Effect of Waves on Reaeration

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Mechanically generated surface waves and their influence on oxygen transfer were investigated. The experiments were conducted in a reaeration column (Reynolds number from 125–937). The water surface was set in oscillatory motion to simulate periodic surface level fluctuation. The wave frequency used ranged from 0.125 Hz to 0.425 Hz for various wave heights ranging from 0.15 cm to 1.5 cm. After bleeding the water column with nitrogen, dissolved oxygen concentration was measured over time below the water surface. A modified surface renewal model was proposed and found to describe the oxygen transfer phenomenon well. In addition, it was found that the mean film thickness δ_D, may be used as the characteristic length to describe the reaeration process under the influence of small perturbation and surface water waves. The proposed model was also extended to include the reaeration process under larger waves reported by other researchers. © 2013 American Institute of Chemical Engineers *AIChE J*, 59: 4839–4845, 2013
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Introduction

Reaeration is a process by which oxygen in the atmosphere diffuses across the interface between the atmosphere and an open water body such as a lake, ocean, and river. This physical diffusion process, like molecular and turbulent diffusions, ultimately takes place at the molecular diffusion level. For slightly soluble gases, such as O_2 and CO_2, the transfer rate is greatly governed by the diffusivity on the liquid side while that on the air side, although with much larger diffusivity, is immaterial when it comes to diffusion across the air-liquid interface. The gas transfer across this interface is typically described using the Fick's law which states that the flux of oxygen from the atmosphere into water is proportional to the dissolved oxygen concentration gradient in water. The constant of proportionality is known as the coefficient of oxygen diffusion. The transfer is positive from higher to lower dissolved oxygen (DO) concentration, i.e.

$$\frac{dm}{Adt} = -D\left(\frac{dC}{dz}\right) \tag{1}$$

where m is the mass of dissolved oxygen, t is time, C is the bulk concentration of dissolved oxygen at time t, D is the molecular diffusion coefficient of dissolved oxygen, A is the area through which oxygen passes, and z is the distance in the direction normal to the surface and is positive downward. Using the two-film theory (Lewis and Whitman[25]), the concentration gradient across the mean film thickness δ_D, is defined as in Eq. 2

$$\frac{dC}{dz} \approx -\frac{(Cs - C)}{\delta_D} \tag{2}$$

Substituting Eq. 2 and $m = CV$ into Eq. 1, the transfer rate of oxygen in the water column may be expressed as follows

$$\frac{dC}{dt} = \frac{D}{\delta_D}\frac{A}{V}(C_s - C) = \frac{K_L}{h}(C_s - C) = k_2(C_s - C) \tag{3}$$

where $K_L = k_2 h = D/\delta_D$ is the oxygen transfer coefficient, C_s is the saturation concentration of dissolved oxygen, h is the average water depth, and $k_2 = K_L/h$ is the reaeration coefficient. Equation 3 has been widely used by a number of researchers to estimate the value of the reaeration coefficient under various scenario (Herlina[13]; Herlina and Jirka[14,15]; Downing and Truesdale[8]; and Daniil and Gulliver,[7] among others). The solution is obtained by integrating Eq. 3 with respect to time. Introducing the initial condition $C = C_o$ at time $t = 0$ yields

$$\mathrm{In}(C_s - C_0) - \mathrm{In}(C_s - C) = k_2 t \tag{4}$$

and k_2 may be estimated as the gradient of the linear plot of the lefthand side term as a function of time. In general, the reaeration coefficient k_2 may be considered as a lump parameter accounting for the effects of a number of factors, including (1) various types of surface agitation induced by waves or wind, (2) turbulence level in the water, (3) temperature of the water, (4) the presence of soluble and insoluble surface contaminants, and (5) forced or natural convection. Indeed,

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Table 1. A Summary of Experimental Conditions and Parameters

