DOI: 10.4025/actascibiolsci.v33i2.7018

The impact of oxygen consumption by the shrimp *Litopenaeus vannamei* according to body weight, temperature, salinity and stocking density on pond aeration: a simulation

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ABSTRACT. A simulation was conducted to determinate the impact caused by the combination of *Litopenaeus vannamei* respiratory rate (mg O_2 shrimp^{-1} h^{-1}), the behavior of SOTR (kg O_2 h^{-1}) of mechanical aerators as a function of salinity, as well as the oxygen consumption rate of the pond water and soil (mg O_2 L^{-1} h^{-1}) on the aeration of shrimp ponds (1, 10, 50 and 100 ha) stocked with different densities (10, 40 and 120 shrimp m^{-2}), salinities (1, 13, 25 and 37 ppt), temperatures (20, 25 and 30°C), and shrimp wet weight (5, 10, 15 and 20 g). Results showed that under lower salinity, with larger shrimp, and higher stocking density, higher will be the quantity of required 2-HP aerators to keep dissolved oxygen over 50% saturation. In addition, under low salinity, with 5 and 10 g shrimp, independent of stocking density, more aerators per hectare are required and electricity cost is higher at 20°C and salinity 1 ppt. Less aerators and lower electricity cost was observed at 30°C, salinities of 25 and 37 ppt, and shrimp of 15 and 20 g.

Keywords: aeration, shrimp farming, respiration, oxygen consumption, density.

RESUMO. Impacto do consumo de oxigênio do camarão *Litopenaeus vannamei* em relação ao peso corporal, temperatura, salinidade na aeração do viveiro: uma simulação. Baseado em estudos de respiração de *Litopenaeus vannamei* (mg O_2 camarão^{-1} h^{-1}), comportamento do *Standard Oxygen Transfer Rate* (SOTR, kg O_2 h^{-1}) de aeradores mecânicos em função da salinidade, assim como as taxas de respiração da água e do solo (mg O_2 L^{-1} h^{-1}), uma simulação foi realizada a fim de determinar o impacto que estas três variáveis juntas têm sobre a aeração de viveiros (1, 10, 50 e 100 ha), estocados com diferentes densidades (10, 40 e 120 camarões m^{-2}) em salinidades de 1, 13, 25 e 37 ppm, temperaturas de 20, 25 e 30°C e peso úmido dos camarões de 5, 10, 15 e 20 g. Os resultados mostraram que em salinidades mais baixas, com animais maiores e maiores densidades de estocagem, maior será a quantidade de aeradores de 2 cv necessários para manter o oxigênio dissolvido acima de 50% da saturação. Igualmente, em baixas salinidades e com camarões de 5 e 10 g, independente da densidade de estocagem, mais aeradores por hectare serão necessários, e o custo com eletricidade é máximo em temperatura e salinidade de 20°C e 1 ppm. A menor exigência de aeradores e de eletricidade é obtida a uma temperatura de 30°C, salinidades de 25 a 37 ppm e com camarões de 15 e 20 g.

Palavras-chave: aeração, cultivo de camarão, consumo de oxigênio, densidade.

Introduction

Intensification of aquaculture in general has caused higher oxygen demand in the culture units and, consequently, in the number of aerators needed to fulfill satisfactorily the organisms demands (BOYD, 1998; HOPKINS et al., 1991). In the culture environments, the bacterial decomposition of organic matter, which occurs in the sediment, consumes a significant part of the dissolved oxygen available for respiratory processes (AVNIMELECH; RITVO, 2003). On the other hand, phytoplankton can be pointed out as the main responsible for the consumption of great part of the oxygen in the water (BOYD, 1990; GARCIA; BRUNE, 1991; MADENJIAN et al., 1987). Low level of water dissolved oxygen is considered to be the major limiting factor in intensive and semi-intensive aquaculture (BOYD; WATTEN, 1989). Critical concentrations of oxygen can be reached after a massive phytoplankton mortality and subsequent decomposition (CHANG; OUYANG, 1988). Boyd (1989) reports that the adverse effects of low oxygen concentrations usually result in reduced growth and higher susceptibility to diseases.

The number of aerators per unit of area can be calculated based on water respiration rate (phytoplankton), sediment respiration rate (decaying organic matter), cultured organisms respiration rate, and the Standard Oxygen Transfer Rate (SOTR) of the aerators (FAST; BOYD, 1992; SANTA; VINATEA, 2007). Currently, the total oxygen demand (TOD, kg O_2 h^{-1}), which is required to calculate the amount of HP ha^{-1}, in semi-intensive systems (biomass up to 7000 kg ha^{-1}) considers the shrimp respiration as 10 to 15% of the total pond respiration, about 0.01 to 0.16 mg O_2 L^{-1} h^{-1} (FAST; BOYD, 1992). In more extensive culture systems, shrimp respiration is not significant (MADENJIAN et al., 1987).

