Experimental study on flash-boiling spray structure of multi-hole gasoline direct injection injector in a constant volume chamber

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Abstract
The macroscopic and microscopic characteristics of flash-boiling spray were experimentally investigated with various optical measurement techniques. The effects of ambient pressure and fuel temperature on flash-boiling characteristics in multi-hole gasoline direct injection injector were analyzed. The analysis was focused on the spray structure and atomization droplet size distributions. In order to increase the understanding of the flash-boiling spray targeting, three injectors with different spray patterns were investigated under strong flash-boiling condition. The results show that ambient pressure and fuel temperature have significant influence on flash boiling. Both lower ambient pressure and higher fuel temperature could accelerate the flash-boiling process. For the macroscopic characteristics, similar influences could be found with the ambient pressure decreased by 0.4 bar and the fuel temperature increased by 10°C. Further, significant difference could be found within cold-jet spray and strong flash-boiling spray, such as the spatial structure. The spray structure always turns from hollow cone into solid when flash boiling occurs. With a higher fuel superheat degree, the spray droplet distribution moves toward smaller sizes and let the larger droplets reduce due to the promotion of atomization. For the strong flash-boiling spray, the Sauter mean diameter has decreased by 50% compared with cold-jet spray. There is a corresponding relationship between collapsed flash-boiling spray target and weighted geometric center of the injector. Spray collapse could be avoided by increasing the plume distance.

Keywords
Gasoline direct injection injector, flash-boiling fuel spray, experimental characterization, spatial structure, laser induced fluorescence

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1. Introduction
The diesel engine suffers from higher noise and vibration level, a limited speed range, and costly exhaust after-treatments.1,2 Hence research has been done to develop an engine which would exhibit a fuel economy similar to a diesel engine and, at the same time, incorporate the features of a PFI engine, like lower emissions. The gasoline direct injection (GDI) engine promises to be a good candidate for such an engine. These engines operate on the concept of direct injection of gasoline into the cylinder, which is known to enhance the specific fuel consumption and the power supply greatly as compared to the PFI system.3,4

In addition to this, directly injecting gasoline into the combustion chamber provides many other critical advantages. For one thing, the knock tendency could be relieved because of the retarded injection events, which lower the in-cylinder temperature due to the liquid fuel evaporation.5 For another, the precisely controllable injection timing and pulse width makes a

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fast response during the transient conditions.\textsuperscript{6} Additionally, the major differences of the GDI system, compared with PFI system, are in the mixture preparation process. There is a lag between the injection of the fuel and the beginning of the intake stroke. This causes a film of liquid fuel to accumulate near the intake valve area.\textsuperscript{7} This fuel wall-wetting causes metering errors and higher UHC emissions. The direct injection of gasoline may be able to overcome these problems since the gasoline is injected directly into the cylinder. The GDI engine also offers the potential for leaner combustion and lower cylinder-to-cylinder air–fuel mixing variation.\textsuperscript{7,8} During cold starting, fuel vapor pressure is much lower and this leads to a lot of liquid fuel getting collected at the intake port area of the GDI system leading to increased UHC emissions.\textsuperscript{9,10}

The high fuel pressure employed in the GDI system leads to a much higher degree of fuel atomization and fuel vaporization rate. Therefore, GDI engines can potentially achieve cold-start UHC emissions. For GDI engines, fuel can be injected in the cylinder in the intake or compress stroke. Especially for the catalyst heating conditions, the gasoline could be injected very late in the compress stroke, which might be 100° before the TDC. This can be of benefit to the combustion stabilities because the retarded injection event enhances the stratified mixture near the spark plug. Moreover, this also will help in significantly reducing the specific fuel consumption as compared to the PFI system.\textsuperscript{11,12} Further, the piston bowl of the GDI engine guides the charge flow to run in the suitable direction and promotes a higher tumble motion. In spite of the above mentioned advantages of the GDI system, it also suffers from several drawbacks. The first drawback is due to its mixture preparation strategy which provides very little time for fuel–air mixing. Second, due to its high pressure operation, the high velocity fuel emerging from the fuel injector may impinge onto the piston head forming a liquid film near the piston and promoting the emission of UHCs.\textsuperscript{13} Common to say, injection spray plays a significant role both in the GDI system and PFI system, so the spray characteristics might largely determine the performance of the engine, especially in GDI engines.\textsuperscript{14,15} Therefore, it is very important to study the atomization and oil–gas mixing process of direct-injection gasoline engine.

