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Microscopic characterization of isooctane spray in the near field under flash boiling condition

Authors: Ziman Wang[a], Bo Wang[a], Changzhao Jiang[a], Hongming Xu[a*], Tawfik Badawy[a]

[a] School of Mechanical Engineering, University of Birmingham, Birmingham, UK
* Corresponding author. Tel: ++441214144153; E-mail address: h.m.xu@bham.ac.uk

Abstract

The isooctane spray characteristics were experimentally investigated under flash boiling condition which represents the part load operating condition for modern gasoline engine. Various tests were carried out with back pressure ranging from 0.2 bar to 1 bar and ambient temperature varying between 20℃ and 100℃. A long distance microscope together with an ultrahigh speed camera was employed to capture the spray development in the near field to study the primary breakup characteristics. The study was performed by using a diesel common rail injection system so that the influence of hydraulic force can be investigated. It was found that flash boiling led to dramatic radial propagation due to the explosion and collapse of the vapor bubbles, significantly boosting the atomization. The strength of vapor bubble explosion in the near field tended to be strongly affected by the flow regime in the nozzle. Besides, higher injection pressure led to larger cone angle during the initial injection stage but smaller cone angle during the quasi-steady stage due to the dominance of the hydraulic force.

Key words: primary breakup, flash boiling, superheating, spray, near field

1. Introduction

The fuel injection for modern GDI engine generally occurs during the intake stroke where the in-cylinder pressure is sub-atmospheric and the gas is quite warm, especially under hot idle condition [1, 2]. At part load, the throttle is not fully open and the in-cylinder pressure may be lower than the vapor pressure of gasoline. Meanwhile, when the engine is fully warm, the cylinder head is quite hot and air sucked in to the cylinder is heated. Two phases, namely, gas phase and liquid phase exist simultaneously when fuel is injected into such operating condition [3]. Generally, the phase transfer from liquid to vapor when liquid is heated under constant ambient pressure is defined as boiling. However, if the phase transfer occurs with constant temperature but lower ambient pressure, cavitation is expected [4]. When fuel is injected into this type of so-called flash boiling condition (the existence of both boiling and strong cavitation), the spray characteristics are quite different. This is because the depressurization leads to the collapse of spray, brings the plumes together and alters the desired direction of spray [4].

Flash boiling condition was reported to produce favorable combustible air/fuel mixture as the fuel pattern and spray atomization can be significantly improved [5]. This is mainly attributed to the explosion of the formed vapor bubbles, allowing the spray to propagate very quickly [2, 3]. The large cone angle caused by the vapor bubble explosion leads to better fuel mixture since the plume becomes less dense. The appearance of flash boiling is thus expected to produce smaller droplets due to the aforementioned improved atomization and propagation [6]. Zhao [7] reported that for indolene, D32 was halved when fuel temperature varied from 20 to 90℃with injection pressure of 11MPa and ambient pressure of 0.1 MPa. This is explained by the occurrence of the flash boiling. However, when the back pressure was set to 0.6 MPa, only 1.9 μm reduction of droplet size was achieved with the rise of temperature from 20 to 90℃. The HC was also reported to be lowered because of the reduced possibility of fuel impingement caused by the reduced plume velocity [8].

The near field primary breakup study under flash boiling is of great interest since this stage initiates the spray breakup and dominates the resultant secondary breakup and fuel mass distribution [9, 10]. To obtain plume morphology development and spray behavior, long distance microscope with the help of lighting is generally employed [11-13]. Aleiferis et al. [4] experimentally studied the impact of various injecting factors, including ambient pressure, fuel temperature and fuel properties on the spray behavior in the near field during the quasi steady stage with a transparent injector. Fuel temperature varied between 20 and 90 ℃ while the ambient pressure was set to 0.5 and 1 bar. The low and high ambient pressures can represent the part load and WOT operating conditions. It was reported that the interaction between the boiling and cavitation considerably complicates the spray behavior. The rise of temperature led to reduced viscosity and surface tension but raised vapor pressure, boosting the growing rate of vapor bubbles. However, the frame speed of the employed Photron- APX camera in their study was 9000 fpm which was very low [4]. This low frame speed resulted in the loss of some very important information, especially during the initial spray developing stage.

The study on the primary breakup of gasoline spray under flash boiling condition at microscopic level is still very limited. The plume development during the initial stage obtained through ultra-high frame speed is unavailable. Besides, the interaction between flash boiling and cavitation at elevated pressure requires deep study. To address these unknown questions, a long distance microscope complete with an ultra-high speed camera was employed in the present study to investigate the plume behavior under various flash boiling conditions. A modern diesel common rail injection system was used so that the study could be carried out under high injection pressure which tended to be a trend for future gasoline engine. A single-hole diesel injector was also employed to eliminate the effects of interaction between plumes when a multiple-hole injector was used.

