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Experimental investigations of the phase change impacts on flash boiling spray propagations and impingements

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Abstract
Flash boiling atomization technique has been considered a potential method for spray breakup performance enhancement utilizing the micro-explosion of superheated liquid. But the strong evaporative features of flash boiling atomization are not thoroughly investigated and understood. Therefore, this work focuses on the phase change impacts of flash boiling atomization and measures the volume flux of the liquid component during flash boiling atomization using phase Doppler interferometry. This work further investigates the consequence of flash boiling spray collapse in the aspect of spray impingement, with the two-dimensional thickness and temperature distribution measured by laser-induced exciplex fluorescence technique. This investigation verifies that due to the phase change of flash boiling atomization, the liquid component inside the plume drops significantly so that the wall impingement performance cannot be evaluated with spray penetration length only. Such observations also hold that even spray collapse takes place using a multi-hole fuel injector.

Keywords
Flash boiling sprays; Spray impingement; Wall film formation; Laser diagnostics; Volume flux

Introduction
In general, the flash boiling spray is considered as injecting superheated liquids into superheated or sub-cooled environments. There are many existing investigations on the advantages of flash boiling sprays with regards to their fuel-air mixing capability, finer droplets, strong evaporative nature, etc. However, there are also comments on the potential drawbacks of flash boiling atomization. The most mentioned issue of flash boiling atomization is spray collapse/targeting change when multi-hole fuel injection is adopted. Spray collapse can either be achieved by increasing the ambient pressure or triggering plume-to-plume interaction under flash boiling conditions. The spray collapse phenomenon, in which all plumes are merged into one cluster or one single jet, will notably increase the spray penetration length. Therefore, many investigations in this field [1, 2] have suggested or concluded that the flash boiling collapse phenomenon would deteriorate the combustion performance in engines since spray impingement is expected to elevate the adhered fuel mass on engine pistons or cylinder walls would cause pool fires and diffusion/rich combustions. There are many existing sub-cooled spray impingement studies[3-5], but fuel film analysis for flash boiling spray impingements is not plenty. Therefore, this work aims to investigate the previously said issues and attempt to understand the actual impingement characteristics of multi-hole, collapsed sprays. The heat transfer and mass transport mechanism are also studied from experimental results.

Material and Methods
Figure 1 demonstrates the experimental setups for spray plume analysis purposes in this work. Panel (a) of Fig. 1 shows the schematic of Mie scattering measurements. In this arrangement,

the fuel (n-hexane in this work) was heated by an external heater. The experiments were conducted in a constant temperature, constant pressure chamber, and the injection pressure was provided with an accumulator and high-pressure nitrogen cylinders. The injection pressure in this work was set to 10 MPa, which approximates the injection pressure in practical combustion systems. The ambient pressure inside the chamber was adjusted by external nitrogen sources and a vacuum pump attached to the bottom of the chamber. The ambient pressure was monitored by a high-accuracy pressure transducer. For the Mie scattering measurements, red light LED array was used to illuminate the spray plumes, and the scattered signal was captured by a high-speed camera (Phantom V1210) to register the propagation and evolvement of the spray. An impingement plate can be added during the Mie scattering testing, as reflected in Panel (b) of Fig. 1. The impingement plate incorporated a transparent window so that impingement fuel films could be captured from the bottom. At the same time, the plate temperature can be controlled by a water bath and cooling system, which can drive the impingement plate as cold as -40˚C. In Mie scattering and phase Doppler interferometry (PDI) studies, the impingement plate primarily serves as a spray-stopper for spray interference analysis. The PDI system used was an Atrium (PDI-x00MD) system which can quantify the droplet size populations, as well as droplet velocity in two components. The rest of the settings are the same as the setup shown in Panel (a).

