# FUEL IMPINGEMENT ANALYSIS OF FLASH-BOILING SPRAY IN A SPARK-IGNITION DIRECT-INJECTION ENGINE

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Fuel impingement has been recognized as one of the major causes for the soot formation in spark-ignition direct-injection (SIDI) engines. Previous study demonstrated that flash-boiling fuel spray provided desirable spray structure with shorter penetration, more homogeneous fuel distribution, smaller droplets and better evaporation. However, it is still unknown whether the flash-boiling spray is capable of reducing fuel impingement compared with the conventional non-flash-boiling spray. In this study, crank-angle resolved Mie-scattered spray images for multiple cycles are recorded to investigate the spray impingement phenomenon in an optical SIDI engine for both the non-flash-boiling spray and flash-boiling spray. An eight-hole direct-injection injector is utilized, and gasoline fuel is heated to achieve flash-boiling spray condition. Image processing algorithm is developed to reveal the fuel impingement in a quantitative manner. It is found that the flash-boiling spray is effective to reduce the overall fuel impingement. In addition, the cycle-to-cycle variation of fuel impingement is demonstrated for both the non-flash-boiling spray and flash-boiling spray.

Keywords: Fuel Impingement, Direct-Injection Spark-Ignition Engine, Flash-Boiling Spray

## 1. INTRODUCTION

The spark-ignition direct-injection (SIDI) engine has gained popularity in today's vehicle market, as it offers reduced fuel consumption, decreased harmful emissions, accurate fuel metering, and fast transient response[1]. In SIDI engines, fuel is directly injected into cylinder, and the ignitable fuel-air mixture needs to be well prepared within the limited time before spark occurs for board engine speed and load ranges. Therefore, the quality of the fuel-air mixture is one of the key control factors for SIDI engine.

To accelerate the fuel atomization and evaporation, high fuel injection pressure is usually employed. Unfortunately, high fuel injection pressure results in excessive spray tip penetration which causes fuel impingement on the engine cylinder, and possibly dilutes the engine lubrication. Likewise, liquid fuel can easily splash on the piston which leads to poor fire and increases the soot and unburned hydrocarbon (HC) emissions[2-6]. In addition, it has been recognized that a large fraction of cycle-to-cycle variability in emissions can be attributed to the uncommon combustion events that take place at or near surfaces inside the cylinder.

Recently, more attention has been put on the effect of higher fuel temperature. As long as the fuel temperature is above its boiling-point temperature or the ambient pressure is below saturation pressure, the injected fuel experiences a so-called flash-boiling[7-9] phenomenon. The flash-boiling spray is typically a desirable spray with shorter penetration, much faster evaporation[10-14] and smaller droplets[15]. Zhang et al.[16-19] utilized particle image velocimetry (PIV) technique to study the break-up mechanisms of flash-boiling spray. However, it is still unknown whether the flash-boiling spray is capable of reducing fuel impingement compared with conventional non-flash-boiling spray.

In this study, crank-angle resolved Mie-scattered spray images of fifty consecutive cycles are recorded in a single-cylinder optical SIDI engine under two conditions: 1) flash-boiling spray and 2) liquid spray (i.e. non-flash-boiling spray). An eight-hole SIDI fuel injector is used for both conditions. Gasoline fuel is heated up to 90 ℃ to achieve the flash-boiling characteristics. Image processing algorithm is developed to reveal the fuel impingement in a quantitative manner. Moreover, the cycle-to-cycle variation of fuel impingement is compared for both flash-boiling spray and non-flash-boiling spray.

## 2. EXPERIMENTAL SETUP

The experiments were undertaken in a single-cylinder four-stroke SIDI optical engine shown in Fig. 1. The engine was equipped with a four-valve pent-roof cylinder head which was based on a configuration of a four-cylinder 2.0 L engine. The optical access to its cylinder was achieved through three locations: (1) full-quartz liner, which provided visualization into cylinder for the entire engine stroke; (2) two pent-roof windows, which allowed for the view through the engine head clearance volume; and (3) a quartz-insert piston with Bowditch[20] extended piston design, provided the view up into the cylinder head through a mirror tilted at 45 °. The head arrangement of the single cylinder engine is depicted in Fig. 2. The eight-hole fuel injector and spark plug were centrally installed in the close proximity of each other. Eight arrows in Fig. 2 illustrate the directions of eight spray plumes. One of eight fuel spray plumes was designed to target at the spark plug. The engine stroke wass 94.6 mm, the bore was 86 mm, and the compression ratio was 11:1. The engine was motored by the AVL AC dynamometer at 800 rpm in this test. Since the engine only consisted of one cylinder, the AVL customized balance system was used to guarantee the engine operating at the lowest vibration level. A throttle valve was used to control the intake MAP (Manifold absolute pressure) regulated at 100 kPa. The AVL coolant and lube oil supply unit were used to control the engine coolant and oil temperature from 30 ℃ to 90 ℃ with variation 0.2 $^{o}$C. The specific engine parameters and operating conditions are tabulated in Table 1.