In order to achieve maximum operational efficiency in the culture of several organisms, further to the correct calculation of the number of aerators per unit of area, it is also important to consider the design of the machines (CANCINO et al., 2004; MOULICK et al., 2002), the aerators positioning according to the format and conditions of the pond (CALLE et al., 2003; NETTO; VINATEA, 2005; PETERSON et al., 2001), the paddle rotation speed of paddlewheel aerators (PETERSON; WALKER, 2002), and water salinity (BOYD; DANIELS, 1987; FAST et al., 1999; VINATEA; CARVALHO, 2007).

With the recent advances in intensive shrimp culture (BROWDY et al., 2001; BROWDY; MOSS, 2005; BRUNE et al., 2003; WASIELESKY et al., 2006), and the shortage of studies addressing the issue of calculating the number of aerators in this type of culture, it is necessary to generate information that contribute to the development of tools useful for this calculation and to chose the aerator most suitable to the conditions. Based on this, the objective of the present study was to analyze the impact of shrimp oxygen consumption, body weight, temperature, salinity, and stocking density on the number of aerators required in *Litopenaeus vannamei* culture ponds at densities of 10 to 120 shrimp m^{-2}.

Material and methods

The L. vannamei respiration rate (mg O_2 $shrimp^{-1}$ h^{-1}) as a function of temperature, salinity, and wet body weight (Table 1) reported by Bett and Vinatea (2009) was used for the calculation of shrimp oxygen consumption (mg O_2 L^{-1} h^{-1}) at different salinities (1, 13, 25 and 37 ppt), temperatures (20, 25 and 30°C), and stocking densities (10, 40 and 120 shrimp m^{-2}). In the calculation, one cubic meter of water per one square meter of area was considered, and the respiratory rate was multiplied by the number of shrimp in each hypothetical stocking density and then divided by 1000 to find the oxygen consumption values (mg O_2 L^{-1} h^{-1}).

To characterize the need of mechanical aeration (aerators ha^{-1}) in the shrimp ponds stocked with 10, 40, and 120 shrimp m^{-2}, the partial mean values (water O_2 consumption + sediment O_2 consumption) of 0.2, 1.0 and 2.0 mg O_2 L^{-1} h^{-1}, respectively, were considered based on the studies by Fast and Boyd (1992), Vinatea and Beltrame (2005), and Santa and Vinatea (2007). To these values, those referring to the shrimp oxygen consumption with specific body weight, water salinity and temperature (BETT; VINATEA, 2009) were added. Therefore, the oxygen demand (OD) was determined by Equation 1:

$$OD = OC + WR + SR \quad (1)$$

Where, OD is the oxygen demand (mg O_2 L^{-1} h^{-1}), OC is the shrimp oxygen consumption (mg O_2 L^{-1} h^{-1}), WR is the water oxygen consumption (mg O_2 L^{-1} h^{-1}), and SR is the sediment oxygen consumption (mg O_2 L^{-1} h^{-1}).

Next, considering the total pond volume (1, 10, 50 and 100 ha; 1 m water column), the pond total oxygen demand (TOD) was calculated by Equation 2:

$$TOD = OD \times V \times 10^{-3} \quad (2)$$

Where, TOD is the total oxygen demand of the pond (kg O_2 h^{-1}); V is the pond volume (m^3) and 10^{-3} the conversion factor (kg g^{-1}).

Table 1. Individual respiratory rate (y = mg O_2 $shrimp^{-1}$ h^{-1}) of *Litopenaeus vannamei* as a function of temperature, salinity and wet weight (x = g) (BETT; VINATEA, 2009).

Salinity	Temperature	y = a (weight)^b	R^2	5 g	10 g	15 g	20 g
	20°C	$y = 0.1044x^{1.2634}$	0.8647	0.80	1.91	3.20	4.60
37 ppt	25°C	$y = 0.4628x^{0.6000}$	0.6379	1.22	1.84	2.35	2.79
	30°C	$y = 0.4203x^{0.8798}$	0.8584	1.73	3.19	4.55	5.86
	20°C	$y = 0.1145x^{1.2160}$	0.9107	0.81	1.88	3.08	4.37
25 ppt	25°C	$y = 0.2358x^{1.0248}$	0.7727	1.23	2.50	3.78	5.08
	30°C	$y = 0.3343x^{0.9835}$	0.8885	1.63	3.22	4.80	6.36
	20°C	$y = 0.1615x^{1.1378}$	0.9141	1.01	2.22	3.52	4.88
13 ppt	25°C	$y = 0.2422x^{1.0192}$	0.8024	1.25	2.53	3.83	5.13
	30°C	$y = 0.3112x^{1.0223}$	0.9151	1.61	3.28	4.96	6.65
	20°C	$y = 0.1907x^{0.9388}$	0.9012	0.86	1.66	2.42	3.18
1 ppt	25°C	$y = 0.2049x^{1.0952}$	0.8031	1.19	2.55	3.98	5.45
	30°C	$y = 0.3011x^{1.1492}$	0.9605	1.91	4.25	6.77	9.42

