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Oxygenation and carbon dioxide control in water reuse systems

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Abstract

Control of dissolved gases, especially oxygen and carbon dioxide, is an essential component of intensive water reuse systems. Control of both dissolved oxygen and carbon dioxide concentrations is typically carried out by means of gas transfer processes, although chemical processes are also used to control carbon dioxide concentration. Theoretical and practical considerations of oxygenation and carbon dioxide removal are reviewed in this paper. The theory of gas transfer is presented in general terms, followed by a more detailed description of the basis for a new calculation procedure for carbon dioxide degassing processes. Equipment used for oxygen injection is described, and a new method for estimating packed column degassing parameters is introduced. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Water reuse systems; Dissolved oxygen control; Dissolved carbon dioxide control

1. Introduction

The use of oxygenation in intensive water reuse systems increases the mass of fish that can be supported in a given water flow by removing oxygen as a limiting factor to a system's carrying capacity. However, it is not uncommon to find elevated, and possibly toxic, concentrations of dissolved carbon dioxide in intensive water reuse systems using pure oxygen injection. Carbon dioxide concentrations build up in these systems because of the relatively low specific water exchange rates used (rate

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of make-up water flow per mass of fish in the system) and the fact that pure oxygen injection systems typically do not allow for the removal of substantial quantities of carbon dioxide. Therefore, effective carbon dioxide control may require aeration for stripping, the use of chemicals to adjust pH, or a combination of gas transfer and chemical methods.

A combination of theoretical and practical considerations related to oxygenation and carbon dioxide control are presented in this paper. In general, oxygenation in aquaculture is a relatively mature technology with well established operational principles, techniques, and equipment. Carbon dioxide control has become an important issue only recently as aquaculture operations have intensified, and the technology is still evolving.

2. Oxygenation

Pure oxygen gas has been used since the 1970s as an economical means to create supersaturated concentrations of dissolved oxygen and intensify fish production in all types of aquaculture systems (Speece, 1981). Recirculating systems, especially, are applying oxygenation and other intensifying technologies to become more cost competitive. Use of pure oxygen can reduce fish production costs by supporting higher fish and feed loading rates and reducing water flow requirements, which in turn reduces the size and cost of pumping, culture tanks, water reuse equipment, and system housing.

2.1. Theoretical considerations

The rate of gas transfer, J_{gas} (mol gas mol⁻¹ water s⁻¹), is defined by Fick's law and is proportional to the product of the total interfacial contact area (A , m²) per unit system volume (V , m³) and the concentration gradient (to convert to the more common unit of molar concentration in mol l⁻¹ s, one can use the conversion factor of 55.6 mol water l⁻¹). For gas absorption, the concentration gradient is the difference between the saturation and existing mol fraction of dissolved gas ($X_{\text{gas}}^{\text{eq}} - X_{\text{gas}}$), yielding Fick's law in the form:

$$J_{\text{gas}} = K_L \frac{A}{V} (X_{\text{gas}}^{\text{eq}} - X_{\text{gas}}) \quad (1)$$

where the proportionality constant K_L (m s⁻¹) is the overall mass transfer coefficient and the term A/V , represents the specific interfacial area, which is sometimes represented by the symbol a . For gas desorption systems, such as those used for carbon dioxide stripping, the saturation and existing molar concentrations are sometimes reversed, giving a positive value for J_{gas} for gas transfer out of the liquid phase.

The overall mass transfer coefficient, K_L (m s^{-1}), is the sum of the resistance to mass transfer across both the liquid and gas sides of the interface, k_L (m s^{-1}) and k_G (m s^{-1}), respectively:

$$\frac{1}{K_L} = \frac{1}{K_H^u \cdot k_G} + \frac{1}{k_L} \quad (2)$$

where K_H^u is the dimensionless representation of Henry's law constant (Cornwell, 1990). Gas transfer equipment is designed to enhance the factors controlling K_L and a , which can be achieved by increasing the area of the gas–liquid interface, reducing the thickness of the boundary layers at the interface, and increasing the rate of interfacial film renewal.

Typically, providing oxygen to cultured fish constitutes a significant production cost. Therefore, ensuring a high efficiency of oxygen transfer is important for both technical and economic reasons. In general, oxygenation technologies used in aquaculture have relatively well established operational principles, techniques, and equipment (Colt and Tchobanoglous, 1981; Speece, 1981; Colt and Watten, 1988; Boyd and Watten, 1989; Colt and Orwicz, 1991; Watten, 1994).

Transferring pure oxygen rather than air into water will increase the mol fraction of gaseous oxygen from 0.2095 (air) to 1.00 (pure oxygen) with a corresponding increase in dissolved oxygen solubility in water. As an example, use of pure oxygen gas at a pressure of 1 atm will increase the solubility¹ of dissolved oxygen from 10.1 to 48.1 mg l^{-1} (at 15°C) (Colt and Watten, 1988). Increasing the pressure from 1 to 2 atm during the transfer of pure oxygen approximately doubles oxygen's solubility to 97.0 mg l^{-1} (at 15°C) (Colt, 1984).

The maximum dissolved oxygen concentration that can be achieved is also influenced by the ratio of gas to water flow rate that is contacted within the gas transfer unit. This is normally expressed as a volumetric gas to liquid (G/L) ratio, with gas at standard conditions of pressure and temperature, and is subject to mass balance limitations. For every G/L of 0.01:1, up to 13.2 mg l^{-1} of dissolved oxygen can be added to the water flow. How much is actually transferred depends on mass transfer characteristics as determined by the previously described factors (Eq. (1)).

When pure oxygen is placed in contact with water, there is a tendency for all dissolved gases to come to equilibrium at saturation: undersaturated gases such as oxygen are transferred from the gas to the water, and supersaturated gases, such as nitrogen, carbon dioxide, water vapor, and argon, are transferred from the water to the gas. If there is venting of off-gas from an oxygenation system, some of these other gases will be removed from the water. However, the amount of gas removed and the resulting concentration changes may not be significant (especially regarding carbon dioxide stripping) because of the relatively low G/L ratios normally used in oxygenation systems (e.g. 0.005:1 to 0.02:1) (Watten et al., 1991). The type of oxygenation equipment selected will affect off-gas venting and the total gas pressure produced, depending on whether the oxygenation process is open and un-pressurized, versus closed and pressurized (Watten et al., 1991).

¹ Solubility refers to the saturation concentration of a gas dissolved in water at a given temperature, pressure, and gas-phase mol fraction.

2.2. Oxygen transfer equipment

Choosing the right oxygenation technology for use in recirculating systems depends on several factors specific to the equipment, including: oxygen absorption efficiency (mass of oxygen absorbed per mass of oxygen applied), oxygen transfer efficiency (mass of oxygen transferred per power required), ability to strip nitrogen and other gases, ease of control, effectiveness when scaled-up, ability to treat flows containing suspended solids without plugging, system layout and intended location of the oxygenation process, and whether flow must be pumped through the unit or if gravity flow is adequate. Units used with flowing water may be either open- or closed-type. Open-type units operate at atmospheric pressure, and examples of such units are multi-staged low head oxygenators (LHOTM), packed columns, and spray towers. Closed-type units operate at a pressure higher than atmospheric pressure, and examples include U-tubes, sealed columns, oxygenation cones, and oxygen aspirators. Typically, open-type oxygenation units have higher G/L ratios and vent more off-gas than closed-type units. The high pressures needed for closed-type units result in increased pumping requirements relative to open-type systems.

The configuration of a recirculation system determines, to a large extent, the most appropriate type of oxygenation unit. The choice of biofilter type and other system design characteristics affects the choice and placement of the oxygenation unit (and of the aeration/stripping unit). For example, gravity-driven oxygenators (e.g. open-type units and sometimes U-tubes) are often used if a 1- to 3-m elevation drop is provided between the biofilter outlet and the water level in the culture tank. This is illustrated in Fig. 1, where an open-type cascade aeration/stripping tower is used following fluidized-sand biofilters and prior to a LHO (Sommerfelt, 1996).

