Numerical simulation of internal and near-nozzle flow of a gasoline direct injection fuel injector

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Abstract. *A numerical study of two-phase flow inside the nozzle holes and the issuing spray jets for a multi-hole direct injection gasoline injector has been presented in this work. The injector geometry is representative of the Spray G nozzle, an eight-hole counterbore injector, from the Engine Combustion Network (ECN). Simulations have been carried out for the fixed needle lift. Effects of turbulence, compressibility and non-condensable gases have been considered in this work. Standard* k$-\epsilon$ *turbulence model has been used to model the turbulence. Homogeneous Relaxation Model (HRM) coupled with Volume of Fluid (VOF) approach has been utilized to capture the phase change phenomena inside and outside the injector nozzle. Three different boundary conditions for the outlet domain have been imposed to examine non-flashing and evaporative, non-flashing and non-evaporative, and flashing conditions. Inside the nozzle holes mild cavitation-like and in the near-nozzle region flash boiling phenomena have been predicted in this study when liquid fuel is subjected to superheated ambiance. Noticeable hole to hole variation has been also observed in terms of mass flow rates for all the holes under both flashing and non-flashing conditions.*

1. Introduction

In the field of fuel injection systems for internal combustion engine applications cavitation and flash boiling are two common phase change phenomena. In the fuel injection systems when the local pressure drops below the saturation pressure corresponding to the fuel temperature, there is a strong potential for the liquid fuel to transform to vapor. Cavitation is prevalent for high pressure diesel injectors, while flash boiling generally occurs for direct injection gasoline injectors with elevated fuel temperatures. Cavitation is pressure-driven vaporization occurring at low fuel temperatures, where heat transfer is almost instantaneous; therefore, cavitation is basically inertia-driven. At elevated fuel temperatures saturation vapor density is going to be much higher compared to the one at low fuel temperatures and consequently, considerably more energy is required for phase-transition per unit volume of vapor, compared to low fuel temperatures. Flash boiling is thus a thermal non-equilibrium process unlike cavitation. This phenomenon can be explained better with the help of non-dimensional Jakob number (Ja), $Ja = \frac{\rho_l C_P \Delta T}{\rho_v h_{lv}}$ [1]. Jakob number is the ratio of sensible heat energy available to energy required for vaporization. Higher Ja indicates process is close to equilibrium, since heat transfer time-scale is much lower than flow time-scale, and hence cavitating. In case of lower Ja process is more likely to be in non-equilibrium i.e. flash boiling, as the heat transfer time-scale will not be negligible compared to flow time-scale. The vapor bubbles, forming inside the injector holes, will expand rapidly at the nozzle outlet where the chamber pressure is relatively low. Such phase transformations internally and in the near-nozzle region affect the spray formation and overall charge formation for in-cylinder combustion.

Several numerical studies on flash boiling for GDI injectors are available in the literature. The modeling studies that resorted to bubble based models looked in to mono/poly-disperse bubbles, bubble-to-bubble interaction (collision, breakup etc.) and effect of different turbulence modeling approaches [2, 3]. The modeling studies that utilize empirical coefficients mainly utilizes the Homogeneous Relaxation Model (HRM) [1, 4–8] which represents the phase transition by one equation by estimating the time scale of phase change. The time scale provides the estimate of the deviation from thermal equilibrium. HRM lies in between the two extremes of thermodynamic two-phase models - homogeneous equilibrium model (HEM) and homogeneous frozen model (HFM). In case of HEM, the two-phases are assumed to be mixed perfectly homogeneous and heat transfer occurring contiguously. In real world scenario of two-pahse flows such as bubbly flows instantaneous heat transfer is not feasible. The other extreme, HFM assumes zero heat transfer or heat transfer time-scale to be infinitely long. HRM manages to capture the in-between practical two-phase flow scenarios. Experimental studies available in the literature adopted different optical and laser-based diagnostics techniques to provide insights of the flash boiling phenomenon [9–11]. The experimental investigations revealed - chances of high levels of spray plume interactions under the influence of intense flashing, possibility of considerable flashing at or above 20 K of superheat etc.

The current study wants to focus on development of high fidelity flash boiling models inside and the near-nozzle regions of multi-hole GDI fuel injector. The CONVERGE CFD code has been used [12]. HRM has been coupled with Volume of Fluid (VOF) approach. The previous published works have successfully demonstrated the potential of the CONVERGE code to predict the cavitating two-phase flow in diesel injectors, operating under high injection pressure e.g. Battistoni et al. (2014) [13]. The present work will investigate HRM performance for different thermodynamic conditions - flashing, non-flashing and non-evaporating.

2. MODEL FORMULATION

The problem considered in this study is a 8-hole counter-bored GDI fuel injector, which is denoted as Spray G nozzle in the Engine Combustion Network (ECN)[14]. The internal geometry of Spray G nozzle is not symmetric since it has 8 holes and 5 dimples which results in uneven flow passages. Therefore for realistic predictions full nozzle geometry has been simulated in this study. Details of the cases studied in this work are summarized in Table 1. The conservation equations of mass, momentum, species, energy, turbulence (standard $k - \epsilon$) are solved. Trace amounts of N_2 and O_2 are assumed to be present within the liquid fuel. The source term in species equation of vaporizing species (iso-octane) is modeled by HRM. HRM provides estimate of rate of change of vapor mass fraction i.e. $\frac{Dx}{Dt}$ [12].

$$\frac{Dx}{Dt} = \frac{\overline{x} - x}{\theta} \tag{1}$$

The time-scale θ is calculated as $\theta = \theta_0 \alpha^{-0.54} \psi^{-1.76}$ where $\alpha = void(gas + vapor) fraction$; $\theta_0 = 3.84 \times 10^{-7}$; $\psi = \frac{p_{sat} - p}{p_{crit} - p_{sat}}$.