The experiment setup is shown in Fig. 3. To offer homogeneous light into engine cylinder, a Nd:YLF laser (527 nm wavelength, 24 mJ/pulse @ 1000 Hz, 100 ns pulse width) was diffused to illuminate the entire combustion chamber through the piston quartz. High-speed camera (Vision Research Phantom v7.3) was used to capture the Mie scattering signal of the liquid spray. The recording rate was set at 9600 Hz, corresponding to 2 images per crank-angle degree at engine speed of 800 rpm. The fuel temperature was controlled through regulating the oil & coolant temperatures in the engine head. In this test, the flash-boiling fuel spray was realized by heating up the fuel to 90 $^{o}$C. For the liquid spray test, the fuel temperature was set at 30 $^{o}$C. All the fuel spray imaging was conducted with the engine under motoring condition without combustion.

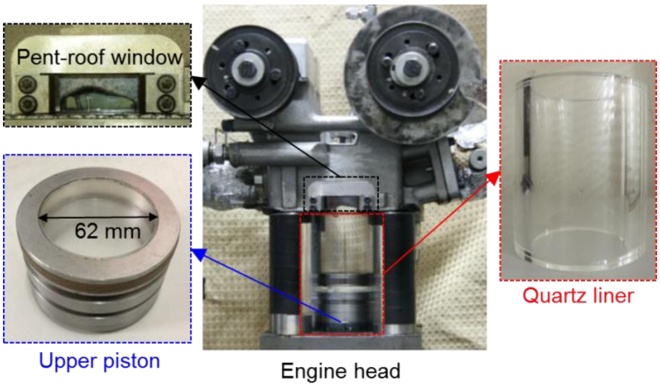


**Fig. 1** Single-cylinder engine with optical access by (1) pent-roof window, (2) quartz liner, and (3) optical piston

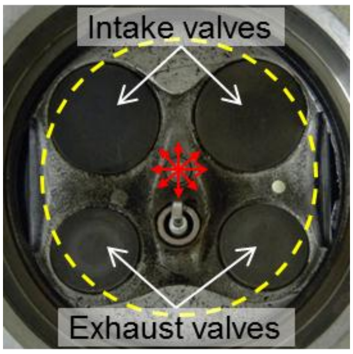


**Fig. 2** Bottom view of engine head with arrows illustrating the spray plumes directions (the dashed circle shows the optical view through quartz piston)

**Table 1.** Engine parameters

| Parameter | Value |
|---|---|
| Displaced volume | 549.51 $cm^3$ |
| Stroke | 94.6 mm |
| Bore | 86 mm |
| Connecting Rod | 160 mm |
| Compression ratio | 11:1 |
| Exhaust Valve Open | 131 °ATDCF |
| Exhaust Valve Close | 372 °ATDCF |
| Intake Valve Open | -366 °ATDCF |
| Intake Valve Close | -114 °ATDCF |
| Engine speed | 800 rpm |
| Fuel | Gasoline |
| Fuel injection pressure | 10 MPa |
| Injection duration | 915 µs |
| Fuel per cycle | 10.7 mg |
| Start of injection | -300 °ATDCF |
| Intake manifold absolute pressure | 40 kPa |
| Intake air temperature | 25 ±1 ℃ |
| Oil & Coolant temperature | 30,90 ±1 ℃ |
| Intake swirl ratio | 0.55 |

