is below saturation and at increasingly lower levels as oxygen increases.
With the use of high purity oxygen, it appears that one can safely exceed dissolved oxygen supersaturation without creating conditions leading to gas bubble disease. Oxygen toxicity can occur when partial pressure exceeds 300 mmHg. This is equivalent to 21 mg/l DO at 12\(^{\circ}\) C, 16 mg/l at 25\(^{\circ}\) C.

What is important is that, as more and more oxygen is dissolved into the water, nitrogen gas must be displaced to avoid exceeding TGP over 100%, especially critical where source water is supersaturated with nitrogen gas to begin with.

To accomplish that a non-pressurized oxygen contractor is required, such as a sealed column. On the other hand, pressurized systems have limitations because they can increase the TGP above 100% saturation. These systems are more suitable for side-stream aeration, where a relatively small portion (10-25%) of the total flow is supersaturated with oxygen (200-400%) then blended into the main flow. This technique can only be used if there is no initial nitrogen gas supersaturation. Since most groundwater sources are naturally supersaturated with nitrogen gas, pressurized systems should not be installed on such sources. Application of high purity oxygen offers an effective means to control nitrogen gas supersaturation. Oxygen introduced into water flowing through a negative pressure system, such as the Michigan spray column, will effectively displace the nitrogen gas with oxygen, while maintaining a total gas pressure near 100%, even when dissolved oxygen levels are elevated to 200% saturation or more (Figure 1). Michigan spray columns, due to their dual function, are only moderately efficient. Figure 2 shows a variety of oxygen contactors, including the Michigan spray column.

**Design and Operational Characteristics of the Michigan Sealed Column**

The column consists of an airtight chamber into which water and oxygen are introduced while preventing outside air from entering (Fig. 1). Whenever clean, nutrient-free water is used, a sealed column such as this can contain packing material, such as pall rings, tri-pack, or other materials to break up the flow of water and create the maximum possible gas-water interface.
In case of nutrient rich water, as in a serial reuse design, packing media quickly biofouls, plugging the systems. In this case, the Michigan sealed column becomes a sealed spray column, equipped with a non-plugging sprayer device. Oxygen can be introduced into the water delivery line at the top of the column, or into the column itself, near the bottom to create a counter current gas flow with the downward flow of the water.

Some studies have shown that at higher water flow rates a better absorption is realized when oxygen is introduced at the top rather than the bottom of the column. A unique feature of the sealed column is that it operates under a partial vacuum, created through venturi action.

One design (Figure 1) shows that the column outlet is reduced to half the diameter of the column proper. This causes the water to back up higher into the column. This height is directly proportional to the water flow rate (hydraulic loading). Because of this, the column can also serve as a flow metering device. By installing a viewing window, water level in the column can be observed. After making a series of flow measurements, the column or sight glass can be marked off to indicate specific flow rates. Table 1 provides operational and performance characteristics. The partial vacuum occurs naturally (law of physics) and varies with flow rate. It is this feature that makes sealed columns an excellent device to control and/or prevent TGP over 100%. Oxygen absorption efficiency is of considerable importance in the economics of using pure oxygen.

However, high absorption efficiencies do not necessarily result in less expensive oxygen injection. The cost per unit of O₂ absorption is a function of amortization, energy cost, O₂ cost, water flow, and DO increase. Excellent absorption efficiencies can be achieved at low oxygen flow rate relative to water flow rate, but this occurs at a higher cost because only a small amount of oxygen is added relative to capital expenditure for the system. In cases like these, mechanical aerators may be more economical. The percent oxygen absorption efficiency (AE) of sealed columns can be determined with equation 1.
AE = \frac{(Q_w \times 100 \times \text{DDO})}{(1.43 \times 1000 \times Q_o)} \quad (1)

Where \( Q_w \) is water flow rate and \( Q_o \) is oxygen flow rate in lpm, \( \Delta \text{DO} \) is DO increase in mg/l, 1.43 is the weight (g) of one liter of oxygen at STP, and 1000 converts mg \( \text{O}_2 \) to g. To mathematically simplify the equation:

\[ \text{AE} = \frac{(Q_w \times \text{DDO})}{(14.3 \times Q_o)} \quad (2) \]

\[ \text{AE} = \frac{(Q_w \times \text{DDO})}{(3.8 \times Q_o)} \quad (2a) \]

The equation must be adjusted based on % oxygen purity. The absorption efficiency or performance optimization of a sealed column depends on many variables. Certain combinations of such variables can result in the same DO gain, but not necessarily at the same cost. Through trial and error it was determined that a sealed column functions well with a cross-sectional area of 1.0 to 2.0 cm\(^2\) per lpm (244 to 122 gpm per square foot).

