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Feature of acoustic sound signals involved in vapor bubble condensation and its application in identification of condensation regimes

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HIGHLIGHTS

- Kurtosis and DWT of acoustic signals could identify condensation regimes.
- Behaviors in signals correspond to dominant frequencies were highly persistent.
- First peak in spectra caused by bubble break-up or split-up was anti-persistent.
- Sound pressure oscillations caused by bubble collapse and split-up were similar.
- Bubble collapse frequency increased with increase in subcooling and injection rate.

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ABSTRACT

Experiments were carried out on the sound pressure oscillations condensation regime map, and bubble collapse frequency during the direct contact condensation of vapor with the aid of an acoustic hydrophone and a high-speed video camera. The injection rate of vapor and liquid subcooling in the experiments were 0.19–3.73 m^3/h and of 10–70 K, respectively. Four different condensation regimes were identified according to features presented on the bubble surface and whether and when the bubble collapse occurred. The state-of-the-art signal processing methods (statistical, spectral, fractal and discrete wavelet transform analyses) were applied to processing the detected acoustic signals. The results showed that only the kurtosis and DWT in the four methods could distinguish the different regimes well. Furthermore, the spectral and fractal analyses showed that strongly persistent behavior in the signals corresponded to the dominant frequency in the range of 120–400 Hz might be arisen from the periodic variation in the vapor bubble volume. While that corresponded to peaks with frequency higher than 7000 Hz in transition and capillary wave regimes were probably the high-frequency oscillation in pressure induced by sudden bubble collapse. Contrarily, the first peak in 0–200 Hz caused by the periodic bubble break-up or split-up was high anti-persistent. DWT analysis showed that the sound pressure oscillation introduced by bubble collapse was similar to that by bubble split-up for all condensation regimes, whereas at very high frequency two different types of oscillations arose. Furthermore, the bubble collapse frequency increased with increase in liquid subcooling and vapor injection rate, and could be obtained from the spectral and Hurst analyses of the signals indirectly.

1. Introduction

Due to its high heat and mass transfer ability, Direct Contact Condensation (DCC) of steam in subcooled water has been widely used in energy, chemical, nuclear and marine industry, such as direct contact feed water heater, steam jet pump and suppression containments in nuclear passive safety systems, etc. Identification of condensation regime and understanding of pressure oscillations induced by condensation, which have been investigated by many researchers experimentally and theoretically, are of great importance in optimal design and safe operation of systems and devices involving DCC.

Chan and Lee (1982) observed three main condensation modes, which were referred to as steam chugging, oscillatory bubble and oscillatory jet according to the location of a condensation region

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relative to injection pipe outlet and the detachment position of vapor bubble. They constructed a condensation regime map in terms of the co-ordinates of water temperature and vapor mass flux. Shortly after that, transition boundaries between different condensation regimes were investigated theoretically by Nariai and Aya (1986), Aya and Nariai (1987) and Elperin and Fominykh (1997). Boundary of bubbling regime was given by utilizing the linear stability analysis, and the Hodgson number was introduced to distinguish the chugging regime and condensation oscillation regime. Liang and Griffith (1994) carried out a series of experiments concerning the transition between different condensation regimes and established the transition criteria on the basis of the transient conduction model and the two-layer turbulent eddy transfer model. The condensation regime map by Chun et al. (1996) from visual observations and dynamic pressure oscillations included six condensation modes of chugging, transient region, condensation oscillation, bubble condensation oscillation, stable condensation, and interfacial oscillation condensation. Lee and No (1998) concluded that the buoyancy dominated the transition between the regimes and introduced Froude number and Jacob number to describe the condensation regime map consequently. Ju et al. (2000) obtained a condensation regime map associated with the downward injection of vapor, and found that the boundary of chugging and subsonic jetting shifted to the larger steam mass flux with the increase in the pipe diameter. Petrovic et al. (2007) used liquid subcooling, vapor mass flow rate and injector size to construct new three-dimensional condensation regime maps for DCC of steam in stagnant and flowing water, respectively. Wu et al. (2009) conducted experiments of condensation of sonic and supersonic steam jet and gave three-dimensional condensation regime maps using steam mass flux, water temperature and pressure ratio. Four and six different steam plume shapes were observed in sonic steam jet and supersonic steam jet regime maps, respectively. A three-dimensional regime diagram was constructed by Xu et al. (2013) for condensation of stable steam jet in a water flow with steam flux, water temperature and Reynolds number. They observed five shapes of plume, and measured the plume length, radial temperature distribution and average heat transfer coefficient.

