Kasetsart J. (Nat. Sci.) 38 : 267 - 277 (2004)

Design of a Combined Propeller and Venturi Tube System for Aquaculture Ponds

Santi Laksitanonta[1] and Gajendra Singh[2]

ABSTRACT

The main objective of the study was to design and develop an aerator (a combined propeller and venturi tube system) and to evaluate its performance characteristics and oxygenating capacity. This system has certain advantages over existing methods of separate water circulation and oxygenation methods. The aerator was designed to perform two functions: circulation, and aeration. A large diameter propeller (0.45 m) rotating at a low speed (60 rpm), to move a large volume of water (0.093 m^3/s), was aimed for circulation. The rotational speed was kept low enough to produce gentle water movement without disturbing or eroding the bottom soil. For oxygenation, a venturi tube was installed horizontally at the center of the propeller, at a depth of 0.5 m below water surface (1.0 m pond depth). The oxygenating experiments were conducted using accepted protocols for various operating parameters. The mixing of fine bubbles and strong current, accomplished by the rotating propeller, quickly transported the dissolved oxygen (DO) to a greater depth. The highest value of standard oxygen-transfer rate (SOTR) of the aerator tests in the range of scope and limitation was found to be 0.78 kg O_2/h, which is higher than other existing aerators, i.e. the paddle wheel aerators and propeller-aspiration-pump aerators. A dimensional analysis was conducted to find the relationship between the dependent variable, SOTR, and the independent variable in the form of PQ/V^2, where P is pressure inside venturi tube, V is water velocity, and Q is volumetric flow rate of water. The results show that the two variables have a linear relationship with $R^2 = 0.93$.

Key words: dissolved oxygen concentration, standard oxygen-transfer rate, standard aeration efficiency

INTRODUCTION

Bottom sediments represent the major consumers of oxygen in shrimp ponds. Fast *et al*. (1988) found that respiration rates in 0.1 ha shrimp ponds, 1.0 m deep, were about 0.43, 0.12 and 0.02 kg O_2/h for sediment, plankton and shrimp, respectively. Sediment respiration rates are further increased by uneaten feed. When organic matter from uneaten feed, faeces and dead plankton settles to the pond bottom and decomposes, it can lead to anaerobic conditions in the superficial layers of bottom sediment and release toxic microbial metabolites into the overlying pond water. Bottom waters are typically depleted of oxygen due to respiration, and are isolated from replenishment via photosynthetic activity and surface diffusion. Aeration alone is not always able to correct this imbalance, since the oxygenation effects of aeration are felt mostly near the surface. Aerators vary in

[1] Department of Mechanical Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand.
[2] Agricultural and Food Engineering Program, Asian Institute of Technology, P. O. Box 4, Klong Luang 12120, Thailand.

Received date : 09/03/04 Accepted date : 27/05/04

their ability to generate horizontal water movement. Water circulators are more appropriate for this purpose. The low-energy water circulation devices could be used to circulate pond water during the daytime when DO concentrations are high. This would blend oxygen-supersaturated surface waters with deep layers of low DO concentrations. Ideally, a water circulator can produce uniform gentle water currents over pond bottoms only to suspend fresh organic particles without suspending mineral soil. Suspending organic particles in the water would enhance the availability of DO for their decomposition. Preventing the deposition of mixtures of organic and mineral particles at the pond bottom would reduce the likelihood of areas with anaerobic conditions at the soil-water interface.

This research seeks to design an aerator (a combined propeller and venturi tube system) to circulate large volumes of oxygen rich water in a shrimp pond. This system has certain advantages over current methods of separate water circulation and oxygenation methods. Moreover, such an aerator can blend the saturated DO concentrations at shallow and greater depths.

MATERIALS AND METHODS

For circulation, a large diameter propeller was used to produce uniform gentle water current over pond bottoms to suspend fresh organic matter, without stirring mineral soil particles. Water velocity generated from a propeller effect on soil erosion. Successful deployment of water circulators depends on proper sizing and selection of flow velocity. Rogers (1990) noted that a minimum velocity of 50 mm per second is necessary to prevent stratification in most ponds, whereas 150 mm per second is required to maintain sediment in suspension. He suggested that an intermediate flow velocity of 76 mm per second would provide sufficient flow for destratification and waste removal, without disturbing the pond bottom. Fortier and Sobey (1926) suggested the limiting velocities for essentially straight canals. For silt loam or alluvial silts, the limiting velocity of water is a 0.6 m/s. Excessive velocity is economically wasteful, and the resulting scouring effect may erode the pond bottom and increase turbidity.