2. Experimental setup

The experimental setup for primary breakup is presented in Figure 1. A high pressure vessel (pressure limit of 7 bar) with 2 inline glass windows (diameter of 10 cm) was employed. A cylindrical single-hole solenoid diesel injector with the nozzle diameter of 0.18 mm was used for the tests. The ambient temperature in the vessel was varied from 20 ℃ to 100 ℃ by using the 8 heaters located at the 8 corners of the vessel. The ambient temperature was kept stable with a close loop PID controller to control the 8 heaters with the feedback from a thermocouple. Meanwhile, the adoption of the vacuum pump allowed the ambient pressure to range between 0.2 and 1 bar and the ambient pressure could be monitored by the pressure gauge.

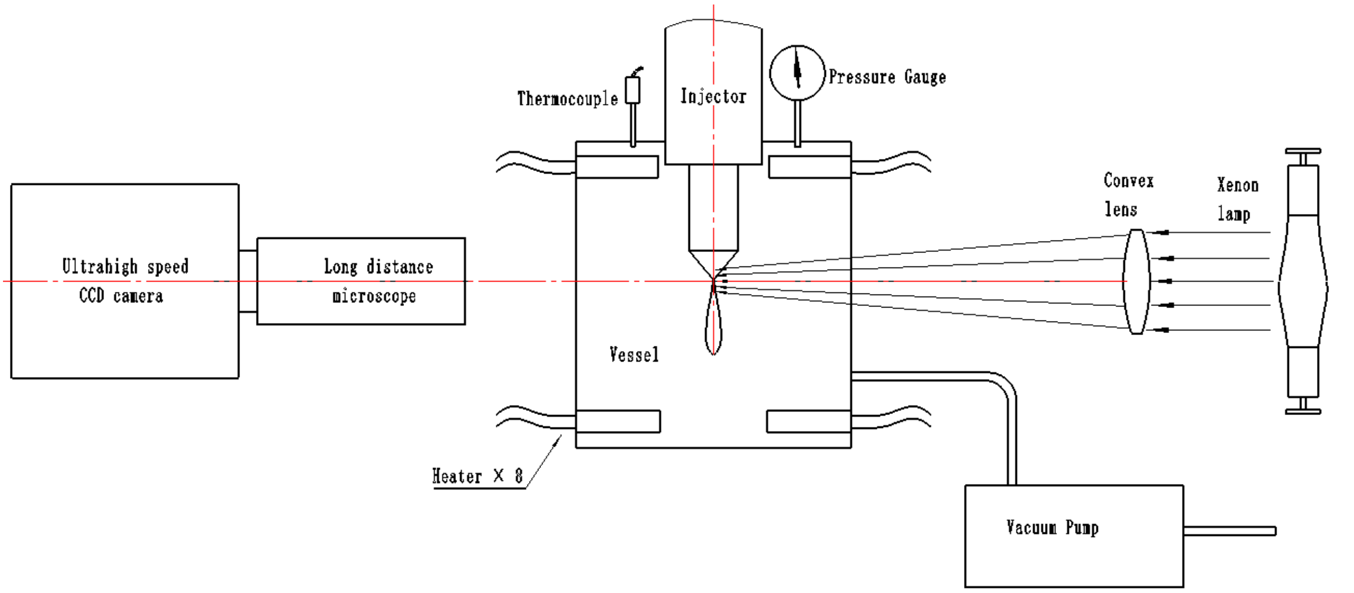


Figure 1. Experimental setup

The optical setup includes an ultra-high speed camera, a long distance microscope, a lens and a 500-Watt xenon lamp. The frame speed of the camera was set to 1 million fps with the resolution of 312×260 pixel^2, giving extremely high temporal resolution (1 microsecond interval between two sequent images). The long distance microscope worked at the focusing distance of 18 cm, allowing an observation field of 1.8×1.46 mm for height and width respectively. This gave very high spatial resolution of 5.8 μm / pixel. The spray development process with detailed information which cannot be studied with traditional high speed imaging technique can be captured accurately by this ultra-high speed imaging technique. The lens was employed to focus the light at the injector tip so that the spray can be illuminated sufficiently when the ultra-high frame speed was used.

3. Test fuel and test conditions

To simplify the tests and quantify the fuel properties, isooctane rather than commercial gasoline was tested in the present study. The vapor pressure (Figure 2) is of great importance for spray dispersion under flash boiling condition. When the ambient pressure is lower than the vapor pressure, isooctane transfers from liquid phase to gas phase. Other properties of isooctane are shown in Table 1.

Table 1. Properties of isooctane [14]

Density @15 ℃ (Kg/m^3)	Kinematic viscosity @ 40 ℃ (mm^2/s)	surface tension @ 40 ℃ (kg/s^2)
690	0.72	18.77 x10^{-3}

