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Study on mechanism of bubble growth within a water droplet under rapid depressurization

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ABSTRACT

This paper reports an experimental and numerical study on mechanism of bubble growth within a water droplet under rapid depressurization. During the experiments, a distilled water droplet was suspended on a thermocouple, which was also used to measure the droplet temperature. A high speed camera was applied to record the bubble expansion. Two mathematical models were developed to describe the bubble growth process. The mass diffusion model considered the bubble growth related to the mass diffusion of nitrogen dissolved in the droplet during pressure drop, and the model was based on the momentum equation of bubble growth coupling with the diffusion equation within the liquid phase. The heat transfer model considered that the droplet superheating resulted in bubble growth. Both of the models considered the influence of thermocouple suspension mode on bubble growth, and a simplified treatment was applied by introducing a friction coefficient. During our experiments, the duration times for bubble growth were mostly 4–8 ms. The verification of mathematical models was achieved by comparing the numerical results with the experimental data. The result shows that the numerical bubble radii calculated by the heat transfer model agree well with the experimental measurement. Through numerical calculations, the factors of pressure difference, droplet diameter and thermocouple suspension mode on bubble growth were analyzed. The results provide insight into the dynamic of bubble growth within a water droplet under rapid depressurization.

1. Introduction

The bubble growth within a droplet during rapid depressurization plays an important role in diverse fields such as spray and atomization, polymer processing and glass refining. There are two mechanisms for bubble growth under pressure drop. The first mechanism considers bubble growth related to mass diffusion. Initially, a certain amount of gas dissolves in liquid. When the ambient pressure decreases rapidly, the solubility of gas becomes smaller. Then gas releases and forms bubble nucleation, the bubble grows gradually depleting the gas and induces a concentration gradient in liquid.

Many experimental and numerical researches have been carried out to study the bubble growth in liquid containing dissolved gas. Payvar [1] developed a mass transfer-controlled model to describe the bubble growth in a liquid during rapid decompression. Arefmanesh [2] numerically studied the mass diffusion-induced growth of a spherical gas bubble surrounded by a viscous Newtonian liquid based on potential theory. The concentration profile of the dissolved gas in the liquid was obtained. Taki [3] numerically investigated bubble nucleation and growth for a batch physical foaming process of PP/CO_2 system under finite pressure release rate. The bubble growth of CO_2 was caused by over saturation due to pressure drop, and the fluid of polymer matrix was assumed to be a Newtonian fluid with constant viscosity.

The bubble growth process was divided into three periods: viscosity-controlled, transition, and diffusion-controlled. During the first stage, the bubble radius almost maintained unchanged, they analyzed the large viscosity of liquid suppresses the bubble growth, which they called Viscosity-controlled period. Ban [4] developed a model to simulate the bubble nucleation and growth of dissolved CO_2 in water across a cavitating nozzle, which coupled bubble dynamics, mass transfer and hydrodynamics. It was found that the bubbles nucleated at the throat of the nozzle and grew along with the flow. Tuladhar [5] experimentally and numerically studied the bubble growth within a pentane loaded molten polystyrene sample achieved by pressure release. A modified Newtonian model incorporating gas diffusion was developed and numerical results were compared with the experimental data. Ammar [6] used a simplified one-dimensional model to investigate the pressure controlled growth of bubbles in fixed-volume

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Nomenclature

A	contact area between thermocouple and liquid (m^2)
c	gas concentration (kg m^{-3})
C_D	friction coefficient
D	diffusion coefficient (m^2 s^{-1})
D_0	initial droplet diameter (m)
h_{fg}	latent heat of vaporization (J kg^{-1})
k_h	Henry's law constant (Pa m^3 kg^{-1})
M	molecular weight (kg mol^{-1})
$\dot{m}$	mass vaporization rate (kg s^{-1})
P_∞	ambient pressure (Pa)
P_g	gas pressure (Pa)
P_l	liquid phase pressure at droplet surface (Pa)
$P_s(T_s)$	saturation pressure corresponding to droplet surface temperature (Pa)
P_V	saturation pressure corresponding to bubble interface temperature (Pa)
r_B	bubble radius (m)
r_c	critical radius (m)
r_s	droplet radius (m)
R	universal gas constant (J mol^{-1} K^{-1})
R_g	gas constant (J kg^{-1} K^{-1})
R_V	gas constant of vapor (J kg^{-1} K^{-1})
T_∞	ambient temperature (K)
T_B	bubble interface temperature (K)
T_l	liquid phase temperature (K)
T_{N0}	nucleation temperature (K)
V_B	bubble growth velocity (m s^{-1})
V_s	droplet growth velocity (m s^{-1})