Based on the standard oxygen transfer rate (SOTR, kg O_2 h^{-1}) of 2-HP (1.5 kW) paddlewheel aerators in salinities 1, 13, 25 and 37 ppt (VINATEA; CARVALHO, 2007), it was possible to determine the rate of oxygen transfer at 20°C (OTR_{20}) using Equation 3:

$$OTR_{20} = \frac{SOTR\,(Cs - C_m)}{Cs} \quad (3)$$

Where, OTR_{20} is the oxygen transfer rate at 20°C (kg O_2 h^{-1}), SOTR is the standard oxygen transfer rate (kg O_2 h^{-1}), Cs is the saturated oxygen concentration at 20°C (mg L^{-1}) and C_m is the minimum oxygen concentration allowed (in this case, 50% saturation). Then, the oxygen transfer rate was adjusted to temperatures 20, 25 and 30°C using Equation 4:

$$OTR_T = OTR_{20} \times 1{,}024^{T-20} \quad (4)$$

Where, OTR_T is the oxygen transfer rate adjusted to the simulation temperatures (kg O_2 h^{-1}) and T the water temperature (°C).

Once these values were calculated, the required number of aerators for 1, 10, 50 and 100 ha ponds were determined using Equation 5:

$$\text{Number of aerators} = \frac{TOD}{OTR_T} \quad (5)$$

These equations were used to generate calculation tables with the aid of the Microsoft Excel 2002 spreadsheet software.

Results and discussion

Based on the calculation of shrimp oxygen consumption rate (mg O_2 L^{-1} h^{-1}), as a function of salinity, temperature, stocking density and wet weight (Table 2), we verified that the combined effect of salinity and temperature on respiration rate (mg O_2 $shrimp^{-1}$ h^{-1}) is transferred to the consumption parameter, corroborating to findings by Bett and Vinatea (2009). Obviously, increase in weight and stocking density have a multiplying effect on this variable. According to calculations, at a stocking density of 10 shrimp m^{-2}, wet weight of 5 g, temperature of 20°C and salinities of 25 and 37 ppt, a low oxygen consumption is registered (0.008 mg O_2 L^{-1} h^{-1}); whereas at the density of 120 shrimp m^{-2}, 20 g wet weight, temperature of 30°C and salinity 1 ppt, the shrimp oxygen consumption is maximum (1.13 mg O_2 L^{-1} h^{-1}).

According to the *L. vannamei* shrimp oxygen consumption (BETT; VINATEA, 2009) and the SOTR of paddlewheel aerators (2 HP, 1.5 kW) as a function of salinity (VINATEA; CARVALHO, 2007), the oxygen transfer rate at 20, 25 and 30°C (OTR_t) was calculated to vary between 1.12 and 2.42 kg O_2 L^{-1}. Also in function of shrimp oxygen consumption, temperature, salinity, wet weight and stocking density, the total oxygen demand (TOD) varied between 2.08 and 13.3 kg O_2 L^{-1} (Table 3). Using data from Tables 2 and 3, it was possible to determine the number of aerators required for culture ponds of 1, 10, 50 and 100 ha, at the stocking densities of 10, 40 and 120 shrimp m^{-2}, at 20, 25 and 30°C and salinities of 1, 13, 25 and 37 ppt, for wet weights of 5 (Table 4), 10 (Table 5), 15 (Table 6) and 20 g (Table 7). The Table 8 shows the difference between the number of aerators in the best and worst culture conditions (salinity and temperature) corresponding to each wet weight, stocking density and culture area of 1 to 100 ha. The Table 9 presents the investment (US$) in aerators, also in the best and worst culture conditions (salinity and temperature) in function of shrimp wet weight, stocking density and culture area of 1 to 100 ha.

Table 2. *Litopenaeus vannamei* shrimp oxygen consumption rate (OC, mg O_2 L^{-1} h^{-1}) calculated from individual respiratory rate (mg O_2 $shrimp^{-1}$ h^{-1}) and as a function of salinity (1, 13, 25 and 37 ppt), temperature (20, 25 and 30°C), stocking density (10, 40 and 120 shrimp m^{-2}), and shrimp wet weight (5, 10, 15 and 20 g).

