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# Surface tension profiles of nanofluid containing surfactant during microwave irradiation

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**Abstract.** Manipulation of the surface tension is useful in improving heat and mass transfer performances of nanofluids in thermal systems. In our previous study, the effect of microwave irradiation on the reduction of surface tension of nanofluids ( $\text{Fe}_2\text{O}_3$ ) was found even after it was turned off. In this study, a synergistic effect of microwave irradiation and surfactant addition (SDS) was investigated to obtain further surface tension reduction of nanofluid. Experimental results indicate that surfactant addition is effective for wider particle number density in reducing surface tension, and the reduction level strongly depends on the surfactant concentration. On the other hand, effect of the number density on the surface tension reduction is less significant for the same concentration of surfactant. From the obtained data, a combination of microwave irradiation and surfactant addition shows potential to be used as a promising method to manipulate surface tension of nanofluids.

## 1. Introduction

Nanofluids, which are the suspensions of nano-sized particles in base fluids, have been reported to possess enhanced heat transfer and mass transfer coefficients in improving heat and mass transfer systems. Calculations and analyses of these systems operated with nanofluids are regulated by key physical properties and one of these main properties is surface tension. Surface tension determines the shape of the liquid droplets and consequently, heat and mass transfer across interfaces are strongly influenced by surface tension. Therefore, lower surface tension is attractive for promoting higher critical heat flux and boiling rate [1-4] and gas-liquid mass transfer especially in packed bed systems [5,6].

In our previous study [7], microwave memory effect on the surface tension of nanofluid was found for long period of time in which lower surface tension due to microwave treatment could be obtained even after the microwave was turned off. From the experimental data, it was also concluded that irradiation power and time are key factors to obtain better microwave effect. However, higher irradiation power and longer irradiation time are not desirable since they may degrade the nanofluids due to sintering of nanoparticles under superheated condition. Therefore, manipulation of surface tension using microwave irradiation should be carried out under medium operating condition to maintain nanofluid properties.



Manipulation of surface tension can also be performed by adding a chemical additive called surfactant. Surfactant addition has also been acknowledged in enhancing boiling heat transfer [8-10] and improving stability of nanoparticles in aqueous suspensions [11,12]. Nevertheless, there has no study in the literature on the synergistic effect of microwave irradiation and surfactant in reducing surface tension of nanofluid at medium operating conditions. This study, therefore, aims to investigate this synergistic effect with a hypothesis that combined benefits from surfactant addition and microwave memory effect will be able to give better reduction of surface tension.

## 2. Experimental

### 2.1. Materials

Fe<sub>2</sub>O<sub>3</sub> nanoparticle-water system was selected as a nanofluid in this study. The solution containing surfactant, SDS (sodium dodecyl sulphate) was prepared by dispersing nanoparticles in distilled water at different concentrations of nanoparticles and surfactant. Fe<sub>2</sub>O<sub>3</sub> with diameter of 15 nm and SDS were obtained from Kanto Chemicals Co., Japan.

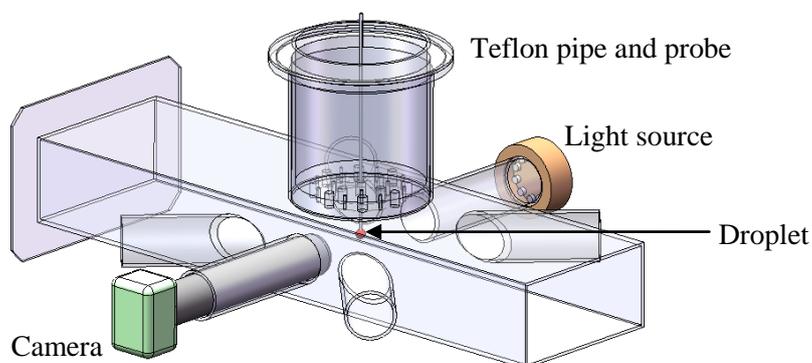
### 2.2. Apparatus

Fig. 1 shows the microwave apparatus, which was designed by Shikoku Instrumentation Co., Inc., Japan. Pendant method was employed for the measurement of surface tension of nanofluids [7]. Teflon pipe with the dimensions of 1 mm inside diameter and 2 mm outside diameter was used to hang the droplet. Nanofluid was introduced through the pipe by injection using syringe [13,14].

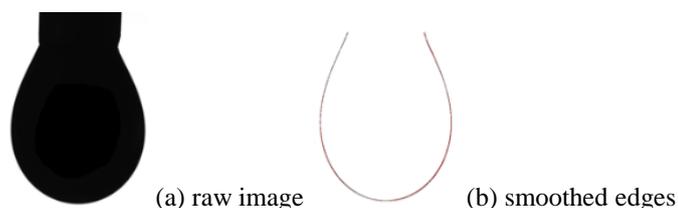
Temperature sensor (model: FL-2000 Optical fiber: FS100-M), was used to measure the droplet temperature during and after microwave irradiation. This probe was inserted from the top of the reactor through the Teflon pipe after the droplet was hung. High speed camera (Sigma Koki Co., LTD Model SK-TC202USB-AT) was installed at the side of the reactor to capture the shape of the droplet. Experimental conditions of the surface tension measurement are listed in Table 1. At moderate conditions, microwave power of 300 W and irradiation time of 120 s [7], the effects of suspension density and surfactant concentration on the surface tension were investigated. Surfactant concentration was normalized by critical micelle concentration (CMC). However, surface tension measurement of nanofluids with concentration near CMC was impossible because it was difficult to hang the droplet. In addition, the measurement of droplet with higher suspension density (1 wt%) was not conducted because particles remains at the bottom of droplet.

