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# Experimental study of sound emission in subcooled pool boiling on a small heating surface

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## HIGHLIGHTS

- Sound emission in subcooled boiling on a small heater was investigated.
- Different from that on large heater, SPL versus superheat took form of '*N*' shape.
- Boiling sound in MEB was related to collapse and volume oscillation of vapor film.
- SPL combined with DWT can predict boiling situations and heat transfer rate.

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## ABSTRACT

In this study, sound emission in subcooled pool boiling with a small plate heater was investigated experimentally. Acoustic signals were recorded using a hydrophone and analyzed using sound pressure level (SPL), fast Fourier transform, and discrete wavelet transform (DWT). The results show that the SPL combined with an analysis of the sound signal by DWT can be used to identify boiling modes and heat transfer intensification. In contrast to those for a large plate heater or long wire, the plot of the SPL against wall superheat in nucleate boiling region exhibits an '*N*" shape. Visualization results indicate that this difference mainly originates from the effects of heater size on bubble growth and departure. Compared with the nucleate boiling, in the region of microbubble emission boiling (MEB), the SPL exhibits a step increase of 10–20 dB, and continues to increase with the further increase of the heat flux. A comparison of the bubble frequency and features of the acoustic signals shows that the loud boiling sound in the MEB could be mainly attributed to the vapor film collapse and vapor volume oscillations, which also significantly affect the heat transfer process.

## 1. Introduction

Boiling is always accompanied by an intense noise sound, which can be heard and easily detected. Owing to the high sensitivity, small response time, and relatively low price, acoustic measurements have various applications including a detection of boiling sound to identify boiling modes (Nishihara and Bessho, 1977; Bode, 2008; Rapisarda et al., 2015), measurement of boiling liquid level (Singh and Mohanty, 2018), and monitoring of boiling incipience (Geraldo et al., 2014; Shibahara et al., 2018; Alhashan et al., 2018) in many systems inaccessible by a direct measurement, including nuclear reactors, accelerators, and space power plants. An analysis of the sound emission can also help reveal boiling mechanisms (Zhang et al., 1999; Schroder and Bode, 2000; Dorofeev and Volkova, 2005; Lloveras et al., 2012). For example, the critical heat flux (CHF) was recently detected with a noise spectral density inversely proportional with the frequency ($1/f$ noise) (Vinogradov et al., 2007; Lloveras et al., 2012), which indicates that the boiling crisis could be attributed to non-equilibrium phase transitions in a boiling system.

Boiling sound has been investigated over half century. It can be mainly attributed to bubble dynamics including bubble growth, condensation, departure, and collapse (Lee and Higgs, 2006; Vazquez et al., 2015; Wu et al., 2015; Alhashan et al., 2018). Early theoretical investigations of sound pressure originating from bubble growth and condensation in subcooled boiling were performed by Bessho and Nishihara (1976) and Schmidt et al. (1970). They observed that the largest value of the acoustic pressure appeared at the initial stage of the bubble growth. Once the bubble grew out of the thermal boundary layer, its growth rate began to decrease. Prior to reaching the maximum size of the bubble, the acoustic pressure became even negative during the oscillation.

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**Nomenclature**

| | |
|---|---|
| $a_j$ | approximation sub-signals |
| $d_j$ | detail sub-signals |
| $D_h$ | diameter of heating surface (m) |
| $E_j^a$ | energy of the approximations in level $j$ ($mV^2$) |
| $E_j^d$ | energy of the details in level $j$ ($mV^2$) |
| $f$ | frequency (Hz) |
| $g$ | gravity ($m/s^2$) |
| $L_b$ | capillary length scale |
| $M$ | receiving sensitivity of hydrophone (dB) |
| $P$ | pressure (Pa) |
| $P_a$ | acoustic pressure (Pa) |
| $q$ | heat flux ($W/m^2$) |
| $R$ | bubble radius (m) |
| $r$ | distance from bubble center to measurement point of acoustic pressure (m) |
| $t$ | time (s) |
| $V_b$ | bubble volume ($m^3$) |
| $T_w$ | wall temperature (K) |
| $u$ | voltage (V) |
| *Greek symbols* | |
| $\Delta T_{sub}$ | liquid subcooling (K) |
| $\Delta T_{sat}$ | wall superheat (K) |
| $\lambda_{Cu}$ | thermal conductivity of copper (W/m K) |
| $\rho$ | density ($kg/m^3$) |
| $\sigma$ | surface tension (N/m) |
| $\psi$ | mother wavelet function |

Dorofeev (1985) and Bode (2008) measured the real-time acoustic pressure wave during growth and condensation of individual bubbles, confirming the results of Bessho and Nishihara (1976). Dorofeev and Volkova (2005, 2006) observed three types of sound pressure waveforms based on the growth and condensation durations of a bubble, as shown in Fig. 1. A shorter condensation period leads to a larger relative oscillation amplitude at the condensation stage.

