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Pressure oscillation and a new method to calculate the heat transfer coefficient for steam jet condensation

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ABSTRACT

The pressure oscillation and heat transfer are two important aspects for direct contact condensation. Both of them have been investigated within the steam mass flux 441–865 kg/(m^2 s) and water temperature 293–343 K in this paper. The frequency of pressure oscillation decreases with the increasing steam mass flux and water temperature. While, the frequency first increases then subsequently decreases with the decreasing pressure ratio of the nozzle. The heat transfer coefficient has the same variation regularities with the frequency of pressure oscillation. Two dimensionless quantity of frequency of pressure oscillation and heat transfer coefficient have been obtained, the dimensionless heat transfer coefficient is proportional to the dimensionless frequency of pressure oscillation. A new simpler method to calculate the heat transfer coefficient for steam jet condensation has been given. The errors between the predicted values and experimental data are within −30% to 25%.

1. Introduction

The direct contact condensation (DCC) has been widely used in nuclear power plant, heat transfer equipment, and chemical industries for the high heat transfer effect. Especially in nuclear power plant, when the pressure of nuclear reactor core is higher than the safe value, the steam with high pressure and temperature will inject into subcooled water pool. The DCC occurs and the pressure releases quickly. However, at the same time, the pressure oscillation caused by the DCC is very dangerous. The load of pressure oscillation will corrode relevant equipment. Furthermore, when the frequency of pressure oscillation is close to the natural frequency of relevant equipment, the resonance will occur, which will destroy relevant equipment. Thus, to investigate the characteristics of heat transfer and pressure oscillation of DCC is very important for wide and safe use of DCC in industries.

The heat transfer characteristics of steam jet condensation were investigated by many scholars. The heat transfer characteristics of steam jet condensation are closely related to the shapes of steam plume. In 1972, Kerney et al. [1] 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. Chun et al. [2] found three typical steam plume shapes as conical, ellipse, and divergent according to the steam mass flux and subcooled water temperatures. Kim et al. [3] 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. [4–6] investigated the sonic and supersonic steam jet condensation within steam mass flux 298–865 kg/(m^2 s) and water temperature 293–343 K. They found six different plume shapes and gave the prediction equations of dimensionless penetration length and average condensation heat transfer coefficient. Shah et al. [7,8] investigated the steam jet pump experimentally and numerically, the performance of interface vibration process in steam jet pump was also studied. Xu et al. [9] 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. [10] and Yang et al. [11] studied the stable steam jet in subcooled water flow in a rectangular mix chamber. Rectangular steam and water nozzles were adopted to form a quasi-planar structural flow. Average heat transfer coefficient were predicted within the range of 3.83–6.24 MW/(m^2 K).

Many scholars also investigated the pressure oscillation caused by the direct contact condensation. In 1982, Chan and Lee [12] investigated the motion of the steam-water interface. Steam

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Nomenclature

A	interface area, m^2	l	plume length, mm
a	amplitude of pressure oscillation, kPa	ms	steam mass flow, kg/s
B	dimensionless condensation potential	n	polytropic index
c_p	specific heat, kJ/(kgK)	ps	steam inlet pressure, MPa
d_e	exit diameter of nozzle, mm	$p\infty$	ambient pressure, MPa
f	dominant frequency, Hz	r	radial distance, mm
G_{cr}	steam mass flux at nozzle throat, kg/(m^2 s)	Tw	water temperature, K
G_m	critical steam mass flux, kg/(m^2 s)	Ts	Steam temperature, K
h	heat transfer coefficient, kW/(m^2 K)	ΔT	subcooling temperature, K
h_{exp}	experimental heat transfer coefficient, kW/(m^2 K)	x	axial distance, mm
ε	pressure ratio	H	submerged depth of nozzle, mm
h_{fg}	latent heat, kJ/kg	ρl	density of water, kg/m3
L	dimensionless penetration length		

