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Numerical assessment of two phase flow modeling using plunging jet configurations

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ABSTRACT

This paper presents unsteady numerical simulation of air entrainment by water plunging jet using Volume of fluid model coupled to PLIC algorithm for phase interface reconstruction and Euler–Euler model considering continuous water phase and dispersed air phase.

Plunging jet simulations aim to find out the ability of each model to reproduce air entrainment phenomenon. The investigation tackled the air plume depth, air entrainment rate and velocity profiles. Further simulations were performed to highlight the influence of the free jet length on the entrainment rate and plume development below the free surface.

The results show good agreement with the available experimental data particularly velocity profiles in both radial and axial directions, plume shape and development along transient intervals. The initial impact is well reproduced referring to literature and bubbles penetration depth is comparable to the empirical correlations.

It is noticed that further improvements are required for interfacial forces modeling in volume of fluid model to ensure good control of bubbles migration in the plume region.

Entrainment rate discrepancies in Euler–Euler model are related to the lack of information about interface location due to averaging process; hence, an appropriate interface detection function is needed.

1. Introduction

The phenomenon of bubbles being entrained into water is widely encountered in nature as well as in many industrial fields; chemical engineering, process engineering, energy, environmental engineering, etc. In wastewater treatment, entrained air by impinging jet is used to improve mixing processes and to provide contact between gas and liquid phases for good aeration of fluids as well as to increase gas–liquid transfer, McKeogh and Ervine (1981), Bin (1993).

In some sewage treatment plants, the sludge activated jet process is used, where bacteria degrade organic residues. For construction, the presence of a small amount of air bubbles in some concrete types allows a better resistance to the cycles of freezing and thawing. Contrariwise, the presence of air in liquids can also be harmful. The existence of trapped air bubbles in glass or plastic objects is not desired. In addition to a possible aesthetic defect, the presence of bubbles can affect the mechanical properties and alter its functioning.

The control of air entrainment mechanisms in a liquid is therefore necessary for many practical situations. A better understanding of the physics and of the details involved in impinging jets and bubble entrainment is of technological and academic interest. Over the last decade, computational fluid dynamics became a powerful tool for examining complex dynamical problems due to the development of new numerical methods and models. However, there are only a few models to deal with impinging jets. Volume of fluid (VOF) is one of this models; it has been successfully resolved a lot of problems as, the

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Nomenclature

Symbols

b_u	Half value radius [m]
C_D	Drag coefficient [–]
C_{TD}	Turbulent dispersion coefficient [–]
C_L	Lift coefficient [–]
d	Jet diameter [m]
d_0	Nozzle diameter [m]
d_b	Bubble diameter [mm]
F_{sv}	Surface tension force [kg m^2/s^2]
$F_{I,i}$	Interfacial forces [kg m^2/s]
Fr	Froude number [–]
g	Gravity acceleration [m/s^2]
h	Free jet length [m]
H	Vessel height [m]
H_p	Bubbles penetration depth [m]
K	Surface curvature [–]
n	Normal to the surface area [–]
P	Fluid pressure [kg m/s^2]
q	Downward flux [m^3/s]
Q	Vertical flux density [m/s]
R	Tank radius [m]
t	Time [s]
U	Velocity components [m/s]
U_{cl}	Center line velocity [m/s]
u	Axial mean velocity [m/s]
V_0	Initial velocity [m/s]
y	Radial coordinate [m]
z	Axial coordinate [m]

Greek symbols

α	Phase volume fraction [–]
μ	Dynamic viscosity [kg/ms]
ρ	Phase density [kg/m^3]
σ	Surface tension [kg m^2/s^2]

Subscripts

air	Air phase
i	Relative to air or water phase
w	Water phase

simulation of the drop breakup phenomenon, Renardy (2008); bubble motion, Annaland et al. (2005).

In plunging jet configuration, Fig. 1, Deshpande and Trujillo (2013) employed volume of fluid method to study the air entrainment characteristics of water jet plunging into a quiescent water pool at angles ranging from $\theta = 10^\circ$ to $\theta = 90^\circ$ measured from the horizontal plane. Results show that the volume of entrained air increases considerably from normal impingement to shallow angles and the size of cavities formed around the jet likewise increases at shallower angles.