No.	C_o (mg/L)	C_s (mg/L)	T (°C)	ν (cm^2/s)	D (cm^2/s)	Sc=ν/D	H (m)	f (Hz)	Re=2Hfd/ν
R1	1.26	6.7	30	0.0080	2.563×10^{-05}	312	0.0015	0.275	206
R2	2.64	6.7	30	0.0080	2.563×10^{-05}	312	0.003	0.275	412
R3	1.35	6.7	30	0.0080	2.563×10^{-05}	312	0.004	0.275	550
R4	1.21	6.26	35.7	0.0071	2.936×10^{-05}	243	0.004	0.275	617
R5	1.17	5.87	39.4	0.0067	3.192×10^{-05}	208	0.004	0.275	661
R6	2.99	6.7	30	0.0080	2.563×10^{-05}	312	0.002	0.125	125
R7	1.36	6.7	30	0.0080	2.563×10^{-05}	312	0.004	0.125	250
R8	1.25	6.26	35.7	0.0071	2.936×10^{-05}	243	0.004	0.125	280
R9	1.21	5.87	39.4	0.0067	3.192×10^{-05}	208	0.004	0.125	301
R10	2.97	6.7	30	0.0080	2.563×10^{-05}	312	0.0065	0.125	406
R11	4.11	6.7	30	0.0080	2.563×10^{-05}	312	0.015	0.125	937
R12	1.28	6.7	30	0.0080	2.563×10^{-05}	312	0.0015	0.425	318
R13	1.23	6.26	35.7	0.0071	2.936×10^{-05}	243	0.0015	0.425	357
R14	1.15	5.87	39.4	0.0067	3.192×10^{-05}	208	0.0015	0.425	383

the reaeration coefficient is not only dependent on the molecular diffusion, but also on the turbulent intensity. According to Gualtieri and Mihailovíc,[11] there are three categories of turbulence sources (a) turbulence generated across an “unsheared” interface, (b) combined wind and stream turbulence, and (c) turbulence generated across sheared interface.

The first case, an “unsheared” interface is associated with a river where the effects of wind-induced turbulence or wave-induced turbulence on reaeration coefficient are considered negligible as compared to the bottom-shear-induced turbulence. The latter is the predominant driving force of gas exchange in a water column. Comprehensive review and investigation of this phenomenon can be found in Brumley and Jirka,[2] Gulliver and Halverson,[12] Isaacs and Gaudy,[16] Jirka and Ho,[21] Moog and Jirka,[28] Chu and Jirka,[3] Tamburrino and Gulliver,[31] Xu et al.,[35] and Herlina and Jirka.[14,15] Wind shear poses significant effects on gas transfer velocity of natural stream as well. As a result, the effects of air flow (wind) and water flow need to be considered in a reaeration process, see Eloubaidy and Plate,[10] Mattingly,[26] Plate and Friedrich,[29] Jirka and Brutsaert,[20] Chu and Jirka,[4] and Duan et al.[9]

In a moderate-size lake, however, the primary driving force of gas transfer from the atmosphere into a water column is wind stress. This wind stress acts on the water surface, leading to the formation of a shear interface, and increases the rate of gas exchange. In most of the published works, bulk concentrations of gases in water phase and air velocity have been measured at a significant distance away the water surface, in part due to the difficulty in measuring information very close to the air–water interface. Thus, the transfer velocities of gases into water were always related to the measured bulk concentration and air velocity. This approach has been used by Jähne et al.,[18] Wanninkhof,[32] and Jähne and Hauβecker.[17] A comprehensive review can be found in Kyoung and Patrick.[24]

Wave induced turbulence may be viewed as one that is generated across a sheared interface. Downing and Truesdale[8] carried out experiments on the influence of mechanically generated waves on oxygen transfer. They reported that increasing the height and frequency of progressive waves in the water caused an approximately linear increase in the rate of oxygen transfer. Daniil and Gulliver[7] studied the influence of both breaking wave and nonbreaking wave on air–water gas transfer. They proposed a number of expressions which constituted the surface renewal model that fit the experimental data well. The gas-transfer coefficient was shown to be proportional to the vertical wave velocity at the water surface, leading to the dependence of oxygen transfer coefficient on the product of wave height and wave frequency. Furthermore, these authors stated that when breaking waves or bubbles were present, the gas transfer increased significantly.