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). All of these three flow patterns had very strong pressure oscillation. Simpson and Chan [13] found that the interfacial motion of a subsonic jet was periodic. The interfacial motion was comprised of bubble growth, bubble translation, and bubble separation. Youn et al. [14] found that the frequency of pressure oscillation increased with the increasing steam mass flux in chugging region. Cho et al. [15] found that the frequency increased with the increasing pitch-to-diameter ratio. Cumo et al. [16] found that the lower of the subcooling temperature, the higher of the intensity of the pressure oscillation. Arinobu et al. [17], Fukadu et al. [18] investigated the pressure oscillation in condensation oscillation region and gave their prediction correlations of frequency in their experimental parameter range. Hong et al. [19] theoretically investigated the frequency of the pressure oscillation in stable condensation region. They gave a semi-empirical formula of frequency through theoretical analysis. Confirmed that the pressure oscillation was caused by the expansion and contraction of the steam plume. Qiu et al. [20–22] investigated the intensity properties and spatial distribution of pressure oscillation for sonic steam jet. They found that the pressure oscillations have two dominant frequencies. The first (lower) dominant frequency is caused by the periodically expansion and contraction of the steam plume. It decreased with the increasing temperature and steam mass flux. While, the second (higher) dominant frequency is caused by the condensation and collapse of large steam bubbles in the tail of the steam plume. Tang et al. [23,24] investigated the sound characteristics of vapor bubbles condensation in a quiescent subcooled pool. The low dominant frequency was induced by the periodic variation in bubble volume. Qu et al. [25,26] 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.

Although, many investigations on heat transfer and pressure oscillation of direct contact condensation have been performed before, since it is very difficult to get a clear steam-water interface, the error of the interface area is so large that different scholars have different heat transfer coefficient results. What's more, the pressure oscillation have a strong relationship with the heat transfer coefficient. The results of Qu et al. [25] also have demonstrated this effect. However, the internal relationship of the heat transfer coefficient and pressure oscillation has not been investigated before. The purpose of present study is to investigate the relationship of heat transfer coefficient and pressure oscillation, and give a new method to calculate the heat transfer coefficient of direct contact condensation without measuring the steam-water interface area.

2. Experimental system and apparatus

The experimental system for the present study is shown in Fig. 1. Steam with high pressure and temperature is generated in the steam generator, and is injected into subcooled water through a sonic/supersonic steam nozzle. The flow meter measures the steam mass flow and the steam valve is used to adjust the steam mass flux to experimental conditions. The steam plume shapes are recorded by the high speed video camera. High frequency pressure sensors are equipped on the three dimensional moving holder to collect the data of pressure oscillation in the water. At the nozzle inlet, there are a pressure sensor and a T-type thermocouple to measure the pressure and temperature of inlet steam. There are four T-type thermocouples at each corner of the water pool, the average temperature of these four thermocouples is regarded as the bulk water temperature in the pool.

The steam generator is a 330 kW electric boiler with 0.7 MPa maximum operating pressure and 400 kg/h maximum steam flow rate. The nozzle is sonic or supersonic nozzle. The throat diameters of both the sonic and supersonic nozzles are 8 mm. The structure of the sonic nozzle is shown in Fig. 2. Pressure ratio is defined as ratio of steam pressure at nozzle exit to steam pressure at nozzle inlet. The pressure ratio 0.577 is critical pressure ratio of saturated steam to sonic speed. So convergent nozzles are designed for sonic steam flow, and convergent-divergent nozzles are designed with pressure ratio below 0.577 for supersonic steam flow. The effect of nozzle shape is reflected by the effect of pressure ratio. The lower the pressure ratio, results in a higher speed of the steam at the exit of the nozzle. According to thermodynamics, when the steam with high pressure injects into the converging–diverging nozzle, the steam undergoes the isentropic expansion process. Different exit area of nozzle is corresponding to different steam pressure at exit of nozzle. Before experiment, we designed six different nozzles with different exit diameters and pressure ratios. The exit diameters of supersonic nozzles are 12, 11.2, 10.4, 9.6, 8.8, 8 mm, which are corresponding to the pressure ratios of 0.113, 0.139, 0.175, 0.228, 0.318, 0.577. When we need different pressure ratios, we need to change corresponding nozzles. The steam flow meter is OPTISWIRL 4070-DN25. The high speed video camera is Phantom V611, the frame rate is 1000 frames per second (fps). All the vessels and piping from the steam generator to nozzle inlet are covered by thermal insulation materials. The high frequency pressure sensor has a measurement range: −100 kPa to 100 kPa, accuracy: 0.2% FS (full scale), the largest measurement error is 0.4 kPa, natural frequency: 40 kHz. The data acquisition system is coded by Labview