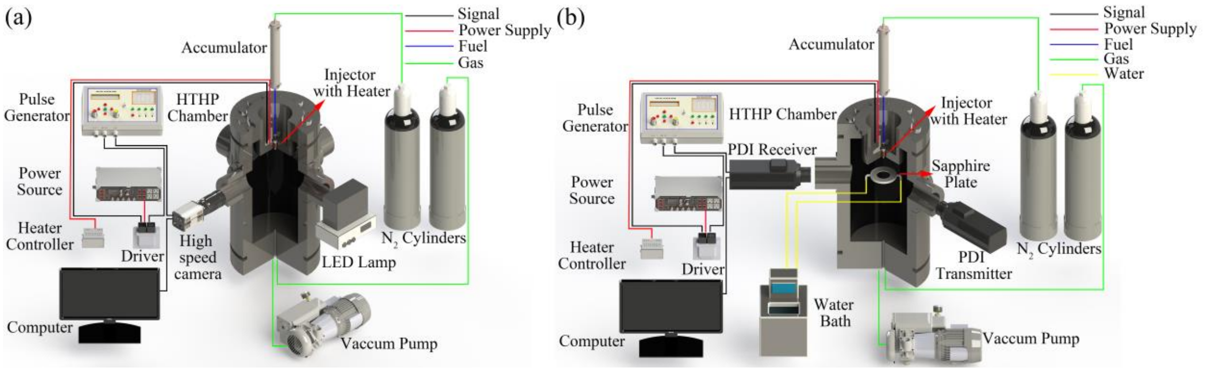

Figure 1. Experimental schematics for spray plume investigations. Panel (a). Mie scattering measurements (setup without impingement plate shown) Panel (b). Phase Doppler interferometry (PDI) measurements (setup with impingement plate shown)

In this work, we explore the impact of superheat index on the macroscopic characteristics of the flash boiling sprays, as well as their impingement responses. Therefore, five different fuel temperatures were used to cover different flash boiling (FB) regimes, as reflected in Table 1. One sub-cooled fuel temperature, two representative transitional flash boiling conditions (early transitional and late transitional), and two flare flash boiling conditions were chosen. The ambient pressure was kept constant at 1 bar in this study, indicating that the radial expansion tendency of the plume would be similar. Note that in the previous study [6], low ambient pressure was used (0.2 bar). In this work, we used a more common ambient pressure of 1 bar, which also reflects representative operational conditions of practical engines. To examine the influence of plate temperature, three plate temperatures of -25.0˚C, 0˚C, and 25.0˚C were used to approximate different engine cold-start scenarios. With these conditions and settings, Fig. 2. depicts the experimental setup of the laser-induced exciplex fluorescence (LIEF) for instantaneous film measurements. The external experimental setup was similar to that shown in Fig. 1. To measure the fluorescence response from the bottom of the plate, 266 nm laser excitation was directed to the bottom of the impingement plate through a dichroic mirror that

reflects UV lights but permits fluorescence at 340 nm and 400 nm. An image double was adopted to split the images so that they can project simultaneously on the same ICCD camera. The LIEF technique can find two-dimensional film thickness and temperature distributions from the two fluorescence channels through calibrations. More details about the LIEF diagnostics method can be found in the previous work of the authors [6].
In this multi-hole fuel injector experiment, we chose a six-hole, side-mounted practical GDI injector. For PDI measurements, the measurement location was 46 mm beneath the injector tip, which was 4 mm above the impingement plate. Due to instrumental limitations (PDI laser beams need to access the measurement location), 4mm above the plate is the physical limitation in this impingement measurement [7].