Propeller

The propeller composed of eight cast aluminum airfoil blades. An airfoil geometry of the National Advisory Committee for Aeronautics (NACA 66 (Mod) with a = 0.8 airfoil blade): 97.56 mm chord length; 11.71 mm maximum thickness or 0.12 of thickness ratio; 0.387 mm leading edge radius; and 0.05 of camber ratio was used. The blades were mounted on a circular hub, 215 mm in diameter, and the blade angle was set at 35 degree. The size of blade and hub were based on an aspect ratio of 1.17, 0.48 of hub to propeller diameter ratio, and 1.15 solidity ratio. The overall outside diameter of the propeller was 445 mm and the total sectional area was 0.155 m^2. These blades were designed according to data from Brockett (1966). All blades and hub were fabricated and machined by the CNC wire cutting machine at The Research and Development Institute of Industrial Production Technology, Kasetsart University. The figure of the propeller is also shown in Figure 1. A full-scale

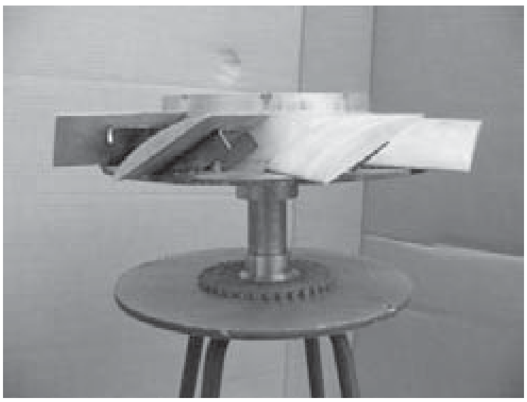

Figure 1 A prototype of propeller (Eight propeller blades were aligned in 35° blade angle around a circular hub).

propeller extended from a scaled-down model with the best performance equation at a 35°blade angle: Q = 0.22 N, where Q is water flow rate (L/s); and N is rotational speed (rpm).

The water flow velocity generated from the propeller running 60 rpm was directly measured by a TS flow meter. Time measurement for this mechanical flow meter type was read in the range of 10 min per replication. The flow meter was mounted horizontally and placed 0.25 m in front of the propeller at a depth of 0.5 m. Water velocities were measured at five places, each at a 100 mm from the center with three replications. Also, water velocities were measured at a 1.00 m in front of the propeller, in the horizontal direction at depths of 0.5 and 1.00 m.

Venturi tube

For oxygenation, a venturi tube was installed horizontally at the center of the propeller, at a depth of 0.5 m below water surface (1.0 m pond depth).

A cross-section drawing of the venturi tube and venturi nozzle is illustrated in Figure 2. Popel (1979) suggested that the angle of the cone should not exceed 7.5°. In this design, the angle of the cone was kept at 2° in order to minimize the pressure loss.

Test rig for oxygenation measurement

The oxygen-transfer tests for the venturi aerator were conducted in an aeration tank. The tank was filled with clean water, 1.0 m deep and the volume of water for oxygen-transfer tests was 24,000 liters. Propeller prototype and venturi tube were constructed together to form one unit. The propeller was freely rotated around the hollow stainless steel tube by means of chain transmission from a motor. A 3-phase electric motor, 2.24 kW, was used for driving the propeller of the venturi aerator. The centerline of the venturi aerator tube was positioned above the bottom of tank in a horizontal direction at a depth of 0.5 m. The venturi tube was connected at the end of the hollow stainless steel tube. Two submersible pumps were used to pump the water within the tank pass through the flow meter and the venturi nozzle at the end of venturi tube. The water flow rate was controlled by a hand glove valve located on a by-pass water pipe. Before each test run the speed was calibrated by the digital hand optical tachometer. The arrangement of the aerator is illustrated in Figure 3. Measurements to determine the SOTR were taken for three different venturi nozzle holes, 6.00, 8.14, and 10.3 mm. For a given venturi nozzle hole, the testing of the SOTR was conducted by varying the velocity of water passing through

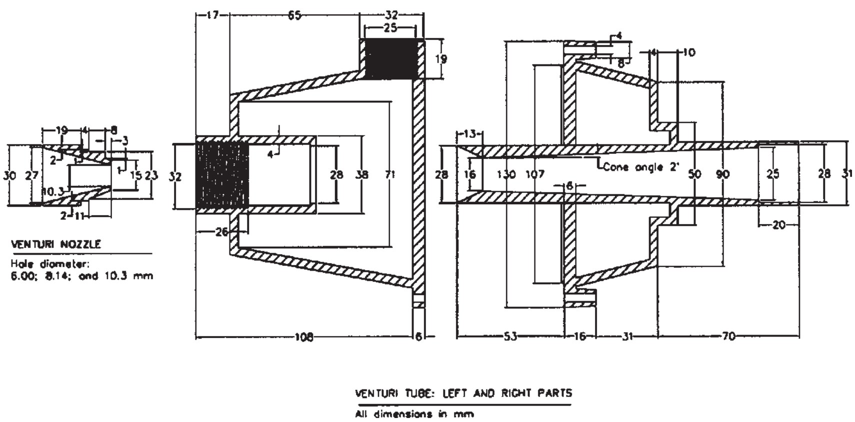

Figure 2 Cross-section drawing of main parts of the venturi tube and a venturi nozzle.

