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Pond water aeration systems

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Abstract

During the past decade, pond aeration systems have been developed which will sustain large quantities of fish and invertebrate biomass. These aeration systems are modifications of standard wastewater aeration equipment. Aeration-performance testing has been important in selecting design features to provide cost-effective yet efficient aquaculture pond aerators. Paddlewheel aerators and propeller-aspirator-pumps are probably most widely used. Amounts of aeration vary from as little as 1–2 kW ha^{-1} in some types of fish culture to as much as 15 or 20 kW ha^{-1} in intensive culture of marine shrimp. Calculations suggest that about 500 kg additional production of fish or crustaceans can be achieved per kW of aeration. Aerators usually are positioned in ponds to provide maximum water circulation. This practice can result in erosion of pond bottoms and inside slopes of embankments, and accumulation of sediment piles in central areas of ponds where water currents are weaker. Recent studies suggest that the use of heavy aeration to provide the greatest possible production is less profitable than moderate aeration to improve water quality and enhance feed conversion efficiency. Automatic devices to start and stop aerators in response to daily changes in dissolved oxygen (DO) concentrations are improving, but they are expensive and not completely reliable. Augmentation of natural supplies of DO in ponds often is necessary to prevent stress or mortality of fish and crustaceans when DO concentrations are low. Several procedures have been used in attempts to increase DO concentrations in ponds. These methods include exchanging part of the oxygen-depleted pond water with oxygenated water from a well, pond, or other source, application of fertilizer to stimulate oxygen production by photosynthesis of aquatic plants, additions of compounds which release oxygen through chemical reactions, release of pure oxygen gas into pond waters, and aeration with mechanical devices which either splash water into the air or release bubbles of air into the water. Water circulation devices also enhance DO supplies in ponds by mixing DO supersaturated surface waters with deeper waters of lower DO concentration. This reduces the loss of oxygen from ponds by diffusion. Also, when surface waters are not

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saturated with DO, water circulation causes surface disturbance and enhances oxygen absorption by the water. Mechanical aeration is by far the most common and usually the most effective means of increasing DO concentrations in ponds. In semi-intensive aquaculture, aeration is applied on an emergency basis. Farmers check DO concentrations, and when low concentrations of DO are expected, aeration is applied. In intensive aquaculture, aeration is applied each night or even continuously. The purpose of this article is to summarize the 'state of the art' of mechanical aeration of aquaculture ponds.

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1. Principles of aeration

The air contains 20.95% oxygen. At standard barometric pressure (760 mmHg), the pressure or 'tension' of oxygen in air is 159 mmHg (760×0.2095). The pressure of oxygen in air drives oxygen into water until the pressure of oxygen in water is equal to the pressure of oxygen in the atmosphere. When pressures of oxygen in water and atmosphere are equal, net movement of oxygen molecules from atmosphere to water ceases. The water is said to be at equilibrium, or at saturation, with dissolved oxygen (DO) when the oxygen pressure in the water equals the pressure of oxygen in the atmosphere. The DO concentration in water at saturation varies with temperature, salinity, and barometric pressure. As water temperature increases, DO concentration at saturation decreases (Table 1). At a given temperature, the DO concentration at saturation increases in proportion to increasing barometric pressure. The concentration of DO at saturation decreases with increasing salinity.

Plants growing in water produce oxygen by photosynthesis, and during daylight hours plants in aquaculture ponds often produce oxygen so fast that DO concentration in water rises above saturation. Water containing more DO than saturation for the existing temperature and pressure is said to be supersaturated with DO. When water is supersaturated with DO, the pressure of oxygen in water is greater than the pressure of oxygen in the atmosphere.

Water also may contain less DO than expected at saturation. At night, respiration by fish, plants, and other pond organisms causes DO concentrations to decline. Thus, during warm months, night-time DO concentrations in ponds often are below saturation. In production ponds, DO may decrease by 5–10 mg l^{-1} at night, and in un-aerated ponds, DO concentrations at sunrise may be less than 2 mg l^{-1} (Boyd, 1990). Such low DO concentrations can cause stress or mortality in culture species. In cool weather, the abundance of plants decreases, the respiration rate of the pond biota declines, the ability of water to hold oxygen increases, and night-time DO concentrations are higher than in warm months.

When water is below saturation with DO, there is a net movement of oxygen molecules from atmosphere to water. At DO saturation, the number of oxygen molecules leaving the water surface equals the number entering (no net movement). There is net movement of oxygen molecules from water to atmosphere when water is supersaturated with DO. The greater the difference between the pressure of

Table 1
The solubility of oxygen (mg l^{-1}) in water at different temperatures and salinities from moist air with pressure of 760 mm Hg

Temperature (°C)	Salinity (ppt)								
	0	5	10	15	20	25	30	35	40
0	14.621	14.120	13.636	13.167	12.714	12.277	11.854	11.445	11.051
5	12.770	12.352	11.947	11.554	11.175	10.807	10.451	10.107	9.774
10	11.288	10.933	10.590	10.257	9.934	9.621	9.318	9.024	8.739
15	10.084	9.780	9.485	9.198	8.921	8.651	8.389	8.135	7.888
20	9.092	8.828	8.572	8.323	8.081	7.846	7.617	7.395	7.180
25	8.263	8.032	7.807	7.588	7.375	7.168	6.967	6.771	6.581
30	7.558	7.354	7.155	6.961	6.772	6.589	6.410	6.236	6.066
35	6.949	6.767	6.590	6.417	6.248	6.084	5.924	5.768	5.617
40	6.412	6.249	6.090	5.935	5.783	5.636	5.492	5.352	5.215

After Benson and Krause (1984).

oxygen in water and atmosphere, the larger the movement of oxygen molecules from atmosphere to water or vice versa.

The saturation of DO concentration for a particular water temperature and barometric pressure may be calculated as follows:

$$C_S = C_{tab} \times \left(\frac{BP - P_{H_2O}}{760 - P_{H_2O}} \right) \tag{1}$$

where C_s is DO concentration at saturation (mg l^{-1}); C_{tab} is DO concentration at the existing temperature and standard barometric pressure (Table 1) (mg l^{-1}); and BP is barometric pressure (mm Hg).

However, for practical purposes, the contribution of vapor pressure can be ignored and Eq. (1) can be written as:

$$C_S = C_{tab} \times \frac{BP}{760} \tag{2}$$

The percentage saturation of water with DO may be estimated as:

$$S = \frac{C_m}{C_s} \times 100 \tag{3}$$

where S is the percentage saturation with DO and C_m is the measured concentration of DO in water (mg l^{-1}).

The pressure or tension of DO in water can be estimated as:

$$P_{O_2} = \frac{C_m}{C_s} \times 0.2095 \times 760 \tag{4}$$

where P_{O_2} is DO pressure in water (mm Hg). The DO pressure in water can be thought of as the equivalent pressure of oxygen in the atmosphere necessary to hold the observed concentration of DO in the water.

The oxygen deficit is the difference between the measured DO concentration and the DO concentration at saturation. That is:

$$OD = C_s - C_m \tag{5}$$

where OD is the oxygen deficit (mg l^{-1}).

The value for OD will be positive when the DO concentration in water is below saturation and negative when the DO concentration in water is greater than saturation. The value of OD may be expressed as a pressure difference if C_s and C_m are in pressure rather than concentration. Oxygen moves from atmosphere to water and vice-versa by diffusion, and the rate of oxygen diffusion depends upon the oxygen deficit. The oxygen deficit is the driving force causing oxygen to enter or exit the water surface.

At a particular oxygen deficit, the amount of oxygen that can enter a given volume of water in a specified time interval depends upon the area of water surface relative to water volume. The amount of oxygen entering increases with greater surface area. Oxygen from the atmosphere readily enters the surface film, and the DO concentration in the surface film quickly reaches saturation. The movement of oxygen from the surface film throughout the entire volume of water is much slower than the initial entry of oxygen into the surface film. Thus, in still water, the surface film quickly saturates with DO, and the rate of diffusion of oxygen into water becomes slow, because no more oxygen can diffuse from atmosphere into the surface film until some of the oxygen in the surface film diffuses into the greater volume of water.

The importance of water mixing (turbulence) on oxygen transfer between the atmosphere and water should be apparent. Mixing makes the surface rough and thereby increases surface area. Mixing also causes mass transfer (convection) of water and DO from the surface to other places within the water body. Mixing of pond water by wind favors diffusion of oxygen, so more oxygen diffuses into or out of pond water on a windy day than on a calm day. Boyd and Teichert-Coddington (1992) presented a technique for estimating the influence of wind velocity on oxygen transfer between air and surface water of aquaculture ponds.

Aerators influence the rate of oxygen transfer from air to water by increasing turbulence and surface area of water in contact with air. Aerators are of two basic types: splashers and bubblers. An example of a splasher aerator is a paddle wheel aerator. It splashes water into the air to affect aeration. Splashing action also causes turbulence in the body of water being aerated. Bubbler aerators rely upon release of air bubbles near the bottom of a water body to affect aeration. A large surface area is created between air bubbles and surrounding water. Rising bubbles also create turbulence within a body of water.

Circulation of pond water by aerators is an additional benefit of aeration for several reasons: (1) oxygenated water moves across the pond and fish can more readily find zones with adequate DO concentrations; (2) without constant movement of well-oxygenated water away from the aerator, aeration will increase DO concentrations in the vicinity of the aerator and greatly reduce oxygen-transfer efficiency; and (3) mixing of pond water by aerators reduces vertical stratification of temperature and chemical substances.