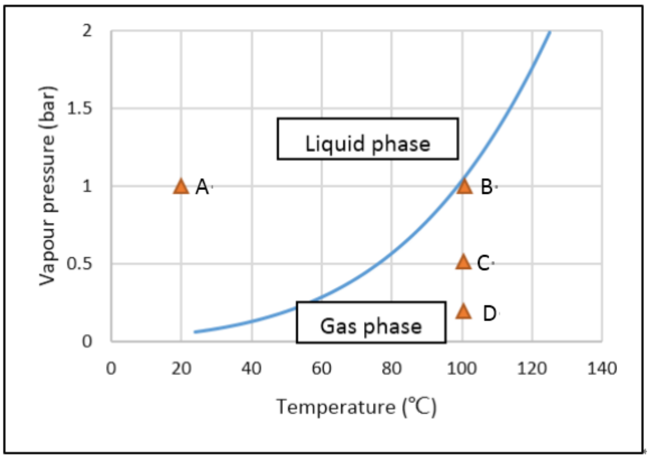
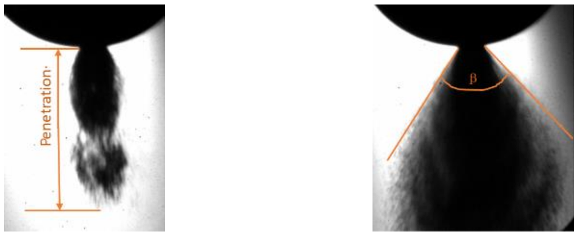


Figure 2. Vapor pressure of isooctane [2]

To study the effects of flashing boiling condition on the spray collapse at the microscopic level, four tests under the injection pressure of 400 bar were carried out, which are A, B, C, and D as shown in Figure 2. The injection duration was set to 1.2 ms, allowing the injector to fully open to study the quasi-steady state characteristics. For test point A with back pressure of 1 bar and ambient temperature of 20℃, no flash boiling could be observed and this point is used as reference for the comparison with other test points. Point B is at the boundary of flash boiling with the back pressure of 1 bar and ambient temperature of 100℃ (marginal flash boiling condition). When the back pressure is decreased to 0.5 bar while keeping the ambient temperature at 100℃, the flash boiling effect becomes strong, as shown at point C. The last testing point is under strong flash boiling condition where the back pressure is set to 0.2 bar and vessel temperature is set to 100 ℃. To further investigate the influence of injection pressure (thereby hydraulic force or cavitation) on spray breakup and dispersion under flash boiling condition, one test under 700 bar injection pressure was performed at point D. Each test was repeated for 15 times to obtain sufficient accuracy for quantifying the spray characteristics.

4. Results

This study mainly focused on the initial injector opening stage (within 100 microseconds after start of injection (ASOI)) and the quasi-steady stage (between 500 microseconds and 600 microseconds ASOI). The penetration (the distance between the injector tip and spray tip), the plume area and the plume angle are quantified to investigate the spray propagation and dispersion. The definitions for penetration and cone angle are presented in Figure 3. It should be noted that the definition of cone angle in the very near field is different from the cone angle for far field. Two lines originating from the injector tip fit the tangent boundary of the plume, giving a quite large cone angle under flash boiling condition. The quickly growing vapor bubbles in the plume expel the fine dispersed droplets away from the plume center and this phenomena leads to the aforementioned large cone angle [3]. The images are processed with a self-built Matlab code so that the parameters can be obtained. The threshold of 0.15 was employed to identify the boundary of the plume accurately. The accuracy of the boundary detection was carried out by the comparison of the calculated value (spray penetration) from the code and the value obtained by counting the pixels manually.



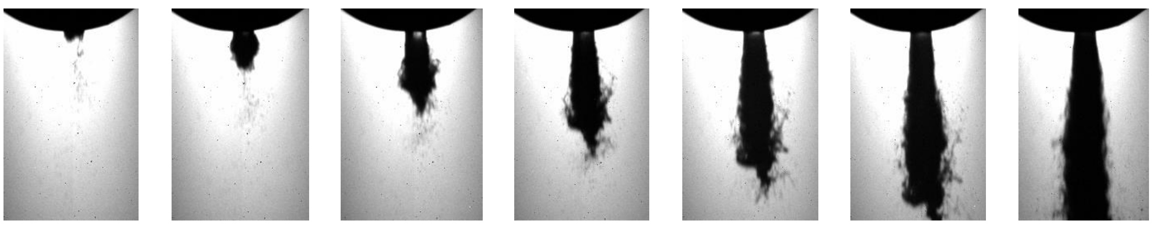
(a) (b)

Figure 3. The definitions for (a) penetration and (b) cone angle

4.1 Influence of raised temperature

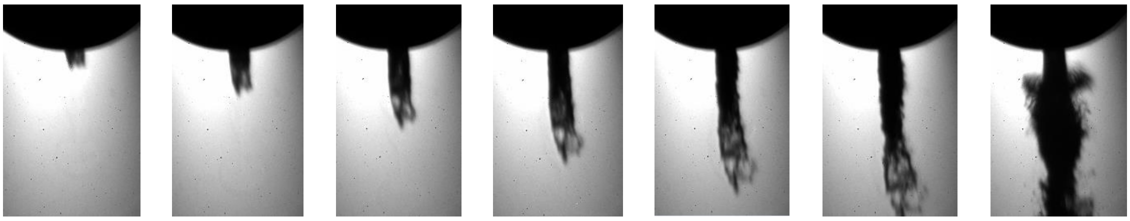
4.1.1 Start of injection

The spray morphology development with ambient temperature of 20℃ and back pressure of 1 bar is presented in Figure 4. Some large ligaments and droplets can be observed at the periphery of plume. The spray is not well dispersed at this stage as a white liquid column can be seen at the very outlet of the injector, showing quite high fuel density. This is mainly attributed to the low effective injection pressure caused by the low needle lift at the very beginning of injection. Pickett et al. [15] reported that from the injector tip to 3 mm downstream, the spray shows similar density to liquid fuel. The overall developing trend is similar to the trend of diesel spray, as reported in literature [16, 17] where the tested fuel was diesel. The main difference is that no mushroom shaped head can be observed in present study. This is probably due to the low viscosity of the employed isooctane. Because no mushroom shaped spray was observed in this study, the effect of fuel viscosity on the formation regime is not discussed in this study. More details about the formation regime of the mushroom head can be found in [16].



