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Void penetration length from air injection through a downward large diameter submerged pipe in water pool

Somboon Rassame [a,*], Takashi Hibiki [b], Mamoru Ishii [b]

[a] Department of Nuclear Engineering, Faculty of Engineering, Chulalongkorn University, Wangmai, Patumwan, Bangkok 10330, Thailand
[b] School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, IN 47907-2017, USA

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ABSTRACT

In the initial event on a Loss of Coolant Accident (LOCA) of a typical Boiling Water Reactor (BWR), mostly non-condensable gas is forced through blowdown pipes submerged downwardly in the Suppression Pool (SP). The void penetration length in the SP is considered as a key parameter to design an alignment of Emergency Core Cooling System (ECCS) pump suction pipe in a pool for avoiding the problem of the gas intrusion to the pump. Therefore, it is very important to predict accurately the void penetration length in the SP during a LOCA. However, the existing models or correlations to predict the void penetration length in a water pool have been developed using test data with small diameter submerged tubes less than or equal to 3.5 cm. In this study, new correlations to predict the axial void penetration length during the initial and the quasi-steady phase air injection, respectively, have been developed particularly for a large diameter submerged pipe cases using the previous experimental results with large diameter submerged pipe of 7.6 and 10.2 cm. The developed correlations consider a bubble plume developed in a liquid medium as a lumped model and use the field equations with necessary assumptions to determine the equation of void penetration length. The predictions of the newly developed correlation are tested by comparing the computed results with available experimental data from the previous studies. The comparisons show a good agreement between them.

1. Introduction

The penetration length of downward gas jets discharging into a liquid tank through a submerged nozzle or pipe is a key parameter of equipment systems and devices design in various engineering fields such as chemical and nuclear engineering. For examples, in chemical engineering, nozzles in industrial fluidized bed reactors use the injection of gas into liquid to promote the mixing and interaction between them. The characteristics of gas jets and penetration length can significantly affect the mixing performance of the reactors (Sauriol et al., 2013). Importantly, in nuclear engineering fields, the downcomer pipes submerged in the SP of a typical BWR are utilized as pathways to release the high temperature gas from the containment to the SP during an accident (Kukita et al., 1984). The void penetration length in the vicinity of downcomer exits plays an important role in determining a proper location of intake pipes in preventing gas entering pumps of the safety system. Fig. 1 illustrates the geometrical characteristic of the pump intakes pipes and downcomer pipes in the MARK I BWR SP.

In general, the void penetration length will be affected by the injected gas velocity, discharging pipe diameter, fluid properties of injected gas and liquid in tank. According to the air injection tests by Rassame et al. (2014), it was found that the axial void penetration length is experienced the first maximum during the initial air injection phase caused by the injection of an initial liquid slug in a pipe. The quasi-steady air injection phase provides less maximum void penetration depth since there is no impact of the initial liquid slug injection. In summary, there is two maximum points of the axial void penetration point during whole periods of the air injection. First point is in the initial air injection phase and the second point is in the quasi-steady air injection phase.

Consequently, this study is performed to develop the new correlation for prediction of the axial void penetration length during the initial gas injection phase with the consideration on the effect of liquid slug inertia pulling the bubble downward and the quasi-steady phase injection for large diameter pipe cases, respectively. The correlation is developed based on the available experimental data from air injection tests for large diameter submerged pipes conducted by Rassame et al. (2014). Moreover, the capability of the new developed correlation to predict the void penetration length is investigated by comparing with the existing data or correlations.

* Corresponding author.
E-mail address: somboon.ra@chula.ac.th (S. Rassame).