2. Types of aerators

Aquaculture aerators are similar to those used in wastewater aeration. However, wastewater aerators generally are too expensive for use in aquaculture, and less expensive modifications of wastewater aerators have been developed for aquaculture. All basic types of mechanical aerators have been used in aquaculture, but vertical pumps, pump sprayers, propeller-aspirator-pumps, paddle wheels, and diffused-air systems are most common in pond aquaculture. Gravity aerators, nozzle aerators, and pure oxygen contact systems are used in fish and crustacean hatcheries and in highly intensive production systems such as raceways and tanks. However, these kinds of aerators have not been used much in ponds and will not be discussed here.

2.1. Vertical pumps

A vertical pump aerator consists of a submersible, electric motor with an impeller attached to its shaft. The motor is suspended by floats, and the impeller jets water into the air to affect aeration. A typical vertical pump aerator is shown in Fig. 1. These aerators are manufactured in sizes ranging from less than <1 to >50 kW, but units for aquaculture are seldom larger than 2 kW. Units for aquaculture have high speed impellers, which rotate at 1730 or 3450 rpm.

2.2. Pump sprayers

A pump sprayer aerator consists of a high pressure pump that discharges water at high velocity through one or more orifices to affect aeration (Fig. 2). Many different designs have been used for the discharge orifices. The simplest procedure is to discharge the water directly from the pump outlet. The most complex method is to discharge the water from small orifices in a manifold that is attached to the pump outlet. Aerator sizes range from 2 to 15 kW, and the impeller speeds are from 500 to 1000 rpm.

2.3. Propeller-aspirator-pumps

The primary parts of a propeller-aspirator-pump aerator are an electric motor, a hollow shaft which rotates at 3450 rpm, a hollow housing inside which the rotating shaft fits a diffuser, and an impeller attached to the end of the rotating shaft (Fig.

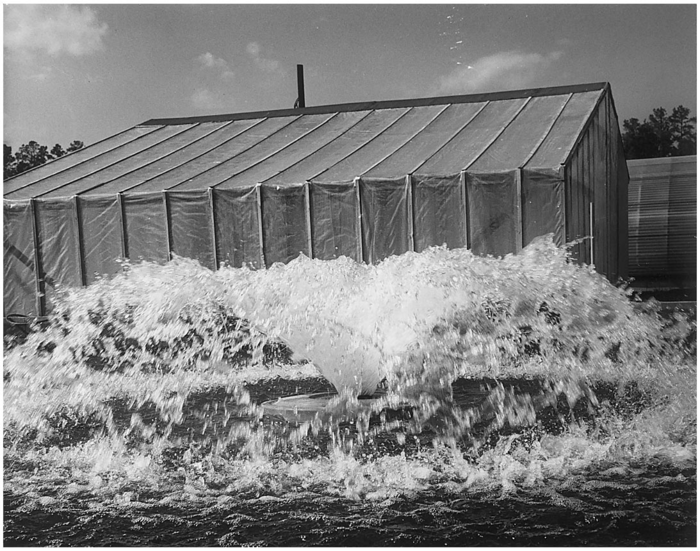

Fig. 1. A vertical pump aerator.

Fig. 2. A pump sprayer aerator.

3). In operation the impeller accelerates water to a velocity high enough to cause a drop in pressure within the hollow, rotating shaft. Air is forced down the hollow shaft by atmospheric pressure, and fine bubbles of air exit the diffuser and enter the turbulent water around the impeller.

2.4. Paddle wheels

The rotating paddle wheel of a paddle wheel aerator splashes water into the air to affect aeration. A floating, electric paddle wheel aerator is illustrated in Fig. 4. The device consists of floats, a frame, motor, speed reduction mechanism, coupling, paddle wheel, and bearings. Motors for paddle wheel aerators usually turn at 1750 rpm, but this speed is reduced so that the paddle wheel rotates at 70–120 rpm. There is considerable variation in the design of the paddle wheel and in the mechanism for reducing the speed of the motor output shaft. Additional information on paddle wheel aerator design will be provided later.

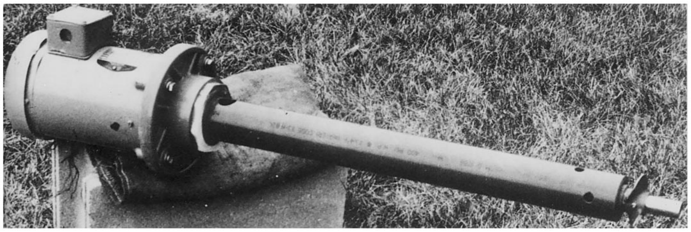

Fig. 3. A propeller-aspirator-pump aerator.

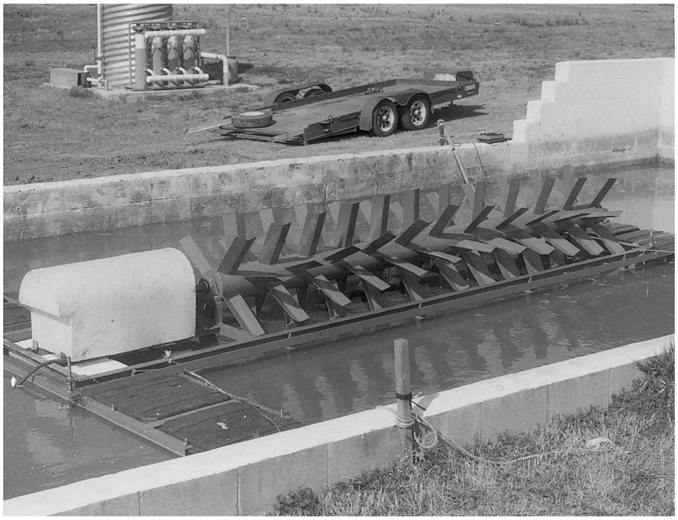

Fig. 4. A floating, electric paddle wheel aerator.

2.5. Diffused-air systems

Diffused-air system aerators use a low pressure, high volume air blower to provide air to diffusers positioned on the pond bottom or suspended in the water. A variety of types of diffusers have been used, including ceramic dome diffusers, porous ceramic tubing, porous paper tubing, perforated rubber tubing, perforated plastic pipe, packed columns, and carborundum air stones. Most diffused-air aerators release a large volume of air at low pressure. The minimum permissible system pressure becomes greater with increasing depth of water above diffusers, because enough pressure must be available to force air through the piping system and cause the air to exit from the diffuser against the hydrostatic pressure at the discharge point. Diffused-air systems that release fine bubbles usually are more efficient than those that discharge coarse bubbles. This results because fine bubbles present a greater surface area to the surrounding water than larger bubbles. Oxygen diffuses into water at the surface, so a large surface area facilitates greater oxygen absorption. Diffused-air systems also are more efficient in deep ponds than in shallow ponds.

A new innovation in diffused-air aeration systems involves placement of the diffuser in a bore hole drilled about 3 m into the pond bottom (Fig. 5). The unit consists of an outer casing and an inner riser pipe. The air diffuser is suspended beneath the riser pipe. In operation, fine air bubbles released by the diffuser ascend the riser pipe. The rising bubbles create an air lift to pump water upward in the riser pipe. Water from the pond bottom descends in the space between the casing and the riser pipe to replace the rising water. The bore hole provides depth to increase hydrostatic pressure on the rising bubbles. Greater pressure facilitates the dissolution of oxygen into water from the rising air bubbles. This device has an extremely high efficiency for transferring oxygen from air bubbles to water (Boyd, 1995a). Of course, the individual units are small, so several units must be placed in a pond to cause uniform aeration and mixing.

2.6. Tractor-powered aerators

Large aerators such as the paddle wheel aerator shown in Fig. 6 have been widely used for emergency aeration in large ponds. Such aerators are driven by the power-take-off (PTO) of farm tractors. The major advantages of PTO aerators are: they are large and can quickly raise DO concentrations, they are mobile and can be easily moved from pond to pond, and they do not require an electrical service. However, they require a large tractor to power each unit and they are less efficient than electric aerators. Therefore, the use of tractor-powered aerators is rapidly diminishing.

3. Aerator performance tests

Aerator performance tests have long been used in evaluating aerators used in wastewater treatment. These techniques have also been applied to aquaculture aerators. Aerator test results can assist in aerator design, aid aquaculturists in selecting aerators, and provide a basis for estimating the amount of aeration required in specific situations.

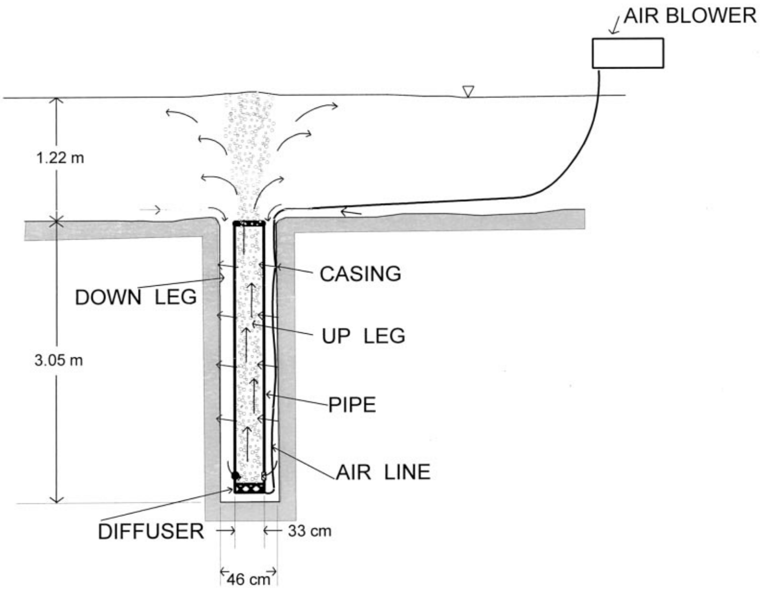

Fig. 5. A diffused-air aeration system with diffuser mounted in a bore hole in the pond bottom.

