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Experimental investigation on pressure oscillations caused by direct contact condensation of sonic steam jet

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ABSTRACT

An experimental study has been carried out to investigate the pressure oscillation of the sonic steam jet in a pool. The exit diameter of the nozzle was 8 mm and the steam mass flux was 298–865 kg/(m^2 s), water temperature 20–70 °C. The dominant frequency and amplitude of pressure oscillation have been analyzed. A theoretical model on pressure oscillation amplitude was set up and a semi-empirical correlation was given to predict the dimensionless R.M.S (root mean square) amplitude of pressure oscillation. The pressure oscillation is mainly caused by the variation of steam speed δu, heat transfer coefficient δh and net steam-water interface δS. The dominant frequency of the pressure oscillation decreased with the increase of the water temperature while increased in CO region and decreased in SC region with the increase of the steam mass flux. The amplitude of the pressure oscillation is inversely proportional to the dominant frequency. The dominant frequencies did not change with the variation of x/d_e and r/d_e. But the amplitudes decreased with the increase of x/d_e and r/d_e. An empirical correlation was suggested to predict the dimensionless R.M.S amplitude based on the experimental data. The predictions agreed well with the experiments, and the discrepancies were within ±30%.

1. Introduction

Steam injected into subcooled water is a common phenomenon in many industrial two-phase flow systems, such as direct-contact condensing heat exchanger, boilers, steam ejector and nuclear reactor coolant systems. When the reactor depressurization system valves are open to discharge steam into the quench tank through a steam discharge device, the direct contact condensation (DCC) phenomenon occurs accompanying pressure oscillations in water. The intensity and frequency of the pressure oscillations impose a serious damage to the water tank and relevant equipments. Therefore, deep studies of direct contact condensation phenomena and characteristics of the pressure oscillation are very necessary for the optimal design and safe operation of relevant equipments.

Although a large number of studies on the steam jet have been presented theoretically and experimentally, the steam jet was not well understood yet. The previous works were mainly concentrated on the following three aspects: penetration length and condensation shape, average condensation heat transfer coefficient and condensation regime map. Penetration length and condensation shape have been researched by many researchers (Kerney et al. [1], Weimer et al. [2], Kudo et al. [3], Chen and Faeth [4], Chun et al. [5], Wu et al. [6,7]). It was a function of the injector diameter, exit mass velocity or steam mass flux, and pool water temperature. Moreover, different steam plume shapes had been found under different conditions. Chun et al. [5] found conical and ellipsoidal shapes in the sonic and subsonic steam jet. Wu et al. [8] found other four different steam plume shapes over a range of steam mass flux 298–865 kg/(m^2 s) and water temperature 20–70 °C in the sonic and supersonic steam jet. The average condensation heat transfer coefficient of steam-water interface has also been widely investigated (Young et al. [9], Cumo et al. [10], Simpson and Chan [11], Chan and Lee [12]). All their results demonstrated that the condensation heat transfer coefficient was in the range of 1.0–3.5 MW/(m^2 K) and mainly affected by the water temperature. Regime maps have been given by Chan and Lee [12], Cho et al. [13], Wu et al. [14] according to different condensation patterns with the changes of the steam mass flux and subcooled water temperature. However, the studies on the pressure oscillations caused by steam jet were relatively rare and mainly concentrated on the low steam mass regions. Simpson and Chan [11] experimentally researched the condensation process and hydrodynamic pressure oscillations of subsonic steam jet. The interfacial motion of a subsonic jet was periodic with the pattern of bubble growth, bubble translation, and bubble separation (necking). The periodic pressure impulses were generated when the necking process occurred. The

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Nomenclature

A	nozzle exit area, m^2	p_σ	R.M.S amplitude, kPa
B	dimensionless index	Q_{in}	supplied steam mass flow rate, kg/s
C	sonic speed, m/s	Q_c	condensed steam mass flow rate, kg/s
d_e	exit diameter of nozzle, mm	r	radial distance, mm
ΔE	mechanical energy, kJ	Re	dimensionless index
Δe	dimensionless mechanical energy	St	dimensionless index
f	dominant frequency, Hz	S	steam-water interface area, m^2
G	steam mass flux, kg/(m^2 s)	T_{sat}	saturation temperature, K
H	submerged depth of nozzle, mm	ΔT	subcooled temperature, °C
h	heat transfer coefficient, W/(m^2 K)	t_w	water temperature, °C
h_{fg}	latent heat, kJ/kg	u	steam speed, m/s
L	dimensionless index	V	volume of steam plume, m^3
M	mach number	x	axial distance, mm
m	steam mass, kg	ρ_s	steam density, kg/m^3
N	dimensionless index	ρ_l	water density, kg/m^3
p_s	steam inlet pressure, MPa		
p_0	ambient pressure, MPa		

