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CARBON DIOXIDE REMOVAL RATE BY AERATION DEVICES IN MARINE FISH TANKS

Micha Eshchar*, Noam Mozes and Michael Fediuk

Israel Oceanographic and Limnological Research Ltd., National Center for Mariculture,
P.O. Box 1212, Eilat 88112, Israel

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Abstract

A procedure for measuring the transfer coefficient K_La for the removal rate of carbon dioxide by aeration devices in fish tanks was developed in the National Center for Mariculture in Eilat, Israel. The K_La for a paddlewheel and a submerged aerator were calculated, following experiments in which the aeration devices were used simultaneously for both carbon dioxide stripping and oxygenation. The paddlewheel was more efficient, with a transfer rate up to 1,200 g CO_2 per hour and a stripping efficiency of 1.2 kg CO_2 per kWh. In intensive sea bream culture, the calculated maximum feed load that a single paddlewheel aerator can support is 43.6 kg feed per day with an energy requirement of about 1.0 kWh per kg fish produced.

Introduction

One of the major production costs in recirculating aquaculture systems is the removal of metabolites from the water (Mozes et al., 2001a). Thus, the removal rate must be quantified to assess the economical feasibility of a particular system. The principal metabolites excreted by fish into the aqueous system are carbon dioxide (CO_2) and ammonia (NH_3). In sea bream (*Sparus aurata*) culture, fish may excrete approximately 15 moles, or 660 g, of CO_2 per consumed kilogram feed, depending on the fish weight and the water temperature (Lupatsch and Kissil, 1998).

In recent years, super-intensive fish production systems have begun to use pure oxygen enrichment, reducing the water-air interface available for gas exchange (Grace and Piedrahita, 1994; Fivelstad et al., 1999; Blancheton, 2000). As a result, CO_2 may accumulate in the water to toxic levels. In a

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* Corresponding author. Tel.: +972-8-6361430, fax: +972-8-6375761, e-mail: meschar@ocean.org.il

super-intensive marine recirculation system at the National Center for Mariculture (NCM) in Eilat, Israel, where fish density reached 94 kg/m^3, further intensification was limited by high CO_2 concentrations (Mozes et al., 2001b,c).

The accumulation of CO_2 to a high concentration is unlikely to occur in aquaculture systems where oxygen is supplied by aeration, e.g., the oxygen source is the atmosphere. The driving force for gas transfer (oxygen dissolution and CO_2 stripping) is the gradient between partial pressures across the atmosphere-water interface. Since the gradient for carbon dioxide is much higher than for atmospheric oxygen, aeration that meets the oxygen supply requirements therefore meets CO_2 removal requirements.

Safe CO_2 concentrations vary primarily with the species and size of the cultured fish and with water conditions such as dissolved oxygen (DO) and other parameters (Summerfelt et al., 2000a). Mature salmonids have been reported to tolerate dissolved CO_2 levels of up to 10-20 mg per liter, while catfish and tilapia may stand much higher concentrations (Wedenmeyer 1996 in Summerfelt et al., 2000a). The general recommendation is to maintain the CO_2 concentration at below 10 mg per liter (Loyless and Malone, 1998; Summerfelt et al., 2000a).

Unlike other soluble gases, CO_2 is part of the chemical equilibrium in the water. An elevated CO_2 concentration reduces the pH in the water and, for a given total carbonate carbon concentration, an elevated pH value reduces the CO_2 concentration (Stumm and Morgan, 1981). Consequently, CO_2 may be controlled by aeration for stripping, pH control, or both (Grace and Piedrahita, 1994; Loyless and Malone, 1997; Summerfelt et al., 2000a).

Low pH values may reduce nitrification biofilter performance (Bisogni and Timmons, 1994; Loyless and Malone, 1998). On the other hand, low pH values also reduce the fraction of un-ionized ammonia (NH_3) from the total ammonia nitrogen (TAN). Since NH_3 is far more toxic than ionized ammonia (NH_4^+), the effects of high carbon dioxide concentrations are not all negative. The flux of respiratory CO_2 to the water can be a means of controlling NH_3 at a safe level (Summerfelt et al., 2000b).