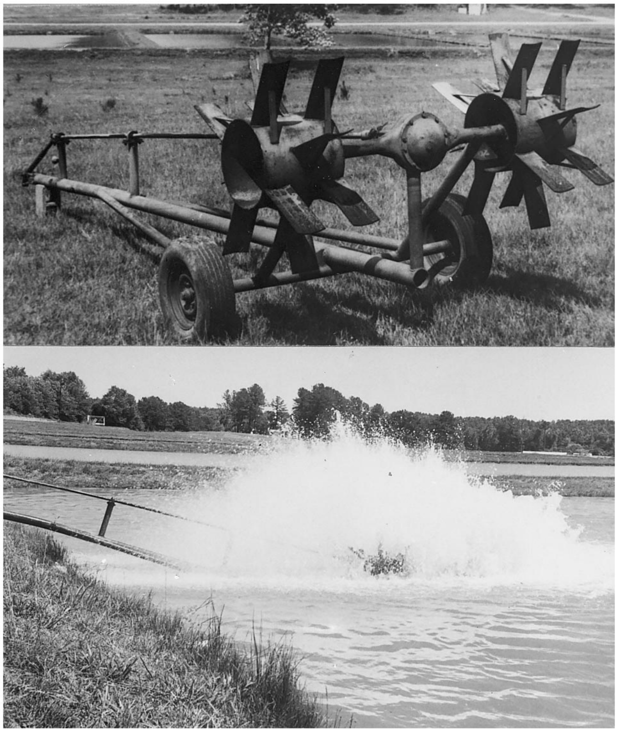

Fig. 6. A tractor-powered paddle wheel aerator.

3.1. Oxygen-transfer

There are two basic types of aerator performance tests, the steady-state test and the unsteady-state test. The steady-state test is conducted by mounting an aerator in a stream of water and measuring flow volume and DO concentration before and after aeration. The difference in the mass of DO between the inflow and the outflow represents the mass of oxygen transferred to the water by the aerator (Colt and Orwicz, 1991). It is difficult to test large, surface aerators used in aquaculture ponds by this technique because a large flow is required. The unsteady-state method of testing aerators in basins of water (American Society of Civil Engineers, 1992) is more appropriate for evaluating the performance of aquaculture aerators.

Unsteady-state tests are conducted by deoxygenating a basin of clean water with sodium sulfite and measuring the change in DO concentration as the water is reoxygenated by an aerator. A convenient basin for testing surface aerators for aquaculture is rectangular in shape and 1.0–1.5 m in depth. Aerator power-to-water volume ratio should not exceed 0.1 kW m^{-3}. Accurate measurements of aerator power and water volume are necessary in computations.

In a typical aerator test, water is deoxygenated with cobalt chloride at 0.05–0.1 mg cobalt l^{-1} and sodium sulfite at 8–10 mg l^{-1} for each milligram per litre of

DO. Cobalt catalyzes the following reaction between molecular oxygen and sodium sulfite:

$$Na_2SO_3 + \frac{1}{2} O_2 \rightarrow Na_2SO_4 \quad (6)$$

The aerator is used to mix cobalt chloride and sodium sulfite with the water. While the aerator is running, DO concentrations are measured with a polarographic DO meter at timed intervals while DO increases from 0% saturation to at least 80% saturation. At least 8 or 10 DO measurements equally spaced in time should be taken. If the basin is larger than 50 m^3 or if the aerator does not mix the water well, DO measurements should be made at two or more locations in the basin and the results averaged.

The DO deficit is computed for each time that DO was measured during reaeration:

$$\text{DO deficit} = C_s - C_m \quad (7)$$

where C_s is the DO concentration at saturation (mg l^{-1}) and C_m is the measured DO concentration (mg l^{-1}). The natural logarithms of DO deficits (Y) are plotted versus the time of aeration (X); the line of best fit is drawn by visual inspection or by aid of regression analysis. The oxygen-transfer coefficient is adjusted to 20°C with the following equation:

$$K_L a_{20} = K_L a_T \div 1.024^{T-20} \quad (8)$$

where $K_L a_{20}$ is the oxygen transfer coefficient at 20°C (hr^{-1}) and T is water temperature (°C).

An example of an unsteady-state oxygen-transfer test is provided (Table 2; Fig. 7). In this example, two points were selected (10 and 70% saturation) for obtaining the oxygen deficits at two different times during aeration for estimating the slope of the reaeration line and determining the oxygen-transfer coefficient. The point method described here requires the reaeration line to be linear. The American Society of Civil Engineers (1992) gave a computer program for a non-linear regression of the oxygen deficit versus time that is more accurate than the point method shown in Fig. 7 for data sets that are less linear than the example.

Results of oxygen-transfer tests normally are reported on a clean water (tap water) basis. If the test cannot be run in clean water, the α-value must be determined for the water in which the aerator test was conducted and the test results adjusted (Boyd and Ahmad, 1987). The α-value is defined as:

$$\alpha = \frac{K_L a_{20} \text{ test water}}{K_L a_{20} \text{ tap water}} \quad (9)$$

The α test can be conducted by using a laboratory scale aerator to determine $K_L a_{20}$ values for small samples of test water and clean, tap water (Shelton and Boyd, 1983). When aerator tests are conducted in pond water, the oxygen-transfer coefficient should be adjusted to a clean water basis as follows:

$$K_L a'_{20} = K_L a_{20} \div \alpha \tag{10}$$

where $K_L \acute{a}_{20}$ is the adjusted $K_L a_{20}$.

Waters that contain appreciable organic matter or an abundance of plankton should be avoided in aerator tests because oxygen may be added by photosynthesis or removed by respiration. Well water usually is suitable for aerator tests, but if well water has a high concentration of iron, oxidation of iron during the test will affect results.

The oxygen-transfer coefficient is used to estimate the standard oxygen-transfer rate for an aerator:

$$\text{SOTR} = (K_L a_{20})(C_{s20})(V)(10^{-3}) \tag{11}$$

where SOTR is standard oxygen-transfer rate (kg oxygen h^{-1}), C_{s20} is DO concentration at saturation and 20°C (g m^{-3} which equals mg l^{-1}), V is tank volume (m^3), and 10^3 kg g^{-1}. By definition, the SOTR is the amount of oxygen that an aerator will transfer to water per hour under standard conditions. Standard conditions are 0 mg l^{-1} DO, 20°C, and clean water.

The SOTR value may be divided by power applied to obtain the standard aeration efficiency (SAE). It has been customary to report power in terms of power applied to the aerator shaft (brake power). However, if an aerator shaft is driven by a belt drive from an electric motor, the power applied to the aerator shaft is somewhat less than the power applied to the motor, because the electric motor is not 100% efficient in converting electrical power to the mechanical power of its rotating output shaft, and the transfer of power from the motor shaft to the aerator

Table 2
Calculation of the rate of change in the oxygen deficit during an oxygen transfer test for an aerator

Time (min)	Measured DO concentration, C_m (mg l^{-1})	DO deficit[a] $C_s - C_m$ (mg l^{-1})	ln DO deficit (mg l^{-1})
0	0.10	7.59	2.03
1	0.31	7.38	2.00
2	0.92	6.77	1.91
3	1.75	5.94	1.78
4	2.54	5.15	1.64
5	3.17	4.52	1.51
6	3.61	4.08	1.41
7	4.18	3.51	1.26
8	4.55	3.14	1.14
9	4.94	2.75	1.01
10	5.23	2.46	0.90
11	5.50	2.19	0.78
12	5.75	1.94	0.66
13	5.98	1.71	0.54
14	6.14	1.55	0.44
15	6.27	1.42	0.35

[a] $C_s = 7.69$ mg l^{-1}.

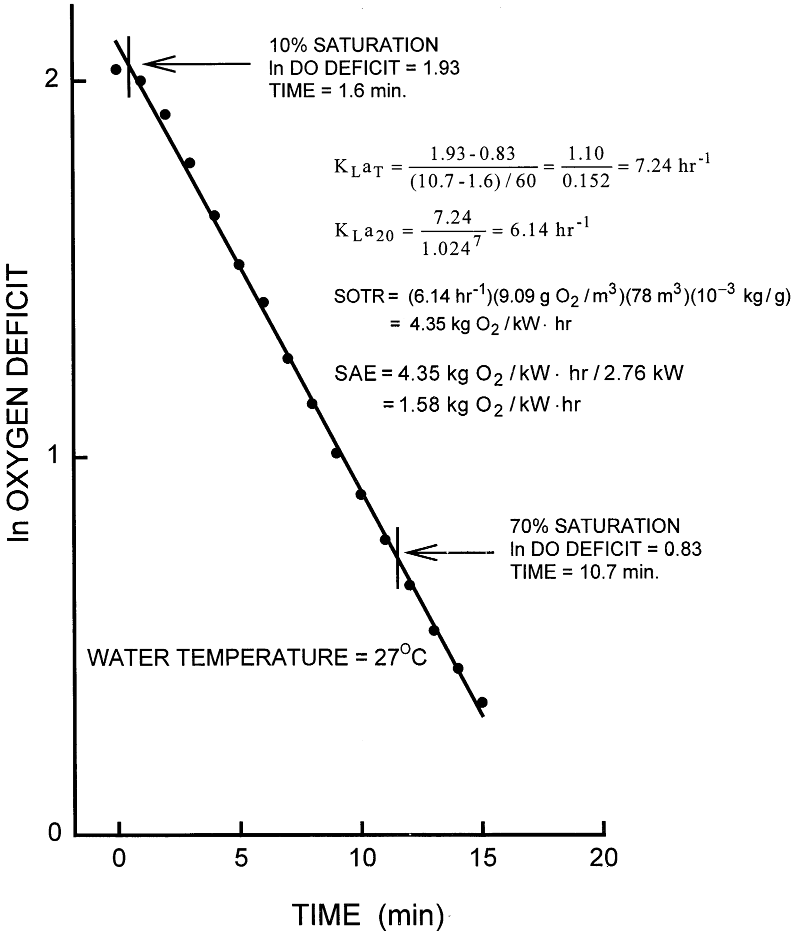

Fig. 7. Graph and calculations for an aerator performance test by the point method.

shaft is not 100% efficient. There also are friction losses in bearings and all power applied to the aerator shaft is not transferred to the water to facilitate oxygenation. Another approach is to express SAE in terms of electrical power (wire power) used. For electric aerators, SAE can be expressed as kilograms of oxygen per kiloWatt·hour. In aerator tests, power input to the motor can be measured with a watt hour meter.