		10 m^{-2}				40 m^{-2}				120 m^{-2}			
Salinity	Temperature	5 g	10 g	15 g	20 g	5 g	10 g	15 g	20 g	5 g	10 g	15 g	20 g
	20°C	0.008	0.019	0.032	0.046	0.032	0.077	0.128	0.184	0.096	0.23	0.383	0.552
37 ppt	25°C	0.012	0.018	0.023	0.028	0.049	0.074	0.094	0.112	0.146	0.22	0.282	0.335
	30°C	0.017	0.032	0.046	0.059	0.069	0.127	0.182	0.235	0.208	0.38	0.546	0.704
	20°C	0.008	0.019	0.031	0.044	0.032	0.075	0.123	0.175	0.097	0.23	0.370	0.525
25 ppt	25°C	0.012	0.025	0.038	0.051	0.049	0.100	0.151	0.203	0.147	0.30	0.454	0.610
	30°C	0.016	0.032	0.048	0.064	0.065	0.129	0.192	0.255	0.195	0.39	0.575	0.764
	20°C	0.010	0.022	0.035	0.049	0.040	0.089	0.141	0.195	0.121	0.266	0.422	0.586
13 ppt	25°C	0.012	0.025	0.038	0.051	0.050	0.101	0.153	0.205	0.150	0.304	0.459	0.616
	30°C	0.016	0.033	0.050	0.067	0.065	0.131	0.198	0.266	0.194	0.393	0.595	0.798
1 ppt	20°C	0.009	0.017	0.024	0.032	0.035	0.066	0.097	0.127	0.104	0.199	0.291	0.381
	25°C	0.012	0.026	0.040	0.055	0.048	0.102	0.159	0.218	0.143	0.306	0.477	0.654
	30°C	0.019	0.042	0.101	0.141	0.077	0.170	0.271	0.377	0.230	0.509	0.812	1.130

Table 3. Oxygen transfer rate (OTRt, kg O_2 L^{-1}) and total oxygen demand (TOD, kg O_2 L^{-1}) for *Litopenaeus vannamei* shrimp with wet weight of 5, 10, 15 and 20 g as a function of temperature (°C), salinity (ppt) and stocking density (shrimp m^{-2}).

				TOD (5 g)			TOD (10 g)			TOD (15 g)			TOD (20 g)		
Salinity	Temperature	SOTR	OTRt	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
	20°C	3.57	1.828	2.08	2.32	2.96	2.19	2.77	4.30	2.32	3.28	5.83	2.46	3.84	7.52
37 ppt	25°C	3.57	2.010	2.12	2.49	3.46	2.18	2.74	4.21	2.23	2.94	4.82	2.28	3.12	5.35
	30°C	3.57	2.317	2.17	2.69	4.08	2.32	3.27	5.82	2.46	3.82	7.46	2.59	4.35	9.04
	20°C	3.75	1.920	2.08	2.32	2.97	2.19	2.75	4.26	2.31	3.23	5.70	2.44	3.75	7.25
25 ppt	25°C	3.75	2.111	2.12	2.49	3.47	2.25	3.00	5.00	2.38	3.51	6.54	2.51	4.03	8.10
	30°C	3.75	2.434	2.16	2.65	3.95	2.32	3.29	5.86	2.48	3.92	7.75	2.64	4.55	9.64
	20°C	3.19	1.633	2.10	2.40	3.21	2.22	2.89	4.66	2.35	3.41	6.22	2.49	3.95	7.86
13 ppt	25°C	3.19	1.796	2.12	2.50	3.50	2.25	3.01	5.04	2.38	3.53	6.59	2.51	4.05	8.16
	30°C	3.19	2.070	2.16	2.65	3.94	2.33	3.31	5.93	2.50	3.98	7.95	2.67	4.66	9.98
	20°C	2.20	1.126	2.09	2.35	3.04	2.17	2.66	3.99	2.24	2.97	4.91	2.32	3.27	5.81
1 ppt	25°C	2.20	1.238	2.12	2.48	3.43	2.26	3.02	5.06	2.40	3.59	6.77	2.55	4.18	8.54
	30°C	2.20	1.428	2.19	2.77	4.30	2.42	3.70	7.09	3.01	4.71	10.12	3.41	5.77	13.30

Table 4. Number of 2-HP (1.5 kW) paddlewheel aerators required for ponds stocked with 5 g wet weight *Litopenaeus vannamei*, considering culture areas of 1, 10, 50 and 100 ha, salinities of 1, 13, 25 and 37 ppt, temperatures of 20, 25 and 30°C, densities of 10, 40 and 120 shrimp m^{-2}, TOD of 2.1 to 4.3 kg O_2 h^{-1} and OTRt of 1.1 to 2.4 kg O_2 h^{-1}.

