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Experimental investigation on the driving force and energy conversion in direct contact condensation for steam jet

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ABSTRACT

The driving force and the energy conversion between condensation, driving kinetic energy of water and pressure oscillation for steam jet have been experimentally investigated in the steam pressure range of 0.2–0.5 MPa and water temperature range of 293–323 K. The axial velocity of the water decreases with the increasing axial distance from the end of the steam plume, and increases with the increasing steam pressure. The driving force are in the range of 1–20 N under different steam pressure and water temperature in the experimental conditions. The driving power increases with the increasing steam pressure. In the stable condensation region, the pressure oscillation power increases with the increasing steam pressure, and decreases with the increasing water temperatures. More than 99% of the energies input are transferred to heat energy of water, and little energy is converted to the driving energy and oscillation energy of the water. The condensation plays a leading role in the energy conversion for steam jet condensation.

1. Introduction

The direct contact condensation (DCC) of steam jet has been widely used in nuclear power plant, heat transfer equipment, and chemical industries for its high heat transfer efficiency. The direct contact condensation for steam jet is very complicated since it accompanies with high speed, high turbulence intensity and high frequency pressure oscillation. Until now, lots of investigations have been done on the direct contact condensation for steam jet. However, the deep mechanism of direct contact condensation for steam jet are still not very clear.

Many scholars investigated the heat transfer characteristics of steam jet condensation. The heat transfer characteristics of steam jet condensation are closely related to the shapes of steam plume. The steam plume shapes were investigated by many scholars. Chun et al. [1] and Kim et al. [2] found three typical steam plume shapes such as conical, ellipse, and divergent shapes according to the steam mass flux and subcooled water temperatures. Wu et al. [3] observed four typical steam plume shapes for sonic steam jet such as contraction shape, expansion-contraction shape, double expansion-contraction shape and double expansion-divergent shape. Another two shapes called contraction-expansion-contraction shape and contraction-expansion-divergent shape were reported in supersonic steam jet by Wu et al. [4]. Kerney et al. [5] established a steam jet condensation model, and gave a dimensionless steam plume penetration length equation based on the condensation drive potential and steam mass flux. Kim et al. [6] calculated the dimensionless penetration length and predicted the heat transfer coefficient using the turbulent intensity model, surface renewal model, and shear stress model. Suggesting the steam plume shape needs more research to get a more accurate prediction of condensation heat transfer coefficient. Wu et al. [3,4,7] investigated the penetration length and expansion rate for sonic and supersonic steam jet condensation. They gave the prediction equations of dimensionless penetration length and average condensation heat transfer coefficient. Chong et al. [8] theoretically and experimentally investigated on the effect of nozzle structure on the steam jet length. The steam jet length of straight pipe nozzle is longer than that of orifice nozzle. Shah et al. [9,10] experimentally and numerically investigated the steam jet pump, the performance of interface vibration process in steam jet pump was also studied. Xu et al. [11] investigated the direct contact condensation of stable steam jet in water flow in a vertical pipe, the average heat transfer coefficient were found to be within the range of 0.34–11.36 MW/(m^2 K). Zong et al. [12] and Yang et al. [13] observed the stable steam jet in subcooled water flow in a rectangular mix chamber. Average heat transfer coefficient were predicted within the range of 3.83–6.24 MW/(m^2 K).

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Nomenclature

b	diffused jet radius, m	P_c	condensation power, W
d_e	exit diameter of nozzle, m	P_d	driving power, W
F	driving force, N	P_{in}	input power, W
h_s	latent heat, kJ/kg	P_o	oscillation power, W
k	jet diffusion coefficient	Q_s	steam mass flow, kg/s
l	penetration length, m	T_w	water temperature, K
p_s	steam inlet pressure, MPa	u_x	velocity of the water at x, m/s
p_{total}	total pressure, MPa	x	axial distance from the exit of nozzle, m
p_{static}	static pressure, MPa	ρ_w	density of the water, kg/m^3
p_{max}	maximum oscillation pressure, kPa	τ	time, s