The actual oxygen transfer rate for an aerator operating in a fish pond can be estimated with the following equation:

$$\mathrm{OTR} = \mathrm{SOTR} \times \frac{C_s - C_p}{9.09} \times 1.024^{T-20} \times \alpha \tag{12}$$

where OTR is oxygen transfer rate in pond water (kg O_2 h^{-1}), C_p is DO concentration in pond water (mg l^{-1}), and T is water temperature (°C). Aeration efficiency (AE) for pond conditions can be estimated by using SAE instead of SOTR in the preceding equation.

If one is interested in aerator performance in brackish or salt water, the C_s value in the preceding equation must be adjusted for salinity. Also, the value for C_s at 20°C and 760 mmHg must be determined for the existing salinity and this value used in place of 9.09 in Eq. (12).

3.2. Oxygen transfer under pond conditions

The driving force causing oxygen to enter water is the saturation deficit which is the difference between the oxygen pressure in the water and the oxygen pressure in the air. This difference is greatest when the DO concentration in the water is 0 mg l^{-1}. As the DO concentration in the water increases, the oxygen deficit or driving force decreases. Thus, the rate at which an aerator transfers oxygen to water decreases as the DO concentration increases. Values for OTR and AE tend to decline relative to SOTR and SAE as water temperature and DO concentration increase (Fig. 8). In a pond with a water temperature of 30°C and 4 mg l^{-1} DO,

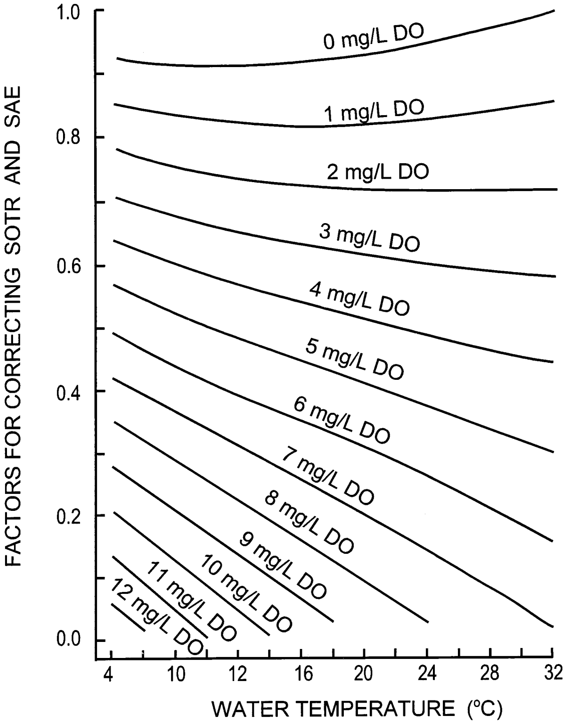

Fig. 8. Nomograph for obtaining factors for adjusting standard oxygen transfer rate (SOTR) and standard aeration efficiency (SAE) to oxygen transfer rate (OTR) and aeration efficiency (AE) under pond conditions of dissolved oxygen (DO) concentration and temperature. An α-value of 0.95 and a β-value of 1.0 were assumed.

OTR and AE would be about one-half of SOTR and SAE. When waters are saturated with DO, aerators cease to transfer oxygen. In waters supersaturated with DO, aerators increase the rate at which oxygen passes from water to air.

Concentrations of DO in ponds usually are above saturation during the day, and aerators that splash water into the air usually should not be operated during daytime. Subsurface aerators do not splash water into the air, but they increase turbulence at the water surface. Nevertheless, the benefits that accrue from mixing surface water with subsurface water to equalize DO concentration throughout the pond volume may offset any increase in oxygen loss to the atmosphere when subsurface aerators are operated during daylight hours. In highly intensive aquaculture, it is sometimes necessary to aerate 24 h day^{-1}.

Salinity has little influence on the oxygen transfer abilities of aerators that splash water into the air (Boyd and Daniels, 1987). However, recent results indicate that diffused-air aerators and propeller-aspirator-pump aerators are considerably more efficient in waters with salinities of 10 ppt and higher than in waters of lower salinity (Ruttanagosrigit et al., 1991).

3.3. Water circulation

Although oxygenation is the most important function of aerators, water movement caused by aerators is beneficial. Circulation of water during aeration moves oxygenated water away from the aerator to other parts of the pond, and it decreases thermal and chemical destratification. Water movement created by an aerator helps maintain high oxygen-transfer efficiency, because the freshly oxygenated water is propelled away from the aerator and replaced by water of lower DO concentration. Water currents have a negative effect by increasing oxygen consumption by fish as they are forced to expend more energy in swimming, but this is probably not an important factor under most conditions.

Two water circulation tests were developed by Boyd and Martinson (1984). In the dye test, an intensely colored dye is poured in front of the aerator and the time required for the aerator to spread the dye over the entire pond surface is measured. Aerial photographs made from an airplane or helicopter are the best means of recording a dye test. The salt test may be used to determine the time required for an aerator to mix the entire volume of water in a pond. Enough sodium chloride to raise the salinity of a pond by 100–200 mg l^{-1} is dissolved in a large container and poured around the aerator. Specific conductance is measured at intervals at several places and depths until all specific conductance values are essentially equal. The mixing rate may be estimated as:

$$\text{MR} = \frac{(A)(D)}{(P)(T)} \tag{13}$$

where MR is mixing rate ($\text{m}^3\ \text{kW h}^{-1}$), A is pond area (m^2), D is pond depth (m), P is power consumption by aerator (kW), and T is time for complete mixing (h).

The water circulating capabilities of aerators also may be estimated from the volumes of water discharged or from the velocities of water discharged. The

Table 3
Summary of SOTR (kg $O_2 \cdot h^{-1}$) and SAE (kg O_2 $kW \cdot h^{-1}$) values for electric aerators used in aquaculture

Type of aerator	Number of aerators	Range of SOTR	SAE	
			Average	Range
Paddle wheel	24	2.5 – 23.2	2.2	1.1 – 3.0
Propeller-aspirator-pump	11	0.1 – 24.4	1.6	1.3 – 1.8
Vertical pump	15	0.3 – 10.9	1.4	0.7 – 1.8
Pump sprayer	3	11.9 – 14.5	1.3	0.9 – 1.9
Diffused-air	5	0.6 – 3.9	0.9	0.7 – 1.2

Values for SAE are in terms of power applied to aerator shaft (brake power).

pumping rate of aerators that discharge water in a well-defined stream or jet can be estimated from pump curves or from measurements with special weirs. The velocity of water at some distance from an aerator may be measured with a current meter. Doty (1971) estimated the amount of water movement in the tidal zone from the rate of dissolution of gypsum blocks, for there is a definite relationship between the quantity of gypsum dissolved from the block and the amount of water passing over the block. The gypsum block method has potential for measuring water movement in ponds containing mechanical devices for aerating and circulating water. Techniques for preparing and using gypsum blocks for making water circulation measurements in ponds are provided by Howerton and Boyd (1992).

4. Comparative performance

Boyd and Ahmad (1987) tested a large number of electric aerators for oxygen-transfer efficiency. Values for SOTR and SAE are summarized in Table 3. Notice that SAE is based on estimated brake power. The reason that SOTR values had a wider range than SAE values was that aerators varied in size. These data demonstrate that paddle wheel aerators, in general, were more efficient than other types of aerators. Of course, some paddle wheel aerators were not as efficient as individual aerators of other types. Propeller-aspirator-pump aerators, vertical-pump aerators, and diffused-air aeration systems also are widely used in aquaculture for aerating small ponds (≤ 1 ha). Diffused-air aerators had the lowest SAE values (Table 3) in comparative tests of Boyd and Ahmad (1987). Recent work by Boyd and Moore (1993) showed that diffused-air aerators can have SAE values equal to the best paddle wheel aerators if a sufficient number of diffusers are used so that air is released to the water at a slow rate. If air is released slow enough, high SAE values can even be achieved in ponds with only 1 m of depth. The diffused-air aeration system illustrated in Fig. 5 has a diffuser depth of 4 m when installed in the bottom of a 3-m deep bore hole in a 1-m deep pond. Boyd (1995a) obtained an SAE of 6.37 kg O_2 kW h^{-1} for the aerator installed under these conditions.

Paddle wheel aerators constructed according to, or similar to, a design by Ahmad and Boyd (1988) had the highest SOTR and SAE values. Several manufacturers use this basic design for 2.25–7.5 kW aerators. Values for SOTR ranged from 17.4 to 23.2 kg O_2 h^{-1} and values for SAE (based on brake power) ranged from 2.6 to 3.0 kg O_2 kW h^{-1}. The average SAE (based on wire power) for these aerators was 2.2 kg O_2 kW h^{-1}.

