# SIMILITUDE OF AIR BUBBLE ENTRAINMENT AND DISPERSION IN VERTICAL CIRCULAR PLUNGING JET FLOWS. AN EXPERIMENTAL STUDY WITH FRESHWATER, SALTY FRESHWATER AND SEAWATER

by

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Abstract :

Air bubble entrainment at plunging jet takes place when the jet impact velocity exceeds a critical velocity $V_e$ which is a function of the jet turbulence. Several researchers proposed an analogy between plunging jet flows and plunging breakers. Most works considered steady plunging jet results obtained with freshwater and there have been suggestions that air entrainment at breaking waves in the sea might be an entirely different process.

This study investigates scale effects affecting air entrainment and bubble dispersion at vertical circular plunging jets. Three scale models were used and detailed air-water measurements were performed systematically for identical Froude numbers. For one scale, three water solutions were tested. All experimental results are presented in Appendices B and C. In freshwater, the results highlight significant scale effects when $We_1 = \rho_w * V_1^2 * d_1/\sigma < 10^3$ or $V_1/u_r < 10$. Identical experiments were performed with freshwater, salty freshwater and seawater. The results show lesser air entrainment in seawater plunging jets for identical inflow conditions. Results with saltwater are intermediate between freshwater and seawater results. Bubble chord times $t_{ch}$ were also measured. The data were analysed in terms of pseudo-bubble chord length $ch_{ab} = V_1 * t_{ch}$, which was found to overestimate real bubble chords by 10 to 30%. The data show that pseudo-bubble chord sizes range from less than 0.5 mm to more than 10 mm. The average pseudo-chord sizes are between 4 and 6 mm for all water solutions. Comparatively, however, more fine bubbles were detected in seawater than in freshwater.

Fine bubbles (less than 0.5 mm) have a slower rise velocity and their underwater residence time is larger in seawater. They give a visual, misleading appearance to the air-water flow suggesting that very fine bubbles are predominantly entrained in seawater plunging jets.

Overall the study contributes to a better understanding of air entrainment and bubble dispersion in vertical circular plunging jets. Differences in air entrainment mechanisms between freshwater and seawater are described. Scales effects are believed to occurs in laboratory wave flumes when the wave height at breaking is less than 0.25 to 0.35 m. Experimental results in seawater and saltwater suggest further that classical dimensional analysis of air entrainment is incomplete, and that further physical, chemical and biological fluid properties must be taken into account.

Keywords : Air bubble entrainment, plunging jet, physical modelling, scale effects, seawater, plunging breaking waves.

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is also available on the Internet at the URL :

{http://www.uq.edu.au/~e2hchans/reprints/tut02.zip}

The Zip file contains four PDF files : tut02_1.pdf (table of contents), tut02_2.pdf (main report), tut02_3.pdf (appendices) and tut02_4.pdf (references).

Abstract (in Japanese) :

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## NOTATION

The following symbols are used in this report :

| | |
|---|---|
| a | specific interface area ($m^{-1}$); |
| C | air concentration defined as the volume of air per unit volume of air and water; it is also called void fraction; |
| $C_{max}$ | maximum void fraction in a cross-section; |
| ch | chord length (m); |
| $ch_{ab}$ | pseudo-bubble chord length (m) defined as : $ch_{ab} = V_1 * t_{ch}$; |
| $ch_{mean}$ | mean bubble chord length (m); |
| $D_t$ | turbulent diffusivity ($m^2/s$) of air bubbles in air-water flow; |
| $D^{\#}$ | dimensionless turbulent diffusivity : $D^{\#} = D_t/(V_1*d_1)$ for two-dimensional shear flow and $D^{\#} = D_t/(V_1*r_1)$ for circular jet; |
| d | 1- characteristic flow thickness (m) measured normal to the flow direction;<br>2- circular jet diameter; |
| $d_{ab}$ | air bubble diameter (m); |
| $d_o$ | nozzle diameter (m); |
| $d_1$ | jet thickness (m) at plunge point; |
| F | bubble count rate or bubble frequency (Hz) defined as the number of bubbles impacting the probe sensor per second; |
| $F_{max}$ | maximum bubble count rate or bubble frequency (Hz) in a cross-section; |
| Fr | Froude number defined as : $Fr = V/\sqrt{g * d}$ ; |
| $Fr_1$ | impingement Froude number : $Fr_1 = V_1/\sqrt{g * d_1}$ ; |
| g | gravity constant ($m/s^2$); |
| $H_b$ | breaking wave elevation (m) measured above still water level; |
| $I_o$ | modified Bessel function of the first kind of order zero; |
| i | integer; |
| L | longitudinal distance (m); |
| $L_R$ | ratio of prototype to model dimensions; |
| Mo | Morton number defined as : $Mo = g*\mu_w^4/(\rho_w*\sigma^3)$; |
| P | pressure (Pa); |
| $P_{atm}$ | atmospheric pressure (Pa); |
| $P_v$ | vapour pressure (Pa); |
| Q | volume discharge ($m^3/s$); |
| $Q_{air}$ | quantity of entrained air ($m^3/s$); |
| $Q_w$ | water jet discharge ($m^3/s$); |
| Re | Reynolds number : $Re = \rho_w * V * d/\mu_w$; |
| $Re_1$ | Reynolds number at jet impingement: $Re_1 = \rho_w * V_1 * d_1/\mu_w$; |
| r | radial distance (m) from the centreline; |