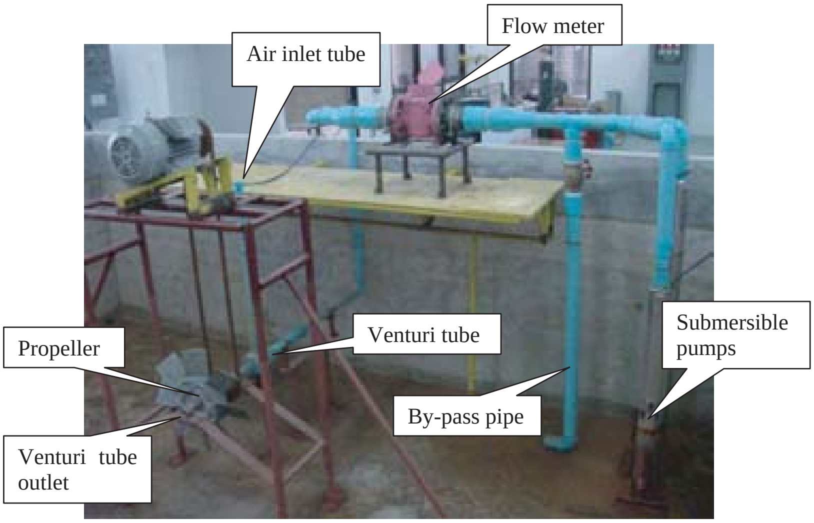

Figure 3 Arrangement of the aerator in aeration tank.

the venturi nozzle to 18, 21, 24, 27, 30 and 34 m/s.

Aerator tests

The oxygen-transfer tests followed protocols suggested by Stuckenburg *et al*. (1977), Boyle (1979) and Boyd and Watten (1989). DO concentrations at standard pressure were taken from Colt (1984). An oxygenation test was conducted in clean water within the temperature range 28.1 to 30.3°C, at atmospheric pressure. Water in the test tank was deoxygenated by adding 0.15 mg/L cobalt chloride and sodium sulfite at the rate of 15 mg/L of sodium sulfite per 1.0 mg/L of DO. Cobalt chloride and sodium sulfite were dissolved in a bucket of water and splashed over the water surface, and mixed by operating the aerator. Two polarographic DO meters (YSI model 85) were used to measure DO concentrations at three places in the tank for each test. Each oxygen-transfer test was replicated three times. DO concentrations were measured at time intervals ranging from 1 to 2 min, while DO rose from near 0 mg/L to 80 or 90% of saturation, and at least twenty DO measurements were made during each trial. The aeration tank was drained and refilled after a maximum of six individual trials. Cobalt chloride was applied only before each initial trial after the tank was refilled. DO deficit was calculated for each time interval by subtracting measured DO concentration from saturation DO. The natural logarithm of oxygen deficit (Y-axis) versus time of aeration (X-axis) was plotted and a regression equation was obtained for each trial. The plot gave a straight line and the slope is the overall oxygen-transfer coefficient (K_La). The regression equation for the natural logarithm of the oxygen deficit versus time of aeration is used to determine the time at which the DO concentration reached 10 and 70% of saturation. The overall oxygen-transfer coefficient is determined with the equation:

$$(K_La)_T = (\ln DO_{10} - \ln DO_{70})/(t_{70} - t_{10}) \quad (1)$$

where

$(K_La)_T$ = overall oxygen-transfer coefficient for existing water temperature (h^{-1})

DO_{10} = oxygen deficit at 10% of saturation (mg/L)

DO_{70} = oxygen deficit at 70% of saturation (mg/L)

t_{10} = time when DO reaches 10% of saturation (h)

t_{70} = time when DO reaches 70% of

saturation (h)

The $(K_La)_T$ value for other temperatures was adjusted to 20°C as follows:

$$(K_La)_{20} = (K_La)_T / 1.024^{T-20} \quad (2)$$

where

$(K_La)_{20}$ = overall oxygen-transfer coefficient at 20°C (h^{-1})

T = existing water temperature (°C)

The standard oxygen-transfer rate was estimated by the following equation:

$$SOTR = (K_La)_{20} \times 9.077 \times V \times 10^{-3} \quad (3)$$

where

SOTR = standard oxygen-transfer rate (kg O_2/h)