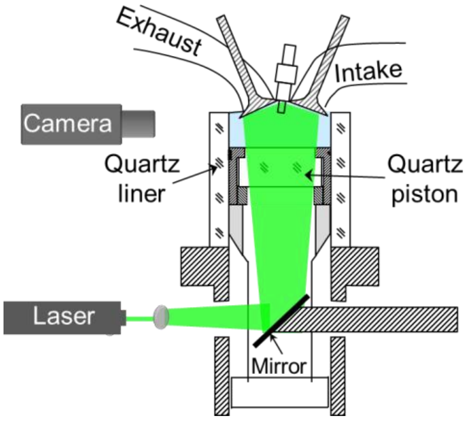


**Fig. 3** Experimental setup (laser beam was diffused to illuminate the combustion chamber)

## 3. IMAGE PROCESS PROCEDURE FOR FUEL IMPINGEMENT

Image processing algorithms are developed to quantitatively investigate the spray impingement at different crank-angles for both liquid spray and flash-boiling spray. The spray images are processed in the following procedures. First, as shown in Fig. 4, the piston top surface is identified for different crank-angle positions. Spatial correlation is used to find the best match of piston positions with respect to different crank-angle locations. Then, in order to have a quantitative value about the fuel impingement magnitude, fuel impingement index[6] on the piston surface is defined based on the image intensity on the identified piston top surface. The pixel intensity on the piston top surface is extracted for further analysis. The size of the piston surface illustrated in Fig. 4 is 6 pixels thickness and 526 pixels long. The average intensity is calculated by averaging the pixel intensity across the thickness as:

$$\overline{I_j} = \frac{\sum_{i=1}^{M} I_{i,j}}{M} \cdot \frac{1}{L-1} \qquad (1)$$

where $i$ is the pixel index along the thickness ($M$ = 6 in this study), and $I_{i,j}$ is the pixel intensity on the piston top surface. The pixel intensity is then normalized in Eq. (1). Note that the spray image is recorded using a 14-bit image format, and therefore $L$ is equal to 16384 ($2^{14}$).

As the fuel impingement is highly transient, it is changing rapidly over the crank-angle degrees even within a single cycle. Also, the impingement magnitude is different from cycle to cycle. Therefore, an overall fuel impingement index ($FII_{CA}$) at certain crank-angle of a specific cycle is defined as the ensemble-average along piston top surface domain (Fig. 4):

$$FII_{CA} = \frac{\sum_{j=1}^{N} \overline{I_{ave,j}}}{N} \qquad (2)$$

where $N$ = 526, is the length of the piston surface defined in Fig. 4.

The fuel impingement value defined in Eq. 1 can be used to quantitatively illustrate the fuel impingement locations. The index in Eq. 2 can be used to track the fuel impingement magnitude at each crank-angle positions within the cycle. For both parameters, comparing among engine cycles represents the cycle to cycle variation of fuel impingement.

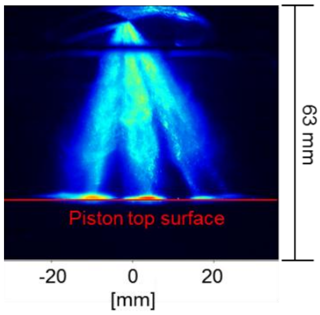


**Fig. 4** Piston top surface identified for impingement analysis

## 4. RESULTS AND DISCUSSIONS

The crank-angle resolved Mie-scattered images have been processed using the algorithms introduced in Section 3 to compare the fuel impingement between liquid spray and flash-boiling spray. This comparison was conducted using the following procedures. First, the start of impingement was compared in Section 4.1. Second, one crank-angle within the spray injection duration was chosen to compare the impingement during spray injection process. Third, a crank-angle position that was relatively long time after the fuel injection was selected for the same comparison. Finally, the impingement throughout the cycle was compared using the fuel impingement index defined in Eq. 2. Also, the cyclic variation of the fuel impingement was demonstrated.

### 4.1 Start of impingement

A systematic study on flash-boiling spray has been conducted by the authors [7, 8, 10-12, 15-19]. Previous studies in constant-volume chamber have demonstrated that the flash-boiling spray could effectively reduce the spray penetration. In this study, the flash-boiling spray is investigated in the real-engine condition. Fig. 5 shows the liquid spray and flash-boiling spray from the same eight-hole SIDI injector at 3.5 °after SOI. As expected, eight spray plumes collapsed together for the flash-boiling spray, and the impingement was much reduced due to its shorter penetration.