The column diameter can be determined with equation 3:

\[ \text{DIA} = \frac{2\sqrt{aQ \times Q_w}}{p} \quad (3) \]

where \( aQ \) is area per unit flow (cm\(^2\)/lpm).

Initial dissolved oxygen concentrations near saturation contribute to relatively poor absorption efficiencies, while initial low DO concentrations can result in high absorption efficiencies. These observations, of course, follow a typical law of diminishing returns.
Reducing the height of a column while maintaining the same level of dissolved oxygen requires an increase in the gas to liquid ratio, hence a reduction in absorption efficiency. Overall, the effect of column height is not as important a design parameter for pure oxygen systems as it is for atmospheric packed columns.

**How Much Oxygen?**

The potential benefits of increased dissolved oxygen levels can be very significant. Generally, these benefits are two-fold, namely improved quality of the rearing water and increased fish production potential.

In situations where the objective is to increase dissolved oxygen level of source and/or rearing water only moderately, mechanical aeration might be the most economical method. Although a low oxygen to water ratio can produce good aeration efficiency, the benefits from a costly oxygenation system make this economically problematic.

In general, any increase in dissolved oxygen makes that much more oxygen available to the fish. An increase of as little as 1.0 mg/l can represent a 20 to 25% increase in carrying capacity. In cases where incoming dissolved oxygen levels already approach saturation, less than 50% of the oxygen will be available to salmonids, evidenced by the fact that the effluent should contain anywhere from 5.5 to 7.5 mg/l DO. When supplemental oxygen is used to increase production, one has to determine to what extent additional production can be accomplished before unionized ammonia reaches the maximum acceptable level (1). As more and more oxygen is made available, carbon dioxide concentrations will continue to rise.

In a previous discussion, we assumed a maximum available oxygen of 30 mg/l (Table 3-V). At maximum biomass, or carrying capacity, the daily requirement is for 30 mg/l DO, the loading is 12 kg/lpm, the rearing volume is 500 m³, the maximum density 100 kg/m³, the resulting maximum biomass 50,000 kg, and the required flow rate is 4167 lpm. To determine the
flow rate of oxygen required \( (Q_o) \) to provide 30 mg/l in a flow rate of 4167 lpm \( (Q_n) \), equation 4 can be used:

\[
Q_o = \frac{(Q_n \times \text{AO})}{(14.3 \times \% \text{abs})}
\] (4)

For our values (assuming a 50% absorption efficiency):

\[
Q_o = \frac{(4167 \times 30)}{(14.3 \times 50)}
\]

\[
Q_o = 175 \text{ lpm}
\]

To determine the minimum capacity of an PSA oxygen system which are rated on volume generated per hour \( (\text{ft}^3 \text{ or m}^3) \) the 175 lpm \( \text{O}_2 \) equals 10490 l/h or 370 ft\(^3\)/h (one ft\(^3\) = 28.3 l). In the case of \( \text{LOX} \) we must decide on the size of the storage tank. One gallon liquid oxygen equates to 115 ft\(^3\) gaseous. Assume that for each 100 ft\(^3\)/h requirement, 720 gallons of liquid are needed per month. For a 6-month supply, a 4,320-gallon tank is needed per 100 ft\(^3\)/h. For 370 ft\(^3\)/h a 15,984-gallon tank is required.

It is important to maintain a steady biomass of fish in the system, and a biomass less than the maximum, yet one that approaches it as much as is practical. This will be covered when discussing maximizing production through sequential rearing (VII).

**Oxygen Source and Cost**

High purity oxygen for aquaculture can be supplied in three basic forms:

1. Bottled oxygen under high pressure (2550 psi). The cost is high, from $8 to $10 per 100 ft\(^3\). Cylinders are sized from 100 to 250 ft\(^3\). Oxygen purity is high, from 98 to 99%. 

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2. Liquid oxygen (LOX) under pressure of 150 to 200 psi. To maintain the low temperature (-182.96°C; -297.3°F), 0.25% is vented daily due to pressure increase. Storage tanks ranging in size from "portable" of 100 l to over 40,000 l (10,000 gals.) Tanks are often rented along with the required evaporator and regulator. The cost of oxygen varies from $0.25 to $3.00 per 100 ft³, depending on distance and company.

Liquid oxygen may be the best choice when:
- an inexpensive, nearby supplier is available.
- the culture site is remote and has very limited and/or unreliable electrical power.
- oxygenation requirements are very large (6 to 10 tons per day or 5,000 to 9,500 ft³/h).

