A Study of Near-field Spray Structure under Superheated Conditions of a Gasoline Fuel Spray

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Abstract
A combined experimental and computational study is undertaken to understand the bubble generation and growth of a superheat liquid inside a prototype gasoline injector. Specifically, the spray characteristics resulting from flash boiling can significantly influence the atomization process and near-field spray plume angle. The microscopic spray structure near the nozzle of a single-hole gasoline injector is measured using a shadowgraph imaging technique and correlated to a dimensionless ambient-to-saturation pressure ratio (Pa/Ps) under steady state operation. CFD simulations are carried out to simulate the nozzle flow dynamics and phase change using a Homogenous Relaxation Model (HRM). The results show that the spray structure is critically dependent on the superheat state of the liquid. As Pa/Ps decreases, the liquid is more superheated and the spray plume becomes wider as observed in both experiments and computations. At higher Pa/Ps ratios the effect of the gas-to-liquid density ratio becomes increasingly important on the resulting plume angle.

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Introduction

Liquid fuel atomization and spray formation processes are critical to efficiency improvement and emissions reduction for today’s internal combustion engines. It is well-known that mixture preparation is tightly coupled to reliable ignition and combustion processes when operating the engine under stoichiometric or lean operation. A systematic characterization of the fuel spray structure and investigation on the breakup mechanisms, therefore, has both academic and practical significance.

Liquid atomization and spray characteristics depend on the thermodynamic state of the fuel during injection. Figure 1 shows the thermodynamic processes of different types of injections in a pressure-temperature diagram. Three types of injections can be found depending on the thermodynamic pathway the liquid undergoes during injection. The first scenario called ‘Liquid’ occurs when the ambient pressure is well above the liquid saturation pressure (i.e., a subcooled state). The atomization in this region is influenced by inertial, viscous, surface tension and aerodynamic forces [1, 2] applied on the liquid. Dimensionless numbers such as Weber, Reynolds and air-to-liquid density ratio quantitatively reflect the competition among those forces and correlate with spray characteristics [2]. Another injection type is called “superheat injection” when high temperature liquid fuel is injected into a low pressure environment. As the liquid temperature increases, the saturation pressure increases accordingly and subsequently exceeds the ambient pressure. If the hot fuel is discharged into the low pressure environment, the liquid is considered to be superheated. Due to the thermodynamic instability of superheated state, phase transition from the liquid to vapor takes place within the liquid resulting in vapor bubble generation. The dynamics of the vapor bubbles (e.g., growth, burst) significantly alter the spray characteristics and improve the atomization [3, 4]. Comparing with non-flash boiling sprays, the force associated with the bubble explosion enhances the atomization and vaporization. Finally, further increasing the fuel pressure and temperature beyond its critical point enters the supercritical region. Since no boundary exists between different phases in this region, the atomization can be completed almost instantly [5]. However, supercritical injection can be rarely found in practical applications since the supercritical temperatures of common hydrocarbon fuels are extremely high.

The spray characterization of superheated injection and flash boiling has been studied but still is not completely understood. Brown and York [6] found flash boiling could be used to improve atomization quality. They showed that the droplet size of flash boiling critically depends on the superheat degree of the liquid, which they defined as the difference between the liquid temperature and its boiling point under corresponding ambient pressures (T_f - T_b). Park and Lee [7] investigated the bubble generation of flash boiling sprays inside the nozzle using a specially design transparent nozzle and correlated the internal bubble behavior with external spray characteristics. They found that atomization quality improved at higher superheated conditions. Peter et al. [8] conducted a series of studies on flash boiling spray using water as the test fluid. They identified four different flash boiling regions based on spray structures: non-shattering, partially shattering, completely shattering and flare flash boiling. Allen [9, 10] investigated the droplet size and velocity distribution of flash boiling propane spray using phase Doppler interferometry (PDI). Simões-Moreira and Bullard[11] investigated the evaporation of flash boiling sprays based on Schlieren imaging technique. Their results showed a shock wave existed near the nozzle upon exit of a highly superheated liquid. They attributed the phenomena to the prompt evaporation at the liquid jet surface. Desnous [12] investigated the evaporation of flash boiling sprays using C6F14 as testing fuel. Their results shown that for relatively large size nozzles the droplet velocity increased linearly with superheat degree while the droplet size kept constant.