Several authors have studied the degasification capabilities of water treatment devices (Bouck et al., 1984; Colt and Bouck, 1984; Loyless and Malone, 1998). Some of the devices modeled and tested were airlift pumps, packed columns, screens, air-blowers, siphons and vacuum tubes. Most of these works regard degasification as a mere positive side effect of some other process (e.g., water delivery in the case of airlift pumps or aeration in the case of nitrification biofilters) or as a pre-treatment of water from natural sources, which may be gas-supersaturated. Loyless and Malone (1998) evaluated the gas transfer capabilities of airlift pumps to a degree that can be used for system design. They reported that the carbon dioxide stripping efficiency of airlift pumps ranges 20-130 g CO_2 per kWh. However, this value may be higher for other aeration devices such as pump sprayers, propeller diffusers and, in particular, paddlewheels. The rate and efficiency of CO_2 stripping by a paddlewheel aerator have not yet been documented though from the oxygen transfer data available for paddlewheels (Mozes and Argaman, 1994), it would tentatively appear that paddlewheels are the preferred stripping device.

The basic equation describing gas transfer across an air-liquid interface may be put in the form: $dc/dt = K_La(C_{eq} - C_{tank})$, where dc/dt = the change of concentration per time, C_{eq} = the equilibrium concentration ("saturation") of the gas in the liquid phase, C_{tank} = the actual concentration of the gas in the liquid phase, and K_La = an overall transfer coefficient per time, combining the diffusion coefficient, the liquid film thickness and the area per volume of the system in concern (Boyd and Watten, 1989).

Following oxygen transfer kinetics, the CO_2 transfer rate (CTR) for an aeration device and a specific system can be calculated as follows: $CTR = K_La \times V \times (C_{tank} - C_{eq}) \times \theta^{(T-20)}$ where V is the volume (m^3) of the tank or pond in consideration, C_{tank} is the actual CO_2 concentration (mg/l) in the tank, assuming it is well-mixed, C_{eq} is the concentration at equilibrium with the atmosphere, θ equals 1.024 and is added as a temperature correction factor (Boyd and Watten, 1989) and T is the temperature (°C).

The experiments described in this paper were carried out to determine the transfer coefficient K_La for CO_2 for two aeration devices operating in an open-to-air seawater fish tank. The K_La for dissolved oxygen (DO) was also determined. The purpose was to develop a method of determining K_La so that the CTR could be calculated for any given CO_2 concentration in the tank.

Materials and Methods

An outdoor 100 m^3 octagonal tank was filled with sea water, salinity 40 g/l total dissolved solids. One aeration device (either a paddlewheel or a submerged aerator) was installed about halfway between the center of the tank and its circumference. The CO_2 concentration was raised to 30-35 mg/l by shifting the carbonate carbon equilibrium down the pH scale. The initial water alkalinity and pH values were measured to compute the total carbonate carbon concentration (C_t). The amount of non-carbonic acid required to achieve a specific (lower) alkalinity was computed (Stumm and Morgan, 1981). For that alkalinity, assuming C_t does not change significantly, a higher concentration of CO_2 can be attained without the costly addition of gaseous CO_2 to the water.

The following chemicals were added to the water: hydrochloric acid, technical concentration of 30-32%; sodium sulfite, to deoxygenate the water; cobalt chloride, to catalyze deoxygenation (only in the first of each triplicate). The use of sodium sulfite and cobalt chloride for water deoxygenation was given by Boyd and Watten (1989) and reported by other sources (Tchobanoglous, 1991; Loyless and Malone, 1998) as part of a procedure for measuring oxygen transfer rates. It is assumed that chemicals used for deoxygenation or reducing pH do not interact to a degree that interferes with the results.

After about 10 minutes of agitating the water in the tank using two jet aspirators without air injection, the aerator was turned on. Water samples were taken at two opposite locations in the tank during the 90-minute test period. Water samples were measured for temperature, dissolved oxygen (DO; mg/l and % saturation) and pH. Samples for alkalinity were taken at the beginning and end of the test period and measured immediately after sampling. Temperature and DO were measured with an Oxyguard Handy Gama portable oxygen meter, pH with an Orion 8165BN pH electrode operated with an Orion 720A meter, and alkalinity was determined by using a titration procedure. CO_2 concentration was computed as a function of carbonate alkalinity and pH (Mehrbach et al., 1973; Stumm and Morgan, 1981).

For a repetition of the test, the aerator was turned off. Sodium bicarbonate (5 kg dissolved in some 20 l fresh water) was added to the tank to compensate for the carbon loss to the atmosphere. The test procedure was repeated six times to obtain three replicates of each device.