3. The pressure swing adsorption (PSA) oxygen generator can provide on-site oxygen production as needed. The generators are available in a wide range of capacities, from less than 1.5 to over 400 ft³/h. Very large systems can be custom designed and assembled on site. PSA systems require dry, filtered air under pressure of 90 to 150 psi. Air compressors of the proper capacity are an integral part of a PSA oxygen generator. Although air contains 21% oxygen, or approximately 1.0 ft³ per 5 ft³ of air, a PSA may require 13 to 15 units of air to generate one unit of O₂. Even then, its purity is only 85 to 95%. The cost of oxygen ranges from $0.30 to $0.70 per 100 ft³, depending on the electric cost.

Recently, a low-pressure PSA has been marketed, although not as yet field tested. This system uses a low pressure, high volume regenerating blower to supply air. Energy costs are significantly reduced because the high pressure air compressor is eliminated. One serious drawback is that the oxygen generated in this manner is only slightly pressurized (<5 psi). An additional component may be needed to pressurize the O₂ so it can be delivered to the oxygen contactor in adequate volumes.
MANAGING CARBON DIOXIDE

Carbon dioxide is very soluble in water and reacts with it in a complex, dynamic, acid-base equilibrium. The lower the pH the more free CO₂ (gaseous); the greater the pH the more CO₂ is present as bicarbonate (HCO₃⁻) and/or carbonate ion (CO₃²⁻).

When removing gaseous (toxic) CO₂ it is replaced from the HCO₃⁻ or CO₃⁻ sink to maintain equilibrium. Below pH 5, almost all CO₂ exists as free CO₂, between pH 7 and 9, it is converted to non-toxic bicarbonate at about pH 11 it exists mostly as carbonate. From a practical viewpoint, there is no free CO₂ above pH 8.4.

Stripping CO₂ from the water requires large quantities of air. The gas-liquid ratio (G/L) must be 5:1 and 10:1. Aeration typically uses a < 3:1 ratio, oxygenation only requires between 0.05:1 and 0.3:1.

The best way to strip CO₂ is to expose the water to the air. The air concentration of CO₂ is low, only about 350 mg/l (0.035%) versus oxygen at 21% has a concentration of 210,000 mg/l. The saturation concentration in water is at 0.69 mg/l for CO₂ versus 10.1 mg/l for DO at 15°C.

A packed column degasser can be used to strip CO₂ from the water. Summerfelt (2000) states that the high gas/liquid ratio is accomplished by forcing air through a 1.0-1.5 m tall cascade column, sized to treat 1000 to 1400 lpm water flows per square meter (1.0 lpm per 10 to 7 cm²) (one square meter is equal to 10.76 ft²). Hydraulic loading rates as high as 1667 to 4167 lpm per m² have been suggested (41 to 102 ft²/gpm).

Air discharged from stripping columns should be vented from buildings to prevent carbon dioxide from accumulating in the building space. The Occupational Safety and Health Administration (OSHA) limits the allowable time-weighted average exposure over an eight-hour
workday to concentrations less than 5000 mg/l (Vinci et al, 1998) A concentration of 50,000 mg/l is considered immediately dangerous to life.

Because pH controls the relative concentrations of each species of CO₂ in the inorganic carbon system, methods to increase the pH will lower the proportion of free CO₂. Adding lime, caustic soda, soda ash, or sodium bicarbonate to the water will increase the water's pH.

When stripping CO₂ the equilibrium is shifted as bicarbonates release carbonate ions. This shifts the pH to a higher value. Within minutes carbonic acid will have dehydrated to establish a new equilibrium replenishing (replacing) some of the carbon dioxide that was removed. This dynamic makes it difficult to strip a large fraction of carbon dioxide from well-buffered waters. Because pH also controls the acid-base equilibrium between ammonia (NH₃) and ammonium (NH₄⁺), increasing the pH to reduce free CO₂ concomittantly increases the proportion of unionized ammonia, a toxic component. This limits the pH range available for CO₂ control (See Figure 3).

**OZONE IN INTENSIVE AQUACULTURE**

**Introduction**

Ozone is a triatomic oxygen gas (O₃). It is unstable and highly reactive, and is thus a very powerful oxidizing agent. These properties make it a better disinfection agent than ultraviolet radiation (UV) and chlorine. It has a pungent odor, which is sometimes noticeable after a violent thunderstorm, when lightening through the atmosphere causes some of the oxygen molecules to change into ozone.

Ozone generators apply this principle by creating an electrical arc (lightening) between two high voltage electrodes (Figure 4). As oxygen, the feed gas, flows between the electrodes some of the oxygen (4 to 6% by weight) is changed to ozone. Much heat is produced as well,
which can represent 90% of the energy applied, with only 10% going toward the production of ozone. Because heat destroys ozone, the units must be either air-or-water cooled.

Although some units can convert 10 to 15% of the oxygen to ozone, generating these higher percentages makes them less efficient, and the cost of ozone produced will be greater.

