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Experimental investigation on the second dominant frequency of pressure oscillation for sonic steam jet in subcooled water

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A B S T R A C T

Experimental investigations and analysis on the dominant frequency of pressure oscillation for sonic steam jet in subcooled water have been performed. It was found that sometimes there is only one dominant frequency for pressure oscillation, and sometimes there is a second dominant frequency for pressure oscillation. The first dominant frequency had been investigated by many scholars before, but the present study mainly investigated the characteristics of the second dominant frequency. The first dominant frequency is mainly caused by the periodical variation of the steam plume and the second dominant frequency is mainly caused by the generating and rupture of the large steam bubbles. A dominant frequency regime map related to the water temperature and steam mass flux is given. When the water temperature and the steam mass flux are low, there is only one dominant frequency of pressure oscillation. When the water temperature or the steam mass flux is high, the second dominant frequency appears for pressure oscillation. The second dominant frequency decreases with the increasing water temperature and steam mass flux. Meanwhile, the second dominant frequency at high steam mass flux and water temperature is lower than the first dominant frequency at low steam mass flux and water temperature. A dimensionless correlation is proposed to predict the second dominant frequency for sonic steam jet. The predictions agree well with the present experimental data, the discrepancies are within ±20%.

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1. Introduction

Steam jet condensation is widely used in military industry, nuclear power, chemical industry, power industry and other fields for its high heat transfer efficiency. However, the pressure oscillation generated in the steam jet is harmful for the relevant equipments. Especially in nuclear power system, when the reactor pressure is higher than the safe pressure, the high pressure steam will inject into the subcooled water pool. Meanwhile, the pressure oscillation coupled with the steam jet will resonate with the pool wall and relevant equipments when the pressure oscillation frequency is low. Therefore, the pressure oscillation of steam jet caused deep interests of many scholars.

Simpson and Chan [1] experimentally researched the hydrodynamic pressure oscillations of subsonic steam jet, and found that the interfacial motion of a subsonic jet was periodic with the pattern of bubble growth, bubble translation, and bubble separation (necking). Chan and Lee [2] investigated the steam injected into the subcooled pool and observed different flow patterns. They gave a regime map based on different flow patterns in steam mass flux 0–175 kg/(m^2 s). On this basis, Cho et al. [3] gave one more accurate regime map in larger steam mass flux 0–450 kg/(m^2 s), which was widely applied by later academics. From then on, the pressure oscillation of steam jet was investigated in different condensation region. Youn et al. [4] investigated the pressure oscillation in chugging region (10–80 kg/(m^2 s)), the frequency was little affected by the subcooled water temperature, but increased with increasing steam mass flux. However, according to Hong et al. [5], CO region occurs at steam mass flux <300 kg/(m^2 s), and SC region occurs at steam mass flux >300 kg/(m^2 s), Hong et al. [5] indicated that the pressure oscillation frequency decreased with increasing water temperature. And the frequency increased in CO region but decreased in SC region with increasing steam mass flux. It was noteworthy that all the investigations above were the pressure oscillation in external steam plume. But Wu et al. [6–9] and Ajmal et al. [10–13] indicated that the expansion wave and compression wave also existed in internal steam plume. Furthermore, Qiu et al. [14] investigated the intensity properties and spatial distribution of pressure oscillation for sonic steam jet. Cho et al. [15] and Park

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Nomenclature

A	amplitude, kPa
d_e	exit diameter of nozzle, mm
f	dominant frequency, Hz
G	steam mass flux, kg/(m^2 s)
H	submerged depth of nozzle, mm
h_{fg}	latent heat, kJ/kg
Ja	dimensionless index
p_s	steam inlet pressure, MPa
p_∞	ambient pressure, MPa
r	radial distance, mm
Re	dimensionless index
St	dimensionless index
ΔT	subcooled temperature, °C
Tw	water temperature, °C
V	exit speed of steam, m/s
We	dimensionless index
x	axial distance, mm
ρ_s	steam density, kg/m^3
ρ_l	water density, kg/m^3
μ	viscosity, N s/m^2
σ	surface tension of water, N/m

et al. [16] investigated the performance of multi-hole sparger respectively.

Although, many investigations on pressure oscillation have been performed before, the main focus is on the first dominant frequency, and the second dominant frequency is still rarely investigated until now. However the second dominant frequency is also very harmful in many conditions. In order to improve the safety of nuclear reactor, it is very important to investigate the characteristics of the second dominant frequency. The present study investigates the characteristics of the second dominant frequency and makes a technical contribution to safe operation of nuclear power.

