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Bubble formation and interface phenomena of aqueous solution under microwave irradiation

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ABSTRACT

Water behavior during and after microwave irradiation is important phenomena for industrial applications. Recently, we reported a non-thermal effect of microwave on water surface tension. The bubble formation during microwave irradiation was suggested as one of the underpinning causes. This study examined the possibility by monitoring bubble formation during and after microwave irradiation. Moreover, the influence of NaCl on surface tension and bubble formation were also investigated. It was found that the presence of NaCl strongly increased both bubble formation and surface tension effect. The results indicated that bubble formation played an important role in surface tension reduction. The phenomena can provide useful pathways to improve the efficiency of chemical processes with microwave.

1. Introduction

Microwave has a number of advantages over the conventional heating processes. These include faster heating time and higher energy efficiency. Furthermore, microwave can be employed to produce selective heating in multiple-phase systems, i.e. water and oil mixtures. Consequently, microwave has been increasingly employed in industrial processes. In addition to thermal effects, the non-thermal effects of microwave for chemical reactions have been reported in the literature [1–4]. While the mechanism for microwave heating is well-accepted, the underpinning mechanism for non-thermal effects remains unclear and debatable [3]. The deficits in understanding are due to the experimental difficulties with microwave: the heating and subsequent cooling processes are too fast for common characterization methods. Consequently, *in situ* study during the irradiation is needed to provide critical insights into microwave effects, especially the bubble formation.

Bubble formation within aqueous solution by heating is a well-known phenomenon. In normal heating of water, vapor bubbles are formed by heterogeneous nucleation along the wall before coalescing into large bubbles (Fig. 1a). The process can be easily observed in everyday cooking. On the other hand, microwave can heat water via molecular motion [5,6]. Consequently, water molecules in the bulk can be heated and vaporized locally. Under microwave irradiation, small bubbles are formed by both heterogeneous (along the wall) and homogeneous (inside the bulk) nucleation as demonstrated in Fig. 1b. The formed bubbles can coalesce with each other or with the air/water interface. At boiling conditions, these bubbles quickly form large and visible bubbles as with normal heating process. Below boiling temperature, however, it is expected that these bubbles remain dispersed in the bulk. The behavior of such bubbles is not well understood. Specifically, the bubble growth during microwave and afterward stability have not been reported in the literature. The bubble formation has a potential application in heat transfer processes, in which localized evaporation can control the local temperature distribution. Furthermore, the homogenous nucleation of nano-bubbles and clusters of water molecules might influence surface tension. Recently, we have reported a non-thermal effect of microwave on water surface tension [7–9], which might be caused by the bubble formation.

This study aims to clarify the above phenomena through *in situ* observation in microwave reactors [7–9]. Since the lifetime of such bubbles (from formation to coalesce) is very short, the *in situ* measurement during microwave is critical. In particular, nano-bubble formation around nano-particle during and after microwave irradiation was monitored and related to the *in situ* surface tension measurement.

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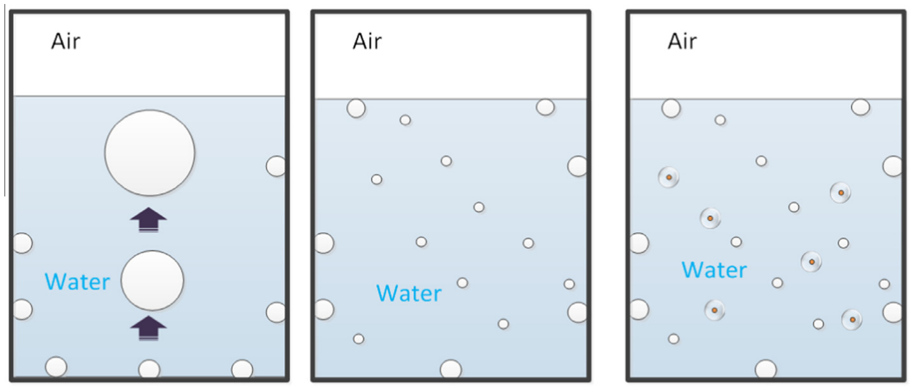

Fig. 1. Bubble formation in aqueous solution: (a) conventional heating (b) microwave and (c) microwave with nanoparticles.