Where atmospheric air is used (21% O₂) only 1-3% of the oxygen is converted to ozone. It is much more advantageous to use pure oxygen, especially in aquaculture situations where oxygen is used to oxygenate the rearing water. Whether air or oxygen is used, the gas must be dry, free of water vapor.

Ozone can also be produced by means of UV radiation, but this requires 6 to 30 times more energy than the corona discharge method. Application of ozone is costly in terms of capital expenditure and energy required. The capacity of ozone generators is rated in weight of O₃ produced over time; kg/hr or lb/hr. John Colt (2000) reports that it requires 6-7 kwh/kg O₃ produced.

There are four unit processes required for ozone use in an aquaculture application: 1) O₃ gas generation (corona discharge method); 2) gas-to-liquid absorption; 3) contact time and concentration for reaction; 4) O₃ removal and destruction.

Gas-to-Liquid Absorption

The high cost of ozone makes its efficient transfer into the water important. Because it can be co-transferred with oxygen, the same device can be used. The rate of ozone transfer into water is a function of the concentration of ozone in the gas, the contact area, the thickness and rate of exchange of the two stagnant layers, and the rate of ozone reaction. Increasing mass-transfer efficiency can be accomplished with the use of media that that creates a large surface area of a thin film of either gas or liquid or by reducing bubble or droplet size.
Increased turbulence decreases the thickness of the stagnant layers. This decreases the resistance to the transfer of ozone across it. It also keeps water and gas mixed.

Units that have a continuous gas phase, i.e., units that disperse liquid drops and films within a gas, such as spray columns, packed columns, LHO's, provide efficient transfer but very little time for reaction. In this case a separate contact chamber may be required for reaction. Most ozone contactors rely on continuous liquid phase units that bubble ozone into the liquid. These units are best suited to situations where reaction is rate limited and an ozone residual must be maintained for a specific length of time, such as during disinfection. Their absorption efficiency is not as good as the continuous gas phase technique. Systems that pass water through air can be designed for much higher transfer efficiencies than systems designed to pass air through water.

**Contact Time and Concentration Necessary for Reaction**

The most common method to provide adequate contact time is by means of a deep basin, separated into three to five chambers by means of baffles (Figure 5). The ozone is introduced by diffusers, venturi eductors or static mixers. The length of contact and strength of the concentration depend on the quality of the water and the objectives. For disinfection, the longer the exposure the greater the kill, but, in theory, ozone requires infinite contact times to reduce microbial populations to zero (sterilization), as shown with the equation:

$$\log \frac{N_t}{N_0} = -k't$$

where

- $N_t =$ number of organisms at time $t$
- $N_0 =$ number of organisms at time $= 0$
- $t =$ time in minutes
- $k'$ = constant (1/minute)
For instance, a concentration of 1,000,000 bacteria/mL is equal to 6 log units ($10^6$). It takes the same contact time to reduce the concentration from 6 to 3 log units (1,000,000 to 1000/mL) as it takes to reduce the concentration from 2 to -1 log units (100 to 0.1/mL). The greater the concentration the less contact time is required as shown:

\[ Ct = \text{constant} \]

where \( C \) = concentration of ozone.

\( t \) = time required to achieve a given kill.

Ozone is rather unstable in water. In pure water the half-life of \( O_3 \) is about 165 min at 20°C. In aquaculture systems the half-life may be less than a few minutes because of an abundance of organic compounds. It can be worse in high-density, water-recirculation systems where half-life can be as short as 15 seconds.

Microbial reductions (disinfection) are largely limited by the ability to maintain a certain dissolved ozone concentration for a given time period. For disinfection, the required residual \( O_3 \) concentration is usually between 0.1 - 1.0 mg/l with a hydraulic retention time anywhere from 0.5 to 20 minutes (Langlais et al. 1991).

Obviously these are rather wide ranges, the result of the target organisms and the quality of the water (organic load).

The high ozone demand of recirculated water, caused by accumulated nitrite and organic matter, makes maintaining an adequate ozone residual difficult. In order to achieve large microbial reductions in RAS or PRAS, much more ozone would be needed to disinfect, for instance, most influent waters of a typical, flow-through aquaculture system.

Studies have shown that adding ozone at the rate of 0.025 kg/meal improved water quality and reduced mortality associated with bacterial gill disease, but failed to produce even a one log
reduction (i.e., 90% reduction) in the numbers of heterotrophic bacteria in the water or on the gill tissue (Summerfelt, et al. 1997, and Bullock et al. 1997).

To achieve a large bacterial reduction in recirculation systems requires more ozone than has been reported in the literature. This increases the cost of ozonation, and in addition the contact time must be increased as well. Because the capital costs for adding ozone are large, the economy of using ozone within recirculation systems is questionable.