9.077 = DO at saturation concentration at 20° C and standard atmospheric pressure(mg/L)

V = aeration tank volume (m^3)

10^{-3} = factor for converting grams to kilograms

Dimensionless analysis

Dimensional analysis was carried out to reduce the number of variables and to formulate the prediction equation for the standard oxygen transfer rate. The dimensional analysis of the parameters using the Buckingham Pi Theorem is summarized as follows:

$$SOTR = -C\,(PQ/V^2) \quad (4)$$

where SOTR = standard oxygen transfer rate (kg O_2/h)

C = constant

P = pressure at venturi nozzle (N/m^2)

Q = volume flow rate of water at outlet tube (m^3/s)

V = water velocity passing through the venturi nozzle (m/s)

Figure 4 shows a schematic diagram of the venturi tube operation. In the case of a venturi tube positioned in the horizontal direction: $Z_1 = Z_2$; $V = V_1$ is the water velocity at venturi nozzle hole (m/s); V_2 is the velocity of water at the outlet port of the venturi tube which had a 25 mm hole in diameter (m/s); and P_2 is the hydrostatic pressure at the outlet port which is equivalent to $\gamma_w H$ (N/m^2). The pressure at a venturi nozzle can be calculated by the Bernoulli equation:

$$P = \gamma_w H + \tfrac{1}{2}\rho V_2^2 - \tfrac{1}{2}\rho V_1^2 \quad (5)$$

where P = pressure at venturi nozzle (N/m^2)

γ_w = specific weight of water (N/m^3)

ρ = water density (kg/m^3)

H = venturi nozzle depth (m)

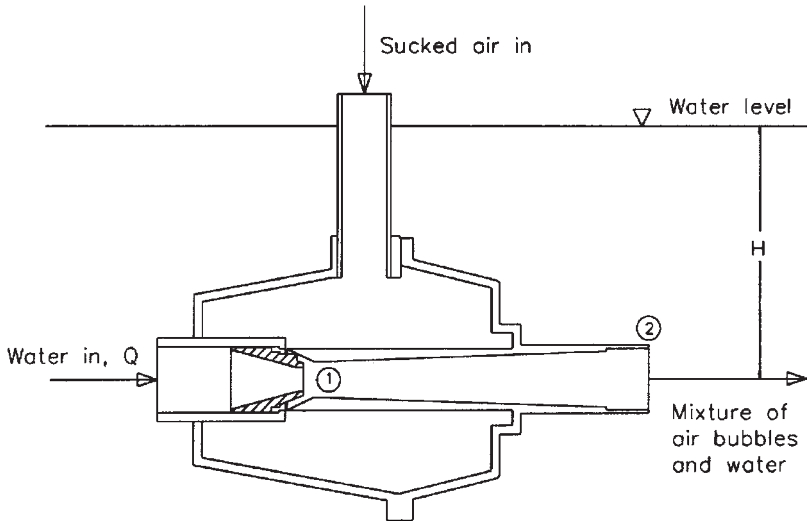

Figure 4 A schematic diagram of the venturi tube operation.

RESULTS AND DISCUSSIONS

Results related to mechanical testing

The propeller was run at a speed of 60 rpm. An average water velocity at 0.25 m distance in front of propeller prototype was 0.59 m/s. This water velocity value is not exceed permissible values suggested by Fortier and Sobey (1926) for silt loam bottom pond (0.6 m/s). The volume flow rate of water was 0.093 m^3/s.

The experiment was also conducted to find the velocity of water generated from the propeller at 1.00 m distance in front of the propeller and two water depths, i.e. 0.5 m and 1.0 m water depths. The average water velocity at a depth of 0.5 m was 0.20 m/s and at 1.0 m was 0.12 m/s, respectively. Figure 5 was obtained by plotting the data of water velocities on a schematic diagram.

Standard overall oxygen-transfer coefficient

The oxygen concentrations were measured for the duration of 24 min to 234 min in all tests. The shortest time of testing was approximately 24 to 25 min for a 10.3 mm nozzle diameter at 34 m/s water velocity at a depth of 1.0 m, while the longest duration was approximately 220 to 234 min for a 6.00 mm nozzle diameter at 18 m/s water velocity at a depth of 1.0 m.