2. Experimental

2.1. Measurement of bubble size

This study focuses on the formation and behavior of bubble during microwave. The suspended bubbles are governed by Brownian motion and thus is measurable by dynamic light scattering (DLS) technique [10]. Nevertheless, DLS is only efficient for particles/bubbles in sub-micrometer range. While it is desirable to investigate the heterogeneous formation, our initial test with pure water showed inconclusive data, which indicated that the free bubbles (such as Fig. 1b) were too small for effective DLS measurement. Consequently, nano-particles were employed as seeds (Fig. 1c).

Fig. 2 shows an overview of the microwave reactor [11,12]. A suspension of monodisperse polystyrene latex (PSL; 100 nm, Duke Scientific Corp.) particles was employed. The PSL particle suspension was mixed with pure water or aqueous solution of sodium chloride. Subsequently, the low density suspension was deposited into an optical quartz cell, with dimensions of 10 mm (width) × 10 mm (depth) × 40 mm (height). Suspension density was maintained at 1.8×10^9 particles/mL. The cell was placed at the center of the waveguide tube in the microwave reactor. By combining DLS with a microwave reactor, particles/bubbles movement in liquid was monitored during and after microwave irradiation. Consequently, the bubble size and diffusion coefficient were calculated. In addition to the water sample, NaCl were added to solutions of suspended particles. The concentration of NaCl in the solution varied from 0.01 to 1 M. Before the irradiation, initial size was measured and demonstrated aggregation due to the addition of salt. The aggregation size varied with the concentration.

Dynamic variations in particle/bubble size during or after microwave irradiation were measured in intervals 10–15 s. Detailed calculations have been described previously [11]. The temperature was monitored by fluorescent temperature probe throughout the experiment. Microwave, at four different power rates, was irradiated until temperature reached either 40 or 90 °C. These temperatures were selected to focus on the below-boiling conditions. Experimental conditions of salt concentration and microwave power are summarized in Table 1. It should be noted that the DLS is only applied to the central location (on horizontal plane). Consequently, the temperature was measured at the top on the same location.

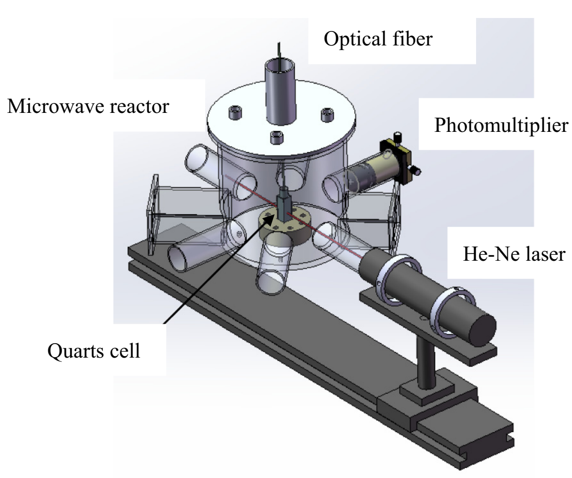

Fig. 2. Microwave reactor with DLS.

2.2. Measurement of surface tension

The surface tension was measured *in situ* using the previous setup [7]. The pendant drop was hanged at the tip of a polytetrafluoroethylene (Teflon) tube, which was placed inside the reactor. The droplet was formed via injection syringe. After the depositing the droplet, an optic fiber was inserted inside the droplet for temperature measurement. The shape of the droplet was monitored optically during and after microwave irradiation. The transient surface tension was calculated by Axisymmetric Drop Shape Analysis (ADSA) [13]. Detailed procedure and calculation have been described in previous study [7]. Experimental conditions of surface tension measurement are listed in Table 2.

3. Results

3.1. Bubble formation

Fig. 3 shows examples of the bubble size, during and after microwave irradiation. The data showed that bubble size in aqueous solution increased gradually during microwave irradiation [11]. As a result, the bubble reached the maximum size around the moment the microwave was turned off. The temperature

Table 1
Operating conditions for bubble size measurement.

Salt concentration (M)	MW Power (W)
0	30
0.01	50
0.1	70
1	100