PAPER

Effects of Plunging Breakers on the Gas Contents in the Ocean

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ABSTRACT

The aeration of the ocean contributes to the transfer of oxygen, nitrogen and carbon dioxide between the ocean and the atmosphere. Breaking waves are known to enhance the aeration process by increasing the turbulent mixing and entraining air bubbles. One type of breaking waves, the plunging breaker, can entrain large quantities of air bubbles to depths as large as 10 to 20 meters. The resulting increase of the air-water interface area and the increase of the gas saturation concentration with the depth induce a massive augmentation of air-water gas transfer. The aeration characteristics of plunging breakers in the deep sea are presented using a similarity with plunging jets. A method is developed to predict the sizes of the entrained bubbes, the resulting interface area, the maximum penetration depth and the air-water gas transfer. The results are consistent with experimental observations and emphasize the role of plunging breakers in the aeration process. The authors also develop a prediction model of the gas transfer rate due to plunging breaking waves in deep sea during a storm event.

INTRODUCTION

Aeration is the process by which atmospheric gases are dissolved into water. The aeration of the ocean is an important process for the exchange of nitrogen, oxygen and carbon dioxide between the atmosphere and ocean. The dissolution of carbon dioxide in the ocean, the supersaturation of oxygen in the ocean, and the oxygen release to the atmosphere contribute to the balance between these gases in the atmosphere (Sarmiento, 1984, 1992). During storm events or for large wind speeds (i.e., $U_w > 10$ m/s), wave breaking with extensive air bubble entrainment occurs. Large numbers of bubbles are entrained by plunging breaking waves as shown by Lin and Hwung (1992) and by the re-attachment of wind blown drops (Koga 1982). Wallace and Wirick (1992) observed that breaking waves can increase the rate of aeration by up to 200 times due to the entrainment of numerous air bubbles. The presence of air bubbles increases drastically the air-water interface area available for gas exchange. Also the saturation content of dissolved gas increases with the ambient pressure and the gas flux per unit surface area increases with the penetration depth of the entrained bubbles. It was suggested that the presence of air bubbles at depths might explain why the world's oceans are on average 3% supersaturated with dissolved oxygen (Stramska et al., 1990). This level of supersaturation can rise to 8% after a storm (Alekseyev and Kokorin, 1984).

It is generally accepted that there are two predominant types of breaking waves in deep water: plunging and spilling (Corkelet, 1977; Longuet-Higgins, 1988). Plunging breaking waves have a much greater potential for air bubble entrainment than the spilling wave type (Hwung et al., 1992). Indeed the spilling wave's air entrainment mechanism is via a surface roller with the bubbles staying close to the surface, whereas the plunging breaker's jet has the potential to entrain large numbers of bubbles to considerable depth. It has sometimes been claimed that there is no such thing as a deep water plunging breaker owing to the lack of a sloping bottom to induce the plunging form of breaking. But there is photographic evidence of deep water plunging waves (Coles, 1967; Griffin, 1984; Longuet-Higgins, 1988). It is believed that surface wind shear and constructive wave interference during high winds can cause deep water plunging waves (Corkelet, 1977).

Observations of bubble entrainment by large plunging breaking waves are difficult in nature and laboratory. An alternative method is to study a similar flow pattern and to transpose the results to plunging breakers (Ciprano and Blanchard, 1981; Hubbard et al., 1987). The analysis of photographs taken during storms (Coles, 1967; Melville and Rapp, 1985; Longuet-Higgins, 1988) and in laboratories (Miller, 1976; Griffin, 1984) shows distinctly that plunging breakers have similar flow patterns to a plunging jet (Figure 1). After the wave breaking, a portion of the water surface overturns and forms a water jet. The overturning aspect is identical to an inclined plunging jet in a cross flow (Figure 1).

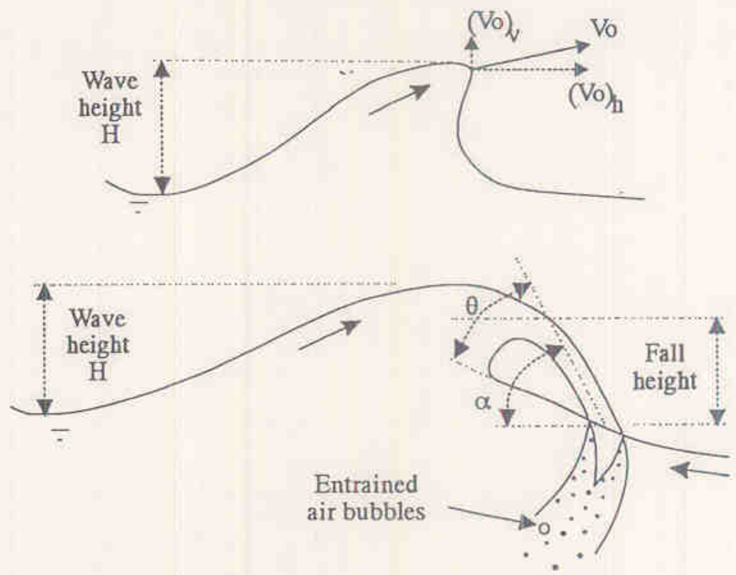
This paper describes the mechanisms of bubble entrainment by plunging breaking waves using an analogy with a water jet plunging into a pool. The results are transposed to calculate the aeration due to plunging breaking waves in the ocean. An application is developed to predict the gas flux during a storm event.

MECHANISMS OF AIR BUBBLE ENTRAINMENT

Air Entrainment by a Plunging Jet

Considering a plunging jet flow (Figure 2), air bubble entrainment at low jet velocities is caused by the plunge pool water being unable to follow the undulations of the jet surface and small air pockets are formed. Air enters the flow in the form of individual bubbles following the passage of these disturbances through the interface between the jet and the receiving flow (Sene, 1988) (Figure 2). The bubble entrainment is intermittent and pulsating. At high jet velocities (i.e. $V > 8$ to 12 m/s), experiments on circular plunging jets (Van De Sande and Smith, 1973) indicate a qualitative change in the air entrainment process. An air layer, set into motion by shear forces at the surface of the jet, enters the flow at the impact point. This air layer becomes established and is continuous along the interface between the jet and the pool water (Figure 2), and the entrainment is characterized by a continuous supply of air. At low and high velocities, the air bubble transport is attributed to an entrapment phenomenon by large scale transient eddies which carry away air bubbles (Goldring et al., 1980; Thomas et al., 1983).

FIGURE 1. Sketch of a plunging breaker.