Boyd and Ahmad (1987) tested several tractor-powered pump sprayer and paddle wheel aerators; SOTR values ranged from 7.8 to 73.8 kg O_2 h^{-1}. The power applied to the aerator shaft was not measured, but a larger tractor was required for pump sprayer aerators than for paddle wheel aerators. For example, one pump sprayer aerator required a 60-kW tractor and had a SOTR of 21.2 kg O_2 h^{-1}, while one paddle wheel aerator required a 50-kW tractor and had a SOTR of 29.8 kg O_2 h^{-1}. In general, paddle wheel aerators performed better than pump sprayer aerators. Busch et al. (1984) measured the brake horsepower required for tractor-powered paddle wheel aerators; SAE values ranged from 1.29 to 1.97 kg O_2 kW h^{-1}.

Although tests have been developed for evaluating water circulation by aerators, few data have been collected. Propeller-aspirator-pump aerators are much more efficient in mixing pond water than vertical pump aerators. A 1.5-kW propeller-aspirator-pump aerator spread dye over the surface of a 0.4-ha pond in 32 min. After 32 min of operation in a 0.4-ha pond, a 2.25-kW vertical pump aerator had spread dye over only one-fifth of the pond surface (Boyd and Martinson, 1984). A 2.25-kW paddle wheel aerator spread dye over a 0.4-ha pond in 28 min. A better comparison of water-mixing capabilities of surface aerators is afforded by salt-mixing tests, because these tests evaluate mixing of the entire pond volume rather than just surface water. The mixing rates for a propeller-aspirator-pump aerator and a vertical pump aerator were 1778 and 305 m^3 kW h^{-1}, respectively. A paddle wheel aerator had a mixing rate of 3235 m^3 kW h^{-1}.

Aeration performance tests in tanks (Boyd and Ahmad, 1987) indicate that paddle wheel aerators were more efficient in transferring oxygen and circulating water than other types of aerators commonly used in aquaculture. Rappaport et al. (1976) made pond tests of several aeration systems (paddle wheels, aspirator, vertical pump, and diffused-air), and they found that paddle wheel aerators were much more efficient than the other types. Mitchell and Kirby (1976) evaluated jet exhauster aerators, diffused-air systems, air-lift pumps, and vertical pump aerators in freshwater prawn ponds. Best results were obtained with vertical pump aerators; paddle wheel aerators were not included in the study. For aerators of 1 kW and larger, paddle wheel aerators are equal or less in cost than other types of aerators. However, small paddle wheel aerators are more expensive than other types of small electric aerators, because gearmotors required for small paddle wheel aerators are very expensive. For this reason, vertical pump aerators, propeller-aspirator-pump aerators, and diffused-air aerators are more commonly used in small ponds than paddle wheel aerators even though paddle wheel aerators are more efficient.

If world wide usage of aerators is considered, the small, paddle wheel aerators which are manufactured in Taiwan probably dominate the market (Fig. 9). These aerators are not as efficient as some other types of paddle wheel aerators, but they are relatively inexpensive, lightweight, of suitable size for intensive ponds, corrosion resistant, and well known. Taiwanese paddle wheel aerators are extremely popular for use in intensive shrimp culture ponds in Asia (Wyban et al., 1989).

4.1. Improved design for paddle wheel aerators

An electric paddle wheel aerator usually consists of a motor, a speed reduction mechanism, and paddle wheel mounted on a flotation device. The oxygen-transfer efficiency of a paddle wheel aerator depends upon design and characteristics of the paddle wheel. Thus, paddle wheel fabrication specifications are strict, while design of the flotation system is flexible.

The highest oxygen transfer efficiency was achieved with a paddle wheel 91 cm in diameter with triangular paddles (120–135° interior angle) spiralled on the hub (Ahmad and Boyd, 1988). The most efficient of the electric paddle wheel aerators tested had paddles that extended 9–11 cm into the water and the paddle wheels rotated at 75–80 rpm. The optimum brake power was about 1 kW for each 40 cm of paddle wheel length. This design works well for 2-kW and larger aerators. A 2-kW paddle wheel aerator is shown in Fig. 10. If either paddle submergence or paddle wheel is increased, power requirement will increase and oxygen-transfer efficiency will decline. The spiral arrangement of paddles on the hub (Fig. 10) allowed a fairly constant area of paddle surface to move continuously through the water, reducing vibration and wear.

The following equations from Moore and Boyd (1992) can be used to assist in the design of small (0.18–1.5 kW) paddle wheel aerators:

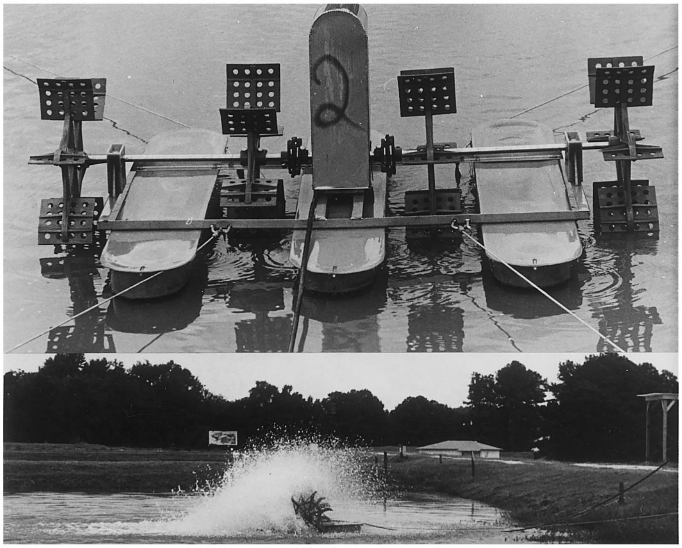

Fig. 9. A Taiwan paddle wheel aerator.

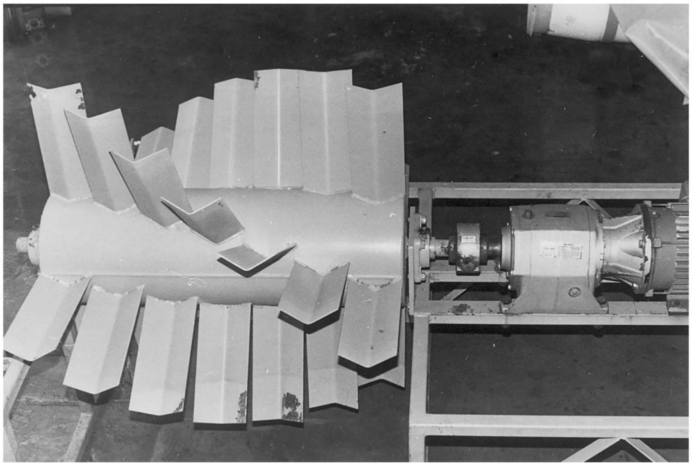

Fig. 10. An improved design paddle wheel aerator.

$$\mathrm{SOTR} = 0.0325\mathrm{D} + 0.0218\mathrm{L} + 0.0913\mathrm{H} + -0.0193\mathrm{S} - 4.9693 \quad (14)$$

$$\mathrm{BP} = 0.0228\mathrm{D} + 0.0115\mathrm{L} + 0.0555\mathrm{H} + 0.0122\mathrm{S} - 3.3256 \quad (15)$$

$$\mathrm{SAE} + 0.0142\mathrm{D} - 0.0065\mathrm{L} - 0.0288\mathrm{H} - 0.0663\mathrm{S} + 4.3285 \quad (16)$$

where D is paddle wheel diameter (cm), L is paddle wheel length (cm), H is paddle depth (cm), S is paddle wheel speed (rpm), and BP is brake power (kW). These equations assume: (1) the paddles will be triangular in cross section, with an interior angle of 135° and 5-cm wide across their open faces; (2) there will be four paddles, each 90° apart, in each row around the circumference of the hub; (3) the paddle rows will be spiralled (15° offset between two rows) on the hub. Also, the equations were developed with data within the following ranges; paddle wheel diameter, 61–91 cm; paddle wheel length, 15–75 cm; paddle depth, 8–18 cm; paddle wheel speeds, 75–125 rpm.

Paddle wheel shafts are fitted with bearings and mounted on a metal frame which is floated with steel boxes, styrofoam blocks, or plastic or metal tanks. Most manufacturers have stopped using roller bearings and simply place the ends of the aerator shafts in holes or depressions formed in polyurethane blocks. This works quite well, and polyurethane blocks are much cheaper than roller bearings and do not require lubrication. Some means of raising and lowering both ends of the paddle wheel are provided so that minor adjustments in depth may be made once the aerator is installed in a pond. Take-up bearings provide one convenient way of adjusting paddle wheel elevation and paddle depth. A more common method is to connect the aerator frame to the floats with a moveable connection and set the paddle wheel depth by adjusting the height of the frame above the water with turnbuckles. Aerators usually are anchored in ponds by aid of two metal stabilizer bars attached to each end of the floating frame and to metal bars driven into the pond bank or into the pond bottom.

A gear reducer is the simplest way to reduce motor output shaft speed to 75 or 80 rpm. A gearmotor has the gear reducer built onto the motor. The output shaft of a gearmotor can be connected to the input shaft of the paddle wheel with a flexible coupling. Alternatively, a gear box may be connected on one side to the output shaft of the motor with sheaves and cog belts and coupled on the other side to the input shaft of the aerator.

Instead of mounting the motor and speed reduction mechanism on the aerator frame, some aquaculturists prefer to mount the motor and speed reduction mechanism on the pond bank. The aerator is installed near the pond bank and driven by a long shaft. This arrangement permits speed to be reduced with a pulley and jack shaft system which is less expensive and more durable than a gear box. In brackishwater shrimp ponds in Southeast Asia, a small island is sometimes left in the middle of a 0.5 or 1.0-ha pond. A long shaft made of 2.5–3.0 cm diameter steel pipe is placed across the pond between the island and the pond bank. The shaft is fitted with 24–36 paddle units and supported end on end by bearings. A small gasoline or electric motor powers the aerator.

