International Journal of Heat and Mass Transfer 122 (2018) 89–98

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Investigations on the penetration length of steam-air mixture jets injected horizontally and vertically in quiescent water

Weichao Li [a], Zhaoming Meng [a], Zhongning Sun [a,*], Lu Sun [b], Chang Wang [b]

[a] Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin, Heilongjiang 150001, China
[b] China Ship Development and Design Center, Wuhan, Hubei 430064, China

ARTICLE INFO

Article history:
Received 24 October 2017
Received in revised form 16 January 2018
Accepted 17 January 2018

Keywords:
Mixture gas
Submerged jet
Direct contact condensation
Penetration length
Flow regime

ABSTRACT

Gas submerged jet penetration length is a key parameter for many industrial applications. Many experimental and theoretical works have been performed on pure steam and non-condensable gas submerged jets. However, the steam-air mixture gas submerged jets are not yet fully understood. So, a series of visualization experiments are performed to investigate the effect of air mass fraction, jetting direction, water temperature and inlet pressure on mixture gas submerged jet penetration length. Two flow regimes are distinguished based on the evolution of the interface between water and mixture gas, which are referred to as stable regime and oscillation regime. A flow regime map is developed based on inlet pressure and air mass fraction. A momentum balance model for predicting jet penetration length is proposed. Results show that the mixture gas jet penetration length increases with the increasing inlet pressure and decreases with the increasing air mass fraction. The water temperature has little effect on the jet penetration length. A new correlation for dimensionless vertical jet penetration length is developed based on the form of model analysis. The discrepancy between predicted results and present experimental data is within ±5%. A new correlation for dimensionless horizontal jet penetration length is developed based on experimental results. The discrepancy between predicted dimensionless horizontal jet penetration length and experimental value is within ±18%.

1. Introduction

Direct discharge of steam into subcooled water is an effective mean to rapid depressurization for light water reactor, such as in-containment refueling water storage tank (IRWST) [1], air hold tank (AHT) [2] and pressure suppression pool (PSP) [3]. In fact, the non-condensable gas will enter the water pool with the steam in the initial stage of injection. Many investigations on pure steam jet condensation [4–20] and non-condensable gas jets [21–29] have been done. However, there is limited information on steam-air submerged jets in the available scientific literature.

The condensation regime, steam plume length and pressure oscillation are generally used to describe characteristics of pure steam submerged jet condensation. Condensation regimes mainly include chugging, condensation oscillation, bubbling condensation oscillation, interfacial oscillation condensation and stable condensation [19]. In the stable condensation regime, the interface of steam-water has a relatively stable shape, including contraction shape, expansion-contraction shape, double expansion-contraction shape and double expansion–divergent shape [12]. Kerney et al. [30] derived a simple model for predicting steam plume length with the assumption of a constant Stanton number, based on the conservation of mass and energy. Later, Weimer et al. [31] revised the model using turbulent entrainment and variable density theories. Several experimental correlations [5,7,12,30–32] for steam plume length have been obtained based on the basic form presented by Kerney et al. [30]. Recently, Heinze et al. [33] presented a one-dimensional two-fluid model, based on Kelvin-Helmholtz and Rayleigh-Taylor instability theories. In addition, submerged steam jet condensation also can induce pressure oscillation in the water, including low frequency composition [4], intermediate frequency composition [8,10,16–18,34] and high frequency composition [5,11].

There are two flow regimes including bubbling and steady jetting for non-condensable gas submerged jets. The transition regime occurred at the Mach number about 0.2 in the aqueous ambient and about 1 in the mercury [29]. Davidson [27] developed a model for non-condensable gas jet penetration length based on the assumption of free jet velocity distribution near the axis of the jet, taking into account the influence of gas velocity, the density of gas and liquid, gravitational acceleration and nozzle diameter. Several correlations [22,24,26,28,29,35] for the non-condensable

* Corresponding author.
E-mail address: sunzhongning@hrbeu.edu.cn (Z. Sun).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.075
0017-9310/

Nomenclature

a	acceleration, m/s^2
d	nozzle diameter, mm
Fr	Froude number
g	acceleration of gravity, m/s^2
G	gas mass velocity, kg/m^2 s
L	jet penetration length, mm
p	pressure, MPa
Q	volume flow rate of gas, m^3/s
u	gas velocity, m/s
V	the volume of gas area, m^3
W	mass fraction
ρ	density, kg/m^3
α	the spread angle of the gas core, °
θ	the angle between the axis of the nozzle and the vertical, °

Subscripts

a	air
e	the exit of nozzle
g	gas core
H	horizontal
l	liquid
s	steam
V	vertical

gas jet penetration length have been developed based on the modified Froude number.

For submerged jets of steam-air mixture, the amount of information available is very scarce. A little non-condensable gas tends to significantly stabilize steam condensation process in the chugging regime [36–39]. Zhao et al. [40] found that both the first and second pressure oscillation dominant frequency decrease greatly with the increase of non-condensable gas mass fraction. However, the pressure oscillation intensity tends to increase with the rise of non-condensable gas mass fraction at low water temperature conditions and decrease with the rise of non-condensable gas mass fraction at high water temperature conditions.

