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Comparing Carbon Dioxide Stripping Column Performance in Freshwater and Seawater

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Abstract

Problems with elevated dissolved carbon dioxide (CO_2) have been encountered in intensive aquaculture systems that supplement dissolved oxygen levels using pure oxygen injection technologies, because these systems support higher fish loading rates and the oxygen transfer processes that are used provide insufficient gas exchange to strip the quantities of CO_2 produced. Previous research in freshwater systems has demonstrated that as much as 5-10 volumes of air per volume of water must be contacted for the most effective CO_2 stripping. However, anecdotal evidence from commercial marine fish farmers indicates that dissolved CO_2 stripping across forced-ventilated cascade columns is more difficult in seawater than in freshwater. Therefore, we conducted empirical studies to determine how air:water loading levels, packing height, and packing type affect dissolved CO_2 removal in freshwater and seawater. CO_2 stripping was studied using two force-ventilated cascade columns, each 38.6 cm diameter (15.2 in. in diameter) and randomly packed with either 1 m or 2 m of 5-cm diameter tubular NORPAC media. The counter-current ventilated cascade columns were located on a side-stream within a recirculating aquaculture system containing a 150 m^3 culture tank at the Conservation Fund Freshwater Institute. Water flow rates were controlled with valves so that each cascade column received a 119, 238, 357, or 476 LPM water flow rate, producing hydraulic loading rates of 1.03, 2.05, 3.07 , and 4.1 m^3/min per m^2 plan area (25, 50, 75, and 100 gpm/ft^2). Volumetric air flow rates were adjusted so that each column received ½, 1, 2, 5, 10, or 20 times the volumetric water flow rate. The combination of airflow and water flow rates resulted in 48 different trials for each column, i.e., four HLR's were tested at six air:water ratios and at two salinities. Each of these trials was conducted at a water temperature of 15.5 ± 0.5°C and repeated at least six times. Salinity levels in the recirculating system were < 0.3 ppt, (freshwater) and 33 ppt, produced by adding NaCl and other salts to create a synthetic seawater solution in the recycle system. Inlet CO_2 concentration was held at 20 mg/L by regulating the amount of CO_2 gas that was diffused into the water. When all else was the same, CO_2 removal efficiency in seawater were 5-15% lower than freshwater. Air:Water contacting had the largest impact on CO_2 removal efficiencies, with a12-24% increase in stripping efficiency at an Air:Water of 10:1 versus an Air:Water of 1:1, all else equal. Increasing packing depth from 1 m to 2 m only increased dCO_2 removal efficiency by approximately 10-15%, all else equal. Mean dCO_2 removal efficiency were fairly consistent over all HLR tested, except at relatively low Air:Water contact ratios (i.e., ≤ 2:1).

Introduction

Dissolved carbon dioxide (CO_2) is found in all natural waters that are in contact with the atmosphere or with an inorganic carbon, such as limestone. In aquaculture, CO_2 is produced by respiration of fish and microbes and can accumulate to concentrations that can inhibit fish growth and health in production systems that provide pure oxygenation but little aeration, especially when water is recirculated. Fortunately, dissolved CO_2 can be stripped from water into air in intensive aquaculture systems, because dissolved CO_2 is often more than 20-40 times the ambient saturation concentration, which is less than 1 mg/L. Ambient air contains only about 350-400 ppm of CO_2. Thus, stripping CO_2 from water can rapidly and significantly increase the partial pressure of CO_2 in the passing air flow (Grace and Piedrahita, 1994). For this reason, large volumes of air volume must be contacted with each unit of water volume to strip CO_2. Additionally, dissolved CO_2 is extremely soluble in water, e.g., much more soluble than O_2 and N_2 gases. Thus, dissolved CO_2 is not stripped from water as readily as nitrogen gas and vented O_2 transfer columns – used to produce supersaturated concentrations of dissolved O_2 and strip N_2 gas from water – are not effective at removing dissolved CO_2 because they operate at air-to-water contact volumes that are at least 100 times too small (Watten et al., 1991). Previous research in freshwater systems has demonstrated that as much as 5-10 volumes of air per volume of water must be contacted for the most effective CO_2 stripping (Grace and Piedrahita, 1993, 1994; Summerfelt et al., 2000; Summerfelt and Sharrer, 2004). However, anecdotal evidence from commercial marine fish farmers indicates that dissolved CO_2 stripping across forced-ventilated cascade columns is more difficult in seawater than in freshwater.

The objectives of this research was to determine how air:water loading levels, packing height, and packing type affect dissolved CO_2 removal in freshwater and seawater.

Materials and methods

Full-scale packed columns

The full-scale, ventilated cascade columns used in this study have been described elsewhere (Summerfelt et al., 2003). The full-scale cascade columns were custom fabricated, side-by-side, using 4.8 mm thick (3/16 in. thick) marine grade aluminum. The two cascade columns were tested with four different packing types, i.e., a random 1.0 m tall collection of 5 cm lengths of 5 cm diameter tubular NORPAC media (NSW, Roanoke, Virginia), a structured collection of 1.0 m tall by 5 cm diameter tubular NORPAC media (NSW), a structured 1.0 m tall stack of cross-corrugated CF-3000 Accu-Pac sheet media with 3.0 cm spacing between sheets (L.S. Enterprises, Fort Myers, Florida), and a structured 1.0 m tall stack of cross-corrugated CF-1200 Accu-Pac sheet media with 1.9 cm spacing between sheets (L.S. Enterprises); the cascade column with no packing media was also tested. The random 5 cm diameter NORPAC, structured 5 cm diameter NORPAC, structured CF-3000 Accu-Pac, and structured CF-1200 Accu-Pac have specific surface areas of approximately 114, 108, 102, and 226 m^2/m^3, respectively. Water was delivered uniformly across the top of each packing with crown nozzles spaced equally on a distribution plate.

