Energy Conversion and Management 160 (2018) 165–175

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Modeling flash boiling breakup phenomena of fuel spray from multi-hole type direct-injection spark-ignition injector for various fuel components

Taehoon Kim[a], Sungwook Park[b,*]

[a] Department of Mechanical Convergence Engineering, Graduate School of Hanyang University, Seoul 04763, Republic of Korea
[b] School of Mechanical Engineering, Hanyang University, Seoul 04763, Republic of Korea

ARTICLE INFO

Keywords:
Direct injection
Flash boiling
Droplet breakup
Fuel injector

ABSTRACT

A flash breakup model was developed in this study, based on bubble dynamics. The Rayleigh-Plesset equation was used to predict bubble growth inside of a droplet. A single bubble for each droplet was assumed. When the void fraction exceeds critical value, breakup was assumed. The velocity component normal to the direction in which the droplet moved was predicted by the sum of the velocities predicted by energy conservation, the pressure difference between the inside and outside of droplet, and the bubble growth rate. The thermodynamic-mechanical breakup model was formed using the flash breakup and Kelvin-Helmholtz Rayleigh-Taylor breakup models. Using the developed breakup module, the decrease in spray tip penetration, spray plume expansion, and change in spray target were predicted for single-component fuels and compared with experimental results. A gasoline flash boiling spray was modeled using various fuel vapor pressure for the Rayleigh-Plesset equation. From the comparison between the analyses with and without the flash breakup model, it was concluded that the flash breakup model should be used to predict deformations in spray structure for flash boiling sprays.

1. Introduction

In real driving conditions, engines operate under low-load or middle-load conditions with low speed [1]. In direct-injection spark-ignition (DISI) gasoline engine, the engine load is controlled by the throttle valve. Therefore, the intake pressure drops to vacuum under a middle-load condition. When the ambient pressure drops below fuel vapor pressure, a flash boiling spray is formed. As the liquid fuel pressure decreases from the injection pressure to ambient pressure, the fuel starts to boil. Boiling inside of a droplet induces breakup. Flash breakup deforms the spray morphology [2] and reduces the spray tip penetration [3]. It also reduces the droplet size [4]. Droplet size is widely investigated [5–8] because it determine evaporation rate and mixture distribution. Because the flash breakup is induced by thermodynamic non-equilibrium, droplets can be disintegrated even in low ambient pressure, where the aerodynamic force acting on the droplets is weak. Therefore, the flash breakup process should be reflected in computational fluid dynamics (CFD) programs to analyze the mixture formation process of DISI gasoline engines under low-load or middle-load conditions.

Common CFD program provides breakup models like Taylor analogy breakup (TAB) [9], Wave [10], Reitz-Diwakar [11], Huh-Gasoman [12], Kelvin-Helmholtz Rayleigh-Taylor (KH-RT) [13], etc. These models are based on the mechanical interaction between liquid phase and gas phase. Therefore, these breakup models cannot capture the breakup process at the flashing condition. There has been little research on modeling flash boiling spray for engine injectors. Price et al. [14] developed an method for modeling flash boiling sprays. They investigated the effects of the initial conditions for flash boiling sprays as their fundamental research [15]. The initial conditions for the droplet radius and spray angle were modified to analyze flash boiling sprays. The initial droplet radius was predicted by predicting the fuel vapor fraction at the nozzle exit using the nucleation model. Senda et al. [16] developed a flash breakup model based on bubble dynamics. They predicted the bubble radius by the Rayleigh-Plesset equation, and the bubble number density was predicted from experimental data. The void fraction was calculated with the bubble radius and bubble number density. When the void fraction exceeded a critical value, flash breakup was assumed. This mechanism was proposed by Sher and Elata [17]. After flash breakup, the number of droplets was assumed to be twice the number of bubbles. From this assumption, the droplet radius could be predicted. They considered vaporization from a liquid drop to a bubble, and the vaporization rate was predicted by the bubble radius and bubble number density. The effect of superheat on the vaporization from liquid to air was considered by suggesting a heat transfer coefficient between the liquid and air [18]. This model was applied to a

* Corresponding author at: School of Mechanical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea.
E-mail address: parks@hanyang.ac.kr (S. Park).

https://doi.org/10.1016/j.enconman.2018.01.042
Received 1 December 2017; Received in revised form 16 January 2018; Accepted 18 January 2018
Available online 30 January 2018
0196-8904/

