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Experimental investigation of air entrainment by vertical plunging liquid jet

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HIGHLIGHTS

- Experiment on air entrainment due to vertical plunging jet was conducted.
- Air entrainment rate database was developed using three different types of fluids.
- Effect of the pool's bottom surface orientation on air entrainment rate was not confirmed.
- Newly proposed model is capable of predicting air entrainment rate at 15.9%.

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ABSTRACT

This paper presents experimental results and predictive model on the air entrainment flow rate due to the vertical plunging liquid jet. Three types of fluids with different physical properties were utilized as a working fluid for the experiment. Air entrainment flow rate was measured using soap meniscus method and various geometrical parameters including nozzle diameter (13–16 mm), fall height (105–210 mm), pool depth (30–180 mm), and angle of the bottom pool surface (0–75°) were changed to investigate the effects on air entrainment rate. Plunging tube was installed around the falling jet and impinging point. For the current experimental conditions, it was found that the air entrainment rate depends on the product of Weber number and Laplace length scale, and new predictive model on air entrainment ratio, defined as the entrained air flow rate divided by impinging jet flow rate, is proposed. The proposed model is capable of predicting air entrainment ratio at a mean absolute relative deviation of 15.9% at the given experimental conditions.

1. Introduction

When a falling water jet interacts with the water pool, air is typically entrained by a form of bubbles at the impinging point of water surface. Fundamental phenomenon of the plunging jet is depicted in Figure. Following the interaction of water jet at falling from the height H_{fall} traveling at velocity V_0 from the nozzle diameter D_0 against pool surface, air sheet formed around the impinging point at the diameter D_E is entrained into the water surface (Chanson, 1996). The air sheet, formed with length L, is sheared off and broken up into smaller bubbles as they are entrained into the pool around the circumference of water jet. Such air entrainment phenomenon is commonly seen in nature where the falling jet interacts with open channel flow (Bin, 1993; Chanson, 1996; Kiger and Duncan, 2012). Air entrainment phenomenon is also observed in various engineering systems including chemical processing plant which involves mixing and stirring, gas absorption systems, hydraulic structures and so on. Hydrodynamic length scale of these applications ranges from few millimeters to 10 m of order, and large number of air bubbles are entrained at downstream of the jet impact point. In view of the industrial applications that involve air entrainment, quantification of the entrained air flow rate is crucial for optimal engineering design and operation. Although it appears to be a simple hydrodynamic phenomenon and has been studied for past few decades by various researchers, fluid dynamics of the impingement phenomenon is still not clearly understood as of now. Hence, intent of this work is to conduct fundamental study on air entrainment rate prediction due to vertical plunging jet using three different types of fluids that are readily available. In this article, air entrainment mechanism, overview of the existing models, air entrainment experiment performed on vertical impinging jet, and new predictive model for the air entrainment rate are presented.

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Nomenclature

A	empirical constant [-]
$A_{Cylinder}$	cylinder area [m^2]
d	plunging tube diameter [m]
D_0	nozzle inner diameter [m]
D_E	diameter of air entrainment pocket [m]
D_j	jet diameter at impact point [m]
Fr	Froude number [-]
g	gravitational acceleration [m/s^2]
H	cylinder length [m]
H_f	water depth [m]
H_{fall}	fall height [m]
k	empirical coefficients [-]
L	depth of the air sheet layer created by impinging jet [m]
La	laplace length scale [m]
L_j	jet length [m]
l_{Nozzle}	nozzle length [m]
l_t	turbulence length scale [m]
m_d	mean absolute error [%]
m_{rel}	mean relative deviation [%]
$m_{rel,abs}$	mean relative absolute deviation [%]
n	empirical constant [-]
Oh	Ohnesorge number [-]
Q_A	air entrainment rate [m^3/s]
Q_L	jet flow rate [m^3/s]
Re	Reynolds number [-]
s_d	standard deviation [%]
t	time [s]
u_t	turbulent velocity fluctuation [m/s]
$V_{Cylinder}$	cylinder volume [m^3]
V_e	onset velocity [m/s]
V_0	jet velocity at nozzle exit [m/s]
V_j	jet impact velocity point [m/s]
We	Weber Number [-]

