International Journal of Heat and Mass Transfer 110 (2017) 643–656

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Mechanisms of pressure oscillation in steam jet condensation in water flow in a vertical pipe

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ARTICLE INFO

Article history:
Received 21 July 2016
Received in revised form 18 November 2016
Accepted 6 March 2017

Keywords:
Direct contact condensation
Steam jet
Pressure oscillation
Condensation regime
Pipe flow

ABSTRACT

Pressure oscillation associated with direct contact condensation of steam jet in water pipe flow is of high significance for industrial processes. In this paper, experimental study is conducted to reveal the mechanisms of the pressure oscillation in steam jet condensation in water flow in a vertical pipe. The interfacial characteristics of the jet plume are acquired by high speed camera, and the pressure oscillation due to condensing jet are captured by using high frequency pressure transducers. Four main types, including Chugging, Oscil-I, Oscil-II and Stable condensation regimes, are identified visually based on the interfacial behavior of the jet plume, and their distribution is described in a three-dimensional condensation regime diagram based on steam mass flux, water temperature, and Reynolds number of water flow. In the Chugging regime, the high-amplitude pressure oscillation appears at low frequency, and the unimodal PDF demonstrates that the pressure oscillation is only dominated by steam mass flux. In the Oscil-I regime, the pressure oscillation is approximately sinusoidal and its intensity is the highest among the four condensation regimes, whereas the intensity of the pressure oscillation remains at a low level and varies little in the Stable regime. In both the Oscil-I and Stable regimes, with increase of water temperature and Reynolds number of water, the unimodal PDF spreads out over a wider range, and finally the bimodal and symmetrical PDF appears for the Oscil-I regime. The statistical analysis shows that both the deviation and maximum of pressure signals could identify the four condensation regimes well, while both the skewness and kurtosis of pressure signals could easily distinguish the Chugging and Oscil-II regimes.

1. Introduction

Phase change such as direct contact condensation (DCC) is one of the basic ways used to enhance the rates of heat and mass transfer. It possesses a wide range of applications pertaining to various industrial processes including nuclear reactor safety systems, direct contact feed water heaters, underwater propulsion systems, etc. DCC of vapor jet in liquid offers several advantages, such as exceedingly efficient heat and mass transfer in compact spaces with a lower rate of coolant liquid flow, easy fabrication process as they involve no extra attachment to separate channel. Besides the above mentioned advantages, however, the process of DCC vapor jet in liquid might induce some unfavorable drawbacks. In liquid-propellant rocket vehicles, the vapor-liquid interface oscillation inside the pipeline of the engine system is likely to cause substantial pressure fluctuation in the fluid system, which leaves the rocket vehicle prone to longitudinal vibration [1]. Although much work has been devoted to the heat transfer characteristics of DCC of vapor jet in liquid, the investigation on the pressure oscillation of DCC of vapor jet in liquid in pipeline is still limited. In this work, we aim to reveal the mechanisms of the pressure oscillation in steam jet condensation in water flow in a vertical pipe.

In recent years, a lot of studies have attempted to better understand the flow and heat transfer mechanisms in DCC of steam jet in water. The interface behavior of the steam-water was generally described in a condensation regime diagram with the dependencies of steam mass flux and water temperature by using the dynamical pressure signal and visual observation [2–5]. Kerney et al. [6] was the pioneer to establish correlation of the jet penetration length as a function of condensation driving potential and steam mass flux. Later researchers developed Kerney et al.'s correlation in terms of different background and experiments [7–14]. Many semi-empirical correlations of heat transfer coefficient have been proposed [7,8,12,15–19]. The heat transfer coefficient was found to in the level of 0.1–10 MW/m^2 K, and increase with the sub-cooling rate, steam flow rate, and Reynolds number of water

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.017
0017-9310/

Nomenclature

A	amplitude of Gauss distribution, 1
d_e	inner diameter of the nozzle, m
d_m	maximum diameter of the steam plume, m
D	inner diameter of the vertical round pipe, m
G_s	steam mass flux at the nozzle exit, kg/m^2 s
i	ordinal of data points in a test sample, 1
Ku	the fourth moments of the pressure signals, 1
m_w	water flow rate, kg/s
N	data points in a test sample, 1
p_0	mean of Gauss distribution, kPa
$\bar{p}$	mean of pressure, kPa
p_{sd}	stand deviation of pressure, kPa
p_i	signal of pressure oscillation, kPa
p_{max}	maximum of pressure signals, kPa
$p_{max,\ 3\%}$	average of the up 3% of the pressure signals, kPa
p_s	steam inlet pressure, MPa
p_w	water pressure at the steam injection point, MPa
PDF	Probability Density Function, 1
Re_w	Reynolds number of water flow equals to $4m_w/\pi D\mu_w$, 1
Sk	the third moments of the pressure signals, 1
t	time, s
T_s	steam inlet temperature, °C
T_w	water inlet temperature, °C
w	standard deviation of the PDF
y_0	constant in the Gauss fitting equation of the PDF, 1