The results of the overall oxygen-transfer coefficient for each trial was calculated for standard condition of 20°C temperature and summarized in Table 1. The standard oxygen-transfer coefficient increased slightly with increasing turbulence. The highest value was found to be 3.59 h^{-1} at 34 m/s water velocity at a depth of 0.5 m for a 10.3 mm diameter nozzle. The lowest standard overall oxygen-transfer coefficient was 0.34 h^{-1} at 18

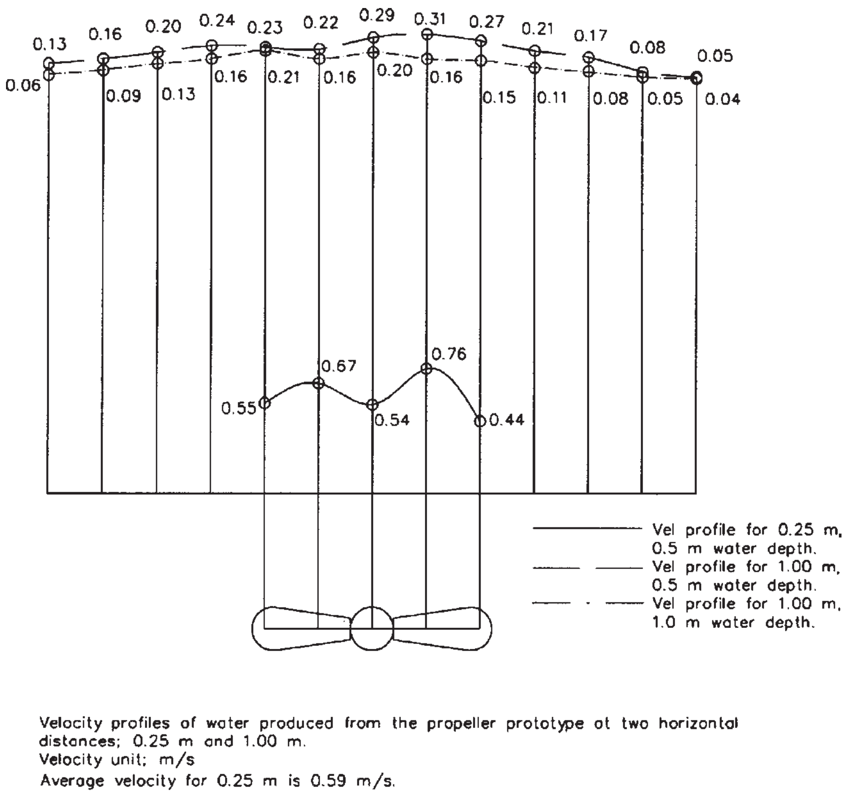

Figure 5 Schematic diagram of velocity profile generated from the propeller.

Table 1 Averages standard overall oxygen transfer coefficient of the aerator at a depth of 0.5 and 1.0 m for three different sizes of nozzle.

Nozzle diameter (mm)	Water depth (m)	$(K_La)_{20}$* Water velocity (m/s)					
		18	21	24	27	30	34
6.00	0.5	0.45(a)	0.61(a)	0.75(a)	0.88(a)	1.03(a)	1.24(a)
	1.0	0.34(a)	0.61(a)	0.72(a)	0.92(a)	1.09(a)	1.33(a)
8.14	0.5	0.78(b)	0.86(b)	1.24(b)	1.53(b)	1.73(b)	1.93(b)
	1.0	0.66(b)	0.82(b)	1.10(b)	1.47(b)	1.75(b)	1.96(b)
10.30	0.5	1.29(c)	1.47(c)	2.17(c)	3.05(c)	3.30(c)	3.59(c)
	1.0	1.04(c)	1.34(c)	2.00(c)	2.71(c)	3.06(c)	3.41(c)

* Means indicated by the same letter were not significantly different at P = 0.05. Differences between nozzles were not tested for significance. Vertical comparisons only.

m/s water velocity at a depth of 1.0 m for a 6.00 mm diameter nozzle. From the statistical analysis of the results there was no significant difference in the standard overall oxygen-transfer coefficient between two different water depths at each water velocity and nozzle.

Pressurized water exiting from a nozzle with higher velocity increases volumetric flow rate of water. High turbulence is created in this mixing area by shear forces and momentum transfer. Popel (1979) stated that turbulence in a system increases the overall oxygen-transfer coefficient. There are two reasons for this. Turbulence minimizes surface film thickness, which maximizes the overall oxygen-transfer coefficient. Turbulence also increases the average rate of surface renewal and frequency of renewal of the water interface.

Standard oxygen transfer rate tests

The SOTR for each trial was calculated and graphical derivation of SOTR as a function of water velocity for various diameter nozzles and two different water depths is shown in Figure 6.

Findings show that SOTR increased with increases in water velocity for all nozzles. The mixing of fine bubbles and strong current, accomplished by rotating propeller, quickly transported the DO to greater depth.

