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Comparison of bubble growth process within a superheated water droplet and in superheated water due to rapid depressurization

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ABSTRACT

This paper reports different characteristics of bubble growth within a superheated water droplet and in superheated water due to rapid depressurization through numerical calculations. Two mathematical models including the classical bubble growth model and the nonequilibrium bubble nucleation model are developed. The classical bubble growth model is based on the momentum equation of bubble growth coupling with the energy conservation equation. The heat transfer due to flash evaporation is considered at the droplet surface. The nonequilibrium bubble nucleation model considers the mechanical nonequilibrium on the formation of bubble nucleus. The numerical results show that a smaller pressure difference ($P_v - P_\infty$) leads to a longer initial stage, and the variation of bubble radius simulated by the nonequilibrium model achieves a shorter initial stage and a faster bubble growth rate. The bubble growth is mainly affected by the competition of pressure difference and surface tension, and the prominent character of bubble growth process within a droplet is the occurrence of accelerating stage. With the bubble interface approaching the droplet surface, the boundary layer becomes thinner, leading to a rapid bubble growth rate. The influencing factors of superheat degree, pressure difference and ambient pressure on bubble growth within a water droplet due to depressurization are analyzed. The results reveal that the pressure difference plays an important role on bubble growth. However, bubble grows slower with a higher ambient pressure, even under the same initial pressure difference. The reason is due to a faster bubble interfacial temperature drop under higher pressure environment. The results can provide insight into bubble growth process during spray and atomization.

1. Introduction

The spray and atomization of fuel jet is one of the key factors to decide the temporal and spatial distribution of fuel in engine cylinder. It also determines the combustion quality and ultimately affects the engine performance and emission. When the liquid is injected into the low pressure environment by nozzle, bubbles can be generated due to rapid pressure drop. These bubbles will lead to breakup of the jet liquid column, and then forms liquid droplets. The droplet could also be superheated resulting in bubble growth within it, which makes droplet burst and forms smaller droplets. This process called secondary breaking will make atomization more uniform. Many researchers [1–5] experimentally and numerically investigated the influencing factors on characters of spray (such as: spray height, pressure difference, initial liquid temperature).

Bubble growth and bubble burst are two important processes which influence the effect of spray. A large number of studies have been preformed on bubble growth in superheated liquid. The classical bubble growth theory based on the momentum conservation equation (Rayleigh-Plesset equation) coupled with the energy conservation equation, and a 'thin thermal boundary layer' was assumed to solve the heat transfer problem [6]. Donne and Ferranti [7] solved the momentum equation and the energy equation by abandoning the thermal boundary assumption, the numerical results revealed the details of the bubble growth during initial stage. Robinson and Judd [8] divided the bubble growth process into three stages, including surface tension controlled domain, transition domain and heat transfer controlled domain. Besides, some investigations have been developed to study the bubble growth in liquid due to depressurization. Lien [9] 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. He also concluded that the interfacial mass transfer resistance does not appear to have appreciable influence upon bubble growth. Gopalakrishna and Lior [10]

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Nomenclature

D_V	diffusion coefficient ($m^2\,s^{-1}$)
h_{fg}	latent heat of vaporization ($J\,kg^{-1}$)
J	mass flux of evaporation ($kg\,s^{-1}\,m^{-2}$)
M	molecular weight ($kg\,mol^{-1}$)
$\dot{m}$	mass vaporization rate ($kg\,s^{-1}$)
P_∞	ambient pressure (Pa)
P_l	liquid phase pressure at droplet surface (Pa)
P_R	liquid phase pressure at bubble surface (Pa)
$P_s(T_s)$	saturation vapor pressure corresponding to droplet surface temperature (Pa)
P_V	saturation vapor pressure corresponding to bubble surface temperature (Pa)
$P_{V\infty}$	vapor pressure in ambient air (Pa)
r_B	bubble radius (m)
r_c	critical radius (m)
r_{s0}	initial droplet radius (m)
R	universal gas constant ($J\,mol^{-1}\,K^{-1}$)
R_g	gas constant ($J\,mol^{-1}\,K^{-1}$)
T_0	initial temperature (K)
T_∞	ambient temperature (K)
T_B	bubble interface temperature (K)
T_l	liquid phase temperature (K)
T_s	droplet surface temperature (K)
V_B	bubble growth rate ($m\,s^{-1}$)
V_l	specific volume of liquid ($m^{-3}\,kg$)