1μs 4μs 8μs 12μs 16μs 20μs 50μs

Figure 4. Spray morphology development during initial injection stage under 40 MPa injection pressure, 1 bar back pressure and 20℃ ambient temperature

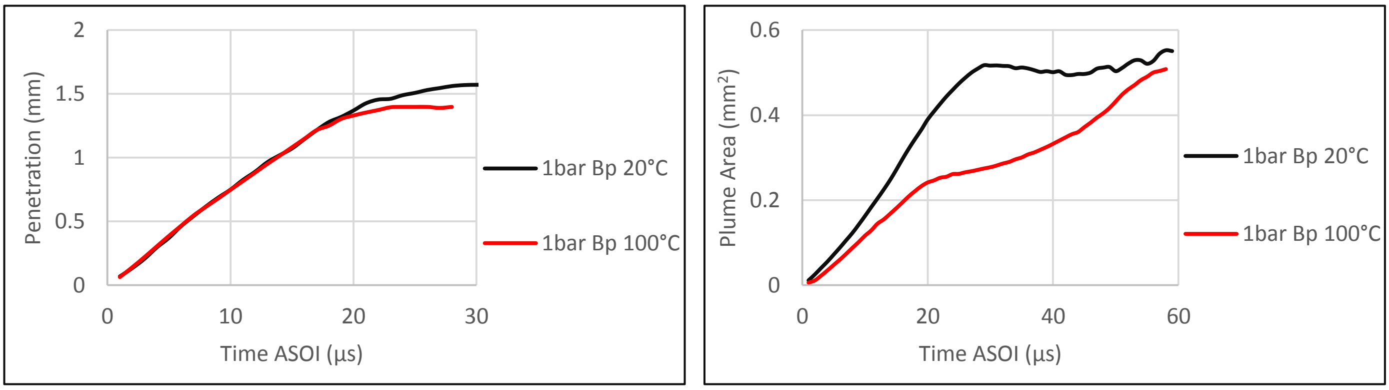


1μs 4μs 8μs 12μs 16μs 20μs 50μs

Figure 5. Spray morphology development during initial injection stage under 40 MPa injection pressure, 1 bar back pressure and 100℃ ambient temperature

When the ambient condition is heated to 100℃, some distinctions for the spray morphology can be seen, as presented in Figure 5. During the initial stage, the plume is thinner and no ligaments or droplets can be observed at the plume periphery. The fuel evaporation at the plume periphery tends to be responsible for this feature. It can also be seen that a large amount of fuel with low speed is pushed away by the main injection with high speed at 50μs after start of injection. The large amount of fuel with low speed (thus poor atomization) may belong to the residual fuel of the previous injection. The low effective injection pressure in the very early stage may also lead to the very low speed of the spray. When compared with the low temperature case (Figure 4), no white intact liquid at the very outlet of the injector can be seen. The rise of temperature lowers the viscosity and surface tension, resulting in better dispersion and atomization although no droplets are observed at the spray periphery.

The corresponding quantified spray characteristics, namely the penetration and spray area of the sprays shown in Figure 5 are shown in Figure 6. Difference in penetration before 20 μs ASOI is hardly identified as shown in Figure 6 (a). A small difference can be observed after 20μs, which is probably due to evaporation of spray tip under 100℃ [6]. By contrast, the spray area under high ambient temperature is obviously smaller than that under room temperature, especially between 20 and 40μs ASOI. This suggests that ambient temperature mainly affect the periphery of the spray where the fuel density is much lower than that in the plume center. When the main injection starts (around 50μs ASOI, as shown in Figure 5), the spray area difference diminishes. The further opening of the injector for the main injection allows a large amount of fuel to be injected with high speed. The effect of the temperature on the spray behavior weakens due to the limited time for evaporation. Manin [18] studied the impact of various boundary conditions, for instance fuel pressure, ambient pressure and temperature. The employed fuel was ethanol. The fuel pressure ranged from 30 to 150 MPa with ambient temperature varying between 30 and 80℃. It was found that penetration was shortened with almost unaffected cone angle when ambient temperature was raised. Their results of cone angle contradict with the result in the present study and this disparity may be attributed to different fuel properties and different injection pressure and ambient temperature. In addition, the view field in their study was up to 6 mm downstream of the injector which was much longer than that in the present study (1.8 mm downstream of the injector) and the effect of ambient temperature on spray was observable.

