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Experimental study on the interfacial behavior of stable steam jet condensation in a rectangular mix chamber

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ABSTRACT

An experimental study on the interfacial behavior of stable steam jet condensation in a rectangular mix chamber was conducted. By high-speed imaging and image processing procedure, the interfacial wave was observed and discussed. From correlation analysis, interfacial wave velocity was obtained, and an empirical correlation for predicting the interfacial wave velocity was also established. Besides, interfacial fluctuation characteristics and corresponding mechanism were also analyzed. The results indicated that, interfacial wave observed in present work was proved to be a manifestation of K-H instability, and the interfacial wave velocities, which were in the range of 25.1–130.4 m/s, were proportional to steam plume penetration length, while inversely proportional to axial position. High frequency component of the interfacial height fluctuation was induced by the interfacial wave, while low frequency component was caused by waving of the whole interface. The results in present work would be significant to understanding the interfacial behavior of steam jet condensation and would be useful for a better design and safe operation on the TFSI.

1. Introduction

Due to the advantages of compact and high heat transfer intensity, Two-phase Flow Steam Injector (TFSI) has been widely used in several industrial applications, such as nuclear energy, petrochemical, etc. [1,2].

The core process of the TFSI is phenomenon of steam-water Direct Contact Condensation (DCC). For a fundamental understanding of steam-water DCC, many investigations on the flow pattern, regime diagram, flow field characteristic and heat transfer characteristics had been conducted [3]. When steam was injected downward into subcooled water pool through a pipe, three flow patterns including oscillatory jet, steam chugging and oscillatory bubble were reported by Chan and Lee [4]. Chun et al. [5] experimentally investigated the DCC of steam jet in stagnant water, two stable steam jet shapes were found to be conical and ellipsoidal. Liang and Griffith [6] observed steam chugging, bubbling, oscillatory jet and stable jet, and the transition criteria between regimes were also proposed. Wu et al. [7–9] experimentally investigated sonic and supersonic steam jet condensation submerged in water pool, a regime diagram based on steam mass flux, water temperature and pressure ratio was established and the average heat transfer coefficients were found to be within 0.63–3.44 MW/m^2 °C. The steam jet condensation in cross and concurrent water flow were experimentally investigated by Xu et al. [10,11], five jet shapes were identified visually, and the heat transfer coefficients were reported to be 0.34–11.36 MW/m^2 °C. Zong et al. [12,13] experimentally investigated the steam jet condensation in water flow in a rectangular mix chamber, the flow pattern was observed as unstable jet, stable jet and divergent jet, and a correlation was established to predicate the penetration length of stable jet, moreover, the average heat transfer coefficients were found within 2.89–7.89 MW/m^2 °C. Yang et al. [14] investigated the steam-air mixture condensation in water flow, and found that heat transfer coefficient would reduce due to the existence of air in steam jet.

Interface is the major area of mass, momentum and energy transfer in steam-water DCC. Simpson and Chan [15] observed periodically interfacial motion in subsonic steam jet, and the bubble formation, growth and detachment were clearly distinguished. Kim et al. [16] developed three interfacial transport models to evaluate the heat transfer characteristics. Celata et al. [17,18] concluded that the thermal resistance of heat transfer of DCC mainly lay on water side of the interface, and disturbance in water side

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Nomenclature

C	set of image pixels
d_{he}	steam nozzle exit equivalent diameter, mm
I	image matrix
G_s	steam mass flux at steam nozzle throat, kg/m^2 s
G_w	water mass flux at water nozzle exit, kg/m^2 s
h	interfacial height, mm
Δh	interfacial height fluctuation, mm
$\bar{h}$	average of the interfacial height, mm
Δh_{low}	low frequency part of the interfacial height fluctuation, mm
l	penetration length, mm
L	dimensionless penetration length, $L = l/d_{he}$
p	probability of gray level
P_s	inlet steam pressure, MPa
P_w	inlet water pressure, MPa
R	cross-correlation coefficient
t_w	inlet water temperature, °C
T	threshold
u_{we}	water velocity at nozzle exit, m/s
v_i	interfacial wave velocity, m/s
V_i	dimensionless interfacial wave velocity, m/s
w	window size
x	position from steam nozzle exit, mm
X	dimensionless position, $X = x/d_{he}$
y	position from lower surface of the mix chamber, mm
Z	gray level
τ	time, ms
μ	average gray value
ω	probability
δ	variance between-class
Φ	ratio of interfacial height fluctuation peak