2. Experimental apparatus and methods

2.1. Experimental apparatus

The schematic diagram of the experimental system has been shown in Fig. 1. The experimental facilities consist of a steam generator, a subcooled water pool, steam lines, a flow meter, a sonic nozzle, a high speed video camera and a mobile probe. The steam generator is 330 kW electric boiler with 0.7 MPa maximum operating pressure and 400 kg/h maximum steam flow rate. The subcooled water pool is equipped with two plexiglass windows for visual observation and video camera imaging. The steam flow meter is OPTISWIRL 4070-DN25. The convergent sonic nozzle with exit diameter of 8 mm has been shown in Fig. 2. The high speed video camera is Phantom V611 with frame rate of 1000 fps. All the pipes are covered by thermal insulators from steam generator to nozzle inlet. Four T-type thermocouples are installed in the four corners of the pool to measure the subcooled water temperature. A dynamic pressure sensor (range of −100 to 100 kPa; accuracy: 0.2%FS; nature frequency: 40 kHz) was equipped on the mobile probe to measure the pressure oscillation in the water. The measurement point has been shown in Fig. 2. Since the oscillation frequency is not changed with the position of the measurement point, as shown in Fig. 3 [14]. We only need to choose the frequency of one point such as $x/d_e = 10$, $r/d_e = 2$ to stand for the frequency of pressure oscillation in the whole subcooled water pool.

2.2. Experimental methods and conditions

Saturated steam is generated continuously inside the steam generator and then injectes into the subcooled water tank through the sonic nozzle. Then the water temperature increases with the steam condensation. When the water temperature reaches the required condition, the steam mass flux will be adjusted to the required condition by turning the control valve. Meanwhile, the steam plume is photographed and the pressure oscillation is processed by the data acquisition system. The sampling time maintains at least 5 s and the sampling rate is 5000 Hz. The probe diameter is 4 mm, so the probe could not have influences on the two phase flow. The probe is perpendicular to the plume axial line, so the static pressure oscillation is measured on the measurement point. Since the characteristics of pressure oscillations are extremely complicated. Fast Fourier Transform (FFT) is used to find the dominant frequency by transforming the time domain to the frequency domain. The test conditions have been shown in Table 1. All the instruments have been calibrated before tests.

2.3. Uncertainty analysis and reproducibility

In this experimental system, the Flow meter accuracy is 1.0% with the range of 22.53–469.51 kg/h. The pressure sensor accuracy is 0.2% with the range of −100 to 100 kPa. T-type thermocouple accuracy is 0.5 K. The uncertainty analysis has been performed using the method of Moffat [17] and the uncertainty evaluation of base 2 Fast Fourier Transfer. The maximum uncertainty of pressure oscillation amplitude and frequency are 12.6% and 12.8% respectively.

Two experiments for $G = 298$ kg/(m^2 s) and $T_w = 40$ °C have been done, the FFT results have been shown in Fig. 4. Both the frequency and amplitude have a good reproducibility.

3. Experimental results and discussions

3.1. Frequency analysis

When steam injects into subcooled water pool, different flow patterns and pressure oscillation patterns will appear based on the balance of the energy that the steam jet releases and the pool water receives. Fig. 5 shows the frequency spectrums of pressure oscillation for different steam mass flux and water temperatures. When the water temperature and steam mass flux are low, as $T_w = 30$ °C and $G = 241$, 270, 298 kg/(m^2 s) in Fig. 5, there is only one dominant frequency in the range of 0–1000 Hz. The dominant frequency is about 500 Hz and the amplitude is about 0.6 kPa. However, when the steam mass flux or the water temperature is high, there are two dominant frequencies in the frequency spectrums as shown in Fig. 5. In order to distinguish the two dominant frequencies, we defined the low dominant frequency as the first dominant frequency and the high one as the second dominant frequency. The first dominant frequency is about 100–400 Hz, the frequency in this range is very close to the nature frequency of the subcooled water pool. And it will easily resonate with the subcooled water pool. Thus, the first dominant frequency has caused wide concern over recent years. The second dominant frequency is about 300–800 Hz, although it is higher than the first dominant frequency, it is also very close to the nature frequency of subcooled

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