Inception Velocity for Bubble Entrainment

Observations on plunging jet flows show that air bubbles are entrained when the impact velocity of the jet V exceeds a critical value. Recent reviews (Wood, 1991; Chanson and Cummings, 1992) show that the quantity of air entrained may be estimated as:

$$Q_{air} = K_1 * (V - V_c)^n \qquad (1)$$

where V is the jet velocity, K_1 is a constant and V_c is the velocity at which air entrainment commences. Most experimental data indicate that the critical velocity does not depend on the thickness of the jet. Experimental results obtained by Ervine et al. (1980) also show that the inception velocity V_c is almost constant for large turbulent intensities (i.e., $Tu > 3\%$). For vertical circular turbulent jets, typical values of V_c are ranging from 0.8 to 1 m/s (Table 1). Experiments performed by Koga (1982) and Detsch and Stone (1992) suggest also that the onset velocity decreases when the angle of the jet decreases (Table 2).

Quantity of Air Entrained

In a plunging jet flow situation, the entrainment of air bubbles is caused by vortices with axes perpendicular to the flow direction. A review of several studies is presented in Table 3. In summary the dimensionless quantity of air entrained may be estimated as:

$$\frac{Q_{air}}{Q_w} = k_1 * Fr^2 \qquad \text{for } V<5\text{m/s (2a)}$$

FIGURE 2. Mechanisms of bubble entrainment by plunging jet.

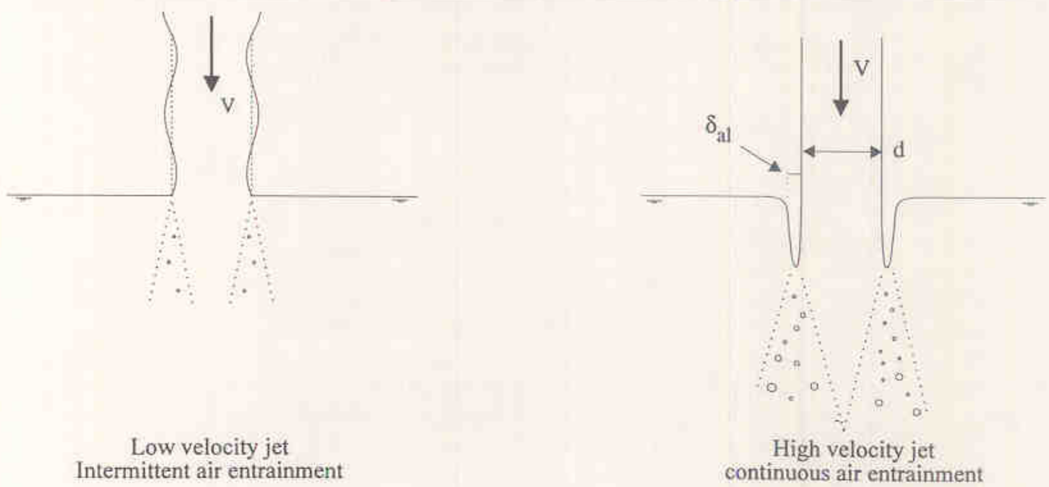


TABLE 1. Measurements of inception velocity for plunging jets.

Reference (1)	Geometry (2)	Tu (3)	V_c (m/s) (4)	Comments (5)
KALINSKE & ROBERTSON (1943)	Hydraulic jump in horizontal circular pipe		1.0	
WISNER (1965)	Hydraulic jump in rectangular conduit		$Fr_c = 1$	Prototype data.
ERVINE & ELSAWY (1975)	Two-dimensional vertical jet		1.1	
CASTELEYN et al. (1977)	Siphon of square cross-section		0.8	
LARA (1979)	Circular vertical jet		0.7 to 4	V_c varies with the jet length.
ERVINE et al. (1980)	Circular vertical jets	0.3% 1% 3% 8%	3.6 2.5 1.0 0.8	
ERVINE & AHMED (1982)	Two-dimensional vertical dropshaft		0.8	
WOOD (1991)	Circular vertical jets		$\frac{V_c^3}{g * \frac{\mu_w}{\rho_w}} = 0.5 \text{ to } 1\ 10^5$	Dimensional analysis

TABLE 2. Inception velocity for inclined plunging jets.

Reference (1)	Geometry (2)	V_c (m/s) (3)	Comments (4)
KOGA (1982)	Circular jet	$2.58 * \theta - 0.30$	$\pi/7.2 < \theta < \pi/2.8$
	Rectangular jet	$1.73 * \theta - 0.73$	$\pi/3 < \theta < \pi/2$
DETSCH and STONE (1992)	Circular jet	$4.25 * 10^{-5} * \frac{\rho_w * \mu_w}{\sigma} * \exp(4.383 * \theta)$	$\pi/12 < \theta < \pi/3$

Note: θ: jet angle in radians

$$\frac{Q_{air}}{Q_w} = k_2 * \frac{1}{\sqrt{Fr}} \qquad \text{for } 5<V<10\text{m/s} \quad (2b)$$

$$\frac{Q_{air}}{Q_w} = k_3 * Fr \qquad \text{for } V>10\text{m/s} \quad (2c)$$

Where Fr is the Froude number defined as $Fr = (V - V_c)/\sqrt{g*d}$, g is the gravity constant and d is the jet thickness (for a plane jet) or the jet diameter (for a circular jet). Equation (2) characterizes three jet behaviors, each of these being associated to a different air entrainment mechanism. For low velocities, individual air bubbles are entrained following the passage of a disturbance from the jet surface to the plunge pool water. The air entrainment is intermittent. For high velocity jets, the air entrainment is continuous. In the transition region between laminar and turbulent regimes, Detsch and Sharma (1990) suggested the occurrence of an intermittent vortex mechanism.

For low velocity jets, experimental data and dimensional analysis indicate that the rate of air entrainment is proportional to the square of the Froude number for circular and two-dimensional plunging jets (Table 3). Taking into account the angle of the jet with the free surface θ (Van De Sande and Smith, 1976; Kusabiraki et al., 1990), the quantity of air entrained can be expressed as:

$$\frac{Q_{air}}{Q_w} = k_4 * \frac{Fr^2}{(\sin\theta)^{1.2}} \qquad (3)$$

Bubble Size Generated by a Plunging Jet

The size of the air bubbles produced by plunging breaking waves is a significant parameter for the air-water gas transfer. Next to the plunge point, a region of high recirculation and energy dissipation is generated where the entrained air is broken into small bubbles before being transported downward by the

