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Surface tension and oscillation of water droplet under microwave radiation

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ABSTRACT

Surface tension of fluids is an important factor controlling multiphase systems and is often manipulated by surfactants during industrial processes. Previously, we have found that water surface tension was reduced under continuous microwave irradiation. The reduction was not explainable by thermal effects. The new insights can lead to important application of microwaves in multiple-phase systems. In this study, effect of various microwave irradiation modes on surface tension of water was investigated. The surface tension reduction was confirmed for pulsed microwave irradiation. The reduction varied with the applied power as well as interval between irradiations. The droplet oscillation and internal convection were also investigated during and after microwave irradiation to clarify the mechanism. It was found that the convection within the water droplet was proportional to the microwave power. In contrast, the frequency of oscillation was independent on the microwave power. These results on surface tension, oscillation and convection will provide important insights for designing microwave applications.

1. Introduction

Microwave has been used extensively in domestic appliances, which replace the traditional heating method. Heating by microwave is more energy efficient and convenient than traditional methods. The microwave can be applied to the industrial processes as well. For multiple phase systems, such as emulsion and foaming, microwave can have selective impact: it significantly influences aqueous phase while has negligible impact on air or oil phase. In addition to heating effects, the applied microwave can have specific benefits for chemical reactions. The influences of microwave irradiation for chemical processes, such as emulsification and polymerization, have been reported in the literature (Kuhnert, 2002; Nüchter et al., 2004). However, the underpinning mechanism remains unclear. In addition to bulk effects, it is expected that microwave can have a finite impact on the interfaces of the multiple-phase systems. Yet, quantifying the microwave influences on the interfacial properties remains a challenging problem.

Amongst the physical properties of the interfaces, the surface tension is an important property which determines operations of chemical engineering processes. Previously, we have quantified the influence of microwave on surface tension of a water droplet (Asakuma et al., 2014; Parmar et al., 2014), in which water tension remains low after the irradiation. This was the first time the in situ surface tension under microwave was reported. The lasting influence on surface tension was independent on heating effect (Parmar et al., 2014). This study investigates the influence of various microwave irradiation modes, i.e. pulsed irradiation, to provide further insights into the phenomenon.

In addition to surface tension, microwave also influences the mechanical behavior of aqueous droplets. Temperature

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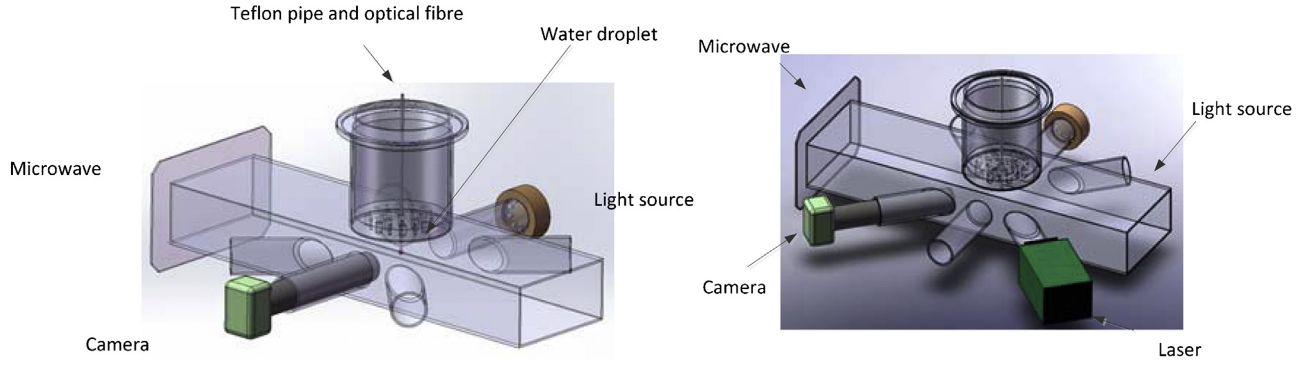


Fig. 1 – Microwave reactor with CCD camera for (a) surface tension measurement and (b) PIV study.

