The availability of dissolved oxygen (DO) is usually the first factor that limits increased carrying capacity and production in intensive recirculation systems. Using only aeration as a means of providing dissolved oxygen, a system can support only about 40 kg per m$^3$ (0.33 lb of fish per gallon) of water. However, by using pure oxygen and high efficient gas transfer devices to increase the amount of dissolved oxygen in the water column, stocking densities can easily be increased to over 120 kg per m$^3$ (1 lb of fish per gallon) of water. For example, by increasing the DO concentration at the inlet to a production tank from 10 mg/L (aeration alone) to 18 mg/L using pure oxygen, and assuming a DO concentration of 6 mg/L at the discharge, the carrying capacity of the system can be increased by a factor of three. Instead of only 4 mg/L DO (10 mg/L minus 6 mg/L) being available for respiration and metabolism by the fish, 12 mg/L becomes available (18 mg/L minus 6 mg/L). Thus stocking densities can be increased from 0.33 lb/gal (40 kg/m$^3$) to 1.0 lb/gal (120 kg/m$^3$). An interesting by-product of this increased stocking density is that the concentration of the discharged solids is also increased, which means more efficient removal by, for example, microscreen filters.
Carrying Capacity Issues

- Fish require O₂ for respiration:
  - 0.3-0.5 kg O₂ consumed per 1.0 kg feed;
  - DO ≤ 4-6 mg/L can reduce growth.

The dissolved oxygen requirements of aquatic organisms depends on numerous factors including stocking density, feed rates, stress levels, water temperature, etc. For cold water species, oxygen requirements for the fish range from 0.3 to 0.5 kg O₂ per kg of feed. At higher temperatures and when the oxygen requirements of the biofilter and other bacteria are included, this could be as high as 1 kg O₂ per kg feed. Minimum values of dissolved oxygen are also highly dependent on species and growing conditions. Tilapia can survive DO levels that would kill trout and salmonids in minutes.
Carrying Capacity Issues

- Methods that increase *carrying capacity*
  - allow feed rates to be increased
    - because more DO is available or
    - TAN, CO₂, spatial, or other limitations are reduced
  - are used to increase *production*
    - if *profitability* is also increased

Since Dissolved Oxygen is usually the first limitation on stocking density, increasing oxygen levels directly increase the carrying capacity of systems, often dramatically.
Carrying Capacity Issues

- EXAMPLE
  - Increasing inlet DO from 10 to 18 mg/L
    - assuming an outlet DO of 6 mg/L and no other limitations
    - TRIPLES the available DO and carrying capacity
    - TRIPLES the potential production
    - TRIPLES the concentration of waste produced
Carrying Capacity Issues

- Intensification with oxygenation & aeration is limited!
  - Every 10 mg/L DO consumed adds:
    - 1.0-1.4 mg/L TAN
    - 13-14 mg/L CO₂
    - 10-20 mg/L TSS

But there are drawbacks to increasing carrying capacity, since with intensification comes additional problems of increased ammonia-nitrogen, carbon dioxide and suspended solids.
Carrying Capacity Issues

- CO₂ becomes limiting:
  - cumulative DO consumption > 10-22 mg/L
    - depending on pH, alkalinity, temp., species
  - without stripping or pH control
When air is in contact with water, dissolved gases in the water attempt to reach equilibrium with the partial pressures of the gases in the atmosphere. Two factors that directly impact the rate of gas transfer are first the area of gas-liquid interface and second the difference between the concentration (partial pressure) at saturation and the existing concentration of the gas in the water. For example, if the water is under saturated with the gas in question (a deficit), the gas will be transferred into solution and if the water is supersaturated, out of solution. In a simple trickling tower, it is possible to have supersaturated nitrogen gas being removed, while under saturated dissolved oxygen, increases in concentration. This overall gas transfer rate is dependent on the deficit (or surplus) of a dissolved gas and a proportionality constant, usually called the gas transfer coefficient. The overall gas transfer coefficient represents conditions in a specific gas transfer system. It is a composite term that includes such factors as the diffusion coefficient for the gas, the liquid-film thickness, and the area of gas-liquid interface. These factors also suggest ways to increase the overall rate of gas transfer. This could be accomplished, for example, by decreasing the liquid-film thickness by turbulence or mixing, increasing the gas-liquid interface by making the bubble size smaller, or increasing the concentration gradient.
Purified $O_2$ gas is contacted with water;
- dissolved $O_2$ super-saturation produced
- some $N_2$ gas is stripped.
Gas Transfer

- When only aeration is used to provide O₂:
  - fish loading levels are relatively low;
  - air-water contact strips CO₂ and avoids toxic accumulations (Speece, 1973).