Table 1 - Test Conditions Used in this Work

Temperature (˚C)	Saturated pressure (kPa)	P_a/P_s	Flash boiling regime
25.0	20.20	5.0	Sub-cooled
80.4	144.29	0.7	Transitional FB
101.0	252	0.4	Transitional FB
141.2	631.25	0.16	Flare FB
186.2	1442.86	0.07	Flare FB

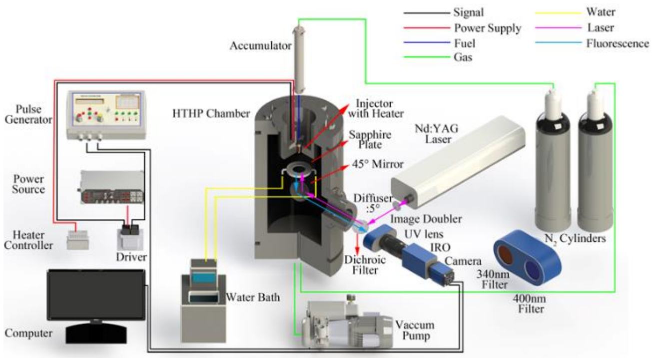

Figure 2. Experimental schematics for impingement fuel investigations. The laser-induced exciplex fluorescence method was used to quantify film thickness and temperature.

Results and Discussion

Figure 3 depicts macroscopic impingement measurements of sprays, with the impingement plate 50 mm away from the injector tip. There is something interesting that can be seen in Fig. 3. The impingement process under sub-cooled conditions was quite expected, with wall jets propagating forward and backward seen at the end of the injection. However, with an increase of the fuel temperature, the wall jets notable at 3.0 ms ASOF became less significant, and no wall jet was seen under the superheat index of 0.16. The Mie scattering intensity under flare flash boiling conditions was also weaker than in sub-cooled conditions or transitional flash boiling conditions. We have discussed the impacts of evaporations/boiling on the phase change of the spray plume. From the results shown in Fig. 3, it is hard to tell the exact spray impingement characteristics since apparently there were fewer fuel droplets inside the flash boiling plumes despite a longer penetration.

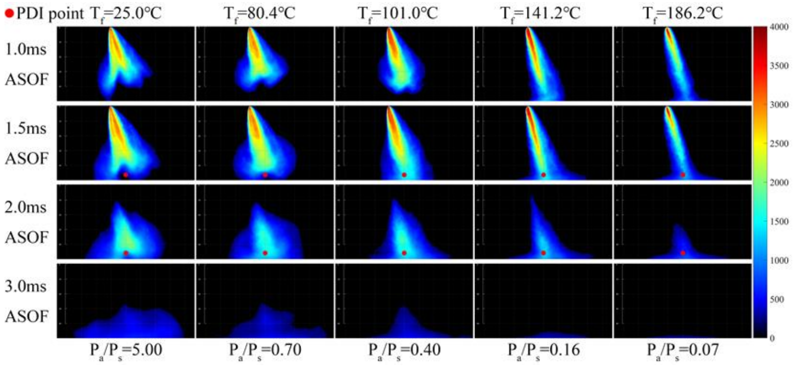

Figure 3. Impinging spray propagation measurements using Mie scattering technique using different fuel temperatures covering sub-cooled injections to flare flash boiling injections. Different injection timings (ASOF) were demonstrated. PDI measurement location was noted by red dots in the side view. The color bar represents the strength of the Mie scattering (reading from the camera, a.u.)

To address this issue, we carried out PDI testings for the sprays under different superheat conditions. Furthermore, the temperature of the impingement plate was also varied to examine the heat transfer impacts in the near field (since a cold plate would reduce the temperature near the plate as well). Besides drop size measurements, we also performed a volume flux measurement based on the PDI system, which counts how many droplets are sampled during a specific time so that the liquid volume flux can be inferred, with the droplet diameter of each droplet measured by the phase Doppler Interferometry technique. It is worth mentioning that the PDI system usually rejects droplet measurement as the droplets are too dense or the droplet is not quite spherical.

