Aeration of Water Supplies for Fish Culture in Flowing Water

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ABSTRACT: An analytical approach to the reaeration of flowing water for aquaculture is presented, together with a rational method for the assignment of dissolved oxygen minima on the basis of respiratory characteristics of fish. Methods for calculation of expected oxygen transfer capabilities of gravity devices and mechanical units are given.

The water requirements for intensive fish culture with respect to the oxygen consumption of fish have been widely documented (Haskell 1955; Willoughby 1968; Piper 1970; Westers 1970; Liao 1971; Westers and Pratt 1977) and the managers of modern hatcheries generally have a working knowledge of this information. The extent to which water can be reused before intolerable levels of un-ionized ammonia accumulate is similarly well understood (Westers and Pratt 1977). Quantitative knowledge concerning the transfer of atmospheric oxygen to water in which the dissolved oxygen (DO) level has been reduced below the equilibrium concentration is required for successful fish culture. In this paper an analytical approach to the aeration of flowing water is offered.

In contrast to the conditions for intensive husbandry of terrestrial animals, in fish farming the supply of the oxygen carrier, water, is limited. Therefore, the first consideration in evaluating a water supply for aquaculture is its volume (Haskell 1955; Willoughby 1968; Piper 1970; Westers 1970; Liao 1971; Westers and Pratt 1977). The fish production that a given volume of water can support depends on the amount of DO in the water, the oxygen consumption rate of the fish, and the efficiency with which fish can extract DO from the water.

Solubility of Oxygen in Water

Although oxygen occupies nearly 21% of the atmosphere by volume, it is only sparingly soluble in water. As with all dissolved gases, its solubility in water decreases as the temperature increases, as atmospheric pressure decreases, or both. Cold water can therefore hold more DO than warm water, and at sea level water can hold more DO than at higher elevations (Table 1). Most fish culturists use similar tables with correction factors for different elevations. I believe a more precise method for determining the solubility of oxygen in water of any temperature at any altitude would be by calculation. Several authors provide empirical formulae for the determination of the equilibrium concentration of oxygen in water (Truesdale et al. 1955; Whipple et al. 1969; Liao 1971) but the expression given by Truesdale et al. (1955) gives the most widely accepted values:

$$Ce = 14.161 - 0.3943T + 0.007714T^2 - 0.0000646T^3$$

where Ce = equilibrium concentration of oxygen (milligrams per liter) at a pressure of 760 mm of mercury, and T = water temperature in degrees Celsius.

Table 1. Equilibrium concentrations (Ce) of dissolved oxygen in water at various temperatures and three elevations (after Truesdale et al. 1955; Liao 1971).

Temperature (°C)	Ce (mg/l) of DO at elevations[a] of		
	0	500	1000
0	14.16	13.29	12.51
2	13.40	12.58	11.84
4	12.70	11.92	11.23
6	12.05	11.31	10.66
8	11.47	10.76	10.13
10	10.92	10.25	9.65
12	10.43	9.78	9.22
14	9.98	9.36	8.82
16	9.56	8.97	8.45
18	9.19	8.62	8.12
20	8.84	8.30	7.82
22	8.53	8.00	7.54
24	8.25	7.74	7.29
26	7.99	7.50	7.06
28	7.75	7.27	6.85
30	7.53	7.07	6.65

[a] Meters above sea level.

The most accurate way to correct for pressure is to measure the barometric pressure when the oxygen solubility is to be calculated. The pressure correction factor then is P/760, where P = measured barometric pressure in millimeters of mercury. If a barometer is not available, elevation can be used as an approximation of barometric pressure. Liao (1971) provides the following pressure correction factor: 760/(760 + E/32.8), where E = elevation in feet above sea level (since this is an empirical formula, the original English units are retained).

Water containing DO at the equilibrium concentration is saturated with oxygen. The amount of DO in water is almost universally expressed in concentration units (milligrams per liter), but for fish respiration problems it is more usefully expressed as pressure in millimeters of mercury, which is equivalent to expressing the amount of DO as percent of saturation. Since standard atmospheric pressure is 760 mm Hg and the atmosphere contains 20.946% oxygen by volume, the tension of oxygen in air at standard conditions is 159.2 mm Hg, in accordance with Dalton's Law. The oxygen tension in air at any barometric pressure is that pressure (in millimeters of mercury) multiplied by the decimal fraction 0.20946. To calculate the oxygen tension in water, the percent of saturation (measured DO concentration divided by the calculated equilibrium concentration) is multiplied by the tension of oxygen in air at the site. If a barometer is not available the average barometric pressure can adequately be estimated if the elevation is known. Thus, P/760 = 760/(760 + E/32.8), where P = average atmospheric pressure in millimeters of mercury and E = elevation in feet above sea level.