Oxygenation units that require pumping (e.g. closed-type units and sometimes U-tubes) can be used when the water flow emerging from a biofilter is already pressurized as in the case of some granular media biofilters. Trickling filters, for example, rely on elevation drops of 1–5 m, so pumps are often used to push the flow through an oxygenation unit before returning to the culture tanks (Fig. 2). A trickling filter preceding an oxygenation unit has some advantages, because a well ventilated trickling filter aerates the water, stripping dissolved carbon dioxide and elevating the dissolved oxygen concentrations, while simultaneously providing biological ammonia removal.

Several examples of gas transfer units frequently used to add pure oxygen within large recirculating aquaculture systems include U-tubes, oxygenation cones (also termed downflow bubble contactors), and multi-staged low head oxygenators (Fig. 3). These oxygenation technologies are not usually prone to problems caused by fouling from organic solids, are readily scaled-up, are easy to control, and the U-tube and LHOTM require only modest hydraulic head to achieve high oxygen absorption efficiencies.

Although placing gas diffusers in culture tanks is common, the relatively shallow depth of culture tanks and the resulting short contact time between bubbles and the water produces relatively low oxygen absorption efficiencies (3–7%; Colt and Watten, 1988). Therefore, diffusers within the culture tank are not usually used as

the primary oxygenation device within more intensive systems. However, this oxygenation technique is useful as an emergency measure when culture tanks lose water flow since no power is required for its operation when liquid or compressed oxygen is used.

3. Carbon dioxide control

Low intensity aquaculture systems do not use oxygenation and generally have sufficient water exchange and/or aeration to keep carbon dioxide from accumulating above safe levels (Speece, 1981; Loyless and Malone, 1997). However, carbon dioxide problems have appeared in intensive systems using oxygenation because of the relatively low specific water exchange rates used (rate of make-up water flow per mass of fish in the system) and the fact that pure oxygen injection systems typically do not allow for the removal of substantial quantities of carbon dioxide (Colt and Orwicz, 1991; Watten et al., 1991; Grace and Piedrahita, 1994). Combining mass balances and acid–base equilibrium relations, Colt et al. (1991) reported that under

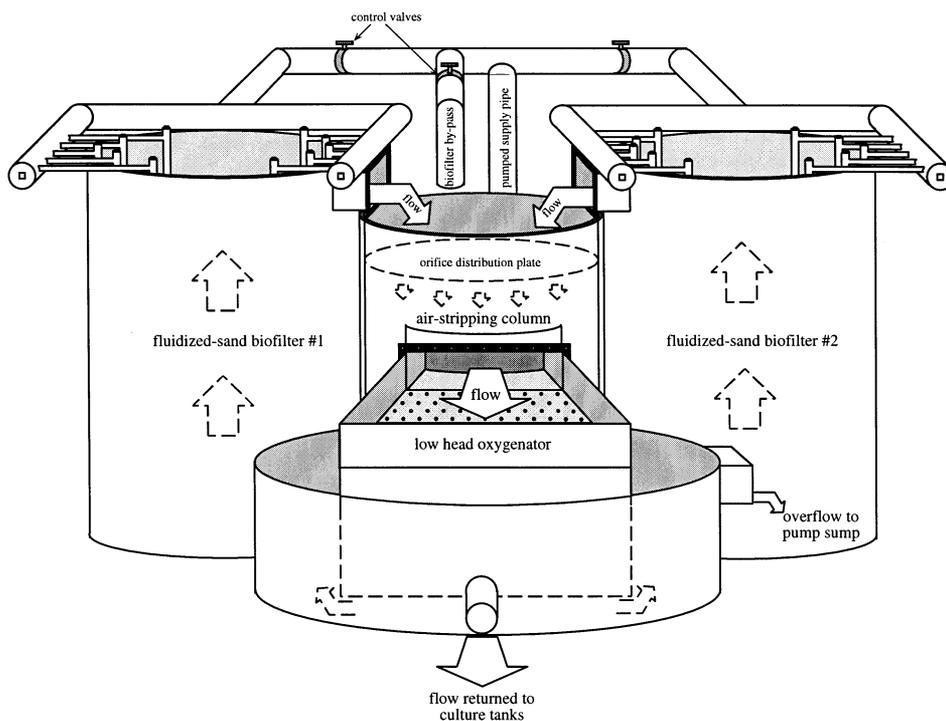


Fig. 1. Water pumped through the biofilter tumbles by gravity through a forced-ventilation cascade aeration/stripping tower followed by a LHO™ in a recirculating system at Glacier Springs Fish Farm (Gunton, Man., Canada) that treats 4560 l min^{-1} ($1200 \text{ USgal min}^{-1}$) in a 54-tank water reuse system used to produce fingerling rainbow trout and arctic charr (Summerfelt and Wade, 1998).

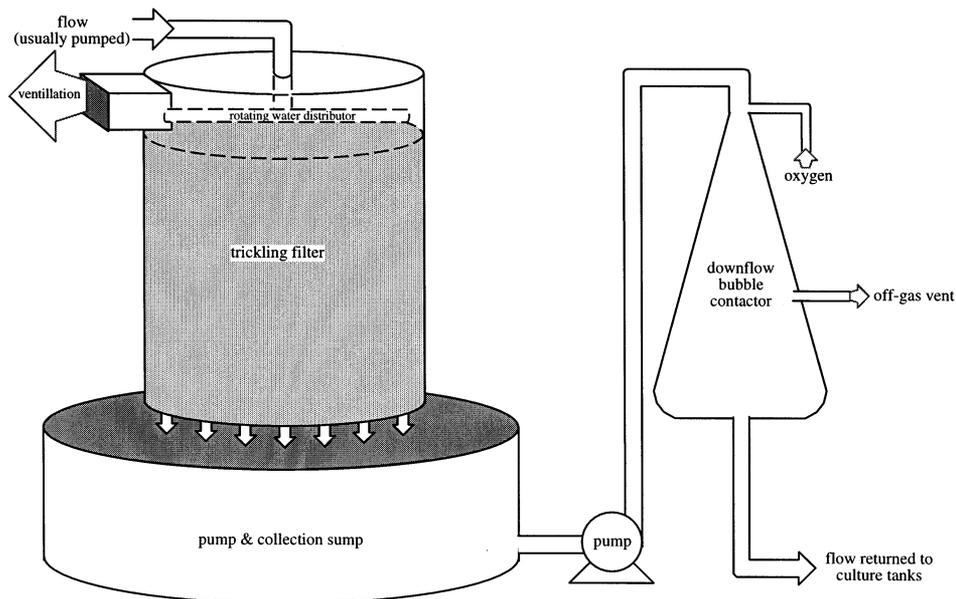


Fig. 2. Water flow collected at the base of a trickling filter is often pumped through a downflow bubble contactor (e.g. oxygenation cone) before returning to the culture tank(s) in recirculating systems used to culture eel in Europe (Knösche, 1994; Nijhof, 1995) and tilapia in North America (Twarowska et al., 1996).

intensive conditions, the accumulated concentration of dissolved carbon dioxide within the culture tank will not be limiting (with no aeration or pH control) when the cumulative dissolved oxygen consumption is less than $10\text{--}22\text{ mg l}^{-1}$, depending upon pH, alkalinity, temperature, and the species and life stage. After reaching this cumulative oxygen consumption level, the water flow cannot be used again unless it is passed through an air-stripping unit, or a chemical is added to reduce carbon dioxide concentrations. Therefore, carbon dioxide control in water reuse systems may require aeration for stripping, the use of chemicals to adjust pH, or a combination of gas transfer and chemical methods (Bisogni and Timmons, 1994; Grace and Piedrahita, 1994; Summerfelt, 1996; Loyless and Malone, 1997; Piedrahita, 1997, 1998). These issues are discussed below.