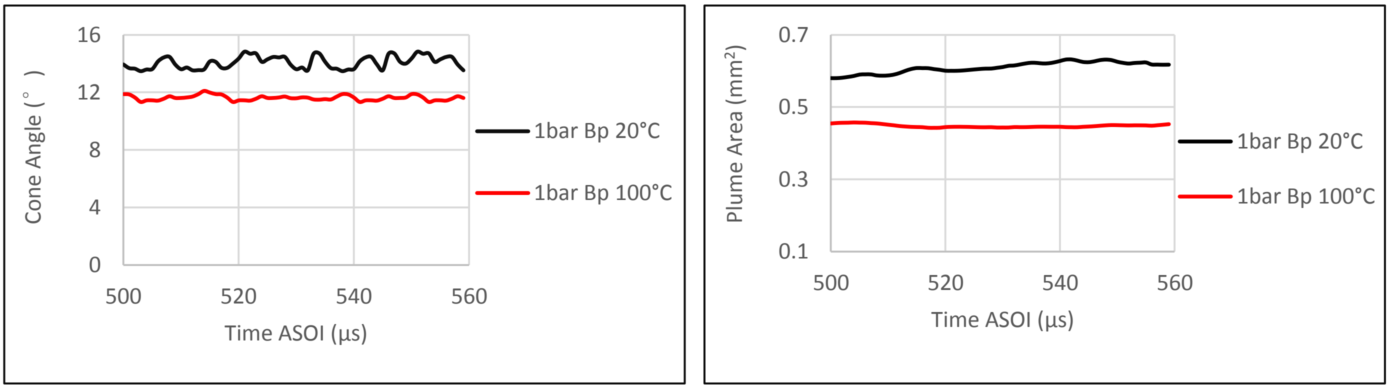


(a) (b)

Figure 6. Influence of ambient temperature on (a) penetration and (b) plume area during the initial injection stage

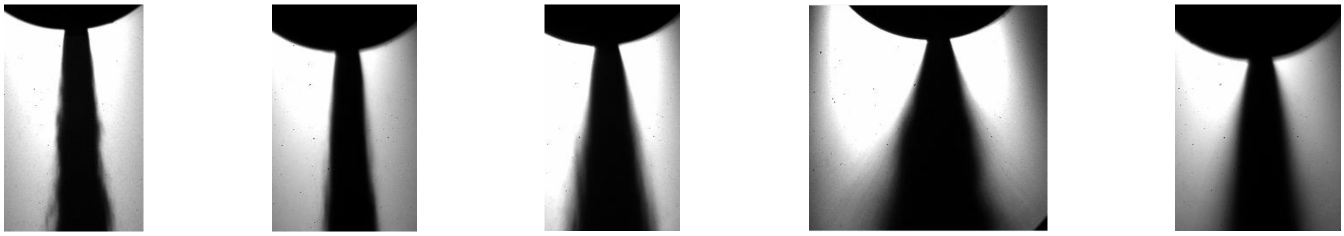
4.1.2 Steady state

For the quasi steady stage, namely the injector being fully open, the impact of temperature on the spray characteristics is small albeit noticeable. Around 4° smaller cone angle and approximate 0.2 mm^2 smaller plume area are found with the rise of ambient temperature, as presented in Figure 7. As mentioned before, the effect of evaporation under high ambient temperature on the spray characteristics is marginal due to the very limited time [2, 3]. The spray morphologies during steady state under these two conditions are presented in Figure 8 (a) and 8 (b) respectively. It should be pointed out that the smaller area under 100℃ can also be partly due to the smaller view field caused by the movement of the imaging system when disturbed. Smoother periphery is found under high ambient temperature condition. Small dispersed particles at the periphery are evaporated and big droplets become small again caused by the evaporation at elevated temperature condition. Better atomization can be expected with high ambient temperature because of the altered fuel properties, for instance reduced viscosity and surface tension.



(a) (b)

Figure 7. Influence of ambient temperature on (a) cone angle and (b) plume area during the quasi-steady stage



(a) (b) (c) (d) (e)

Figure 8. Spray morphology at quasi steady stage under various conditions: (a) 40 MP P_{inj}, 1bar B_p and 20℃, (b) 40 MPa P_{inj}, 1 bar B_p and 100℃, (c) 40 MPa P_{inj}, 0.5 bar B_p and 100℃, (d) 40 MPa P_{inj}, 0.2 bar B_p and 100℃, (e) 70 MPa P_{inj}, 0.2 bar B_p and 100℃