For brackishwater application, aerators must be constructed of corrosion-resistant material. Plastic construction has been used most extensively, but aerators have been constructed of stainless steel or made of galvanized metal. Epoxy resins and other types of coating also have been applied to reduce corrosion.

5. Use of aerators in ponds

Aerators can increase fish and shrimp production in ponds, but there are few generally accepted guidelines on how to best apply aeration in ponds. A brief overview of the use of aerators in ponds will be provided.

5.1. Effects on production

Experience with channel catfish (*Ictalurus punctatus*) ponds in the southern US suggests that at feeding rates below 30 kg ha^{-1} day^{-1}, aeration usually will not be necessary and an annual production of 2000–3000 kg ha^{-1} can be achieved. At feeding rates between 30 and 50 kg ha^{-1} day^{-1}, emergency aeration must be applied occasionally to most ponds or low DO concentrations will cause stress or mortality in fish. In this range of feeding rates, an annual production of 3000–4500 kg ha^{-1} of catfish is normal. Where feeding rates exceed 50–60 kg ha^{-1} day^{-1}, aeration will be needed frequently in nearly all ponds during warm weather.

Aerators should be installed in each pond and operated as needed. Research at Auburn University (Lai-fa and Boyd, 1989) suggests using nightly aeration (midnight to dawn) with aerators controlled by timers. At identical stocking and feeding rates, better feed conversion ratio (FCR) and greater production of catfish was achieved in ponds with nightly aeration (4813 kg ha^{-1}; FCR = 1.32) than in ponds where aeration was used only on an emergency basis (3657 kg ha^{-1}; FCR = 1.75). This resulted because DO concentrations were consistently higher in the ponds aerated nightly. These results were for ponds stocked at a moderate density of 10000 fish ha^{-1} and fed at a maximum rate of 53 kg ha^{-1} day^{-1}. In ponds at the Delta Research and Extension Center, Stoneville, MS with higher stocking and maximum daily feeding rates of 12000 fish ha^{-1} and 112 kg feed ha^{-1}, respectively, there was no difference between production or FCR in ponds aerated nightly or only on an emergency basis (Steeby and Tucker, 1988). Studies at Auburn University (Thomforde, 1990) failed to show that nightly aeration or continuous aeration was superior to emergency aeration in ponds with maximum daily feeding rates below 100 kg ha^{-1} day^{-1}.

In an experiment designed to evaluate the effect of feeding rate on water quality and fish production, channel catfish were stocked at 1200, 4300, 8600, 17300, 26000, and 34600 ha^{-1}, and maximum daily feeding rates of 0, 28, 56, 84, 112, 168, and 224 kg ha^{-1}, respectively, were established (Cole and Boyd, 1986). Aeration was applied when DO concentration was expected to fall below 2 mg l^{-1}. It was seldom necessary to aerate ponds with feeding rates of 0–56 kg ha^{-1} day^{-1}. Aeration was applied almost constantly at night in ponds with feeding rates of 112 kg ha^{-1} day^{-1} and above. Even though aeration prevented extremely low DO concentrations in all ponds, net fish production increased with feeding rate only up to 112 kg ha^{-1} day^{-1}. Feed conversion ratios were between 1.6 and 1.8 for daily feeding rates of 28–112 kg ha^{-1}. Feed conversion ratios were above 2.5 for daily feeding rates of 168 and 224 kg ha^{-1}. Net production of 6000 kg ha^{-1} was achieved at a feeding rate of 112 kg ha^{-1} day^{-1}. Ammonia accumulated in ponds, and high ammonia concentrations apparently limited production at high feeding rates. This experiment suggests that if economic considerations are ignored and enough aeration is applied to prevent DO depletion at high feeding rates, production cannot be increased without limit because high ammonia concentrations will impose limits on production even though there is adequate DO. Pond bottom soil quality also deteriorates in ponds fed at high rates (Boyd, 1995b).

Practical experience by commercial producers indicate that about 6000–8000 kg ha^{-1} usually is the maximum production of channel catfish possible in static-water ponds. However, production of more than 10000–15000 kg ha^{-1} of channel catfish has been achieved with heavy aeration (Hariyadi, 1991) or with heavy aeration and water exchange (Plemmons and Avault, 1980). It is seldom possible to exchange appreciable water in freshwater ponds. Water exchange rates of 5–20% of pond volume per day are commonly applied in brackishwater shrimp ponds to permit high rates of production in aerated ponds.

Shrimp can be reared in intensive systems with aeration. Chen et al. (1988) produced 12000 kg ha^{-1} of shrimp (*Penaeus penicillatus*) in 141 days in ponds stocked initially with 286 postlarvae m^{-2}. They used aeration with paddle wheel aerators at 11.7 kW ha^{-1} and water exchange up to 30% of pond volume per week. Concentrations of DO remained above 3.5 mg l^{-1}, and feed conversion ratio was 1.7. Sandifer et al. (1987) stocked 45 postlarval *P. vannamei* m^{-2}, used paddle wheel aerators at 7.5 kW ha^{-1}, and applied an average water exchange of 17% per day. Production in 169 days was 7500 kg ha^{-1}. Concentrations of DO as low as 0.3 mg l^{-1} were recorded near the pond bottom; feed conversion efficiency was 2.5.

On commercial shrimp farms, production of 10000–12000 kg ha^{-1} may be achieved by using high stocking and feeding rates, heavy aeration, and high rates of water exchange. However, such high rates of shrimp production are not advisable. The high rates of aeration cause excessive water currents and erode pond bottoms badly. Organic matter resulting from feeding wastes settles on pond bottoms and causes low DO concentrations in the pond soil and at the soil-water interface. Shrimp ponds discharge into coastal waters which are both water supplies and effluent recipients for shrimp ponds. High feeding rates necessary in ultra-intensive shrimp ponds cause water quality deterioration both in ponds and in surrounding coastal areas. Self-pollution has caused the demise of shrimp farming in some localities in Southeast Asia. In order to develop a sustainable shrimp farming industry in a locality, growers should be encouraged to stock and feed at moderate rates. Based on present knowledge, it appears more reasonable to stock ponds at 20–30 shrimp m^{-2} and obtain production of 4000–6000 kg ha^{-1} per crop than to stock and feed at maximum possible rates as often done.

There currently is interest in intensive production in small, concrete tanks (50–100 m^2) or small, earthen ponds (0.05–0.5 ha). More than 6000 kg of fish have been produced annually in 50 m^3 tanks employing 0.75–1.5 kW of aeration and water exchange rates of two to four tank volumes per day. Tanks or ponds often are equipped with center drains, and circular water currents created by aerators cause solid, organic wastes to accumulate on the bottom at the center of the pond. Wastes can be drained from ponds once or twice per day to reduce the oxygen demand. Where water is scarce, water from intensive production ponds can be recycled through reservoirs which serve as waste treatment lagoons (Muir, 1982; Van Rijin et al., 1986).

5.2. Aerator placement

Fish become conditioned to high DO concentrations around an aerator, and they will come to this area when low DO concentrations occur in other parts of a pond. some farmers feed fish in the area around an aerator to encourage fish to frequent this area. If aerators are permanently installed, there must be access to a power source and easy access to the aerator from an all-weather road for maintenance purposes. If an aerator fails, the replacement aerator should be placed near the failed unit so that fish do not have to swim through oxygen-deficient water to reach the replacement. Mobile aerators should be positioned in the end of the pond where DO concentration is highest because the fish will be there. If the mobile aerator is used frequently, it should be used in the same place night after night so the fish train to it. For emergency aeration, an aerator that discharges water over a large area is desirable, because this increases the probability that fish or other aquatic organisms will find the oxygenated water.

A recent study (Boyd and Watten, 1989) showed that for enhancing water circulation in a 0.4-ha rectangular pond, the best place to mount a paddle wheel aerator was at the middle of one of the long sides of the pond. The aerator directed water parallel to the short sides of the pond. The worst arrangement was to mount the aerator in one corner of the pond to direct water diagonally across the pond. When several aerators of any type are put in the same pond, it is best to mount the aerators so that they do not work against each other in producing currents. For example, if four paddle wheel or propeller-aspirator-pump aerators are to be installed in a square or rectangular pond, an aerator should be placed in each corner to direct water parallel to the pond bank. All aerators should direct water in the same clockwise or counter-clockwise direction. In this way, the current from each aerator compliments the currents produced by other aerators to produce a circular pattern of water movement.

Water circulation in ponds can be excessive. According to Boyd (1995b), in 1-ha shrimp ponds with several paddle wheel aerators positioned for circular flow, mounds of clay 30–45 cm in depth often formed over 30–50% of central areas of ponds (Fig. 11). Mounds resulted because high velocity water currents produced by aerators detached soil particles from 10 to 15-m wide bands around the peripheries of ponds and from inside slopes of levees. Material was deposited in central areas where water velocities were lowest. To prevent erosion by aerators, pond embankments should be sloped and compacted properly, and easily erodible areas of embankments on bottoms should be reinforced with a liner or stone rip-rap. Aerators should be positioned at least 3 or 4 m from the toes of the embankments, and they should not be positioned so that they cause high velocity currents to impact on embankments.