3.1. Carbon dioxide background

In contrast to oxygen, nitrogen, and other gases, the concentration of carbon dioxide in water is determined not only by a gas-liquid equilibrium relationship, but also by a series of acid-base reactions. The gas-liquid equilibrium influences the transfer of carbon dioxide between air and water. In turn, the acid-base reactions determine the chemical form in which dissolved inorganic carbon is present in water. Therefore, carbon dioxide concentration is a function primarily of

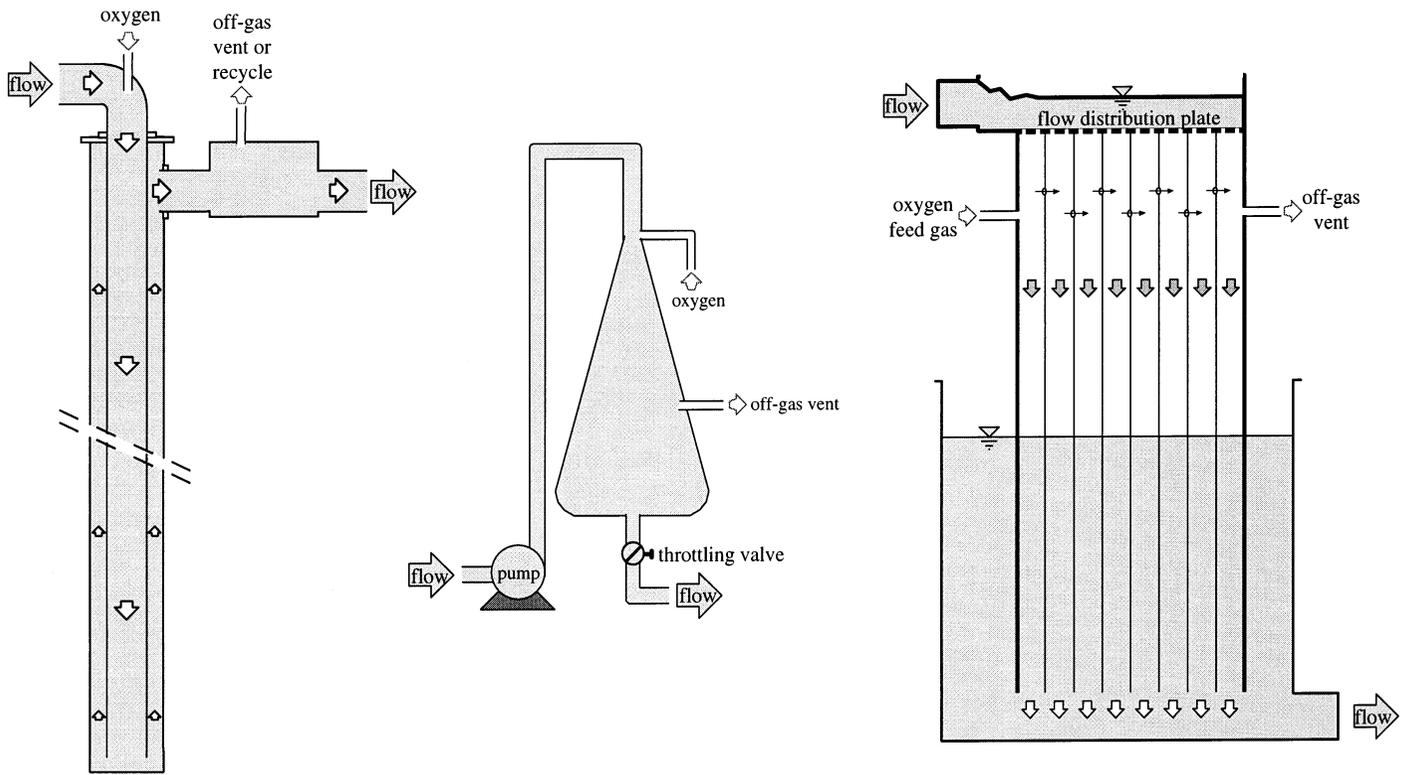


Fig. 3. U-tubes (left), oxygenation cones (middle), and multi-stage low head oxygenators (right) are examples of technologies used to add pure oxygen in large recirculating systems.

the total amount of dissolved inorganic carbon (CtCO_3) present in water (i.e. carbon dioxide, carbonic acid, bicarbonate ions, and carbonate ions) and of pH. As a result, changes in the concentration of carbon dioxide can be effected by gas transfer or chemical means.

Several researchers have reviewed the acid–base equilibrium relationships between pH and carbon dioxide in freshwater and seawater aquaculture systems (Bisogni and Timmons, 1994; Grace and Piedrahita, 1994; Piedrahita and Seland, 1995; Sanni and Forsberg, 1996; Summerfelt, 1996; Loyless and Malone, 1997), and the detailed relationships will not be presented here. In summary, however, dissolved carbon dioxide exists in water as part of the carbonate acid–base system (Table 1).

Acid–base equilibrium, and thus pH, controls the relative concentrations of each species in the inorganic carbon system (Table 1). A number of equations are available for calculating the total dissolved carbon dioxide concentration depending on what information is available (e.g. alkalinity, total carbonate carbon, pH) (DOE, 1996). For example, total dissolved carbon dioxide, $[\text{H}_2\text{CO}_3^*]$, can be calculated from $[\text{CtCO}_3]$ and pH:

$$[\text{H}_2\text{CO}_3^*] = [\text{CtCO}_3] \cdot \frac{1}{\left(1 + \frac{K_0 K_1}{[\text{H}^+]} + \frac{K_0 K_1 K_2}{[\text{H}^+]^2}\right)} \quad (3)$$

where the equilibrium constants K_0 , K_1 , and K_2 are defined in Table 1, square brackets indicate molar concentration, $[\text{H}_2\text{CO}_3^*] = [\text{H}_2\text{CO}_3] + [\text{CO}_2]$, and $[\text{CO}_2] > 600 \cdot [\text{H}_2\text{CO}_3]$ (according to the definition of K_0 found in Table 1).

Eq. (3) illustrates the fact that the concentration of total dissolved carbon dioxide can be altered by changes in either the total amount of carbonate carbon in

Table 1
Acid–base equilibrium reactions and equilibrium constants for the carbonate system^a

Equilibrium type	Equilibrium relationships	Equilibrium constants at 25°C ^b
Gas–liquid	$\text{CO}_2(\text{g}) \leftrightarrow \text{CO}_2(\text{aq})$	$K_{\text{H}} = P_{\text{CO}_2} / X_{\text{CO}_2} \cong 6.11 \times 10^{-4} \text{ atm}^{-1}$
Hydration/dehydration	$\text{CO}_2(\text{aq}) + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3$	$K_0 = [\text{H}_2\text{CO}_3] / [\text{CO}_2] \cong 1.58 \times 10^{-3}$
Acid–base	$\text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+$	$K_1 = \frac{[\text{H}^+][\text{HCO}_3^-]}{[\text{H}_2\text{CO}_3]} \cong 2.83 \times 10^{-4} \text{ mol l}^{-1}$
Acid–base	$\text{HCO}_3^- \leftrightarrow \text{CO}_3^{2-} + \text{H}^+$	$K_2 = \frac{[\text{H}^+][\text{CO}_3^{2-}]}{[\text{HCO}_3^-]} \cong 4.68 \times 10^{-11} \text{ mol l}^{-1}$
Acid–base	$\text{H}_2\text{O} \leftrightarrow \text{OH}^- + \text{H}^+$	$K_{\text{w}} = \frac{[\text{H}^+][\text{OH}^-]}{[\text{H}_2\text{O}]} \cong 1.00 \times 10^{-14} \text{ mol}^2 \text{ l}^{-2}$
Dissolution/precipitation	$\text{CaCO}_3 \leftrightarrow \text{CO}_3^{2-} + \text{Ca}^{2+}$	$K_{\text{sp}} = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{[\text{CaCO}_3]} \cong 4.57 \times 10^{-9} \text{ mol}^2 \text{ l}^{-2}$

^a Square brackets signify molar concentrations (mol l^{-1}); the units of the partial pressure of carbon dioxide (P_{CO_2}) are (atm). The equations are presented for freshwater where activity effects are ignored and a simplified alkalinity equation is used (Stumm and Morgan, 1996).