Table 1 – Experimental conditions for surface tension.

No.	MW power [W]	Total time [s]	Mode ("on" and "off" time)	Cycle	Energy [J]
1	150	240	Continuous (240 s, 0 s)	1	36,000
	300	120	Continuous (120 s, 0 s)		
	600	60	Continuous (60 s, 0 s)		
2	600	120	Pulse (30 s, 30 s)	2	36,000
			Pulse (15 s, 15 s)	4	
			Pulse (10 s, 10 s)	6	
3	600	120	Pulse (30 s, 30 s)	2	36,000
		100	Pulse (30 s, 20 s)	2	
		80	Pulse (30 s, 10 s)	2	

rises by microwave irradiation can leads to a higher evaporation rate, thermal expansion and internal convection within the water droplet. For small droplets, the convection and thermal expansion might affect the interfacial properties. The microwave-controlled convection can provide an attractive non-contact mixing in comparison to conventional ultrasound (Katou et al., 2005). Moreover, natural oscillation of the suspended droplet (such as pendant drop and levitated drop) always exists and its frequency can be related with surface tension as predicted by Rayleigh's theory (Rayleigh, 1878). The influence of microwave on the oscillation of a small droplet has not been quantified.

This paper investigates the influence of microwave on water droplet behavior. In addition to surface tension measurement, the oscillation is studied by a high-speed camera and convection is monitored by Particle Imaging Velocimetry (PIV). The new results can provide important insights for designing microwave applications in multiple-phase systems.

2. Experimental

2.1. Surface tension

Fig. 1 is the schematic diagram of the microwave reactor (designed and build by Shikoku Instrumentation Co., Inc.). Pendant drop method (Fig. 1(a)) was employed for the surface tension measurement. A Teflon pipe with the dimension of 1 mm inside and 2 mm outside diameter was used for the experiment. A water droplet, with volume ~20 μL, was produced via the syringe. Temperature inside the droplet was monitored with a temperature probe, designed by Anritsu meter Co., LTD (device model: FL-2000 Optical fiber: FS100-M). The temperature probe was inserted from the top of the reactor and can monitor the temperature inside the droplet during and after microwave irradiation. The different microwave modes, either continuous or pulsed, were applied. The experimental conditions of microwave irradiation are tabulated in Table 1.

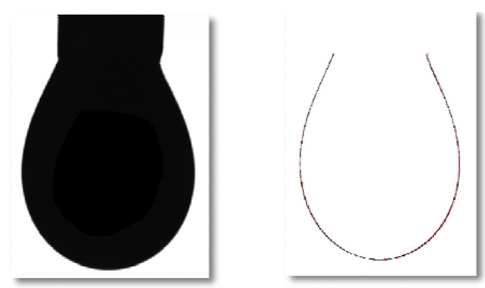
Light source was used from one side of the droplet and camera at 15 fps (Sigma Koki Co., LTD Model SK-TC202USB-AT) was employed from opposite side to capture the shape of the droplet. Experiments analysis consisted of two parts:

1. Confirmation of initial surface tension of water droplet before microwave irradiation.
2. Capture of the images during and after microwave irradiation.

Axisymmetric drop shape analysis (ADSA) in Fig. 2 was employed to measure the surface tension from the shape of the droplet (Zuo et al., 2004). Droplet volume was calculated from the shape by the software at the same time.

2.2. Droplet oscillation

For oscillation, the pendant drop was used produced using the same setup for surface tension measurement. The droplet shape was recorded at 300 fps using a high-speed camera (K-ILEX, KATO KOKEN CO., LTD) for 6 s during and after microwave irradiation. Subsequently, the bottom interface of droplet was



(a)Drop profile (b)Smoothed edges

Fig. 2 – ADSA method for surface tension measurement.