		1 ha			10 ha			50 ha			100 ha		
Salinity	Temperature	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
	20°C	1.1	1.3	1.6	11.4	12.7	16.2	56.9	63.4	80.9	113.8	126.9	161.8
37 ppt	25°C	1.1	1.2	1.7	10.6	12.4	17.2	52.8	61.9	86.0	105.6	123.7	172.1
	30°C	0.9	1.2	1.8	9.4	11.6	17.6	46.9	58.1	88.0	93.8	116.2	176.0
	20°C	1.1	1.2	1.5	10.8	12.1	15.5	54.2	60.5	77.4	108.4	121.1	154.8
25 ppt	25°C	1.0	1.2	1.6	10.1	11.8	16.4	50.3	59.0	82.2	100.6	118.0	164.5
	30°C	0.9	1.1	1.6	8.9	10.9	16.2	44.4	54.5	81.2	88.9	108.9	162.4
	20°C	1.3	1.5	2.0	12.9	14.7	19.7	64.3	73.6	98.3	128.6	147.1	196.5
13 ppt	25°C	1.2	1.4	1.9	11.8	13.9	19.5	59.2	69.6	97.4	118.3	139.2	194.8
	30°C	1.0	1.3	1.9	10.4	12.8	19.0	52.2	63.9	95.0	104.4	127.8	190.1
	20°C	1.9	2.1	2.7	18.5	20.8	27.0	92.6	104.1	134.8	185.2	208.2	269.6
1 ppt	25°C	1.7	2.0	2.8	17.1	20.0	27.7	85.6	100.0	138.6	171.1	200.1	277.2
	30°C	1.5	1.9	3.0	15.3	19.4	30.1	76.7	96.8	150.5	153.5	193.7	300.9
	Maximum	1.9	2.1	3.0	18.5	20.8	30.1	92.6	104.1	150.5	185.2	208.2	300.9
	Minimum	0.9	1.1	1.5	8.9	10.9	15.5	44.4	54.5	77.4	88.9	108.9	154.8
	Difference	1.0	1.0	1.5	9.6	9.9	14.6	48.2	49.7	73.1	96.4	99.3	146.1

Table 5. Number of 2-HP (1.5 kW) paddlewheel aerators required for ponds stocked with 10 g wet weight *Litopenaeus vannamei*, considering culture areas of 1, 10, 50 and 100 ha, salinities of 1, 13, 25 and 37 ppt, temperatures of 20, 25 and 30°C, densities of 10, 40 and 120 shrimp m^{-2}, TOD of 2.2 to 7.1 kg O_2 h^{-1} and OTRt of 1.1 to 2.4 kg O_2 h^{-1}.

		1 ha			10 ha			50 ha			100 ha		
Salinity	Temperature	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
	20°C	1.2	1.5	2.4	12.0	15.2	23.5	59.9	75.8	117.6	119.9	151.5	235.3
37 ppt	25°C	1.1	1.4	2.1	10.8	13.6	20.9	54.2	68.2	104.7	108.5	136.3	209.5
	30°C	1.0	1.4	2.5	10.0	14.1	25.1	50.1	70.6	125.6	100.1	141.1	251.2
	20°C	1.1	1.4	2.2	11.4	14.3	22.2	57.0	71.7	110.9	114.0	143.4	221.8
25 ppt	25°C	1.1	1.4	2.4	10.7	14.2	23.7	53.3	71.0	118.3	106.6	142.0	236.7
	30°C	1.0	1.4	2.4	9.5	13.5	24.1	47.7	67.5	120.4	95.4	135.1	240.9
	20°C	1.4	1.8	2.9	13.6	17.7	28.5	68.0	88.4	142.7	136.0	176.8	285.4
13 ppt	25°C	1.3	1.7	2.8	12.5	16.8	28.1	62.7	83.9	140.3	125.5	167.8	280.5
	30°C	1.1	1.6	2.9	11.2	16.0	28.6	56.2	79.9	143.2	112.4	159.9	286.5
	20°C	1.9	2.4	3.5	19.2	23.6	35.4	96.1	118.2	177.0	192.3	236.4	354.0
1 ppt	25°C	1.8	2.4	4.1	18.2	24.4	40.9	91.0	121.9	204.3	182.1	243.9	408.7
	30°C	1.7	2.6	5.0	17.0	25.9	49.7	84.9	129.5	248.4	169.8	259.0	496.8
	Maximum	1.9	2.6	5.0	19.2	25.9	49.7	96.1	129.5	248.4	192.3	259.0	496.8
	Minimum	1.0	1.4	2.1	9.5	13.5	20.9	47.7	67.5	104.7	95.4	135.1	209.5
	Difference	1.0	1.2	2.9	9.7	12.4	28.7	48.4	62.0	143.7	96.9	123.9	287.4