would enhance the heat transfer, which had been verified by the results of Xu et al. [10] and Zong et al. [12]. Chawla [19] theoretically investigated interfacial Kelvin-Helmholtz instability with sonic and subsonic incondensable gas jet. Chan et al. [20] analyzed the interfacial Kelvin-Helmholtz instability in sonic gas jet with mass transfer on the basis of Chawla [19], and the improved model was convinced by hydrogen chloride-ammonia reactive jet. Khan et al. [21] experimental investigated interfacial instability propagation and dissipation with supersonic steam jet, and the discontinuity of dynamic temperature distribution evidenced the existence of interfacial K-H instability. Kwidzinski [22] investigated the interfacial fluctuation characteristic in TFSI with central water nozzle configuration, and found that the interfacial fluctuation would promoted the heat and mass transfer, and the local heat transfer obtained in the experiments are within 0.2–0.8 MW/m^2 °C.

In previous studies, steam-water DCC was almost investigated in stagnant water pool or water flow by circular nozzles or pipes. When the steam-water DCC occurs in a confined channel in water flow, it would experience different features. By using circular nozzles of or pipes, the steam jet was condensed by water all around, thus, the flow field is three-dimensional, and inner structure of the steam jet could not be observed directly. To solve this problem, a visualized experimental rig with rectangular steam nozzle and water nozzle was designed and fabricated in present work to create a quasi-planar structure of flow field. The purpose of this paper was to investigate the interfacial behavior of stable steam jet in subcooled water flow in a rectangular mix chamber. In present work, the interfacial propagation and fluctuation characteristic were investigated, and corresponding mechanism was also analyzed. The results in present work would be significant to understanding the interfacial behavior of steam jet condensation and would be useful for a better design and safe operation on the TFSI.

2. Experimental system and method

2.1. Experimental system

The diagram of experimental system for investigating interfacial behavior of stable steam jet condensation in subcooled water flow is the same with Zong et al. [12], which is schematically presented in Fig. 1. The experimental system mainly consists of test section, electric steam generator, water tanks, high-speed imaging system and data acquisition system.

Saturated steam is generated from the steam generator with electric heaters of 330 kW, water is derived from a single-stage horizontal shaft centrifugal pump, steam and water flow rate are both controlled by valves manually. Due to a constant pump power heating and in order to ensure the water flow rate out of the pump doses not change much in experiments, there is an auxiliary bypass line to control inlet water flow rate and inlet water temperature simultaneously. To reduce heat loss, all the steam lines are wrapped by fiberglass insulation. The high speed imaging system contains a high speed camera of Phantom V611 type, a separate led background light and corresponding acquisition computer

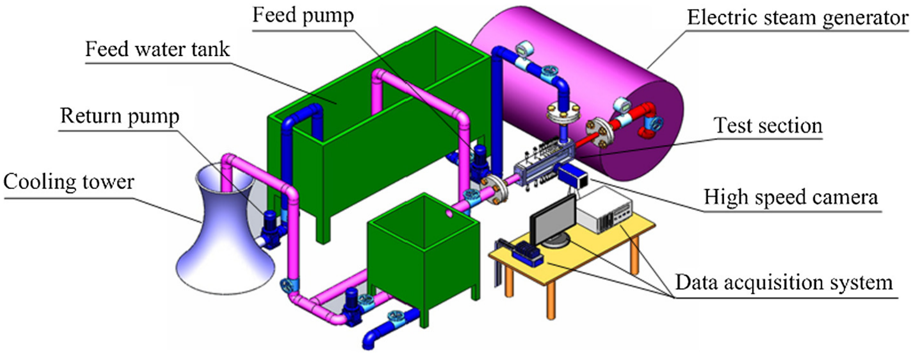

Fig. 1. Schematic diagram of experimental system [12].