Surface renewal model

The concept of surface-renewal model $K_L \sim (\mathrm{Dr})^{1/2}$ first proposed by Danckwerts[6] is considered in this study. Here r is defined as the rate of surface renewal (s^{-1}). Daniil and Gulliver[7] reported that their proposed surface-renewal model is applicable to describe the gas exchange phenomenon associated with mechanically generated wave. In their study, r was expressed in terms of the wave characteristics and defined as $\frac{a_r^2 V_{max}}{H} \mathrm{Re}_w$, where the wave height (H) was the characteristic depth, and $\mathrm{Re}_w = V_{max}$ H/ν was wave Reynolds number. Here V_{max} was defined as πHf, a_r was a constant, and f was wave frequency. These authors found that $K_L Sc^{1/2}$ is proportional to Hf and proposed the following relationship

$$K_L Sc^{1/2} = cHf + b \tag{5}$$

in which Sc = Schmidt number = ν/D, c and b are constants, c = 0.0159, and b = 0 as reported by Daniil and Gulliver.[7] The term $K_L Sc^{1/2}$ is a parameter that measures the rate of oxygen transfer, and Sc accounts for the effects of temperature.

This article includes the findings on the effects of mechanically generated waves on oxygen transfer rate under low-turbulence environment for which there is little reported information in the literature. A dedicated test rig was designed and fabricated to investigate reaeration process under low turbulence condition. Eq. 5 is adopted to describe the reaeration process, and the mean film thickness δ_D, is proposed to unify the reaeration process in a still water body with surface perturbations (surface wave, ripples, for example).

Laboratory Experiments

The experimental results are presented in Tables 1 and 2. The fluid viscosities, ν and μ, were functions of temperature and determined according to (Kestin et al.[22]), and D was calculated from the Stokes–Einstein equation (see Eq. 6)

Table 2. A Summary of the Experimental Results and Parameters

No.	H.f (m/s)	k_2 (1/day)	$K_L = k_2 h^a$ (m/s)	$\delta_D = D/K_L$ (m)	$K_L Sc^{1/2}$
R1	4.125×10^{-4}	0.263	1.218×10^{-6}	2.11×10^{-3}	2.152×10^{-5}
R2	8.250×10^{-4}	0.325	1.505×10^{-6}	1.70×10^{-3}	2.659×10^{-5}
R3	1.100×10^{-3}	0.379	1.755×10^{-6}	1.46×10^{-3}	3.101×10^{-5}
R4	1.100×10^{-3}	0.445	2.060×10^{-6}	1.43×10^{-3}	3.212×10^{-5}
R5	1.100×10^{-3}	0.495	2.292×10^{-6}	1.39×10^{-3}	3.308×10^{-5}
R6	2.500×10^{-4}	0.279	1.278×10^{-6}	2.01×10^{-3}	2.258×10^{-5}
R7	5.000×10^{-4}	0.347	1.606×10^{-6}	1.60×10^{-3}	2.839×10^{-5}
R8	5.000×10^{-4}	0.409	1.894×10^{-6}	1.55×10^{-3}	2.952×10^{-5}
R9	5.000×10^{-4}	0.456	2.111×10^{-6}	1.51×10^{-3}	3.047×10^{-5}
R10	8.125×10^{-4}	0.437	2.023×10^{-6}	1.27×10^{-3}	3.576×10^{-5}
R11	1.875×10^{-3}	0.621	2.875×10^{-6}	8.92×10^{-4}	5.081×10^{-5}
R12	6.375×10^{-4}	0.280	1.296×10^{-6}	1.98×10^{-3}	2.291×10^{-5}
R13	6.375×10^{-4}	0.327	1.514×10^{-6}	1.94×10^{-3}	2.360×10^{-5}
R14	6.375×10^{-4}	0.363	1.681×10^{-6}	1.90×10^{-3}	2.426×10^{-5}

[a]Note: h = depth water in the reaeration column (=0.4m) and the bulk DO concentration was considered homogeneous.

