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A novel model for the bubble growth in the cavitation region of an injector nozzle

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ABSTRACT

A novel thermodynamic model was developed to calculate the bubble growth in the cavitation region of an injector nozzle. The influence of liquid pressure on bubble growth process was evaluated for both homogenous nucleus and heterogeneous nucleus. In this model, the energy equation coupling with the quadratic temperature distribution within the thermal boundary layer was applied with consideration of temporal variation of bubble pressure, radius, velocity and the thickness of the thermal boundary layer. The results show that the evolution of the bubble growth can be divided into three stages, i.e., surface tension controlled stage, transitory stage, and heat transfer controlled stage. The evolution processes of bubble growth from a homogeneous nucleus or a heterogeneous nucleus are much alike other than in the surface tension controlled stage.

1. Introduction

The process of fuel injection and fuel atomization plays a predominant role in the combustion characteristics and soot emission of a diesel engine. Hydrodynamic cavitation phenomenon can often be observed in the vicinity of the fuel injector nozzle entrance [1,2] (see Fig. 1). An abrupt decrease of flow area at the nozzle entrance tends to accelerate the liquid velocity within the tiny nozzle hole, which causes a great pressure drop. Thus the local pressure is lower than the saturation pressure corresponding to the local temperature. The superheat degree, which is defined as the difference between the fuel temperature (T_l) and the fuel boiling point (T_{sat}) at the local pressure [3], together with the pressure difference and the chemical potential difference between liquid and vapor are responsible for the bubble growth in the liquid. As these cavitation bubbles are swept out from the nozzle into the combustion chamber, they will implode and contribute to further disintegration of the liquid jet to produce finer droplets of fuel, which will enhance the spray atomization [4]. Since the cavitation phenomenon is highly unsteady and includes complicated interactions between various phases, it is important to understand the fundamental of the bubble growth in the cavitation region so as to capture the injection process accurately.

The vapor bubble growth in metastable liquid was theoretically studied for the first time by Rayleigh [5], who presented an approximate analytical solution for the growth of a spherically symmetric bubble only considering the inertial force. Subsequently, the researches on the bubble growth process were conducted by many other investigators. The asymptotic zero-order solution presented by Plesset [6], with consideration of the thermal diffusion through the liquid-vapor interface, provided an approximate description for the liquid film temperature distribution with an assumption of a thin thermal boundary layer. The solution showed satisfactory agreement with the experimental data of water under moderate superheat degree conditions. The analytical solution of Plesset was further extended by Mohammadein [7] and Prosperetti [8] in some special cases.

Bubble growth in constant as well as time-dependent pressure fields has been formulated by Theofanous [9], who considered the effect of non-equilibrium at the liquid-vapor interface. Mikic [10] presented a new method of the bubble growth through the combination of the inertia effect and the thermal diffusion to give a generalized closed expression over the entire growth range. However, the effect of surface tension, which plays a vital role in the initial process of bubble growth, was ignored in the proposed analytical solution. Froster [11] proposed a closed-form solution for the bubble growth in superheated liquid by integrating the temperature distribution given by the well-known Green's function with the aid of Clausius-Clapeyron equation. In addition, the effect of increasing bubble surface area on the temperature gradient within

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Nomenclature

A	coefficient in PR equation [–]
B	coefficient in PR equation [–]
c_p	constant-pressure specific heat [J/(kg·K)]
c_v	constant-volume specific heat [J/(kg·K)]
E	internal energy [J]
G	Gibbs energy [J/kg]
h_{fg}	latent heat of vaporization [J/kg]
Ja	Jakob number [–]
k	heat conductivity coefficient [W/m·K]
M	molar mass [g/mol]
m	mass [kg]
P	pressure [Pa]
Q	heat transfer [J]
R_g	gas constant [J/(kg·K)]
R	radius [m]
R^+	non-dimensional radius in Fig. 4(a)
r	distance from bubble center [m]
T	temperature [K]
t	time [s]
t^+	non-dimensional time in Fig. 4(a)
u	velocity [m/s]
V	volume [m^3]
Z	compressibility factor [–]