^b Refer to Piedrahita and Seland (1995) for temperature dependence of the equilibrium constants.

solution, or in the pH of the water. Minor changes can also result as temperature and salinity change, since they impact the equilibrium constant values (Piedrahita and Seland, 1995). The two possible avenues by which the dissolved carbon dioxide concentration can be changed give rise to two alternate strategies for carbon dioxide control in aquaculture: degassing, where dissolved carbon dioxide is removed by venting off-gas to the atmosphere reducing the total carbonate carbon concentration; and pH control, where bases are added to cause a pH rise and a shift in equilibrium such that a smaller proportion of the total carbonate carbon present will be in the carbon dioxide form. In practice, it is common to see a combination of the two control methods, and the general characteristics of single and combined control methods will be examined below.

3.2. Carbon dioxide production and toxicity

Safe levels of dissolved carbon dioxide depend on fish species, developmental stage of the fish, and other water quality variables that include alkalinity, pH, and dissolved oxygen levels. Sufficiently elevated carbon dioxide levels can decrease the ability of hemoglobin to transport oxygen (the Bohr effect), decrease the maximum oxygen binding capacity of blood (the Root effect), and increase blood acidity (Jobling, 1994). Sustained exposure to elevated levels of carbon dioxide may also produce nephrocalcinosis, i.e. the formation of calcareous deposits in the kidneys (Landolt, 1975). Dissolved carbon dioxide begins to affect salmonids at concentrations of approximately 20 mg l^{-1} , but tilapia and catfish will tolerate considerably higher dissolved carbon dioxide levels in their environment (Wedemeyer, 1996). In addition, the safe carbon dioxide level increases if dissolved oxygen concentrations in the water are near or greater than saturation (Colt and Orwicz, 1991; Wedemeyer, 1996). Given the general uncertainty regarding safe levels of carbon dioxide, it is not possible to specify strict targets. However, dissolved carbon dioxide accumulation should be maintained as low as economically and technologically possible.

3.3. Gas transfer — aeration and stripping

In theory, oxygen and carbon dioxide can be transferred to and from water with any open aeration system where water is brought into contact with air (Colt and Tchobanoglous, 1981; Speece, 1981; Boyd and Watten, 1989; Watten, 1994). In practice, the choice of system depends on the treatment objectives and on economic and technical considerations of the particular installation. In general, techniques that rely on moving water droplets through air, as is done with surface aerators and packed column aerators, are more effective than aeration technologies that move air bubbles through water, as is done with diffused aeration systems and sub-surface aerators (Colt and Orwicz, 1991).

As water cascades down an air-stripping column and dissolved carbon dioxide is removed, the dissolved carbon dioxide concentration changes, making the driving force for mass transfer a function of depth. Fick's law (Eq. (1)) can be manipulated

to relate the mass transfer per differential change in depth, $d(Z)$ (m), as shown by Cornwell (1990):

$$d(Z) = \frac{L_{\text{vol}} \cdot d(X_{\text{CO}_2})}{K_L \cdot a \cdot (X_{\text{CO}_2} - X_{\text{CO}_2}^{\text{eq}})} \quad (4)$$

where L_{vol} is the liquid velocity (m s^{-1} , or $\text{m}^3 \text{s}^{-1} \text{m}^{-2}$), X_{CO_2} is the molar concentration of dissolved carbon dioxide, and $X_{\text{CO}_2}^{\text{eq}}$ is the limiting molar concentration of dissolved carbon dioxide defined by Henry's Law. After integration, the resulting expression can be used to calculate the column depth required to achieve a given effluent concentration ($X_{\text{CO}_2}^{\text{eff}}$) for a given influent concentration ($X_{\text{CO}_2}^{\text{inf}}$):

$$Z = \frac{L_{\text{vol}} \cdot (X_{\text{CO}_2}^{\text{inf}} - X_{\text{CO}_2}^{\text{eff}})}{K_L \cdot a \cdot \text{DF}_{\text{LM}}} \quad (5)$$

where DF_{LM} is the log mean of the driving force at column exit and entrance:

$$\text{DF}_{\text{LM}} = \frac{\text{DF}_{\text{eff}} - \text{DF}_{\text{inf}}}{\ln\left(\frac{\text{DF}_{\text{eff}}}{\text{DF}_{\text{inf}}}\right)} \quad (6)$$

and

$$\text{DF}_{\text{eff}} = X_{\text{eff}} - X_{\text{eff}}^{\text{eq}} \quad (7)$$

$$\text{DF}_{\text{inf}} = X_{\text{inf}} - X_{\text{inf}}^{\text{eq}} \quad (8)$$

Independent measurement of K_L and a is difficult, therefore, the product of the terms ($K_L a$) is generally determined experimentally. The measurement of $K_L a$ is dependent upon water quality factors and the type of stripping equipment used. Piedrahita and Grace (1989) and Sherwood and Holloway (1940) have measured $K_L a$ values for carbon dioxide removal using packed air-stripping columns. However, Onda et al. (1968) reported a method for calculating the values of k_L , k_G , and a (actually the wetted specific surface area of the packing, a_w [$\text{m}^2 \text{m}^{-3}$]), for use in the design of air-stripping columns that remove volatile gases, including carbon dioxide:

$$k_L \left(\frac{\rho_L}{\mu_L \cdot g} \right)^{1/3} = 0.0051 \cdot \left(\frac{L_{\text{mass}}}{a_w \cdot \mu_L} \right)^{2/3} \cdot \left(\frac{\mu_L}{\rho_L \cdot D_L} \right)^{-1/2} \cdot (a_t \cdot d_p)^{0.4} \quad (9)$$

$$\frac{a_w}{a_t} = 1 - \exp \left\{ -1.45 \cdot \left(\frac{\sigma_c}{\sigma_L} \right)^{0.75} \cdot \left(\frac{L_{\text{mass}}}{a_t \cdot \mu_L} \right)^{0.1} \cdot \left(\frac{L_{\text{mass}}^2 \cdot a_t}{\rho_L^2 \cdot g} \right)^{-0.05} \cdot \left(\frac{L_{\text{mass}}^2}{\rho_L \cdot \sigma_L \cdot a_t} \right)^{0.2} \right\} \quad (10)$$

$$\left(\frac{k_G}{a_t \cdot D_G} \right) = 5.23 \cdot \left(\frac{G_{\text{mass}}}{a_t \cdot \mu_G} \right)^{0.7} \cdot \left(\frac{\mu_G}{\rho_G \cdot D_G} \right)^{1/3} \cdot (a_t \cdot d_p)^{-2} \quad (11)$$

where: a_t = total specific surface area of the packing ($\text{m}^2 \text{m}^{-3}$); d_p = nominal packing diameter (m); σ_L = surface tension for the liquid (N m^{-1}); σ_c = critical surface tension for the particular packing material (N m^{-1}); L_{mass} = liquid mass

flux ($\text{kg m}^{-2} \text{s}^{-1}$); G_{mass} = gas mass flux ($\text{kg m}^{-2} \text{s}^{-1}$); μ_G = gas viscosity ($\text{kg m}^{-1} \text{s}^{-1}$); μ_L = liquid viscosity ($\text{kg m}^{-1} \text{s}^{-1}$); ρ_G = gas density (kg m^{-3}); ρ_L = liquid density (kg m^{-3}); D_G = gas diffusivity ($\text{m}^2 \text{s}^{-1}$); D_L = liquid diffusivity ($\text{m}^2 \text{s}^{-1}$); and, g = gravitational acceleration constant (m s^{-2}). Consistent units must be used throughout (e.g. the SI units shown).