The tested devices were: (a) a paddlewheel aerator (Nan-Rong, Taiwan) with a nominal power of 0.75 kW (1.0 HP) and (b) a submerged aerator (Splash 2001, acqua&co, Italy) with a nominal power of 0.37 kW (0.5 HP). Nominal power is a figure supplied by the manufacturer and, in general, represents the output power of the engine. Measured power consumptions were higher - 1.0 kW for the paddlewheel and 0.63 kW for the submerged aerator.

Results

The oxygen and CO_2 concentrations where measured for each replication. The logarithm of the difference between the actual concentration (C_{tank}) and the concentration in equilibrium with the atmosphere (C_{eq}) was plotted against time (h). Examples of data plotting and K_La computation for one replicate of the paddlewheel aerator are shown in Figs. 1 and 2. The C_{eq} was assumed to be 0.5 mg/l (following Loyless and Malone, 1998). The resulting curve was approximated by a linear regression. The slope of the regression equals K_La for a particular setup.

Table 1 shows the average K_La values for

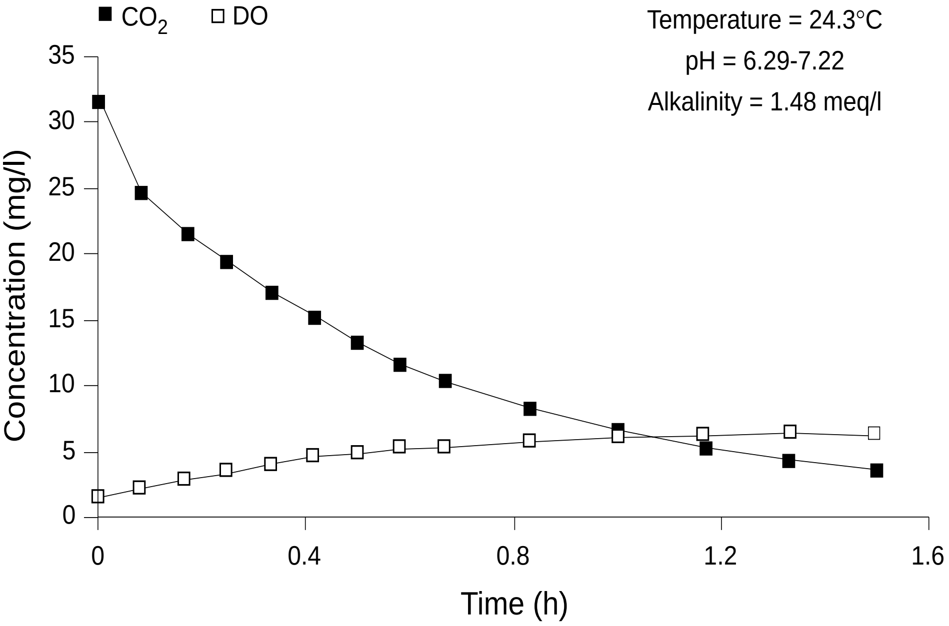

Fig. 1. Dissolved CO_2 and oxygen versus time in replicate number 1 for a paddlewheel aerator.

