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Pressure oscillation and steam cavity during the condensation of a submerged steam jet

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ABSTRACT

Steam jet condensation is important in many industrial applications. In this work, the pressure oscillation and steam jet patterns during submerged jet condensation in quiescent water is investigated experimentally. Firstly, it is found that even at stable condensation region, the steam cavity length varies all the time and steam bubbles separate from the steam cavity periodically. With the variation of steam cavity length and separated bubble oscillation, condensation also undergoes oscillation. Along the axial direction, the pressure oscillation intensity increases first and then decreases gradually. There is an distinct pressure oscillation peak, and the peak position varies over a length-to-diameter ratio range of $X/D = 2$ to $X/D = 7$. The axial position of pressure oscillation peak corresponds to the end of steam cavity. Moreover, oscillation energy analysis shows that the oscillation energy generated by separated steam bubble is much higher than that generated by the steam cavity length variation. Finally, based on the relationship between the axial distribution of pressure oscillation and the steam cavity, a method is proposed to determine the maximum steam cavity length by measuring the pressure oscillation distributions. The predicted deviation is only in range of ±16% for the test conditions.

1. Introduction

The steam jet condensation is a special form of steam-water direct contact condensation. It is widely used in industrial production, such as the surge tank and pressure suppression pool in nuclear reactor. The surge tank and pressure suppression pool plays an important role to ensure safety of nuclear reactor. When the primary circuit pressure of nuclear reactor exceeds the safety value that surge tank could maintain, steam will be jetted into the pressure suppression pool through spargers to ensure safety of nuclear reactor. Then the direct contact condensation occurs. Once the steam is jetted into water, the momentum and energy begin to exchange between steam and surrounding water drastically which affect the safety of equipment and nuclear reactor greatly. So the research on steam jet condensation is significant to the design and operation of safety system in nuclear reactor.

For the steam jet condensation, a lot of works have been developed for many years, like the condensation regime (Cho et al., 1998; Petrovic de With et al., 2007; Wu et al., 2009; Song and Kim, 2011), the steam jet pattern (Chun et al., 1996; Wu et al., 2009), the coefficient of heat transfer (Kim et al., 2001; Shah et al., 2010, 2013; Patel et al., 2014) and the steam jet condensation load (Chan, 1978; Fukuda, 1982; Simpson and Chan, 1982). When steam is jetted into water and condensed by water, there will generate some pressure impulse in water pool, which is called condensation oscillation. The pressure impulse may be harmful to the steam jet devices, such as the water pool. Especially, when the condensation oscillation frequency is close to the natural frequency of device, resonance will happen which may make great damage to the pool.

To avoid this damage, much attention has been paid to condensation oscillation for many years (Fukuda, 1982; Simpson and Chan, 1982; Nariai and Aya, 1986). In the past few years, many investigations have been focused on the low mass flux region, for example the chugging region (C), transient chugging region (TC) and condensation oscillation region (CO), as shown in Fig. 1. Fukuda (1982) investigated the shapes of steam cavity at low mass flux and found that the shapes of steam cavity correspond to the condensation oscillation. Also he found that the condensation oscillation frequency was proportional to the water subcooling and inverse proportional to the nozzle diameter. Chan and Lee (1982) investigated the flow and condensation pattern under low mass flux. Three typical condensation patterns were observed. They were the oscillation jet, chugging and bubble jet. Simpson

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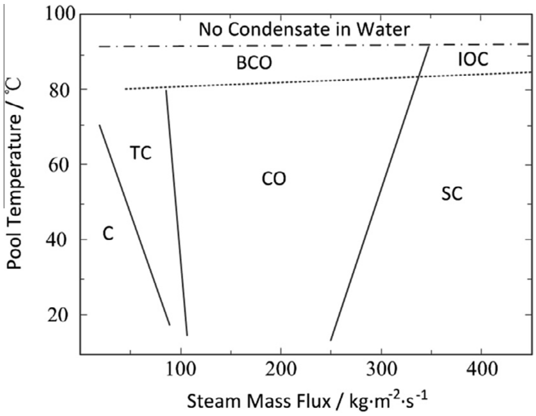

Fig. 1. Condensation regime map.