For a 6.00 mm diameter nozzle, for water velocity in the range of 18 to 24 m/s, SOTR at two water depths, 1.0 m and 0.5 m, were the same. For water velocity varying from 24 to 34 m/s, SOTR at the deeper point was slightly higher than at the shallow point. SOTR for 34 m/s water velocity at a depth of 1.0 m was 0.29 kg O_2/h, while at a depth 0.5 m it was 0.27 kg O_2/h.

For a 8.14 mm diameter nozzle, for water velocity in the range of 18 to 27 m/s, SOTR increased from 0.17 to 0.33 kg O_2/h at a depth of 0.5 m, while SOTR at the depth of 1.0 m increased from 0.14 to 0.32 kg O_2/h. However, the SOTR value increased equally to 0.38 kg O_2/h at 30 m/s water velocity for the two water depths. At the water velocity of 34 m/s, SOTR at the deeper point was slightly higher than at the shallow point, SOTR at a depth of 1.0 m was 0.43 kg O_2/h, while at the depth of 0.5 m it was 0.42 kg O_2/h.

In the case of a 10.3 mm diameter nozzle and water velocity in the range of 18 to 30 m/s, SOTR increased dramatically from 0.28 to 0.72 kg O_2/h at a depth of 0.5 m, while at 1.0 m it increased from 0.23 to 0.67 kg O_2/h. At water velocity ranging from 30 to 34 m/s, SOTR increased slightly

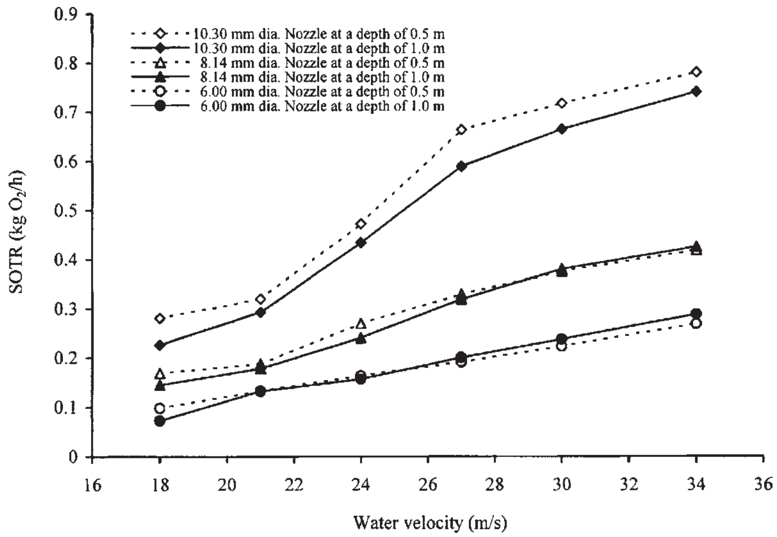

Figure 6 Graphical derivation of SOTR as a function of water velocity for various nozzles.

to 0.78 kg O_2/h at a depth of 0.5 m, while at the depth of 1.0 m it increased further to 0.74 kg O_2/h. However, the SOTR values at two different depths were very close.

SOTR had the tendency to be independent of water velocity. For a range of studied water velocity, it could be seen that there was a significant effect of turbulence on SOTR at different depths. A high volumetric flow rate, with high velocity, created higher turbulence than a low volumetric flow rate with low velocity. This is a complex process. However, it can be stated that the operations accomplished between turbulence process and rotating propeller quickly transport DO from shallow to greater depths. From the results, for a 6.00 mm and a 8.14 mm diameter nozzle within a range of water velocity from 18 to 34 m/s, the circulation affected DO transportation. But for a 10.3 mm diameter nozzle within the same range of water velocity, the circulation had no effects on DO transportation. However, the SOTR values at two different depths were close.

Determination of prediction equation

Fifty-four pairs of data were used to determine the best-fitting regression models of the relationship between SOTR and ($-PQ/V^2$) terms. These pairs of data were obtained from the three replications of oxygenating measurements and summarized. The graphical presentation of the relationship is plotted in Figure 7.

The general formula for all tests was found to be a linear regression line. The relationship among these variables showed a straight line with $R^2 = 0.93$ as follows:

$$SOTR = -0.0648 - 0.5945\ (PQ/V^2)$$

Based on the empirical formula, the quantity affecting the SOTR values, the most is the water volumetric flow rate. Since air volumetric flow rate in term of pressure different is function of water depth, water velocity passing through the venturi nozzle and the water velocity outlet. Thus, the water velocity has the second largest effect on SOTR. The lower they are, the higher the SOTR.