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Nomenclature

C_D	drag coefficient
c_p	specific heat
d	pipe or tube diameter
F_g	force due to gas pressure
F_{ph}	force due to hydrostatic pressure
F_D	drag force
F_z	force acted on X-direction
Fr	froude number
Fr'	modified froude number
G_t	gas mass flux at nozzle tip
G_m	averaged gas mass flux at gas/liquid interface
g	acceleration due to gravity
h_{fg}	heat of vaporization of liquid
j_g	gas volumetric flux
l	axial void penetration length
l_i	initial void penetration length
l_h	initial height of liquid slug in a submerged pipe
m_l	mass of liquid slug
m'	virtual mass
P_a	absolute pressure at water surface
P_i	momentum input
P_o	momentum output
Q_a	air volumetric flow rate
r_b	radius of the bubble plume
r	radius of submerged pipe
r_i	radius on back area of liquid slug
r_o	radius on front area of liquid slug
t	time
T_s	steam temperature
T_α	liquid bath temperature
u_o	gas velocity in a tube
V_p	volume of gas plume
v_i	gas–liquid interface velocity
v_{ls}	liquid slug velocity
$v_{r\alpha}$	bubble rising velocity
y	axial distance from the submerged pipe exit to back area of liquid slug

Greek letters

α	gas jet cone half angle
β	angle of boundary of submerged jet
σ	surface tension
ρ_f	liquid density
ρ_g	gas density

Symbols

Σ	total

Subscripts

cal	calculated results
exp	experimental results
f	at final stage
i	at initial stage
l	liquid

Acronyms

ESBWR	Economic Simplified Boiling Water Reactor
BWR	Boiling Water Reactor
SP	Suppression Pool
PUMA-E	Purdue University Multi-Dimensional Integral Test Assembly for ESBWR application
RPV	Reactor Pressure Vessel

2. Previous related models and correlations

Several researchers have studied the formation of gas bubbles by performing experiments using gas injection through a small tube submerged in a liquid bath or tank. The key parameters, such as the bubble radius and volume and the jet penetration length during the gas injection, were experimentally measured. Several models of related bubble formation and correlations of the jet penetration have been proposed based on their experimental data. Some of the relevant researches in this effort are described below.

Davidson and Schuler (1960) introduced a model of bubble formation in a viscous liquid. They also performed an experiment by upward injection of gas through an orifice with diameter of 0.086 cm in the high viscosity liquid bath under various gas flow rates conditions between 0 and 50 ml/s. The volume of gas bubbles formed by the developed model agreed well with their experimental results.

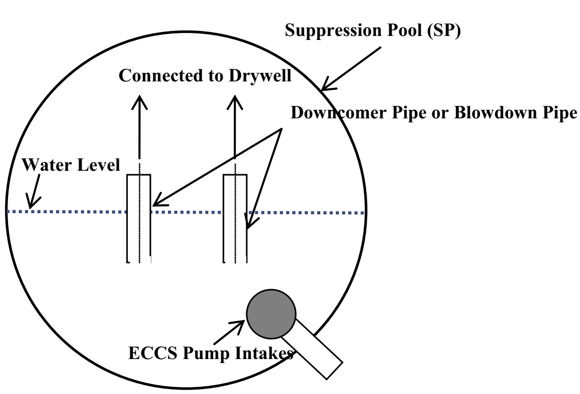

Fig. 1. Geometrical characteristic of the MARK I pressure suppression chamber (US NRC, 2010).

Krishnamurthi et al. (1968) studied the formation of bubbles in viscous liquid under constant flow conditions. The nozzle diameters used in their experiment were ranged between 0.227 and 0.312 cm and air flow range conditions were ranged between 0.02 and 0.5 cm^3/s. The bubble formation model was developed in the two-stage of bubble formation, namely, the bubble growth stage and the detachment stage. The equation of bubble volume based on the developed modeled were obtained and verified with their experimental data. The predicted bubble volume was in good agreement with the test results within ±5%.

Wraith (1971) proposed a simple two stages model of bubble formation at a plate orifice submerged in an inviscid liquid under the high gas injection flow rates. The first stage involved the growth of hemispherical bubbles by the gas inertia force. The second stage developed when the buoyancy force became dominant. Supporting experiments were performed using air injection flow rate at range between 200 and 20,000 cm^3/s and nozzle diameter sizes of 0.317–0.593 cm. The experimental data showed a good agreement with the predicted bubble volumes.

Chen et al. (1977) developed the model for the vent clearing in the downcomer pipe submerged in the SP. The time dependent momentum equation for the liquid slug movement was derived with the assumption that liquid slug acted as the rigid body moving. The equation for estimation of the vent clearing time was obtained by their study.

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