4.2 Influence of decreased back pressure

4.2.1 Start of injection

The decrease of back pressure under hot condition leads to the inception of flash boiling, presenting a quite different picture for the spray primary breakup in the near field as shown in Figure 9. Although normal morphology for the very early stage (before 12μs ASOI) is seen, a much different one is seen when the main injection starts. The fuel spray appearing first is generally the remaining fuel of the previous injection. The following fuel spray with more dispersion and higher velocity is thought to be the main spray [17, 19]. During the start of injection process, the needle moves upward and the injector opens further. The further injector opening leads to the increase of the effective injection pressure and the resultant spray hydraulic force. The flow regime correspondingly changes from laminar to turbulent and even to cavitating flow. This flow regime transition generally occurs very quickly [17, 19]. In the present study, the flow regime is thought to go through these transition stages within the first 50μs and the spray morphology simultaneously goes through an obvious change from a poorly dispersed one to a well dispersed one. This means that the flow regime or inertia of the plume is quite important for the special shape of the spray under flash boiling condition and this will be further discussed in the later section. The plume shows remarkable radial propagation, giving a much larger cone angle than the normal one. Well dispersed droplets are seen at the periphery of the plume and fuel becomes leaner at the central part of the plume. Reitz [6] studied the developing regime of flash boiling for water under a wide range of temperatures, varying from 27 to 153 ℃. The injection pressure was set to 70 MPa and the ambient condition was atmospheric. It was reported that a dense spray enveloped by well dispersed droplet was observed under flash boiling condition. This finding agrees quite well with the results in present study although the tested objects are different.

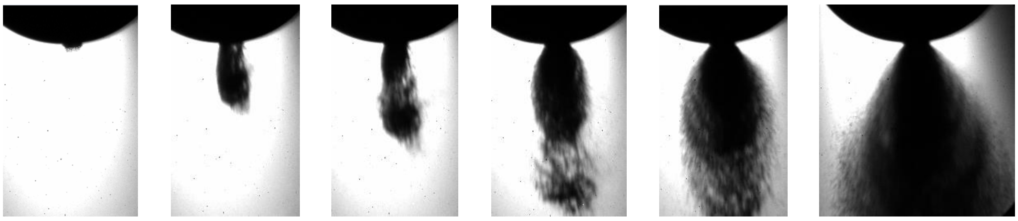


Figure 9. Spray morphology development during initial injection stage under 40 MPa injection pressure, 0.5 bar back pressure and 100℃ ambient temperature

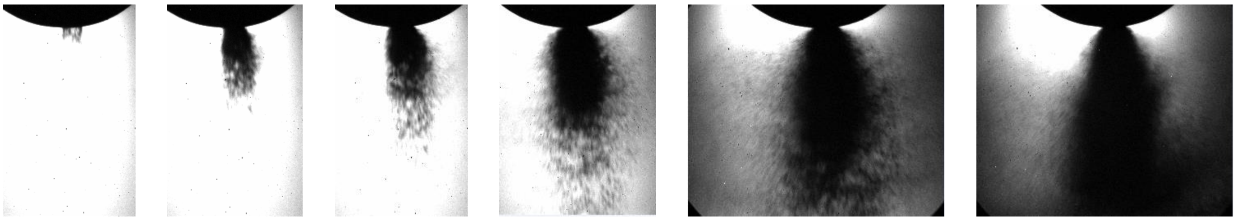


Figure 10. Spray morphology development during initial injection stage under 40 MPa injection pressure, 0.2 bar back pressure and 100℃ ambient temperature

Further reduction of back pressure results in a more prominent radial expansion for the plume, as presented in Figure 10. The droplets are further scattered away from the plume center, leading to dramatic increase of cone angle. The larger injector opening (thereby higher effective injection pressure) however decreases radial expansion of the spray, causing a drop of the cone angle, as shown at 50μs ASOI. When comparing Figures 5, 9 and 10, it can be seen that the reduction of ambient leads to stronger flash boiling, better dispersion and more obvious radial propagation. According to the vapor pressure of the employed isooctane shown in Figure 2, under 100℃, the liquid fuel transfers to gas phase when ambient pressure goes down to 0.5 bar and further down to 0.2 bar. Park and Lee [20] reported that the plume atomization is closely governed by the internal flow regime which is highly responsive to the strength of superheating. The raised superheating strength changes the flow from bubby flow to slug flow and then to annular flow [20]. For the first flow regime, the existence of big intact core with droplets around was reported. When superheating becomes stronger, more vapor bubbles appear. Big slug liquid formed through the accumulation of the small bubbles could be seen for the second regime, leading to the introduction of massive ligaments and droplets in the plume core when the slug liquid is discharged [20]. For the last one with very strong superheating, the formation of vapor flow in the nozzle center with film attaching to the nozzle wall causes very well dispersed droplets when vapor flow is discharged [20].

By combining the experimental results in the present study and the explanation from the literature, the influence of flash boiling on spray characteristics can be summarized as follows. Generally, small vapor bubbles are released from the liquid fuel and big accumulated bubbles explode when leaving the injector tip due to the abrupt pressure reduction. The explosion of the vapor bubbles gives the droplets quite high radial inertia, enabling the droplets to move radially for a quite long distance. Apart from that, the low air density under low ambient back pressure and high temperature ensues very low drag force or resistance for the droplets. Even quite small radial inertia enables the droplets to propagate significantly radially. The effects of temperature and ambient pressure on the flash boiling can be quantified and expressed in Equation 1 [3]:

$$\gamma = \frac{P_{Vapor}(T) - P_{ambient}}{P_{ambient}} = \frac{P_{Vapor}(T)}{P_{ambient}} - 1 \tag{1}$$

Where γ is flash boiling number (denoting superheating), $P_{Vapor}(T)$ is vapor pressure @ temperature T and $P_{ambient}$ is ambient pressure.