and Chan (1982) made a further effort on low mass flux steam condensation. The process of bubble growth, bubble translation, and bubble separation (necking) was found and the process occurred periodically. Couple with the bubble separation process, pressure pulse was appeared periodically. Nariai and Aya (1986) researched the condensation oscillation frequency with three typical bubble shapes. They were the cylindrical bubble, spherical bubble and hemispherical bubble. The predicted frequency showed good corresponding to the experimental data. Aya and Nariai (1991) made some efforts on steam jets pressure oscillation in the chugging region and condensation oscillation region. Pressure oscillation was thought to be induced by the balance action between the supply of steam to steam cavity and its condensation on the steam-water interface. Tanskanen et al. (2014) simulated steam condensation for chugging regime, the information of bubble size and chugging frequency was revealed. Youn et al. (2003) found that when the steam bubble detached from the nozzle exit with the necking phenomenon, high pressure pulses with relatively low frequency were observed. To investigate the condensation oscillation frequency, the Strouhal number was adopted and it was related with Jacob number, Reynolds number, Weber number by previous researchers (Damasio et al., 1985; Simpson and Chan, 1982). Cho et al. (2004) investigated the characteristics of pressure oscillations in condensation oscillation (CO) region with multi-hole sparger and confirmed that the amplitude of the pressure pulse showed a peak at the pool temperature range of 45–85 °C. The dominant frequency was also affected by the pitch-to-hole diameter. Park et al. (2007) performed the tests in condensation oscillation (CO) and stable condensation (SC) region to a multi-hole sparger. At stable condensation (SC) region, the pressure oscillation for multi-hole was also found and it was different with the pressure oscillation of single hole.

However, the research on the oscillation of steam jet condensation at stable condensation is relative less than the research on the low mass flux and oscillation condensation region. According to Hong et al. (2012), the steam condensation oscillation for stable condensation region (SC) was generated by the variation of steam jet length. Based on that, a one-dimensional oscillation model was proposed to predict the steam condensation oscillation frequency. Qiu et al. (2014a,b, 2015) investigated the pressure oscillation with sonic and supersonic nozzles. Both the oscillation intension and dominant frequency was researched. Besides the first domain frequency, the second dominant frequency was found under some test condition.

Furthermore, although the steam cavity is thought to be related with the steam condensation oscillation, the relationship between steam cavity length and condensation oscillation at stable condensation region is rarely studied. Also, there are few works on the pressure oscillation intensity distribution along the axial direction. In order to solve these problems, the condensation oscillation and steam cavity for high mass flux is researched which is of signification to the industry application. With help of high speed camera and dynamic pressure sensors, the photos of steam cavity under high sample rate and pressure oscillation are acquired and analyzed, respectively. Also, the relationship between the steam jet pattern and pressure oscillation is investigated.

2. Experimental apparatus and measurement point

2.1. Experimental apparatus

The experimental apparatus of steam jet submerged in quiescent water adopts the system which was reported by Qiu et al. (2014a), as shown in Fig. 2. Steam is generated at steam generator and then flow through the steam pipe. Finally, it is jetted into subcooled water with a nozzle and then condensed. Steam mass flux is controlled by an electric control valve and measured by vortex type steam flow meter which accuracy is 0.5% full span (FS). The steam pressure and temperature before nozzle inlet are measured with a pressure transducer (0.1% full span) and a T-type thermocouple (0.5 °C), respectively. Eight T-type thermocouples are distributed uniformly to measure the pool water temperature. The test nozzles are installed horizontally and submerged with depth of 500 mm in square tank. The nozzles with inner diameters of 8 and 10 mm are tested.

Two high frequency dynamic pressure sensors are used to measure the pressure oscillation, and they are equipped on the three-dimensional mobile mounting bracket. The dynamic pressure sensors are manufactured by the Xi'an Jiecheng sensor measurement and control technology company limited and the model is CYG41000T. Also, the pressure sensors have been calibrated by the Changcheng institute of metrology & measurement which has the certificates of lab accreditation issued by China national accreditation board for laboratories. The resonant frequency of dynamic pressure sensors is 26 kHz and it can acquire the dynamic pressure signal with accuracy of 0.5% full span (FS). Then the pressure signal is transformed and acquired by a dynamic pressure acquisition cards (NI 4472) and transmitted to the industrial personal computer. The noise level is tested, and the maximum noise level is turned out to be about 0.01 kPa. A high speed camera (Phantom V611) is applied to take photos of steam cavity. The maximum photo sample rate can reach to 100,000 frames per seconds.

2.2. Measurement point

The test parameters are shown in Table 1. Two high frequency dynamic pressure sensors are installed at the three-dimension mobile scaffold, as shown in Fig. 3. Sensor probes and nozzle center line are in the same horizontal plane, and sensor probes are vertical to the steam jet direction. The position of dynamic pressure sensors could be adjusted by the three-dimension mobile scaffold. The horizontal plane where the nozzle center line locates is adopted as the reference plane and nozzle exit center is used as the origin of coordinates. The steam jet direction is defined as the *X* axis and the nozzle radial direction is defined as the *R* axis. Also, the dimensionless axis distance X/D and radial distance as R/D is defined, respectively, where the D is the diameter of nozzle. At initial moment, two sensors are fixed at the position of $X/D = 0$, 10 respectively, with $R/D = 2$. Then the sensors are moved along the *X* axis simultaneously. The moving distance is $\Delta X/D = 1$ for every step, as show in Fig. 4.

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