TABLE 3. Quantity of air entrained by plunging jets

Reference (1)	Geometry (2)	Q_{air}/Q_w (3)	Comments (4)
KALINSKE & ROBERTSON (1943)	Hydraulic jump in horizontal circular pipe	$0.0066*(Fr-1)^{1.4}$	Model data.
RAJARATNAM (1962)	Hydraulic jump	$0.018*(Fr-1)^{1.245}$	Model data.
WISNER (1965)	Hydraulic jump in rectangular conduit	$0.014*(Fr-1)^{1.4}$	Prototype data. $5 < Fr < 25$
	Bottom outlet	$0.024*(Fr-1)^{1.4}$	Prototype data. $3 < Fr < 20$
	Bottom outlet air demand	$0.033*(Fr-1)^{1.4}$	Prototype data. $20 < Fr < 65$
VAN DE SANDE and SMITH (1972)	Circular jets	$q_{air}=K'*(\sin\theta)^{-1.2}$	
VAN DE SANDE and SMITH (1973)	Circular jets	$q_{air}=K'(V)*(\sin\theta)^{-1.4}$	$30 < q < 75$ degrees
		$q_{air}=K'(\theta)*V^{2.6}$	$V < 5$ m/s $\theta = 30$ degrees
		$q_{air}=K'(\theta)*V^{0.53}$	$5 < V < 10$ m/s $\theta = 30$ degrees
		$q_{air}=K'(\theta)*V^{1.8}$	$10 < V < 25$ m/s $\theta = 30$ degrees
ERVINE & ELSAWY (1975)	Two-dimensional jets	$K'*\left(1-\frac{V_c}{V}\right)$	$1.5 < V < 9$ m/s
RENNER (1975)	Rectangular jets impinging horizontally onto a solid wall	$K'(\theta)*Fr^{2.0}$	$2 < Fr < 9$ $30 < \theta < 90$ degrees
		$K'(\theta)*Fr^{0.77}$	$9 < Fr$ $30 < \theta < 90$ degrees
VAN DE SANDE and SMITH (1976)	Low velocity circular jets	$Q_{air}=K'*\frac{d^{3/2}*V^{9/4}}{(\sin\theta)^{9/8}}$	$2 < V < 5$ m/s $2.8 < d < 10$ mm $20 < \theta < 60$ degrees Shorts jets.
CASTELEYN et al. (1977)	Siphon of square cross-section	$q_{air}=K'*(V-V_c)^3$	$1 < V < 2.8$ m/s
ERVINE & AHMED (1982)	Two-dimensional vertical dropshaft	$q_{air}=0.00045*(V-V_c)^3$	$\theta = 90$ degrees $3 < V < 6$ m/s
SENE (1988)	Supported two-dimensional jets	$0.004*Fr^2$	Rough turbulent jets. $3 < Fr < 8.5$
		$0.0004*Fr^2$	Smooth turbulent jets.
SENE (1988)	Low velocity jets	$K'*Fr^2$	Dimensional analysis
	High velocity jets	$q_{air}=K'*V^{3/2}$	Dimensional analysis
WOOD (1991)	High velocity jets	$K'(Re, Tu)*Fr^2$	Dimensional analysis

Note: V_c critical velocity (table 1)

water flow. The maximum bubble size is determined by the balance between the surface tension force and the inertial force caused by the velocity changes over distances of the order of the bubble size. Dimensional analysis indicates that the break-up of air bubbles occurs for:

$$\frac{\rho_w * v'^2 * d_b}{2 * \sigma} > (We)_c \qquad (4)$$

where ρ_w is the water density, d_b is the bubble diameter, v'^2 is the spatial average value of the square of the velocity differences over a distance equal to d_b, σ is the surface tension and $(We)_c$ is a critical Weber number. The critical Weber number can be rewritten as:

$$(We)_c = \frac{\rho_w * v'^2 * d_m}{2 * \sigma} \qquad (5)$$

TABLE 4. Critical Weber number for bubble splitting.

Reference (1)	$(We)_c$ Eq.(5) (2)	Fluid (3)	Flow situation (4)	Comments (5)
HINZE (1955)	0.585		Two co-axial cylinders, the inner one rotating	Dimensional analysis. Re-analysis of CLAY's (1940) data.
SEVIK and PARK (1973)	1.26	Air bubbles in water	Circular water jet discharging vertically	Experimental data. V in the range 2.1 to 4.9 m/s.
KILLEN (1982)	1.017	Air bubbles in water	Turbulent boundary layer	Experimental data. V in the range 3.66 to 18.3 m/s.
LEWIS and DAVIDSON (1982)	2.35	Air and Helium bubbles in water and Fluorisol	Circular jet discharging vertically	Experimental data. V in the range 0.9 to 2.2 m/s.
EVANS et al. (1992)	0.60	Air bubbles in water	Confined plunging water jet	Experimental data. V in the range 7.8 to 15 m/s.

Note: bubble size measurements outside the jet mixing zone.

where d_m is the maximum bubble size. Experiments have shown that the critical Weber number is a constant near unity (Table 4). Observations of bubble diameters in turbulent water jets indicate that the length scale of the eddies responsible for breaking up the bubbles is close to the bubble size (Sevik and Park, 1973; Kumar et al., 1989). For vertical bubbly turbulent jets, computations by Sun and Faeth (1986) suggest that the characteristic eddy size ranged from 0.5 to 5 times the bubble diameter. In bubble column flows, Avdeev et al. (1991) indicated that the momentum mixing length is nearly equal to the bubble diameter at the location of the maximum turbulent shear stresses. Assuming that the maximum bubble diameter is in the order of magnitude of the Prandtl mixing length, the turbulent fluctuation v'^2 equals : $v'^2 = (d_m * dV/dy)^2$ where y is the direction perpendicular to the jet centerline. With this assumption the maximum bubble size becomes:

$$d_m = \sqrt[3]{\frac{2*\sigma*(We)_c}{\rho_w*\left(\frac{dV}{dy}\right)^2}} \qquad (6)$$

In the developing flow region of a plunging jet, an idealized bubble entrainment by plunging jet is presented on Figure 3. This model provides an analytical method to estimate the maximum bubble size of individual air bubbles entrained by low velocity jets (i.e., V < 2 m/s). For vertical water jets, Equation (6) becomes:

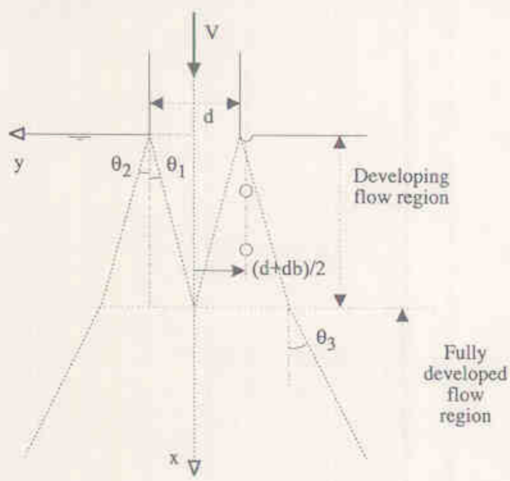
$$d_m = K_2 * \frac{(We)_c}{V^2} \qquad (7)$$

where $K_2 = 2.11*10^{-4} m^3/s^2$ for two-dimensional plane jets and $K_2 = 2.74*10^{-4} m^3/s^2$ for circular jets at 20 Celsius and atmospheric pressure (Chanson and Cummings, 1992). For high velocity jets, an established air layer is formed at the intersection of the jet and the receiving pool (Figure 2) and Equation (6) yields to:

$$d_m = K_3 * \sqrt[3]{(We)_c} * \left(\frac{\delta al}{V}\right)^{2/3} \qquad (8)$$

where δ_{al} is the thickness of the air layer (Figure 2) and K_3 is a constant of proportionality (K_3 = 0.0595 $s^{-2/3}$ for plane jets; K_3 = 0.0649 $s^{-2/3}$ for circular jets). At the present time there is little information available on the thickness of the air layer. High-speed photographs and experiments performed by the authors suggest that δ_{al} is in the range 1 to 5 mm for plunging jet velocities between 2 and 6 m/s.

