

# Numerical Study on Flash Boiling Spray of Multi-Hole Injector

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## ABSTRACT

Flash boiling spray is effective in improving the atomization and evaporation characteristics for gasoline direct injection engines. However, for a multi-hole injector the morphology structure of spray has an obvious change with the fuel temperature increasing or the ambient pressure decreasing, which influences the process of mixture formation and flame propagation. Specially, the spray collapses with both long penetration and a narrow spray angle above certain high superheat degree, which deteriorates air/fuel mixing and hence increases emissions. It is not desired for engine applications while the mechanism of spray structure transformation for multi-hole injector still remains unclear. In the present study, a systematic flash boiling spray model for multi-hole injector is built to investigate the flash boiling spray of multi-hole injector. Key physics involved in flash boiling, including bubble formation, bubble growth, as well as bubble breakup are added to the traditional spray model in KIVA-3V to describe the development process of flash boiling spray. The simulation results of spray structure and spray penetration for multi-hole injector agree well with experimental observation under various conditions. The numerical results of the pressure field, velocity field and vapor distribution are analyzed under different superheat degree. It is found that the low pressure region has a significant effect on the formation of eddies in velocity fields and the greater the pressure drop is, the more intense the eddy is. The interactions of low pressure regions and eddies change the trajectories of droplets and then change the spray structure. When flare flash boiling occurs, although the evaporation of fuel increases greatly, the fuel vapor is relatively concentrated in the spray center due to spray collapse, which deteriorates air/fuel mixing.

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## INTRODUCTION

The spray atomization process in internal combustion engines directly affects the heat release rate and the duration of combustion and subsequently impacts the thermal efficiency and emissions of engines [1, 2]. For gasoline direct injection (GDI) engines, it is desired that the homogenous fuel/air mixture can be formed rapidly, which requires the spray with a proper penetration, a wide cone angle and small droplets [3, 4]. To meet these requirements, high injection pressure is used generally to improve the atomization of the spray, but sometimes overlong spray penetration leads to fuel impingement on cylinder walls [5]. The impingement produces thick films of fuel and rich mixture, and deteriorates the combustion. Flash boiling of spray is an effective method to improve the atomization by the explosion of vapor bubble formed in superheated liquid when the liquid temperature is higher than its boiling point or the local pressure is lower than its saturation pressure [6, 7, 8, 9]. Therefore, the flash boiling of spray can decrease droplet diameter and improve liquid

evaporation without increasing the injection pressure [1, 10], promote fuel/air mixture formation [11], flame propagation, and then improve thermal efficiency and reduce smoke emission [12].

For multi-hole injector the morphology of spray has an obvious change with the fuel temperature increasing or the ambient pressure decreasing [13, 14], which influences the process of mixture formation and flame propagation. According to the spray morphology of a multi-hole injector, Zeng et al. [15] divided the spray into non-flash boiling spray, transitional flash boiling spray and flare flash boiling spray under different superheat degrees. At the transitional flash boiling stage, the spray penetration becomes short and spray plume becomes wide; whereas spray penetration and spray plume width has inverse trends at the flare flash boiling stage [16, 17]. Further study showed that multi-hole injector spray collapsing at high superheat degree would result longer spray penetration and narrower spray angle, which subsequently leads to wall wetting and then increases fuel consumption and soot emission [10]. This spray morphology is undesirable for the application of flash boiling in GDI

engines. Dondè et al. [18] found that the spray angle decreased and the hollow cone structure was lost when the flash boiling spray collapsed. It was considered that the collapse phenomenon was caused by the air entrainment flow. Moon et al. [19] investigated the effect of fuel temperature on the collapse phenomenon and considered that spray was driven toward the spray axis as a result of the augmented pressure drop inside the spray and entrained air. Yang et al. [10] compared the differences in spray characteristics among single-hole, two-hole, and six-hole injectors and suggested that the collapse phenomenon was caused by the combined effect of the low pressure core and the overlap region. However, in these studies, the details of the pressure and velocity fields, which determine the spray structure, are not provided due to the difficulties in the measurement.