The near-plate measurement results are incorporated in Fig. 4. Panel (a) of Fig. 4 shows the Sauter mean diameter (SMD) measured by the PDI system as a function of superheat index. As seen, the atomization performance of the measurement location was already quite good even under sub-cooled conditions, with an SMD around 12 μm. Increasing the fuel temperature can reduce the spray SMD to around 4 μm at the measurement location. Furthermore, as can be seen, the droplet SMD was slightly reduced as the 25 ˚C plate was installed under each superheat level, while the SMD was roughly the same with the free spray as the -25 ˚C plate was installed under each superheat level. These observations indicated that the plate would impact the SMD characteristics at the same location, but the impact was not quite pronounced. Panel (b) of Fig. 4 shows the statistical sample frequency under each condition. As can be seen, the sampling frequency of the free spray dropped steadily as the fuel temperature increased. For impinging sprays, the sampling frequency was higher, and the sampling frequency did not decrease notably until the fuel temperature rose to 186.2 ˚C, when the spray almost became a gaseous jet to some extent. Panel (c) of Fig. 4 demonstrates the volume flux of the spray at this specific location. In this set of results, the rejection rates were not counted. The volume flux F can be expressed by:

$$F = \frac{\pi}{6} D_{30}^{3} \cdot \frac{N}{AT} \tag{1}$$

Where D_{30} is the volume mean diameter, N is the number of particles measured, T is the time elapsed for acquiring the sample, and A is the probe area for measurement, respectively. In this study, the quantity A can be obtained from the experiments, and we scaled this area to a constant value so that the volume fluxes were comparable. In this manner, the volume flux is primarily determined by the mean diameter D_{30}, and sample frequency N/T. Nevertheless, as can be seen in Panel (c) of Fig. 4, the volume flux at the measurement location steadily dropped as the fuel temperature increased. For free sprays, the liquid volume flux was reduced from 400×10-5m3/(m2·s) to around 1×10-5m3/(m2·s) as the fuel temperature increased from 25 ˚C to 186.2 ˚C. Similar results are seen in impingement cases, but the measured volume flux during impingement was notably lower than that of the free spray, which we will explain in the following section. The results in Panel (c) of Fig. 4 actually indicated that although the penetration of transitional or flare flash boiling spray could be higher than sub-cooled sprays, there are much fewer droplets inside the spray plume, i.e., a sparse plume compared to a dense plume. Therefore, using the penetration length to evaluate the impingement fuel characteristics is not quite practical. Panel (d) of Fig. 4 depicts the volume fluxes with the PDI pass rates counted and scaled (with a basis of sub-cooled, free spray injection). As can be seen, the consideration of the PDI accept rates did not vary the conclusions significantly, and the volume fluxes declined steadily with the superheat index as well.

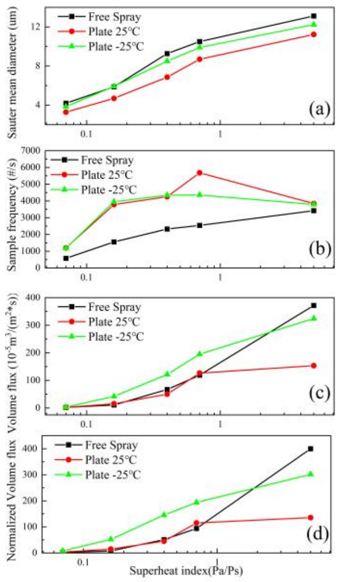

Figure 4. Phase Doppler interferometry results at the test position with and without the impingement plate. Panel (a). Sauter mean diameter (SMD) as a function of superheat index. Panel (b). Sample frequency as a function of superheat index. Panel (c). Volume flux as a function of superheat index. Panel (d). Normalized volume flux as a function of superheat index based on PDI rejection rate (based on sub-cooled, free spray data)