FIGURE 3. Idealized plunging jet regions.



AIR-WATER GAS TRANSFER

Introduction

The presence of air bubbles entrained by plunging breakers enhances the air-water transfer of atmospheric gases (e.g., nitrogen, oxygen, carbon dioxide). Fick's law states that the mass transfer rate of a chemical across an interface normal to the x-direction and in a quiescent fluid varies directly as the coefficient of molecular diffusion D_{gas} and the negative gradient of gas concentration in the fluid (Streeter and Wylie, 1981). For atmospheric gases and using Henry's law, it is usual to write Fick's law as:

$$\frac{d}{dt}C_{gas} = K_L * a * (C_s - C_{gas}) \qquad (9)$$

where C_{gas} is the concentration of the dissolved gas in water, a is the specific surface area defined as the air-water interface area per unit volume of air and water, and C_s is the (local) saturation concentration of dissolved gas. The coefficient of transfer K_L is estimated by empirical or semi-empirical correlations. A recent review showed that, in turbulent flows, K_L is almost constant regardless of the bubble size and flow situations (Kawase and Moo-Young, 1992). For sea water at 10 Celsius Woolf and Thorpe (1991) give: $K_L = 8\ 10^{-5}$ m/s.

The presence of air bubbles enhances the gas transfer rate by increasing the air-water interface area due to the cumulative bubble surface areas. For example, if the bubble diameter is 1 mm and the air content is 10%, the specific interface area is 600 m^{-1}. Furthermore the pressure of the gas inside the bubble increases with depth as the bubbles are entrained downward, and hence both the local saturation concentration C_s and the gas transfer rate increase. In sea water at 10 Celsius the saturation concentration of dissolved oxygen can be estimated as:

$$C_S = 8.715*10^{-8}*\left(P_{atm} + \rho_w*g*z + \frac{4*\sigma}{d_b}\right) (\text{in kg/m}^3)$$

where P_{atm} is the atmospheric pressure and z is the depth (Woolf and Thorpe, 1991).

For spherical air bubbles the specific area equals:

$$a = 6 * \frac{d_b}{C} \qquad (10)$$

where C is the air concentration. (The air concentration is defined as the volume of undissolved air per unit volume of air and water. It also is called the void fraction.) At the free-surface, the initial air concentration is deduced from the quantity of air entrained by plunging jet:

$$C(z=0) = \frac{\frac{Q_{air}}{Q_w}}{1 + \frac{Q_{air}}{Q_w}} \qquad (11)$$

where Q_{air}/Q_w is computed using Equation (2). The quantity of air entrained and the size of the entrained bubbles can be estimated from Equations (2), (3) and (6), and a first estimate of the mean specific interface area at the end of the developing flow region can be deduced (Equation (10)).

Bubble Penetration Depth

As the bubbles are entrained downwards, oxygen and nitrogen are dissolved in the water. The entrained air bubbles reach a depth where the bubble rise velocity equals the vertical water speed, called the maximum bubble penetration depth, before rising towards the free surface.

A theoretical value of the maximum bubble penetration depth can be made using the continuity equation for diffusing jets. Assuming that the bubbles are entrained to a depth where the vertical component of the mean jet velocity equals to the bubble rise velocity, the authors used the same method as that developed by Ervine and Falvey (1987) and extended the method to inclined plane and circular jets. For plane jets the penetration depth D is:

$$\frac{D}{d} = 0.0240*\left(\frac{V}{u_r}\right)^2 * \frac{(\sin\alpha)^3}{(\tan\theta_3)^2} \qquad (12a)$$

$$*\left(1 + \sqrt{1 - 20.81*\left(\frac{u_r}{V}\right)^2 * \frac{\tan\theta_3}{(\sin\alpha)^2}}\right)^2$$

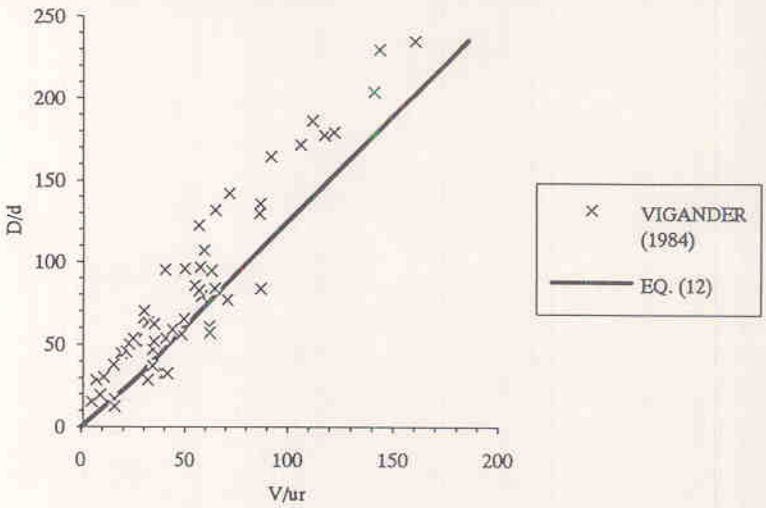
and for circular jets:

$$\frac{D}{d} = 0.04*\frac{V}{u_r}*\left(\frac{\sin\alpha}{\tan\theta_3}\right)^2 \qquad (12b)$$

$$*\left(1 - 12.5*\frac{u_r}{V}*\frac{\tan\theta_3}{\sin\alpha} + \sqrt{1 - 25*\frac{u_r}{V}*\frac{\tan\theta_3}{\sin\alpha}}\right)$$

where d is the jet thickness or jet diameter, u_r is the bubble rise velocity, a is the angle of the jet with the horizontal (Figure 1) and θ_3 is the outer spread angle in the fully developed flow region (Figure 3). For circular jets, Ervine and Falvey (1987) estimated θ_3 around 14 degrees on both models and prototypes. Figure (4) presents a comparison between Equation (12) and experimental data (Vigander, 1984). These data were obtained for circular vertical jets with bubble sizes in the range 0.7 to 2 mm. Equation (12) is computed assuming θ_3 = 14 degrees and

FIGURE 4. Penetration depths of air bubbles entrained by plunging jets.



u_r is estimated as the rise velocity in still water computed as Comolet (1979). The agreement between the data and Equation (12) is good.