In this study, a systematic flash boiling spray model for a multi-hole injector is built to investigate the flash boiling spray. The key physics involved in flash boiling, including bubble formation, bubble growth, as well as bubble breakup are added to the traditional spray model in KIVA-3V to describe the development process of flash boiling spray. First, the parameters of these sub-models are discussed, and then the effects of initial fuel temperature and ambient pressure on the flash boiling spray structure of multi-hole injector are investigated. In addition, experiments of flash boiling are conducted in a constant volume chamber and the macroscopic morphology of multi-hole injector spray is obtained by Mie scattering method to verify the flash boiling spray model of multi-hole injector. Subsequently, the pressure field, velocity field and vapor distribution under different conditions are analyzed.

## MODEL FORMULATION OF FLASH BOILING

The flash boiling of a superheated liquid includes flash boiling inside the nozzle and outside the nozzle. Sato et al. [20] has investigated the effect of flash boiling inside the nozzle on the spray characteristics of superheated water, and found that the flash boiling inside the nozzle could be ignored when the ratio of the orifice length to the orifice diameter ( $l/d$ ) was less than 7.0. In the present study, the ratio of the orifice length to the orifice diameter is 2.0. Thus, only the flash boiling outside the nozzle is considered. The processes of atomization and vaporization of superheated liquid outside the nozzle mainly consist of primary breakup, bubble nucleation, bubble growth, bubble dispersion, liquid vaporization, and droplet collision and coalescence. Since the flash boiling of spray is essentially caused by the micro-explosion of vapor bubbles formed in superheated droplets, a flash boiling model of a single droplet is first built to describe the micro-explosion process of the single droplet, and then sub-models describing the process of the interaction of liquid droplets, such as droplet collision and coalescence, are added into the flash boiling model. Finally, the flash boiling model is coupled with the traditional spray model in KIVA-3V. The sub-models of flash boiling spray respectively are described in the following subsections.

### Bubble Nucleation Model

Bubble nucleation processes can be homogeneous or heterogeneous. In homogeneous nucleation, bubbles are formed in the bulk liquid and this nucleation process becomes dominant when the tensile

force can oppose to the molecular force of the liquid with the liquid pressure decreasing [21]. In this study, this process can be ignored because the molecular force of the liquid is always much stronger than the tensile force as the pressure decreases in the numerical simulation. In contrast, heterogeneous nucleation occurs at interfaces and boundaries where gas or solid exists. In heterogeneous nucleation process, an activated cluster grows to a critical size and becomes a nucleus in the presence of crevices on the solid surface, fine solid particles, dissolved gas in the liquid. For the nucleation on solid surfaces inside nozzle, bubble nucleation on solid surface has little influence on the spray behavior when the  $l/d$  of nozzle orifice is less than 7.0 [22]. Thus, the nucleation on solid surface is negligible for small  $l/d$  of nozzle orifice (2.0 in this study). The estimation of nucleation from dust or solid particles in liquid is difficult and the fuel used for the experiments is well filtered for flash boiling spray model calibration. Thus, the nucleation on dust or particles is also neglected in this study. Therefore, only the heterogeneous nucleation due to dissolved gas in the liquid is considered. Adachi et al. [23] have proved that the number of bubble nucleation only considering the heterogeneous nucleation of dissolved gas in the liquid obtained by numerical simulation agrees well with the experimental data. Thus, the same simplified bubble nucleation model is used to describe the nucleation process in this study as follows:

$$N = C \exp\left(\frac{-\Delta A}{k\Delta T}\right) \quad (1)$$

$$\Delta A = \frac{4}{3} \pi R^2 \sigma \quad (2)$$

where  $N$  is the number density of bubble nucleation in liquid,  $C$  is a constant,  $k$  is the Boltzmann constant,  $\Delta T$  is the difference between fuel temperature ( $T$ ) and its saturation temperature ( $T_s$ ), and  $\sigma$  is the surface tension. In this study, the number density  $N$  of bubble nucleation are estimated using the following equation suggested by Senda et al. [24]:

$$N = 5.575 \times 10^{12} \exp\left(\frac{-5.279}{\Delta T}\right) \quad (3)$$

### Bubble Growth Model

If the initial bubble radius is greater than a critical value  $R_c$ , a small fluctuation of the pressure on the bubble surface will result in either collapsing or bubble growth [1]. In this study, only the bubble growth is considered. The growth of the bubble is determined by the inertial force, the surface tension, the viscosity, and the thermal diffusion [25, 26]. The growth rate is calculated by coupling the liquid momentum and energy equations through the nonlinear convection term. In addition, bubbles in a superheated droplet are assumed to be spherical during the growth, and the temperature and pressure inside bubbles are assumed to be uniform. Therefore, the Rayleigh-Plesset model is used to describe the process of bubble growth as follows [25]:

$$R_i = \frac{2\sigma}{P_v - P_\infty} \quad (4)$$

$$R_b \frac{d^2 R_b}{dt^2} + \frac{3}{2} \left( \frac{dR_b}{dt} \right)^2 = \frac{P_v(T_v) - P_\infty}{\varepsilon \rho_l} - \frac{2\sigma}{\varepsilon \rho_l R_b} - 4 \frac{\mu}{\varepsilon \rho_l R_b} \frac{dR_b}{dt} \quad (5)$$

$$\varepsilon = 1 - \frac{\rho_v}{\rho_l} \quad (6)$$

where  $R_b$  is the bubble radius,  $\sigma$  the surface tension of the liquid,  $\mu$  the liquid viscosity,  $\rho_l$  and  $\rho_v$  the densities of the liquid and the gas phases respectively,  $P_v$  the saturation pressure of the liquid,  $P_\infty$  ambient pressure, and  $T_v$  the vapor temperature.

### Droplet Breakup Model

Being different from the breakup of droplets in traditional sprays, the breakup of droplets in flash boiling sprays is not only determined by the aerodynamic force, but also affected by the bubble growth in the superheated droplet, especially during the secondary breakup of droplets, the effect of bubble growth on droplet breakup is predominant [20]. In this study, a modified KH-RT breakup model considering the effect of vapor bubble in liquid [27] was used to describe the process of breakup caused by aerodynamics force, while a bubble-droplet breakup model proposed by Zeng and Lee [28] was used to describe the breakup process caused by bubble growth.

### Droplet Breakup Due to Aerodynamic Force

For the primary breakup of spray, the breakup process is mainly controlled by the Kelvin-Helmholtz (KH) unstable wave at the gas-liquid interface. For the flash boiling spray, the bubble growth in the superheated liquid increases volume of droplets, decreases equivalent density, and then changes the Reynolds number and Weber number. Thus, considering the effect of vapor bubble in droplets, the maximum growth rate of KH unstable waves  $\Omega_{KH}$  and its  $\Lambda_{KH}$  wavelength are given respectively as below:

$$\Omega_{KH} = \frac{0.34 + 0.38 We_g^{1.5}}{(1 + Oh)(1 + 1.4 Ta^{0.6})} \sqrt{\frac{\sigma}{\rho_e R_e^3}} \quad (7)$$

$$\Lambda_{KH} = \frac{9.02(1 + 0.45\sqrt{Oh})(1 + 0.4 Ta^{0.7})}{(1 + 0.865 We_g^{1.67})^{0.6}} \quad (8)$$

where  $We_g$  is the gas Weber number,  $We_g = \frac{\rho_g U_r^2 R_e}{\sigma}$ ,  $We_l$  is the liquid Weber number,  $We_l = \frac{\rho_l U_r^2 R_e}{\sigma}$ ,  $Oh$  is the Ohnesorge number,  $Oh = \frac{\sqrt{We_l}}{Re_l}$ ,  $Ta$  is the Taylor number,  $Ta = Oh \sqrt{We_g}$ ,  $Re_l$  is the Reynolds number of liquid,  $Re_l = \frac{\rho_l U_r R_e}{\mu_l}$ ,  $U_r$  is the relative velocity between the liquid and gas,  $R_e$  is the equivalent radius of droplets,  $R_e = \sqrt[3]{R_b^3 + R_d^3}$ ,  $\rho_e$  is the equivalent density of droplet,  $\rho_e = (1 - \varphi)\rho_l + \varphi\rho_g$ , and  $\varphi$  is the void ratio of droplets,  $\varphi = \frac{R_b^3}{R_e^3}$ .