Table 6. Number of 2-HP (1.5 kW) paddlewheel aerators required for ponds stocked with 15 g wet weight *Litopenaeus vannamei*, considering culture areas of 1, 10, 50 and 100 ha, salinities of 1, 13, 25 and 37 ppt, temperatures of 20, 25 and 30°C, densities of 10, 40 and 120 shrimp m^{-2}, TOD of 2.2 to 10.1 kg O_2 h^{-1} and OTRt of 1.1 to 2.4 kg O_2 h^{-1}.

		1 ha			10 ha			50 ha			100 ha		
Salinity	Temperature	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
	20°C	1.3	1.8	3.2	12.7	17.9	31.9	63.5	89.7	159.6	126.9	179.4	319.2
37 ppt	25°C	1.1	1.5	2.4	11.1	14.6	24.0	55.6	73.1	119.9	111.2	146.3	239.8
	30°C	1.1	1.6	3.2	10.6	16.5	32.2	53.0	82.5	161.1	106.0	164.9	322.1
	20°C	1.2	1.7	3.0	12.0	16.8	29.7	60.1	84.2	148.4	120.2	168.4	296.8
25 ppt	25°C	1.1	1.7	3.1	11.3	16.6	31.0	56.3	83.2	154.9	112.7	166.4	309.8
	30°C	1.0	1.6	3.2	10.2	16.1	31.9	50.9	80.5	159.3	101.9	161.0	318.6

Continue...

...continuation

		1 ha			10 ha			50 ha			100 ha		
Salinity	Temperature	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
	20°C	1.4	2.1	3.8	14.4	20.9	38.1	72.0	104.3	190.5	144.0	208.6	380.9
13 ppt	25°C	1.3	2.0	3.7	13.3	19.7	36.7	66.3	98.3	183.5	132.7	196.6	367.1
	30°C	1.2	1.9	3.8	12.1	19.2	38.4	60.3	96.2	192.0	120.5	192.4	384.0
	20°C	2.0	2.6	4.4	19.9	26.4	43.6	99.5	131.8	217.9	199.1	263.6	435.8
1 ppt	25°C	1.9	2.9	5.5	19.4	29.0	54.7	96.8	145.0	273.4	193.6	289.9	546.9
	30°C	2.1	3.3	7.1	21.1	33.0	70.9	105.6	164.8	354.3	211.1	329.6	708.6
	Maximum	2.1	3.3	7.1	21.1	33.0	70.9	105.6	164.8	354.3	211.1	329.6	708.6
	Minimum	1.0	1.5	2.4	10.2	14.6	24.0	50.9	73.1	119.9	101.9	146.3	239.8
	Difference	1.1	1.8	4.7	10.9	18.3	46.9	54.6	91.6	234.4	109.3	183.3	468.8

Table 7. Number of 2-HP (1.5 kW) paddlewheel aerators required for ponds stocked with 20 g wet weight *Litopenaeus vannamei*, considering culture areas of 1, 10, 50 and 100 ha, salinities of 1, 13, 25 and 37 ppt, temperatures of 20, 25 and 30°C, densities of 10, 40 and 120 shrimp m^{-2}, TOD of 2.2 to 13.2 kg O_2 h^{-1} and OTRt of 1.1 to 2.4 kg O_2 h^{-1}.

		1 ha			10 ha			50 ha			100 ha		
Salinity	Temperature	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
	20°C	1.3	2.1	4.1	13.5	21.0	41.1	67.3	105.0	205.6	134.6	210.0	411.2
37 ppt	25°C	1.1	1.6	2.7	11.3	15.5	26.6	56.7	77.5	133.1	113.4	155.1	266.3
	30°C	1.1	1.9	3.9	11.2	18.8	39.0	55.8	93.8	195.0	111.6	187.6	390.0
	20°C	1.3	2.0	3.8	12.7	19.5	37.8	63.5	97.6	188.8	127.1	195.3	377.5
25 ppt	25°C	1.2	1.9	3.8	11.9	19.1	38.3	59.4	95.5	191.7	118.8	191.0	383.5
	30°C	1.1	1.9	4.0	10.8	18.7	39.6	54.2	93.4	198.0	108.3	186.8	395.9
	20°C	1.5	2.4	4.8	15.2	24.2	48.1	76.2	121.0	240.5	152.3	242.0	481.0
13 ppt	25°C	1.4	2.3	4.5	14.0	22.6	45.4	70.0	112.8	227.1	139.9	225.7	454.2
	30°C	1.3	2.3	4.8	12.9	22.5	48.2	64.4	112.6	241.1	128.7	225.2	482.3
	20°C	2.1	2.9	5.2	20.6	29.0	51.6	102.9	145.2	257.9	205.7	290.3	515.8
1 ppt	25°C	2.1	3.4	6.9	20.5	33.8	69.0	102.7	168.8	344.8	205.5	337.5	689.6
	30°C	2.4	4.0	9.3	23.9	40.4	93.1	119.5	201.9	465.7	239.0	403.8	931.4
	Maximum	2.4	4.0	9.3	23.9	40.4	93.1	119.5	201.9	465.7	239.0	403.8	931.4
	Minimum	1.1	1.6	2.7	10.8	15.5	26.6	54.2	77.5	133.1	108.3	155.1	266.3
	Difference	1.3	2.5	6.7	13.1	24.9	66.5	65.3	124.4	332.6	130.7	248.7	665.1