The cascade columns were operated using independent air and water flows. Butterfly valves were used to set a water flow to each cascade column of 1136, 2271, or 3407 LPM. Water flow rates were measured with a transit-time ultrasonic flow meter and high performance clamp-on transducers (Transport Model PT868-2, Panametrics, Inc., Waltham, Massachusetts). Airflow was delivered to the base of each column by ¾-hp forward-curve blowers (Grainger, Model Number 7C490, Springfield, Virginia). Airflow rates delivered by the blowers were not adjustable, and were measured with a digital handheld anemometer (Omega Engineering, Inc., Model HH30, Stamford, Connecticut) as the air discharged from each cascade column and out of the building through 25 cm (10 in.) diameter pipes. The resulting airflow rates coupled with the controlled water flow rates yielded air to water ratios of approximately 12:1, 9:1, 5:1, 2:1, and 1:1. Each of these trials was repeated at least six times.

Side-stream packed columns

Two side-stream, ventilated cascade columns were custom fabricated and constructed side-by-side. Each cascade column measured 38.6 cm in diameter and was randomly packed with 2 in. tubular NORPAC media. One cascade column was packed to a depth of 1 m, the other to a depth of 2 m. Recirculated water was delivered to each column through separate 4 in. schedule 40 PVC pipe.

This system was designed to control hydraulic loading rate (HLR) independent of air and water flow rates. Water flow rates were controlled with valves so that each cascade column received a 119, 238, 357, or 476 LPM water flow rate, producing hydraulic loading rates of 1.03, 2.05, 3.07 , and 4.1 m^3/min per m^2 plan area (25, 50, 75, and 100 gpm/ft^2). Water flow rates were measured with a transit-time ultrasonic flowmeter and high performance clamp-on transducers (Transport Model PT868-2, Panametrics). Airflow was delivered by blowers set on each column's air pipe. Air supply pipes were 15.4 cm diameter schedule 40 PVC. Airflow rate was adjusted with ball valves so that each column received ½, 1, 2, 5, 10, or 20 times the water flow rate. Airflow rates were measured with a thermal anemometer with telescopic probe (Testo, Inc., Model 425, Flanders, New Jersey).

The combination of airflow and water flow rates resulted in 24 different trials for each packing depth (Table 1) for freshwater conditions, i.e., four HLR's were tested at six air:water ratios. These same 24 trials were conducted again, at each packing depth, in artificial seawater. Every trial was repeated at least six times.

Table 1. Trials for each side-stream carbon dioxide stripping column

HLR (gpm/ft^2)	25	50	75	100
Water flow (LPM)	119.0	238.0	357.1	476.1
Air:Water		Airflow (LPM)		
½	59.5	119	178.5	238
1	119	238	357	476
2	238	476	714	952
5	595	1190	1785	2380
10	1190	2380	3571	4761
20	2380	4761	7141	9522

Recirculating system details

Both types of cascade columns used in this study were installed within the water recirculating system at the Freshwater Institute, which has been described elsewhere (Davidson and Summerfelt, 2005). In summary, this system (Figure 1) uses two 5-HP pumps to recirculate 4800 LPM (1250 gpm) of water. The water flows through a 2.7 m (9 ft) diameter by 6.1 m (20 ft) tall fluidized-sand biofilter. The water then exits the top of the fluidized-sand biofilter and flows by gravity through the full-scale cascade stripping column, a LHO unit, and a UV irradiation unit before being piped to a 150 m3 (40,000 gal) culture tank. About 93% of the water exits the culture tank through its 'Cornell-type' sidewall drain and then passes through a microscreen drum filter before returning to the sump pump. About 7% of the water exits the culture tank through its bottom drain and flows to a radial flow settler. Water treated by the radial flow settler is redirected to the microscreen drum filter. The side-stream stripping columns were installed adjacent to the side wall of the RAS culture tank. Water was pumped from the RAS culture tank to the side-stream system using a 3.0-HP pump.