If only air is used to provide oxygen, carrying capacity is usually limited to less than 40 kg/m³ (1/3 lb/gal). Carbon dioxide is also not usually a problem.
Gas Transfer

- The rate of gas transfer depends on:
  - gas-water interfacial area
  - rate of surface film renewal
  - concentration gradient
Gas Transfer

- gas-water interfacial area is increased by:
  - using packing,
  - creating fine bubbles/droplets.
- rate of surface film renewal is increased by:
  - creating more turbulence
Gas Transfer

- Driving force for gas transfer out of water

  = concentration gradient

  = \{(\text{bulk conc.}) - (\text{saturation conc.})\}
Gas Transfer

- Increase concentration gradient with:
  - ✔ methods to increase saturation concentration
    - • pure O₂ feed gas
    - • pressurized systems
  - ✔ increasing G:L
    - • keeps gas-phase partial pressures from large changes across transfer unit
Enriched O₂ increases DO solubility nearly 5-fold compared to air.
- 48.1 mg/L vs. 10.1 mg/L (@ 15°C)

Increasing pressure from 1 to 2 atm doubles the DO solubility.
- 97 mg/L vs 48 mg/L (@ 15°C)
Oxygen Source - PSA

- Enriched O\textsubscript{2} can be produced on site using pressure swing adsorption (PSA) equipment:
  - 85 to 95% purity
  - requires PSA unit and
    - air dryer,
    - compressor to produce 90 to 150 psi,
    - stand-by electrical generator.
  - costs about 1.1 kWh of electricity per kg O\textsubscript{2} produced.

In aquaculture, three sources of oxygen are commonly used: high-pressure oxygen gas, liquid oxygen (LOX), and on-site oxygen generations. To insure availability and as backup, usually at least two sources are available at most facilities. High pressure oxygen gas is easily available in cylinders containing from 100 to 250 ft\textsuperscript{3} (3 to 7 m\textsuperscript{3}) of gas at 2550 psi (170 atmospheres of pressure). A number of cylinders can be connected together using commercially available manifolds to increase the total capacity. Due to their cost and limited capacity, oxygen cylinders are normally used only as emergency backup systems.
Oxygen can also be generated on-site using either a pressure swing adsorption (PSA) or a vacuum swing adsorption (VSA) unit. In both cases, a molecular sieve material is used to selectively adsorb or absorb nitrogen from the air, producing an oxygen-enriched gas. Commercially available units can produce anywhere from 1 to 30 lbs (0.5 to 14 kg) of oxygen per hour at from 10 to 50 psi (0.7 to 3.3 atmospheres). A source of dry, filtered air at 90 to 150 psi (6.0 to 10.0 atmosphere) is required to produce an oxygen stream that is from 85–95% pure. PSA and VSA units operate on a demand basis and produce oxygen only when needed. They have proven to be very reliable and require little maintenance. However, they are both expensive in terms of capital and operationally expensive, due to the compressed air requirements. Also, since they require electrical power, some other source of oxygen is needed in the event of power failures or else the facility must be equipped with large backup generators and transfer switches.
Oxygen Source - LOX

- Enriched O₂ can be purchased as a bulk liquid:
  - 98 to 99% purity
  - Capital investment and risk are lower than PSA,
  - Annual liquid O₂ cost can be 3-times > PSA O₂
    - Location specific
    - Transportation costs are a MAJOR component of the total LOX cost

In many areas, liquid oxygen is commercially available in bulk and can readily be transported and stored in on-site Dewar’s type storage containers. At one atmosphere, liquid oxygen boils at -297.3°F (-182.96°C), thus special insulated cryogenic containers are required for storage. These containers range in size from 30 gal (0.11 m³ liquid) to a much as 10,000 gal (38 m³ liquid), and are usually rented or leased from the suppliers, although the smaller units can be purchased. One gallon of liquid oxygen is equal to 115 ft³ (3.26 m³) of gaseous oxygen. The maximum gas pressure in these containers is in the range of 150 to 200 psi (11.7 atmospheres). Prior to its use, the LOX is vaporized by directing it through heat exchanger coils. A liquid oxygen supply system will consist of a storage tank, vaporizer, filters, and pressure regulators. The economics of LOX use are dependent upon the transport cost, and the reduced capital and maintenance cost as compared to pressure swing adsorption (PSA) systems. In general, a LOX system is very reliable, operating even during power failures. Failures on farms using LOX systems as backup to power outage are caused by under-sizing the LOX system in the first place or unanticipated severe weather conditions that extend longer than predicted. Carefully consider your risks for such cases and size your LOX system with these potential dangers in mind. As a minimum, a LOX system should be able to maintain a facility with oxygen for 30 days. Remember that upon the first sign of major weather problems, it is probably prudent to take your fish off of feed, which will lower their oxygen demand dramatically over the next 24 hours.
Oxygenation Devices