$$D = 7.4 \times 10^{-8} \frac{(xM)^{1/2} T}{\mu V^{0.5}} \quad (6)$$

The coefficients were 2.26 (Reid et al.[30] and Cussler[5]), and 25.6 cm^2/mol for association factor (x) of H_2O and molar volume (V) of O_2 (Wilke and Chang[33]), respectively. The Reynolds number Re, of the reaeration column was defined as 2Hfd/v and ranged from 125 to 937, where d was the diameter of reaeration column. 2Hf (=H/[Period/2]) was the average oscillating velocity. Thus, one may use the Reynolds number threshold of flow in pipes to figure out the degree of turbulence. The Schmidt number $Sc = v/D$ ranged from 208 to 312. The range of Re and Schmidt numbers indicated that the laboratory experiments had been conducted in low-turbulent environment.

Experiment setup

A series of experiments was performed using a test-rig which comprised a jacketed water column with a concentric double cylinder and a "wave maker". A schematic drawing of the test-rig is shown in Figure 1. The two concentric cylinders were made of acrylic tubes 2 m in length, and the respective diameters were 30 cm and 20 cm, making an outer water jacket and an inner test column. The water jacket was used to maintain the water temperature of the inner water column.

The water level oscillation system consisted of an air compressor and a parallel auxiliary water column which was connected to the main water column/reaeration column through a tube at the base. The air pressure above the water level of the parallel auxiliary water column was regulated to

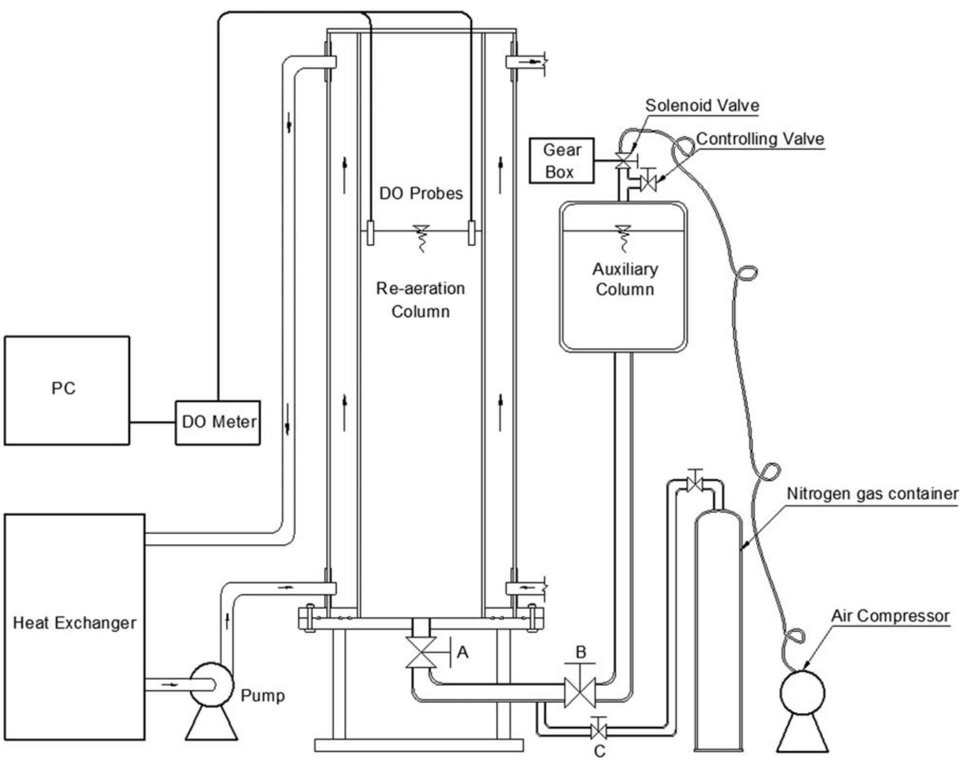

Figure 1. A diagrammatic sketch of the DO experiment water column (not to scale); arrows in the jacket indicate direction of circulation of constant temperature water through the system.