Flash boiling sprays could also take place during the fuel injection processes in internal combustion engines [13, 14] and influence the mixing and engine combustion. The situation is especially critical for direct injection (DI) gasoline engines where the fuel
injector is mounted on the engine head to directly inject fuel to engine cylinder. The fuel temperature in injector body could be high due to the heat transfer from the engine coolant and combustion species. When the hot fuel is injected into the engine cylinder during the intake stroke, the cylinder pressure could be significantly below the saturation pressure and trigger flash boiling. Due to different atomization processes, flash boiling sprays show unique structure, which need to be well understood. Schmitz et al. [15] investigated the flash boiling spray structure of a high pressure swirl injector based on laser induced exciplex fluorescence (LIEF) technique. They found under flash boiling conditions large amount of fuel mass collapsed towards the injector centerline, transferring the hollow cone spray to a solid cone structure. Moon et al. [16] conducted precise measurements on the pressure distribution inside flash boiling swirl sprays. They found a low pressure region existed near the spray centerline region that could be responsible for the spray collapsing. Mojtabi et al.[17] observed similar spray collapsing structure using a high pressure multi-hole DI injector. Zeng et al.[18] conducted a systematic study on flash boiling spray using a multi-hole DI injector. They identified three different flash boiling regions based on the degree of spray collapsing, namely non flash boiling, transition and flare flash boiling. Later studies on flash boiling spray evaporation [19] and flow formation [20] using the same multi-hole injector as Zeng et al. [17] suggested that the width of liquid jets increased as the fuel became superheated. The interaction between liquid jets from different holes became strong in the spray near field since very limited space available in those region, which may trigger the spray strcture transformation and be responsible for spray collapsing. The initial increase of plume width was the direct reason for the plume interaction. However, it was difficult to acquire measurements of a single plume (especially near the nozzle) of the multi-hole injector since neighboring plumes absorbed the optical access. The effects of superheat and plume-to-plume interaction on flash boiling spray formation are still coupled.

In this study, a prototype single hole DI injector was used to investigate plume behavior under superheated conditions. Microscopic backlit imaging technique was applied to acquire the near-field spray structure. To further clarify the physical mechanism of bubble generation and its impact on spray structure, CFD calculations were carried out based on the homogeneous relaxation model (HRM) and was compared with experimental observations. The objective of current study is to understand the effects of superheat on plume behavior without consideration of plume-to-plume interaction. These findings lay a solid foundation to understand the more complicated multi-hole flash boiling spray formation.

**Experimental Setup and Test Conditions**

Microscopic backlit imaging technique was applied to obtain the near-field spray structure of flash boiling sprays. Figure 2 shows the experimental setup. A high pressure optical accessible chamber was used to provide the ambient pressure and contain the spray. A vacuum pump and a high pressure nitrogen supply were connected to the chamber to provide ambient pressure both above and below atmospheric. During the experiment continuous nitrogen was flowed through the chamber to evacuate the residual fuel droplets. A high pressure prototype single-hole DI injector was mounted on the top of the chamber. A water jacket was designed around the injector to control the fuel temperature. The injection pressure was supplied using a piston-type accumulator. The fuel sprays was illuminated using a high-intensity continuous Xenon lamp and imaged using a high speed CMOS camera (resolution: 640x480, frame rate: 30,000fps). To obtain the magnified view of the near field spray structure, a long distance microscopic lens was mounted in front of the high speed camera. The injection event and image timing was synchronized using a programmable time unit.

![Figure 2. Experimental setup of microscopic backlit imaging](image)

Figure 3 shows a typical microscopic image of the near field spray structure. The spray plume has a 30° angle tilt relative to the injector axis. The image covers a spatial area of 8mm×6mm in the near field of the injector where the plume structure can be seen in great detail. Based on this image, the plume width
and plume angle can be calculated using image processing techniques written in Matlab.

Figure 3. Microscopic image of near-field spray

The test conditions are listed in Table 1. N-hexane was chosen as the test fuel in current study having a boiling of 69°C at atmospheric condition. The injection pressure was fixed as 15MPa. The fuel temperature was in the range of 25°C~85°C. The ambient pressure was 20kPa~200kPa. The ambient pressure was kept at 25±1°C.