| | |
|---|---|
| $r_1$ | jet radius (m) at impingement point (e.g. of plunging jet); |
| T | temperature (K); |
| Tu | turbulence intensity defined as : Tu = u'/V; |
| $Tu_1$ | turbulence intensity at jet impact measured on the centreline; |
| t | time (s); |
| $t_{ch}$ | bubble chord time (s) defined as the time spent by the bubble on the probe tip; |
| u | dimensionless parameter; |
| $u_r$ | bubble rise velocity (m/s); |
| u' | root mean square of longitudinal component of turbulent velocity (m/s); |
| V | velocity (m/s); |
| $V_e$ | onset velocity (m/s) for air entrainment; i.e., air entrainment occurs for $V_1 > V_e$; |
| $V_1$ | impact flow velocity (m/s) of plunging jet; |
| v' | root mean square of lateral component of turbulent velocity (m/s); |
| W | channel width (m); |
| We | Weber number : $We = \rho_w * V^2 * d/\sigma$; |
| $We_1$ | Weber number at impingement : $We_1 = \rho_w * V_1^2 * d_1/\sigma$; |
| x | distance along the flow direction (m), measured from the nozzle; |
| $x_1$ | distance (m) between nozzle and impingement point (e.g. of plunging jet); that is, $x_1$ is the free-jet length; |
| $Y_{Cmax}$ | radial distance (m) measured from the jet centreline where $C = C_{max}$; |
| $Y_{Fmax}$ | radial distance (m) measured from the jet centreline where $F = F_{max}$; |
| y | distance (m) measured normal to the flow direction; |

*Greek symbols*

| | |
|---|---|
| $\mu$ | dynamic viscosity (Pa.s); |
| $\mu_{air}$ | dynamic viscosity (Pa.s) of air; |
| $\mu_w$ | dynamic viscosity (Pa.s) of water; |
| $\nu$ | kinematic viscosity ($m^2/s$) : $\nu = \mu/\rho$; |
| $\pi$ | $\pi = 3.14159265358979323846264 3$; |
| $\rho$ | density ($kg/m^3$); |
| $\rho_{air}$ | air density ($kg/m^3$); |
| $\rho_w$ | water density ($kg/m^3$); |
| $\sigma$ | surface tension between air and water (N/m); |

*Other symbols*

| | |
|---|---|
| $\varnothing$ | diameter (m); |

*Subscript*

| | |
|---|---|
| air | air flow; |

| | |
|---|---|
| o | nozzle conditions; |
| R | ratio of prototype to model dimension; |
| w | water solution flow (i.e. freshwater, salt water or seawater); |
| 1 | upstream flow conditions or inflow conditions (e.g. at impingement); |

*Abbreviations*

| | |
|---|---|
| DO | Dissolved Oxygen; |
| DOC | Dissolved oxygen Content; |
| Ln | Neperian logarithm; |
| $\log_{10}$ | decimal logarithm; |
| Pdf | probability distribution function; |
| ppm | parts per million; |
| ppt | parts per thousand; |
| Std | standard deviation; |
| $\partial/\partial r$ | partial derivative with respect to r; |
| $\partial/\partial x$ | partial derivative with respect to x; |
| $\partial/\partial y$ | partial derivative with respect to y; |

*Chemical symbols*

| | |
|---|---|
| $H_2O$ | water; |
| $O_2$ | oxygen; |
| $N_2$ | Nitrogen; |
| NaCl | sodium chloride; |
| Pt | Platinum; |
| SS | stainless steel. |

## ABOUT THE AUTHORS

Hubert Chanson is a Reader in environmental fluid mechanics and water engineering at the University of Queensland since 1990. He received a degree of 'Ingénieur Hydraulicien' from the Ecole Nationale Supérieure d'Hydraulique et de Mécanique de Grenoble (France) in 1983 and a degree of 'Ingénieur Génie Atomique' from the 'Institut National des Sciences et Techniques Nucléaires' in 1984. He worked for the industry in France as a R&D engineer at the Atomic Energy Commission from 1984 to 1986, and as a computer professional in fluid mechanics for Thomson-CSF between 1989 and 1990. From 1986 to 1988, he studied at the University of Canterbury (New Zealand) as part of a Ph.D. project. He was awarded a Doctor of Engineering from the University of Queensland in 1999 for outstanding research achievements in gas-liquid bubbly flows.