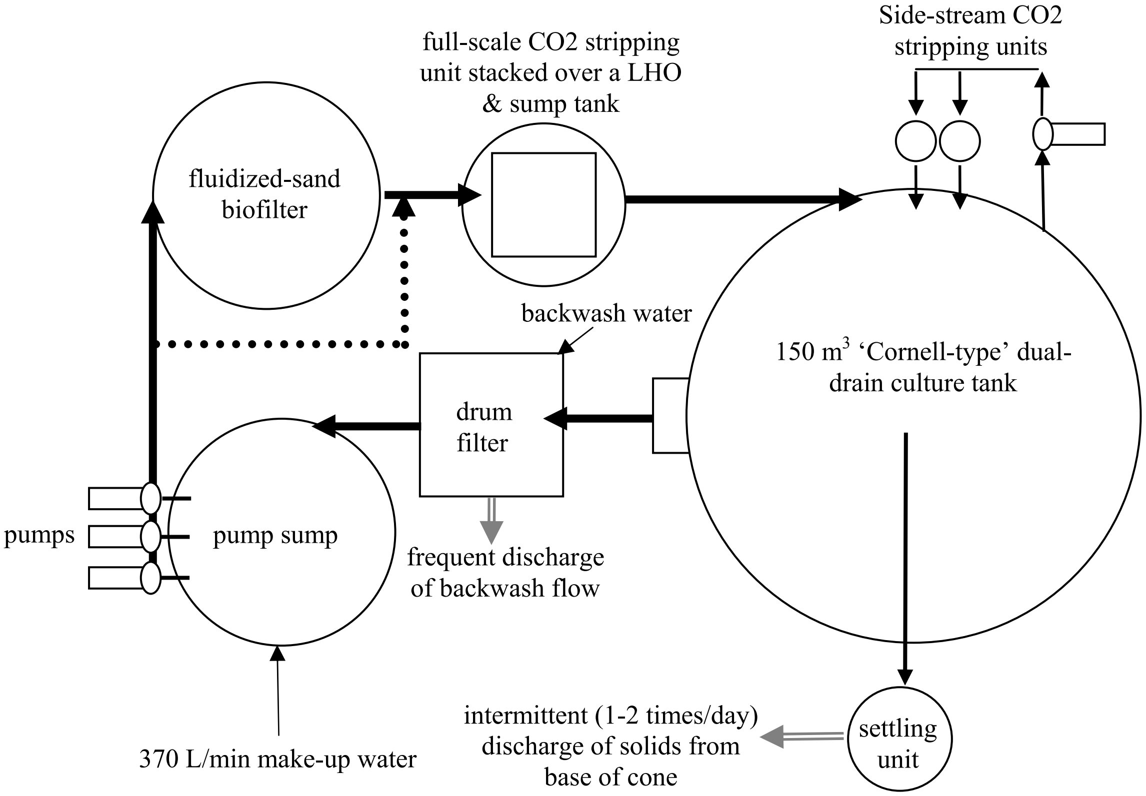

Figure 1. Process flow drawing of the recirculating salmonid growout system located at the Freshwater Institute, Shepherdstown, WV (after Davidson and Summerfelt, 2005).

Additional experimental conditions

During all trials, the inlet concentration of dissolved CO_2 was held at 20 ± 4 mg/L by regulating the amount of CO_2 gas that was diffused into the water at the LHO sump.

Temperatures of 15.5 ± 0.5°C were investigated in both cascade column systems. To maintain this temperature range in the RAS during warmer months, three bolt-together stainless steel heat exchangers were installed in the pump sump that allowed for 12.5ºC spring water flow of up to 400 LPM through the heat exchangers. The feed water for all trials originated from a natural spring on the TCFFI property. Having an average salinity of <1 ppt, it was used in freshwater experiments for the side-stream cascade column system. In addition, synthetic seawater was created using the spring water and the recipe reported by Berges et al. (2001). Average salinity was kept at 33 ppt during the synthetic seawater trials and investigated for each system.

Experimental measurements

Dissolved CO_2 (dCO_2) was measured by empirically developing a calibration curve relating dissolved CO_2 concentrations to pH using the equation developed by Watten et al. (2004):

$$dCO_2(mg/L) = \frac{\%CO_2}{100} \cdot \frac{BP(mm\,Hg)}{0.3845} \cdot \beta_{CO_2}$$

Where,
$\% CO_2$ = percent CO_2 from standard gas cylinder
BP = barometric pressure in millimeters mercury (mmHg)
β_{CO_2} = Bunsen coefficient

For each condition (i.e. temperature and salinity), points for the calibration curve were developed by purging 500 mL respective water type with known CO_2 gas standard (GTS, Hagerstown, Maryland) and monitoring for pH stabilization using a convertible-style digital pH sensor and sc100 controller (Hach Company, Loveland, Colorado). The CO_2 gas standards used included:

- 0.035% CO_2 (outdoor air)
- 0.105% CO_2
- 0.302% CO_2
- 0.797% CO_2
- 0.996% CO_2
- 1.25% CO_2
- 2.10% CO_2

Water temperature was held constant in a water bath while samples were sparged with each gas until a stable pH was reached. Barometric pressure was measured with a tensionometer (Alpha Designs Ltd., Model 300E, Victoria, British Columbia).

The stable pH value was plotted versus the corresponding log10 of dCO_2 as calculated above. From linear regression, dissolved CO_2 values were then determined from pH. The prediction equation for dissolved CO_2 concentration in freshwater at 15°C was determined to be:

$$dCO_2 = 10^{(9.3292-(1.0813 \text{ x pH}))}$$

The prediction equation for dissolved CO_2 concentration in artificial seawater produced at TCFFI at 15°C was determined to be:

$$dCO_2 = 10^{(9.0134-(1.0967 \times pH))}$$

Based on these two empirically derived equations, a dissolved CO_2 concentration entering the stripping columns of 20 mg/L was achieved by maintaining a pH of 7.41 and 7.03, respectively, for freshwater and artificial seawater conditions.

During this experiment, pH and water temperature were monitored immediately before and immediately after the cascade columns using digital pH sensors and a sc100 controller (Hach). The pH measured immediately after the cascade column was monitored in a side-stream bucket with an approximately 7 min HRT. The increased retention time allowed the dehydration of carbonic acid, i.e., the rate limiting step, and reallocation of bicarbonate and carbonate (both nearly instantaneous) to return to acid-base equilibrium (Kern, 1960; Grace and Piedrahita, 1993, 1994). Stripping dissolved CO_2 increases the pH of water as it decreases the total inorganic carbon concentration, but it does not change the concentration of alkalinity.

The composition of CO_2 in the air entering and exiting the cascade columns were measured using a portable infrared CO_2 gas monitor (CEA Instruments Inc., Model GD-444/1, Emerson, New Jersey).

Pressure loss generated by the suction of the fans in each air pipe in the side-stream system was measured with a digital, handheld manometer (Dwyer Instruments, Inc., Model Mark III, Michigan City, Indiana). The change in pressure per length of packing media in each column was used to illustrate the pressure differential created from each blower in achieving the experimental air:water for each HLR.

