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Study of acoustic emission due to vaporisation of superheated droplets at higher pressure

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A B S T R A C T

Bubble nucleation in superheated liquids can be controlled by adjusting the ambient pressure and temperature. At higher pressure the threshold energy for bubble nucleation increases, and we have observed that the amplitude of the acoustic emission during vaporisation of superheated droplet decreases with increase in pressure at any given temperature. Other acoustic parameters such as the primary harmonic frequency and the decay time constant of the acoustic signal also decrease with increase in pressure. This behavior is independent of the type of superheated liquid. The decrease in signal amplitude limits the detection of bubble nucleation at higher pressure. This effect is explained by the emission of shockwave generated during the supersonic growth of the microbubble in superheated liquids.

1. Introduction

Superheated liquids are known to vaporise when irradiated by energetic particles since the invention of the bubble chamber [1]. For over three decades superheated liquids have been used for the preparation of superheated emulsion detectors, where superheated microdroplets are dispersed in a viscoelastic gel (superheated droplet detector, SDD [2]) or in a soft polymer matrix (bubble detector, BD [3]). These detectors are used for the detection of neutrons, charged particles, gamma-rays etc. [2–5]. The SDD and BD are threshold-type detectors where by changing the operating temperature and/or pressure the threshold can be controlled [2].

It is well known that whenever an energetic particle passes through the superheated liquid, it deposits energy along its path and if the energy is sufficient then it can trigger the bubble nucleation [2,6]. The bubble nucleation and subsequent vaporization of a superheated droplet generate an acoustic pulse which can be detected by transducers [7]. Though different techniques have been used for the detection of droplet vaporisation in superheated emulsions [7–10], acoustic detection of nucleation is still one of the important techniques used in this field [11–14]. Acoustic detection is important because of its ability to detect vaporization of a single droplet, which also could enable one to identify the nature of the particle triggering the bubble nucleation [12–14]. This technique can be used to discriminate bubble nucleation events due to different types of radiation [12–14], which already has proved its applicability not only in studying the bubble nucleation in SDDs but also in the study of bubble nucleation events in detectors used in dark matter search experiments [14,15].

It has been observed that the bubble nucleation rate decreases during the experiments at higher pressure [16], and that, despite visual observation of bubble formation, the signal goes undetected by the transducer. This loss of count results in the reduction of the detection efficiency of the SDD. On the other hand the detector becomes more stable at higher pressure due to the increase of energy threshold for bubble nucleation. The study of nucleation at different pressure is important to understand how the change in ambient pressure affects the bubble nucleation process in superheated droplets [16–18].

In this paper, we have studied the acoustic emission during bubble formation in three different SDDs by using a ^{137}Cs gamma-ray source. The experiments have been carried out by varying pressure to observe the effect on different acoustic parameters of sound waves emitted during bubble formation in superheated liquids. We have studied three different acoustic parameters of the sound wave viz. the amplitude, primary harmonic frequency and decay time constant. It is observed that with increase in ambient pressure at a given temperature, all parameters shift towards lower values. It is also observed that the increase in ambient pressure substantially reduces the number of acoustic pulses detected.

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In this paper we discuss the probable reason of acoustic parameter shifts with the change in applied pressure considering of the dynamics of microbubble growth in superheated liquids. The possible reason for the reduction of detected bubble nucleation events is also discussed here.

2. Theory

According to Seitz's thermal spike model [6], as the energetic radiation deposits energy along its path inside the superheated liquid, microbubbles are formed along the path. The bubble nucleation occurs if a microbubble reaches a critical size (r_c), and only then can the vapour bubble grow spontaneously to observable size. The energy needed to form a critical size microbubble is known as the threshold energy (W) for bubble nucleation, which varies with temperature and pressure. For bubble nucleation to occur two conditions need to be satisfied: (i) the energy deposition must be greater than W, and (ii) this amount of energy must be deposited within a certain minimum distance inside the superheated liquid. The expression for r_c and W are given in Eq. (1) and Eq. (2), respectively [2,6].

$$r_C = \frac{2\gamma}{(P_{\text{SVP}} - P)} \tag{1}$$

$$W = 2\pi r_C^2\left(\gamma - T\frac{\partial\gamma}{\partial T}\right) - \frac{4}{3}\pi r_C^3(P_{\text{SVP}} - P) + \frac{4}{3}\pi r_C^3 \rho_v h_v \tag{2}$$

Here γ is the surface tension, P_{SVP} is the saturation vapour pressure, P is the ambient pressure, T is the operating temperature, ρ_v is the saturated vapour density, and h_v is the latent heat of vaporization.

