International Journal of Heat and Mass Transfer xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Study on heat and mass transfer of droplet cooling in ultrasound wave

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ARTICLE INFO

Article history:
Received 27 May 2016
Received in revised form 31 October 2016
Accepted 1 November 2016
Available online xxxx

Keywords:
Mass transfer
Ultrasound
Heat transfer

ABSTRACT

The application of ultrasound to liquid freezing has focused growing attention over the last few years and its potential seems very promising. In order to make clear droplet freezing assisted by ultrasound, the heat and mass transfer characteristic was studied based on ultrasound theory, penetration theory of mass transfer and energy conservation. The results showed that ultrasound could accelerate mass transfer and make droplet rapid cooling. In the effect of ultrasound, bubble size in the droplet was decreased with ultrasound frequency, and bubble number in the droplet was increased with ultrasound frequency. Mass transfer coefficient of droplet was increased with ultrasound intensity and reduced with ultrasound frequency. For the mass transfer and heat transfer direction were same in the droplet freezing process, the heat transfer was strengthened by mass transfer in the droplet freezing process. Comparing with no ultrasound, droplet temperature with ultrasound was lower 2.0°C–2.5 °C after the same time. Hence the ultrasound helps to cool and freeze droplet.

1. Introduction

It is well known that freezing assisted by ultrasound is gradually used in food engineering, ice making and medical science [1–3]. Ultrasound can cause cavitation effect which induces bubbles inside liquid. When the bubbles escape from the liquid surface, the mass transfer is intensified. By the mass transfer, heat transfer at the surface is improved. It is helpful for liquid cooling and freezing. Some studies have been done on ultrasound-induced crystal nucleation of ice in water. Yu [4] analyzed the effect of ultrasound on nucleation, and cavitation was major factor for sonocrystallisation of ice. Based on moving boundary vapor diffusion, one-dimensional model was described the ultrasound assisted atmospheric freezing-drying of foodstuffs by Santacatalina [5]. It revealed that the most relevant operating parameter affecting the drying time was ultrasound power level. Naji [6] presented a mathematical model to simulate growth characteristics of a single bubble in liquid. The results showed that bubble growth mainly was affected by ultrasound pressure amplitude. Saclier [7] analyzed the empirical correlations between final frozen product ice crystals' characteristic and ultrasound assisted freezing operation conditions. It was found that increasing supercooling and acoustic power resulted in decreasing ice crystals' mean size. Inada [8] experimentally studied the use of ultrasound vibration to control the phase change from supercooled water to ice, and simulated phase change. It showed that ultrasound vibration was mainly factor to control phase change. The other researchers [9–12] clarified different factors that influenced phase change from supercooled water to ice and tried to realize methods to control freezing temperature. Effect of ultrasound on both crystal structure and kinetics of palm oil crystallization were studied by Patrick [13]. Modeling and simulation of ice nucleation triggered by acoustic was studied by Saclier [14]. The results showed that nucleation could be initiated with moderated acoustic pressure amplitude. According to study [15], the moderate oscillation of bubble may induce ice nucleation. Zhang [16] noticed that water, when supercooled at −1 °C and subjected to an ultrasound exposure during 9 s, had a phase change probability increasing from 0.18 to 0.75. Gondrexon [17] presented experimental results focused on heat transfer intensification and enhancement of ultra filtration by ultrasound. However, the theory model and analysis was not given.

The above literatures presented different explanations about freezing assisted by ultrasound. They included the role of the ultrasound in the freezing-drying, single bubble growth, phase change, crystal structure etc. However, the analyses considering ultrasound frequency, ultrasound intensity and ultrasound power together into droplet freezing was not presented, in which the heat and mass transfer model was also not given.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.11.002
0017-9310/