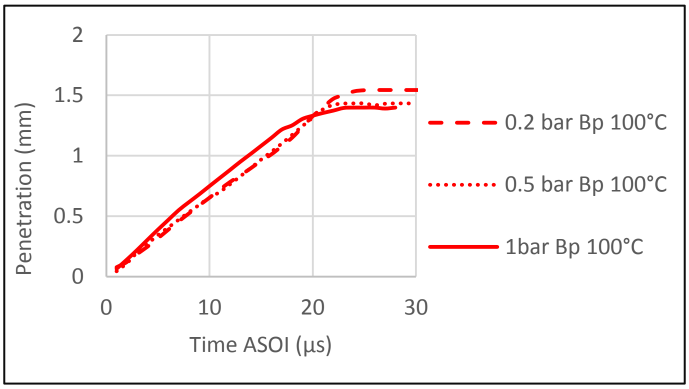
It can be seen that the simultaneous increase of vapor pressure and the decrease of ambient pressure lead to the increase of flash boiling number. More obvious phase transfer from liquid to gas is also expected. This means it is easier for the vapor bubbles to explode as the resistances, for instance the surface tension force and liquid viscous force, are decreased.

Besides, the cavitation is also believed to boost the propagation [21]. Kawano [22] investigated the flash boiling spray characteristics by modeling and experiment. It was found that the spray can atomize obviously quicker with flash boiling. The thermodynamic instability caused by superheating features flash boiling, however, the cavitation is mechanically related. Cavitation can significantly boost the flash boiling through the formation of vapor bubbles [2]. The definition of the cavitation number is shown as:

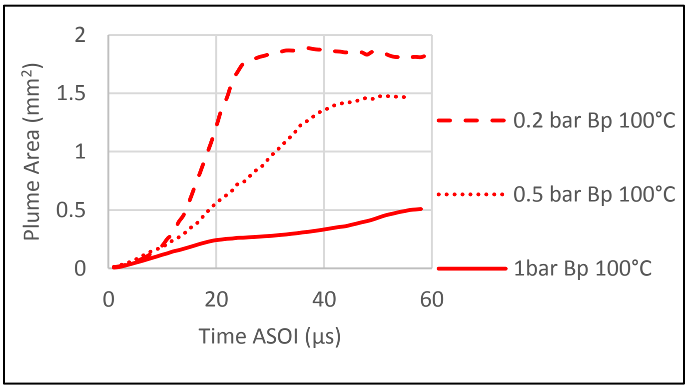
$$\mathrm{K} = \frac{P_{inj} - P_v}{P_{inj} - P_b} \tag{2}$$

When the ambient temperature is set, the decrease of back pressure leads to lower cavitation number. When the flow regime in the nozzle is cavitating, the air resolved in the fuel accumulates, forming small bubbles. When these small bubbles grow quickly when heated and the growing big bubbles collapse when leaving the injector tip.

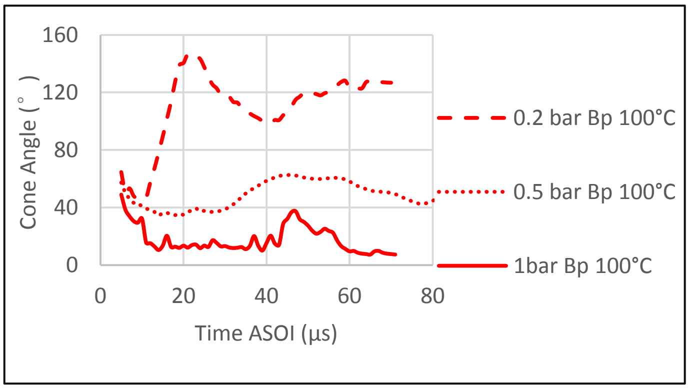
The spray characteristics shown in Figure 11 accordingly present remarkable developing trends, especially for the spray area and cone angle. Specifically, the plume under flash boiling condition penetrates quicker than the plume under atmospheric condition. The air density under low back pressure is lower and this leads to lower air drag force for the plume. Apart from that, the explosion of the vapor bubbles is believed to accelerate droplets, further accelerating the droplets. The cone angle and plume area present an obvious increase when ambient pressure drops down to 0.5 bar. However, a sharp increase of the plume area is noticed when back pressure decreases further down to 0.2 bar. The sharp increase of plume area is partly caused by the quick improvement of dispersion and partly caused by the increase of fuel mass. When the injector further opens, the hydraulic force and the inertia of the spray increase, leading to better dispersion and more obvious radial propagation. More importantly, more fuel is injected and the explosion of the vapor bubbles formed in the injected fuel causes quick increase of spray area. According to Equation 1, the reduction of back pressure greatly boosts strength of flash boiling and the boosting effect for plume area is more obvious under lower back pressure.