As shown in Fig. 5, for the liquid spray, some of the spray plumes have started to hit on the piston surface at 3.5 °aSOI. Since the injector was mounted tilting with the cylinder axis by 8 degree, the spray plumes at left side splashed on the piston earlier than the right side plumes. From the three cycles selected, strong cyclic variation was found. For instance, the spray in cycle #1 had its left plume impinged on the piston first (highlighted by the circle in Fig. 5). Differently, the center plume of spray in cycle #16 splashed on the piston earlier than the other plumes, and at least two plumes started to impinge on the piston in cycle #38. This is reasonable since some spray variation was found even under constant-volume chamber by a previous study[21]. The spray under the effect of in-cylinder air motion in this study should have much larger variations.

For the flash-boiling spray (Fig. 5), the spray penetration was about 9 to 11 mm shorter than the liquid spray at 3.5 aSOI. Therefore, for all cycles, the flash-boiling spray plume still did not impinge on the piston yet. However, it can be seen in Fig. 5 that there was still slight distance variation between the spray tip and piston top surface. Figure 6 depicts the spray images of next half crank-angle degree from the same engine cycles as in Fig. 5. For the liquid spray, all plumes have impinged on the piston. For the flash-boiling spray, the spray tip is very close (less than 1 mm) to the piston top surface, but still not hit on the piston yet. As shown in the Section 4.2, the flash-boiling spray impinged on the piston top at 4.5 ° aSOI. In summary, in comparison to the liquid spray, the flash-boiling spray is capable of delaying the start of impingement for about one crank-angle at engine speed of 800 rpm in this specific engine configuration.

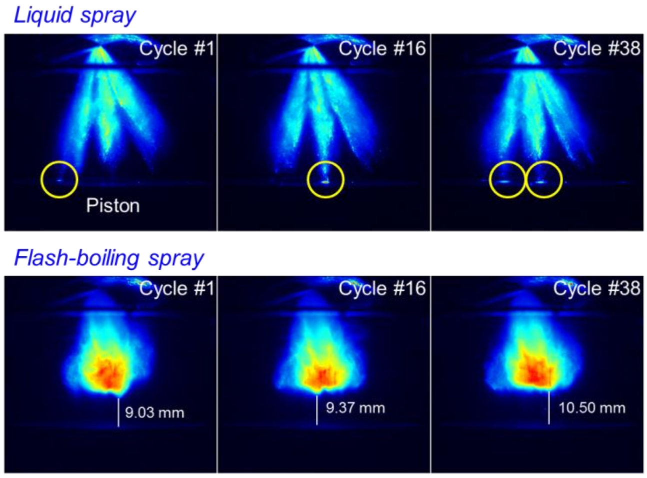


**Fig. 5** Fuel spray structures at 3.5 °aSOI

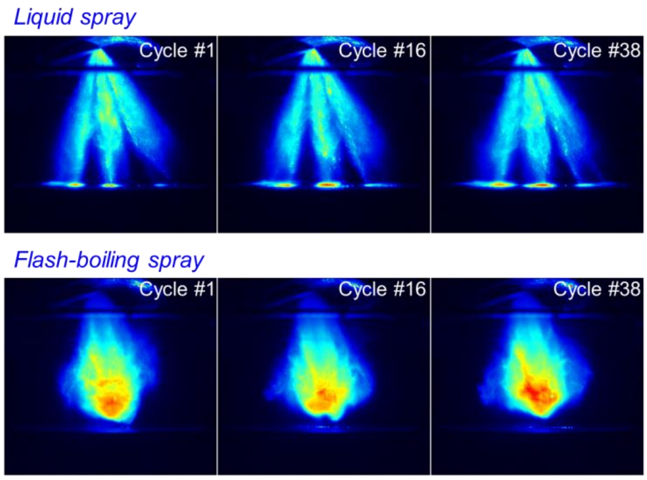


**Fig. 6** Fuel spray structures at 4.0 °aSOI

### 4.2 Impingement during fuel spray injection

At the moment of 4.5 ° aSOI, as shown in Fig. 7, the spray impinged on the piston for both liquid spray and flash-boiling spray. The direct observation from Fig. 7 is that the impingement region was separated into eight locations for each plume for liquid spray. In contrast, the flash-boiling spray impingement region concentrated in one single spot, which resulted from the collapse of flash-boiling spray[7, 8].