Oxygen Requirements of Fish

In respiration fish blood picks up oxygen and releases carbon dioxide at the gills and picks up carbon dioxide and releases oxygen at the tissues. The efficiency at which the blood combines with oxygen and carbon dioxide at different tensions therefore determines the reaction of the fish to reduced DO concentrations in the water. Brungs (1971), in a carefully controlled long-term study, found that the growth of fathead minnows (*Pimephales promelas*) was reduced at all DO concentrations below saturation. Andrews et al. (1973) reported that channel catfish (*Ictalurus punctatus*) ate less and grew more slowly at 60% saturation than at 100% saturation. The DO tension in fish culture systems cannot be kept at the saturation level because fish respiration continuously depletes the oxygen present in the water. Minimum oxygen tensions acceptable for adequate growth and health of the fish should be defined as aquaculture facility design criteria.

Fish in warm water can tolerate lower concentrations of DO than can fish in cold water because the tension of a given concentration of oxygen becomes greater as the solubility decreases. This relation has been verified by field observations from the literature. Smith and Piper (1975), Piper (1970), Willoughby (1968), and Westers and Pratt (1977) suggested that aquaculture facilities for trout be designed so that the fish are exposed to a minimum DO concentration of 5.0 mg/L. Buss and Miller (1971) called for aeration at trout hatcheries when the DO concentration was predicted to fall below 5.0–7.0 mg/L. Burrows and Combs (1968) reported that salmon growth was reduced when the DO concentration fell below 6.0 mg/L. Warmwater fish are reported to be able to survive prolonged exposures as low as 1.0 mg/L, but in the range of 1.0–5.0 mg/L growth is reduced (H. S. Swingle, Auburn University, unpublished data). Carlson et al. (1980) found that at 25° C the growth of channel catfish was reduced at a constant DO exposure of 3.5 mg/L but not at 5.1 mg/L.

Piper (1970) reported a water temperature of 10° C and an elevation of 1,500 m above sea level for his station. At this site a minimum DO of 5.0 mg/L is probably a reasonable design criterion for trout culture. A rational basis for assigning DO minima to warmwater aquaculture systems could thus be the degree of oxygen tension in the water supply. For example, the average oxygen tension of water at 10° C, 1,500 m above sea level and a DO concentration of 5.0 mg/L is 72.8 mm Hg, corresponding to a concentration of 3.44 mg/L at a water temperature of 30° C at standard pressure. This analysis compares with that of Downey and Klontz (1981), who recommended a minimum DO tension of 90 mm Hg.

When fish respiration has reduced the DO tension to about 70–90 mm Hg, water can no longer be used for fish culture because at this pressure the fish cannot efficiently extract the oxygen present in the water. The water must be reconditioned by aeration (i.e., more oxygen must be dissolved into the water) if it is to be of further use for fish production.

The extent to which water can be reconditioned with aeration as the only treatment measure depends on the accumulation of un-ionized ammonia. The number of water uses permissible before un-ionized ammonia reaches unacceptably high levels depends on water temperature, feeding rate, protein content of the diet, and especially on the pH of the water.

Aeration Technology

Gravity Devices

Transfer of oxygen into water is a three-stage process in which gaseous oxygen is transferred to the surface film, diffuses through the surface film, and finally moves into the liquid bulk by convection (Wheaton 1977). The rate of oxygen transfer depends on the surface area over which transfer occurs. Oxygen transfer in aquaculture systems where water is quiescent or moving in laminar flow is too slow to be an important source of DO for fish respiration unless the area of air-water interface is significantly increased by artificial turbulence or agitation. Aeration of water streams used for aquaculture can be accomplished by gravity where the energy released when water loses altitude is used to increase the area of air-water interface or by mechanical devices that spray water into the air or pump air into the water (Wheaton 1977). The most logical means of improving oxygen regimes of cultured fish is by gravity fall of water between production units, which can be provided by the topography at the facility. The extent to which water is reaerated by gravity is a fundamental concern for practical fish culture in flowing water.

Haskell et al. (1960) compared aeration by water passage over a simple weir (Fig. 1A) with that obtained by flow over a splashboard (Fig. 1B) that broke up the water fall part way down, and that from flows over various screens and slat arrangements at the dam. Chesness and Stephens (1971) evaluated several devices for increasing oxygen transfer over a gravity fall, including a splashboard, an inclined sheet of corrugated roofing material (Fig. 1C), a similar corrugated sheet pierced with holes (Fig. 1D), and an open stairstep device referred to as a lattice (Fig. 1E). Tebbutt (1972) studied aeration down closed stairstep arrangements of various heights that he called cascades (Fig. 1F).