The parameters a_t , d_p , and σ_c can be looked up in tables for many types of commercially available packing (Cornwell, 1990; Perry et al., 1997). Therefore, the K_L and a coefficients for a given commercial packing material can be estimated using Onda's correlations. Vinci et al. (1998) developed a computer program to estimate carbon dioxide removal in packed columns. The program incorporates Eqs. (5)–(11), and is therefore less data intensive than the previously proposed model of Grace and Piedrahita (1993, 1994) which requires measured values for the gas transfer coefficients. The Vinci et al. (1998) model can also be used to calculate carbon dioxide stripping efficiencies, building ventilation rates required to control ambient airspace carbon dioxide, and the corresponding heating and ventilating costs.

Chemical reaction also plays a role in carbon dioxide stripping because removing carbon dioxide increases the pH and reduces the total carbonate carbon of the water. Fortunately, for the purpose of estimating carbon dioxide stripping performance, the half-life of the dehydroxylation of bicarbonate to carbon dioxide is slow compared to the treatment time within many stripping devices; this means that chemical reaction need not be considered at the same time as mass transfer (Grace and Piedrahita, 1993, 1994). However, carbonate chemical equilibrium must be considered after stripping is complete to correctly estimate the carbon dioxide concentration after equilibrium has been reached. Grace and Piedrahita (1993, 1994) described how to calculate the final carbon dioxide concentration after equilibrium has been achieved in packed column aerators. This approach is reflected in the Vinci et al. (1998) computer software, where gas transfer calculations and the estimation of carbon dioxide removed to the atmosphere are based on an assumption of slow chemical reactions. As such, an initial estimate of the effluent carbon dioxide concentration (X_{eff}) (mol mol^{-1} water) is made based on a process removal efficiency (f_{rem}) (Table 2). The process removal efficiency represents the fraction of influent carbon dioxide that is removed from the system in the gas flowing through the stripping unit. Given the assumption of a slow dehydroxylation reaction, the difference between the influent and effluent carbon dioxide concentrations ($X_{\text{inf}} - X_{\text{eff}}$) (mol mol^{-1} water) is also equivalent to the change in total carbonate carbon concentration for the water (ΔCtCO_3) (mol l^{-1}), and can be used to perform a mass balance on the degassing system to estimate the carbon dioxide content in the effluent gas phase, and to calculate the effluent carbonate carbon concentration ($[\text{CtCO}_3]_{\text{eff}}$) (mol l^{-1}). Therefore, the carbon dioxide removed in the gas flowing through the packed column is ($\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$):

$$\text{CO}_{2,\text{removed}} = (Y_{\text{eff}} - Y_{\text{inf}}) \cdot G_{\text{mol}} \quad (12)$$

where Y_{eff} and Y_{inf} represent the effluent and influent molar concentrations of CO_2 in the gas leaving and entering the packed column, respectively ($\text{mol CO}_2 \text{ mol}^{-1}$ gas) (Table 2); and G_{mol} is the molar gas flux ($\text{mol m}^{-2} \text{ s}^{-1}$).

Table 2

Equations and constants for calculating packing height and equilibrium adjusted effluent dissolved carbon dioxide for a CO₂ stripping unit^a

1. Constant inputs

$$MW_{\text{CO}_2} = 44.0 \text{ g mol}^{-1}$$

$$MW_{\text{air}} = 29.0 \text{ g mol}^{-1}$$

$$MW_{\text{H}_2\text{O}} = 18.0 \text{ g mol}^{-1}$$

$$[\text{H}_2\text{O}] = 55.6 \text{ mol l}^{-1}$$

$$P_{\text{T}} = 1 \text{ atm}$$

$$K_{\text{H}} = 1.43 \times 10^3 \text{ atm}$$

$$K_{\text{H}}^{\text{a}} = 1.07$$

$$g = 9.8 \text{ m s}^{-2}$$

$$\rho_{\text{G}} = 1.2 \text{ kg m}^{-3}$$

$$\rho_{\text{L}} = 998 \text{ kg m}^{-3}$$

$$\mu_{\text{G}} = 1.82 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$$

$$\mu_{\text{L}} = 0.0010 \text{ kg m}^{-1} \text{ s}^{-1}$$

$$\sigma_{\text{L}} = 0.073 \text{ N m}^{-1}$$

$$D_{\text{L}} = 19.6 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$$

$$D_{\text{G}} = 1.38 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$$

2. Variable inputs

$$C_{\text{CO}_2}^{\text{inf}} = 30.0 \text{ mg l}^{-1}$$

$$f_{\text{rem}} = 1 - \frac{X_{\text{eff}}}{X_{\text{inf}}} = 0.8$$

$$L_{\text{vol}} = 0.015 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-2}$$

$$G/L = 5$$

$$a_{\text{t}} = 105 \text{ m}^2 \text{ m}^{-3}$$

$$\sigma_{\text{c}} = 33 \times 10^{-3} \text{ N m}^{-1}$$

$$d_{\text{p}} = 0.0508 \text{ m}$$

$$Y_{\text{inf}} = 0.00035 \text{ mol mol}^{-1}$$

$$\text{ALK} = 2.0 \text{ mequiv. l}^{-1}$$

3. Calculation of mol fractions and required flow rates

$$X_{\text{inf}} = \frac{C_{\text{CO}_2}^{\text{inf}}}{1000 \cdot [\text{H}_2\text{O}] \cdot MW_{\text{CO}_2}}$$

$$X_{\text{inf}}^{\text{eq}} = \frac{P_{\text{T}} \cdot Y_{\text{inf}}}{K_{\text{H}}}$$

$$X_{\text{eff}} = X_{\text{inf}} \cdot (1 - f_{\text{rem}})$$

$$Y_{\text{eff}} = \frac{X_{\text{inf}} \cdot f_{\text{rem}}}{G_{\text{mol}}/L_{\text{mol}}} + Y_{\text{inf}}$$

$$X_{\text{eff}}^{\text{eq}} = \frac{P_{\text{T}} \cdot Y_{\text{eff}}}{K_{\text{H}}}$$

$$L_{\text{mass}} = L_{\text{vol}} \cdot \rho_{\text{L}}$$

$$L_{\text{mol}} = \frac{L_{\text{mass}} \cdot 1000}{MW_{\text{H}_2\text{O}}}$$

$$G_{\text{vol}} = L_{\text{vol}} \cdot G/L$$

$$G_{\text{mass}} = G_{\text{vol}} \cdot \rho_{\text{G}}$$

$$G_{\text{mol}} = \frac{G_{\text{mass}} \cdot 1000}{MW_{\text{air}}}$$

5. Calculation of wetted area and mass transfer coefficients

$$a_{\text{w}} = a_{\text{t}} \cdot \left\{ 1 - \exp \left\{ -1.45 \cdot \left(\frac{\sigma_{\text{c}}}{\sigma_{\text{L}}} \right)^{0.75} \cdot \left(\frac{L_{\text{mass}}}{a_{\text{t}} \cdot \mu_{\text{L}}} \right)^{0.1} \cdot \left(\frac{L_{\text{mass}}^2 \cdot a_{\text{t}}}{\rho_{\text{L}}^2 \cdot g} \right)^{-0.05} \cdot \left(\frac{L_{\text{mass}}^2}{\rho_{\text{L}} \cdot \sigma_{\text{L}} \cdot a_{\text{t}}} \right)^{0.2} \right\} \right\}$$

$$k_{\text{L}} = 0.0051 \cdot \left(\frac{\rho_{\text{L}}}{\mu_{\text{L}} \cdot g} \right)^{-1/3} \cdot \left(\frac{L_{\text{mass}}}{a_{\text{w}} \cdot \mu_{\text{L}}} \right)^{2/3} \cdot \left(\frac{\mu_{\text{L}}}{\rho_{\text{L}} \cdot D_{\text{L}}} \right)^{-1/2} \cdot (a_{\text{t}} \cdot d_{\text{p}})^{0.4}$$