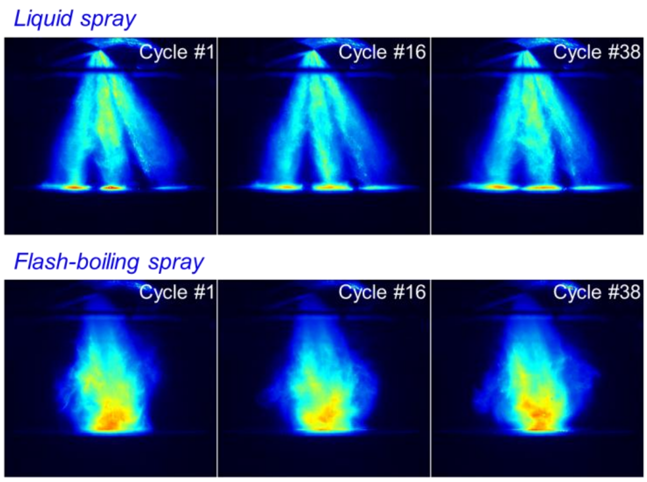


**Fig. 7** Fuel spray structures at 4.5 °aSOI

To have a quantitative comparison of spray impingement between the liquid spray and flash-boiling spray, the fuel impingement index obtained from Eq. 1 for the six spray images (in Fig. 7) is plotted in Fig. 8. The curves in Fig. 8 depict the spray impingement magnitude along the piston top surface. Two observations can be made from Fig. 8. First, three peaks were identified for liquid spray, and only one peak was found for flash-boiling spray. The liquid spray impingement amount for all three peaks together should be larger than that of the flash-boiling spray. Second, the liquid spray encountered larger variation than that of flash-boiling spray. For the liquid spray, the left two peaks (in Fig. 8a) of cycle #1 were higher than other two cycles, and the right peak of cycle #1 was weaker. In Fig. 8b, all three cycles of flash-boiling spray varied less than the liquid spray.

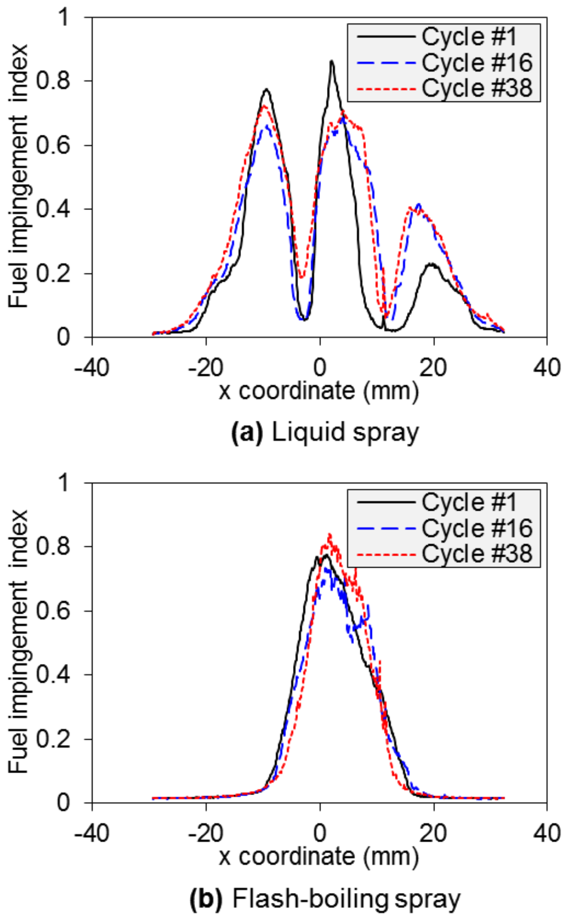


**Fig. 8** Spray impingement distribution variation for **(a)** Liquid spray, and **(b)** Flash-boiling spray at 4.5 ºaSOI

The impingement analysis in the previous section is based on the results from three engine cycles for each condition. To give a quantitative study for all cycles, the ensemble average over all 50 cycles and its variation have been investigated as follows. Figure 9 depicts the fuel impingement index along the piston surface, which is obtained from the ensemble average over all 50 cycles. Compared with the results from instantaneous cycle Fig. 8, the curves in Fig. 9 are smoother. The trend in Fig. 9 remains similar with that in Fig. 8. For liquid spray, three peaks can be identified. The left two peaks are much strong than the right peak. This result is likely attributed to the fact that the injector was slightly tilted to the left. For the flash-boiling spray, one peak is found, and it is much stronger than all three peaks in the liquid spray. From this figure, it is qualitatively reasonable that the overall impingement for liquid spray is stronger than that of flash-boiling spray.