An acoustic pressure pulse with high energy and frequency was detected by Plesset (1966) and Benes and Uher (2009) when a bubble collapses in a subcooled liquid or bursts at a free water surface. Ceccio and Brennen (1991) and Husin and Mba (2010), Husin et al. (2013) demonstrated that the sound was more intense for a larger bubble. Further studies by Divoux et al. (2008) showed that a larger viscosity leads to a larger acoustic energy release during the process of bubble burst. Wu et al. (2015) compared acoustic signals from experiments of nucleate boiling on a Zirlo-alloy-cladding tube associated with bubble growth, departure, and collapse, and concluded that bubble collapse was the most powerful acoustic source in highly subcooled nucleate boiling.

Boiling sound can be measured with different types of acoustic sensors installed underwater, on the tank wall, or in the air. Acoustic measurement techniques for investigations of boiling sound are summarized in Table 1. These acoustic detection techniques are also widely used in marine, metallurgy, and chemical industries (Vazquez et al., 2015; Moghadam et al., 2017; Zhou et al., 2018). Hydrophone is a microphone designed to be used underwater for the detection of underwater sound, with a sampling frequency up to tens of MHz. Hydrophone employs piezoelectric transducers to detect sound waves; therefore, it does not require a power source, as it converts mechanical energy into electrical energy. Although hydrophone is an intrusive device, not suitable for limited and compact spaces, it is very sensitive to pressure signals originating from underwater bubble oscillation or collapse. One of its drawbacks is that it can only detect sound or pressure fluctuations, limiting the ability to distinguish multiple objects and artificial noise (Vazquez et al., 2008). An alternative technique is to detect transient elastic waves within a material caused by the rapid release of localized stress energy (Baek et al., 2017) with acoustic emission (AE) sensors attached to the outer surface of a water tank or tube. As a direct contact in the process is not required, the AE sensor can monitor boiling without intrusion. Electret condenser microphone can also be used to measure the acoustic signal of boiling.

The objective of the boiling sound detection is to correlate the intensity and frequency of the acoustic signals to boiling modes and heat transfer rate. Early studies of Westwater et al. (1955) showed that the boiling sound intensity was a function of the heat transfer rate; they presented the dependence of the heat flux as a function of the sound pressure level (SPL). Methyl alcohol was employed as the working fluid in their experiments with a copper bayonet heater with a diameter of 3/8 in. The SPL in nucleate and transition boilings increased monotonously with the wall superheat; it was almost unaffected in film boiling. Schwartz and Siler (1965) obtained another type of boiling sound curve for a thinner heated stainless-steel tube with a diameter of 0.093 in. The SPL first increased in the nucleate boiling and then decreased in the transition boiling with the increase of the temperature difference between the heater and liquid. At the film boiling region, the SPL started to increase again. Based on experimental data in the nucleate boiling, they proposed an empirical correlation between the SPL and wall superheat:

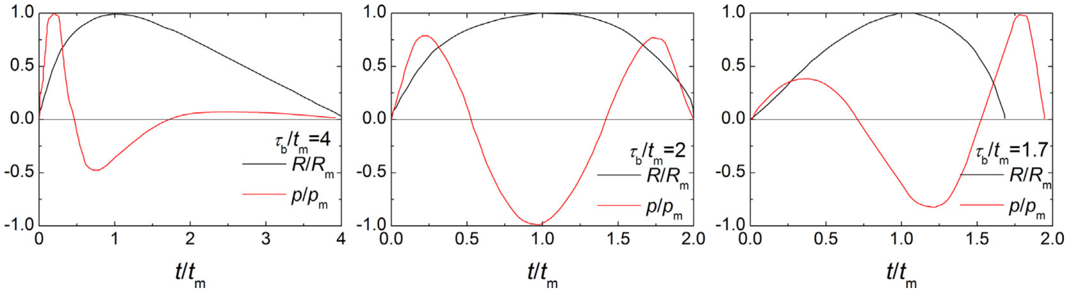

**Fig. 1.** Bubble history and associated acoustic pressure fluctuations during bubble growth and condensation in subcooled boiling, according to Dorofeev and Volkova (2006).