During the process of high pressure injection, fuel droplets will show a sudden drop in pressure at the nozzle outlet. For the injection process of sub-cooled liquid, the pressure in the combustion chamber is usually higher than the saturated steam pressure of fuel at the current temperature. Therefore, the spray development is dominated by the cold jet mode. However, the temperature of fuel in the injector is normally high due to the heat transfer from the engine cylinder head and combustion gas. If the combustion chamber pressure is lower than the fuel saturated vapor pressure at current fuel temperature, overheating fuel will experience rapid boiling and atomization, namely the flash-boiling spray process.\textsuperscript{16,17} In the early stage, the research of flash-boiling spray was mainly focused on diesel engine.\textsuperscript{18} In recent years, due to the increasing attention of many research institutions on GDI engine, the research on gasoline is gradually increasing. Existing researches show that the spray droplet diameter of flash-boiling spray is smaller, the vaporization rate increases correspondingly, and the mixing process of fuel and intake charge will also be strengthened, so it has certain potential in improving the combustion thermal efficiency.\textsuperscript{19,20}

Aleiferis et al.\textsuperscript{21} studied the influence of spray on the mixture formation and combustion under the condition of superheated fuel with multi-hole injector, and the results show that the gasoline flash-boiling spray would have an impact on the formation of mixture. Li et al.\textsuperscript{22} studied the flash-boiling characteristics of the multi-hole injector under lower backpressure and considered that the flash-boiling spray is highly sensitive to the environmental pressure. Xu et al.\textsuperscript{23} also conducted many researches on gasoline flash boiling and believed that flash-boiling spray had potential advantages in improving the emission of direct-injection gasoline engines.\textsuperscript{23,24} On the basis of previous studies, Muhammad et al.\textsuperscript{25} and Christophe et al. carried out a study about the influence mechanism of flash-boiling spray collapse. It was found that the distance of each oil plume would have a direct impact on spray collapse. By optimizing the oil plume arrangement, the collapse problem in the case of severe flash boiling could be effectively reduced.

With the research going on, a large number of advanced optical testing technologies are involved in the research on atomization process. The research on atomization morphology is also gradually deepened.\textsuperscript{26} At present, the existing research results mainly focus on the study of gasoline alternative components, such as n-heptane and octane.\textsuperscript{27} These alternative components have simplified molecular structure which could be of benefit for comparison. After all, the actual gasoline could not be simulated well by the alternative due to the complex composition in it.\textsuperscript{28} For example, the distillation ranges of these alternatives are very different from actual gasoline. Based on these researches, flash-boiling macroscopic and microscopic characteristics have been investigated with actual gasoline by using various optical diagnostic techniques in current work. The present study also aims to provide further information on the spatial structural transformation of the flash-boiling sprays with a statistical emphasis about...
the influence of spray targeting on flash-boiling characteristics.

2. Experimental section

2.1. Experimental engine and test equipment

2.1.1. Spray macroscopic characteristics test. The main objective of this research is to investigate the practical flash-boiling characteristics under simulated conditions with conventional gasoline fuel. Further, the spatial structure of superheated spray would be reconstructed by spray targeting scanning on various target layers. A constant volume chamber with three 100 mm diameter quartz windows was used for the investigation. For the test, the inside pressure was varied from 0.4 to 1.5 bar absolute pressure using a vacuum pump and a high pressure nitrogen gas cylinder. The ambient temperature was kept consistent by nitrogen airflow. A five-hole GDI injector was applied and mounted at the top or side of the chamber according to different test purpose. For high speed imaging test, the imaging set-up consisted of Photron high speed camera, LED light source, and programmable timing unit (PTU). While for spray targeting test, the high speed camera was replaced by an ICCD and the light source would be an Nd:YAG laser. During the test, the PTU was used for synchronizing the injection events with the trigger of lighting. The schematic experimental set-up is shown in Figure 1.