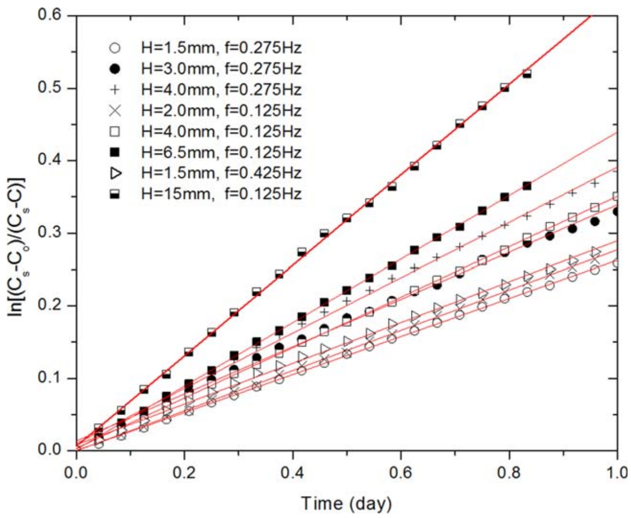

Figure 2. Distribution of DO concentration with time for various water level perturbations (constant temperature = 30°C).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

produce pressure pulses on the water column, and hence generated periodic water level in the main water column. The cyclic movement of the water surface simulated vertical harmonic motion at the preselected frequency. This frequency and pressure above the water surface (auxiliary column) could be adjusted to create mechanical excitation/water level fluctuation of different frequency and height in the reaeration column.

It is noted the pressure above the reaeration column was atmospheric because it was open to the atmosphere. The oxygen concentration in the air was that of the atmosphere and was treated as constant. There was no circumstance of subvacuum being formed and the need for refilling with oxygen. The pressure in the parallel auxiliary column might be positive (above atmospheric) when the solenoid valve was open, and at atmosphere pressure when the solenoid valve was closed. The air pressure in the auxiliary column did not influence the DO concentration in the reaeration column.

The water temperature in the reaeration column was set at a preselected temperature between 30°C and 40°C. Two optical dissolved oxygen (ODO) probes (YSI made; model: ProODO) were placed close to the free surface ($z = 0.065$ m) to measure instantaneous dissolved oxygen concentration in the water column. These two ODO probes were calibrated before each and every experiment.

Deoxygenation of water

In this study, the DO measurement/experiment was conducted in accordance to the procedure stipulated in the handbook (ASCE[1,27]). The reaeration column was first filled with fresh water to the desired water depth (ranging from 1.6 m to 1.7 m from base), see Figure 1; valves A, B, and C were all closed. Then nitrogen gas was bubbled through the column from the bottom for 5 to 10 min to purge dissolved oxygen from the water column to the required initial DO concentration (valve B was closed, and valves A and C were opened). Finally, valve C was closed, and valves A and B were opened so that the water levels between the reaeration column and auxiliary (wave-maker) column were balanced. At its dynamic equilibrium state, the water depth in the reaeration column ranged between 1.1 to 1.2 m. It was noted that the initial dissolved oxygen concentration might not had been exactly the same for all the experiments. The duration of the experiment was 24 h for each test, except for experiments 3, 4, and 5 which had been extended to 9, 8, and 7 days, respectively. The extended periods were intended to establish DO saturation and measure the corresponding saturation concentration of the saturated DO were then assumed to be the same for other cases (24 h) maintained at the same temperature.

Results of Experiments and Discussion

All measured values of DO were based on the average of the two measured DO values obtained using the two DO probes at a fixed depth, $z = 0.065$ m.

Estimation of reaeration coefficient (k_2)

The maximum span of concentration change measured from the two probes was 0.1 mg/L and the standard deviation (SD) was 0.07 for each experiment. The results in Figure 2 were only presented in average values. Using Eq. 4, the experimental results of concentration over time after deoxygenation are plotted and shown in Figure 2. The gradients of the fitted straight lines yield the values of k_2, which are in turns used to determine $K_{L,}$ see Table 2.