Greek symbols

δ	length of air layer [m]
μ_f	dynamic viscosity of fluid [Pa s]
σ	surface tension of fluid [N/m]
ρ_f	density of fluid [kg/m^3]
θ	jet angle [°]
θ_{plate}	plate angle [°]

1.1. Air entrainment mechanism

Air entrainment phenomenon is dependent on various parameters including: physical properties of fluids, geometrical properties of the jet impingement system (jet fall height, nozzle diameter, nozzle shape and angle), operational condition (fluid velocity, temperature, pressure), and so on. Mechanism of the air entrainment due to the vertical jet impingement has been studied by various researchers since 1970s, and difference in entrainment process due to the jet velocities is confirmed by the past experiments (Bin, 1993; Chanson, 1996). It is reported that the entrainment process tends to be different for low jet impact velocity ($V_j < 4$ m/s) and high jet impact velocity ($V_j > 4$–12 m/s). However, the sequence of the entrainment process is similar for both cases as depicted in figure.

When the jet vertically enters the pool at velocity V_j, local oscillation is generated at the contact point. Once the incoming velocity reaches critical point (called onset velocity, V_e), pool surface cannot follow its undulation and air pocket is created right underneath the pool surface. Consequently, air is entrained through the vacant space generated by the pocket. The air pocket interface is highly unstable due to the re-entrant jet which tends to make up the vacant space. Consequently, the pocket is disintegrated into multiple small bubbles. Such mechanism is also observed for high velocity jet case where the length of the air pocket tends to fluctuate at larger degree than the low velocity jet case. The entrained bubbles are then carried away within the pool by the large-scale eddies, and it has been found that most of these large-scale vortices are oriented orthogonal to the flow direction (Chanson, 1996).

Several correlations and models are reported for the analysis of the air entrainment rate (Q_A) at a given liquid flow rate (Q_L) with respect to V_j. Entrainment ratio, Q_A/Q_L, is a commonly utilized dimensionless air entrainment rate quantity and at a given jet impact velocity V_j, it can be expressed as a function of Froude number as follows:

$$\frac{Q_A}{Q_L} = k_1 Fr^2 \quad \text{for } V_j < 5 \text{ m/s} \tag{1}$$

$$\frac{Q_A}{Q_L} = k_2 Fr^{1/2} \quad \text{for } 5 \text{ m/s} < V_j < 10 \text{ m/s} \tag{2}$$

$$\frac{Q_A}{Q_L} = k_3 Fr \quad \text{for } V_j > 10 \text{ m/s} \tag{3}$$

Note that Eqs. (1)–(3) were developed at a deep receiving pool condition without any flow motion, and working fluids are air and water. Empirical constants k_1 through k_3 are determined through experiments. In simplified form, above formulations can be summarized as follows:

$$\frac{Q_A}{Q_L} = k_m Fr^n. \tag{4}$$

As can be seen, entrainment air rate is expressed in terms of empirical coefficient k_m and Froude number, which is defined as follows:

$$Fr = \frac{V_j - V_e}{\sqrt{gD_j}} \tag{5}$$

Here, V_e, g, and D_j are the onset velocity, gravitational acceleration, and jet diameter at impinging point, respectively. Based on the previous experiments, identification of V_e is a crucial part of the entrainment analysis. According to Chanson (1996), V_e is a function of various parameters, and dimensionless analysis shows that,

$$V_e = f(\rho_f, \mu_f, \sigma, g, u_t, l_t, \theta). \tag{6}$$

Here, ρ_f, μ_f, σ, u_t, l_t, and θ are the water density, water dynamic viscosity, surface tension, turbulent velocity fluctuation, turbulent length scale and angle of the jet against the liquid surface, respectively. The air entrainment rate formulations shown in Eqs. (1)–(3) are depicted in Fig. 3, and three distinctive regions (Region I to III) are defined based on the jet impact velocity (V_j). Region II is known as a transition region, where occurrence of an intermittent vortex was observed by Detsch and Sharma (1990).

Recent review article published by Kiger and Duncan (2012) summarizes the nondimensional variables that influence the entrainment ratio. Of all the available dimensionless variables, useful ones are summarized as follows:

$$\frac{Q_A}{Q_L} = f\left(Fr, We, Ca, \frac{\rho_g}{\rho_f}, \frac{\mu_g}{\mu_f}, V^*, \frac{\lambda}{L}, \theta_j\right) \tag{7}$$