Application to Plunging Breakers

Considering a wave of height H, the analysis of photographs (Coles, 1967; Melville and Rapp, 1985; Longuet-Higgins, 1988) suggests that the main parameters of a plunging breaker can be estimated as: fall height between 0.2 and 0.5*H, jet thickness from 0.01 to 0.1*H, jet angle θ = 15 to 45 degrees and free surface slope $(\alpha - \theta)$ = 0 to 30 degrees (Figure 1). Photographs (Miller, 1976) and breaking wave computations (Longuet-Higgins and Corkelet, 1976; Schultz et al., 1986) suggest that the crest velocity components at the breaking point are about: $(Vo)_h$ = 1.1 to 1.4*C_w and $(Vo)_v$ = 0.15 to 0.25*C_w where C_w is the wave celerity (see notation on Figure 1). This yields the jet impact velocity:

$$V = \sqrt{V_o^2 + 2*g*(\text{Fall height})}.$$

Johnson and Cooke (1979) measured bubble size distributions at Margaret's Bay, Nova Scotia. With wave heights of 1.8 m (March 1977), they observed a maximum bubble size of 0.13 mm from 1.5-m depth. For 2-m wave heights (April 1977), their data indicate a maximum bubble size of 0.30 mm from 0.7-m depth. For these wave heights, Equation (8) would predict bubble sizes ranging from 0.31 to 0.43 mm assuming δ_{al} = 2 mm. The calculated results are comparable to the observations of Johnson and Cooke (1979).

During a storm in the North Atlantic, Kanwisher (1963) observed air bubbles up to 20 meters depth. Kolovayev (1976) recorded bubble size distributions in deep sea with wind speeds of 11 to 13 m/s. He observed a maximum bubble size of 0.35 mm from 1.5-m depth and noted air bubble detection to depths of 8 meters. For these observations, the wave heights were not noted but a wind speed of 13 m/s could have induced waves of about 3 meters in height if the sea was nearly fully arisen (Ippen, 1966; U.S. Army, 1984). Assuming a wave height H = 3 m and using the assumptions developed above, Equations (8) and (12) predict bubble sizes between 0.25 (plane jet) and 0.3 mm (circular jet), and bubble penetration depths between 0.4 (circular jet) and 8.1 meters (plane jet) assuming a bubble rise velocity about 0.25 m/s. These results are close to the maximum bubble size of 0.35 mm from 1.5-m depth and the bubble detection at 8 meters observed by Kolovayev (1976).

Discussion

The overturning of breaking waves is an unsteady and three-dimensional process. The above calculations were developed with analogy to steady jet flows. To a first approximation, the unsteadiness and three-dimensional aspects of wave breaking do not affect the maximum bubble size calculations nor the bubble penetration depth computations. But the authors believe that the rate of air bubble entrainment cannot be estimated accurately from steady plunging jet correlations. It is believed that, in Equation (3), the constant of proportionality k_4 would be much lower than values reported in Table 3.

APPLICATION: PREDICTION OF OXYGEN TRANSFER DURING A STORM

During a storm event, plunging breaking develops on the sea surface. The air bubble entrainment caused by the plunging breakers enhances the air-water gas transfer and contributes to the oxygen transfer. Assuming a fully arisen sea with a linear wave theory, a Sverdrup-Munk-Bretschneider wave prediction theory and independent Rayleigh probability distributions for the wave heights (H) and the square of the wave periods (T^2), U.S. Army (1984) provides estimations of the mean wave height and length, and wave height probability distributions as a function of the wind velocity at 10 m above the sea level.

To a first approximation the sea surface gas transfer is small compared with the air bubble gas transfer. The gas flux Q_{gas} per sea surface area can be obtained by integrating the dissolved gas concentration and specific area in terms of the sea surface and the depth:

$$Q_{gas} = \frac{1}{A} * \int_A \left(\left(\int_{z=0}^{z=D} K_L*a(z)*(C_S(z) - C_{gas})*dz \right) *dA \right. \quad (13)$$

where A is the sea surface area. Combining the probability of a wave height H and plunging wave breaking and Equation (10), and assuming that all the entrained bubbles are of a constant diameter d_m, it yields:

$$Q_{gas} = \int_{H=0}^{+\infty} P(H)*\left(\int_{z=0}^{z=D} K_L*\frac{6*C(z)}{d_m(H)}*(C_S(z)-C_{gas})*dz\right)*dH \qquad (14)$$

where P(H) is the probability of a wave height H and plunging breaking, C is the concentration of undissolved air at depth z and $C_s(z)$ is the local saturation concentration. The probability of plunging wave breaking and wave height H can be deduced from Griffin (1984). A histogram of the combined wave height and plunging breaking is shown on figure 5 assuming a critical wave steepness for plunging breaking : $(H/L)_c = 0.131$ (Melville, 1982).

Only bubbles entrained at the center of the jet will achieve maximum penetration and most bubbles will start rising before they reach this depth. Hwung et al. (1992) observed a hyperbolic bubble concentration distribution from a maximum value at the free-surface down to zero at the maximum penetration depth. To a first approximation their data can be fitted with a linear distribution.

The gas flux per surface area becomes:

$$Q_{gas} = \int_{H=0}^{+\infty} P(H)*\left(\int_{z=0}^{z=D} K_L*\frac{6*C(z=0)*\left(1-\frac{z}{D(H)}\right)}{d_m(H)}*(C_S(z)-C_{gas})*dz\right)*dH \qquad (15)$$

where $C(z=0)$ is deduced from Equation (11) and the rate of air bubble entrainment is estimated from Equation (3). For these calculations, the constant k_4 was assumed equal to 0.00004.