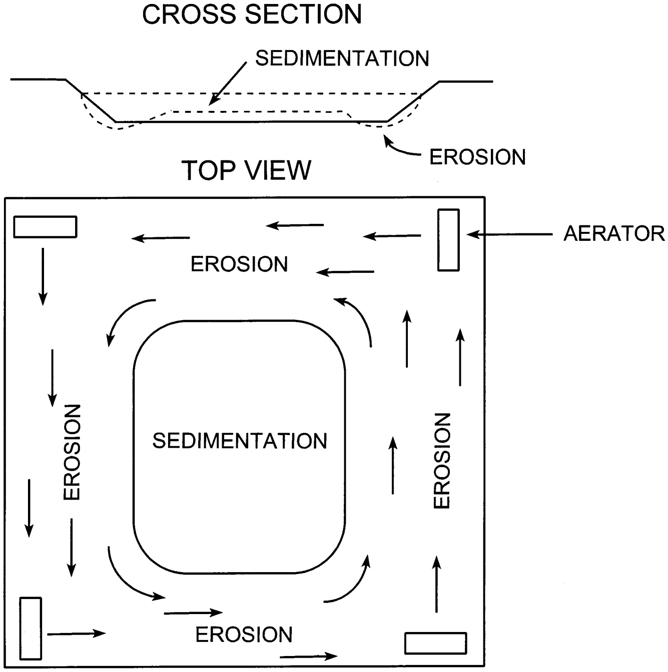

Fig. 11. Illustration of erosion pattern in shrimp pond bottom caused by paddle wheel aerators positioned for circular flow.

5.3. Amount of aeration

As mentioned earlier, the oxygen dynamics of a pond are complex. Phytoplankton produces oxygen and all organisms (fish, crustaceans, plankton, and benthos) use oxygen. Water temperature and DO concentration change continuously, and it is virtually impossible to compute the actual oxygen transfer rate of an aerator. Furthermore, it is difficult to know how much of the oxygen provided by aeration is used in fish or crustacean respiration and how much is used by other organisms in the pond. Although there is no formula for estimating the amount of aeration necessary for a given combination of stocking and feeding rates, it is possible to make rough estimates. Suppose that an aerator has an SAE of 1.5 kg O_2 kW h^{-1}. During the daylight hours, aerators transfer little if any oxygen to the water because the water is near or above saturation with DO. In a properly aerated pond, the DO concentration during the night usually averages about 4 mg l^{-1}. At this DO concentration and with water temperatures of 25–30°C, the actual oxygen transfer efficiency of an aerator is about 50% of the SAE (Fig. 8). Thus, the actual oxygen-transfer efficiency in the pond will be about 0.75 kg O_2 kW h^{-1}. During a 12-h night, the aerator will transfer about 9 kg O_2 kW^{-1}. Studies of DO budgets of ponds (Boyd, 1990) revealed that no more than 20% of the DO in the water normally is used by the aquaculture species. The remainder is consumed by respiration of phytoplankton, bacteria in the water column, and bottom soil organisms. Thus, only 1.8 kg O_2 kW^{-1} is available to the culture species from the oxygen added during the night by the hypothetical 1 kW aerator. Shrimp and fish respiration usually ranges from 200 to 400 mg O_2 kg $animal^{-1}$ h^{-1} (Boyd, 1990) or 2.4–4.8 O_2 kg $night^{-1}$. Assuming the respiration rate averages 3.6 O_2 kg $night^{-1}$, 1 kW of aeration should support about 500 kg of fish or shrimp (1800 g O_2 available from aeration $\div$ 3.6 g O_2 kg^{-1} of animals). For safety, no allowance will be made for the amount of production possible without any aeration. With assumptions given above, each kilowatt of aeration can be expected to permit a 500 kg ha^{-1} increase in shrimp or fish production. This calculation agrees with the common experience that each horsepower of aeration will support 500 kg of shrimp production (Boyd, 1997).

Experience suggests that about 2000 kg ha^{-1} of most species of shrimp and fish can be produced in ponds without aeration. Therefore, if 8-kW aeration is applied to a pond, a production of 6000 kg ha^{-1} is a reasonable expectation, and this estimate agrees closely with observations of shrimp production in aerated ponds. Of course, channel catfish farmers often produce 4000–5000 kg ha^{-1} with only 2–3 kW of aeration per hectare. Nevertheless, fish in such ponds are probably frequently stressed by low DO concentrations at night. There are notable exceptions to the relationship between amount of aeration applied and production. For example, tilapia can tolerate low DO better than most species, and it is not unusual to obtain production in excess of 5000 kg ha^{-1} in unaerated ponds.

5.4. Automation of aeration

Devices are available for turning aerators on and off. Timers can be used for turning aerators on at a particular time at night and turning them off in the morning. Some companies are selling systems that activate and deactivate aerators in response to DO concentrations in pond waters. Hoagland (1998) compared energy use in ponds where aerators were turned on and off by DO sensors, timers, and manually in response to measured DO concentrations. Aerators operated by DO sensors used 62% less electricity than those operated by timers, and 80% less electricity than aerators operated manually. The use of DO sensors for operating aerators is still expensive, and the systems are not totally reliable. However, in the future, this practice will probably be perfected and become commonplace.

6. Water exchange

Water exchange already has been mentioned several times for it serves several purposes: it flushes nutrients and phytoplankton from ponds to prevent excessive phytoplankton blooms; it removes toxic metabolic wastes such as ammonia; it dilutes pond water so that salinity does not become excessive during the dry season, and it is a substitute for aeration.

Water pumped into ponds should be applied at the pond surface. Water should be drained from near the pond bottom and at the opposite side from which it is introduced. The most beneficial means of exchanging water in a pond is to first drain out the volume to be exchanged and then pump in an equal volume of replacement water. For example, the ammonia concentration could be reduced by 50% if one-half of the pond water could be discharged and rapidly replaced with water containing no ammonia. Many farmers just pump water into a pond and allow the pond to overflow. The incoming water mixes with the pond water and the water discharged is a mixture of the new water and the old water. This reduces the effectiveness of water exchange in diluting the concentration of dissolved substances such as ammonia in pond water (McGee and Boyd, 1983).

In brackishwater aquaculture, water is readily available and farmers use water exchange rates of 2 to more than 40% per day; the average rate probably is around 5–10% per day. In shrimp farming, a rate of 10% per day appears to be more than adequate for ponds with stocking densities of 8 or 12 shrimp m^{-2}. If water quality in ponds is good, there is no reason to exchange water. Water should not be exchanged when water in supply canals or reservoirs is of lower quality than waters in ponds. Of course, water exchange is a bad practice from an environmental viewpoint because it flushes nutrients and organic matter from ponds before they are assimilated by natural processes. The water pollution potential of aquaculture ponds increases as water exchange rates increase (Boyd and Queiroz, 1997).

In freshwater aquaculture, water for ponds often is taken from wells, and the volume of water available for exchange is small. For example, in channel catfish farming, there usually is one well with a capacity of 7.5–11 m^3 min^{-1} for four ponds, each with a volume of about 70000 m^3. Thus, to pump a quantity of water equal to the volume of one pond would take the entire discharge of a 10 m^3 min^{-1}-capacity well for nearly 5 days. Well water usually is depleted of DO, so it would have to be passed over a gravity aerator for water exchange to be effective at all in combating oxygen depletion. Assuming complete saturation of water at 25°C with DO, the daily discharge of the well would contain 118,656 g O_2 (10 m^3 $min^{-1} \times 1440$ min $day^{-1} \times 8.24$ g O_2 m^{-3}). This would amount to an increase in DO concentration of 1.70 mg l^{-1} in the pond. In the same period, a 7.5-kW electric paddle wheel aerator could transfer twice as much oxygen to the water at about one-fifth the cost of pump operation. Use of water exchange to improve DO concentrations in most freshwater ponds is inadvisable.

7. Water circulation

There is a consensus among aquaculturists that water circulation in ponds is beneficial. Water circulation prevents thermal and chemical stratification. This makes the entire pond volume habitable for aquatic animals, and it eliminates the danger of overturns in deep ponds. Water circulation moves water across the pond bottom and helps maintain oxygenated conditions at the mud-water interface. Water circulation devices create surface turbulence and this affects a small degree of aeration. Air-lift pumps use air bubbles to move water, so some oxygenation is affected by the rising bubbles (Parker, 1983), but water circulators should not be considered aerators in the usual sense. The greatest influence of water circulators on DO concentration is the blending of surface water with subsurface water. During daylight hours, surface waters in ponds often are supersaturated with DO, and water at greater depths may have low DO concentrations. By mixing pond water, a uniform DO profile can be established. Oxygen produced by phytoplankton possibly is conserved by water mixing, because the high degree of DO supersaturation normally found at pond surfaces during daylight is eliminated by mixing (Busch and Flood, 1980). Circulation of pond water also seems to stimulate phytoplankton growth (Sanares et al., 1986), and this could possibly increase DO production by photosynthesis. Preliminary evidence suggests that the total DO content of a pond can be increased by mixing (Fast et al., 1983). A few methods of circulating pond water and some preliminary studies of water circulation will be discussed, but the value of circulation has not been clearly demonstrated.

An air-lift pump designed by Parker (1983) is illustrated in Fig. 12. The pump is constructed of a length of PVC pipe, termed the eductor, and a PVC elbow. Air from an air blower is released through a 90° hose adaptor into the PVC pipe. If desired, an air diffuser that releases smaller bubbles of air can be placed in the pipe. The rising air bubbles lift water through the eductor and discharge it at the surface. A pump holder is attached between the anchor post and the pump. This holder contains a flotation device and it permits the pump to pivot. Ballast must be provided at the bottom of the pump.