Proposed mean film thickness (δ_D)

In addition to adopting the surface renewal model (Eq. 5), the authors also draw on the two-film theory. The model has merits in simplicity and being intuitive. The mean film thickness δ_D, may be viewed as a characteristic length scale to describe the reaeration process. It is assumed that the thickness of this layer δ_D decreases with increasing turbulence intensity and may be estimated as the ratio between the molecular diffusivity (D) and oxygen transfer coefficient

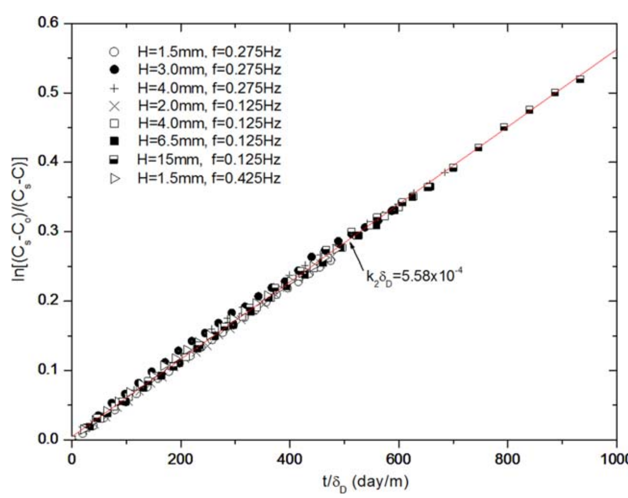

Figure 3. Temporal distribution of DO concentration under various water level perturbations presented with respect to time scaled mean film thickness (δD) (constant temperature = 30°C).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

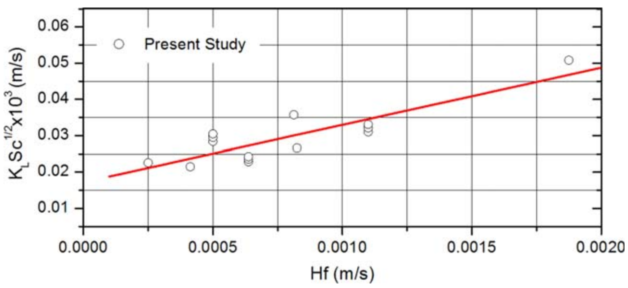

Figure 4. Variation of $K_L Sc^{1/2}$ with *Hf* (P < 0.01).

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(K_L); that is $\delta_D = D/K_L$. Here D is the physical fluid property of the diffusivity of the gas in liquid, and K_L is determined experimentally. Note that δ_D is in the order of mm, as shown in Table 2.

In fact, Janzen et al.[19] has shown that the film model and the surface divergence model estimated well the oxygen transfer coefficients under the range of Reynolds number reported in the literature.

The time scale in the abscissa of Figure 2 may be presented in terms of speed, in this case, inverse of speed, i.e., t/δ_D. Figure 3 is Figure 2 replotted with the abscissa expressed in t/δ_D. It can be seen from Figure 3 that the data for various wave conditions collapse into a straight line. Indeed, Eq. 4 could have been rewritten with the righthand side term expressed as $(k_2\delta_D)\left(\frac{t}{\delta_D}\right)$. Based on Figure 3, the gradient of the best fitted curve yields the value of $k_2 \delta_D = D/h = 5.58 \times 10^{-4}$ m/day. It is noted that the product $k_2\delta_D = D/h$ contains two parameters, k_2 and δ_D which define the reaeration process. In fact, δ_D may be viewed as a universal length scale that reflects the variation of reaeration with depth under various external forcing. One could visualize that under a certain external influence [forcing] (temperature, wave, wind, ship wake, etc.) or a combination of external influences the reaeration process would be reflected in the terms k_2 and δ_D. The interesting and significant point is that the product of these two parameters has been shown to be a constant. Therefore, one needs only to determine either k_2 or δ_D, whichever is more readily available, to establish the other. For instance, if one can measure δ_D directly, then the corresponding reaeration coefficient can be determined readily. However, the main drawback of the film model is that it does not provide physical insight on the driving mechanism of gas transfer which will be overcome by introducing the modified surface renewable model, as is described later.