### 2.3. Analytical method

Axisymmetric drop shape analysis (ADSA) was employed to measure surface tension by analyzing the edge profiles of the droplet [15]. Fig. 2 shows an example of raw image and the fitting results. ADSA software estimates the surface tension by fitting the whole droplet profile (Fig. 2(b)). Detailed procedure of shape analysis has been described previously [13].



**Figure 1.** Microwave apparatus for surface tension measurement.



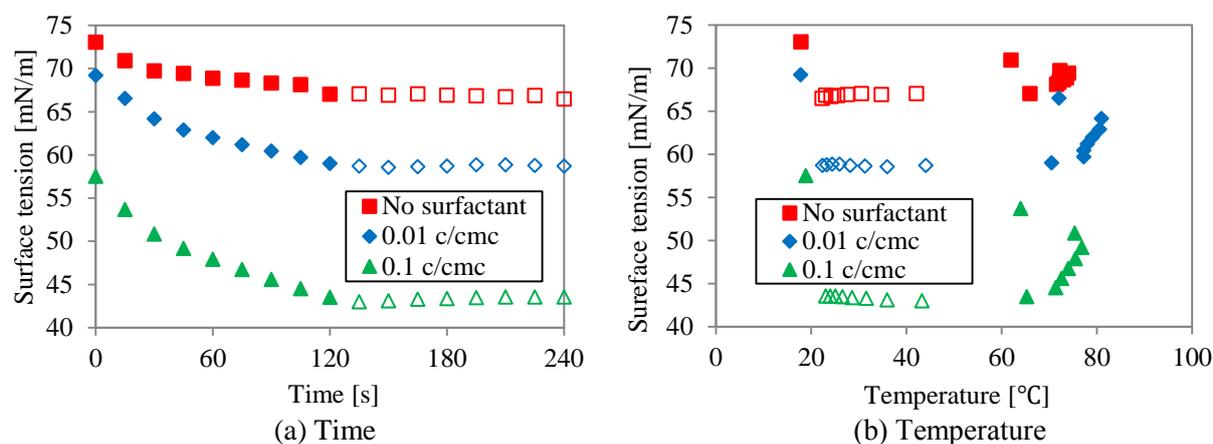
**Figure 2.** ADSA method for surface tension measurement.

**Table 1.** Experimental condition

No.	Suspension density [wt%]	Surfactant conc. [c/cmc]
1	0.01	0, 0.01, 0.1
2	0.001, 0.01, 0.1	0.1

### 3. Results and discussions

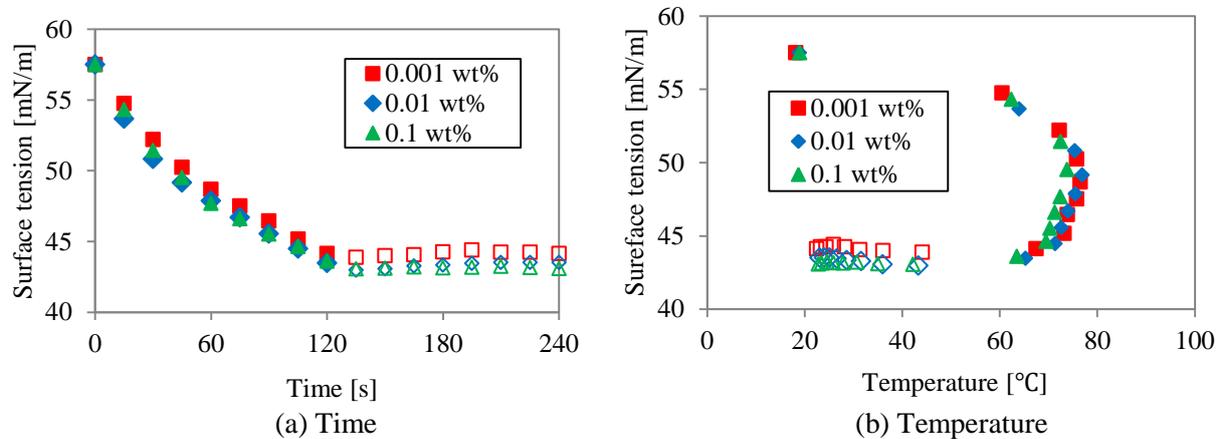
Fig. 3 shows surface tension profiles of nanofluids containing surfactant during and after microwave irradiation as a function of time and temperature for the experimental condition 1. Solid and unfilled symbols indicate data during and after the irradiation, respectively. Generally, surface tension during the irradiation decreased with the time because of temperature rise. Initial surface tensions were different depending on the concentrations of added surfactant. From Fig. 3(b), it is obvious that reduction levels of surface tension vary concentrations of surfactant even though maximum temperatures achieved during irradiation were approximately the same. This points out that higher surfactant concentration in the nanofluid resulted in much better surface tension reduction after microwave was turned off.



