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Experimental study on direct contact condensation of stable steam jet in water flow in a vertical pipe

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ABSTRACT

Direct contact condensation is widely used in industrial applications due to its highly efficient heat and mass transfer. Many experimental and theoretical works have been performed on steam jet condensation in stagnant water in pool. However, the condensation of steam jet in water flow in pipes is not yet fully understood. Here, experiments are performed to study the direct contact condensation of stable steam jet in water flow in a vertical pipe. By using high speed camera and mobile thermocouple probe, we investigate condensation characteristics including the plume shape, plume length, temperature distribution, average heat transfer coefficient, and average Nusselt number. Five different plume shapes (hemispherical, conical, ellipsoidal, cylinder, and divergent) are identified visually, 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. The dimensionless plume length and average heat transfer coefficient are found to be within the range of 0.29–4.64 and 0.34–11.36 MW/m^2 K, respectively. Besides, empirical correlations are obtained for the dimensionless plume length, average heat transfer coefficient, and average Nusselt number as a function of three dimensionless parameters, i.e., dimensionless steam mass flux, condensation driving potential, and Reynolds number of water flow. The dimensionless radial temperature decreases exponentially from the center to the pipe wall and shows good self-similarity.

1. Introduction

Direct contact condensation (DCC) of steam in water is a common phenomenon encountered in many industrial gas–liquid two-phase flow systems, such as nuclear reactor safety systems, underwater propulsion systems, and direct contact feed water heaters, etc. A fundamental understanding of the condensation process is essential for the design and optimization of industrial systems. Although DCC of steam jet in stagnant water in pool has been extensively studied [1–9], little information on DCC of stable steam jet in water flow in pipes is available.

The steam plume shape and length are generally used to describe the geometric behavior of steam jet condensation in water. When steam is injected into stagnant water in pool, six typical plume shapes were observed, such as contraction (i.e., conical), expansion–contraction (i.e., ellipsoidal), double expansion–contraction, contraction–expansion–contraction, contraction–expansion–divergent, and double expansion–divergent (i.e., divergent) [1–7]. Kerney et al. [8] derived the first plume length correlation as a function of steam mass flux, water temperature, and mean transport modulus by assuming a smooth surface of the plume. Other researchers improved Kerney et al.'s correlation based on their own experimental data [1–5,9]. However, forsteam jet condensation in water flow in pipes, a remarkable difference of the plume shape and length is formed, since the heat transfer at the steam-water interface is significantly enhanced by the movement of water. With et al. [10,11] observed plume shapes of hemisphere, conical, and ellipsoidal. They also found that the plume length in pipes is lower than that in pool by 60–65%. Nevertheless, there is still an unmet need for experimental data on the plume shape and length of stable steam jet condensation in water flow in pipes.

Temperature distribution in jet region has been analyzed to reveal heat transfer and fluid flow processes associated with steam jet condensation in water. Kim et al. [1] reported that the variation of axial and radial temperature in the ellipsoidal jet was caused by the expansion and compression waves. Wu et al. [4,5] found that four typical plume shapes could be described using different axial temperature distribution. Wilson and Danckwerts [12] concluded that the radial temperature distribution of a heated air jet obeyed a self-similarity pattern, and this trend was also observed for steam jet condensation in stagnant water in pool [5,13]. The momentum exchange between the plume core and ambient water could be increased by the thermal expansion across the plume surface, which was verified by experimental temperature distribution [14–17]. However, there are, to the author's knowledge, no

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Nomenclature

A	actual surface area of the steam plume, m^2
A_i	surface area of the steam plume calculated from a binary image
B	condensation driving potential
C_p	water specific heat, J/kg K
d_e	inner diameter of the nozzle, m
d_s	steam plume maximum diameter, m
D	diameter of the vertical circular pipe, m
G_e	steam mass flux at nozzle exit, kg/m^2 s
G_m	critical steam mass flux, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
h_{av}	average heat transfer coefficient, W/m^2 K
h_{cor}	correlated average heat transfer coefficient, W/m^2 K
k_i	scale of the actual size to one pixel, m
l	plume length, m
l_i	sum of pixels in the steam plume shadow in the vertical line in a binary image
L	dimensionless plume length
Nu	average Nusselt number
p	pressure, MPa
Q	water flow rate, kg/s
r	radial distance from the centerline, m
$r_{0.5}$	radial distance from the centerline when $\theta = \theta_{max}/2$, m
Re	Reynolds number of water flow equals to $4Qv/\pi D$
S_m	mean transport modulus
T_{rad}	temperature in the radial direction, °C
T_s	steam saturation temperature, °C
T_w	water temperature, °C

Greek letters

θ	excess of radial temperature above the ambient water flow temperature, °C
θ_{max}	excess of axial temperature above the ambient water flow temperature, °C
λ_w	thermal conductivity of water, W/m K
ρ	density, kg/m^3
v	kinematic viscosity of water, m^2/s

reported studies on the temperature distribution for stable steam jet in water flow in pipes, which can be used to validate theoretical models and improve our understanding of DCC.

