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Experimental study on the direct contact condensation of the steam jet in subcooled water flow in a rectangular channel: Flow patterns and flow field

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ABSTRACT

Direct contact condensation (DCC) of steam jet in subcooled water flow in a channel was experimentally studied. The main inlet parameters, including steam mass flux, water mass flux and water temperature were tested in the ranges of 200–600 kg/(m^2 s), 7–18 × 10^3 kg/(m^2 s), 288–333 K, respectively. Two unstable flow patterns and two stable flow patterns were observed via visualization window by a high speed camera. The flow patterns were determined by steam mass flux, water mass flux and water temperature, and the relationship between flow patterns and flow field parameters was discussed. The results indicated that whether pressure or temperature distributions on the bottom wall of channel could represent different flow patterns. And the position of pressure peak on the bottom wall could almost represent the condensation length. The upper wall pressure distributions were mainly dependent on steam and water mass flux; and the upper wall temperature distributions were affected by the three main inlet parameters. Moreover, the bottom wall pressure and temperature distributions of different unstable flow patterns had similar characteristics while those of stable flow patterns were affected by shock and expansion waves. The underlying cause of transition between different flow patterns under different inlet parameters was reflected and discussed based on pressure distributions.

1. Introduction

Steam-water direct contact condensation (DCC), which has an advantage of strong heat transfer, plays an important role in various industrial applications, such as the safety depressurization system, negative water-supply system in advanced pressurized-water reactor (PWR), feed water system of boiling water reactor (BWR), desalination system, exhaust steam reclamation system, refrigeration, and mixing-type heat exchanger, etc.

Many researchers have studied the characteristics of DCC for steam jet in large-space stagnant water, e.g., flow patterns, condensation regime maps, flow and heat transfer characteristics. Specific flow patterns are discovered when steam jet is submerged in stagnant water, and the flow pattern is of great importance for understanding the DCC process (Kerney et al., 1972; Chun et al., 1996; Petrovic, 2004; Wu et al., 2007). Many investigations on flow patterns have been carried out on the features of flow patterns, e.g., the configuration, distribution and turbulence characteristics. Kerney et al. (1972) considered that the flow pattern was related to the degree of expansion. Chan and Lee (1982) observed three flow patterns, which were bubble, chugging and oscillation jet, and a regime map was also given by considering water temperature and steam mass flux. A transition criterion based on the energy and mass balance between different flow patterns was proposed by Liang and Peter (1994). Three flow patterns of conical, ellipsoidal and divergent shapes were discussed for the steam jet in subcooled water by Chun et al. (1996). Besides, the flow pattern shape distribution based on water subcooling and steam mass flux was proposed. Kim et al. (2001) reported conical and ellipsoidal shapes of the flow pattern in an experiment of steam jet in subcooled water as well. In addition, the influences of steam mass flux, water temperature and steam nozzle diameter on axial and radial temperature profiles of the flow field were discussed. They found that the water temperature had great influence on the temperature profiles of all flow field regions except the steam region. According

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Nomenclature

A_c	the cross-area of channel, m^2
A_w	the cross-area of water nozzle outlet, m^2
d_c	equivalent diameter of channel, m
d_e	equivalent diameter of steam nozzle outlet, m
G_s	steam mass flux at steam nozzle throat, kg/(m^2 s)
G_w	subcooled water mass flux at water nozzle outlet, kg/(m^2 s), $G_w = m_w/A_w$
m_w	subcooled water flow rate, kg/s
P_e	steam nozzle outlet pressure, MPa
P_f	fluid pressure, MPa
P_s	steam inlet pressure, MPa
P_w	water inlet pressure, MPa
P_{we}	steam nozzle outlet pressure, MPa
P_{we}	water nozzle outlet pressure, MPa
Re_w	Reynolds number of water flow, $Re_w = G_w A_w d_c / A_c \mu_w$
T_f	fluid temperature, K
T_{sa}	saturated steam temperature, K
T_w	water inlet temperature, K
ΔT	temperature different, K, $\Delta T = T_{sa} - T_w$
μ_w	dynamic viscosity coefficient of water, Pa s

to particle image velocimetry (PIV) experiment results of Van Wissen et al. (2004), the turbulence produced by the steam jet in water was related to water temperature other than steam pressure and nozzle size. A three-dimensional regime map based on steam mass flux, diameter of steam nozzle and water subcooling was presented by de With et al. (2007). Wu et al. (2007, 2009, 2010) conducted experiments on the supersonic/sonic steam jet submerged in water and six flow patterns were observed as conical, ellipsoidal, double expansion–contraction, double expansion–emanative, contraction–expansion–contraction, and contraction–expansion–emanative shapes. Furthermore, the temperature distributions, which were considered to be capable in reflecting the flow patterns, were greatly affected by steam mass flux and water temperature.