4. Calculation of log mean driving force

$$D_{\text{eff}} = X_{\text{eff}} - X_{\text{eff}}^{\text{eq}}$$

$$D_{\text{inf}} = X_{\text{inf}} - X_{\text{inf}}^{\text{eq}}$$

$$DF_{\text{LM}} = \frac{DF_{\text{eff}} - DF_{\text{inf}}}{\ln(DF_{\text{eff}}/DF_{\text{inf}})}$$

Table 2 (Continued)

$$k_G = 5.23 \cdot a_t \cdot D_G \cdot \left(\frac{G_{\text{mass}}}{a_t \cdot \mu_G} \right)^{0.7} \cdot \left(\frac{\mu_G}{\rho_G \cdot D_G} \right)^{1/3} \cdot (a_t \cdot d_p)^{-2}$$

$$K_L = \frac{1}{\frac{1}{K_H \cdot k_G} + \frac{1}{k_L}}$$

6. Calculation of column height

$$Z = L_{\text{vol}} \cdot \left(\frac{X_{\text{inf}} - X_{\text{eff}}}{K_L \cdot a_w \cdot \text{DF}_{\text{LM}}} \right)$$

7. Carbonate carbon mass balance and chemical equilibrium calculation

$$\text{CO}_{2,\text{removed}} = (Y_{\text{eff}} - Y_{\text{inf}}) \cdot G_{\text{mol}} = X_{\text{inf}} \cdot f_{\text{rem}} \cdot L_{\text{mol}}$$

$$\Delta \text{CtCO}_3 = \left(\frac{\text{CO}_{2,\text{removed}}}{L_{\text{vol}} \cdot 1000} \right) \cdot \left(\frac{1 \text{ mol C}}{1 \text{ mol CO}_2} \right)$$

$$[\text{CtCO}_3]_{\text{eff}} = [\text{CtCO}_3]_{\text{inf}} - \Delta \text{CtCO}_3$$

Iteratively solve for $[\text{H}^+]$:

$$\text{ALK} = 1000 \cdot \left\{ [\text{CtCO}_3]_{\text{eff}} \cdot \left(\left(\frac{1}{1 + \frac{[\text{H}^+]}{K_0 K_1} + \frac{K_2}{[\text{H}^+]}} \right) + 2 \cdot \left(\frac{1}{1 + \frac{[\text{H}^+]}{K_2} + \frac{[\text{H}^+]^2}{K_0 K_1 K_2}} \right) \right) + \frac{K_w}{[\text{H}^+]} - [\text{H}^+] \right\}$$

$$[\text{H}_2\text{CO}_3^*] = [\text{CtCO}_3]_{\text{eff}} \cdot \frac{1}{\left(1 + \frac{K_0 K_1}{[\text{H}^+]} + \frac{K_0 K_1 K_2}{[\text{H}^+]^2} \right)}$$

^a The inputs selected in this illustration assume a temperature of 20°C, a process removal efficiency (f_{rem}) of 0.8, a 5-cm nominal diameter random pack plastic media, a volumetric gas to liquid ratio (G/L) of 5:1, and carbon dioxide concentration in the air inlet equal to standard atmospheric levels.

$$\Delta \text{CtCO}_3 = \left(\frac{\text{CO}_{2,\text{removed}}}{L_{\text{vol}} \cdot 1000} \right) \cdot \left(\frac{1 \text{ mol C}}{1 \text{ mol CO}_2} \right) \quad (13)$$

$$[\text{CtCO}_3]_{\text{eff}} = [\text{CtCO}_3]_{\text{inf}} - \Delta \text{CtCO}_3 \quad (14)$$

The software then iteratively calculates pH ($[\text{H}^+]$) using the acid–base relationships in Table 1, the effluent carbonate carbon, and conservation of alkalinity (ALK, mequiv. l^{-1}):

$$\text{ALK} = 1000 \cdot \left\{ [\text{CtCO}_3]_{\text{eff}} \cdot \left(\left(\frac{1}{1 + \frac{[\text{H}^+]}{K_0 K_1} + \frac{K_2}{[\text{H}^+]}} \right) + 2 \cdot \left(\frac{1}{1 + \frac{[\text{H}^+]}{K_2} + \frac{[\text{H}^+]^2}{K_0 K_1 K_2}} \right) \right) + \frac{K_w}{[\text{H}^+]} - [\text{H}^+] \right\} \quad (15)$$

Table 3

Dissolved carbon dioxide removal was measured across an enclosed, forced-ventilation, counter-current cascade column and compared to the removal predicted using the Vinci et al. (1998) software program^a

<i>G/L</i> (vol/vol)	Dissolved CO ₂ inlet (mg l ⁻¹)	Measured CO ₂ removal efficiency (%)	Calculated CO ₂ removal efficiency (%)	Relative error between measured and calculated (%)
10:1	30.6 ± 0.6	63.4 ± 1.1	65.3	+3.0
10:1	11.5 ± 0.3	52.5 ± 0.6	56.8	+8.2
1.2:1	34.7 ± 0.7	46.0 ± 1.3	44.7	-2.8
1.2:1	13.6 ± 0.4	39.0 ± 1.3	40.4	+3.6

^a See Appendix A for methods used in the stripper study and input values used in the stripping tower program simulation runs.

Once pH is determined, Eq. (3) is used to calculate the equilibrium dissolved carbon dioxide concentration for the effluent pH, CtCO₃, and ALK.

As an illustration, the Vinci et al. (1998) program can be used for estimating stripping tower packing height under the specific design criteria shown in Table 2. Eqs. (12)–(15) are also incorporated in the program to account for carbonate chemical equilibrium. The accuracy of the Vinci et al. (1998) software was tested by comparing the program's output against data collected on an air-stripping unit in operation at the Freshwater Institute (Table 3); the methods used in this stripping experiment are summarized in Appendix A. In this case, the program accurately predicted dissolved carbon dioxide removal (4.4% mean error, range -2.8 to 8.2%) across a packed air stripping tower when operated at low (11–14 mg l⁻¹) and high (30–36 mg l⁻¹) inlet dissolved carbon dioxide concentrations, and at *G/L* loading rates of 1.2:1 and 10:1 (Table 3). The method of Onda et al. (1968) used in the Vinci et al. (1998) program has also been reviewed intensively (Kavanaugh and Trussell, 1980; Cornwell, 1990; Haarhoff and Cleasby, 1990; Thom and Byers, 1993), particularly for estimating stripping of volatile organic carbon compounds in the water treatment field; it has been shown to perform with an accuracy of ± 30% with 90% confidence (Staudinger et al., 1990).

Given the very low concentration of carbon dioxide in a normal atmosphere and the relatively high levels of dissolved carbon dioxide supersaturation observed in recirculating systems (to over 50 mg l⁻¹ carbon dioxide), carbon dioxide stripping can cause large increases in the fraction of carbon dioxide in the passing air flow. In the Freshwater Institute study (Table 4), a *G/L* of 1.2:1 increased the gas-phase carbon dioxide concentration leaving the stripper by 690%, and removed about 20% less dissolved carbon dioxide than was removed at a *G/L* of 10:1. The increase in carbon dioxide partial pressure in the air passing through the stripping column reduced the rate of dissolved carbon dioxide removal. A software-generated sensitivity analysis (Fig. 4) demonstrates the dependence of carbon dioxide stripping on *G/L* loading rates. Therefore, very large volumes of air are needed for carbon dioxide degassing, with *G/L* loading levels of 3:1 to 10:1 being recommended to

maximize carbon dioxide removal (Grace and Piedrahita, 1994; Summerfelt, 1996). In comparison, the G/L loading levels used in oxygenation units are only 0.005:1 to 0.03:1, which corresponds to gas flow requirements that are several hundred times smaller than for carbon dioxide stripping units. Fortunately, providing large air volumes is relatively inexpensive when air-handling or building ventilation-type blowers are used because of the relatively low power needed due to the low back-pressures involved.

