

DISCUSSION

Of: **Oxygen-Transfer Efficiency of Fine-Pore Diffused Aeration Systems: Energy Intensity as a Unifying Evaluation Parameter**, B.W. Newbry, **70**, 323 (1998).

R. Iranpour, A. Magallanes, M. Stenstrom, J.J. Lee, A. Torkian

This is an excellent paper on an important topic. The author has provided a detailed exposition of the derivation of a quantitative theory of oxygen transfer in clean water from basic physical and chemical principles as background for his argument that his energy-intensity parameter provides a uniform basis for evaluating performance of the many types of fine-bubble aeration devices that are currently available. The great care with which Newbry presents his theory has made it possible to rethink many aspects of oxygen-transfer testing in both clean and dirty water. Thus, several questions are raised by his work, as follows:

First, has he looked into the consequences of his theory's prediction that bubbles at the bottom of the size range covered by the theory could reach equilibrium with surrounding water well before they reach the surface of an apparatus of realistic size? This question is prompted by the following reasoning.

He derives the following formula for R_{O_2} , the rate of oxygen transfer per unit volume of liquid, in grams per cubic meter per second, for bubbles of a uniform diameter, D :

$$R_{O_2} = 3.171 \times 10^{-3} D^{-7/4} (H + 3.298 \times 10^{-3} H^2) Q_A / V_w$$

Where

H = distance through which the bubbles rise, m;

Q_A = volumetric airflow, m³/s; and

V_w = volume of water in which transfer occurs, m³.

This formula depends on an application of Stokes' law that assumes a constant value for a friction factor for the air bubble. The friction factor is approximately constant for the Reynolds number (Re) for the bubble in the range $500 < Re < 200\,000$. The Reynolds number depends on D , such that for $D = 0.002$ m, $Re = 480$, and for $D = 0.015$ m, $Re = 9900$. Thus, this formula holds for bubbles of diameters from 0.002 m up to sizes that must be considered as medium or coarse bubbles.

To estimate fractional mass-transfer efficiency of oxygen, this formula is multiplied by the volume to remove volume dependence, and it is divided by rate of oxygen mass flow in the air to find the ratio of oxygen mass-transfer rate to oxygen mass flow rate

$$SOTE = R_{O_2} V_w / (0.23 Q_A \rho_A)$$

Where

SOTE = standard oxygen-transfer efficiency;

ρ_A = density of air under standard conditions, 1.28×10^3 g/m³; and

0.23 = mass fraction of oxygen in the atmosphere.

Simplifying gives

$$SOTE = 1.068 \times 10^{-5} D^{-7/4} (H + 3.298 \times 10^{-3} H^2)$$

A common depth for aeration basins in large wastewater treatment plants is approximately 4.5 m (15 ft). Evaluation of this last formula to estimate SOTE for $H = 4.5$ m using millimeter increments for D from $D = 0.002$ to 0.010 m (2 to 10 mm) is shown in Table D1, which shows that, for diameters of 2 or 3 mm, predicted efficiency is greater than 100%. Although such a result may initially seem nonsensical, further thought shows that it should be understood as showing that Newbry's theory predicts that bubbles this small reach equilibrium with surrounding anoxic water in less than 4.5 m of rise.

The second question that arises is have efforts ever been made to test clean water oxygen-transfer efficiency (OTE) under more realistic physical conditions than are commonly used in manufacturer tests, such as using warmer air and water with CO₂? Newbry's work allows a clearer understanding of how the commonly calculated α factor (reduction in OTE) overstates the decline in performance from clean water conditions to process conditions because physical conditions of clean water testing by manufacturers are sufficiently unrealistic that the results of these tests overestimate the oxygen transfer that is considered feasible.

He derives the formula given above for R_{O_2} by setting up and solving a quadratic equation for M_{O_2} , total mass of oxygen transferred per unit volume of water in time T (time in which a bubble rises to the surface), and then using $R_{O_2} = M_{O_2}/T$. Derivation of the equation for M_{O_2} assumes anoxic water, as is commonly used in clean water OTE tests. However, under process conditions, transfer of O₂ to water is to some extent balanced by a transfer of CO₂ from water to bubble. It is common for offgas from an aeration basin to have a mole fraction of 2 or 3% CO₂ (Ewing Engineering Company, 1993, and U.S. EPA, 1989); so a more realistic test of clean water OTE would use anoxic water with CO₂.