Table 1. Summary of Test Conditions

<table>
<thead>
<tr>
<th>Fuel</th>
<th>n-hexane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel pressure (MPa)</td>
<td>15</td>
</tr>
<tr>
<td>Fuel temp. (°C)</td>
<td>25, 35, 45, 55, 65, 75, 85</td>
</tr>
<tr>
<td>Amb. pressure (kPa)</td>
<td>20, 30, 40, 100, 200</td>
</tr>
<tr>
<td>Amb. temp. (°C)</td>
<td>25±1</td>
</tr>
<tr>
<td>Injector</td>
<td>Single hole (L/D=1.5)</td>
</tr>
</tbody>
</table>

The structure of flash boiling sprays is critically dependent on the superheat degree of the injected fuel. In this study, a non-dimensionless ambient-to-saturation pressure ratio (Pa/Ps) was chosen to evaluate the superheat degree. The physical meaning of Pa/Ps is similar to a temperature difference to define the degree of superheat of the fuel [18]. The dimensionless Pa/Ps is preferred due to past experience in correlating with measured data. A previous study [18] on multi-hole flash boiling sprays identified three flash boiling regions based on different values of Pa/Ps with unique macroscopic spray structure presented in each region. When Pa/Ps>1, the spray is non-flash boiling. Individual plumes from each hole of the injector were not interacting. When 0.3<Pa/Ps<1, the spray was in the transition region where spray plumes started to interact with each other due to increased plume width. The multi-hole spray demonstrated the onset to collapse towards the spray centerline. When Pa/Ps<0.3, the spray enters flare flash boiling region where a solid collapsed spray structure is formed due to intense plume-to-plume interaction. Figure 4 shows the test matrix of current study with Pa/Ps value calculated in each test point. The three flash boiling regions are well covered in the test conditions outlined in Table 1.

Figure 4. Pa/Ps and different flash boiling region of each test point

Computational Model

CFD calculations of the internal nozzle flow field are conducted as an additional tool to complement the experimental measurements of spray plume angle. The numerical solver is HRM Foam which has been presented in detail in past works [21]. The flow solver has been demonstrated to compute phase change (including flash boiling) within three-dimensional injector geometries.

A polyhedral computational mesh is chosen to spatially discretize the flow domain. The 3D computational domain extends 5mm upstream of the injector tip to allow resolution of the flow around the injector needle, seat area, and nozzle region. At the outlet of the nozzle, the flow empties into a 3mm diameter hemispherical plenum. The mesh consists of roughly 383,000 computational cells. An extrusion layer of 2 cells lengths is used to resolve the near wall region. The computational grid is limited to resolve the fuel exiting the nozzle in the near tip region since the current model does not predict atomization. A schematic of the grid with emphasis on the injector nozzle area is shown in Figure 5. The target grid size in this region has a length scale of 30μm.
Figure 5. Computational mesh of the needle region for the CFD nozzle flow simulations.

The transient numerical solver is run at the maximum lift condition to steady state at each operating condition. The inlet and outlet boundaries are prescribed with constant pressure conditions equaling the injection and ambient pressure, respectively. A second order scheme is used for the divergence terms and no-slip boundary conditions are imposed at the walls. These computations used an isenthalpic assumption, heat transfer is neglected. A fluid properties table of equilibrium values is created using the REFPROP database and read as input to the flow solver. Turbulence closure is modeled using the k-epsilon approach.

Spray Image Processing Procedure

Previous studies [18-20] have shown that bubble growth inside liquid jet could significantly enhance spray plume width under flash boiling conditions. To quantify the increasing behavior of plume width under superheat conditions, plume angle was calculated from both the experimental and CFD calculation results. The procedures to derive the plume angle will be discussed in this section.

A raw image acquired from the experiment is shown in Figure 6a. The image is thresholded to convert to a binary image that can be used to calculate the spray boundary. Figure 6b shows the identified spray boundary superimposed onto the spray image. To calculate the plume angle, a least square linear regression algorithm was used to fit all the pixels on the spray boundary to straight lines, as shown in Figure 6c. It can be seen that the plume development is well approximated by the two lines. The plume angle is obtained by calculating the angle between those two lines, as shown in Figure 6d. A systematic testing has shown that the image processing algorithm is insensitive to threshold level value and able to provide reliable results for both experimental images and CFD calculation output.