Relative humidity, ambient and in each air pipe, was measured with a handheld relative humidity meter (The Dickson Company, Model TH300, Addison, Illinois) in side-stream system trials.

Results and Discussion

Side-Stream Studies: Seawater versus Freshwater

Removal efficiency of dCO_2 in artificial seawater was approximately 5-15% less than in freshwater, for both packing depths and under all hydraulic loading rates when Air:Water contacting was $\geq 5:1$ (Figures 2-5). For example, mean dCO_2 removal efficiency averaged approximately 53% in seawater and 63% in freshwater across a 1 m bed depth at a HLR of 1.03 m^3/min per m^2 (25 gpm/ft^2) and Air:Water of 10:1. The difference between dCO_2 removal efficiency in seawater and freshwater was most pronounced at the highest Air:Water contacting. In contrast, when Air:Water contacting was $\leq 2:1$, differences between dCO_2 removal efficiency in seawater and freshwater were much less pronounced and practically negligible.

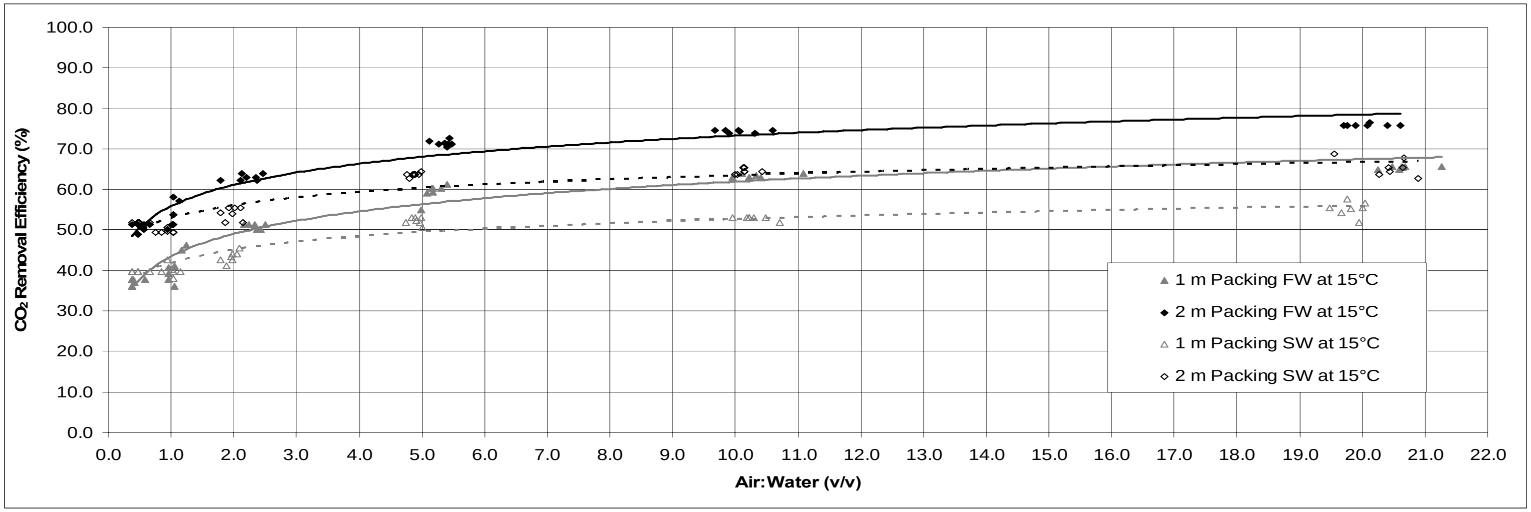

Fig. 2. Side-stream carbon dioxide removal efficiencies at a HLR of 1.03 m^3/min per m^2 (25 gpm/ft^2) (solid line is freshwater; dashed line is 33 ppt).