2.1.2. Spray microscopic characteristics test. In this paper, spray particle and spray droplet size distributions in real were measured by Malvern Spraytec laser diffraction system (LDS). Three hundred millimeter lens and 36-element log-spaced silicon diode detector array have been applied in the test system, by this way, the LDS is capable of detecting particle sizes from 0.1 to 900 μm. The constant volume chamber was placed between LDS collimating optics module and detector module. HeNe laser goes through the spray plume and the diffraction spot could be detected by the detector. The schematic experimental set-up is shown in Figure 2. In order to clarify the micro-characteristics of flash-boiling spray, droplet size measurements were made at different distance downstream of the nozzle tip (Z = 30 mm and Z = 50 mm). The injection pulse width was set to 1.5 ms. Each measurement was taken up to 100 pulses at an injection rate of 10 Hz.

The fuel temperature was conditioned by a water jacket mounted on the vessel. In order to keep the fuel temperature constant, a water jacket was designed to heat or cool the injector. The water temperature, which could be set within −10 to 90°C, was adjusted by an independent heat exchanger accurately. A thermocouple placed in contact with the injector measured the injector tip temperature. The injection duration was set to 3 ms and the injection pulse frequency was limited to 1 Hz in order to guarantee that the fuel temperature was as close as possible to that of the injector tip. In order to avoid the temperature fluctuations, only six injections with 1 Hz were carried out in test. The heating system uses the value measured by thermocouple as feedback for controlling the injected fuel temperature precisely. Because of the heat transfer losses, the water temperature may not be equal to the fuel injected.

2.2. Test conditions and data processing

In this study, a high-quality gasoline with an octane number of 95 was selected as the test fuel. The test conditions are listed in Table 1. The ambient pressure ranged from 0.4 to 1.5 bar. The fuel temperatures were adjusted to 30, 40, 50, and 65°C separately by the heated water jacket around the injector. The injection pressure was fixed at 100 bar, and the injection duration was 1.5 ms. The spray widths and penetration were

![Figure 1](image-url) The experiment set-up: (a) high speed imaging test and (b) spray targeting test. ICCD: Intensified Charge Coupled Device; LED: Light Emitting Diode.
extracted from the captured images. The procedure is depicted in Figure 3. Six injection events and a background image were captured. The background image was subtracted from the averaged six injection images and the separated spray image could be acquired. In the averaged image, the edge of the spray was obtained from the raw image. Finally, the spray width was obtained by measuring the distance from the left side to the right side of the spray because of the good repeatability.

3. Results and discussion

As mentioned above, the aim of this work was to study the flash-boiling characteristics under various degrees of superheat conditions. Several combinations of atmosphere pressure and fuel temperature were set for measuring the spray structure. In the present study, the morphology development under various flash boiling condition were recorded by high speed imaging technique.

