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Effect of non-condensation gas on pressure oscillation of submerged steam jet condensation

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HIGHLIGHTS

- Oscillation intensity of steam–air jet increases with rise of water temperature.
- Oscillation intensity reduces obviously when air is mixed.
- Both first and second dominant frequencies decrease with rise of air mass fraction.
- Air has little effect on power of 1st & 2nd frequency bands under low temperature.
- The maximum oscillation power occurs under case of $A = 1\%$ and $T \geqslant 50$ °C.

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ABSTRACT

The effect of air with low mass fraction on the oscillation intensity and oscillation frequency of a submerged steam jet condensation is investigated under stable condensation region. With air mixing in steam, an obvious dynamic pressure peak appears along the jet direction. The intensity peak increases monotonously with the rise of steam mass flux and water temperature. Peak position moves downstream with the rise of air mass fraction. Moreover, when compared with that of pure steam jet, the oscillation intensity clearly decreases as air is mixed. However, when water temperature is lower than approximately 45 °C, oscillation intensity increases slightly with the rise of air mass fraction, and when water temperature is higher than 55 °C, the oscillation intensity decreases greatly with the rise of air mass fraction. Both the first and second dominant frequencies decrease with rise of air mass fraction. Finally, effect of air mass fractions on the oscillation power of the first and second dominant frequency bands shows similar trends. Under low water temperature, the mixed air has little effect on the oscillation power of both first and second frequency bands. However, when water temperature is high, the oscillation power of both first and second frequency bands appears an obvious peak when air mass fraction is about 1%. With further rise of air mass fraction, the oscillation power decreases gradually.

1. Introduction

Steam submerged jet condensation has been used widely in the industry because of its characteristics of high heat transfer and mass exchange capacity. Steam jet condensation system has the characteristic of passive, no motion part and no electrical control. Therefore, it is widely used in the fast heat discharge systems and residual heat reutilization industry applications, such as pressure relief pool in boiler water reactor, refueling water storage tank in advanced light water reactor, steam ejector and steam water direct contact heat exchanger.

However, steam submerged jet can cause pressure oscillation in the water. Pressure oscillation leads incessant load on the water tank or other apparatus in the tank. Specifically, when pressure oscillation frequency is close to the natural frequency of the water tank or relevant apparatus in pool, the resonance phenomenon happens. This phenomenon should be taken into account and avoided in the system design. Thus, the original experimental data of steam jet condensation oscillation is needed in the design database of nuclear reactor plant or other steam jet condensation systems.

Numerous scholars have investigated the jet condensation oscillation for many years. Chan (1978) measured the dynamic pressure impulse of submerged steam jet with sonic speed. They

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found that the oscillation frequency decreased with the rise of water temperature and nozzle diameter. Moreover, the interface oscillation caused by expansion and compression was more suitable for the explanation explaining of condensation oscillation. Simpson and Chan (1982) investigated the condensation oscillation under subsonic jet. They found that the pressure oscillation was closely related to the bubble separation process, and the oscillation frequency was affected by the heat transfer and steam jet mass flux. Therefore, they built a relation between dimensionless frequency, Strouhal number, with Jacobi number and Reynolds number, which was used widely by later researchers (Cho et al., 2004; Damasio et al., 1985; Qiu et al., 2014). Fukuda (1982) also investigated the jet oscillation frequency under sonic and subsonic speeds. He proved that the oscillation frequency was proportional to the pool water subcooled degree and inversely proportional to the nozzle diameter. Nariai and Aya (1986) considered that pressure oscillation was induced by the balance action between the steam supply and condensation at the steam–water interface. They proposed three models for steam cavity at condensation oscillation (CO) region to predict the condensation oscillation intensity and oscillation frequency. Hong et al. (2012) researched the condensation oscillation at stable condensation (SC) region. Based on the varying of steam jet lengths, they proposed a one-dimensional oscillation model to predict the steam condensation oscillation frequency, and the predicted frequency well agreed with the dominant frequency they measured. Qiu et al. (2014, 2015) investigated the pressure oscillation with sonic and supersonic jets. They found that steam mass flux, subcooled water temperature and the design pressure ratio all had great significant affect effects on the condensation oscillation frequency. Besides the condensation oscillation dominant frequency, a second dominant frequency was also found. Chong et al. (2015) proved that the second dominant frequency has always existed in the SC region, and the oscillation power of the second dominant frequency band was larger than that of the first dominant frequency band. Zhao et al. (2015) investigated the distribution characteristic of condensation oscillation intensity at sonic jet condensation. They found that along jet direction, an oscillation intensity peak exists. The oscillation peak was well corresponding to the steam plume tail. Chen et al. (2016) discovered the low-frequency oscillation in the jet wake region and proved that the oscillation is caused by turbulent vortex. On the basis of oscillation power distribution, the affected region of low-frequency oscillation is obtained. Tang et al. (2013, 2015) investigated the acoustic characteristic of steam bubble condensation under different water temperatures and steam injection rates. They found that acoustic sound frequency increased with the rise of water subcooling and steam injection rate. However, the amplitude of acoustic sound increased first and then decreased with the rise of water subcooling. Su et al. (2002) proposed a criterion to predict the stability thresholds for the two-phase flow with lumped parameter method. The characteristic of density wave oscillation was investigated under different parameters. Moreover, the oscillation frequency correlation of density wave oscillation was obtained theoretically.