When the equivalent radius of droplet ( $R_e$ ) is greater than the critical radius of the KH unstable wave ( $R_{KH}$ ), small droplets are assumed to be peeled off from parent droplets, [29]. The critical radius of KH unstable wave ( $R_{KH}$ ), the change rate of droplet radius ( $\frac{dR_e}{dt}$ ), and the breakup time of KH unstable wave ( $\tau_{KH}$ ) are given respectively as follows:

$$R_{KH} = B_0 \Lambda_{KH} \quad (9)$$

$$\frac{dR_e}{dt} = \frac{R_e - R_{KH}}{\tau_{KH}} \quad (10)$$

$$\tau_{KH} = \frac{3.726 B_1 R_e}{\Omega_{KH} \Lambda_{KH}} \quad (11)$$

where  $B_0 = 0.61$  is the constant of critical radius of the KH unstable wave, and  $B_1 = 20$  is the a constant for the breakup time of KH unstable wave.

For the secondary breakup process, the droplet breakup mainly depends on the critical wave length of Rayleigh-Taylor (RT) unstable wave. Considering the effect of vapor bubble in droplets, its frequency  $\Omega_{RT}$  and wavelength  $\Lambda_{RT}$  are given respectively as follows [29]:

$$\Omega_{RT} = \sqrt{\frac{2a}{3}} \left( \frac{a \rho_e}{3\sigma} \right)^{0.25} \quad (12)$$

$$\Lambda_{RT} = 2\pi \sqrt{\frac{3\sigma}{a(\rho_e - \rho_g)}} \quad (13)$$

where  $a = \frac{3}{8} C_D \frac{\rho_g U_r^2}{\rho_e R_e}$  is the acceleration.

When the life time of a droplet is greater than the breakup time of RT unstable wave ( $\tau_{RT}$ ) and the critical wave length of RT unstable wave ( $\Lambda_{RT}$ ) is less than the droplet diameter ( $2R_d$ ), the droplet is assumed to break up [27]. The breakup time of Rayleigh-Taylor unstable wave ( $\tau_{RT}$ ) and the equivalent radius of droplet ( $R_{e(n+1)}$ ) after breakup are given respectively as follows:

$$\tau_{RT} = \frac{C_\tau}{\Omega_{RT}} \quad (14)$$

$$R_{e(n+1)} = \frac{C_{RT} \Lambda_{RT}}{2} \quad (15)$$

where  $C_\tau = 1.0$  is the breakup constant of RT unstable wave,  $C_{RT} = 0.1$  is the constant of critical radius of RT unstable wave.

### Droplet Breakup Due to Bubble Growth

Based on the elastic force theory and the linear stability analysis, Zeng and Lee [30] developed a bubble-droplet breakup model to describe the breakup process caused by bubble growth. It is assumed that the bubble growth will result in shock disturbance at radial direction and if the disturbance growth rate exceeds the critical value, the bubble-droplet system will break up. For the bubble-droplet system, the breakup variable  $K$  is defined as

$$K(t) = \frac{R_{e0} e^{\int_0^t \omega dt}}{R_e - R_b} \quad (16)$$

where  $R_e$  is the equivalent droplet radius,  $R_b$  the bubble radius,  $R_{e0}$  the initial equivalent droplet radius, and  $\omega$  the disturbance growth rate.

It is assumed that the bubble-droplet system breaks up when the breakup variable  $K$  is greater than a threshold  $K_{crit}$ . In this study,  $K_{crit}$  is equal to 5 as suggested by Zeng and Lee [30]. A linear stable analysis was used to determine the disturbance growth rate ( $\omega$ ) through combining the linearized momentum and continuity equations. A normalized formula for disturbance growth rate ( $\omega$ ) is given as follows:

$$\begin{aligned} &(\Delta - \Delta^2 - \psi_o \Delta) \Omega^2 + (-1 + \Delta^4 + \psi_o) We_o^{1/2} \Omega + \\ &2\Delta^2 + 2\Delta^{-2} - 3\psi_i \frac{We_i}{Ma_i^2} \frac{\Omega}{\Omega + 3We_i^{1/2}} \Delta^2 = 0 \end{aligned} \quad (17)$$

where  $\Omega = \sqrt{\frac{\rho_l R_b^3}{\sigma}} \omega$ ,  $We_o = \frac{\rho_l U_r^2 R_b}{\sigma}$ ,  $We_i = \frac{\rho_l U_b^2 R_b}{\sigma}$ ,  $Ma_i = \frac{U_b}{c}$ ,  $\Delta = \frac{R_e}{R_b}$ ,  $\psi_o = \frac{\rho_g}{\rho_l}$ ,  $\psi_i = \frac{\rho_b}{\rho_l}$ .