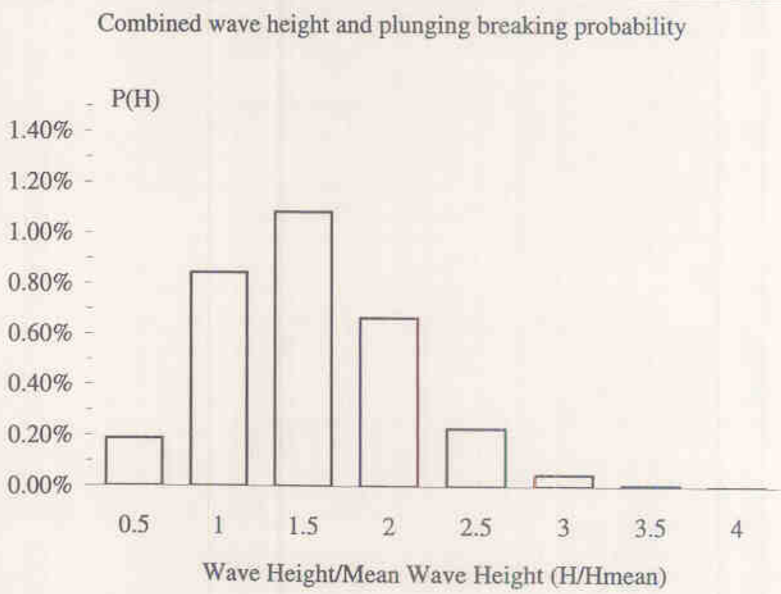
Using Equation (15) and the assumptions previously described, the authors estimated the oxygen flux caused by plunging breakers for a wind velocity of 10 m/s with an ambient DO concentration of 100% saturation at 10 Celsius in sea water at 1.0 atm. The result is an oxygen gas flux of 1.1 10^{-5} mole/s.m^2 (3.4 10^{-7} kg/m^2.s). This result compares favorably with flux values of 3.75 10^{-6} to 1.85 10^{-5} mole/s.m^2 (1.2 10^{-7} to 5.92 10^{-7} kg/m^2.s) quoted by Wallace and Wirick (1992) for wind velocities of 4.3 to 18.8 m/s and temperatures of 7.7 to 12.5 Celsius in the Middle Atlantic Bight, and values of 1.5 10^{-5} mole/s.m^2 (4.8 10^{-7} kg/m^2.s) deduced by Farmer et al. (1993) for wind velocities up to 15 m/s and temperatures of about 9 Celsius in the Georgia Strait. The Georgia Strait location had a limited fetch of 50 km and was initially less saline than typical sea water and was 19.9% undersaturated in DO.

CONCLUSION

The aeration of the ocean is enhanced by breaking waves during storms. One type of breaking waves, called the plunging breaker, is characterized by an important entrainment of air bubbles to depths larger than the wave height. The large amount of entrained air bubbles increases the air-water interface area. Further, as bubbles are entrained downward to region of higher static pressure, the increased pressure increases the saturation concentration and hence the gas transfer into the water.

A similarity between plunging breaking waves and plunging jets is developed in this paper. Using the experience of plunging jets in civil, chemical, and mechanical engineering applications, estimations of the air bubble entrainment, bubble size, and bubble penetra-

FIGURE 5. Combined probability of wave height and plunging breaking for 10 m/s wind speed.



tion depth are presented. Experimental and analytical results obtained from plunging jet situations are found to match observations of air bubbles in the ocean and their behavior during storms. The reasonable agreement between simple plunging jet calculations and observations suggests that the proposed model of plunging breaker (Figure 1) might provide useful information for the estimate of the ocean aeration due to plunging breakers. Several researchers showed a drastic increase of dissolved gas contents in the oceans after storm events. This paper proposes a first attempt to understand the air-water gas transfer potential of plunging breaking waves.

It must be emphasized that there is little experimental data available on the air-water interface area resulting from plunging jet flows and real plunging breakers. Further experimental studies are needed.

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REFERENCES

Alekseyev, V.V. and Kokorin, A.O. 1984. "The Effect of Bubbles formed by breaking Wind Waves on Air-Sea Gas Transfer." *Izvestiya* (in Russian) (translated in *Atmospheric Ocean Physics*, Vol. 20, No. 7, pp 554–559).

Avdeev, A.A., Drobkov, V.P., and Khalme, P.S. 1991. "Turbulent Momentum Transfer in a Bubble Layer." *Teplofizika Vysokikh Temperatur*, Vol. 29, No. 4, pp 775–780 (in Russian). (Translated in *High Temperature (USSR)*, Vol. 29, 1991, pp 608–612).

Casteleyn, J.A., Kolkman, P.A., and Van Groen, P. 1977. "Air Entrainment in Siphons: Results of Tests in Two Scale Models and an Attempt at Extrapolation." *Proc. of the 17th IAHR Congress*, Baden-Baden, Germany, pp 499-506. (also: Delft Hydraulic Laboratories, Holland, Report n°187).

Chanson, H. and Cummings, P. 1992. "Aeration of the Ocean due to Plunging Breaking Waves." *Research Report No. CE142*, Dept. of Civil Engineering, University of Queensland, Australia, November 1992, 42 pages.

Cipriano, R.J. and Blanchard, D.C. 1981. "Bubble and Aerosol Spectra Produced by a Laboratory 'Breaking Wave'." *Jl of Geophysical Res.*, Vol. 86, No. C9, pp 8085–8092.

Clay, P.H. 1940. "The Mechanism of Emulsion Formation in Turbulent Flow." *Proc. Ro. Acad. Sci. (Amsterdam)*, Vol. 43, Part I: pp 852–865 & Part II: pp 979–990.

Cokelet, E.D. 1977. "Breaking Waves." *Nature*, Vol. 267, pp 769–774.

Coles, K.A. 1967. "Heavy Weather Sailing." *Adlard Coles*, London, 303 pages.

Comolet, R. 1979. "Sur le Mouvement d'une bulle de gaz dans un liquide." ('Gas bubble motion in a liquid medium.') *Jl La Houille Blanche*, 1979, No. 1, pp 31–42 (in French).

Detsch, R.M. and Sharma, R.N. 1990. "The Critical Angle for Gas Bubble Entrainment by Plunging Liquid Jets." *Chem. Eng. Jl*, Vol. 44, pp 157–166.

Detsch, R.M. and Stone, T.A. 1992. "Air-Entrainment and Bubble Spectra of Plunging Liquid Jets at Acute Angles." *AIChE Symposium Series*, No. 286, Vol. 88, pp 119–125.

Ervine, D.A. and Ahmed, A.A. 1982. "A Scaling Relationship for a Two-Dimensional Vertical Dropshaft." *Intl. Conf. on Hydraulic Modelling of Civil Engineering Structures*, BHRA Fluid Eng., Coventry, U.K.

Ervine, D.A. and Elsawy, E.M. 1975. "The Effect of Falling Nappe on River Aeration." In: *Proc. of the 16th IAHR Congress*, Sao Paulo, Brazil, Vol. 3, p 390.

Ervine, D.A. and Falvey, H.T. 1987. "Behaviour of Turbulent Water Jets in the Atmosphere and in Plunge Pools." In: *Proc. Instn Civ. Engrs.*, Part 2, March 1987, 83, pp 295–314.