Newbry's derivation can be modified to include not only M_{O_2} , but also M_{CO_2} , mass of CO₂ transferred, by letting $M_{CO_2} = aM_{O_2}$, for some multiplicative factor a . Because CO₂ transfer counteracts mass change caused by O₂ transfer, M_{O_2} is replaced by $(1 - a)M_{O_2}$ in the expression for the mass of the bubble. Analysis of Newbry's equations 21 to 26 with this change shows that M_{O_2} should be highly sensitive to CO₂ transfer. In this case, it is no longer possible to ignore the constant term of the quadratic equation, as he validly does on the assumption of no CO₂. For nonzero a , the parabola shifts to the left, and for $a \geq 1$ (which is possible as CO₂ has a higher molecular weight than O₂ and mole fractions exchanged may be approximately equal), and the physically meaningful positive solution of the parabola becomes small. This is plausible in physical terms because CO₂ continues to diffuse in as O₂ diffuses out, causing a more rapid decrease of O₂ partial

Table D1—Predicted efficiencies for 2-mm diameters or greater.

<i>D</i> , mm	Oxygen transfer efficiency, %
2	286
3	141
4	85
5	57
6	42
7	32
8	25
9	21
10	17

pressure (and thus a decrease of the driving force propelling its diffusion into water) than what Newbry's formulas assume.

We have also observed that compression by blowers raises temperature in an air distribution system to approximately 75 °C and the temperature of offgas as it emerges from the surface is typically approximately 35 °C (Iranpour et al., 1998, and Metcalf and Eddy, 1979). A 55 °C temperature rise from standard conditions at 20 °C is an approximate 20% rise in absolute temperature. Applying the perfect gas law $PV = nrt$ to spherical bubbles of a known diameter, as Newbry does, makes number of molecules, n , in a bubble inversely proportional to the absolute temperature, t , so that for a specified flow of Q_A in standard cubic meters of air per second, a higher temperature implies a larger number of bubbles, and so a higher total surface area and lower oxygen mass and total mass in each bubble. Cooling also tends to counteract expansion of the bubble as it rises through decreasing water pressure, maintaining a higher surface-to-volume ratio. Although the saturation concentration of O₂ in water decreases with increasing temperature, it probably would be valid to assume that the effect of heat transfer from a single bubble is negligible, as is assumed for the oxygen transfer from a single bubble in Newbry's discussion. Thus, it seems that higher air temperature tends to enhance O₂ transfer from what would be expected under standard conditions.

The third question is how much would results of this theory be changed by considering that oxygen concentration in a bubble declines approximately exponentially with time instead of linearly as assumed by Newbry's approximation 3? This point follows, as above, from observing that transfer rate is proportional to concentration gradient and thus, for anoxic water, to O₂ partial pressure. Thus, transfer rate slows as the bubble becomes depleted even when there is no CO₂ in the water. The resulting tendency for oxygen transfer to be most rapid deep in the tank would further be amplified by the observation that small bubbles may reach equilibrium with water before reaching the surface, even with the linear transfer rate assumption. Results consistent with this idea appear in Newbry's Table 1, where he presents data for diffuser number 2, a membrane disk that he tested for a confidential client. At a depth of 5.97 m, with air flows of 4.72×10^{-4} to 4.77×10^{-4} Nm³/s, SOTEs of 39.22 to 41.65% were observed, but at a depth of 8.90 m with diffusers of the same size and airflow, SOTEs of 48.3 to 48.7% were observed. In short, increasing depth of submergence by approximately 50% increased SOTE by less than 25%.

As development of a theory along similar lines as in this paper, but with more realistic assumptions, would be much more difficult mathematically, it is appropriate to begin with a simplified ap-

proach like Newbry's even if the primary focus is on mathematical development instead of on developing a background for the energy intensity parameter. However, we believe that the success of Newbry's development shows that additional effort would be justified to develop both more realistic laboratory tests for clean water and more realistic mathematical models. We would like to close by encouraging him or other interested researchers to undertake such work and we invite correspondence from anyone interested in further details.