Statistical analysis and model development

A linear least-squares regression analysis was performed and significance of correlation coefficient was also tested for the data obtained in this study. The Student's t-tests and statistical significance were performed using commercial software (Origin 8.5 (OriginLab) and Excel 2007 (Microsoft)). The significance, *P* value corresponding to the two-tailed test was estimated to be less than 0.01.

Figure 4 shows the relationship between $K_L Sc^{1/2}$ and Hf based on experiments carried out for this study. The wave frequency ranges from 0.125 Hz to 0.425 Hz and wave height varies from 0.15 cm to 1.5 cm. The results are plotted in Figure 4 where the constant, "c", is found to be 0.0158 ($K_L Sc^{1/2} = 0.0158 Hf + 1.72 \times 10^{-5}$, $R^2 = 0.74$), and is comparable to the value of 0.0159 reported by Daniil and Gulliver[7] (wave frequency range of 1.59 Hz-2.65 Hz and wave height from 0.70 cm to 5.35 cm). Another reported work in this area, Downing and Truesdale[8] performed experiments with wave frequency of 0.6 Hz-1.25 Hz for various wave heights ranging from 2.8 cm to 10.8 cm. Using their data, the constant, "c", has been estimated to be 0.0163, which is also comparable to that obtained in this study.

The authors found a way to unify these three sets of data. After evaluating the basis and development of the surface renewal model, and knowing that there is inevitable large degree of errors in the experimental measurements, the authors propose to include an error factor α, in the surface renewal model as described herein.

By definition, an experimental/measurement error is the relative deviation from the true value, and may be represented as follows

$$\text{error} = \frac{\text{True Value–Measured value}}{\text{True value or Measured value}} = \frac{\text{True value}}{\text{Measured value}} - 1 \tag{7}$$

The denominator could be the true value or the measured value if the error is small. In this case, the authors choose to use the measured value as the denominator. Then by rewriting Eq. 7 one obtains

$$\text{True value} = (1 + \text{error}) \times \text{measured value} \tag{8}$$

In this article's context, the true value is given by the function (cHf + b). The measured value is expressed as ($K_L Sc^{1/2}$). Therefore, Eq. 8 may be expressed as

$$(cHf + b) = (1 + \text{error}) \times (K_L Sc^{1/2}) \tag{9}$$

With the error represented by α, one can consequently derive Eq. 10

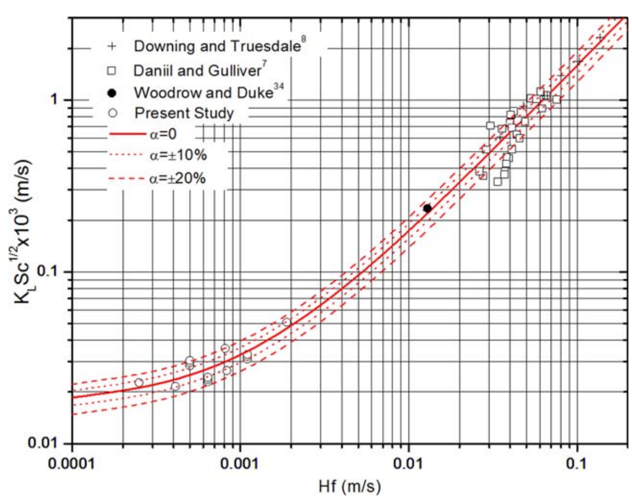

Figure 5. Variation of $K_L Sc^{1/2}$ with Hf for various wave conditions.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