Nomenclature

P_A	ultrasound amplitude (Pa)	I	ultrasound intensity (W/m^2)
t	time (s)	C	sound velocity (m/s)
f	ultrasound frequency (Hz)	S'	interface area in the effect of ultrasound (m^2)
ρ	medium density (kg/m^3)	γ	kinetic viscosity (N·s/m^2)
P	ultrasound power (W)	P_h	static pressure of liquid (Pa)
R	radius (m)	D	mass diffusion coefficient (m^2/s)
σ	surface tension (N/m)	S_L	total surface of droplet (m^2)
N	bubbles numbers	T	temperature (K)
ϕ	surface renewal ratio	c_p	specific heat at constant pressure (J/(kg·K))
λ	thermal conductivity (W/(m·K))	V	volume of droplet (m^3)
a	acoustic absorption coefficient	q_m	quantity of heat by mass transfer (W)
ρ	liquid density (kg/m^3)		
q_h	quantity of heat by convection (W)	*Subscripts*	
q_u	quantity of heat by ultrasound heat effect (W)	d	droplet
ω	acoustic angular frequency (rad/s)	a	environment
p_a	pressure on medium (Pa)		

In this paper, in order to make clear droplet freezing assisted by ultrasound, the heat and mass transfer characteristic were studied based on ultrasound theory, penetration theory of mass transfer (Higbie, 1935). It states that diffusion is unsteady state process and the molecules of the solute are in constant random motion, where clusters of these molecules arrive at the interface, remaining there for a fixed period of time, and some of them penetrate while the rest mixes back into the bulk of the phase) and energy conservation. The mass transfer in the process was analyzed in different ultrasound intensity and ultrasound frequency. The droplet temperature variation was given under effect of ultrasound. Some photographs were contrasted for droplet freezing with ultrasound and without ultrasound. This study would be beneficial to understanding the effect and mechanism of ultrasound in liquid freezing.

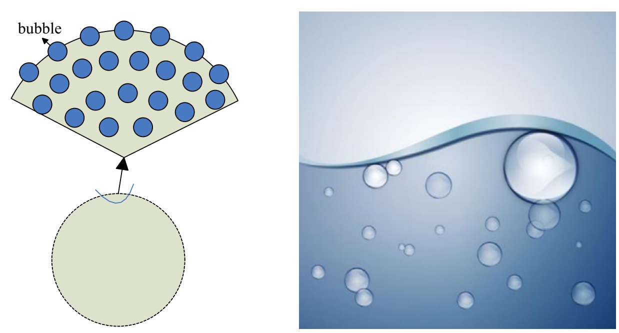

Fig. 2. Bubbles escaping from liquid surface.

2. Physical model and formulation

The droplet in ultrasound is different from ordinary state (there are very few bubbles without ultrasound), because ultrasound bubbles in liquid are produced by ultrasound that intensify the surface renewal. The diagram is shown in Fig. 1. The bubbles are easy to escape from the droplet surface with ultrasound because the surface tension is decreased with ultrasound. In the bubble escaping process, the mass transfer is intensified. Hence, the surface of droplet under effect of ultrasound would be more suitable for mass transfer than normal state. The bubbles escaping from liquid surface is shown in Fig. 2. The bubbles produced by ultrasound intensify surface renewal and mass transfer of liquid surface.

With considering the bubbles caused by ultrasound, distribution of bubbles inside droplet is deemed as be uniform and shape of droplet is deemed as be spherical when analyzing heat and mass transfer. When ultrasound is travelling in liquid, interaction between ultrasound and medium depends on cavitation. Cavitation is formation of cavities, which is the consequence of forces acting upon medium. Burdin [18] studied the cavitation bubble cloud at 20 kHz of ultrasound, and presented the size and volumetric concentration of acoustic bubbles. It usually occurs when medium is subjected to pressure change that causes the formation of cavities. When subjected to higher pressure, the voids may be more easily fragmented. When subjected to lower pressure, the voids may be developed. Through the periodic process, the cavitation is produced. For liquid with ultrasound, a large number of bubbles are produced by ultrasound cavitation. In this process, pressure on medium by ultrasound is shown as follows,

$$P_a = P_A \sin \omega \cdot t \tag{1}$$

(a) with ultrasound (b) without ultrasound

Fig. 1. Droplet state under effect of ultrasound and un-ultrasound.

Please cite this article in press as: P. Gao et al., Study on heat and mass transfer of droplet cooling in ultrasound wave, Int. J. Heat Mass Transfer (2016), http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.11.002