Ozone Removal and Destruction

Increasing the ozone concentration to accomplish some measure of disinfection requires the incorporation of a mechanism to remove ozone residual from the water before it enters the culture tanks.

Either the contact time must be extended until the ozone is fully "used up" or other treatments must be applied, such as activated charcoal, stripping, or UV destruction. Residual gases from a contact chamber must be collected and vented to an ozone destruction device before entering the atmosphere.

Ozone is harmful to humans as well as aquatic organisms. It is important that there are no leaks within the ozone delivery system. Only ozone compatible materials should be used, such as stainless steel, Teflon®, special fiberglass, and cement.

At low concentrations in the air, ozone has a very distinctive odor, and can be detected well below the daily safety criteria limits of 0.1 p.m. by volume determined as a time-weighted average over a full working day (8-hour maximum) or 0.2 ppm by volume as a maximum 10-minute exposure. For fish, lethal levels can be as low as 9.3 µg/l (0.0093 mg/l). However, production conditions concentrations in the range of 10-20 µg/l (0.01 - 0.02 mg/l) have been found to have no impact on salmonid eggs and fry. The chemical ozone demand from uneaten
feed and waste products will quickly reduce the ozone residual to near zero. Ozone has attracted a great deal of interest. Improvements in water quality and solids removal have resulted from applied doses in the range of 0.025 to 0.045 kg \( O_3 \)/kg feed.

In an earlier presentation (I) it was concluded that, based on \( O_2 \) demand by feed of 250 g/kg, one can feed 0.004 kg feed per lpm for every mg/l DO available.

If ozone is applied at the rate of 0.025 kg per kg feed, 0.004 feed requires 0.001 kg of ozone per lpm or 0.1 g/lpm/mg DO/day.

Because one lpm \( @ \) 1.0 mg/l delivers 1.44 g/day, the 0.1 g/day \( O_3 \) represents a concentration of 0.07 mg/l \( (0.1 ÷ 1.44) \) or 70 \( µg/l \).

Using the range of 0.025 to 0.045 kg \( O_3 \)/kg feed for water quality improvements is rather risky with respect to potential toxicity problems relative to the fish. Accordingly, Colt (2000) recommends that a more focused research is needed to rationally develop the design parameters and operational strategies for the use of ozone in aquaculture systems.


TABLE 1.—Operation and performance characteristics of a sealed packed column at the Harrietta State Fish Hatchery (Figure 1). Column diameter is 30.5 cm and discharge pipe diameter is 15.25 cm. Water characteristics: temperature, 8.2°C; dissolved oxygen (DO), 10.7 mg/L; O₂ saturation, 92%; N₂ saturation, 101–105%.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Water flow in L/min</th>
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<tr>
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<td>Cross-sectional area-to-flow relationship (cm²/[L/min])</td>
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<td>DO gain in mg/L for O₂ inflows of</td>
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<td>% gas:liquid ratios for O₂ inflows of</td>
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<td>%O₂ saturation for O₂ inflow of 1.5 L/min²</td>
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<tr>
<td>%N₂ saturation for O₂ inflow of 1.5 L/min²</td>
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</table>
Gas Management in Aquaculture

Gases of Concern:

Oxygen (DO)
Carbon Dioxide (CO₂)
Nitrogen (N₂)
Hydrogen Sulfide (H₂S)

Also of Interest:

Ozone (O₃)

Oxygen Required
Salmonids: 250 g – 17 hr. Day
(Per kg Feed) 350 g – 24 hr. Day

Biofilter: 1.0 g TAN – 4.4 g O₂
(TAN → NO₃)

Also Heterotrophs Exert an O₂ Demand

RAS: 500 to 1000 g/kg Feed
½ to 1.0 lb/lb Feed
How Much Oxygen Do Fish Require?

Depends on their metabolic rate, which depends on fish size ($W_t$) & water temperature - And - …these same criteria determine the feeding level!

Therefore: Oxygen required per unit of feed is independent of these criteria – It is a constant.

For Salmonids: 200 – 250 g/kg feed/day (17hrs)  
$OF = 200 \text{ to } 250$

$$MR = \frac{\% BW \times OF}{0.1 \times 17 \text{ (hrs)}}$$
MR (OF 250) = % BW \times 147

MR (OF 200) = % BW \times 118

But to determine O_2 required use food required.