To make comparisons between liquid spray and flash-boiling spray in a more quantitative way, the ensemble average is made along the piston surface for all cycles at this crank-angle position. For each cycle, a single value (obtained from Eq. 2) representing the overall impingement magnitude is obtained. For both liquid spray and flash-boiling spray, this value for each of 50 cycles is plotted in Fig. 10. Two quantitative results can be achieved from this figure. First, in general, the impingement intensity for flash-boiling spray is smaller than that of liquid spray. Based on the images, the average over the 50 cycles for flash-boiling is 0.20, and the average for the liquid spray is 0.31. Compared with liquid spray, the flash-boiling spray could reduce the spray impingement by 51.9%. This is a significant reduction, which could be very helpful for limiting the soot and unburned HC emissions. Second, the coefficients of variation (COV) among the 50 cycles for liquid spray is 7.79%, it is 7.56% for the flash-boiling spray. Compared with liquid spray, the flash-boiling spray also slightly reduced the cycle to cycle variation of impingement.

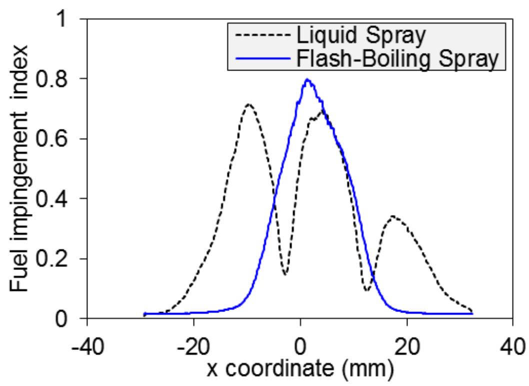


**Fig. 9** Spray impingement comparison between liquid and flash-boiling spray at 4.5 ºaSOI (Average over all 50 cycles)

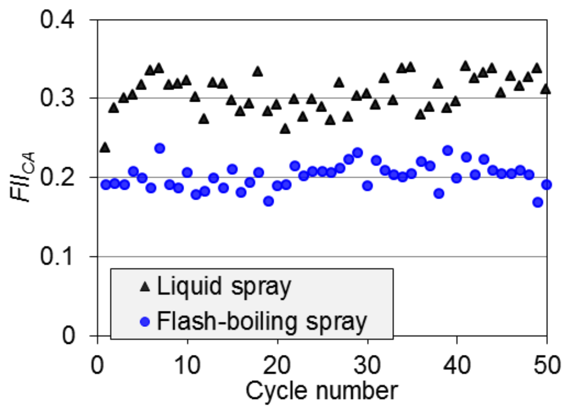


**Fig. 10** Overall spray impingement variations among all 50 cycles between liquid spray and flash-boiling spray at 4.5 ºaSOI

### 4.3 Impingement after injection

In previous section, it has been demonstrated that the flash-boing spray is capable of reducing the fuel impingement for about 51.9% at a moment during the fuel injection. For the current study, the engine ran at the homogeneous charge mode, meaning that the fuel spray occurred during the intake stroke, but the combustion process was initiated about 290 crank-angle degrees later. Therefore, it is also important to study if the flash-boiling spray could reduce the impingement for a longer while after the injection event. In this section, using the same method as in section

4.2, the fuel impingement is studied at the instant of 19 °aSOI.