3.1. Effect of ambient pressure and fuel temperature on spray structure

In this section, the spray characteristics obtained with four fuel temperatures and five ambient pressures were compared to each other for analysis. To illustrate the influence of the superheat degree on the spray structure, a photograph of sprays under various ambient pressure and fuel temperature conditions is shown in Figure 4. These figures, which are taken at 1.5 ms after start of injection (ASOI), highlight that significant effects of ambient pressure and fuel temperature could be found on spray structure. With the fuel temperature increased, the spray plumes' penetrating direction changed. At the same time, the penetration of the spray also changed obviously. This transformation also could be observed with the ambient pressure reduced at specific fuel temperature. More details could be found in this figure, where the interaction between different spray plumes is different. All of the spray plume has its individual identification at the lower superheat degree.
of $T_{\text{fuel}} = 30^\circ \text{C}$ and $P_{\text{amb}} = 1.5$ bar. The interaction between different plumes is negligible. In addition, the spray widths stay constant when the fuel temperature raised from $30^\circ \text{C}$ to $65^\circ \text{C}$ under 1.5bar ambient pressure. By contrast, at $T_{\text{fuel}} = 65^\circ \text{C}$ and $P_{\text{amb}} = 0.4$ bar, that is the higher superheat degree for the light fraction in gasoline, the spray plumes were found to gather with each other and collapsed to form a single solid spray, then the spray width decreased. Under this condition, no individual spray plume from each nozzle can be identified because of the so-called spray collapse. According to Mojtabi, this is caused by a transition from liquid to vapor with a drop in pressure. The enthalpy of the flash-boiling spray drops exceeds the saturated liquid enthalpy and fast bubble growth would occur. Consequently, the bubbles undergo a rapid expansion process, which results in a rapid bursting into small droplets. More droplets might spread out toward the radial direction of the spray due to the momentum of lower droplets and the interaction between liquid phase and gas phase. The spray collapse under flash-boiling conditions was attributed to low-pressure zone caused by the high speed jets and the jets overlap. On the macroscopic perspective, the spray shrinks to a slim pattern. In general, equivalent effects on spray structure can be achieved both by 0.4 bar ambient pressure reduction and $10^\circ \text{C}$ fuel temperature increase within test conditions.

Figure 5 shows the temporal evolution of the sprays under various conditions. For a better comparison, the condition of cold jet (or non-flash-boiling), mild flash boiling, and strong flash boiling were selected as references. The spray photographs are presented from 0.2 to 1.1 ms ASOI for each condition. As these figures depicted, there were significant difference among the plume morphologies under these conditions. In the cold-jet spray images, there is limited interaction between the plumes. By contrast, under the other conditions, different levels of collapse were seen by the spray penetration. Especially for the strong flash-boiling condition, the jets are collapsed toward the injector center and the plumes cannot be separated. Under flash-boiling conditions, during the initial injection stage, some small vortexes occurred by the side of spray tips, which means an intense air entrainment. With the elapse of time, the vortexes grew and were dragged to be the shape of feather by spray plumes. Due to the gathered spray plumes, the spray penetration was expected to be increased monotonously with the superheat degree strengthened after fully developed. However, the penetration of mild flash-boiling spray seems to be the shortest and has a medium spray collapse degree, as illustrated in Figure 4.

As stated in Zhang et al., the droplet size becomes very small under flash-boiling conditions. During the injection, the droplet velocity may slow down and spread toward radial direction due to the momentum
Thus, the spray penetration would be shortening as the air inside the spray cone is accelerated. This explains why the mild flash-boiling spray penetration is shorter than that under non-flash-boiling condition. However, that is not the case under strong flash-boiling condition. Although the droplet size at the condition of lower ambient pressure and higher fuel temperature is smaller than the other two
conditions, the momentum exchange with gas in the spray center reduced because of the spray collapsing. In order to further reveal the influence of spray collapse on spray structure, a spatial analysis of spray characteristic is given hereinafter.

To further reveal the effect of the superheated fuel on the spray structure, a three-dimensional map of the entire flash-boiling spray structure is illustrated. The three-dimensional map is constructed by stacking several two-dimensional spray target configuration planes which were collected with an ICCD. Figure 6 shows the experimental principle in capturing fluorescence images. The cross-section in arbitrary distance from injector nozzle would be illuminated by the laser sheet which vertically passes though the spray cone. Various two-dimensional cross-section images can be captured by offsetting the laser sheet and ICCD camera simultaneously. To produce a laser sheet thin enough, the 266 nm wavelength of UV laser output from an ND:YAG laser is passed through cylindrical and spherical lens. The thickness of the laser sheet for measurements was 2 mm. A 360 nm filter, with a 20 nm band pass, was used for filtering the stray light.