Lyes et al. (2015) used large eddy simulation based on the Smagorinsky dynamic sub-grid scale model in combination with the multiphase volume of fluid model, to simulate the flow of two turbulent plunging water jets. A weakly disturbed jet with low turbulence content and a highly disturbed jet with a profile almost fully developed at the exit. The simulation captured successfully the previous experimentally observed topological phenomena-taking place during the transient impact and continuous-entrainment regime. It showed that surface instabilities in the free jet, due to its turbulence content, have remarkable effect on submerged interfacial area, air volume and air entrainment rate.

Schmidtke et al. (2009) presented different approaches of gas entrainment modeling by using the Euler–Euler two-fluid model with

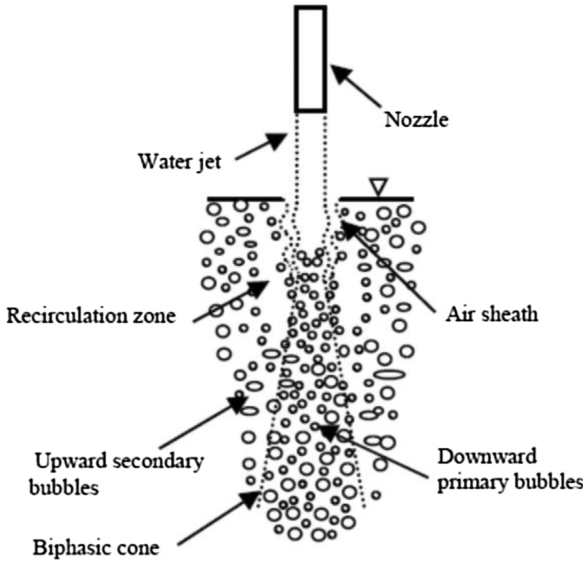

Fig. 1 – Schematic representation of bubble formation due to liquid jet impingement.
Roy et al. (2013).

a single dispersed gas phase. This work examined different drag-models dependent on air entrainment rate and proposed the Algebraic Interfacial Area Density (AIAD)-model, Höhne and Vallée (2009), which found as most suitable. Nevertheless, the investigation was not based on physical models regarding the air entrainment process when the amount of entrained gas was calculated.

Ma et al. (2009, 2011) proposed a sub-grid air entrainment model, two-stage air entrainment mechanisms were implemented into an Euler–Euler two-fluid computational multi-fluid dynamics (CMFD) model. The simulation resolves both a continuous liquid phase and one mono-dispersed gas phase, which only appeared as a source term in the liquid phase while the free surface was modeled by using a single-phase level set function, and with one way coupling. In Qu et al. (2011a) work, the mixture model and the level-set approach were investigated regarding their suitability to reproduce experimental and empirical data of impinging jet. They found reasonable agreement regarding penetration depths and the liquid velocity decay along the centerline but noticeable differences in the free surface deformations, maximum velocity at the jet centerline and the associated bubble concentration when using the different approaches.

So far, the simulation of an impinging jet with a mono-dispersed gas phase in a continuous liquid is not widely tackled. However, the size of the air bubbles produced by an impinging jet is a significant parameter for air-water transfer and several works assume a big influence of different bubble sizes and the associated bubble velocities, on the length of the entrained bubble plume, Chanson and Cumming (1994), Clanet and Lasheras (1997) and the jet velocity profile under the impinging region Zidouni et al. (2012).

Further improvement was carried out in Euler–Euler modelisation framework in order to deal with complexity of multiphase flow mechanisms.

Zidouni et al. (2011) studied the plume generation and bubble motion in comparison between mono-dispersed Euler–Euler model and inhomogeneous poly-dispersed model MUSIG. In the first model, bubble distribution is quietly smooth around the jet axis. However, with poly-dispersed bubbles size, the bubbles motion is controlled by the lift force according to their diameter, This force acts on the small bubble to trap then below the jet while it moves the large bubbles outside the jet plume if their diameter exceed 5.8 mm.

Hänsch et al. (2012) developed a new GENTOP model based on inhomogeneous Multiple Size Group model. The model includes a continuous gas phase representing the largest gas structures in whole domain for which the gas–liquid interfaces are resolved via a numerical hypothetic bending force. The computational results show good qual-