Per kg: 250 g O_2/Day

However in recirculation the biofilter consumes Oxygen as well!
$O_2$ Required for a RAS

**Biofilter:** Nitrifiers Oxidate TAN

1.0 g TAN – 4.4 g $O_2$

Feed generate 30 g TAN/kg food

$O_2$/kg feed: $30 \times 4.4 \text{ g} = 132 \text{ g } O_2$

*Heterotrophic bacteria consume oxygen too. Much depends on solids control*

**Total $O_2$/kg feed for RAS**

- Fish ——— 250 g
- Nitrifiers ——— 132 g
- Heterotrophs ——— 118 g (More or Less)

$500 \text{ g } O_2$/kg Feed
Many Variables:

1. Feed Quality (Fines, etc.)

2. Feed Protein Level

3. Feeding Strategy

4. RAS Intensity (%)

5. Biofilter Type

6. Rearing Tank Design

7. Rearing Tank Operation (H₂O Turnover Rate) Etc.
An Exercise (Method)

1. RAS – System Volume: 10,000 m³  
a) Fish Rearing Volume: 8,000 m³

2. Intensity 80% (20% Volume Replacement Per Day) = 200 m³/Day = 1400 lpm

3. Final Rearing Density 80 kg/m³  
a) Max. Biomass: 80 × 8000 = 64,000 kg  
b) Final Feeding Level: 1.5% BW

4. Max. $DO_{in} = 20$ mg/l  
Min. $DO_{out} = 4.0$ mg/l (Out of Biofilter)  
$AO = 20 - 4 = 16$ mg/l

VII-7
5. Circular Rearing Unit

6. \(OF = 250 \text{ (fish)} + 250 \text{ (biofilt.)} = 500 \text{ g/kg Feed}\)

\[Ld(\text{kg Fish/lpm}) = \frac{16(\text{AO}) \times 100}{500 \text{ (OF)} \times 1.5} = 2.1 \text{ kg/lpm}\]

Rearing Unit Flowrate \((Q_{ru})\):

\[Q_{ru} = \frac{640,000}{2.1} = 304,762 \text{ lpm}\]

Exchange Rate \((R)\) :

\[R = \frac{Q_{ru} \times 0.06}{RV} = \frac{18,286}{8,000} = 2.3/\text{hr} \quad (26 \text{ min})\]
How Much Oxygen Per Day ($O_d$)

\[ Q_{dg} = Q \times AO \times 1.44 \text{ g} = \text{g} \ O_2 / \text{d} \]

\[ Q_{dl} = Q \times AO = \text{L} \ O_2 / \text{d} \]

In Our Example:

\[ Q_{dl} = 304,762 \times 16 = 487,619 \ \text{L/d} \]

\[ = 487.6 \ \text{m}^3/\text{d} = 20.3 \ \text{m}^3/\text{h} \]

\[ = 717 \ \text{ft}^3/\text{h} \]

At 80% Efficiency ($\%E = 80$)

\[ 717 \times \frac{100}{80} = 896 \ \text{ft}^3/\text{h} \]
Introduce the Oxygen

1. Aeration: Take O₂ from Air (21% O₂)
   A. Exposing Water to Air
      a) Columns
      b) Surface Aerators
      c) Gravity (Steps, etc.)
   
   B. Exposing Air to Water
      a) Diffusers
      b) Sparges
      c) Jets

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Water to Air More Efficient.

In general, aeration not effective for oxygenation in RAS, but does have the advantage that it also can dispel some of the carbon dioxide.

Trickling and rotating biological filters combine some aeration/degassing. They are high volume biofilters with a “low” surface to volume ratio (150-300 m²/m³) versus granular filters, i.e., sand and micro beads (5000-10,000 m²/m³).

In RAS: Oxygenate, i.e., use pure or high purity oxygen.

LOX or PSA Source.
Controlling Carbon Dioxide in RAS

In Previous Example: 16 mg/l DO
Needed to support maximum biomass.

Carbon Dioxide exists in four forms (species) kept in an acid-base (dynamic) equilibrium:

\[
\text{CO}_2 + \text{H}_2\text{O} = \text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3 \rightleftharpoons \text{H}^+ + \text{CO}_3
\]
Carbonic Acid ($\text{H}_2\text{CO}_3$) instantly releases $\text{H}^+$ ions, lowering the pH.

Result: More (Toxic) Free $\text{CO}_2$ (Gas).

Free $\text{CO}_2$ Must be kept below 20 mg/l

Hypercapnia (High $\text{CO}_2$)

Acidosis: Blood pH lowered due to $\text{CO}_2$ build-up.