As shown in Figure 7, some obvious differences could be found among these typical conditions. Under cold-jet spray condition, the jets penetrate in a straight line without any interaction during the entire injection procedure. In comparison with cold-jet sprays, the spray structure under superheated conditions is noticeably different. During the initial spray period, the jet-to-jet interaction becomes stronger at higher superheat degree. With the development of fuel spray, the degree of collapse weakened in the far field and the focused jets separated under mild flash-boiling condition. This is mainly because during the initial spray period, much of spray particles are pushed to the space between the plumes and the adjacent plume interaction keeps strong. However, the jet interaction weakens because of the relatively lower superheat degree and further jet-to-jet distance. In comparison to the other conditions, the degree of collapse maintained strong in the entire injection procedure for strong flash-boiling spray. In addition, the spray spatial structure transformed from hollow cone to solid.

3.2. Effect of ambient pressure and fuel temperature on spray droplet sizing

For flash-boiling spray, the fuel was heated to raise its temperature to higher than the saturation temperature under specified ambient pressure. Bubbles may generate under flash-boiling conditions and these bubbles push against each other and “micro-explosion” would come into being inside the liquid droplets. After these bubbles break up, smaller droplets may generate, which could further promote atomization. Spray droplet size distributions at two planes downstream from the injector tip under different flash-boiling conditions are illustrated in Figure 8. In these figures, same flash-boiling conditions as Figure 5 were chosen for comparison. Each data point represents a size band of particles and the value of the data point represents the volume frequency that is within that band. With a higher fuel superheat degree, the distribution moves toward smaller sizes and causes the larger droplets size reduced due to the promotion of atomization. In addition, for different measurement distance downstream of the nozzle tip, the particle diameter may be smaller with longer distance, suggesting that the spray secondary breakup plays a major role in the droplet size. At nearer distance \((Z = 30 \text{ mm})\), where the liquid spray had not completely developed into dispersive droplets, larger droplets were present at this time.

The above results show that the significant effect on droplet size could be found under different flash-boiling conditions. In order to highlight the effect of flash boiling on droplet size distribution distinctly, several related indicators were chosen for further study. The Sauter mean diameter (SMD) is an important parameter to investigate spray development and droplet formation. For this reason, SMD was compared with the experimental data under various flash-boiling conditions in this study. SMD is defined as the total volume-to-area ratio of the atomized droplets within the injection region in this test. The defining formula is

\[
D_{32} = \frac{\int_{D_{\text{min}}}^{D_{\text{max}}} D^3 \, dN}{\int_{D_{\text{min}}}^{D_{\text{max}}} D^2 \, dN}
\]

The characteristic diameter is another important parameter for expressing the droplet size in terms of injected fuel. In total, three characteristic diameters with different volume fraction of droplet were used.

![Figure 6. Experimental principle for fluorescence images capture.](image-url)
which is defined in a format of $D_{XX}$. The XX represents XX% of the total injected spray volume which is made up of fuel droplets with diameters smaller or equal to these values. The corresponding value is calculated based on the cumulative volume percentage mentioned above. In this paper, figures show error bars representing 95% confidence. The characteristic diameters adopted in this study are $D_{10}$, $D_{50}$, and $D_{90}$. As shown in Figure 9, the $D_{90}$ tends to decrease significantly with higher fuel superheat degree, indicating that flash-boiling spray could produce fewer large size droplets than cold-jet spray. For the strong flash-boiling spray, the $D_{90}$ has decreased by 55% compared with cold-jet spray. This is mainly because the enhanced evaporation and bubbles inside the droplet breaking up make the larger droplets be smaller ones. As atomization involves the formation of liquid fuel droplets in the fuel spray vapor, most of the droplet sizes were smaller than 20 $\mu$m, which might be beneficial to the soot emission under some extreme engine operating conditions, such as higher load and transient conditions. Similar effect also could be found for $D_{10}$,

![Figure 7](image-url)  
*Figure 7.* Spray targets on various layers in different flash-boiling conditions: (a) cold-jet spray, (b) mild flash-boiling spray, and (c) strong flash-boiling spray.