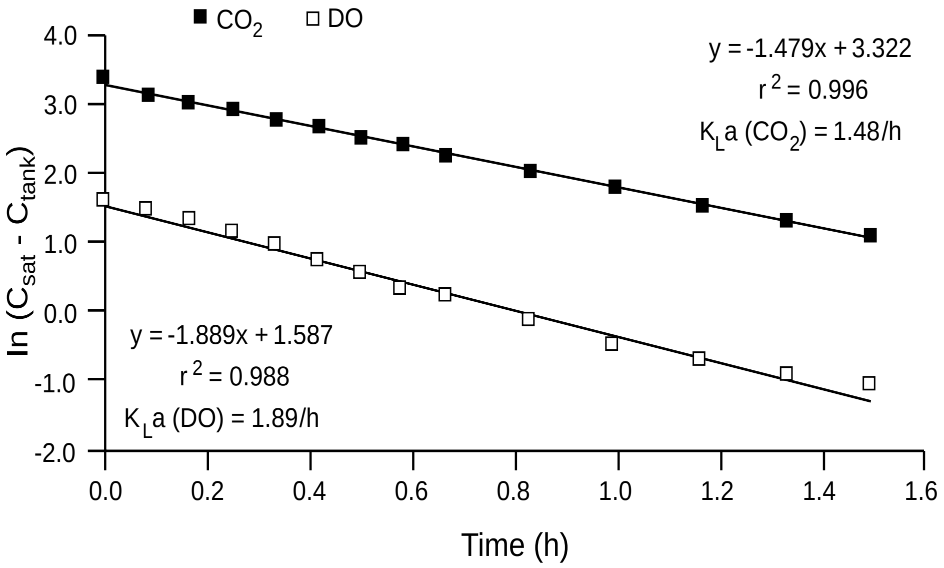

Fig. 2. Computation of the transfer coefficients KLa for the removal rate of CO_2 and oxygen dissolution for a paddlewheel aerator.

Table 1. K_La values for CO_2 stripping and dissolved oxygen (DO) absorption.

	K_La for CO_2			*K_La for DO*			*n*	*K_La*
	Average (1/h)	*SD (1/h)*	*CV (%)*	*Average (1/h)*	*SD (1/h)*	*CV (%)*		*Ratio CO_2/DO*
Paddlewheel	1.55	0.06	3.9	1.92	0.03	1.6	3	0.81
Submerged aerator	0.76	0.03	3.7	1.30	0.03	2.0	3	0.59

CV = Coefficient of variance = standard deviation/average

dissolved oxygen and CO_2 for each treatment, as well as the ratio between the two K_La values. The ratio between the K_La for CO_2 and the K_La for DO significantly differed between the tested aerators.

Discussion

Contrary to the assumption that the CO_2 removal rate can be estimated from the oxygen transfer rate of the aeration device (Colt and Bouck, 1984; Grace and Piedrahita, 1994), our results suggest that there is a wide range within which the K_La ratio (CO_2/DO) lies. Further, the kinetics of the two gas-exchange processes somewhat differ. For CO_2, it involves dehydroxylation of bicarbonate to aqueous carbon dioxide, especially in the liquid boundary layer where the carbon dioxide concentration is probably lower than it is in the bulk of the water. This reaction is not instantaneous and may lower the CO_2 removal rate (Stumm and Morgan, 1981). This phenomenon does not exist in the transfer process of a presumably inert gas such as oxygen. In all, the K_La for CO_2 should be measured rather than computed from the diffusivity ratio (Weast, 1973; Grace and Piedrahita, 1994).

The measured K_La for CO_2 can be used to calculate the removal rate of CO_2 (CTR) as a function of CO_2 concentration in the water, as well as the stripping efficiency which is the CO_2 removed per unit of energy input. Calculated CTR and stripping efficiency values are shown in Table 2, assuming that the CO_2 concentration in the water was 8 mg/l, the water salinity was 40 g/l total dissolved solids, the water temperature was 20°C, and power consumption was 1.0 kW for the paddlewheel and 0.63 kW for the submerged aerator. Given these conditions and at a CO_2 excretion rate of 660 g/kg feed, the amount of feed an aerator could support on a daily basis can be computed. The theoretical energy input for CO_2 stripping per kg fish produced (kWh/kg fish) can also be computed, assuming a feed conversion ratio of 1.8 kg feed/kg fish (Table 3).

Table 2. Computed CO_2 transfer rates (CTR) and stripping efficiency (SE)*.

	CTR (g/h)	*SE (kg/kW/h)*
Paddlewheel	1,200	1.20
Submerged aerator	570	0.90

* Culture conditions: CO_2 concentration in the water = 8 mg/l CO_2, water salinity = 40 g/l total dissolved solids, water temperature = 20°C, power consumption was 1.0 kW for the paddlewheel and 0.63 kW for the submerged aerator.

In the grow-out systems at NCM, where paddlewheel aerators are used for CO_2 stripping (Mozes et al., 2002), recent measurements have confirmed predictions of CTR and CO_2 concentrations in a sea bream culture system. Our current work focuses on developing a control model for pH and carbonate carbon in a grow-out system.

Table 3. Daily feed load* and theoretical energy demand of the aeration devices in a sea bream culture system.

	Daily feed load (kg feed/day)	*Energy demand (kWh/kg fish)*
Paddlewheel	43.6	0.99
Submerged aerator	21	1.32

* Computed according to a feed conversion ratio 1.8:1.

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