Some widely used correlations for the jet penetration length in the literature have been summarized in Table 1. Based on the above review, it is clear that all available correlations for predicting gas jet penetration length focus on non-condensable gas or pure steam jets. The objective of present investigation is to explore the effect of air mass fraction, jetting direction, water temperature and inlet pressure on mixture gas submerged jet penetration length experimentally and theoretically. The steam-air mixture gas submerged jet penetration length is obtained using high speed camera and image processing. The present experimental data would be useful for verification of CFD (Computational Fluid Dynamics) results.

Table 1
Proposed correlations for submerged jet penetration length.

Authors	Correlations	Gas/liquid	Direction	Remarks
Kerney et al. [30]	$\frac{L}{d} = 0.7166\left(\frac{c_p(T_g-T_w)}{h_{fg}}\right)^{-0.8311}\left(\frac{G_e}{G_m}\right)^{0.6446}$	Steam/water	Horizontal	d = 0.4–11.2 mm G_e = 332–2050 kg/m^2 s T_w = 28–85 °C
Weimer et al. [31]	$\frac{L}{d} = 17.75\left(\frac{\rho_g}{\rho_w}\right)^{1/2}\left(\frac{h_{w,sat}-h_w}{h_g-h_w}\right)^{-1}\left(\frac{G_e}{G_m}\right)^{0.5}$	Steam/water, ethylene and iso-octane	Horizontal	d = 3.17 mm G_e = 332–2050 kg/m^2 s T_w = 20–83 °C
Chun et al. [7]	$\frac{L}{d} = 0.5923\left(\frac{c_p(T_g-T_w)}{h_{fg}}\right)^{-0.66}\left(\frac{G_e}{G_m}\right)^{0.3444}$	Steam/water	Horizontal and vertical	d = 1.35–10.85 G_e = 200–1500 kg/m^2 s T_w = 16–87 °C
Kim et al. [32]	$\frac{L}{d} = 0.503\left(\frac{c_p(T_g-T_w)}{h_{fg}}\right)^{-0.70127}\left(\frac{G_e}{G_m}\right)^{0.47688}$	Steam/water	Horizontal	d = 5–20 G_e = 250–1180 kg/m^2 s T_w = 35–80 °C
Wu et al. [12]	$\frac{L}{d} = 0.597\left(\frac{c_p(T_g-T_w)}{h_{fg}}\right)^{-0.8}\left(\frac{G_e}{G_m}\right)^{0.5}\left(\frac{p_g}{p_w}\right)^{0.2}$	Steam/water	Horizontal	d = 8 G_e = 298–865 kg/m^{2}s T_w = 20–70 °C
Chong et al. [5]	$\frac{L}{d} = 0.3866\left(\frac{c_p(T_g-T_w)}{h_{fg}}\right)^{-0.8}\left(\frac{G_e}{G_m}\right)^{0.78}$	Steam/water	Horizontal	d = 8 mm G_e = 400–800 kg/m^2 s T_w = 10–70 °C
Igwe et al. [35]	$L_H = 0.97p_{in}d + 6.4$ $L_V = 1.20p_{in}d\cos\theta + 0.78$ $L_H = 2.04p_{in}d\sin\theta + 5.6$	Nitrogen/water	Horizontal incline	d = 0.38–5.1 mm p = 20–215 Pisa θ is the angle between the axis of the nozzle and the vertical
Hoefele and Brimacombe [29]	$\frac{L_H}{d} = 10.7\left(\frac{u_e^2}{gd}\frac{\rho_g}{\rho_l}\right)^{0.46}\left(\frac{\rho_g}{\rho_l}\right)^{0.35}$	Air, argon, and helium/water, zinc-chloride solution and mercury	Horizontal	d = 2–4.76 mm $\rho_g u_e = 20\text{–}1800$ kg/m^2 s
Carreau et al. [28]	$\frac{L_H}{d} = 1.37\left(\frac{\rho_g u_e^2(p_e-p_a)}{(\rho_l-\rho_g)d}\right)^{0.39}$	Nitrogen/water	Horizontal	d = 0.3–1 mm p_a = 0.5–10 MPa sonic
Davidson et al. [27]	$\frac{L_V}{d} = 1.5\left(\frac{u_e^2}{gd}\frac{\rho_g}{\rho_l-\rho_g}\right)^{0.5}$		Vertical downward	Model analysis
Emami and Briens [26]	$\frac{L_V}{d} = 2.3155\left(\frac{u_e^2}{gd}\frac{\rho_g}{\rho_l}\right)^{0.358}$	Helium, argon and air/water, ethanol and sucrose solutions	Vertical downward	d = 1.07–4 mm (Ma < 0.3)
Harby et al. [24]	$\frac{L_V}{L_Q} = 2.29\left(\frac{u_e^2}{gd}\frac{\rho_g}{\rho_l-\rho_g}\right)^{0.305}$	Air/water	Horizontal	d = 2–5 mm Ma = 0.59–1.05
Rassame et al. [22]	$\frac{L_V}{d} = 2.353\left(\frac{u_e^2}{gd}\frac{\rho_g}{\rho_l}\right)^{0.385}$	Air/water	Vertical downward	d = 76, 102 mm. u = 7.9–24.7 m/s