Ervine, D.A., Mckeogh, E., and, Elsawy, E.M. 1980. "Effect of Turbulence Intensity on the rate of Air Entrainment by Plunging Water Jets." In: *Proc. Instn Civ. Engrs*, Part 2, June 1980, pp 425–445.

Evans, G.M., Jameson, G.J., and Atkinson, B.W. 1992. "Prediction of the Bubble Size Generated by a Plunging Liquid Jet Bubble Column." *Chem. Eng. Sc.*, Vol. 47, No. 13/14, pp 3265–3272.

Farmer, D.M., McNeil, C.L., and Johnson, B.D. 1993. "Evidence of the Importance of Bubbles in Increasing Air-Sea Gas Flux." *Nature*, Vol. 361, pp 620–623.

Goldring, B.T., Mawer, W.T., and Thomas, N. 1980. "Level Surges in the Circulating Water Downshaft of Large Generating Stations." In: *Proc. of the 3rd Intl Conf. on Pressure Surges*, BHRA Fluid Eng., F2, Canterbury, U.K, pp 279–300.

Griffin, O.M. 1984. "The Breaking of Ocean Surface Waves." *Naval Research Lab. Memo.*, Report No. 5337, Washington, D.C.

Hinze, J.O. 1955. "Fundamentals of the Hydrodynamic Mechanism of Splitting in Dispersion Processes." *Jl of AIChE*, Vol. 1, No. 3, pp 289–295.

Hubbard, D.W., Griffin, O.M., and Peltzer, R.D. 1987. "Foam Generation and Air Entrainment near a Free Surface." *Naval Research Laboratory Memorandum Report 6038*, September 1987, Washington D.C.

Hwung, H.H., Chyan, J.M., and Chung, Y.C. 1992. "Energy Dissipation and Air Bubbles Mixing inside Surf Zone." In: *Proc. of the 23rd Intl Conf. on Coastal Eng.*, Paper No. 128, October 1992, Venice, Italy.

Ippen, A.T. 1966. "Estuary and Coastal Hydrodynamics." McGraw-Hill, New York, New York.

Johnson, B.D. and Cooke, R.C. 1979. "Bubble Populations and Spectra in Coastal Waters : a Photographic Approach." *Jl of Geophysical Res.*, Vol. 84, No. C7, pp 3761–3766.

Kalinske, A.A. and Robertson, J.M. 1943. "Closed Conduit Flow." *Trans. ASCE*, Vol. 108, pp 1435–1447.

Kanwisher, J. 1963. "On the Exchange of Gases between the Atmosphere and the Sea." *Deep-Sea Research*, Vol. 10, pp 195–207.

Kawase, Y. and Moo-Young, M. 1992. "Correlations for Liquid-Phase Mass Transfer Coefficients in Bubble

Column Reactors with Newtonian and Non-Newtonian Fluids." *Can. Jl of Chem. Eng.*, Vol. 70, February 1992, pp 48–54.

Killen, J.M. 1982. "Maximum Stable Bubble Size and Associated Noise Spectra in a Turbulent Boundary Layer." In: *Proc. Cavitation and Polyphase Flow Forum*, ASME, pp 1–3.

Koga, M. 1982. "Bubble Entrainment in Breaking Wind Waves." *Tellus*, Vol. 34, No. 5, pp 481–489.

Kolovayev, P.A. 1976. "Investigation of the Concentration and Statistical Size Distribution of Wind-Producing Bubbles in the Near-Surface Ocean Layer." *Oceanology*, Vol. 15, pp 659–661.

Kumar, S., Nikitopoulos, D.N., and Michaelides, E.E. 1989. "Effect of Bubbles on the Turbulence near the Exit of a Liquid jet." *Experiments in Fluids*, Vol. 7, pp 487–494.

Kusabiraki, D., Murota, M., Ohno, S., Yamagiwa, K., Yasuda, M., and Ohkawa, A. 1990. "Gas Entrainment Rate and Flow Pattern in a Plunging Liquid Jet Aeration System using Inclined Nozzles." *Jl. of Chem. Eng. of Japan*, Vol. 23, No. 6, pp 704–710.

Lara, P. 1979. "Onset of Air Entrainment for a Water Jet Impinging Vertically on a Water Surface." *Chem. Eng. Sc.*, Vol. 34, pp 1164–1165.

Lin, C. and Hwung, H.H. 1992. "External and Internal Flow Fields of Plunging Breakers." *Experiments in Fluids*, 12, pp 229–237.

Lewis, D.A. and Davidson, J.F. 1982. "Bubble Splitting in Shear Flow." *Trans. IChemE*, Vol. 60, pp 283–291.

Longuet-Higgins, M.S. 1988. "Mechanisms of Wave Breaking in Deep Water." *See Surface Sound*, Kerman, B.R. (Ed) Kluwer Academic Publishers, NATO ASI Series C, Vol. 238, pp 1–30.

Longuet-Higgins, M.S. and Corkelet, (Eds.) 1976. "The Deformation of Steep Surface Waves on Water: 1. a Numerical Method of Computation." In: *Proc. R. Soc. Lond.*, Vol. 350, A, pp 1–26.

Melville, W.K. 1982. "The Instability and Breaking of Deep Water Waves." *Jl of fluid Mech.*, Vol. 115, pp 165–185.

Melville, W.K. and Rapp, R.F. 1985. "Momentum Flux in Breaking Waves." *Nature*, Vol. 317, pp 514–516.

Miller, R.L. 1976. "Role of Vortices in Surf Zone Prediction: Sedimentation and Wave Forces." *Soc. Econ. Paleontol. Mineralog.*, Spec. Publ. No. 24 : 'Beach and Nearshore Sedimentation', pp 92–114.

Rajaratnam, N. 1962. "An Experimental Study of Air Entrainment Characteristics of the Hydraulic Jump." *Jl of Instn. Eng. India*, Vol. 42, No. 7, March 1962.

Renner, J. 1975. "Air Entrainment in Surface Rollers." *Symp. on Design & Operation of Siphons & Siphon Spillways*, BHRA Fluid Eng., London, paper A4, pp 48–56.

Renner, J. and Naudascher, E. 1975. "Air Entrainment in Surface Rollers." *Jl Hyd. Div.*, ASCE, Vol. 101, No. HY2, pp 325–327.

Sarmiento, J.L. and Toggweiler, J.R. 1984. "A New Model for the Role of the Oceans in Determining Atmospheric." *Nature*, Vol. 308, April 1984, pp 621–624.

Sarmiento, J.L., Orr, J.C., and Siegenthaler, U. 1992. "A Perturbation Simulation of CO_2 Uptake in a Ocean General Circulation Model." *Jl of Geophys. Res. (Oceans)*, Vol. 97, No. C3, pp 3621–3645.