![Figure 8](image-url)  
*Figure 8.* Droplet size distributions under different flash-boiling conditions: (a) $Z = 30$ mm and (b) $Z = 50$ mm.
$D_{50}$, and SMD and the value decreased by 48, 53, and 50%, respectively.

### 3.3. Effect of spray targeting set-up on collapse

The low pressure zone generated by the radial diffusion of the fuel droplets between the adjacent jets would cause the overall collapse. As a result, the spray targeting will have an effect on the degree of collapse of the flash-boiling spray. At the same time, the injector flow rate of different holes might also be a considerable factor for the generation of low pressure zone between adjacent jets. Therefore, two parameterized variants might contribute to the weighted average distance $X$: $L_i$ (distance between each spray target and geometric center of all the targets), $f_i$ (flow-rate ratio of each jet)—equation (2). Spray collapse degree $Y$, which represents the ratio between spray penetration and...
maximum spray width, can be expressed by the ratio of $S_t$ over $N_t$—equation (3)

$$X = \frac{L_1 \times f_1 + L_2 \times f_2 + \ldots + L_i \times f_i}{f_1 + f_2 + \ldots + f_i}$$

$$Y = \frac{S_t}{N_t}$$  (3)

$X$ displayed in equation (2) was suggested as the compactness of space in spray cone, $Y$ displayed in equation (2) was suggested as the degree of spray collapse. In this paper, three injectors with different spray targeting were used to study the effect on spray collapse. Figure 10 shows the targets and weighted geometry centers of the three injectors. The spatial distribution and basic parameters of the injectors used in the test are shown in Figure 11. The percentage beside the spray plume in the figure is the flow ratio of the corresponding nozzle, which indicated as $f_i$ in equation (2).

Figure 12 shows the macro-morphology contrast of different injector spray under strong flash-boiling condition. Different injector axes are maintained in vertical direction to ensure comparability. Spray collapse might happen with all of the injectors under strong flash-boiling conditions. The collapse spray seems to be a thicker plume and the penetration direction has some relationship with the weighted geometric center.

Figure 13 shows the corresponding relationship between the spray collapse degree $Y$ and the target weighted average distance $X$ at different times. It can be found from the figure that the collapse degree of spray is different at various times. The spray collapse degree is lower in the initial period under strong flash-boiling condition and higher in the final period. The collapse degree of the flash-boiling spray decreases monotonically with the expansion of spray target.
A certain linear relationship could be found between the weighted average distance and the collapse degree. In general, the results show that the flash-boiling spray collapse degree could be reduced by optimizing the spray targeting configuration, such as increasing the interval of spray jets.

4. Conclusions

In this study, the flash-boiling sprays from a multi-hole DI injector are systematically characterized using various optical diagnostic techniques. Large amount of data and information concerning the flash-boiling formation process are generated and analyzed. Based on those results, the physics involving in the flash-boiling spray formation are examined. The main conclusions are as follows:

1. The structure of flash-boiling sprays is dominated by the superheat degree, which is denoted by the ambient pressure and fuel temperature. Spray penetration and plume width show strong correlation with the ambient conditions.
2. Both lower atmosphere pressure and higher fuel temperature could accelerate the flash-boiling process. In the macroscopic level, there would be the same effect between the atmosphere pressure decreased by 0.4 bar and the fuel temperature increased by 10°C.
3. A significant difference could be found within cold-jet spray and flash-boiling spray. The spray structure always turns from hollow cone into solid when flash boiling occurs. The flash-boiling spray will be less sensitive to the fuel temperature when the injection pressure is increased.
4. With a higher fuel superheat degree, the distribution moves toward smaller sizes and let the larger droplets reduce due to the promotion of atomization. For the strong flash-boiling spray, the D90 has decreased by 55% compared with cold-jet spray. Similar effect also could be found for D10, D50, and SMD and the value decreased by 48, 53, and 50%, respectively.
5. There is a corresponding relationship between collapsed flash-boiling spray target and weighted geometric center of the injector. Spray collapse could be avoided by increasing the plume distance.

Declaration of Conflicting Interests

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