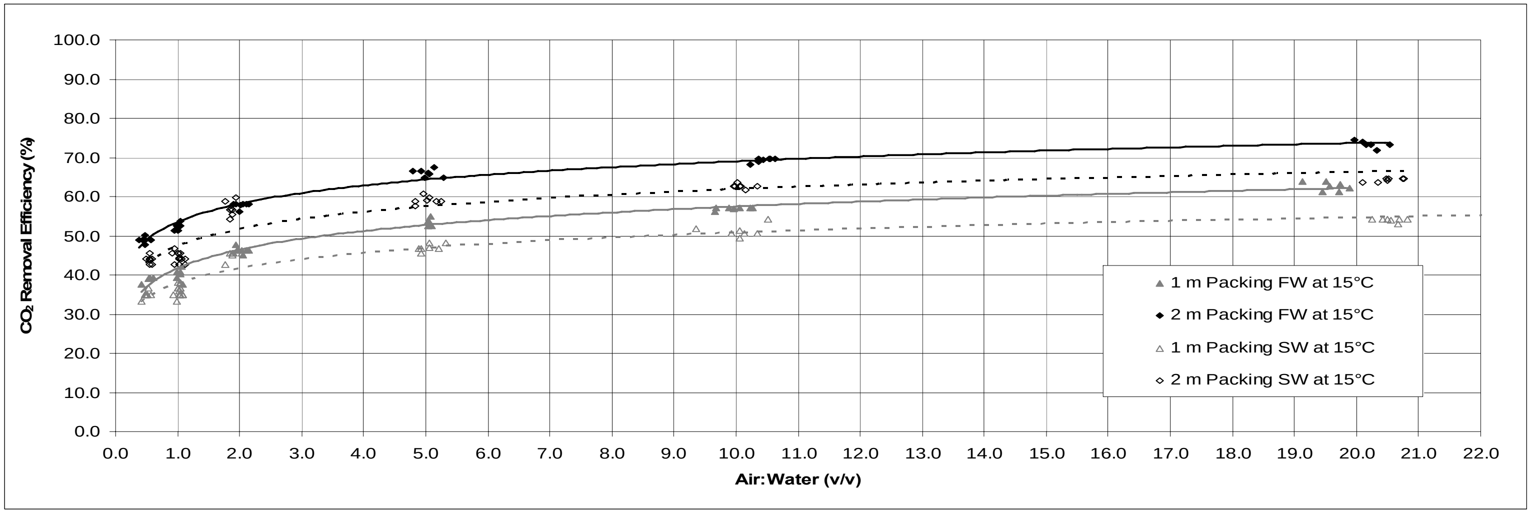

Fig. 3. Side-stream carbon dioxide removal efficiencies at a HLR of 2.05 m^3/min per m^2 plan area (50 gpm/ft^2) (solid line is freshwater; dashed line is 33 ppt).

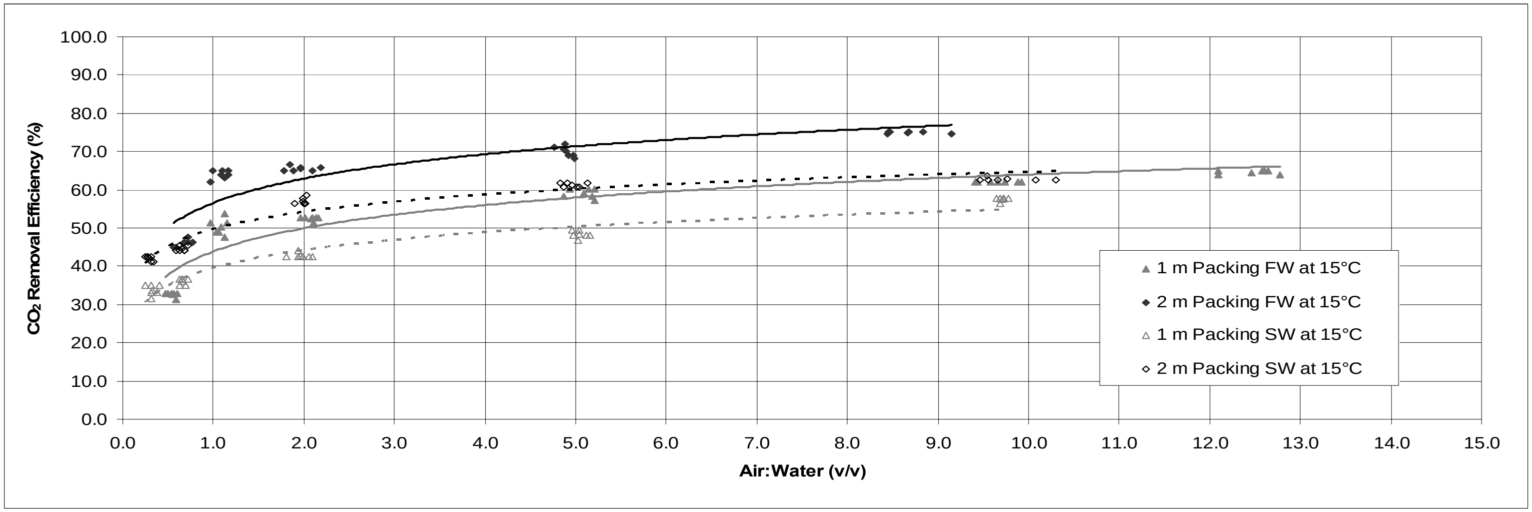

Fig. 4. Side-stream carbon dioxide removal efficiencies at a HLR of 3.07 m^3/min per m^2 plan area (75 gpm/ft^2) (solid line is freshwater; dashed line is 33 ppt).