Greek symbols

α_l	liquid thermal diffusivity (m^2 s^{-1})
μ_l	dynamic viscosity (Pa s)
λ_l	liquid phase thermal conductivity (W m^{-1} K^{-1})
ρ_l	liquid density (kg m^{-3})
ρ_V	vapor density (kg m^{-3})
σ	surface tension (N m^{-1})

microchannels. The results showed that with a fixed volume, bubble growth increased the system pressure, and the increased pressure decreased the diffusion drive, which inhibited bubble growth. A nonlinear equation for system pressure was derived relating these coupled effects. Barlow [7] developed a mathematical model to describe single bubble growth in free rising, non-reacting polymer foam irradiated by an acoustic standing wave. The results showed that increasing acoustic pressure leaded to a reduced steady state bubble volume. Zhang [8] theoretically investigated the mass transfer during radial oscillations of gas bubbles in viscoelastic mediums under acoustic excitation. The influences of several parameters such as shear modulus, saturation condition and viscosity on mass diffusion across bubble interfaces were discussed.

The other mechanism considers liquid superheating caused by pressure drop results in bubble growth. Rayleigh [9] first proposed a momentum conservation equation to describe the bubble growth process in superheated liquid. Plesset and Zwick [10] considered the bubble growth process as a heat transfer problem coupled with a dynamic problem. An energy conservation equation was introduced, and a thin thermal boundary layer assumption was applied to solve the heat transfer problem. Donne and Ferranti [11] solved the momentum equation and the energy equation by abandoning the thermal boundary assumption. Lien [12] experimentally and theoretically studied the bubble growth rate in water at reduced pressure. He found that the dynamic effect is of increasing importance with decreasing pressure.

Most of studies have been performed on bubble growth in superheated liquid, while the researches on bubble growth within a droplet are limited. Shephered [13] experimentally explored the transient processes when a single droplet of butane at the superheat limit by immersing it in high temperature ethylene glycol. Short-exposure photographs measurement was used to record the complete explosion process. Then Shusser [14] established a mathematical model to describe the vapor bubble growth within a droplet during explosive boiling. His numerical results were verified by the experimental data of Shepherd [13]. Satoh [15] and Liu [16] experimentally investigated the flash evaporation of a water droplet due to rapid depressurization. It was found that bubble may occur within the droplet during flash evaporation, and the bubble growth and burst accelerated droplet cooling. Lv [17] numerically simulated cavitation bubble expansion within the diesel droplet based on the volume of fluid (VOF) method, and the control mechanism of bubble growth process were analyzed by Rayleigh-Plesset equation. In our previous study [18], the bubble growth processes within a superheated water droplet and in superheated liquid due to rapid depressurization were numerically compared. However, due to the small scale of droplet and the rapid expansion of bubble, the detailed experimental description of bubble growth with time is lacked. Therefore the numerical results have not been compared with the experimental data.

In this paper, the bubble expansion within a water droplet was recorded by a high speed camera during depressurization. The droplet was suspended by a thermocouple, which was also used to measure the temperature variation. Then two mathematical models were established to describe the bubble growth based on mechanisms of mass diffusion and droplet superheating, respectively. The numerical results were compared with the experimental data. The model calculations help to comprehensively understand the bubble growth process within a droplet under rapid depressurization.

2. Experimental system and experimental results

2.1. Experimental system

During experiments, the bubble growth processes within a water droplet are captured by a high speed camera, and the droplet is suspended by a thermocouple, which is also used to measure temperature transition. The schematic diagram of experimental system is shown in Fig. 1. It is consisted of four subsystems including a test vessel, a vacuum system, a photography system and a data acquisition system.

The test vessel is made from stainless steel, with two pieces of transparent plexiglass on both sides. The test vessel is covered with an electric heating belt, and a heating plate is inserted in the test vessel to adjust the ambient temperature and the initial droplet temperature. The vacuum system contains a vacuum pump and a vacuum chamber. The vacuum chamber, which has a volume of 600 times larger than that of the test vessel, is used to maintain the pressure stability in the test vessel. The vacuum chamber is connected to the test vessel through a tube of 25 mm in diameter. An electro-magnetic valve is stalled between the tube and the test vessel. The photographic system includes a high speed camera (Optronis CamRecord 450, Germany) which can take 2000 frames per second. Two cold light lamps are arranged on the same side