Schultz, W.W., Griffin, O.M., and Ramberg, S.E. 1986. "Steep and Breaking Deep Water Waves." In: *Proc. of the 16th Symp. on Naval Hydrodynamics*, Office of Naval Res. Council, pp 106–115.

Sene, K.J. 1988. "Air Entrainment by Plunging Jets." *Chem. Eng. Science*, Vol. 43, Bo. 10, pp 2615–2623.

Sevik, M. and Park, S.H. 1973. "The Splitting of Drops and Bubbles by Turbulent Fluid Flow." *Jl Fluids Engrg.*, Trans. ASME, March 1973, pp 53–60.

Stramska, M., Marks, R., and Monahan, E.C. 1990. "Bubble Mediated Aerosol Production as a Consequence of Wave Breaking in Supersaturated (Hyperoxic) Seawater." *Jl of Geophys. Res.*, Vol. 95, No. C10, pp 18281–18288.

Streeter, V.L. and Wylie, E.B. 1981. "Fluid Mechanics." McGraw-Hill, 1st SI Metric edition, Singapore.

Sun, T.Y. and Faeth, G.M. 1986. "Structure of Turbulent Bubbly Jets-II. Phase Property Profiles." *Intl Jl of Multiphase Flow*, Vol. 12, No. 1, pp 115–126.

Thomas, N.H., Auton, T.R., Sene, K., and Hunt, J.C.R. 1983. "Entrapment and Transport of Bubbles by transient Large Eddies in Multiphase Turbulent Shear Flows." In: *Proc. of the Intl Conf. on Physical Modelling of Multiphase Flow*, BHRA Fluid Eng., Coventry, U.K, pp 169–184.

U.S. Army Engineer Waterways Experiment Coastal Engineering Research Centre 1984. *Shore Protection Manual.* Dept. of the Army, U.S. Army Corps of Engineers, 4th ed., Washington, D.C.

Van De Sande, E. and Smith, J.M. 1972. "Eintragen von Luft in eine Flüssigkeit durch eine Wasserstrahl Teil 1: Strahlen mit geringer Geschwindigkeit." *Chem. Inger. Tech.*, Vol. 44, No. 20, pp 1177–1183. (in German)

Van De Sande, E. and Smith, J.M. 1973. "Surface Entrainment of Air by High Velocity Water Jets." *Chem. Eng. Science*, Vol. 28, pp 1161–1168.

Van De Sande, E. and Smith, J.M. 1976. "Jet Break-up and Air Entrainment by Low Velocity Turbulent Water Jets." *Chem. Eng. Science*, Vol. 31, pp 219–224.

Vigander, S. 1984. "Bubbles, Drops and Friction on the Judgment Scale: Case Histories from TVA Engineering Laboratory's Model Tests." In: *Proc. of the Intl. Symp. on Scale Effects in Modelling Hydraulic Structures*, IAHR, Esslingen, Germany, Kobus, H. (Ed.) paper 5.1.

Wallace, D.W.R. and Wirick, C.D. 1992. "Large Air-Sea Gas Fluxes associated with Breaking Waves." *Nature*, Vol. 356, April 1992, pp 694–696.

Wisner, P. 1965. "Sur le Rôle du Critère de Froude dans l'Etude de l'Entraînement de l'Air par les Courants à Grande Vitesse." ('On the Role of the Froude Criterion for the Study of Air Entrainment in High Velocity Flows.') In: *Proc. of the 11th IAHR Congress*, Leningrad, USSR, paper 1.15. (in French)

Wood, I.R. 1991. "Air Entrainment in Free-Surface Flows." *IAHR Hydraulic Structures Design Manual No. 4*, Hydraulic Design Considerations, Balkema Publ., Rotterdam, Netherlands.

Woolf, D.K. and Thorpe, S.A. 1991. "Bubbles and the Air-Sea Exchanges of Gases in Near-Saturation Conditions." *Jl of Marine Res.*, Vol. 49, pp 435–466.

LIST OF SYMBOLS

A	sea surface area (m^2);
a	specific air-water interface area (m^{-1});
C	air concentration defined as the volume of undissolved air per unit volume of air and water;
C_{gas}	concentration of dissolved gas in water (kg/m^3);
C_s	gas saturation concentration in water (kg/m^3);
C_w	wave celerity (m/s): $C = g*T/(2*\pi)$;
D	maximum bubble penetration depth (m);
d	1- jet thickness (m) (for two-dimensional plane jet); 2- jet diameter (m) (for a circular jet);
d_b	air bubble diameter (m);
d_m	maximum air bubble diameter (m) in turbulent shear flow;
Fr	Froude number defined as: $FR = (V-V_c)/\sqrt{g*d}$;
g	gravity constant (m/s^2);
H	wave height (m);
H_{mean}	mean wave height (m);
$(H/L)_c$	critical wave steepness for plunging breaking;
K_L	liquid film coefficient (m/s);
K'	constant of proportionality;
$(K_i)_{i=1,3}$	constant of proportionality;
$(k_i)_{i=1,4}$	constant of proportionality;
L	wave length (m);
$P(H)$	normalized probability of a wave height H and plunging breaking;
P_{atm}	absolute atmospheric pressure (Pa);
Q_{air}	quantity of air entrained by plunging jet (m^3/s);
Q_{gas}	gas flux per sea surface area ($kg/m^2.s$);
Q_w	water jet discharge (m^3/s);
Re	Reynolds number;
T	wave periodicity (s);
Tu	turbulence intensity : $Tu = u'/V$;
t	time (s);
U_w	wind speed (m/s);
u'	root mean square of longitudinal component of turbulent velocity (m/s);
u_r	bubble rise velocity (m/s);
V	jet velocity (m/s);
V_c	critical velocity (m/s) at which air entrainment by plunging jet commences;
Vo	wave crest velocity at the wave breaking (m/s);
$(Vo)_h$	horizontal component of the crest velocity at wave breaking (m/s);
$(Vo)_v$	vertical component of the crest velocity at wave breaking (m/s);
v'^2	spatial average value of the square of the velocity differences (m^2/s^2) over a distance equal to the bubble diameter;
$(We)_c$	critical Weber number defined as : $(We)_c = \rho_w*v'^2*d_m / (2*\sigma)$;
x	distance along the jet centerline (m);
y	distance from the jet centerline measured perpendicular to the centerline (m);
z	vertical distance from the free surface (m), $z = 0$ at the free surface;
α	angle between the water jet and the horizontal;
δ_{al}	thickness (m) of the air layer at the intersection of high velocity jet and water pool;
μ_w	water dynamic viscosity ($N.s/m^2$);
θ	angle of the water jet with the free surface of the receiving pool of still liquid;
$\theta_1,\theta_2,\theta_3$	spread angle of a diffusing jet;
ρ_w	water density (kg/m^3);
σ	surface tension between air and water (N/m).

Subscript

air	air flow.