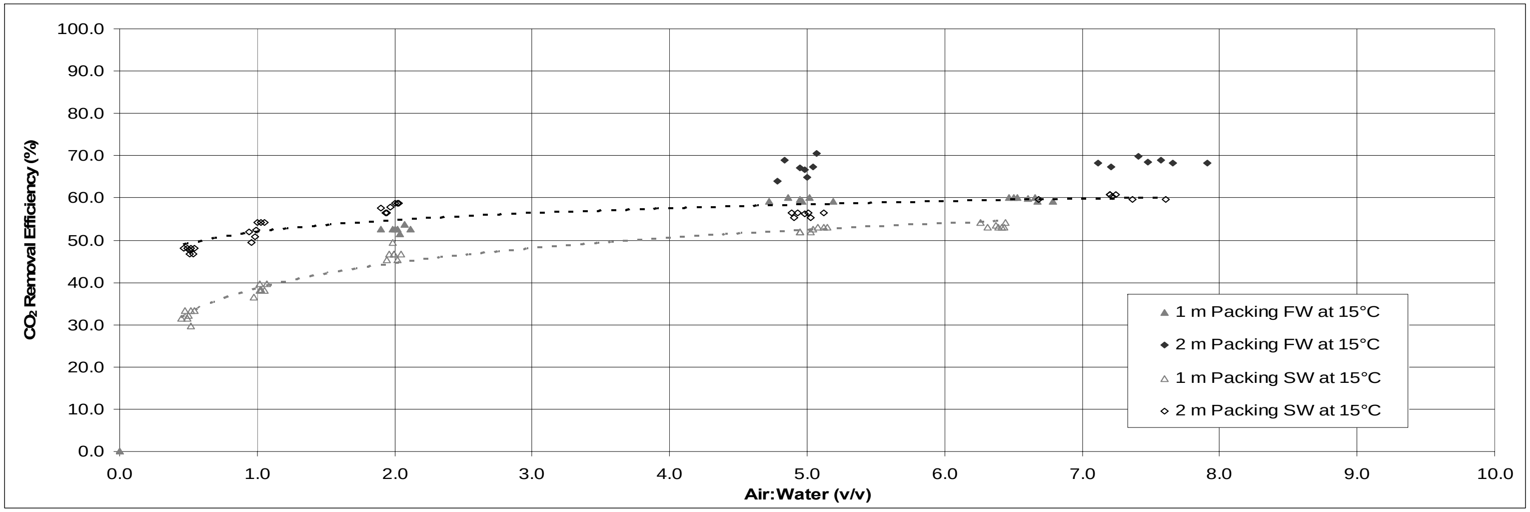

Fig. 5. Side-stream carbon dioxide removal efficiencies at a HLR of 4.1 m^3/min per m^2 plan area (100 gpm/ft^2) (solid line is freshwater; dashed line is 33 ppt).

Side-Stream Studies: Packing depth: 1 m versus 2 m

Increasing packing depth from 1 m to 2 m was found to increase dCO_2 removal efficiency by 10 to 15% (Figures 2-5). Again, the highest Air:Water contacting produced the most pronounced difference (approximately 10-15% difference) between dCO_2 removal efficiency as packing depth increased from 1 m depth to 2 m depth, which held for both seawater and freshwater, at all HLR tested, and all Air:Water ratios. For example, mean dCO_2 removal efficiency averaged approximately 63% across 1 m of packing depth and 74% across 2 m of packing depth in freshwater applied at a HLR of 1.03 m^3/min per m^2 and an Air:Water of 10:1. However, when Air:Water contacting was $\leq$ 2:1, dCO_2 removal efficiency across a column with 2 m packing depth was still 10% greater than the removal efficiency across a 1 m deep column, when all else was held equal. It is somewhat surprising that only a limited improvement in dCO_2 removal efficiency could be achieved by doubling the packing depth to 2 m, because the surface area and hydraulic retention time with 2 m packing depth were both twice what was provided with only 1 m of packing depth. However, stripping CO_2 from water can rapidly and significantly increase the partial pressure of CO_2 in the passing air, which reduces the driving force for mass transfer. In addition, the short retention time within the cascade aeration column likely provided insufficient time to allow the dehydration of carbonic acid, i.e., the rate limiting step, and reallocation of bicarbonate and carbonate (both nearly instantaneous) to take full advantage of gas transfer within the deeper columns. This would suggest that placing two 1 m tall packed columns in series, with a water reservoir between the two columns, could provide better dCO_2 removal than a single 2 m tall column.

Side-Stream Studies: Air:Water Contacting

The single largest factor influencing dCO_2 removal efficiency was the Air:Water contact ratio (Figures 2-5). The dCO_2 removal efficiency was approximately 12-24% higher at an Air:Water of 10:1 versus an Air:Water of 1:1 for seawater and freshwater, at both packing depths, and most HLR's, but not at the highest HLR of 4.1 m^3/min per m^2 plan area (100 gpm/ft^2). For example, mean dCO_2 removal efficiency averaged approximately 43% at an Air:Water of 1:1, 63% Air:Water of 10:1, and 67% Air:Water of 10:1 across a 1 m packing depth in freshwater applied at a HLR of 1.03 m^3/min per m^2 plan area (25 gpm/ft^2).

Side-Stream Studies: Hydraulic Loading Rate

Mean dCO_2 removal efficiency were fairly consistent, for a given condition over all hydraulic loading rates tested, i.e., 1.03, 2.05, 3.07 , and 4.1 m^3/min per m^2 plan area (25, 50, 75, and 100 gpm/ft^2), except at Air:Water contact ratios that were $\leq$ 2:1 (Figures 2-5). For exampled, the mean dCO_2 removal efficiency was consistent at approximately 55-60%, independent of HLR, across a 1 m packing depth at an Air:Water of 5:1 in freshwater. However, when Air:Water contact ratios were $\leq$ 2:1, mean dCO_2 removal efficiency were generally better at the lower HLR's tested (1.03 and 2.05 m^3/min per m^2 plan area), compared to the higher HLR (3.07 and 4.1 m^3/min per m^2 plan area). In addition, due to increasing air flow pressure drop at the highest HLR (i.e., 4.1 m^3/min per m^2 plan area), we were unable to supply enough air flow to test an Air:Water of 10:1 or 20:1. Thus, the most significant effect of HLR was likely due to the increased pressure requirements to force counter-current air ventilation. Thus, air stripping columns can be design at a HLR as high as 4.1 m^3/min per m^2 plan area (100 gpm/ft^2) without compromising mean dCO_2 removal efficiency, as long as a sufficiently powerful fan/blower is provided to overcome the increased head pressure created at higher Air:Water contacting.