Many scholars also investigated the speed distribution and pressure oscillation caused by the direct contact condensation. Eden et al. [14] investigated the stable pressure and the cavity shape of horizontal plane choked vapor jets with low condensation potential. van Wissen et al. [15] measured the velocity field using PIV. The production of turbulent kinetic energy has been quantified for the process conditions. Kim et al. [16] measured the axial velocity and temperature distributions of the turbulent jet. Chan and Lee [17] investigated the motion of the steam-water interface. Steam chugging, oscillatory bubble and oscillatory jet were observed when the steam mass flux were within 0–50, 50–125 and 125–175 kg/(m^2 s). Simpson and Chan [18] found that the periodic interfacial motion of the steam plume can cause the pressure oscillation. The interfacial motion included bubble growth, bubble translation, and bubble separation. Youn et al. [19] observed that the frequency of pressure oscillation increased with the increasing steam mass flux in chugging region. Cho et al. [20] investigated the effect of the pitch-to-diameter ratio on the pressure oscillation, found that the frequency increased with the increasing pitch-to-diameter ratio. Cumo et al. [21] found that the lower of the subcooling temperature, the higher of the intensity of the pressure oscillation. Arinobu [22] and Fukuda [23] investigated the pressure oscillation in condensation oscillation region and gave their prediction correlations of frequency in their experimental parameter range. Hong et al. [24] theoretically investigated the frequency of the pressure oscillation in stable condensation region. A semi-empirical formula of frequency was given. Qiu et al. [25–27] investigated the intensity properties and spatial distribution of pressure oscillation for sonic steam jet. The frequency of the pressure oscillation decreased with the increasing water temperature and steam mass flux. Under some conditions, there will be two dominant frequencies. The second dominant frequency mechanism was also investigated. Meanwhile, Qiu et al. [28,29] also found that the variation of penetration length and the heat transfer coefficient for steam jet condensation have a very close internal relationship with the pressure oscillation. A correlation between the frequency and heat transfer coefficient was given. Qu et al. [30,31] investigated the acoustic and gas volume fraction distribution characteristics of a steam jet plume with non-condensable gas in it. The dominant frequencies shifted to low frequency direction as the water temperature and air content increased, which was mainly caused by the reduced condensing rate.

The driving force caused by the steam jet is very important for the underwater propulsion. Although, many investigations on steam plume shapes, heat transfer coefficient, velocity and temperature field, and pressure oscillation of direct contact condensation for steam jet have been performed before. The driving force of the steam jet, the energy conversion between the condensation, driving force and pressure oscillation were rarely investigated before. Since the results of Qiu et al. [28,29] indicated that there were strong relationships between the condensation, penetration length, and pressure oscillation. It is very important to investigate the energy conversion between them. The purpose of present study is to investigate the driving force and the energy conversion between the condensation, driving force and pressure oscillation. It is also very important to have a further understanding of the energy conversion for the direct contact condensation.

2. Experimental system

The experimental system in this study is similar with the experimental system of Qiu et al. [28], which is shown in Fig. 1. The steam with high pressure and temperature inject into the subcooled water. The steam plume is recorded by the high speed video camera. The high speed video camera is manufactured by Vision Research. The model is Phantom V611, 1 million frames per second max at reduced resolution, 32 GB memory. The frame rate in this experiment is 1000 fps. The steam flow rate is measured by a vortex type steam flowmeter. The range of steam mass flux is 298–724 kg/(m^2 s). The inlet pressure and temperature of the steam are measured by the pressure sensor and thermocouple equipped on the nozzle inlet. The steam from the steam generator is saturated steam. All the pipes between the generator and nozzle are covered with the thermal insulation materials. There is also electric heating wire on the pipe. The electric heating wire, the thermocouple and pressure sensor at the inlet of the nozzle confirm that the steam is saturated steam. The temperature of the water is measured by 4 T-type thermocouples, which are calibrated by a standard thermometer with accuracy 0.1 K. The pressure oscillation is measured by the high frequency pressure sensor at axial dimensionless distance $x/d_e = 5$ and radial dimensionless distance $r/d_e = 2$, as is written by Qiu et al. [28]. Meanwhile, the total pressure and static pressure of the steam plume and the whole turbulence area at the end of the steam plume are measured by a mobile test probe, which could be equipped with a Pitot tube, the geometry of the tube can be seen in Yan et al. [32]. The Pitot tube is parallel to the direction of flow. Thus, the total pressure includes the kinetic pressure and the static pressure. The static pressure inside the turbulent region is the same as in the water pool. The radial velocity components are negligible according to the jet theory. Based on the kinetic pressure, the axial velocity components can be calculated. From the photo of the plume, the length and the volume of the steam area in the plume can be measured. The parameters of steam, water, and uncertainties of the measurement and calculated parameters can be seen in Qiu et al. [28] and Yan et al. [32].

3. Results and discussions

3.1. Velocity of the turbulence area

The steam plume recorded by the high speed camera at steam pressure 0.3 MPa and water temperature 313 K is shown in