The following equation (Downing and Truesdale 1955) can be used to evaluate and compare gravity aeration devices:

$$E = 100 \times \frac{\text{actual increase in DO}}{\text{possible increase in DO}}$$

or E = 100 x (Cb–Ca)/(Ce–Ca), where E = efficiency, Cb = DO below the device, Ca = DO above the device, and Ce = equilibrium concentration (all in milligrams per liter). Selected data on measured efficiencies of some gravity aerators over various distances of water fall are presented in Table 2.

Practical application of this information requires rearrangement of the efficiency equation to solve for the expected DO concentration below an aeration device of a known efficiency:

$$Cb = \frac{E\,(Ce - Ca)}{100} + Ca$$

The use of this equation is best illustrated by example. Suppose there is a 30.5-cm drop between two ponds, with a simple weir separating them. If the water temperature is 10° C and the elevation is 183 m above

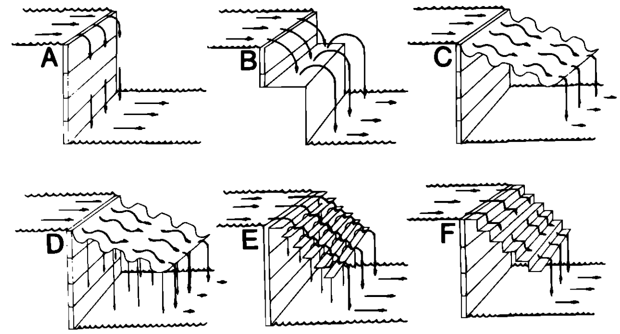

Fig. 1. Diagrams of gravity aerators. A, Simple weir (Haskell et al. 1960; Chesness and Stephens 1971); B, splashboard (Haskell et al. 1960; Chesness and Stephens 1971); C, inclined corrugated sheet (Chesness and Stephens 1971); D, inclined corrugated sheet with holes (Chesness and Stephens 1971); E, lattice aerator (Chesness and Stephens 1971); and F, cascade aerator (Tebbutt 1972).

Table 2. Selected data on measured efficiencies of some gravity aerators over various distances of water fall.

Device and distance of water drop (cm)	Efficiency (%)
Simple weir	
22.9[a]	6.2
30.5[b]	9.3
61.0[b]	12.4
Inclined corrugated sheet[b]	
30.5	25.3
61.0	43.0
Inclined corrugated sheet with holes[b]	
30.5	30.1
61.0	50.1
Splashboard	
22.9[a]	14.1
30.5[b]	24.1
61.0[b]	38.1
Lattice[b]	
30.5	34.0
61.0	56.2
Cascade[c]	
25.0	23.0
50.0	33.4
75.0	41.2
100.0	52.4

[a] Haskell et al. (1960).
[b] Chesness and Stephens (1971).
[c] Tebbutt (1972).

sea level, by using the equation of Truesdale et al. (1955) and Liao's (1971) pressure correction factor, we find that the solubility of DO will be

$$Ce = 14.161 - 0.3943(10) + 0.007714(10)^2 - 0.0000646(10)^3 \times \frac{760}{760 + 600/32.8}$$

or Ce = 10.67 mg/L. If the fish loading in the upstream pond is such that the DO concentration is depressed to 5.0 mg/L, Ca will be 5.0. We know that a 30.5-cm fall over a simple weir is 9.3% efficient (Table 2). Using the equation of Downing and Truesdale (1955), we can determine the DO below the weir (Cb) as follows:

$$Cb = \frac{9.3\ (10.67 - 5.0)}{100} + 5.0$$

or Cb = 5.53 mg/L. However, if a lattice structure (Chesness and Stephens 1971) is constructed between the ponds, the efficiency rating of the 30.5-cm fall will rise to 34%, so

$$Cb = \frac{34\ (10.67 - 5.0)}{100} + 5.0$$

or Cb = 6.93 mg/L. Although the estimated benefit of this gravity aeration device is considerable, most aquaculture sites require mechanical aeration to realize the full production potential of their water supplies.

