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# Bubble formation in water with magnetite nanoparticles during microwave irradiation

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ABSTRACT

In this study, bubble formation phenomena in the dispersion medium of magnetite nanoparticle in water during microwave irradiation were investigated. From the experimental results, it was found that under microwave treatment, the maximum bubble size was greatly influenced by the suspension density at a given temperature due to the distribution of microwave energy to the particles itself or the liquid-air interface of bubbles around the particle. Nanoparticles in the dispersion medium were also found to play a key role in achieving stable nucleation of bubbles on particles surface. Smaller bubble sizes were produced at higher suspension density. Microwave power also has a positive impact on the maximum bubble size especially at low suspension density. Moreover, particle material having dielectric constant property was also found to be an important factor for bubble size during microwave irradiation. From these results and findings, it is envisaged that bubble size can be controlled by the presence of nanoparticle and microwave irradiation.

## 1. Introduction

Bubble formation has been a subject of interest of research due to extensive applications of bubbles in chemical and petrochemical industries, power plants, mineral processing, colloids engineering, pharmaceutical industries and advanced biomedical technology [1–3]. Traditionally, it has been acknowledged that bubble formation is greatly influenced by some parameters including surface morphology, thermophysical properties of solid, liquid and gas phases, gas flow rate and the geometries of nozzle [1]. Thus, studies on the effect of these parameters on the bubble formation and their mechanisms have attracted great attentions from many researchers. Nevertheless, recent reports have indicated that the presence of dispersed nanoparticles has also an impact on the bubble formation [1,2,4–10].

Studies on the boiling and bubble formation around nanoparticles were mostly conducted through conventional heating [11–15] and laser induced-heating [9,10]. For example, in the case of conductive heat transfer, bubble is produced as heterogeneous nucleation because temperature near the wall is higher. Bubble size distribution become wider because growth rate of bubble is different in heterogeneous temperature distribution. Especially, when thermal conductivity of liquid is lower, this tendency is remarkable. Moreover, rising bubbles and coalescing bubbles cause further wider distribution. Mixing process is required to enhance convective heat transfer to compensate the limitation of conductive heat transfer. However, heating rate is not necessarily enough although convective heat transfer can get homogeneous bubble size to some extent. On the other hand, microwave irradiation is attractive for quick heating response because water molecules are vibrated directly. Consequently, liquids such as water and alcohol, which have higher dielectric constant, can be heated during the microwave irradiation, and homogeneous bubble nucleation can be expected. However, the behavior of bubble formation is not well understood. Investigation on the bubble generation due to microwave heating is very scarce in the literature. In our previous study, heat transfer around PSL (polystyrene latex) nanoparticles during the irradiation was studied and bubble formations in water during irradiation were observed even at temperatures below the boiling point of water [16]. Recently, nanofluid has been attractive for higher thermal conductivity and heat capacity and we found special effect for surface tension of nanofluid by microwave irradiation [17]. However, irradiation power and the suspension density must be carefully controlled to obtain an efficient microwave effect of nanofluid because particle material used in nanofluid absorbs microwave. For example, when a solution includes particle with magnetic property, it is more difficult to avoid behaviors of local heating [18] or super heating [19] caused by heat generation during microwave irradiation. Nevertheless, the mechanism of it has been hypothesized that nanobubbles formation around catalysis during the irradiation and higher energy or free radical

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produced by the bubble collapse are influencing factors for rapid chemical reaction and decomposition of hardly decomposable matter in microwave process [20–22]. Therefore, this work aims to study the effects of suspension density of magnetite nanoparticle and irradiation power on the bubble size during the irradiation. It is expected that the results and new findings from bubble size profiles will be useful in explaining the special phenomena in process with nanoparticles under microwave irradiation.

## 2. Experimental

### 2.1. Material

In this study, suspensions of monodisperse magnetite particle, $Fe_3O_4$, with particle size of 100 nm was used. This particle was obtained from Micromod Corp., Japan, and the average size and mono-dispersed property were guaranteed in good qualities. Therefore, experiments could be carried out by varying suspension density.