Table 8. Difference between the number of 2-HP (1.5 kW) paddlewheel aerators required for ponds in the best and worst culture conditions (maximum number of aerators minus minimum number of aerators, tables 4 to 7) of ponds stocked with 5, 10, 15 and 20 g wet weight *Litopenaeus vannamei*, considering culture areas of 1, 10, 50 and 100 ha and densities of 10, 40 and 120 shrimp m^{-2}.

	1 ha			10 ha			50 ha			100 ha		
Weight	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
5 g	1.0	1.0	1.5	9.6	9.9	14.6	48.2	49.7	73.1	96.4	99.3	146.1
10 g	1.0	1.2	2.9	9.7	12.4	28.7	48.4	62.0	143.7	96.9	123.9	287.4
15 g	1.1	1.8	4.7	10.9	18.3	46.9	54.6	91.6	234.4	109.3	183.3	468.8
20 g	1.3	2.5	6.7	13.1	24.9	66.5	65.3	124.4	332.6	130.7	248.7	665.1

Table 9. Difference in investment (US$) in 2-HP (1.5 kW) paddlewheel aerators in the best and worst culture conditions (maximum number of aerators minus minimum number of aerators, tables 4 to 7) of ponds stocked with 5, 10, 15 and 20 g wet weight *Litopenaeus vannamei*, considering unit price of US$ 350, culture areas of 1, 10, 50 and 100 ha and densities of 10, 40 and 120 shrimp m^{-2}.

	1 ha			10 ha			50 ha			100 ha		
Weight	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
5 g	337.3	347.6	511.4	3372.9	3476.1	5113.8	16864.3	17380.5	25568.8	33728.5	34761.0	51137.7
10 g	339.0	433.7	1005.8	3390.3	4337.5	10057.8	16951.4	21687.5	50289.1	33902.9	43374.9	100578.2
15 g	382.4	641.5	1640.7	3824.1	6415.4	16407.5	19120.5	32076.8	82037.3	38241.0	64153.6	164074.6
20 g	457.3	870.6	2327.9	4573.2	8705.8	23278.9	22865.9	43529.2	116394.3	45731.7	87058.3	232788.6

Table 10. Difference in monthly electricity cost (US$) of 2-HP (1.5 kW) paddlewheel aerators in the best and worst culture conditions (maximum number of aerators minus minimum number of aerators, tables 4 to 7) of ponds stocked with 5, 10, 15 and 20 g wet weight *Litopenaeus vannamei*, considering US$ 0.1 kWh^{-1}, 10 hours of operation per day, culture areas of 1, 10, 50 and 100 ha and densities of 10, 40 and 120 shrimp m^{-2}.

	1 ha			10 ha			50 ha			100 ha		
Weight	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
5 g	43.4	44.7	65.7	433.7	446.9	657.5	2168.3	2234.6	3287.4	4336.5	4469.3	6574.8
10 g	43.6	55.8	129.3	435.9	557.7	1293.1	2179.5	2788.4	6465.7	4358.9	5576.8	12931.5
15 g	49.2	82.5	211.0	491.7	824.8	2109.5	2458.4	4124.2	10547.7	4916.7	8248.3	21095.3
20 g	58.8	111.9	299.3	588.0	1119.3	2993.0	2939.9	5596.6	14965.0	5879.8	11193.2	29930.0

Tables 10 and 11 bring the effect of such differences on the monthly and annual electricity costs (US$), respectively, considering US$ 0.1 kWh^{-1}, 10 hours operation per day and 10 months of culture per year.