Acknowledgments

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Closure

B.W. Newbry

The discussion raises several fundamental questions and suggests several valuable extensions to the theory and results presented in the paper. The theory developed in the paper was to explain oxygen-transfer data from conventional fine-pore diffused-aeration systems. The discussion offers excellent points that may extend the theory beyond the bounds of the data and are likely to be useful in future research.

The points raised in the discussion do not affect the theory developed in the paper as it applies to conventional systems. For other systems (specifically, those using very deep tanks and very fine bubbles), points raised in the discussion may become important and must be considered. The questions posed by the discussion are summarized as follows:

1. Examining the oxygen-transfer rate expression shows that oxygen equilibrium is predicted between air bubbles and surrounding water before the bubbles reach the top of the water column. That is, oxygen equilibrium is an obvious physical boundary condition. How does this affect the theory developed in the paper?
2. Aeration systems typically operate under conditions that differ from those used in manufacturers' performance tests. In particular, air temperatures and water CO₂ concentrations are higher in operating systems than in test conditions. Have clean water oxygen-transfer efficiency tests been conducted under "more realistic physical conditions" and how do these conditions affect performance?
3. Oxygen concentration in a rising bubble declines approximately exponentially with time. How does this affect the theory developed in the paper?

Table C1—Predicted SOTEs for various bubble diameters.

d_0 , mm	SOTE, %
2	204
3	100
4	61
5	41
6	30
7	23
8	18
9	15
10	12

Oxygen Equilibrium as a Boundary Condition

The first question posed in the discussion comes from observing that standard oxygen-transfer efficiency (SOTE) increases as air bubble diameter decreases and water column height increases. The discussion suggests that the theory predicts SOTE values greater than 100% under certain conditions. Such a prediction is possible because the theory was developed without considering boundary conditions. However, the conditions in which high SOTEs are predicted will occur in typical aeration system applications, as demonstrated below.

The discussion proposes an equation for SOTE. Modification of this equation will provide an equation that more accurately reflects conditions in the water column. In particular, pressure in the water column should be taken into account. Pressure varies linearly with depth in the water column. The following assumptions can be used to develop a relationship between air density and water depth: (a) air bubbles are discrete spheres at constant temperature, (b) top of the water column is at atmospheric pressure, (c) air is an ideal gas, and (d) gas transfer does not significantly affect density (which is reasonable for gases that have approximately the same individual densities as air). Then, diameter of an individual bubble at the top of the water column (d_T) is related to its diameter at the point of release (d_0) by

$$d_T = (1 + 0.0967H)^{1/3} d_0 \quad (1)$$

Similarly, density of the bubble at the point of release is given by

$$\rho_0 = (1 + 0.0967H)\rho_A \quad (2)$$

Assume, as in the paper, that the bubble can be characterized by the average of its properties at the point of release and at the top of the water column. Then a reasonable estimate of SOTE is given by

$$\text{SOTE} = R_{O_2} V_w [0.115 Q_A (2 + 0.0967H)\rho_A] \quad (3)$$

or, combining with equation 26 of the paper,

$$\text{SOTE, \%} = 0.00362 \{ [1 + (1 + 0.0967H)^{1/3} d_0]^{-7/4} \times (H + 0.0180H^2) / (1 + 0.0484H) \} \quad (4)$$

This expression is revised from that given in the discussion. Using this expression, values presented in Table D1 in the discussion become those shown in Table C1 here (using a depth of submergence of 4.5 m as in the discussion). Standard oxygen-

transfer efficiency values in the data set used for theoretical development range from 5 to 60%. These values correspond to predicted SOTEs for bubble diameters of 4 to approximately 15 mm. For smaller bubble diameters (2 to 3 mm), physically impossible SOTEs are predicted. As pointed out in the discussion, physical conditions can be conceived where oxygen equilibrium will occur and net oxygen transfer will cease. Extremely small bubble diameters and large submergences will cause this. The paper cited work in which a similar conclusion was reached and a bubble diameter of 5 mm was concluded to be the limit beyond which no significant improvements in oxygen-transfer efficiency occur. In developing the theory, diffusion in liquid film was assumed to limit oxygen transfer (development of equations 3 and 4 in the paper). As partial pressure of oxygen decreases, transfer will become limited by gas-phase diffusion. Equation 4 (in the paper) will cease to apply as written; instead, boundary conditions will apply.