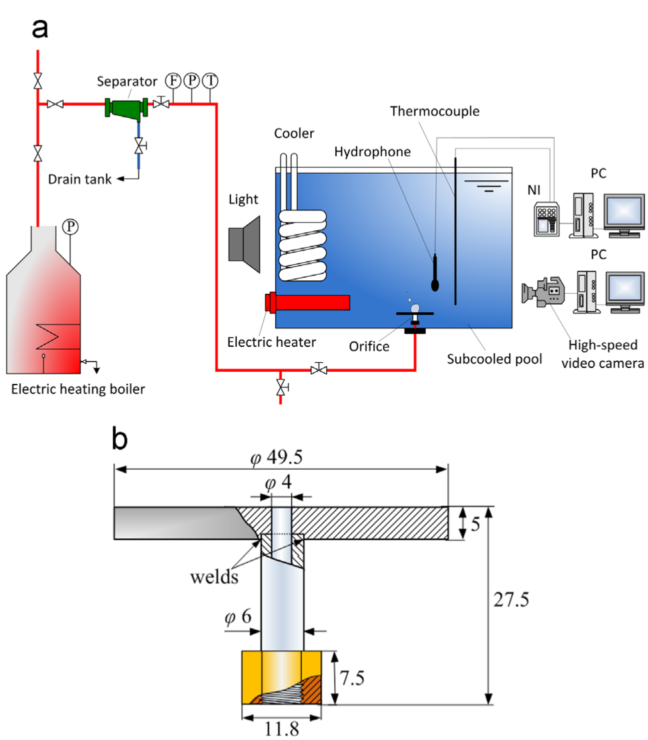

Fig. 1. Schematic diagram of (a) experimental apparatus and (b) orifice nozzle.

The research on pressure oscillations induced by condensation using the pressure transducer could be found in many literatures. Youn et al. (2003) observed intermittent pulses of high dynamic pressure in the chugging region. Hong et al. (2012) studied the dominant frequency in regions of stable condensation and interfacial oscillation condensation, and proposed a prediction model basing on the balance of kinetic energy. While Qiu et al. (2014a, b) investigated the dominant frequency in condensation oscillation and stable condensation regimes. Two dominant frequencies were found at high water temperature or vapor mass flux. The first one increased in condensation oscillation regime, but decreased in stable condensation regime with the increase in steam mass flux. The second one decreased with the increase in water temperature and steam mass flux. Cho et al. (2004) studied the effects of multiple holes on pressure fluctuation induced by condensation, and found that the dominant frequency increased with the increase in subcooling and pitch-to-hole diameter.

The emission of acoustic sound is inevitable in the process of DCC. Signal detected by a hydrophone is also a kind of pressure oscillation at that case, which is however different from that detected by a pressure transducer in some ways. The hydrophone is very sensitive to pressure oscillations and can offer a flat frequency response over a very wide frequency range. Therefore, many researchers (Nishihara and Bessho, 1977; Al-Masry et al., 2006, 2007; Ajbar et al., 2009; Salehi-Nik et al., 2009; Geraldo et al., 2014) utilized the acoustic signals to study the system behaviors and identify flow regions in multi-phase flow systems, whereas few works dealt with the acoustic signals induced by vapor condensation. The main objectives of current work are to investigate the sound pressure oscillations detected by a hydrophone and validate the applicability of acoustic signals in recognizing condensation regimes.

2. Experimental apparatus

The schematic diagram of the experimental apparatus is shown in Fig. 1(a). All experiments were carried out using an experimental setup in earlier publication (Tang et al., 2015). The vapor generated in a 240 kW electric heating boiler was introduced into the water tank through an orifice nozzle. The schematic diagram of the orifice nozzle is shown in Fig. 1(b). It includes an upper orifice and a connection tube. The inner and outer diameters of the upper orifice plate are 4 mm and 49.5 mm, and those of the connection tube are 4 mm and 6 mm, respectively. The connection tube is welded to the upper orifice to form the entire orifice nozzle, which is then fastened to the vapor injection tube by screw thread connection. The electric heating boiler and pipings were wrapped up with thermal insulating materials to reduce heat loss. An electric heater of 15 mm in diameter and a copper cooler were employed to maintain and control the bulk temperature. The injection rate was controlled by the steam regulating valves as well as a valve on the bypass line. A K-type sheathed thermocouple was installed in the steam pipe to measure the vapor temperature. The experiments were conducted under atmosphere pressure and 1 K superheating of the vapor over the local saturation temperature was attained by adjusting the pressure inside the electric heating boiler. In present study, the liquid subcooling could be defined as $(T_s - T_b)$, where T_s denotes the saturation temperature of the system under atmospheric pressure, and T_b is the bulk temperature. Five K-type sheathed thermocouples of 0.5 mm in diameter were placed at 10, 15, 20, 30 and 45 mm horizontally apart from the central axis of the orifice and 5 mm above the injection orifice outlet to measure the bulk temperature. The drop in temperature between the five positions was less than 1 K. As a result, the water temperature T_b was taken as that