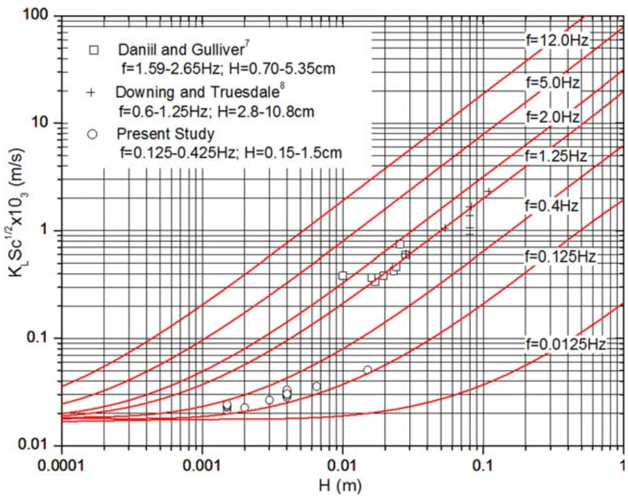

Figure 6. Effects of wave height and frequency on oxygen transfer (K_L).

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$$K_L Sc^{1/2} = \frac{(cHf + b)}{(1+\alpha)} \quad (10)$$

Equation 10 reverts to Eq. 5 when $\alpha = 0$. The constant α, defines the error bound of the experimental data. In this way, Eq. 10 not only describes the surface renewal process, but also provides an indication of the error band of the measured data.

Figure 5 shows the comparison of these results expressed in terms of $K_L Sc^{1/2}$ as a function of (Hf). Also included are the data extracted from Daniil and Gulliver[7] and Downing and Truesdale.[8] The dotted lines ($\alpha = \pm 10\%$) and the dash lines ($\alpha = \pm 20\%$) represent the confidence interval of 10 and 20%, respectively. Figure 5 indicates that most of the data fall within the $\pm$ 20% band. It may be deduced that the surface renewal model (Eq. 10) clearly describes very well the reaeration process for wave frequency between 0.125 Hz and 2.65 Hz, and wave height from 0.15 cm to 10.8 cm.

It is noted that progressive water waves have water surfaces that vary temporally and spatially. However, this article's objective was to study the effects of small perturbations or ripples on vertical oxygen transfer across the air–water interface. In comparison, the spatial change of wave (progressive movement) would have less impact on the transfer of oxygen across the interface. As shown in Figure 5, these data fitted well with published data.

In addition, the gas exchange process, at the microscale very near the interface, is the due to eddies generated by the vertical rise and fall of the water surface. In the microscale, the rise and fall of the water surface, be it a result of vertical oscillation or progressive wave, would involve the same physical process. It is conceded that this is an acute observation and excellent description of the description of the process.

Effects of wave height and frequency on oxygen transfer coefficient

In order to evaluate the effects of both wave height and wave frequency on oxygen transfer, and for ease of presentation, the authors used Eq. 10 and set $\alpha = 0$, $c = 0.0158$, and $b = 1.72 \times 10^{-5}$ in the illustration shown in Figure 6. Figure 6 shows clearly that higher wave frequency results in higher values of $K_L Sc^{1/2}$, hence, higher oxygen renewal rate, for a constant wave height. For a constant wave frequency, higher wave height results in higher oxygen renewal rate. Figure 6 also reflects very well the (H, f) space occupied by this study and those by Daniil and Gulliver,[7] and Downing and Truesdale.[8] One may also deduce intuitively from Figure 6 that for a surface wave of small amplitude, the surface renewal rate is independent of the frequency. In the limit, the value of $K_L Sc^{1/2}$ approaches the value of 1.72×10^{-5} m/s for a still water surface.

Conclusions

The effects of mechanically generated waves on oxygen transfer were investigated. This study focused on small amplitude wave similar to those produced by ripples. The wave frequency ranged from 0.125 Hz to 0.425 Hz for different wave heights H, which ranged from 0.15 cm to 1.5 cm. A modified surface renewal model was proposed and the model successfully unified the findings of this study and those reported by Daniil and Gulliver[7], Downing and Truesdale,[8] and Woodrow and Duke.[34] The main findings of the study include the followings:

1. It was found that the mean film thickness δ_D, may be adopted as the characteristic length to describe the reaeration process;
2. For a constant wave height, oxygen renewal rate increases with wave frequency; similarly, oxygen renewal rate increases with wave height for a constant wave frequency.

Acknowledgments

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