Fast and Boyd (1992) calculated the number of required aerators per unit of area considering the

Table 11. Difference in annual electricity costs (US$) of 2-HP (1.5 kW) paddlewheel aerators in the best and worst culture conditions (maximum number of aerators minus minimum number of aerators, tables 4 to 7) of ponds stocked with 5, 10, 15 and 20 g wet weight *Litopenaeus vannamei*, considering US$ 0.1 kWh^{-1}, 10 hours of operation per day, 10 months per year, culture areas of 1, 10, 50 and 100 ha and densities of 10, 40 and 120 shrimp m^{-2}.

	1 ha			10 ha			50 ha			100 ha		
Weight	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}	10 m^{-2}	40 m^{-2}	120 m^{-2}
5 g	433.7	446.9	657.5	4336.5	4469.3	6574.8	21682.6	22346.4	32874.2	43365.2	44692.7	65748.5
10 g	435.9	557.7	1293.1	4358.9	5576.8	12931.5	21794.7	27883.9	64657.4	43589.4	55767.8	129314.8
15 g	491.7	824.8	2109.5	4916.7	8248.3	21095.3	24583.5	41241.6	105476.6	49167.0	82483.3	210953.1
20 g	588.0	1119.3	2993.0	5879.8	11193.2	29930.0	29399.0	55966.1	149649.8	58797.9	111932.1	299299.7

relationship existing between total oxygen demand (TOD) and the oxygen transfer rate of aerators (OTRt), according to water temperature. In TOD consumption of 0.01 to 0.16 mg L^{-1} h^{-1} for semi-intensive *Penaeus monodon* shrimp culture with a biomass of up to 7000 kg ha^{-1}. Comparing the maximum OC values with maximum WR and SR values of 0.86 and 0.72 mg L^{-1} h^{-1}, respectively, in relatively low stocking densities as in semi-intensive cultures, animal's oxygen consumption represents approximately 9% of the pond total oxygen demand; thus, daily oxygen losses are mainly due to pond water and sediment respirations, as previously reported by Santa and Vinatea (2007).

Regarding the culture systems, a number of authors agree that the oxygen demand increases proportionally with the increase in stocking density (BOYD, 1998; BRUNE et al., 2003), and it can become critical in cultures with recirculation and/or zero-water exchange (HOPKINS et al., 1995; BROWDY et al., 2001; BROWDY; MOSS, 2005; WASIELESKY et al., 2006). Nevertheless, studies on oxygen consumption of animals at high densities and aeration requirements are still scarce. According to the simulation results, at a density of 120 shrimp m^{-2}, 20-g (wet weight) shrimp oxygen consumption can be as high as 1.13 mg L^{-1} h^{-1}. Assuming, based on the calculations, that the sum of the rest of the respiration system (WR + SR) is 2.0 mg L^{-1} h^{-1}, shrimp oxygen consumption would be responsible for 36% of the pond total oxygen demand, i.e., four times higher than the value reported by Fast and Boyd (1992) for semi-intensive cultures.

Salinity seems to be a crucial factor for the calculation of the number of aerators because of its impact on shrimp respiration (ZHANG et al., 2006; LI et al., 2007; BETT; VINATEA, 2009), and on the behavior of the SOTR of the aerator used (VINATEA; CARVALHO, 2007; FAST et al., 1999). In the simulation it was clear that the lower the salinity, higher the number of aerators and electricity consumption, resulting in great operational cost. As recently the possibility of farming marine shrimp in freshwater or low salinity waters has been taken into consideration (McINTOSH; FITZSIMMONS, 2003; SAMOCHA et al., 2002), we should keep in mind that besides the mortality problems resulting from poor ionic composition (McGRAW; SCARPA, 2004; SAOUD et al., 2003; VALENÇA; MENDES, 2009), this type of culture will imply in high investment in aerators and high production costs due to the increased cost of oxygen caused by low Standard Aeration Efficiency (SAE).

Based on the results of this study, the calculation of the number of aerators for extensive, semi-intensive and intensive cultures according to shrimp size, stocking density, water temperature and salinity, and SOTR of the aerators as a function of salinity, is relatively reliable. However, field studies are required to confirm and adjust the presented calculations.

Conclusion

We conclude that the calculation of the number of aerators for extensive, semi-intensive and intensive cultures according to shrimp size, stocking density, water temperature and salinity, and SOTR of the aerators as a function of salinity, is relatively reliable.

Acknowledgements

We wish to thank Professor Elpídio Beltrame (*in memorian*), who was the coordinator of the Marine Shrimp Laboratory, Federal University of Santa Catarina (LCM/UFSC), at time the study was performed; the Post-graduate Program on Aquaculture (UFSC) for the partial financial support; Bernauer Aquacultura Ltda. for providing the equipment.

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Received on May 11, 2009.
Accepted on September 2, 2009.