**Figure 3.** Surface tension profiles at different surfactant concentrations.

The mechanism of surface tension reduction is not well-understood. However, nanobubble formation is hypothesized as a driving force of surface tension reduction after microwave was switched off. Nanoparticle absorbs microwave very well, and the heat generation causes abrupt temperature rise of the solvent around nanoparticles. Then, bubbles are rapidly generated because of the evaporation [14,16]. These nanobubbles became more stable because surfactant molecules are adsorbed on the liquid-air interface. As a result, nanobubbles interrupt the tension along the interface. Fig. 4 shows surface tension of nanofluid at different suspension densities (experimental condition 2). From this figure, the effect of suspension density on the reduction of surface tension tends to be

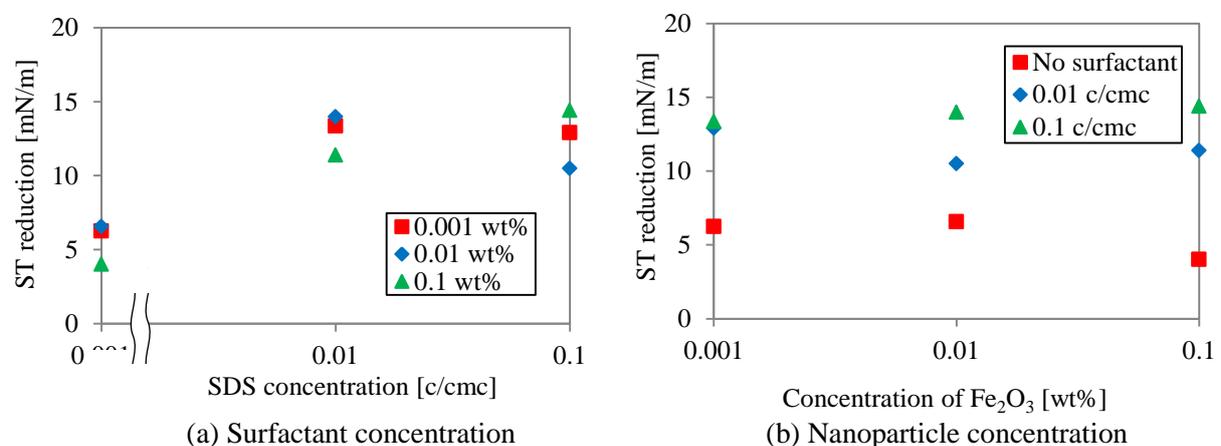
neutral. This insignificant effect may indicate that the reduction is mostly influenced by addition of the surfactant.



**Figure 4.** Surface tension profiles at different suspension densities.

Fig. 5 summarizes surface tension reductions extracted from Figs. 3 and 4. Effect of surfactant additions under microwave irradiation was relatively saturated at around 0.01 c/cm<sup>c</sup> as shown in Fig. 5(a). Results in Fig. 5(a) also indicate that higher concentration near CMC (more than 0.01 c/cm<sup>c</sup>) is not necessarily effective. It means that 0.01 c/cm<sup>c</sup> is an optimum concentration for reducing surface tension of nanofluid. In our previous study, surface tension reduction of nanofluids was around 5 mN/m when surfactant was not added. From Figs. 5(a) and 5(b), it is evident that better surface tension reduction (up to 10 mN/m) of nanofluid with higher suspension density by microwave irradiation can be possibly achieved at moderate surfactant concentration.

The underlying mechanism on surface tension reduction by microwave irradiation is still unclear. Nevertheless, it may be explained as follows. When water is used as a base fluid, the reduction may be driven by “microwave memory effect” [13,16]. Microwave is absorbed at the interface and consequently polar molecules heavily vibrate. Clusters of hydrogen bonds or nano-bubbles were hypothesized as one of reasons. The presence of nanoparticle in water further enhances the microwave energy absorbance. This absorbance greatly influences the surface tension [17] and causes a new conformation of molecules network [18]. Surfactant itself is adsorbed at liquid-air interface of the cluster and nano-bubble during the irradiation. These absorptions further contribute stability of the interface. As shown by Figs. 3(a) and 4(a), the surface tension reduction by the irradiation lasts for an extended period of time when nano-fluids includes surfactant.



**Figure 5.** Surface tension reduction after microwave was turned off.

#### 4. Conclusions

Surface tension of Fe<sub>2</sub>O<sub>3</sub> nanofluid containing surfactant during and after microwave irradiation was investigated at different surfactant concentrations and suspension densities. From the experimental data, it is apparent that a combination of microwave irradiation and surfactant addition is effective to give significant surface tension reduction. Experimental results also indicate that surfactant addition is effective for wider particle number density in reducing surface tension, and the reduction level strongly depends on the surfactant concentration. On the other hand, effect of the number density on the surface tension reduction is less significant for the same concentration of surfactant.

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