Mechanical Devices

Mechanical units that agitate the water surface are normally used in flowing water aquaculture systems because of their convenience and ease of installation. Aerators are evaluated and compared on the basis of their ability to transfer oxygen to water. Tests are conducted under standard conditions of 760 mm Hg pressure, 20° C temperature, and zero DO in the water to be aerated. The amount of oxygen added to the water in a given amount of time under a certain power level is measured. The kilograms of oxygen per shaft kilowatt per hour (kg/kW•h) is given by the aerator manufacturer as a measure of its efficiency and can be used to compare units. Actual oxygen transfer depends on the oxygen concentration gradient: as saturation is approached an increasing amount of power is required per unit of DO transferred. Reaeration above 95% of saturation can seldom be justified on a cost basis (Mayo 1979). Westers and Pratt (1977) list 90% of saturation as a reasonable design criterion for reaerated water. Since aquaculture systems operate at the relatively high DO minima of 3–7 mg/L, actual transfer rates will be less than those determined under standard conditions; thus these figures may not be used as design criteria.

Surface aerators are generally rated to transfer 1.9–2.3 kg/kW•h under standard conditions (Eckenfelder 1970). Whipple et al. (1969) found that mechanical aerators in polluted rivers generally provided oxygen transfer rates of 0.61 kg/kW•h or less, but their test water supply was higher in oxygen demand than is usual for aquaculture effluents. Soderberg (1980) reported an average transfer rate of 0.83 kg/kW•h in static-water trout ponds where the fish were heavily fed and aeration began when DO tensions reached 70 mm Hg. Aeration of flowing water should be more efficient because processed water is continually being replaced from upstream rather than being recirculated around the unit, as might occur in static water conditions. To estimate aeration requirements, we may use a conservative value such as 0.6 kg/kW•h or we may estimate oxygen transfer by using the formula presented by Whipple et al. (1969):

$$RT = RS\ \frac{(Ce_t - Ca)\ (1.025^{T-20})\ (0.85)}{Ce_{20}}$$

where RT = actual oxygen transfer, RS = oxygen transfer under standard conditions, Ce_t = equilibrium concentration of DO at aeration site, Ca = DO above aerator, Ce_{20} = equilibrium concentration of DO under standard conditions, and T = water temperature in Celsius degrees.

The following example illustrates the use of this formula. Suppose an aerator is rated by the manufacturer to transfer 2.0 kg O_2/kW•h under standard conditions. The actual oxygen transfer at a site where the water temperature is 10° C, barometric pressure is 725 mm Hg, and the DO in the water to be aerated is 5.0 mg/L, may be estimated as follows:

$$RS = 2.0\ \text{kg/kW•h}$$

$$Ce_t = 14.161 - 0.3943\ (10) + 0.007714\ (10)^2 - 0.0000646\ (10)^3 \times 725/760 = 10.42\ \text{mg/L}$$

$$Ca = 5.0\ \text{mg/L}$$

$$Ce_{20} = 14.161 - 0.3943\ (10) + 0.007714\ (20)^2 - 0.0000646\ (20)^3 = 8.84\ \text{mg/L}$$

$$T = 10°C$$

$$RT = 2.0\ \frac{(10.42 - 5.0)\ (1.025^{10-20})\ (0.85)}{8.84}$$

and, thus, RT = 0.81 kg/kW•h.

When the actual oxygen transfer rate (RT) has been estimated, an estimate of the aeration capability of a particular unit and set of conditions can readily be obtained. For the above example, suppose that a 1.0-kW unit will be used in a water flow of 4,000 L/min. The DO concentration below the aerator (Cb) is calculated as follows:

$$Cb = Ca + \frac{0.80\text{ kg}}{\text{kW•h}} \times \frac{10^6\text{ mg}}{\text{kg}} \times 1.0\text{ kW} \times \frac{\text{min}}{4{,}000\text{ L}} \times \frac{\text{h}}{60\text{ min}}$$

$$Cb = 5.0 + 3.38 = 8.38\text{ mg/L}$$

A more practical application of this knowledge might be to size an aerator for a particular job. Suppose that for the same example a unit that will return the DO to 90% of saturation is desired. The amount of oxygen needed would be

$$[(0.9)(10.42) - (5.0)]\text{mg/L} \times \frac{\text{kg}}{10^6\text{ mg}} \times \frac{4{,}000\text{ L}}{\text{min}} \times \frac{60\text{ min}}{\text{h}} = \frac{1.05\text{ kg}}{\text{h}}$$

The size of the unit required (in kilowatts of shaft power) would be

$$\frac{1.05\text{ kg}}{\text{h}} \times \frac{\text{kW•h}}{0\ 81\text{ kg}} = 1.3\text{ kW}$$

The final step in evaluating an aeration program is to compare the cost of purchasing and operating the equipment with the potential value of the increased fish production anticipated. The relation between shaft power and brake power is given by the motor manufacturer as the efficiency, and this can be used to estimate energy consumption. For example, a 1.30-kW motor that is 75% efficient would draw 1.73 kW of energy. If run continuously on electrical power that was purchased for $0.10/kW•h, the unit would cost $124.80 per month to operate.

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