Table 1. Cases Studied

Parameters	Spray G	Spray G2	Spray GCool
Inj. Press.(MPa)	20	20	20
Chamber Press.(kPa)	600	53	600
Chamber Temp.(K)	573	293	293
Fuel Temp.(K)	363	363	363
Chamber Fluid	Pure N_2	Pure N_2	Pure N_2

3. Results and Discussions

In this work results using 180 μm and 140 μm as base grid sizes have been presented. There are 1.4 million cells for 180 μm base grid size while 2.8 million cells are available for 140 μm base grid size. Smallest cell sizes are 22.5 μm and 17.5 μm respectively. These resolutions are relatively finer than the ones used by Moulai et al. [8]. From thermodynamic considerations it can be assessed that Spray G is non-flash boiling and Spray G2 is moderately flashing, since for Spray G2 iso-octane fuel is subjected to 12 K of superheat and Ja number equal to 24.

For Spray G considerable vapor formation has been observed in the outlet domain, which can attributed to evaporation due to high chamber temperature. SprayGcool has been studied to isolate this issue by making the chamber temperature much lower. Figure 1 unravels the

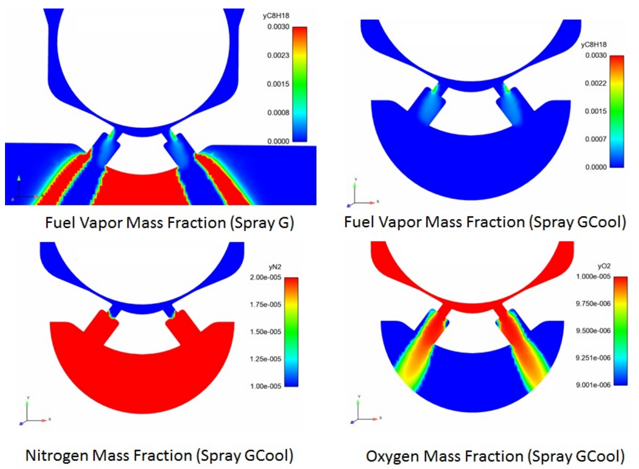

Figure 1. Contours of Spray G and Spray GCool

that the vapor formation for Spray G case is indeed due to the high temperature evaporative environment. The color codings in the contours have been carefully adjusted to analyze the nature of the two-phase composition inside the holes and the counter-bores. It is evident that there is mild vapor formation i.e. cavitation-like phenomenon occurring inside the holes. N_2 and O_2 concentrations are at 1.0e-05 mass fraction inside the holes. However in the counter-bores there is relatively higher presence of N_2 gas. Considering the variation of O_2 mass fraction it can be postulated that counter-bore region is subjected to back-flow of N_2 from the chamber. Spray GCool have been carried out with a smaller outlet domain to save computational time.

For Spray G2 the vapor mass fraction contours on a vertical cut-plane are provided in Fig. 2 and moderate flash boiling is observed in the near-nozzle regions. The left image shows the full

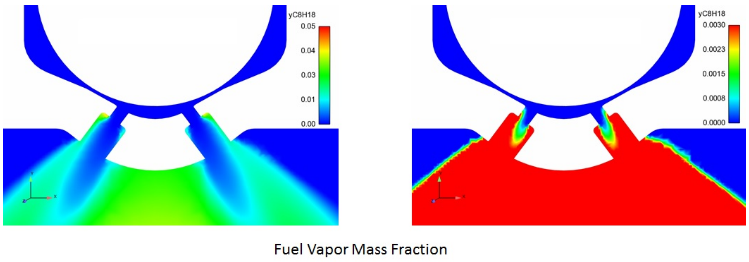

Figure 2. Vapor mass fraction contours of Spray G2

range of variation of the iso-octane vapor mass fraction. Moulai et al. [8] predicted modest level of flashing for Spray G2 condition with the peak mass fraction being 0.03, which is close to the peak mass fraction estimate (= 0.05) from the present study. The right image has an adjusted color coding to unravel the mild vapor formation inside the holes. The chamber pressure for Spray G is 600 kPa and that for Spray G2 is 53 kPa. Spray G2 being a higher pressure differential case with same fuel temperature and nozzle geometry, vapor formation inside the holes is obvious, since Spray G case had vaporization inside the holes. The full-range contour of mass fraction also demonstrates the possibility of plume-to-plume interaction as time progresses.

For both Spray G and Spray G2 hole-to-hole variations have been noticed in terms of mass flow rates. The internal geometry is very asymmetric because of five dimples that narrow down the internal flow passage. More in-depth analysis of hole-to-hole variations is necessary and will be investigated at a later time.

4. Summary

As a summary of the numerical findings it can be mentioned that Homogeneous Relaxation Model coupled with Volume of Fluid approach, implemented in CONVERGE, has been successfully applied to analyze flash boiling and cavitation-like phenomena in a Gasoline Direct Injection Spray G nozzle. Further studies with Large Eddy Simulations and moving needle problems will be undertaken in future.

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