### 2.2. Methods

Experiments were carried out in a microwave reactor (Micro Denshi Co., Ltd., model) equipped with a Dynamic Light Scattering (DLS) system as shown in Fig. 1 [16]. Distilled water was added to the magnetite particle suspension, and this low-density suspension was then poured into an optical quartz cell (10 mm x 10 mm x 40 mm; 4 mL). This cell was placed in a sample holder made of polyether ether ketone resin at the center of the waveguide tube inside the reactor. The position and angle of the holder were adjusted against the pathways of a He-Ne laser and scattered light detector [16]. A fluorescent temperature probe (Anritsu Meter Co., Ltd., FL-2000; Optical fiber: FS100-M) was used to measure the temperature near the surface throughout the experiment. When the laser irradiated a sample containing nanoparticles or bubbles, the light was scattered. The amount of scattered photons was counted by a photomultiplier (Hamamatsu Photonics Co., Ltd., model) and the bubble size was then calculated using a time-averaged autocorrelation function of the photon count. Detailed DLS theory and procedure have been described previously [16]. Before the irradiation, the initial value was confirmed to be its primary size and no aggregation was observed. Changes in particle size during and after microwave irradiation were observed every 10–15 s. During the experiments, suspension density and irradiation power were varied to investigate the effect of microwave irradiation on the profiles of bubble size. Microwave treatments were carried out until the temperatures reached the values of 40 °C and 90 °C, respectively. Since volume of the particles is much less than of water, time required to irradiate and heat the particles is negligible and the irradiation time is assumed to be the time required to irradiate and heat the water. Table 1 summarizes the operating conditions of the experiments. If final particle size became larger due to the aggregation, the change of suspension density by sedimentation must be carefully observed and controller. However, after the experiment it was confirmed that the size profile returned to the original value. Moreover, sintering never happens because the irradiation power is not too high in this experimental condition. Accordingly, size profile, which is larger than initial size, should be bubble formation. In addition, because similar size was obtained for cooled boiling water, bubble should be generated at non-thermal equilibrium condition for microwave heating [18].

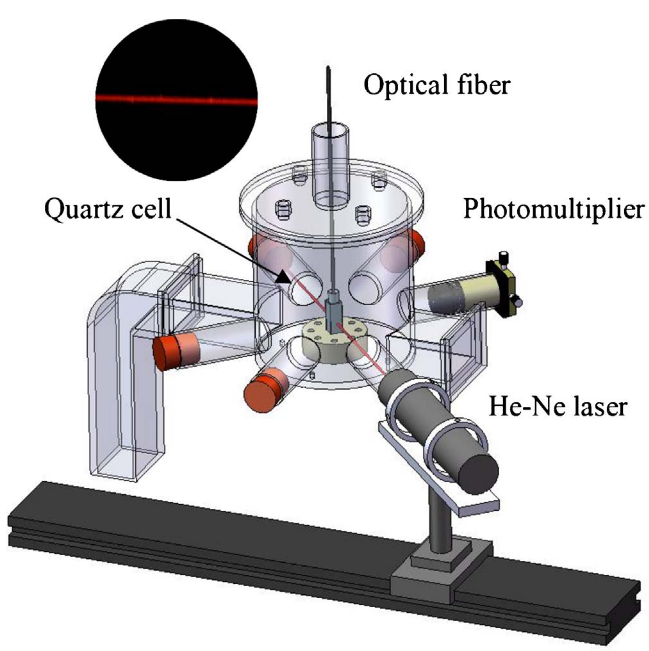


**Fig. 1.** Microwave reactor with DLS.

**Table 1**
Operating conditions of the experiments.

| No. | Irradiated microwave power [W] | Irradiation time [s] | Suspension density x $10^9$ [particle/mL] |
|---|---|---|---|
| 1 | 30, 50, 70, 100 | Time required to reach 40 °C (83, 48, 34, 28) | 1.8, 3.6, 7.2 14.4 |
| 2 | 30, 50, 70, 100 | Time required to reach 90 °C (299, 147, 93, 67) | 1.8, 3.6, 7.2 14.4 |

## 3. Results and discussions

Fig. 2 shows bubble size and temperature in the suspension during and after microwave irradiation. Solid fill and unfilled symbols indicate sizes during and after microwave irradiation, respectively, and the lines represent the dynamic behaviors of the temperature. During microwave irradiation, temperatures and bubble sizes increase as a function of time. When the temperature reached 40 °C or 90 °C, which is below the boiling point of water, the microwave was switched off where temperature gradually dropped afterward maximum bubble sizes were achieved around the time when the microwave was turned off, after which the bubbles sizes steadily decreased.

The maximum bubble sizes were plotted against the irradiation power and suspension density in Figs. 3 and 4. The effects of various microwave power and suspension densities on the maximum bubble sizes were shown at lower maximum temperature (40 °C) and higher maximum temperature (90 °C). From these figures, it can be observed that suspension density, microwave power and temperature greatly influence the bubble size. Thus, the underlying mechanisms of bubble formation under microwave irradiation are proposed as follows. Bubble formations due to vibrations of water molecules mostly occur on the surface of particle. This is due to weaker molecular force at the interface than that of bulk [16]. When microwave continuously irradiates, the role of heat generation by the absorbance cannot be neglected. When suspension density is lower, microwave absorbance per one particle is higher. At higher suspension density, microwave energy, which is used for the vaporization, is distributed to more particles and their surroundings. Consequently, larger bubbles were generated at lower suspension density due to concentration of microwave irradiation on the liquid-air interface and particle. Thus, it can be deduced that different bubble sizes can be generated from suspensions with different densities even when the microwave heating occurs at the same temperature. This behavior may be related to non-equilibrium local heating [18] or super heating [19] where apart from physical properties such as dielectric constant and dielectric loss, suspension density plays an important role. From Figs. 3 and 4, it is also apparent that variations of microwave