It is well known that r_c and W for bubble nucleation increase with ambient pressure at a given temperature [16]. For superheated R-12 (CCl_2F_2, boiling point −29.8 °C at atmospheric pressure) we have calculated the variation of r_c with pressure at three different temperatures (Fig. 1). When a liquid is sufficiently superheated it can be used for the detection of low LET radiations like the gamma-rays. The gamma-rays deposit energy via their secondary electrons through Coulomb interactions. The SDDs are generally insensitive to gamma-rays below a reduced superheat (s) of 0.51 at atmospheric pressure [5]. The reduced superheat is defined as

$$s = (T - T_b)/(T_c - T_b) \tag{3}$$

Here T_c and T_b are respectively the critical temperature and boiling point of the superheated liquid, and T is the detector temperature.

The bubble nucleation and the subsequent vaporization of superheated droplet occur on a time scale of few microseconds [19]. The dynamics of bubble growth in a superheated liquid and the acoustic emission are complex phenomena, which are the subject of ongoing research [20]. After nucleation, the accelerating microbubble can produce a shockwave when its growth becomes supersonic in the metastable liquid. The newly-formed bubble in the SDD can oscillate with different harmonics which appear to be triggered by the shockwave [21]. It is to be noted that in a bubble chamber [1,22], with a bulk volume of superheated liquid, the bubble nucleation and the subsequent vaporization of superheated liquid also produces acoustic emission [22]. Unlike the SDD, here the microbubble continues increasing and can vaporise the entire superheated liquid. In bubble chamber, there is no question of bubble oscillation and the acoustic emission is only due to the shockwave generated by the supersonic growth of the microbubble. In a SDD the rapid growth of the microbubble and the subsequent bubble oscillation produce a pressure pulse that spans for a few milliseconds. As has been mentioned earlier, a piezoelectric transducer can be used for the detection of this acoustic signature of bubble formation.

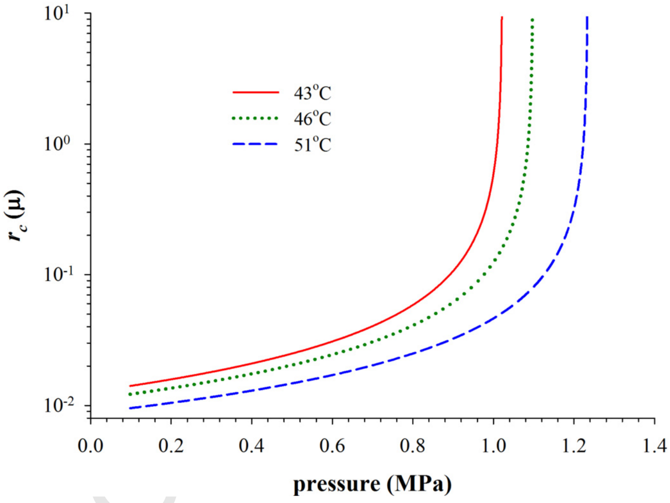

Fig. 1. For R-12 the variation of critical radius (r_c) for bubble nucleation with applied pressure at 43 °C, 46 °C, and 51 °C.

3. Experiment

The experiments were performed using an in-house designed, computer controlled high pressure manifold as shown in Fig. 2. The system is capable of pressurization up to about 4.22 MPa with a precision of ±0.01 MPa. The pressure manifold consists of a storage tank T_1 which can be pressurized by a compressed air tank connected through a solenoid valve S_1, ball valves (V_i and V_1) and a regulator (R). A needle valve is connected to the vent V_t, and a pressure gauge (PG) and a pressure sensor (WIKA R-1) read the internal pressure. The WIKA R-1 pressure sensor is coupled with this system for automated pressure readout. A LabVIEW program was used for changing the pressure by controlling the solenoid valves S_1 and S_2. A round-bottom thick-walled glass vial containing the SDD is connected to the storage tank T_1 through the ball valve V_2 and solenoid valve S_2. The experiments were performed using three different types of SDDs consisting of micron sized droplets of R-12 (CCl_2F_2, boiling point −29.8 °C at atmospheric pressure), R-134A ($C_2H_2F_4$, boiling point −26.3 °C at atmospheric pressure) and R-1216 (C_3F_6, boiling point −29.4 °C at atmospheric pressure).

The detectors were fabricated using the simple emulsification technique reported earlier in Mondal et al. [23]. In brief, first a viscoelastic gel was prepared by mixing the glycerol with commercial ultrasound gel in a suitable proportion such that it can hold the droplets in suspension. We also added a surfactant Tween 80 to the gel (0.1% of the gel by volume) to improve the detector stability. The gel was then degassed for few hours to remove the air pockets. About 200 ml of this degassed gel was placed in a pressure tight container, where a measured amount of low boiling point liquid was also transferred under pressure. The amount of liquid used varied from liquid to liquid. The gel and liquid were sheared with the help of an electric stirrer, which breaks the liquid into small droplets. After shearing, the droplets were brought to the superheated state by slowly releasing the container pressure. The emulsion was then poured into glass vials and stored in a refrigerator. The droplet size distribution can be controlled to some extent by controlling the stirring time and speed. The detectors used in this work were prepared with a stirring speed of 1400 rpm for about 10 minutes. The droplet size distributions of the different SDDs were measured using an optical microscope. For

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