Interferes with $\text{O}_2$ uptake and transport in the blood!
## Acid-Base (pH and Alkalinity) Equilibrium

<table>
<thead>
<tr>
<th>pH</th>
<th>6.5</th>
<th>7.0</th>
<th>7.5</th>
<th>8.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalinity (CaCO₃)</td>
<td>18.9</td>
<td>6.0</td>
<td>1.9</td>
<td>0.6</td>
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<tr>
<td>Concentrations of Free CO₂ in mg/l</td>
<td>31.6</td>
<td>10.0</td>
<td>3.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>Alkalinity (CaCO₃)</td>
<td>44.3</td>
<td>14.0</td>
<td>4.4</td>
<td>1.4</td>
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<tr>
<td>Concentrations of Free CO₂ in mg/l</td>
<td>56.9</td>
<td>18.0</td>
<td>5.8</td>
<td>1.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>7.5</th>
<th>8.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalinity (CaCO₃)</td>
<td>69.9</td>
<td>22.0</td>
<td>6.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Concentrations of Free CO₂ in mg/l</td>
<td>100</td>
<td>90</td>
<td>70</td>
<td>50</td>
</tr>
</tbody>
</table>
Alkalinity: Buffering Capacity Resisting pH Change

In RAS, Nitrifiers Use Up Alkalinity and Generate CO₂ Which Lowers the pH.

Should Maintain Alkalinity > 50 mg/l
And pH 7.2 – 7.4

Low pH: Favors Unionized Ammonia (Less NH₃) But More Free CO₂!
CO₂ Control in RAS
1. Air Stripping
2. pH Control (Alkalinity = Buffer)

**Air Stripping:** Need a high gas to liquid ratio g/l from 5 to 10/1.0

**Aeration:** 3 to 1 (inadequate for CO₂)
**Oxygenation:** 0.05 to 1.0 (No CO₂ stripping)

Stripping accomplished with packed column and forced air. In a building – CO₂ must be vented out to prevent build-up – health concerns.

Vinci et al. (1998) Developed Software Program for Air Stripping CO₂
Summary:

Guidelines for O₂ and CO₂ control

1. Strip CO₂ after it reaches its highest level and before O₂ supersaturations are created:
   a) After biofilter
   b) Before oxygenation

Note: Airstripping CO₂ elevates DO to ± 90% saturation – Therefore pure oxygen should only be used to create supersaturation! And...produce DO supersaturation just before the water enters the rearing tanks.
Four Unit Process

1. O₃ Generation
2. Gas to Liquid
3. Contact Time / Concentration
4. Removal / Destruction

O₃ Generation:

a) Expensive – 6 – 7 kwh/kg O₃ *
b) Air Feed Gas (21% O₂) – 1 –3% O₃

c) O₂ Feed Gas: 4-6% O₃ (10-15%)

d) Energy: 90% as Heat

e) Cooling Required – Heat Destroys Ozone.

f) Rating in g/hr!
Note: \[ 1.0 \text{ mg/l per l/min} = 1.44 \text{ g/day} \]
\[ (1.0 \text{ mg} \times 1.0 \times 60 \text{ min} \times 24 \text{ hr} = 1440 \text{ mg} = 1.44 \text{ g}) \]

* 6-7 kwh/kg O$_3$

\[ \text{O}_2 \text{ $0.50/100 ft}^3 = $0.50/4.0 \text{ kg O}_2 \]
\[ \text{O}_2 \text{ $0.50/100 ft}^3 = 0.1254/\text{kg O}_2 \]
Contact Time and Concentration

Need Deep Basin (Large Volume)

Length of contact time and strength of $O_3$ concentration needed depends on quality of the water and objectives.

In theory, ozone requires infinite contact time to reduce a microbial population to zero (sterilization)
\[
\log = \frac{N_t}{N_o} = k^1 t
\]

\(N_t = \text{Number of organisms at time } t\)

\(N_o = \text{Number of organisms at time } o\)

\(t = \text{Time in minutes}\)

\(k^1 = \text{Constant (1/minute)}\)

For instance, a concentration of 1,000,000 bacteria/ml is equal to 6 LOG units (10^6)
Ozone (Lack of) Stability

1. In pure water $\frac{1}{2}$ life $\pm$ 165 min.
2. In aquaculture water $\frac{1}{2}$ life maybe less than a few minutes (organics)
3. In RAS, $\frac{1}{2}$ life as short as 15 seconds

**RAS:** Disinfection is limited by the ability to maintain a certain $O_3$ concentration for a given time period.

Required: 0.1 – 1.0 mg/l
0.5 – 20 min.

Depends on the target organism and water quality.
In RAS: Difficult to disinfect due to:

a) \[ O_3 + NO_2 \rightarrow NO_3 + O_2 \]

b) Organic Load

Ozone relative to feed (source of NO\(_2\) and organics)
Rate: 0.025 kg O\(_3\) (25 g)/kg feed.
0.025 kg (25 g) $O_3$/kg Feed

1. Improved water quality
2. Reduced mortality due to Bacterial Gill Disease
3. Failed to reduce bacteria significantly (heterotrophic as well as gills)

To achieve a large bacterial reduction in a RAS requires more ozone than the literature reports (Summerfelt et al. 1997, and Bullock et al. 1997)
Water Quality Improvements – Yes.