Although the DCC in large-space water has been widely studied, the case becomes more complex when DCC process occurs in a limited channel like in a steam-driven jet injector (SDJI) where the water flow is affected by the wall shear stress. Malibashev (2001) studied the temperature and pressure distributions in the mixing chamber and diffuser of an SDJI, the results showed that the steam continued to expand and condense simultaneously in the mixing chamber. Besides, fluid parameters along the axis were quite different from those on the wall. Cattadori et al. (1995) developed a high pressure SDJI and investigated the effect of inlet steam pressure on its efficiency. Different mathematical models have been proposed for predicting performance of SDJI (Deberne et al., 1999; Beithou and Aybar, 2000; Yan et al., 2005). However, these models just considered the mixing chamber as a controlled volume but failed to consider the details of DCC process therein. Fukuichi et al. (2009) experimentally studied the radial distribution of the streamwise velocity and total pressure in the mixing chamber of SDJI. They found that the streamwise velocity increased when approaching the steam nozzle. And the total pressure fluctuated sharply in the steam-water mixing region, which would affect the interface. Experimental and numerical researches on SDJI performance were conducted by Shah et al. (2011, 2013), and the numerical results of pressure and temperature distributions on the wall agreed well with their experimental results. In recent years, some researchers have studied the DCC for steam jet in subcooled water flow in the limited space. Visualization investigation on subsonic/sonic steam jet in subcooled water flow was performed by Xu et al. (2013), with a regime map given by considering steam mass flux, water Reynolds number and temperature. In previous work (Zong et al., 2015), the effects of steam-water parameters on flow pattern, penetration length and average heat transfer coefficient were presented, with empirical correlations given to predict the dimensionless penetration length and average heat transfer coefficient of stable flow patterns respectively. However, the characteristics of the flow field parameters, as well as the relationship between the flow pattern and flow field have not been discussed in detail.

Previous researches on SDJI mainly focus on its overall performance, but there is a deficiency of further study into the characteristics of DCC process inside the mix chamber of an SDJI. In conventional visualization researches on DCC in large space water pool or inside the SDJI, the test section usually had cylindrical axisymmetric structure and the steam nozzle was surrounded by subcooled water, thus the steam cavity was wrapped by non-transparent two-phase flow region so that the internal structure of the flow patterns was hard to be observed directly. Additionally, plug-in sensors, which were employed for pressure and temperature measuring inside the steam cavity, would interfere in the flow field and reduce the accuracy of experimental results, especially in the case of supersonic steam jet.

In the present study, in order to capture the internal distinct structure of different flow patterns, visualized test section with rectangular nozzles and narrow channel was designed. The one-side influent mode for subcooled water was achieved. The special design of the test section allowed us to split the steam cavity so that the internal structure of flow patterns could be observed. Moreover, the flow field parameters could be measured by non-intrusive sensors being arranged on the upper and bottom walls of the rectangular channel without destroying the flow field. The objective of this study was to concentrate on the flow and heat transfer characteristics of DCC in a narrow channel, including flow patterns under various test conditions and the effect of inlet parameters on the flow field, which would be helpful for understanding the DCC process and provide some guidance for its application.

2. Experimental apparatus

A schematic diagram of the experimental system for studying the steam jet in the water flow in a rectangular channel is shown in Fig. 1(a), which mainly consists of a data acquisition system, a test section, an electric steam generator, a main tank, an ancillary tank, a high-speed camera, a feedwater pump, a circulating pump and a cooling tower. Saturated steam was generated by a 330 kW electric steam generator with the maximum steam pressure of 0.7 MPa. Subcooled water flow in the rectangular channel was supplied by the feedwater pump. The hot water was discharged into the ancillary tank and then cooled in the cooling tower. The water and steam flow rate were controlled by adjusting the manual valves. The water temperature in the main tank was controlled by a bypass of the steam line.

Fig. 1(b) describes the schematic diagram of the visualized test section whose body was made of stainless steel plates. The channel, steam nozzle and water nozzle all had rectangular cross section. The steam nozzle was a Laval nozzle. Two pieces of tempered glasses were installed on two flanks of the test section for taking photos. There was no gap between the glasses and the stainless steel plates, thus the water just entered the channel from above the steam nozzle. 11 groups of measuring points were arranged on the centerline of the upper and bottom walls of the