Hubert Chanson's research interests include design of hydraulic structures, experimental investigations of two-phase flows, coastal hydrodynamics, water quality modelling, environmental management and natural resources. He is the author of four books : "Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways" (*Pergamon*, 1995), "Air Bubble Entrainment in Free-Surface Turbulent Shear Flows" (*Academic Press*, 1997), "The Hydraulics of Open Channel Flows : An Introduction" (*Butterworth-Heinemann*, 1999) and "The Hydraulics of Stepped Chutes and Spillways" (*Balkema*, 2001). His publication record includes over 190 international refereed papers and his work was cited more than 700 times since 1990. Hubert Chanson has been active as a consultant for both governmental agencies and private organisations. He has been awarded five fellowships from the Australian Academy of Science. In 1995 he was a Visiting Associate Professor at National Cheng Kung University (Taiwan R.O.C.) and he was Visiting Research Fellow at Toyohashi University of Technology (Japan) in 1999 and 2001.

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Shin-ichi AOKI is an Associate Professor in the Department of Architecture and Civil Engineering at Toyohashi University of Technology, Japan. He has been working in the field of coastal and harbour engineering since 1983 when he became a Research Associate in the Department of Civil Engineering at Osaka University. He was awarded a Doctor of Philosophy in 1991 from Osaka University, Japan. His main research topics between 1983 and 1993 were related to wave-structure interaction and wave forces on offshore structures especially floating and membrane structures. He was awarded the Incentive Prize from the Japan Society of Civil Engineers for his paper "Prediction of wave-induced ship motion in a harbour and its attenuation" (*Jl. of Civil Engineering*, JSCE, No. 438/II-17, pp. 81-90, 1991). From 1991 to 1992, he was a postdoctoral research fellow at the University of British Columbia, Vancouver, Canada working on chaotic response of moored ships. Since he moved to Toyohashi University of Technology in 1993, he has been working on a variety of coastal problems, especially coastal environments. Current research topics include : long period waves and harbour oscillation, remote sensing of water quality in a eutrophic bay, aeration and water quality improvement

in an estuary, hydrodynamic forces on membrane structures, beach deformation and sediment transport, air bubble entrainment due to wave breaking and its effects on wave energy dissipation and long wave generation (in collaboration with Hubert CHANSON).

He is a co-author of "Coastal Engineering - Waves, Beaches, Wave-Structure Interactions" (*Elsevier Science*, SAWARAGI 1995). He contributed also to three Japanese books on coastal engineering. Since 1997, he has been one of the editors of *Coastal Engineering Journal* (JSCE). He also collaborated with the project of Higher Education Development Support for Indonesia by the Japanese government.

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Figure i - Map of Australia

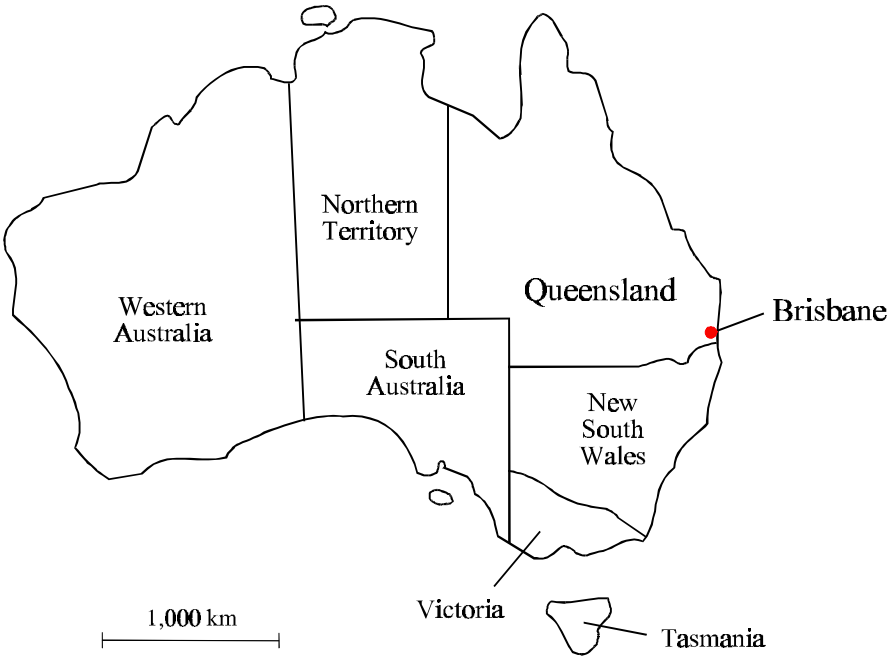


Figure ii - Map of Japan