Comparisons of SOTR mean with actual and calculated values

Comparison of SOTR values among SOTR measured at a depth of 0.5 m, SOTR calculated values from prediction equation, and SOTR

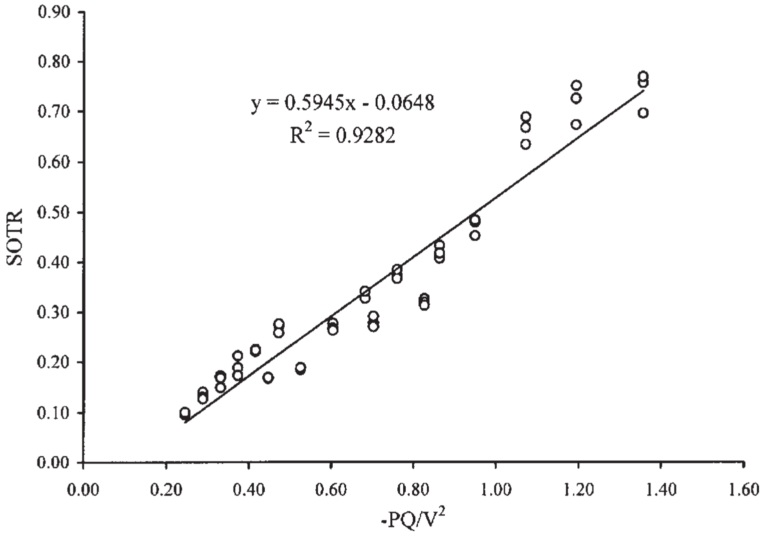

Figure 7 Master curve for relationship between SOTR and – PQ/V^2.

measured at a depth of 1.0 m are shown in Table 2. The statistical mean values indicated that the values of SOTR calculated from the prediction equations, the values of SOTR measured at a depth of 0.5 m and the values of SOTR measured at a depth of 1.0 m were all approximately the same, for P = 0.05.

Comparison of current aerators

Oxygenating tests of the aerator found that the highest value of SOTR was 0.78 kg O_2/h at 34 m/s water velocity at a depth of 0.5 m for a 10.30 mm diameter nozzle. The lowest value of SOTR was 0.07 kg O_2/h at 18 m/s water velocity at a depth of 1.0 m for a 6.00 mm diameter nozzle. Observations from the graphical derivation of SOTR as a function of water velocity (Figure 6), the SOTR values will be increased with the higher water velocities.

It is difficult to compare the oxygenating capacities of the aerator prototype with existing aerators. The aerator was designed in a new style and operated with two main functions. Its oxygenating capacities on the SOTR were tested by consideration their effects on soil erosion, while existing aerators were not. However, the highest value of SOTR of the aerator tests in the range of scope and limitation is higher than other existing aerators, i.e. the paddle wheel aerators and propeller-aspiration-pump aerators. Moreover, the aerator generated sufficient turbulence, enabling rapid transportation of dissolved oxygen from a upper to lower depth. The SOTRs at 0.5 m and 1.0 m were almost the same.

The paddle wheel aerators commonly used in Thailand had a flat plain paddle shape. Ahmad and Boyd (1987) conducted an experiment to test the influence of paddle shape on oxygen-transfer characteristics of paddle wheel aerators. An aeration tank dimensions were 13.0 m long, 6.1 m wide, and 1.2 m deep. Three flat paddles were 5, 10, and 15 cm wide on a 51 cm paddle wheel diameter with a paddle tip depth of 12.5 cm and a speed of 105 rpm. There were 9, 5, and 3 paddle wheels for 5, 10, and 15 cm wide paddles, respectively were tested for their oxygenating capacity. The SOTR values were 0.76, 0.70, and 0.69 kg O_2/h, respectively. In addition, Ruttanagosrigit *et al.* (1991) conducted an experiment to compare the oxygen-transfer efficiencies of two 1.5 kW propeller-aspirator-

Table 2 Comparisons of SOTR mean with actual and calculated values.

PQ/V^2	SOTR		
	Measured SOTR at 0.5 m	Calculated SOTR from prediction equation	Measured SOTR at 1.0 m
0.24	0.10	0.08	0.07
0.29	0.13	0.11	0.13
0.33	0.16	0.13	0.16
0.37	0.19	0.16	0.20
0.42	0.22	0.18	0.24
0.45	0.17	0.20	0.14
0.47	0.27	0.22	0.29
0.53	0.19	0.25	0.18
0.60	0.27	0.29	0.24
0.68	0.33	0.34	0.32
0.70	0.28	0.35	0.23
0.76	0.38	0.39	0.38
0.83	0.32	0.43	0.29
0.86	0.42	0.45	0.43
0.95	0.47	0.50	0.43
1.07	0.66	0.57	0.59
1.20	0.72	0.65	0.67
1.36	0.74	0.74	0.78