Nomenclature

A	droplet surface area
a	correlation factor.
$[C_A]$	inter-diffusional difference of energy flux between fuel and air
C_t	time constant for bubble growth time scale
$\overline{C}_p$	liquid heat capacity
$E_{elastic}$	elastic energy
$h_{i,eff,s}$	heat transfer coefficient
L	latent heat of fuel
$\dot{m}$	vaporization rate
Nu	NUSSELT number
n	polytropic index
P_r	far-field pressure
P_v	vapor pressure
R	bubble radius
$\dot{R}$	first time derivative of bubble radius
$\ddot{R}$	second time derivative of bubble radius
R_b	bubble radius
$R_{d,new}$	droplet radius after breakup
$R_{d,old}$	droplet radius before breakup
R_o	outer radius of bubble-drop system
r_0	droplet radius
Sh	sherwood number
T_{boil}	boiling temperature
T_{sur}	surrounding gas temperature
ΔT	difference between interior temperature and boiling temperature of droplet
$y_{F,sur}$	mass fraction of fuel at far-field
α_{sh}	heat transfer enhancement by nucleation
η	energy transfer efficiency
κ	surface dilatational viscosity
λ	thermal conductivity
μ_l	liquid viscosity
ρ_l	liquid density
σ	surface tension

Subscript

0	initial condition

Abbreviations

CFD	computational fluid dynamics
CI	compression ignition
DISI	direct-injection spark-ignition
DME	dimethyl ether
HCCI	homogeneous charge compression ignition
KH	Kelvin-Helmholtz
RT	Rayleigh-Taylor
TAB	Taylor analogy breakup

single-hole nozzle with multi-component fuel [19]. Another flash breakup modeling approach was carried out by Zeng and Lee [20]. They determined the blob radius from the bubble number density. A single bubble for each droplet was assumed, and the Rayleigh-Plesset equation was utilized to predict the bubble radius. Flash breakup was predicted by a linear stability analysis, and when the disturbance exceeded the critical value, flash breakup was assumed. Aerodynamic breakup was considered by a modified TAB model. From the bubble radius predicted by the Rayleigh-Plesset equation, the void fraction of the droplet was predicted. The fuel properties were linearly interpolated using the void fraction and modified fuel properties were used for the TAB breakup model. As the TAB breakup model predicts the normal direction velocity after breakup, the change in spray angle for the flash boiling spray can be predicted.

In previous study [21], flash breakup model was developed and combined with aerodynamic breakup model to predict breakup process at flashing condition. In this study, a thermodynamic-mechanical breakup module was improved and validated with experimental data for various fuel types and fuel temperatures. Details of improvements in developed model is descripted in Sections 2.3 and 2.4.

2. Computational methodology

2.1. Concept of flash breakup model

In the operating range of conventional engines, the bubble expansion process starts outside of the nozzle [22–24]. Therefore, the conventional blob method [10,11] was used to analyze the flash boiling sprays. The flash breakup model developed in this study is based on the approach of Senda et al. [16,18,19]. However, a single bubble for each droplet was assumed; this approach simplifies the model. Bubble growth was predicted by the Rayleigh-Plesset equation. When the void fraction calculated from the bubble radius exceeds the critical void fraction, flash breakup is assumed. The critical void fraction was set to 0.55 according to Senda et al. [16]. This approach used in the model of Senda et al. [16,18,19] is more intuitive than the instability analysis used in the model of Zeng and Lee [20]. Two droplets are generated after breakup. The droplet radius was chosen by the Rosin-Rammler distribution, of which the mean value is predicted by mass conservation. The tangential velocity component was assumed to be conserved, and the velocity component in normal direction was predicted by energy conservation, the bubble growth rate, and the pressure gradient between the bubble and ambient air. To simplify the modeling process, a spherical droplet was assumed to calculate the drag force and the collision model was excluded.

2.2. Bubble growth prediction

Bubble growth inside the droplet was calculated by the Rayleigh-Plesset equation, as the time scale for bubble growth is much lower than the conventional time scale used for spray analysis. Therefore, the internal time step was used to calculate the bubble growth within the flow time step. Based on the fuel properties, the bubble radius is calculated by the following equation.

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho_l}(P_w - P_r)$$

$$P_w = P_v + \left(P_{r0} + \frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3n} - \frac{2\sigma}{R_0} - \frac{4\mu_l\dot{R}}{R} - \frac{4\kappa\dot{R}}{R^2}$$

All of the fuel properties are updated for every flow time step, because the droplet temperature varies during vaporization. P_{r0} is the initial far-field pressure. This value is set to the injection pressure for droplets that enter the computational domain, and ambient pressure for droplets that experienced breakup. When the drop containing bubble is exposed to ambient gas, the pressure of liquid drop is different from the ambient gas pressure because of surface tension. However, magnitude of pressure difference is much smaller than the ambient pressure. Therefore, to simplify the problem, ambient pressure was used for P_r. n is the polytropic index, and the value was set to one by assuming an iso-thermal process. The surface dilatational viscosity was proposed by Scriven [25] and expressed by κ in the Rayleigh-Plesset equation. Ida and Sugiya