Packing height also has a large effect on carbon dioxide stripping efficiency (Fig. 4). However, practical limitations on the use of tall columns (e.g. taller ceilings and increased pumping heights) coupled with diminishing returns on removal rate with increasing column depth (Fig. 4) will generally limit the depth of the packed column to between 1 and 1.5 m.

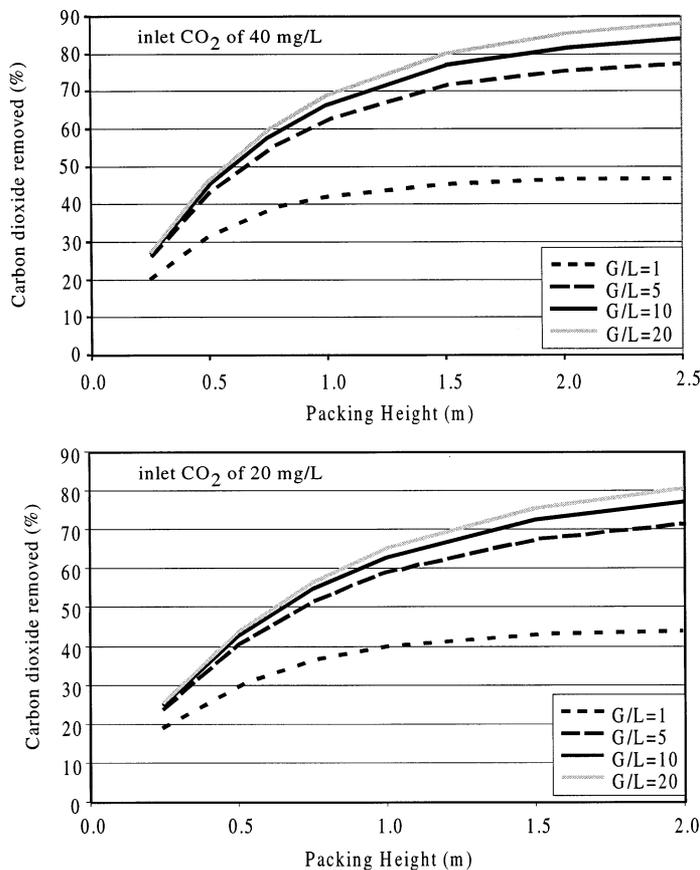


Fig. 4. The Vinci et al. (1998) software program was used to estimate stripping column performance as a function of packing depth and G/L ratio when treating an inlet dissolved carbon dioxide of 20 mg l^{-1} (bottom graph) and 40 mg l^{-1} (top graph).

Table 4

Carbon dioxide concentrations were measured in both water and air passing through an enclosed, forced-ventilation, counter-current cascade column^a

Packing depth (m)	<i>G/L</i> (vol/vol)	Dissolved CO ₂ inlet (mg l ⁻¹)	Dissolved CO ₂ outlet (mg l ⁻¹)	Dissolved CO ₂ removal efficiency (%)	Inlet air CO ₂ concentration, (ppm) ^b	Outlet air CO ₂ concentration (ppm)	CO ₂ increase in air (%)
1	10:1	30.6 ± 0.6	11.2 ± 0.1	63.4 ± 1.1	910 ± 6	2147 ± 19	136 ± 1
1	10:1	11.5 ± 0.3	5.5 ± 0.2	52.5 ± 0.6	623 ± 9	1050 ± 15	68 ± 1
1	1.2:1	34.7 ± 0.7	18.7 ± 0.8	46.0 ± 1.3	1063 ± 13	8380 ± 29	688 ± 10
1	1.2:1	13.6 ± 0.4	8.3 ± 0.2	39.0 ± 1.3	700 ± 10	2730 ± 25	290 ± 5
0	10:1	32.7 ± 0.5	18.9 ± 0.2	42.1 ± 0.8	977 ± 3	1803 ± 9	85 ± 1
0	10:1	13.6 ± 0.1	8.6 ± 0.2	36.5 ± 1.2	777 ± 19	1057 ± 9	36 ± 2
0	1.2:1	36.4 ± 0.8	23.6 ± 0.6	35.1 ± 1.5	1053 ± 15	6253 ± 66	494 ± 2
0	1.2:1	14.0 ± 0.2	10.0 ± 0.1	28.6 ± 0.5	730 ± 23	2103 ± 3	189 ± 10

^a The stripping column was operated with either 1 m of packing or with no packing, at two *G/L* loading rates (1.2:1 and 10:1), and at two dissolved carbon dioxide inlet concentrations (11–14 and 30–36 mg l⁻¹). See Appendix A for details.

^b The carbon dioxide concentration in air is expressed in parts per million (ppm); ppm = 1 000 000 × (mol fraction).

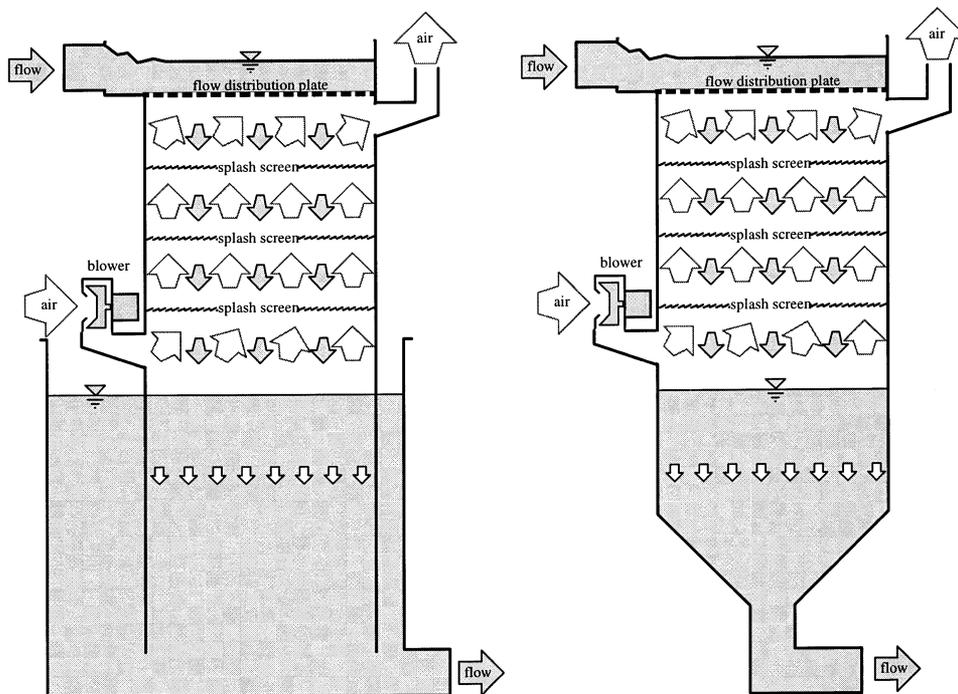


Fig. 5. Air is blown through cascade columns, often counter-current (shown here) to the water falling through splash screens or media (not shown here), to strip a portion of the dissolved carbon dioxide from the water. Flow is distributed at the top of the chambers using an orifice plate or spray nozzles (not shown here); flow then cascades down through the splash screens or media and is recollected in the sump pool, which may or may not be a separate vessel. Air-stripping columns can also be constructed within cone-bottom cylindrical tanks (right diagram) to avoid a sump were settleable solids can accumulate (left diagram).