Greek symbols

η	dimensionless factor in computational coordinate
λ_l	liquid phase thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ_l	dynamic viscosity (Pa s)
ρ_l	liquid density ($kg\,m^{-3}$)
ρ_V	vapor density ($kg\,m^{-3}$)
σ	surface tension ($N\,m^{-1}$)

studied the bubble rise and growth due to flash evaporation caused by reducing the pressure in the vapor space above a liquid pool. A bubble momentum equation was developed by considering the effect of pressure wave. Zhang [11,12] simulated the process of dimethoxyethane (DME) vapor bubble growth under flash evaporation, and the influences of ambient pressure, fuel temperature, surface tension and viscous stress on the DME bubble growth were analyzed. Kostoglou et al. [13] numerically investigated bubble growth on a hot plate during decompression of a volatile liquid at temperatures close to saturation and in the presence of dissolved gas. An inverse problem of computing the average bubble temperature evolution corresponding to the experimental growth curve was set up and solved.

The classical bubble growth theory assumed that the bubble formation is based on mechanical and thermal equilibrium with surrounding, and it can be used to explain some fundamental mechanisms. However, it is unable to accurately predict the initial stage. A number of studies modified the classical bubble growth theory by considering the thermal and mechanical nonequilibrium. Kagan [14] investigated the nonequilibrium vapor pressure from a mechanical nonequilibrium nucleation theory. Blander and Katz [15] modified Kagan's model to investigate the hydrodynamic constraints on nucleation rates. Li et al. [16] investigated the vapor pressure, bubble interface velocity and the rate of bubble growth during the initial stage of bubble nucleation by considering the mechanical nonequilibrium. The initial nonequilibrium vapor pressure and the initial bubble growth rate with different initial embryo sizes and different rates of temperature rise were analyzed.

All of the above references are focused on bubble growth in superheated liquid, but the studies of bubble growth within a superheated droplet are limited. Henry and Miyazaki [17] experimentally studied the effect of system pressure on bubble growth from highly superheated water droplets. Their experiments were conducted by superheating water droplets to spontaneous nucleation temperatures in a hot silicon oil bath, and the results showed that the bubble growth is suppressed as the pressure increases for a fixed superheat. Existing experimental data of bubble radius with time during explosive boiling within a superheated droplet is from Ref. [18]. This paper 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 construct a description of the complete explosion process. Then Shusser and Weihs [19] established a mathematical model to describe the vapor bubble growth within a liquid droplet during explosive boiling. He considered the effect of mass flux of evaporation on vapor bubble growth, and his numerical results were verified by the experimental data of Shepherd [18].

However, during spray cooling, the droplet superheated is caused by rapid depressurization, and the droplets are surrounded by ambient air. Satoh et al. [20] experimentally investigated the flash evaporation of a water droplet due to rapid depressurization. He found that bubble may occur within the droplet during flash, and the bubble growth and burst will accelerate droplet cooling. Then Liu [21] compared different characters of flash evaporation processes among water droplets, ethanol droplets and kerosene droplets. His conclusion was that the bubble growth process within a droplet is related with the physical properties of liquid. Due to the small scale of droplets, and the difficult in achieving a rapid depressurization environment around a single droplet, the detailed experimental description of the change of bubble size with time is lacked. The numerical studies on bubble growth within a droplet due to rapid depressurization are also very limited. To our knowledge, Lv et al. [22] 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. However, the heat transfer and mass transfer due to nonequilibrium flash evaporation was ignored, the different characters of bubble growth within a droplet and in superheated liquid due to rapid depressurization have never been compared.

This paper compares different characteristics of bubble growth process within a superheated water droplet and in superheated water due to rapid depressurization through numerical calculations. Two models were developed including the classical bubble growth model and the nonequilibrium bubble nucleation model. The classical bubble growth model was based on the momentum equation of bubble growth coupling with the energy conservation equation within the liquid phase. As for bubble growth within a droplet, the heat transfer due to flash evaporation was considered at the droplet surface. The nonequilibrium bubble nucleation model considered the mechanical nonequilibrium on the formation of bubble nucleus. The Landan coordination transformation method [23] was used to solve the moving interface problem. Through numerical calculations, the factors influencing bubble growth were discussed. The model calculations help to comprehensively understand the bubble growth process during spray and atomization.