1. **Solids Coagulation** – Better removal with microscreening.

2. **Removes Color** (Recent study by Christensen et al. 2000) reports: 0.007 kg (7 g) to 0.015 kg (15 g) $O_3$ per kg feed removes color from RAS.

3. Also: **COD** (chemical oxygen demand)
   Reduced from 50 mg/l to 15 mg/l
Assume 0.025 kg $\text{O}_3$/kg Feed

Earlier Discussion:

RAS: 500 g O$_2$/kg feed
Can feed: 0.02 kg feed/lpm/AO/day

\[
LdF = \frac{\text{AO}}{\text{OF}} = \frac{1}{500} = 0.002
\]

Ozone: 0.025 kg $\times$ 0.002 = 0.00005 kg $\text{O}_3$
Or: 0.05 g/lpm/AO/day

For 16 AO: 0.8 g $\text{O}_3$/lpm/day
0.8 g/lpm/day = 0.56 mg/l

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Previous discussion:

RAS @ 300,000 lpm flow

Need to generate

$$0.8 \times 300,000 = 240,000 \text{ O}_3 = 240 \text{ kg O}_3 /\text{day}$$

$$@ \$0.50/\text{kg} = \$120/\text{day}$$

But need to consider absorption efficiency at:

50% : $240/day

At 15%: $$\frac{100}{15} \times 120 = \$1,333/\text{day}$$
Final comments

1. Use O₃ Compatible Materials
   a) Stainless Steel (AISI 316; 316L)
   b) Teflon
   c) PVC (?)
   d) Concrete (Type 2 or Type 5 Portl. Cem)
   e) Fiberglass (Depends on Resin Used)

2. Disinfection: 0.5 to 1.5 mg/l

\[ C_t = \text{Concentration} \times \text{Exposure Time} \]

\[ 0.5 \times 30 \text{ min.} = 1.5 \]

\[ 1.5 \times 1.0 \text{ min.} = 1.5 \]

Same Result
3. **Water Quality:** $0.025$ to $0.045$ kg $O_3$ per kg feed

$0.025$ kg $O_3$/kg feed:
Assume requires $500$ g $O_2$/kg feed

$$LdF = \frac{AO(1)}{500} = 0.02 \text{ kg feed/lpm}$$

And: $0.02$ (kg feed) $\times 0.025$ kg $O_3 = 0.00005$ kg $O_3$

Per lpm, per one AO

For 16 AO: $0.0008$ kg $O_3$/lpm ($0.8$ g/lpm)

$0.8$ g $O_3$/lpm $= 0.56$ mg/l ($0.8/1.44$)

At rate Of $0.045$ $O_3$/kg feed: $1.0$ mg/l $O_3$
Ozone Toxicity to Fish

Under Production Conditions

10 to 20 ug/l (0.01 – 0.02 mg/l)

Recall: Rate of 0.025 kg O₃/kg feed

Concentration is 0.035 mg/l per AO per lpm.

For AO = 16 → 0.56 mg/l (560 ug/l)
$O_3$ Removal

a) Detention Time (Short Half Life)
b) Air Stripping
c) Activated Carbon
d) UV Radiation

Gas Phase: Thermal or Catalytic Unit.

Human Toxicity

0.1 ppm (By Volume) – 8 hour
0.2 ppm (By Volume) – 10 min.

NOTE: Smell of $O_3$ can be detected well before it reaches these concentrations.
Monitoring O$_3$
Difficult to measure, especially in liquid phase.

Gas Phase: UV Absorption Technique.
Liquid Phase:
Indigo Trisulfonate Potentiometric - Probe

Final Comment
Ozone is Expensive
Ozone is Risky
But: Can improve water quality in RAS (solids & clarity)

Can disinfect – but difficult to accomplish the proper combination of concentration and exposure time.

\[ C_t \]  

**RAS**: Heavy Organic Load

Need more research:

a) **RAS** improvements (esp. solids)

b) **O_3** application, control
Figure 1. Design of a sealed column

O$_2$ Application

1. Packed columns
2. Screened columns
3. Lowhead oxygenators (LHO)
4. U-tube design (hydrostatic pressure)
5. Bubble contactor

![Diagram of downflow bubble contactor]

Downflow bubble contactor
Source: John Colt (2000)
Encyclopedia of Aquaculture R.R. Stickney, ED. John Wiley & Son (p 705-712)
Technologies used in aquaculture to oxygenate fish rearing water

U-tubes

Multistage Lowhead oxygenator (LHO)

Packed column

Screened column