Figure 6. Image processing procedures to calculate the spray plume angle

The CFD images are processed using the same post-processing algorithm as described for the experimental results. As noted in past work, the current flow solver uses a “submerged” fluid approach. Namely, the entire domain is filled with fuel at the appropriate thermodynamic state. To separate the fuel flowing through the nozzle from the fuel in the ambient, a passive tracer is initialized at the inlet to ‘tag’ the injected fuel which emanates from the inlet boundary. Namely, the tracer demarks separation between the nozzle flow and ambient as shown in Figure 7. Here, a tracer value of 1 denotes fuel emanating from inlet boundary and a tracer value of 0 is the ambient fuel. Gray scale shading in between symbolized mixing of the injected and ambient fluid.

Results and Discussions

The degree of superheat can significantly influence the spray structure due to the bubble generation and growth. When the valve is fully open, the flow inside the nozzle gradually achieves steady state and the plume structure remains relatively stable. In this section, we will first discuss the steady state spray structure under various superheat conditions to reveal the impact of superheat degree. A systematic characterization and understanding of the spray development is undertaken.
Spray structure and vapor growth

Figure 8 shows the near field spray structure at various superheat conditions. The images are taken at constant ambient pressure with varying fuel temperature to cover non-flash, transition and flare flash boiling regions. When $Pa/Ps=2.0$, the fuel is not superheated and little-to-no bubbles grow inside the liquid resulting in a relatively small plume angle. The atomization of liquid jet in this region mainly depends on the competing effects among the inertia force, viscous forces, surface tension forces and aerodynamic forces. Reducing $Pa/Ps$ to 0.62 shifts the spray into transition flash boiling region where vapor bubbles form and grow inside the liquid as indicated by the increased plume width. Further reducing the $Pa/Ps$ to 0.44 continues this trend. When reducing $Pa/Ps$ to 0.24, the liquid fuel is severely superheated and the liquid jet is in flare flash boiling. Due to the very high superheat degree in this region, tremendous amount of vapor bubbles are generated inside the bulk liquid.

The change in vapor growth internal to the nozzle is modeled by the CFD calulations. The results are shown in Figure 9 for the extreme cases of non-flashing injection ($Pa/Ps=2$) and flare flash boiling ($Pa/Ps=0.24$). The images show the quality (i.e., vapor mass fraction) in the nozzle, counter bore, and exit plenum regions for cells that have a tracer value (as defined in Figure 7) greater than 0.25. This approach was chosen to visually remove the quality contours of the ambient environment and focus on the ‘flow-through’ liquid originating from the nozzle inlet. For $Pa/Ps=2.0$, only trace amounts of vapor mass (< 1%) are evident from the calculations. For $Pa/Ps=0.24$, an increase in vapor mass is present as expected. The vapor begins to form near the inlet of the nozzle and grows as the fluid exits into the plenum. The fluid quality in this case ranges from 2-5% at the plenum exit.

The implications of this result for a production-intent gasoline multi-hole injector is that the plume angle increase under flash boiling conditions can lead to plume-to-plume interaction when several nozzles are closely positioned on the injector tip. The significant enlargement of each plume results in a remarkable difference in spray structure (i.e., spray collapse) and fuel distribution compared to non-flash boiling conditions [19, 20]. Under non-flash boiling conditions, liquid jets from different nozzles have little interaction resulting in a well-defined targeted footprint.
**Plume angle variation with Pa/Ps**

Figure 10 shows that the experimentally measured and computed plume angles vary with Pa/Ps at all test conditions. The error bar in the experiments indicate the maximum and minimum plume angle obtained among 20 different injection events. The prediction from the calculation follows the general trend of the experimental results, indicating the HRM model is capable to captured the effect of phase change under superheat conditions. Under non-flash boiling conditions, both the experimental and calculation shows little variation of the plume angle with superheat degree. As discussed before, the plume angle under non-flash boiling conditions depends on the various forces applying on the liquid jet during breakup. Under superheat conditions, however, the spray plume angle shows a remarkable increasing trend with increasing superheat degree when lower Pa/Ps values are achieved. A good correlation exists between the plume angle and superheat degree. At Pa/Ps<1 the plume angle growth is very fast as the fuel is flare flash boiling (Pa/Ps approaches 0). In general, the model predictions show good qualitative agreement with the experiments over the range of test conditions. The model tends to under-predict the plume angle pressure ratio decreases from a value of 1, which could be a by-product of the submerged fluid formulation of the flow solver.