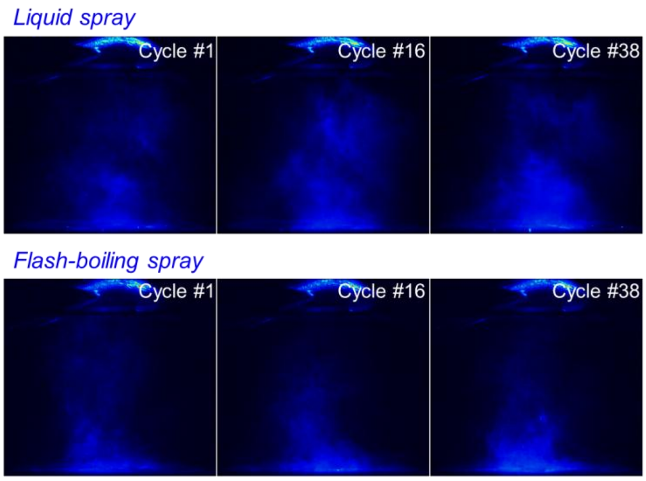


**Fig. 11** Fuel spray structures at 19 °aSOI

Figure 11 shows the in-cylinder fuel cloud of the Mie-scattered images for the same three engine cycles for liquid spray and flash-boiling spray respectively. First of all, since it is already 12 crank-angle degrees (about 2.5ms) after the end of injection, it is reasonable that the envelop structures of the fuel spray did not exist anymore for both conditions. Second, the direct observation of the images in Fig. 11 reveals that the intensity of Mie-scattered flash-boiling spray images is weaker than that of liquid spray. Recall in our previous publications [12, 14] that the flash-boiling spray evaporates faster than liquid spray, hence the liquid part of the flash-boiling spray should be less than that of liquid spray in the instant of 19 ° aSOI. Since the recorded Mie-scattering image only captured the liquid fuel signal, it is reasonable that the smaller amount of liquid for flash-boiling spray has weaker intensity than that of liquid spray.

The focus in this section is the impingement magnitude for both conditions at the moment of 19 ° aSOI. It is worth noting that the piston is about to go out of the field of view in this instant. Figure 12 depicts the fuel impingement index along the piston surface, which is achieved from the ensemble average over all 50 cycles. Compared with the impingement index in Fig. 9, the impingement at 19 °aSOI is much weaker. For liquid spray, the three peaks (Fig. 8a) during the fuel injection disappear, and only one peak is found at 19 °aSOI. Also, the peak is offset to the right side of the cylinder center, which is reasonable since the fuel injector is tilted to the same direction as well. For the flash-boiling spray, there is still one peak, and it is located around the center of the cylinder. This is because that the flash-boiling spray has smaller droplet size[15], thus the spray is easier to be affected by the in-cylinder air motion. On the other hand, the liquid spray has more momentum and capable of retaining its moving direction. This could be the reason for the peak location difference between liquid spray and flash-boiling spray. Figure 12 also depicts that the overall impingement for liquid spray is stronger than that of flash-boiling spray. The peak for liquid spray is stronger than the peak of flash-boiling spray by about 34.6%.

To quantitatively compare the impingement between liquid spray and flash-boiling spray, the ensemble average is computed along the piston surface (Eq. 2) for all cycles at this crank-angle position. For each cycle, a single value representing the overall impingement magnitude is obtained for this crank-angle position. For both liquid spray and flash-boiling spray, this value for all 50 cycles is depicted in Fig. 13. Two quantitative results can be achieved from this figure. First, for most of the cycles, the impingement intensity for flash-boiling spray is smaller than that of liquid spray, but the difference is much smaller compared to the results during the injection process (Fig. 10). The average over the 50 cycles for liquid spray is 0.048, and the average for the flash-boiling is 0.033. Compared with liquid spray, the flash-boiling spray still can reduce the spray impingement by about 44.7%. Again, this is a still a significant reduction by flash-boiling spray. Second, the coefficient of variation (COV) among the 50 cycles for liquid spray is 12.64% and it is 10.93% for the flash-boiling spray. At the moment of 19 ° aSOI, the flash-boiling spray slightly reduces the cycle to cycle variation of impingement as well.