The data set presented in the paper suggests that oxygen equilibrium will not be approached in most conventional aeration systems. The paper suggests a median effective bubble diameter, based on the data set, of approximately 7 mm for conventional fine-pore aeration systems. As the theory presented in the paper is extended to other systems, modifications may be needed, perhaps along the lines indicated above.

Carbon Dioxide Effects

The discussion argues that CO₂ transfer to air bubbles will cause O₂ partial pressure to decrease more rapidly than assumed in the theoretical development. Carbon dioxide transfer has some effect but is less than is claimed in the discussion. Equation 14 can be rewritten to take into account CO₂ transfer (where M_{CO_2} represents mass of CO₂ transferred to the air bubble and M'_{O_2} accounts for CO₂ transfer)

$$P_{O_2,T} \approx \left[\frac{(0.23)(\pi/6)(D^3)\rho_A - M'_{O_2}}{(\pi/6)(D^3)\rho_A - M'_{O_2} + M_{CO_2}} \right] \frac{0.21}{0.23} \quad (5)$$

This equation is approximate because the mole-to-mass ratio (0.21/0.23) is no longer exact; it is nearly so, however. Following the development presented in the paper leads to a modified version of equation 21

$$M'_{O_2} = 1.09 \times 10^{-4} D^{-9/4} \frac{Q_A}{V_w} H^2 \times \left[1 + 0.0962H + \frac{154D^3 - M_{O_2}}{154D^3 - 0.23M_{O_2} + 0.23M_{CO_2}} \right] \quad (6)$$

Rearranging equation 6, retaining only significant terms, leads to a modified version of equation 25

$$M'_{O_2} = [5.82 \times 10^{-4} + 1.05 \times 10^{-5}H - (1.09 \times 10^{-4} + 1.05 \times 10^{-5}H)M_{CO_2}] D^{-9/4} H^2 (Q_A/V_w) + M_{CO_2}^2 M_{O_2} \quad (7)$$

Dropping the last term in this equation reflects a minimum oxygen mass transfer (the limiting condition for examining the effect of CO₂ transfer) because it is additive. One way to examine SOTE with CO₂ transfer considered is to calculate the ratios of mass transfer of oxygen, which correspond to ratios of SOTEs. Dividing equation 7 by equation 25 gives

$$M'_{O_2}/M_{O_2} = 1 - 0.187(1 + 9.63H)M_{CO_2}/(1 + 0.0180H) \quad (8)$$

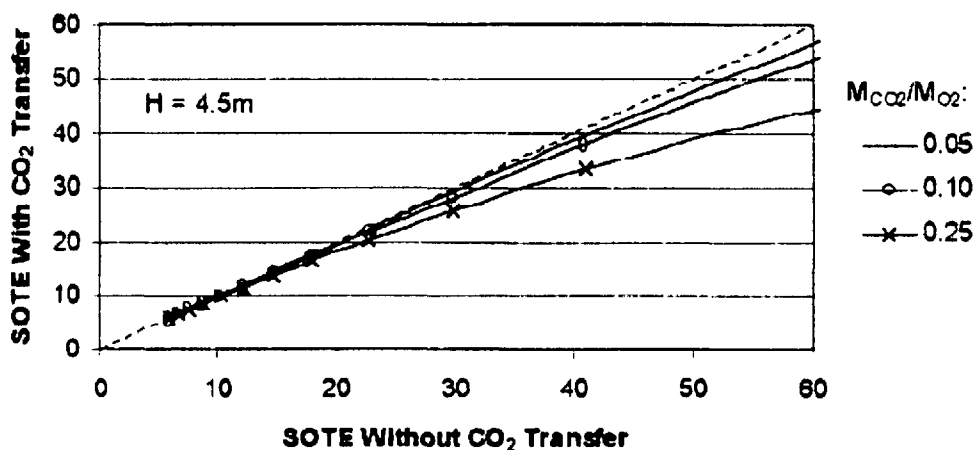


Figure 1—Predicted effect of CO₂ transfer on O₂ transfer.