- Oxygen transfer equipment used:
  - Continuous liquid phase (bubbles in water)
    - U-tubes,
    - Oxygenation cones (downflow bubble contactors),
    - Oxygen aspirators,
    - Bubble diffusers,
Oxygenation

- Oxygen transfer equipment used:
  - Continuous gas phase (water drops in air)
    - Multi-staged low head oxygenators (LHO),
    - Packed or spray columns,
    - Pressurized columns,
    - Enclosed mechanical surface mixers.
Oxygenation

- Three units used to oxygenate large flows within recirculating systems:
  - Multi-stage low head oxygenators (LHO).
  - U-tubes,
  - Oxygenation cone (down flow bubble contactor)
- Advantages:
  - Readily scaled-up,
  - Easy to control,
  - Modest hydraulic head w/ good O₂ adsorption eff.
Low Head Oxygenators (LHO) are being used more frequently, particularly because of their adaptability to high flows using minimal hydraulic head, hence their name Low Head Oxygenator. The original LHO design was developed and patented by Watten (1989). LHO’s vary in configuration, but all are fundamentally similar in operation. These units consist of a distribution plate positioned over multiple (5 to 10) rectangular chambers. Water flows over the dam boards at the end of a raceway or is pumped upwards from an indoor fish tank, through the distribution plate, and then falls through the rectangular chambers. These chambers provide the gas-liquid interface needed for mixing and gas transfer. The streams of falling water impact a collection pool at the bottom of each chamber where the effluent water flows away from each chamber equally in parallel. All of the pure oxygen is introduced into the outer or first rectangular chamber. The mixture of gases in the first chamber, which now has a diluted oxygen concentration passes, sequentially through the remaining chambers. The gaseous mixture will decrease in oxygen concentration from chamber to chamber as the oxygen is continued to be absorbed. Finally the gaseous mixture will exit from the last chamber. This gas is referred to as off-gas. Each of the rectangular chambers is gas tight and the orifices between the chambers are properly sized and located to reduce back-mixing between chambers.
Low Head Oxygenators

- LHO’s and solids:
  - use without packing
  - construct within cone bottom cylinders
    - avoid sludge build-up
    - reduce foot print
Multi-Stage LHO

- Maximize $O_2$ adsorption efficiency:
  - reuse $O_2$ through a series of chambers;
  - reduces gas short-circuiting.
- LHO units degas $N_2$ while adding $O_2$
- Oxygen Gas:Water Flow – 0.5-2%
- Hydraulic Loading – 50-100 gpm/ft$^2$
LHO Chambers
**Multi-Stage LHO**

$O_2$ Transfer experiments in cold water (12-17ºC).

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<tr>
<td>&gt; 8 mg/L</td>
<td>&lt; 0.01:1</td>
<td>60-90%</td>
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<td>~15 mg/L</td>
<td>0.02:1</td>
<td>50%</td>
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9th Annual Recirculating Aquaculture Systems Short Course
Absorption Efficiency as Affected by the Number of LHO Chambers and the Gas Liquid G/L Ratio (Arbitrary Set of Model Inputs were: Y2 = 9.5 mm; Y3 = 13 cm; Y4 = 61 cm; Y1 = 7.5 cm; Temp = 20.0°C; Top Area = 0.1 m2; Active Hole Area = 10.0%; Chambers = Varies; G/L = Varies; DOin = 6.0 mg/L; DNin = 14.0 mg/L; DCO2 = 0.0; Pressure = 760.0 mm Hg; Oxygen Fraction in Inlet Gas = 0.99).

The LHO model is used to demonstrate the effects of LHO chamber number on gas absorption efficiency and effluent DO for various G/L ratios. As can be seen in the figure, an LHO should have at least 4 or 5 chambers to obtain high gas transfer efficiency. This is reflected in current commercial units that typically have 7 chambers. It is also quite evident from the figure that gas transfer efficiency is severely degraded at a G/L ratio of 2% (slightly over 50%). Thus, increasing G/L ratios to obtain higher effluent DO to meet biological fish demand is not an economical choice. In fact, the producer would probably be economically ahead to reduce fish density than to try to maintain the higher densities by using elevated G/L flow rates.
Effluent DO as Affected by the Number of LHO Chambers and the Gas Liquid G/L Ratio (Arbitrary Set of Model Inputs Were: Y2 = 9.5 mm; Y3 = 13 cm; Y4 = 61 cm; Y1 = 7.5 cm; Temp = 20.0°C; Top Area = 0.1 m^2; Active Hole Area = 10.0%; Chambers = Varies; G/L = Varies; DO_{in} = 6.0 mg/L; DN_{in} = 14.0 mg/L; DCO_2 = 0.0; Pressure = 760.0 mm Hg; Oxygen Fraction in Inlet Gas = 0.99).