Side-Stream Studies: Air Flow Pressure Drop

The pressure differential (per unit packing depth) on the flow of air passing through the packed columns increased with both increasing HLR and increasing Air:Water contacting (Figure 6). There was no clear difference in pressure drop between freshwater and seawater. However, much more powerful fans are required to supply the desired Air:Water contacting and overcome pressure drop across the packing when a higher HLR (e.g., 3.07 and 4.1 m^3/min per m^2 plan area) is selected. Thus, ventilation fans must be sized to provide for air flow against much higher back pressures when higher HLR's are used. For example, over 10 cm of air pressure is required for every 1 m of packing depth to achieve an Air:Water of > 5:1 at a HLR of 4.1 m^3/min per m^2 plan area, which is data collected on clean packing headloss. For a biofilm coated packing, backpressure and flooding conditions could create a pressure drop that is orders of magnitude greater than the clean packing headloss. Thus, even if a lower HLR is selected, blower capacity should be provided to account for 2-3 orders of magnitude higher pressure drops across the packed column. We suspect that the combination of high HLR (3-4 m^3/min per m^2 plan area) and the eventual biofouling of the packing have increased pressure drop requirement in cascade aeration columns and decreased air flow through the column (Air:Water contacting), which could significantly reduce CO_2 removal efficiency and allow higher dCO_2 concentrations to accumulate in the culture tank.

Full-Scale Studies

More dCO_2 was also removed under freshwater conditions than under seawater conditions from the full-scale stripping columns (Figure 7). As expected, CO_2 stripping increased in efficiency as the air:water increased. For each condition, the randomly packed NORPAC column produced more efficient removal of dCO_2 than the structurally packed Accu-Pac column. No packing yielded the lowest dCO_2 removal.

Seawater Frothing

No fish and no fish feed were used during this study. Thus, we discovered that clean seawater, when it does not contain low levels of oil from fish feed, will froth heavily and create a 2-phase flow as it passed through the cascade aeration column. This frothing nearly completely floods the packed column and creates significant problems. However, we found that adding only several hundred g of vegetable oil to the recirculating flow would prevent frothing of the clean water for over 24-hrs. Considerably more vegetable oil has to be added when the recirculating system is being cleaned, after fish are removed, because of the high level of particulate matter brushed from the surfaces increasing foam production.

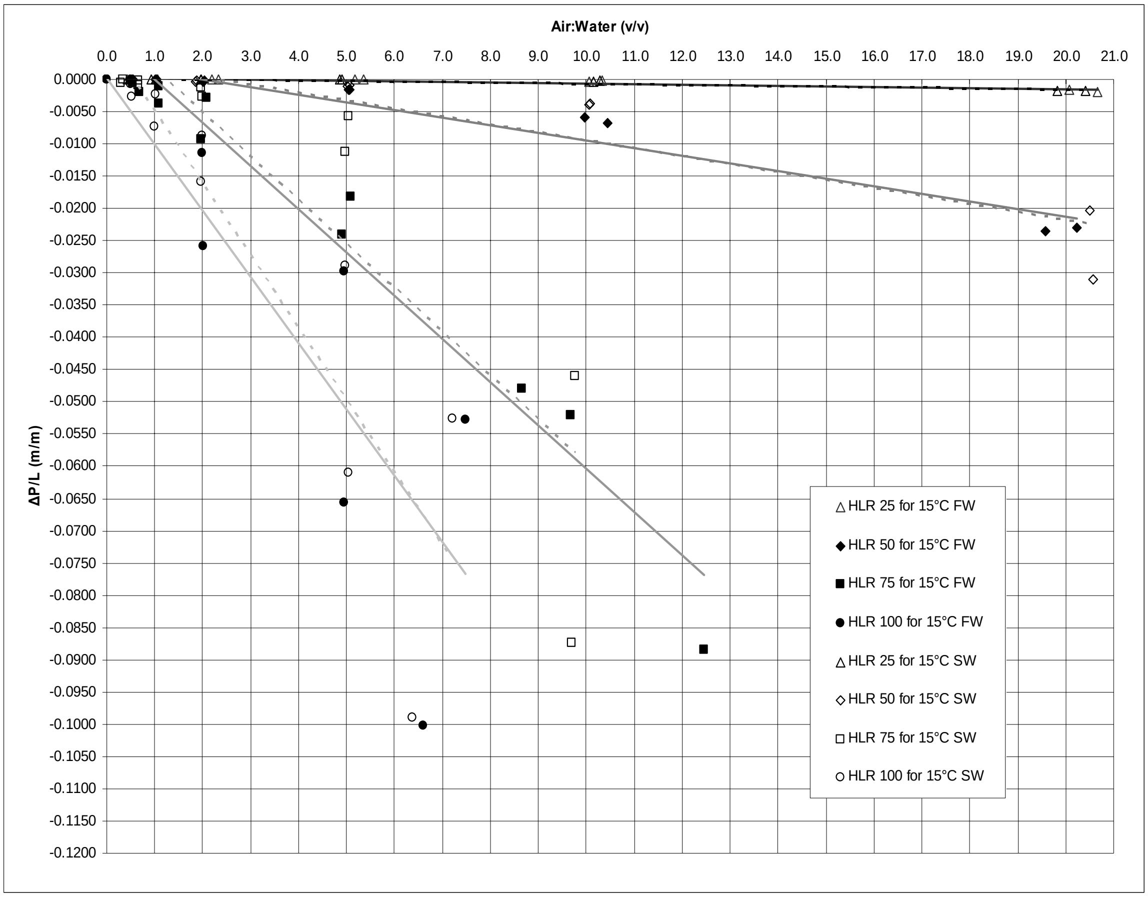

Fig. 6. Pressure differential per length of NORPAC media versus air to water loadings in side-stream system (solid line is freshwater; dashed line is 33 ppt).