Heat transfer coefficient is used to evaluate the heat transfer capacity of DCC. In stagnant water in pool, many semi-empirical correlations of heat transfer coefficient have been established in the vicinity of plume interface [1–3,16,18–23]. The heat transfer coefficient was found to vary between 0.1 and 3.5 MW/m^2 K, and increase with the sub-cooling rate and steam flow rate. Three theoretical models (i.e., the interfacial transport model, surface renewal model, and shear stress model) were developed to determine the heat transfer coefficient, based on the knowledge that the major resistance to the heat transfer of DCC lay in the liquid side [18]. For steam jet condensation in stagnant water in pool, the heat transfer resistance in the liquid side is reduced by small eddies around the plume surface, which is resulted from the high speed steam condensation. However, for steam jet condensation in water flow in pipes, heat transfer in the liquid side is enhanced by two additional factors: the constant supply of fresh water and the large eddies generated from the turbulent movement of water. Therefore, it is of great importance to study the heat transfer coefficient and Nusselt number of stable steam jet condensation in water flow in pipes.

The objective of present experimental study is to explore condensation characteristics of the stable steam jet in water flow in a vertical pipe, including the plume shape and length, temperature distribution, heat transfer coefficient, and Nusselt number. The DCC phenomena are observed using a high speed camera, and the temperature distribution is obtained with a mobile thermocouple probe. The influences of the steam mass flux, water temperature, and Reynolds number of water flow on condensation characteristics are discussed. This study provides new insights into DCC in water. The presented experimental data would be helpful for further theoretical study on the mechanisms underlying the steam jet condensation in water flow in pipes.

2. Experimental apparatus and procedures

The overall schematic diagram of the experimental apparatus for investigating DCC of stable steam jet in water flow in a vertical pipe is presented in Fig. 1. The experimental system consists of four main components, i.e., a steam supply line, a water supply line, a test section, and a data acquisition unit.

The central part of the steam supply line is a 72 kW electric steam generator continuously producing saturated steam. The maximum operating pressure of the electric steam generator is 0.7 MPa, and the maximum steam flow rate is 0.03 kg/s. To maintain the supplied steam saturated during testing, the steam supply line is first wrapped with tap heaters, and then insulated with 30 mm fiberglass covering. The steam flow rate is controlled by adjusting the manual control valves, and is measured by a vortex flow meter with a maximum relative deviation of 0.5%. Filtered tap water is circulated by a multi-stage centrifugal water pump, and the water flow rate is measured by a magnetic flow meter with a maximum relative deviation of 0.5%. The flow rate of water is regulated by control valves on the feed and bypass lines.

The test section is a vertical round pipe made of stainless steel, with an 80 mm inner diameter and 2.0 m length. Fig. 2 displays the local schematic diagram of the steam inlet. The nozzle is made of stainless steel with a constant inner diameter of 8 mm. A stainless steel duct with an external diameter of 2 mm is inserted into the steam passage in the nozzle to measure the local pressure by a pressure transducer, which is installed at the other end of the duct. The temperature at the same location is also measured by a thermocouple installed at the central of the duct. In order to take pictures of the steam jet with high speed camera, two observation windows are installed at the pipe wall. A temperature probe transverse system equipped with K-type thermocouple (0.5 mm) is installed to measure the temperature distribution in the steam jet region and ambient water flow.

The Keller pressure transducer is in the range of 0–1.0 MPa with a maximum relative deviation of 0.1%. The K-type thermocouple is in the range of 0–200 °C with a maximum relative deviation of 0.1%. All signals are processed using the Labview data acquisition unit, which consists of a personal computer, a high speed PCI-6259 acquisition board to obtain the voltage signal of the pressure transducer and flow meter, and a high speed SCXI-1102E acquisition module to obtain the temperature signal. The sampling frequency is set as 5 kHz for each sensor, and the sampling time is 30 s. The video images taken by the high speed camera are analyzed later with image processing software.

Before each run, the water in the tank is first heated to the desired temperature by a set of electric heating tubes. And then the