Greek letters

θ	angle between the nozzle center line and the pipe wall, °
μ_w	dynamic viscosity of water, m^2/s

Subscripts

s	the steam phase
w	the water phase

flow. To reveal the detailed flow field of the turbulent condensing jet, techniques such as the Particle Image Velocity, Planar Laser Induced Fluorescence and mobile thermocouple probes have been utilized [20–23]. The mean axial velocity and temperature distributions of the turbulent condensing jet are found to exhibit good self-similarity features. For jets of fluid interaction with crossflow, fruitful achievements on the jet interface behavior, penetration length and trajectory were reported [24].

The pressure oscillation induced by DCC of steam jet in water is also an area of interest in literature. Simpson and Chan [25] and Youn et al. [26] measured the dominant frequency of the pressure oscillation at low steam mass flux and found that the dominant frequency was proportional to the steam mass flux and water subcooling, but inversely proportional to nozzle diameter. Cho et al. [27] ascertained that the amplitude of the pressure oscillation increased gradually with water temperature and then decreased steeply, and it peaked at water temperature of between 60 and 80 °C. Hong et al. [28] and Qiu et al. [29–31] found that the dominant frequency of the pressure oscillation was inversely proportional to water temperature, and it was proportional to steam mass flux for steam mass flux under 300 kg/m^2 s and inversely proportional for steam mass flux over 300 kg/m^2 s. Qiu et al. [31] and Chong et al. [32] suggested that the first dominant frequency was primarily attributed to the periodical variation of the steam plume, whereas the second dominant frequency was largely due to the generation and rupture of the large steam bubbles. Chen et al. [33] found that the low-frequency pressure oscillation was generated by turbulent jet vortexes in the jet wake region. Zhao et al. [34] confirmed that the steam jet cavity shape was unsteady even at high steam mass flux and the pressure oscillation appeared with the variation of steam cavity length and bubble separation. Tang et al. [35,36] found that the acoustic signal were boosted in their maximum amplitude with increase in subcooling, and two typical waveforms corresponding to bubble split-up and collapse were observed. Khan et al. [37] and Sanaullah et al. [38] confirmed that the instabilities were created at the steam water interface, which produced pressure stresses in a non-deterministic way. Qu et al. [39] found that the dominant frequency shifted to low frequency direction with increase of water temperature and air content.

From the literature review mentioned above, the previous studies predominantly focused on the pressure oscillation of steam jet in stagnant water in pool either at low steam mass flux corresponding to Chugging, or at high steam mass flux corresponding to Stable regime. Few of them is systematically involved with the pressure oscillation mechanisms of steam jet in water flow in pipes. Especially little attention is paid to the pressure oscillation mechanisms under various condensation regimes. The objective of present experimental study is to explore the mechanisms of the pressure oscillation in steam jet condensation in water flow in a vertical pipe. The interfacial characteristics of the jet plume are observed with a digital high-speed video camera, and the pressure oscillation due to condensing jet are captured by using high-frequency pressure transducers. The influences of steam mass flux, water temperature and Reynolds number on the pressure oscillation characteristics and condensation regimes are discussed. The results would be helpful for further investigation on the physical mechanisms underlying DCC of steam jet in water flow in pipes.

2. Experimental apparatus

A sketch of the experimental facility is shown in Fig. 1. This system consists of a steam supply line, a water supply line, and a test section. In order to reduce the influences of vibrations and other perturbations on the flow within the vertical test pipe, flexible hoses and buffer tanks are applied to isolate the test section with the water and steam supply lines. An electric steam generator is applied to produce saturated steam with maximum mass flow rate of 0.03 kg/s. A control valve (15) is installed at the outlet of the generator to adjust the steam mass flow rate, which is measured by a vortex flowmeter with relative deviation lower than 0.5%. Because the pressure before the control valve is very high at about 0.8 MPa, the steam flow is sonic flow at the control valve for all the test conditions in present work. Therefore, changing the position of the control valve (15) has no influence on the compressible volume and the pressure oscillation results. Then the saturated steam from the generator is transported by a stainless steel pipe with 20 mm inner diameter and 3 m length, which is enfolded by tap heaters and fiberglass coverings to insure saturation of the steam. A control valve (17) is installed at the end of the stainless steel pipe, which is generally in fully open position during the test. A stainless steel flexible hose with inner diameter of 20 mm and length of 2 m is applied to connect the control valve (17) with the steam inlet.

Water is pumped from a water tank (1) by a centrifugal water pump (2). A control valve (3) is installed at the outlet of the water