\[ \theta = f\left(\frac{\rho_a}{\rho_l} \frac{Pa}{Ps}\right) \]  

(1)

A simple empirical correlation was developed using the experimental measurements in Figure 10. The correlation includes the traditional expression of density ratio in addition to the influence of phase change due to flashing (see eqn 2).

\[ \theta = 29.7 \left(\frac{\rho_a}{\rho_l}\right)^{0.09} + 2.5 \left(\frac{Pa}{Ps}\right)^{-1} \]  

(2)

The correlation is plotted against the experimental measurements and is shown in Figure 11. Here a perfect fit would indicate all of the data point lying on a straight line of slope=1. The regression equation has a reasonable $R^2 = 0.96$ with most of the points within a +/-10% band (dashed lines) about the measured value.

**Empirical plume angle correlation**

The experimental data in Figure 10 provide an opportunity to develop a correlation for near tip spray plume angle spanning flashing and non-flashing conditions. Well-known correlations for spray plume angle (from a single hole nozzle) are present in the literature [22]. Generally speaking, these empirical correlations are strong functions of a dimensionless ambient ($\rho_a$) to liquid ($\rho_l$) density ratio raised to a exponent since the experimental data sets under consideration are derived from high gas density and/or vaporizing ambient conditions typical in diesel engine applications. Under flash-boiling, the superheat degree, as reflected in the pressure ratio Pa/Ps, strongly influences the plume angle as eluded to in Eq. 1. As the fuel transitions to non-flashing operation, one can intuitively imagine that the physics driving the exit plume angle changes, eventually recovering similar trends as observed for past correlations previously described.

\[ \theta = f\left(\frac{\rho_a}{\rho_l} \frac{Pa}{Ps}\right) \]  

(1)

**Figure 10.** Experimental and CFD predictions of steady state plume angle varies with Pa/Ps

**Figure 11.** Empirical correlation of spray plume angle.
The correlation is a useful tool to highlight the trade-off between the contribution of the density ratio and the contribution of the pressure ratio to the resulting plume angle of the spray. Figure 12 shows that at $Ps/Ps < 0.2$ (highly flashing conditions) the pressure ratio plays a dominant role in the resulting exit angle (up to 64% at $Pa/Ps=0.1$). At $Ps/Ps=0.2$, both terms contribute equally to the exit angle. At higher pressure ratios, the effect of the density ratio is dominant, especially as $Pa/Ps$ nears 10, where the density ratio accounts for nearly 100% of the exit angle. This trend is consistent with earlier citations of plume angle predictions for diesel sprays.

Summary and Conclusions

A combined experimental and computational study was carried out in this paper to understand the effects of bubble generation and growth on microscopic spray structure under superheat conditions. The near-field jet structure of a single hole prototype direct-injection gasoline injector was obtained based on backlit microscopic imaging technique. A Homogeneous Relaxation Model (HRM) based calculation was implemented to capture the detail vapor dynamics internal the nozzle and spray plume angle exiting the injector. The following conclusions can be made:

1. The microscopic spray structure critically depends on the thermodynamic states of the liquid injected. Specifically, a remarkable increase of the plume width and plume angle can be seen under superheat conditions when the influence bubble generation and growth becomes dominant.

2. The near-field spray plume angle depends on different factors under non-flash boiling and flash boiling conditions. The ambient-to-liquid density primarily decides the plume angle of non-flash boiling sprays while superheat degree becomes dominant for flash boiling conditions. A quantitative correlation was developed to reflect the relative importance of those factors under different superheat conditions.

3. The HRM model is able to capture the general trends of plume angle variation with superheat degree. The model under predicts the plume angle under flare flash boiling conditions. The under-prediction could be an artifact of the single fluid, submerge nozzle assumption of the model.

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References