The effect of G/L ratio on absorption and effluent DO is demonstrated explicitly in the above figure for the standard LHO unit selected as noted above. This graph indicates that a 1.4% G/L ratio is the largest gas flow that could be used if one were trying to achieve a minimum oxygen absorption efficiency of 70%; this would correspond to an increase in the effluent DO by 12 mg/L over the influent DO value of 6 mg/L. Rule of thumbs then emerge from this that delta DO’s of 10 to 12 are target values for operating LHO units. The rapid drop in absorption efficiency as G/L ratios are increased is also a clear warning to the aquaculturalist that LHO gas usage should be closely monitored to avoid the easy solution of simply increasing G/L to increase effluent DO.
A often used design is to place the CO₂ stripping tower directly above the LHO and allow the water to cascade down.
The U-tube aerator operates by increasing the gas pressure, thus increasing the overall gas transfer rate. It consists of either two concentric pipes or two pipes in a vertical shaft 30 to 150 ft (9 to 45 m) deep. Oxygen is added at the upper end of the down-leg of the U-tube and as the water/gas moves downward through the contact loop, an increase in hydrostatic pressure increase the oxygen transfer rate. The overall oxygen transfer efficiency is a function of the depth of the U-tube, inlet gas flow rate, water velocity, diffuser depth and inlet DO concentration. Concentrations of dissolved oxygen ranging from 20–40 mg/L can be achieved, but the overall oxygen transfer efficiency if only 30–50%. Off-gas recycling can improve the absorption efficiency to 55–80%. Two advantages of the U-tube are the low hydraulic head requirements that allow operation with no external power if sufficient head is available, and that it can be used with water containing high levels of particulates or organics. Its chief disadvantages are that it does not vent off gasses such as nitrogen or carbon dioxide very efficiently and construction costs can be high, particularly if bedrock is present.
U-tube Oxygenator

- Diffuse O$_2$ into down-pipe:
  - water velocity of 1.0 to 3.0 m/s,
  - entrain the bubbles down,
  - buoyant velocity of bubbles = 0.3 m/s
- O$_2$ transfer increases as flow passes 10-45 m depths.
- Does not vent N$_2$ effectively.

U-tubes are designed for flows where the downflow velocity is between 1.8 to 3.0 m/s. A particularly unique problem with U-tubes is that if too much oxygen is added a gas bubble blockage can occur that results in flow interruption. This will tend to happen if gas-liquid ratios exceed 25%. Be careful when adding oxygen.
U-Tube Oxygenator

- 20-40 mg/L outlet DO can be achieved, but
  - \( \text{O}_2 \) adsorption of only 30-50%,
  - off-gas recycling improves adsorption to 55-80%.
- Only 1-6 m of water head required to operate.
  - larger pipes with large flows have lower water head requirements than smaller pipes.
The aeration cone, bicone, or downflow bubble-contact aerator consists of a cone-shaped cylinder or a series of pipes with reducing diameters. Water and oxygen enter at the top of the cone, flow downward, and out. As the cone’s diameter increases, the water velocity decreases, until the downward velocity of the water equals the upward buoyant velocity of the bubbles. Thus, the bubbles are held in suspension, until they dissolve into the water. The performance of aeration cones is determined by gas and water flow rates, influent DO concentration, cone geometry and operating pressure. Absorption efficiency range from 95–100% with effluent concentrations from 30 to 90 mg/L. Commercial units are available that transfer from 0.4 to 10.8 lbs of oxygen per hour (0.2 to 4.9 kg/hr) at 25 mg/L, at flow rates from 45 to 600 gpm (170 to 2,300 Lpm).
Commercially available fiberglass Speece cones.
Oxygenation Cone

- Also called a down flow bubble contactor:
  - widely used in European eel farms;
  - some tilapia farms;
- resists solids plugging;
- can be pressurized to obtain 20-40 mg/L oxygen concentrations,
  - does not vent N₂ well when pressurized
Downflow Bubble Contactor
Guidelines for O₂ & CO₂ Control

- Strip CO₂ after it reaches its highest level and before O₂ supersaturations are produced:
  - after biofilter.
Guidelines for $O_2$ & $CO_2$ Control

- Air strip before the oxygenation unit:
  - air stripping elevates DO to ~90% saturation level
  - pure $O_2$ should only go toward DO supersaturation
  - don’t waste pure $O_2$ to add DO at levels < saturation
Guidelines for O₂ & CO₂ Control

- Produce DO supersaturation just before the water enters the culture tank:
  - keep the supersaturated DO from atmospheric contact.