This ratio is also the ratio of SOTEs with and without CO₂ transfer:

$$M'_{O_2}/M_{O_2} = \text{SOTE}'/\text{SOTE} \quad (9)$$

A reasonable range of values for M_{CO_2}/M_{O_2} is probably 0.05 to 0.25, based on the range of CO₂ mass fractions noted in the discussion (0.01 to 0.03). Using these values, Figure 1 was developed. Inspection of this figure suggests that effect of CO₂ transfer is probably not significant in most cases for conventional aeration systems. Further discussion on this conclusion is welcome.

Temperature Effects

The discussion points out that air temperatures are well above 20 °C in most cases as a result of the effects of air compression. It argues that higher temperatures will result in higher total air–water interface areas (because number of molecules in an individual air bubble, of fixed volume, will decrease as temperature rises). Changes in air temperature and air volume are inversely proportional. Therefore, higher temperatures resulting from compression will result in fewer (rather than more) air bubbles from a specific unit volume of air at standard conditions. Higher temperatures will cause higher molecular velocities and higher film diffusion rates. These two effects (fewer air bubbles and higher diffusion rates) are likely to nearly offset one another.

The discussion correctly points out that oxygen-transfer rates are likely to increase as a function of air temperature if all other factors are constant. Because other factors change along with temperature, the net effect on oxygen transfer is likely to be small for conventional aeration systems. However, further investigation of this point is warranted.

Exponential Decrease in P_{O_2}

The discussion suggests that the decrease in oxygen partial pressure is likely to be exponential, rather than linear as was assumed in the paper, and uses data from the paper to demonstrate this point. Using the same data and applying equation 4 with $d_0 = 0.0058$ m gives a predicted SOTE at 5.97 m (19.6 ft) submergence of 39.5% (35.9% with 1.0% CO₂ in offgas), compared with observed values of 39.2 to 41.6% and a predicted SOTE at 8.90 m (29.2 ft) submergence of 52.7% (43.8% with 1.0% CO₂ in offgas),

compared with the observed range of 48.3 to 48.7%. Using 5.97 m submergence as the reference condition, the predicted SOTE at 8.90 m submergence was approximately 9% greater than predicted. These calculations use the assumption of linear decrease in oxygen concentration.

The discussion may be correct that the decrease in oxygen concentration is not linear. However, close agreement between predicted and observed SOTE values for this comparison case suggests that the assumption of linearity is a reasonable starting point for examining conventional diffused aeration systems. Clearly, this does not prove the validity of the linearity assumption.

Again, the thoughtful discussion provided is appreciated. There are opportunities for improving knowledge of oxygen-transfer phenomena. The discussion points out a number of these opportunities.

Modifications to Original Equations

Equation 4 should read as follows:

$$r_{O_2,l} = \frac{A_B C_{SAT}}{V_w} \sqrt{\frac{4D_{AB}\mu}{\pi d}}$$

Equation 22 should read as follows:

$$M_{O_2}^2 - [670D^3 + (5.819 \times 10^{-4}D^{-9/4} + 1.046 \times 10^{-5}HD^{-9/4})(Q_A/V_w)H^2]M_{O_2} + (0.1458 + 7.011 \times 10^{-3}H) \times D^{3/4}(Q_A/V_w)H^2 = 0$$

The first expression in the third line following equation 24 should read as follows:

$$\geq 7.011 \times 10^{-3}D^{3/4}$$

Equation 26 should read as follows:

$$R_{O_2} = 3.171 \times 10^{-3}(H + 1.798 \times 10^{-2}H^2)(Q_A/V_w)D^{-7/4}$$

The second coefficient for equation 27 should be as follows:

$$k_2 = 1.798 \times 10^{-2}$$

In equation 41, the value 3.298×10^{-3} should be 1.798×10^{-2} .