We also presented the film characteristics measured by the laser-induced exciplex fluorescence. The fuel film thicknesses and temperatures were calibrated in a similar fashion with the previous work [6]. Therefore, we will not explicate the details in this work. Figure 5 depicts representative impingement wall film thickness distributions under different conditions with the injection timing of 2.5 ms ASOI. 5 tests were made for each condition. In comparison with the single-plume flash boiling spray impingement results [6], the wall film distribution for the multi-hole, skewed fuel spray is more complicated. Even under sub-cooled injection conditions and no flash boiling spray collapse took place, the impingement wall film merged into one on the plate due to film spreading. The footprint of the fuel film was much larger than single plume impingement results. The film even propagated out of the observation limit under some circumstances, although under these conditions there is no doubt the wall wetting would be a challenge. Therefore, we chose a measurement timing of 2.5 ms so that the films were still mostly within the impingement plate, and the droplets above the impingement plate have a limited interference on the fluorescence signal (as can be reflected under 186.2 ˚C fuel temperature conditions). As seen in Figure 5, under the same plate temperature, the film shrank as the superheat index decreased (stronger flash boiling levels), while it appeared that the thickness of the fuel film was not higher than those under sub-cooled injection conditions. The film finally became a circular one on the plate, indicating strong spray collapse effects, but the footprint of the film was quite insignificant. Under the same fuel temperature, the film area and mass increased as the plate temperature dropped, which is expected due to suppressed evaporation near the plate.

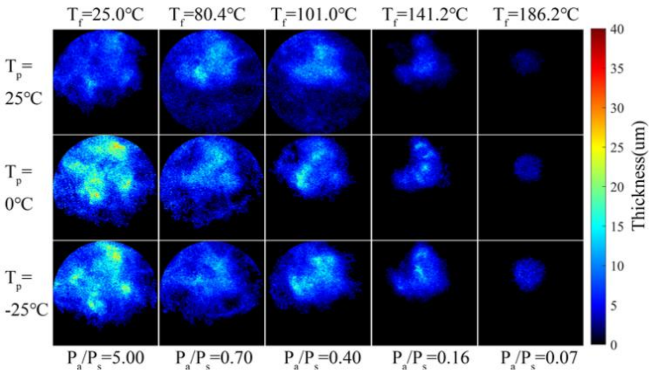

Figure 5. Two-dimensional impingement wall film thickness distribution at 2.5 ms ASOI. Different fuel temperatures and plate temperatures were tested.

Figure 6 demonstrates the statistical film measurement results over 5 independent tests corresponding to the results shown in Fig. 5. Panel (a) of Fig 14 plots the mean and std of the film area as a function of superheat index, and Panel (b) of Fig. 14 plots the film mass, respectively. The timing was chosen to be 2.5 ms AOSI when the film just formed on the plate. The evaporation effect of the film was less significant at this moment compared to later timings (such as 5 ms ASOI). As can be seen in Panel (a), increasing the temperature of the fuel generally resulted in a smaller film area, except for the transitional flash boiling sprays cases that were impinging onto the 25 ˚C plate. While from the results shown in Panel (b) of Fig. 14, the impingement film mass was comparable to the rest of the plate temperatures under transitional flash boiling conditions. These results indicated that transitional flash boiling film tends to spread larger and thinner with a relatively high plate temperature. Nevertheless, we can see that the film mass steadily dropped as the superheat level increased, and the impingement mass was less sensitive to the plate temperature under flash boiling conditions. The reason is that at 2.5 ms ASOI, the film did not have sufficient time for evaporation. Thus, the initial fuel mass was about the same under different plate temperatures, meaning the plate temperature does not impact the film formation too much from a mechanism perspective. Fur sub-cooled injections, the plate temperature notably affected the initial fuel film, suggesting the film would soon become cold and thick, absorbing more droplets into the fuel film during injections. We stopped our measurements at 3.0ms ASOI since a notable amount of the film had escaped the observation zone afterward. Inferring from the single plume results, the fuel films from flash boiling impingement would experience faster evaporations since their temperatures were higher.

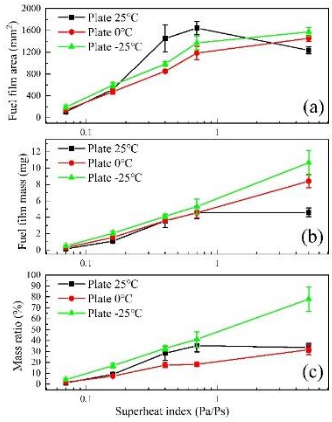

Figure 6. Impingement fuel film characteristics under different superheat conditions. Panel (a). Film area as a function of the superheat index. Panel (b). Film mass as a function of the superheat index. Panel (c). The mass ratio between the adhered mass and total injected fuel mass.