Greek symbols

ζ	dimensionless parameter in Eq. (1) [–]
δ	thermal boundary layer thickness [m]
γ	specific heat ratio [–]
α	thermal diffusivity [m^2/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
μ	kinematic viscosity [N·s/m^2]

Subscripts

0	initial
c	critical
b	bubble
∞	infinite region/far field
l	liquid
r	radical
sat	saturation
sup	superheat
v	vapor

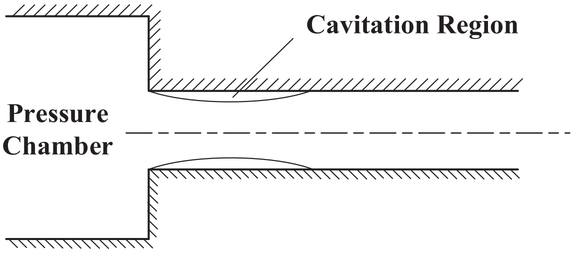

Fig. 1. Schematic illustration of cavitation formation inside a nozzle hole.

the thermal boundary layer was also considered. Scriven [12] successfully predicted bubble growth process without consideration of the thermal boundary layer. Riznic [13] validated and then developed Scriven's model by including the influence of the interface curvature on the temperature gradient near the liquid-vapor interface. However, the assumption of thermal layer is physically reasonable and necessary, since it is impossible for the temperature to change abruptly at the bubble interface from T_∞ to T_v.

Lee [14] and Robinson [15] made significant contributions to understand the bubble growth dynamics by coupling momentum equation and energy equation. The influences of surface tension, liquid inertia, and heat diffusion were considered in their models, so the vapor bubble growth in the initially uniformly superheated liquid can be accurately described. One of the pioneering work on the effect of the thermal boundary layer on the bubble growth was conducted by Chang [16]. An exponential temperature profile and a polynomial temperature profile were assumed in Chang's model to estimate the boundary layer thickness and the spatial temperature derivative near the interface, respectively. Chang's model made a compromise between calculation cost and simulation precision, and indicated a good consistency with experiment data. Thus it has been widely used in the simulation of the flash boiling spray in swirl nozzles.

In the context of the injection nozzles, Delale [17] considered the energy equation within the bubble which is composed of vapor and gas in the uniform pressure approximation with low vapor concentration. Subsequently, Giorgi [18,19] studied a gas bubble growth with a convective approach assuming that the behavior of the gas in the bubble is polytropic. His results showed that the restriction of thermal effects on the bubble expansion, and a cavitation model based on a mechanical growth during the evaporation could overestimate the cavitation intensity. Bicer [20] proposed the modified Rayleigh equation to predict the growth and collapse of cavitation bubbles in a diesel fuel injector.

The representative experiments attempting to figure out the process of bubble growth under wide operating conditions were conducted by Dergarabedian [21] and Lien [22]. In their studies, special attention was taken to ensure that the bubble growth took place in the uniformly superheated liquid far away enough from the walls of the vessel. It has also been evidently observed in the experiment that under the realistic diesel injection conditions, the pressure at the place close to the entrance of the injection nozzle hole usually fluctuates at very high frequencies [23], which is caused by the well-known water hammer effect in the needle chamber [24]. Furthermore, the upstream pressure fluctuation has a significant impact on the cavitation process within the injection nozzle hole [25,26]. The study of Ramamurthi [25] provided a strong evidence that both partial cavitation and supercavitation are sensitive to the inlet pressure fluctuation. Therefore, the influence of liquid pressure should be taken into account when the cavitation bubble formation and growth are investigated.

Overall, a deep understanding of the bubble growth has been achieved through various numerical simulations, theoretical analyses, and experiments over the past years. However, the relationship between the bubble growth and the liquid pressure has not been well revealed. In this paper, a new theoretical model is proposed using the unsteady one-dimensional analytical method for the process of bubble growth in the cavitation condition near the nozzle entrance which is filled with uniformly superheated liquid. The model was developed on the basis of Kwak's work [27], in which a general bubble dynamic model was proposed considering the influence of the thermal boundary layer on the bubble growth without considering the phase change. Different from the previous research, the phase change through the bubble interface is taken into consideration in the present model. Based on the updated model, the growth of an isolated bubble is studied with a thin