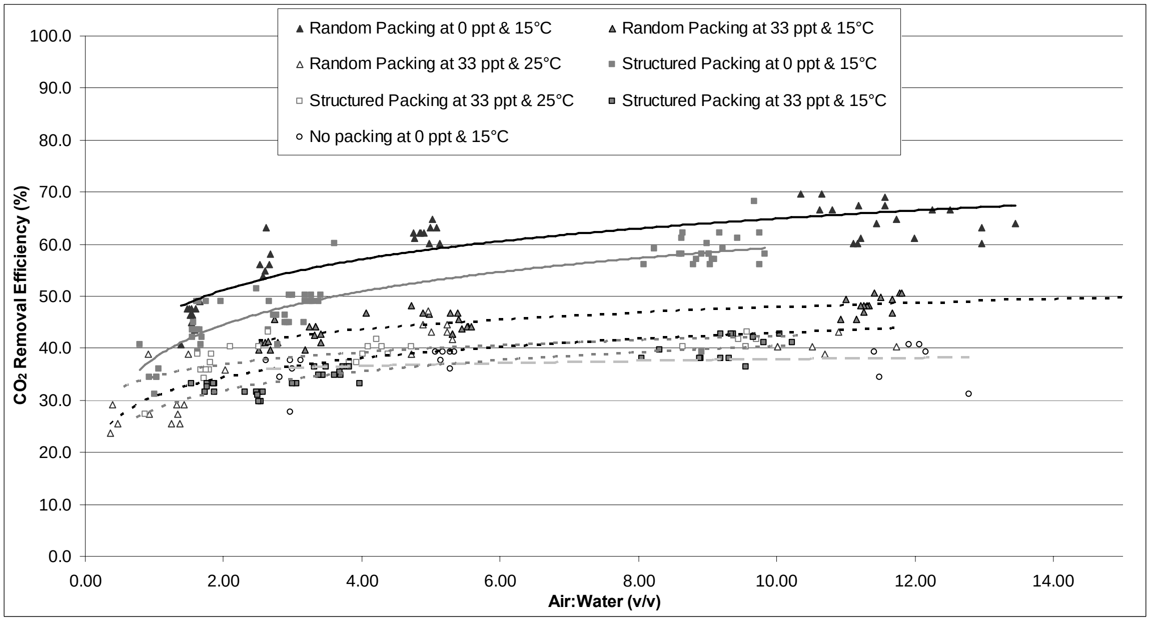

Fig. 7. Full-scale cascade column studies on carbon dioxide removal efficiencies as a function of Air:Water contacting (solid line is freshwater; dashed line is 33 ppt).

Design Summary

When a unit treatment process, such as a stripping column is designed, a steady state mass balance should be used to predict the expected water quality exiting a culture tank within a water recirculating system. The water quality exiting the culture tank is determined by unit process treatment efficiency each pass through the unit, waste production rate (which is directly proportional to feeding rate), and recirculating water flow rate (Summerfelt and Vinci, 2004); the make-up water exchange rate through the system only has minor influence on parameters such as dCO_2 or total ammonia nitrogen, unless water flushing is extremely high as is the case when biofilters are not used. The dCO_2 production rate is approximately equal to or a little larger than the dissolved oxygen consumption rate, i.e., approximately 0.4-0.6 kg of dCO_2 is produced for every 1 kg of feed consumed when salmonids are swimming in circular tanks. These calculations help ensure that the design will provide safe water quality for the fish when reared at maximum carrying capacity, i.e., feed loading.

For both freshwater applications (Summerfelt et al., 2003; Vinci et al., 2004) and seawater applications (Wolters et al., 2009), we typically design forced-ventilated packed columns for dCO_2 stripping using a 5 cm diameter random plastic packing, a packing depth of 1 m, a conservative HLR of approximately 2 m^3/min per m^2 plan area, and an Air:Water of 10:1, which is supplied by a blower that can overcome a pressure drop of 2-3 cm water head at the design air flow. However, to account for the 5-15% lower dCO_2 removal efficiency in seawater versus freshwater, we must increase the water flow rate through the stripping column and the hydraulic exchange rate through the culture tank in seawater systems to achieve the same dCO_2 concentration in the culture tank, when all else is equal.

The random packing provides a higher dCO_2 removal efficiency than the structured packing types that we tested. However, we only recommend using random packing in water recirculating systems that have both effective solids removal and biofiltration. Biosolids accumulation and heavy biofilm growth within random packing can plug the packing and cause flooding conditions that increase backpressure on the air supply, ultimately reducing air flow through the column. The structured packing is a more appropriate choice in heavily loaded warm water systems for species such as tilapia, sturgeon, or eel, where biofilm growth and particulate loading could be high.

Conclusions

Results indicate that random packing performed better than structured packing and no packing. In addition, dCO_2 removal efficiency in seawater is 5-15% lower versus freshwater for 1 or 2 m packing depth. Additionally, increasing packing depth from 1 m to 2 m was found to increase dCO_2 removal efficiency by only 10 to 15%. Air:Water contacting had the largest impact on dCO_2 removal efficiency, which were approximately 12-24% higher at an Air:Water of 10:1 versus an Air:Water of 1:1 for both seawater and freshwater, at both packing depths, and most HLR's. Mean dCO_2 removal efficiency were fairly consistent, for a given condition over all HLR tested, i.e., 1.03, 2.05, 3.07 , and 4.1 m^3/min per m^2 plan area (25, 50, 75, and 100 gpm/ft^2), except at relatively low Air:Water contact ratios (i.e., $\leq 2:1$). Pressure drop to air flow was increased significantly at the higher HLR tested (3.07 and 4.1 m^3/min per m^2 plan area) and at the higher Air:Water ratios($\geq 5:1$), which could be exacerbated if the random packing eventually became heavily biofouled and flooding occurred. Additionally, the two-phase flow created when seawater froths (typically when fish are not fed or little fish/vegetable oil is in the water) can create significant problems and decrease dCO_2 stripping.

Acknowledgements

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