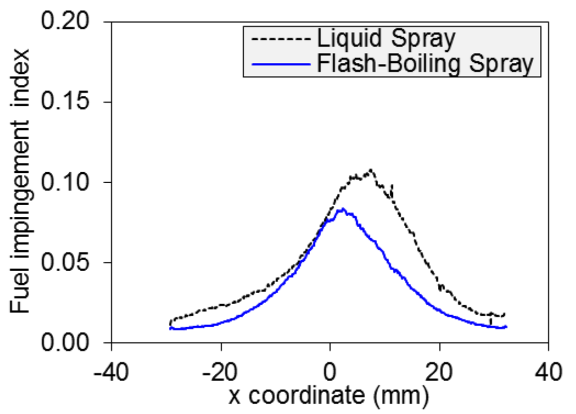


**Fig. 12** Spray impingement comparison between liquid and flash-boiling spray at 19 °aSOI (Average over all 50 cycles)

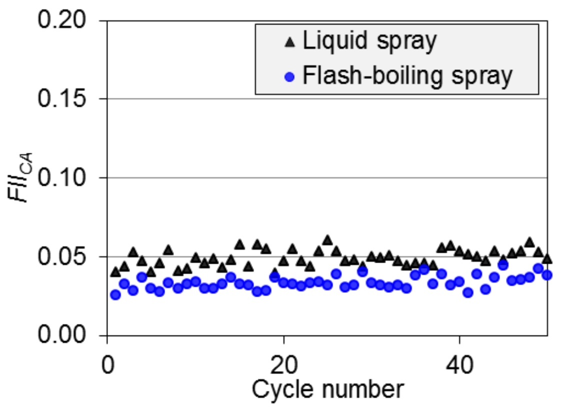


**Fig. 13** Overall spray impingement variations among all 50 cycles, comparison between liquid spray and flash-boiling spray at 19 ° aSOI

## 4.4 Impingement throughout the cycle

It has been demonstrated that fuel impingement index can provide a single value for the impingement magnitude for one specific certain crank-angle degree (Fig. 10 & Fig. 13). Hence, by computing the ensemble average among all 50 cycles for each crank-angle within the cycle, the extent of fuel impingement in the engine cycle can be tracked. The results for both liquid spray and flash-boiling spray are depicted in Fig. 14.

Figure 14 provides the following important observations. First, it is re-confirmed that the flash-boiling spray delayed the start of impingement by one crank-angle degree. Second, within the whole engine cycle, the impingement of flash-boiling spray is weaker than that of liquid spray. Compared with the liquid spray, the flash-boiling spray reduces the extent of impingement by 31% at the peak locations. Third, comparing with the liquid spray, the peak of the flash-boiling spray is also delayed by one crank-angle degree.

This results from the delayed start-of-impingement.

Overall, it is fair to conclude that the flash-boiling spray is an effective way to reduce the fuel impingement. Therefore, low level of soot and unburned HC emissions is anticipated.

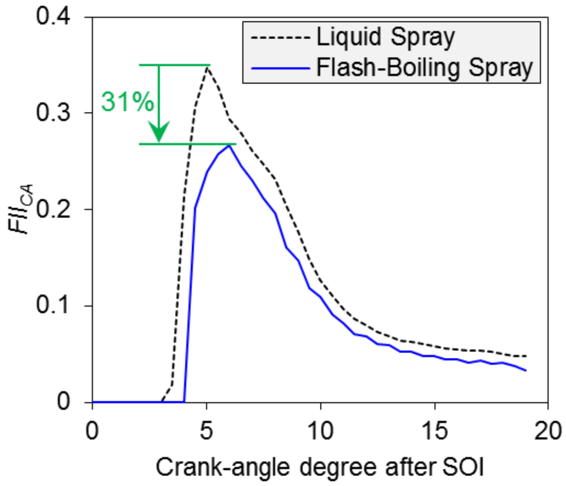


**Fig. 14** Crank-angle resolved fuel spray impingement on piston surface, comparison between liquid spray and flash-boiling spray

## 5. CONCLUSIONS

In this study, multiple-cycles of crank-angle resolved Mie scattered fuel spray imaging were recorded in a single-cylinder optical SIDI engine for two conditions: (*i*) liquid spray, and (*ii*) flash-boiling spray. The spray impingement for both conditions was quantitatively investigated. Within the experimental conditions of this investigation, several main findings can be summarized as follows:

(1) Compared with liquid spray, the flash-boiling spray delayed the start-of-impingement for about one crank-angle degree.
(2) During the fuel spray (4.5 ° aSOI), the impingement of flash-boiling spray is 51.9% less than that of liquid spray.
(3) At the moment of 19 ° aSOI (12 ° after end of injection), the flash-boiling spray reduces the fuel impingement by 44.7% compared to the liquid spray.
(4) The cycle to cycle variation of fuel impingement for flash-boiling spray is also slightly smaller than that of the liquid spray.
(5) Within the cycle, for both liquid spray and flash-boiling spray, the fuel impingement increases during the spray injection process, and decreases after the end of spray. Comparing the maximum impingement amount for two conditions shows that flash-boiling spray diminishes the impingement by 31%.

Overall, the flash-boiling spray was found to be an effective way to reduce the fuel impingement. Combined with other advantages found in our previous studies (faster evaporation, smaller drop size, etc.), flash-boiling spray is expected to be very useful in the SIDI engines.

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