pump aerators and a 1.5 kW Taiwan-style paddle wheel aerator in an aeration tank with a water depth of 1.0 m and a volume of 49 m^3. One of propeller-aspiration-pump aerators was imported from the United States and rotated at 3,450 rpm speed, while the other was a modification of the imported model manufactured in Thailand and rotated at 1,730 rpm speed. The paddle wheel aerator had four paddle wheels contained six flat paddles with a 15 cm width, 61 cm wheel diameter, and a paddle tip depth of 9.0 cm rotated at 110 rpm. They found that the paddle wheel aerators had higher standard aeration efficiency than the both of propeller-aspirator-pump aerators. The SAE value of the paddle wheel aerator with four paddle wheels was 0.78 kg O_2 kW/h while the SAE values of propeller-aspirator-pump aerators made in United State and the SAE values of propeller-aspirator-pump aerators made in Thailand were 0.60 kg O_2 /kWh and 0.31 kg O_2 /kWh, respectively.

CONCLUSIONS

Oxygenating tests of a combined propeller and venturi tube system found that the highest value of SOTR was 0.78 kg O_2/h at 34 m/s water velocity at a depth of 0.5 m for a 10.3 mm diameter nozzle. The lowest value of SOTR was 0.07 kg O_2/h at 18 m/s water velocity at a depth of 1.0 m for a 6.00 mm diameter nozzle. A combined propeller and venturi tube system generated sufficient turbulence, enabling rapid transportation of dissolved oxygen from a higher to lower depth. The SOTR values at 0.5 m and 1.0 m, water velocity in the range of 18 to 34 m/s with 6.00, 8.14, and 10.3 mm diameter nozzles, were almost the same.

The highest value of SOTR of the aerator tests in the range of scope and limitation is higher than other existing aerators, i.e. the paddle wheel aerators and propeller-aspiration-pump aerators.

The experimental approaches using the dimensional analysis to model the prediction equation of the SOTR and ($-PQ/V^2$) were found to be feasible. The regression models of the relationship between SOTR and PQ/V^2 is as follows:

$$SOTR = - 0.0648 - 0.5945 (PQ/V^2)$$

Where P is the pressure inside the venturi tube, V is the water velocity passing through the nozzle, and Q is the volumetric flow rate of water. The result showed that the two variables have a linear relationship with $R^2 = 0.93$. The equation is valid when used in the range of 18 to 34 m/s water velocity with a 0.00051 to 0.0028 m^3/s volumetric flow rate at a depth of 0.5 m. Findings also indicated that the volumetric flow rate of water has a significantly higher effect than water velocity on SOTR.

The statistical mean values indicated that the values of SOTR calculated from the prediction equations, the values of SOTR measured at 0.5 m water depth and the values of SOTR measured at 1.0 m water depth were all approximately the same, for P = 0.05.

LITERATURE CITED

Ahmad, T. and C. E. Boyd. 1987. Design and performance of paddle wheel aerators. **Aquacultural Engineering** 7: 39-62.

Boyle, W.C. 1979. **Proceedings: Workshop towards an oxygen-transfer standard. US Environmental Protection Agency and American Society of Civil Engineers, Pacific Grove, California**, April 11-14, 1978, USEPA-600/9-78-021, Cincinnati, Ohio.

Boyd, C.E. and B.J. Watten. 1989. Aeration systems in aquaculture. CRC Critical Rev. **Aquatic Sciences** 1: 425-72.

Brockett, T. 1966. **Minimum pressure envelopes for modified NACA-66 sections with NACA a = 0.8 camber and buship type I and type II sections.** DT NSRDC Report No. 1780.

Colts, J. 1984. **Computation of dissolved gas concentrations in water as functions of temperature, salinity, and pressure.** Amercan Fisheries Society, Special Publication No. 14, Bethesda, Maryland.

Fast, A., K.E. Carpenter, V.J. Estilo and H.J. Gonzalez. 1988. Effects of water depth and artificial mixing dynamic Phillippines brackishwater shrimp ponds. **Aquacultural Engineering** 7: 349-361.

Fortier, S. and F.C. Sobey. 1926. Permissible canal velocities. **Transactions of the American Society of Civil Engineers** 89: 940-956.

Popel, H.J. 1979. **Aeration and Gas Transfer**. Academic Press, Delft University of Technology, Germany. 120 p.

Rogers, G.L. 1990. **Aeration and Artificial Circulation in Aquaculture.** Fish Farming International. July, 1990. 33 p.

Ruttanagosrigit, W., Y. Musig, C.E. Boyd and L. Sukchareon. 1991. Effect of salinity on oxygen transfer. **Aquacultural Engineering** 10: 121-131.

Stuckenburg, J.R., V.N. Wahbeh and R.E. McKinney. 1977. Experiences in evaluating and specifying aeration equipment. **Journal of Water Pollution Control Federation** 49: 66-82.