The cross-sectional area of air-stripping columns is determined based on a hydraulic loading rate of $60\text{--}84\text{ m}^3\text{ h}^{-1}\text{ m}^{-2}$ (Summerfelt, 1996) to $100\text{--}250\text{ m}^3\text{ h}^{-1}\text{ m}^{-2}$ (Grace and Piedrahita, 1994). The lower rates are suggested especially to reduce the back-pressure on the air-handling blowers when the columns have more than 1–2 m of packed media.

A variety of packing media are used in air stripping columns, ranging from random packing media such as Pall™ rings, to structured media such as Munters™ packing. Media with smaller elements tend to result in more efficient gas transfer, but at the expense of increased maintenance problems due to biofouling, and increased head requirements for the air blowers. Fouling problems are less serious in relatively clean coldwater recirculating systems (Heinen et al., 1996). However, plugging due to biofouling is a serious problem in warmwater systems, and special precautions need to be taken with the design of the column and the choice of media and air distribution screens. Therefore, when high solids loadings are expected in a warmwater system, a stripping tower with screens (Fig. 5) may be easier to

maintain than a tower packed with media. The elimination of the packing media can decrease stripping efficiency by 10–20% (Table 4), but this may be an efficiency loss worth sacrificing to avoid later maintenance problems associated with fouled packing.

Air discharged from stripping columns that are part of indoor systems should be vented from buildings to prevent carbon dioxide from rising inside buildings. Vinci et al. (1998) summarized building ambient airspace carbon dioxide concentration limits: 5000 parts per million (ppm) is the maximum allowable time-weighted average exposure over an 8-h workday and 50 000 ppm is immediately dangerous to life and health. In contrast, ambient atmospheric carbon dioxide concentrations are about 350 ppm. However, a considerable amount of heat may be lost when venting the building air space in cold climates, resulting in higher operating costs. The Vinci et al. (1998) computer software program can be used to estimate heat lost from ventilating the building. Under some conditions, a portion of this heat can be recovered by venting the air through an air–air heat exchanger. Alternatively, the air (and heat) can be conserved if carbon dioxide can be scrubbed in a column designed to contact the air with a highly caustic solution such as sodium hydroxide. Recycling the air through such a scrubbing unit can reduce the need for building air exchange (B. Watten, USGS Leetown Science Center, Kearneysville, WV, pers. commun.).

3.4. Chemical equilibrium and pH control

An alternate strategy for carbon dioxide control relies on the addition of bases to increase the pH and shift the chemical equilibrium (Bisogni and Timmons, 1994; Grace and Piedrahita, 1994; Summerfelt, 1996; Loyless and Malone, 1997; Piedrahita, 1997, 1998). In typical aquaculture applications, the addition of bases does not result in the removal of dissolved inorganic carbon from solution, but merely causes a decrease in the carbon dioxide concentration by shifting the carbonate carbon balance to bicarbonate and carbonate ions as the pH is increased.

Two general classes of chemicals are used in aquaculture to regulate pH and control carbon dioxide concentrations: strong bases which do not contain any carbon, such as sodium hydroxide, and bases that contain carbon, such as sodium bicarbonate. In all cases, the addition of these chemicals causes an increase in the alkalinity of the water. In the case of the carbon-containing bases, this alkalinity increase is accompanied by a rise in the total carbonate carbon. The pH increase caused by the chemical addition is determined by the initial characteristics of the water (pH, alkalinity, and total carbonate carbon) and by the type and amount of base added. For a given alkalinity addition, the smaller the amount of carbonate carbon added, the larger the pH increase. Estimates of the amount of base that needs to be added to reach a target carbon dioxide concentration are obtained from equations derived from those shown in Table 1 (e.g. Bisogni and Timmons, 1994; Grace and Piedrahita, 1994; Loyless and Malone, 1997; Piedrahita, 1997, 1998).

A common practice in industry is to combine gas removal and chemical addition. The combination of methods often offers advantages over a single method strategy (Piedrahita, 1997, 1998).

4. Conclusions and recommendations

Recirculating aquaculture systems use oxygenation technologies to increase system carrying capacity or reduce culture tank flow requirements, both of which can decrease production costs. However, carrying capacity can only be increased to a cumulative oxygen consumption of 10–20 mg l⁻¹ before ammonia or dissolved carbon dioxide concentrations accumulate to a point where they must be treated for the water to be reused. Therefore, recirculating systems that do not use pure oxygen addition can rely on aeration to achieve both oxygen absorption and carbon dioxide stripping. However, intensive recirculating systems that add large amounts of pure oxygen will require aeration units designed to strip dissolved carbon dioxide. Properly designed air-stripping columns are a preferred method to remove dissolved carbon dioxide. Large volumes of air (as much as 10 vol. air per vol. water) must be contacted with water for the most effective carbon dioxide stripping. The software package discussed in this paper can be used to estimate stripping tower performance. Recirculating systems also require chemical addition to replace alkalinity lost during nitrification and the resulting pH increase is also an effective method for maintaining dissolved carbon dioxide at safe levels.

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Appendix A. Carbon dioxide stripper study

Dissolved carbon dioxide removal was evaluated across an enclosed, forced-ventilation, counter-current cascade column treating 753 l min⁻¹ of water flow within a recirculating aquaculture system. The recirculating system, described by Bullock et al. (1997), was used to produce nearly 9000 kg year⁻¹ of pan-sized rainbow trout. During the carbon dioxide stripper study, the stripping column was operated under the following conditions:

- 1 m depth of 5 cm Norpac (NSW, Roanoke, VA) or with no packing;
- 1.2:1 or 10:1 volumetric *G/L* loading rates;
- low (11–14 mg l⁻¹) or high (30–36 mg l⁻¹) dissolved carbon dioxide inlet concentrations.

The lower dissolved carbon dioxide concentrations were obtained by fish respiration under normal operating conditions. The higher dissolved carbon dioxide concentrations were achieved by diffusing carbon dioxide gas into the fluidized-sand biofilter (just before the stripping column) during the study and for at least 1 day before the study. The diffused carbon dioxide gas dissolved rapidly, and no bubbles were observed leaving the biofilter. Carbon dioxide dissolution created a slight reduction in the pH of water entering the stripping column.

Data were collected on the stripping column inlet and outlet dissolved carbon dioxide concentrations and on the inlet and outlet carbon dioxide concentration in the passing air; results are reported in Table 4. Dissolved carbon dioxide was measured by titration (APHA, 1989) and the carbon dioxide mol fraction in air was measured using a gas-phase monitor (CEA, Emerson, NJ). Water parameters during the study include: temperature of 14.2–14.6°C, alkalinity of 3.74–3.92 mequiv. l^{-1} , total dissolved solids of 336–368 $mg\ l^{-1}$, and total gas pressure of 92.2–94.5% on the column inlet and 97.5–100.5% on the column outlet. Water pH entering and exiting the stripping column was 7.09–7.42 and 7.33–7.90, respectively. As would be expected, the lower pH values were measured during trials where carbon dioxide gas was dissolved before the stripping column and when the stripping column was operated without packing. The carbon dioxide concentration within the building air which was blown into the stripping column (Table 4) was two to three times the normal atmosphere values of 350 ppm carbon dioxide. Air leaving the stripping column was vented outside of the building through an air-to-air heat exchanger (AAA Associates, Niles, MI).

The following input parameters were used in the Vinci et al. (1998) computer software to predict the stripping column dissolved carbon dioxide removal efficiencies reported in Table 3:

Input parameters	Input values
Water temperature	14.4°C
Barometric pressure	750 mmHg
Alkalinity	3.88 mequiv. l^{-1}
Carbon dioxide concentration in stripping column air inlet	900 ppm
Packing depth	1 m
Packing specific surface area	105 $m^2\ m^{-3}$
Packing critical surface tension	0.033 N m^{-1} (plastic)
Packing nominal diameter	0.0508 m
Hydraulic loading rate	20 $kg\ m^{-2}\ s^{-1}$

Note that dissolved oxygen and nitrogen concentrations do not affect carbon dioxide stripping.

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