As we discussed before, the volume flux near the plate was substantially reduced under flash boiling conditions. Thus it is desirable to understand the impact of the liquid volume flux on the impingement film mass under flash boiling conditions. Figure 7 demonstrates such relationships under different plate temperatures as a function of superheat indices. As seen in Fig. 7, the adhered fuel mass showed a clear correlation with the volume flux near the plate. Under -25 ˚C plate temperature conditions, such a relationship was quite linear, while 0 ˚C plates and 25 ˚C plates produced less linear relationships. If we look back to the results shown in Fig. 5, it can be found that the penetration distance of the spray (i.e. at 1.5 ms ASOI) does not have a clear correlation with the impingement fuel mass. As such, we conclude that the actual dominant parameter that determines the quantity of the fuel film is the volume flux near the impingement plate. This conclusion appears to contradict the common sense that a longer spray penetration would result in less impingement fuel film mass. In fact, for sub-cooled spray impingement cases, there is an assumption by default that the volume flux in the spray plumes is about the same. If the spray plume hits the plate, then a high volume flux is expected, and notable fuel film is formed. Otherwise, the dense spray does not contact the plate, reflecting a low volume flux. For phase-changing sprays, the volume flux in the spray plume reduces gradually as a function of the superheat index, under which scenarios, the penetration is no longer a good criterion for spray impingement evaluations. A more general criterion to evaluate adhered fuel mass is the liquid volume flux near the plate.

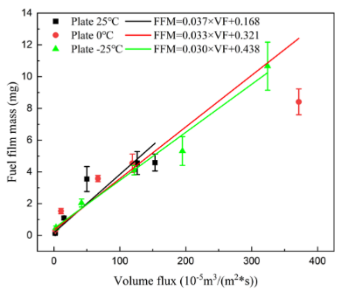

Figure 7. Deposited fuel film mass as a function of liquid volume flux near the impingement plate at 2.5 ms AOSI. Different plate temperatures were examined

The observations and results directly justified that as long as a low volume flux can be sustained, flash boiling target change (collapse) does not impact its impingement performance notably, though the impacts on fuel-air mixing in the combustor should be evaluated with flash boiling spray collapses. Finally, it should be noted that the volume flux we obtained was only at a certain location, which may not represent the overall liquid volume fluxes on the cross-sectional plane. Nevertheless, we believe the results shown in Fig. 7 can justify our conclusions on the impact of liquid volume flux.

Conclusions

In this study, we have performed a combined analysis of flash boiling impingement using phase Doppler interferometry and laser-induced exciplex fluorescence. Both the liquid volume flux and the resultant impingement film were measured and analyzed. To summarize, the main contribution of this work is that flash boiling spray collapse does not mean deteriorated impingement performance (i.e., more fuel adhered to the solid surface). It is the liquid volume flux near the plate that determines how much liquid is deposited onto the wall rather than the penetration of the spray plume (although other factors such as droplet impingement criteria, film evaporations, etc. would also affect the impingement wall film). The rest of the conclusions are summarized as follows:

1) The liquid volume flux drops rapidly with the increase of the fuel temperature. Such a decrement is attributed to droplet diameter drops and droplet number density variations. The decrease of droplet diameter contributes more significantly to the drop of volume flux;

2) Flash boiling collapse does not necessarily increase the volume flux and consequently the impingement wall film mass. Although a higher droplet number density can be reached in transitional flash boiling cases, such effects can be reversed by the decrease of the spray droplets;

3) The plate temperature does not impact too much on the fuel mass of initial flash boiling fuel films. It is expected that a higher fuel temperature would promote the evaporation of the fuel film over its lifespan, though. Therefore it would make the final film mass lower with a high fuel temperature.

Acknowledgments

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