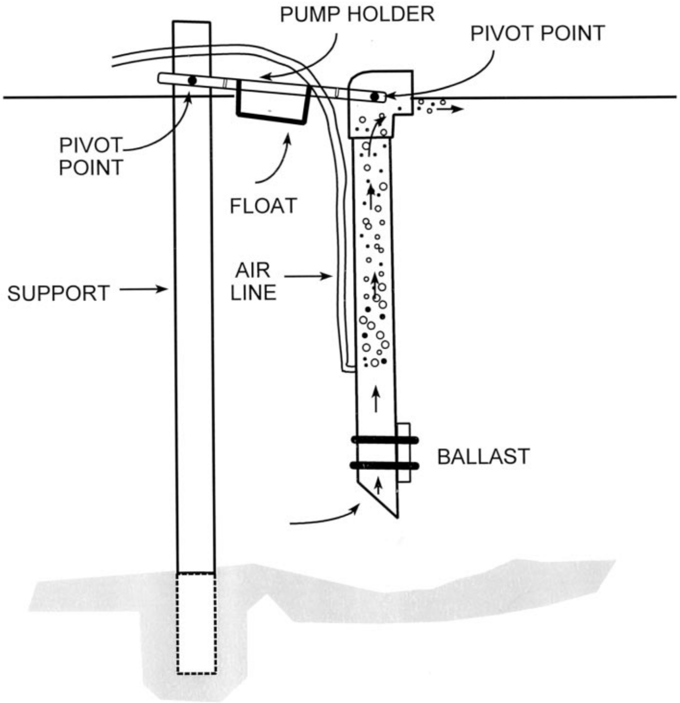

Fig. 12. An air-lift pump.

Parker (1983) demonstrated that two, 10-cm diameter air-lift pumps with 122 cm vertical risers would pump the entire volume of water in a 0.2-ha pond in 3 days if 0.14 m^3 min^{-1} of air was injected into each vertical riser at a depth of 76 cm. Obviously, if a high degree of mixing is desired, a large and probably excessive number of air-lift pumps would be required. For example, to achieve a pumping rate of one pond volume per day a 1-ha pond with a depth of approximately 1 m would require 30, 10-cm diameter air-lift pumps. Air feed lines would interfere with fish harvesting operations. Air-lift pumps are probably best suited for relatively small tanks or ponds where pumping requirements are relatively low and the equipment can be removed easily from the vessels when required.

Circulation of surface waters with paddle wheel aerators will mix oxygen-enriched surface waters with deeper waters. A total of six, 0.19-kW electric paddle wheel aerators provided circular water movement in a 0.53-ha pond stocked with channel catfish (Busch et al., 1978). Aerators were operated 5 h each afternoon. Concentrations of DO increased in deep water and decreased slightly in surface water. However, net fish production was no greater than that achieved in unaerated ponds. Based on this research, a 0.055-kW paddle wheel was constructed which rotated at 40 rpm to provide slow horizontal water currents with a minimum of surface splashing. The paddle wheel operated in a channel made of sheet metal that restricted all surface flow. The inlet to the paddle wheel channel was at a depth of

50 cm. Most of the discharge was in the surface 20 cm. The slow speed paddle wheel aerator was given the name 'water blender.' There were two water blenders installed in a 0.73-ha pond, and they pumped a volume equal to the pond volume every 20 h. Surface circulation averaged 5 m min^{-1} on the discharge side; return flow averaged 2 m min^{-1} Continuous operation reduced the thermal gradient in the pond and increased DO concentrations in bottom water. Concentrations of DO were relatively constant throughout the water column. No studies have been conducted to determine the influence of water blenders on fish production.

Researchers in Hawaii (Fast et al., 1983) designed, fabricated, and tested a device which they called a water circulator (Fig. 13). It consisted of a 61-cm diameter fan (turbine impeller) attached to a shaft which was connected to a 0.19-kW electric gearmotor that provided an impeller speed of 60 rpm. The device was mounted on a small cart to facilitate mobility. Discharge was estimated at 5.7 m^3 min^{-1}. The water circulator was tested in a 0.2-ha prawn pond. In calm conditions without artificial circulation, the pond developed thermal stratification, and DO concentra-

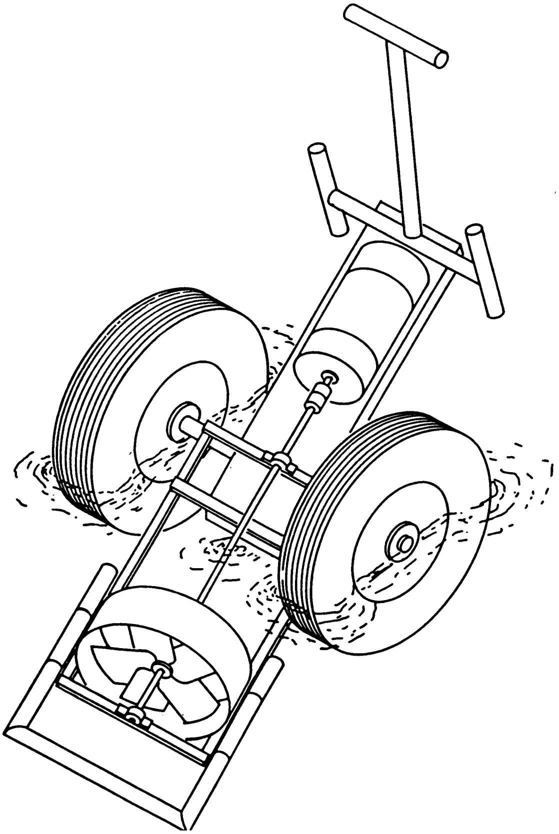

Fig. 13. A water circulator designed by researchers at the University of Hawaii (Fast et al., 1983).

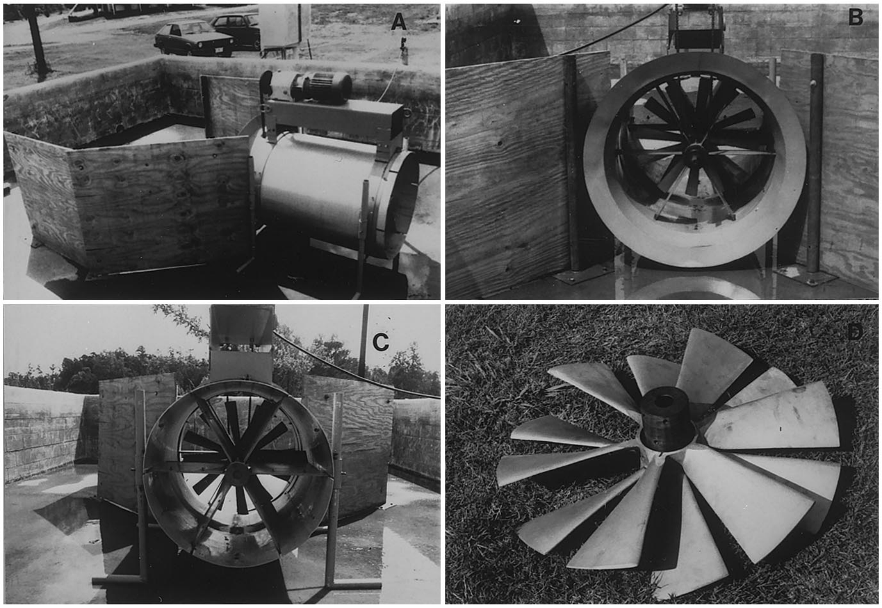

Fig. 14. A water circulator designed by researchers at Auburn University (Howerton et al., 1993).

tions in bottom water were often less than 5 mg l^{-1} during late afternoon. With artificial circulation, DO concentrations in bottom water sometimes exceeded 12 mg l^{-1} during late afternoon. Minimum daily DO concentration in bottom water averaged 1.0 mg l^{-1} higher and maximum daily DO concentration in bottom water averaged 4.0 mg l^{-1} higher during artificial circulation. These findings suggested that artificial circulation increased the potential for prawn production.

Howerton and Boyd (1992) developed a large, horizontal flow water circulator (Fig. 14). The device consists of a motor, a large casing (80 cm diameter × 1 m long) with a flared entrance to streamline flow of entering water, stabilizer surfaces to streamline flow inside the casing, shaft horizontal to water surface, bearings to support shaft, and fan blade impellers (each fan blade unit had six, 15-cm wide blades and a diameter of 74 cm), drive system, and support frame. This device will discharge 30 m^3 min^{-1} when fitted with four fan blade units and operated at 90 rpm. The power required at the impeller shaft is 0.67 kW. Tucker and Steeby (1995) showed that use of the water circulator in daytime reduced the amount of aeration needed during the night in channel catfish ponds. However, power cost savings for aeration were largely offset by the cost of daily circulator operation.

Lawson and Wheaton (1983) considered the problem of water circulation in large, shallow, crawfish ponds. When water is simply pumped into the pond on one end and allowed to flow to the exit on the other end, there were considerable ‘dead’ areas of poor water circulation. They demonstrated that dead areas could be eliminated by use of aerators to augment flow and baffle levees to direct flow (Fig. 15). The baffle levee concept is used widely in intensive, brackishwater shrimp

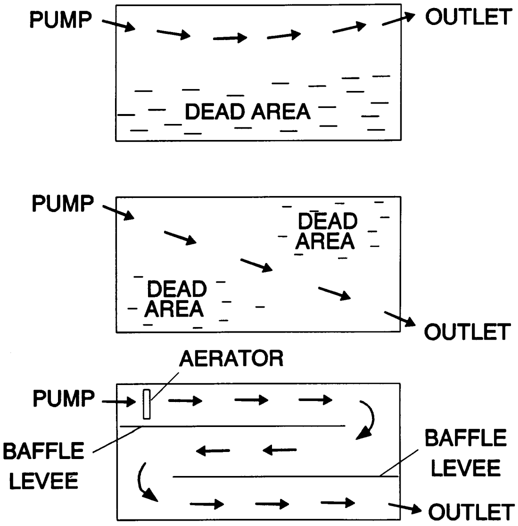

Fig. 15. Baffle levees for improving water circulation in ponds.

ponds in Thailand and Indonesia. Rectangular ponds have a single baffle levee extending down the middle of the long axis of the pond with gaps at each end. This design facilitates a circular movement of water when paddle wheel aerators are operated. This system has merit in many types of aquaculture.

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