To sum up, most studies focus on the pure steam jet condensation. However, in the process of release pressure in a nuclear reactor, some non-condensable gas may be mixed in the steam, and this will change the jet condensation characteristic. Norman and Revankar (2010a,b) found that heat transfer capacity would decrease when non-condensable gas was mixed in steam. For the steam–air mixture jet, thermal stratification occurred in the water pool when water temperature was above 40 °C and air mass fraction was below 0.5%. Thermal stratification disappeared when water temperature was below 40 °C and air mass fraction was higher than 1.0%. Liang and Griffith (1994) found that with non-condensable gas present, heat transfer resistance at the steam–water interface increased and the condensation process was greatly retarded. Therefore, the chugging process transformed into an oscillation jet. Chan and Yuen (1990) carried out direct-contact condensation experiments and investigated the effects of air on direct-contact condensation heat transfer. They correlated the average Nusselt number with the average steam–air Reynolds number and air concentration. Choi et al. (2002) experimentally investigated the heat transfer coefficient of direct contact condensation with non-condensable gas. They found that the condensation heat transfer coefficient decreased with the rise of air fraction and then they proposed a modified correction multiplier to predict the condensation heat transfer coefficient of steam–air mixture. Qu et al. (2015) researched condensation characteristic of steam–air mixture bubble experimentally and numerically. They found that non-condensable air inside the bubble was near the interface and deteriorated the condensation heat and mass transfer.

Song et al. (2001) considered the effect of non-condensable gas on the heat transfer of steam jet condensation and realized that non-condensable gas would also affect the characteristic of condensation oscillation. Experimental results indicated that the oscillation dominant frequency decreased with air mixing. Air had a great influence on the oscillation intensity at CO region, but little effect on the oscillation intensity at SC region.

Based on previous research, non-condensable gas has a great influence on submerged steam jet condensation. However, few researches focus on the condensation oscillation characteristic, especially on the effect of non-condensable gas on oscillation characteristic at the SC region and the distribution characteristic of steam jet condensation's oscillation intensity. Moreover, there are two dominant frequencies at stable condensation region (Chong et al., 2015; Qiu et al., 2014), though the effects of non-condensable gas on these two dominant frequencies, including the frequency and amplitude, are still unclear. To solve the above-mentioned problems, the present study is performed to investigate the effect of non-condensable gas on the condensation oscillation characteristic at the SC region.

2. Experimental apparatus and uncertainty

2.1. Experimental apparatus

The experimental system of submerged steam jet in quiescent water is shown in Fig. 1. The steam jet system, nozzle structure and data acquiring system are similar to those of Zhao et al. (2015). Air is supplied by an air compressor and an air storage tank is used to keep the air supply steady and continuous. Air flows from the air storage tank and is then heated to the required temperature of saturated steam. Finally, the heated air is injected into a steam flow pipe to mix with steam. To ensure that steam and air are mixed homogeneously, the mixture pipe is long enough before the nozzle. The test parameters are shown in Table 1 and measurement point distribution is displayed in Fig. 2.

2.2. Repeatability and uncertainty

Similar to pure steam jet condensation oscillation, root mean square pressure oscillation intension is introduced to describe the average oscillation intensity.

$$P = \sqrt{\frac{\sum_{i=1}^{N}(P_i - \overline{P})^2}{N}} \tag{1}$$

where P_i is the instantaneous pressure, N is the sample number and $\overline{P} = \frac{1}{N}\sum_{i=1}^{N} P_i$.

The experimental repeatability is then checked and verified. Fig. 3 shows the repeatability of experiment under following