The distribution of droplet diameter is assumed to obey  $\chi^2$  distribution after breakup and its velocity consists of the velocity of parent and the additional velocity. The Sauter mean radius ( $R_{32}$ ) and the additional velocity ( $U_a$ ) of droplet after breakup can be determined as:

$$R_{32}^{-1} = \frac{R_e^2 + R_b^2}{R_e^3 - R_b^3} + \left( \frac{3}{2} \frac{R_b^4 (R_b^{-1} + R_e^{-1})}{R_e^3 - R_b^3} U_b^2 - \frac{U_a^2}{2} \right) \frac{\rho_l}{3\sigma} \quad (18)$$

$$U_a = \frac{3R_b U_b (R_e - R_b)}{R_e^3 - R_b^3} \quad (19)$$

### Evaporation Model of Superheated Droplets

For the evaporation of flash boiling spray, the evaporation rate mainly depends on local vapor concentration, superheat degree and heat transfer at droplet surface. An evaporation model of superheated droplet has been proposed by Zuo et al. [31] based on three assumptions: the surface temperature of the superheated droplet is equal to the saturation temperature; all the heat transferred from

ambient gas to droplet is used for evaporation and does not change droplet temperature; the evaporation due to superheat at droplet surface restrains the heat transfer from ambient to droplet and decreases evaporation rate. For a spherical superheated droplet, the evaporation formula is given as follows:

$$4\pi R_d^2 \rho_l \frac{dR_d}{dt} = \dot{m}_i + \dot{m}_f \quad (20)$$

where  $\dot{m}_f$  is the evaporation rate due to flash boiling,  $\dot{m}_i$  is the evaporation rate due to heat transfer.  $\dot{m}_f$  is given as follows:

$$\dot{m}_f = 4\pi R_d^2 \alpha_s \frac{\Delta\theta}{L} \quad (21)$$

where  $\alpha_s$  is heat transfer coefficient given as follows:

$$\alpha_s = \begin{cases} 0.76\Delta T^{0.26} & (0 \leq \Delta T \leq 5.0) \\ 0.027\Delta T^{2.33} & (5.0 \leq \Delta T \leq 25.0) \\ 13.8\Delta T^{0.39} & (\Delta T \geq 25.0) \end{cases} \quad (22)$$

$\dot{m}_i$  is given as follows:

$$\dot{m}_i = 2\pi R_d \frac{k_L}{c_{pl}} \frac{Nu}{1 + \frac{\dot{m}_f}{\dot{m}_i}} \ln \left[ 1 + \left( 1 + \frac{\dot{m}_f}{\dot{m}_i} \right) B_i \right] \quad (23)$$

where  $k_L$  is the thermal conductivity of liquid,  $c_{pl}$  is specific heat capacity at constant pressure for liquid,  $Nu$  is the Nusselt number;  $B_i$  is the Spalding mass transfer number.

With the evaporation of superheated droplet, the temperature of the droplet will decrease. If the droplet has not been completely evaporated when the droplet temperature goes below the saturation temperature, the evaporation is calculated using the Spalding evaporation model built-in original KIVA-3V.

### Numerical Simulation

The simulation conditions are listed in Table 1. The calculation time was 1.0 ms. The maximum time step was 0.05 ms and the minimum time step was 1  $\mu$ s. Fuel injection quantity and injection velocity were calculated through a virtual injection rate generator proposed by Payri [32] and Pickett [33]. The initial droplet parcels was set as 2000 and the initial Sauter mean radius (SMR) was 95  $\mu$ m. The fuel properties provided by fuellib in original KIVA-3V were invoked by sub-models and updated at each time step. The calculation region (Figure 1) set as a circular cylinder with a height of 100 mm and a diameter of 100 mm. The computational grid size was 2 mm  $\times$  2 mm  $\times$  1.25 mm, and the number of cells was about 2,000,000.