pool temperature had the main influence on dynamic behavior. Aya et al. [15] researched the pressure oscillation of steam jets in the region of chugging[C] and condensation oscillation [CO]. The pressure oscillation was induced by the balance action between the supply of steam to steam plume and its condensation on the steam-water interface enclosing the steam plume. Youn et al. [16] investigated the pressure oscillation in the chugging region. High pressure pulses with relatively low frequency were observed when the steam bubble detached from the nozzle exit by the necking phenomenon. The pressure pulse generation rate increased rapidly when the condensation mode was changed. Literatures [8,17,18] measured the centerline pressure and temperature of the steam plume. The variation of the axial temperature confirmed the existence of expansion and compression waves within the steam plume. Cho et al. [19] investigated the characteristics of pressure oscillations in CO region to a multi-hole sparger, which confirmed that the amplitude of the pressure pulse showed a peak at the pool temperature range of 45–85 °C and the dominant frequency increased with the subcooled water temperature and pitch-to-hole diameter. Park et al. [20] performed the tests in CO and SC region to a multi-hole sparger, and confirmed that the pressure oscillation was also existed in SC region. A range of steam mass fluxes were selected to define the transition region from the CO region to the SC region. Hong et al. [21] investigated the frequency of the pressure oscillation in SC region to a single-hole nozzle and gave a one-dimensional mechanistic model of the dominant frequencies which excellently predicted the frequencies. The intensity of the pressure oscillations was not involved in their work.

From the above, the previous studies mainly focused on the steam jet pressure oscillations in the regions of C and CO with low steam mass flux. Because of the complexity of the two-phase flow and direct contact condensation, theoretical analysis on the pressure oscillation was very difficult. Therefore, most of the previous study methods on the pressure oscillation were the experimental analysis. The theoretical analysis was really rare, especially for the sonic steam jet. Setting up a theoretical model and developing theoretical analysis on the pressure oscillation for sonic steam jet were very necessary and urgent. The objective of this study was to theoretically and experimentally analyze the pressure oscillations in SC region by sonic steam jet. It should be useful to find out the generation mechanism and characteristics of pressure oscillation.

2. Experimental apparatus and method

2.1. Experimental apparatus

The experimental facilities consisted of a steam generator, a surge tank, steam supply lines, a sonic nozzle, a high speed video camera, a water tank and a three-dimensional mobile mounting bracket. The steam generator was electric boiler with electric heaters of 330 KW, maximum operating pressure 0.7 MPa and maximum steam flow rate 400 kg/h. The steam flow meter was OPTISWIRL 4070-DN25. The sonic nozzle was processed by 45# carbon steel with the exit diameter of 8 mm. It was connected with the steam pipe by thread. The square quenching tank was equipped with two plexiglass windows for visual observation and video camera imaging. Its size was 3000 mm × 1200 mm × 1200 mm. Light source was equipped on the back side window in order to ensure the shooting effect. All the pipes were covered by thermal insulators from steam generator to nozzle inlet. Four T-type thermocouples were installed in the four corners of the tank to measure the subcooled water temperature. An overflow hole lied on the 500 mm height above the nozzle to ensure nozzle submerged depth. The schematic diagram of the experimental system was shown in Fig. 1.

2.2. Experimental method and conditions

Saturated steam was generated continuously from the steam generator and then injected into the cold water through the sonic nozzle. The steam mass flux was changed by adjusting the control valve. When the water temperature and steam mass flux reached to the required conditions and kept stable, the condensation form was photographed and the pressure oscillations were processed by the data acquisition system. The test conditions were shown in Table 1. The measurement locations and the sonic nozzle were shown in Fig. 2. The mobile mounting bracket and the pressure sensor installation method were shown in Figs. 1 and 3. Defining the nozzle axial plane was the *xor* plane. One fixed pressure sensor M was installed on x = 0 mm and r = 90 mm. Meanwhile, four pressure sensors were equipped on the three-dimensional mobile mounting bracket at x/d_e = 0, 10, 20, 40. when the steam-water parameter reached to the required condition and kept stable, move the three-dimensional mobile mounting bracket to the r/d_e = 2 and