(a)



(b)

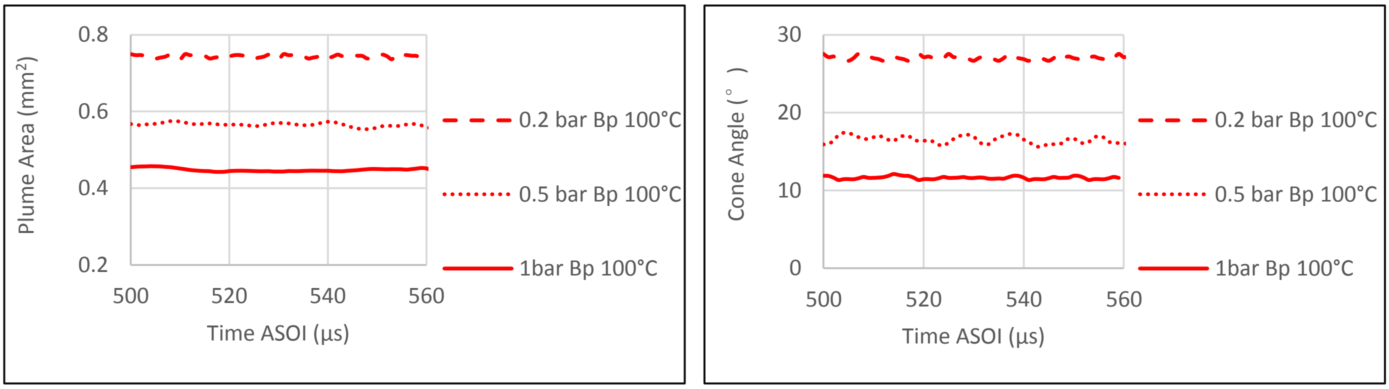


(c)

Figure 11. Influence of back pressure on (a) penetration, (b) plume area and (c) cone angle during initial injection stage under 40 MPa injection pressure and 100℃ ambient temperature

4.2.2 Steady state injection

It is interesting to find that the plume under sub atmospheric condition behaves quite different when develops from initial injection stage to quasi steady state. Both the cone angle and the plume area show an obvious reduction when compared with the initial stage (Figure 11), as shown in Figure 12. This is also illustrated from the spray morphology shown in Figure 8 (c) and Figure 8 (d). When injector further opens, the influence of effective injection pressure (thus hydraulic force) becomes more important [19, 23]. This is probably due to the much increased axial velocity, leading to limited time for the radial propagation. This assumption can be verified from the spray morphology in Figure 8 (c) and (d) where very well dispersed droplets are observed at the periphery of the plume. When looking at the initial stage in Figures 9 and 10, obviously larger droplets can be found at the plume periphery.



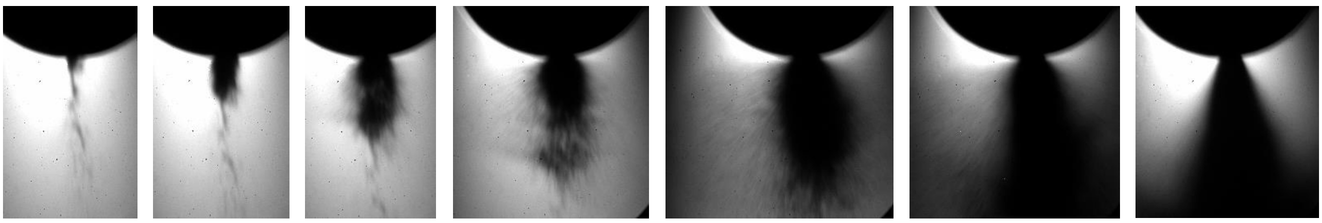
(a) (b)

Figure 12. Influence of back pressure on (a) plume area and (b) cone angle during quasi-steady stage under 40 MPa injection pressure and 100℃ ambient temperature

4.3 Influence of injection pressure

4.3.1 Start of injection

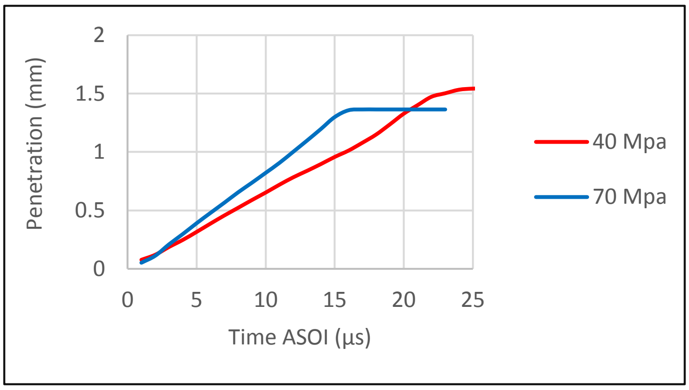
The injection pressure is believed to be important for the spray characteristics which are dominated by the inertial force. The spray morphology development under higher injection pressure (70 MPa) shows a quite different picture compared with the low injection pressure case (40 MPa, Figure 10), as shown in Figure 13. Much smaller droplets are observed, meaning much better dispersion quality even at the initial spray stage. Crua et al. [24] investigated the droplet size at the spray periphery and reported that the droplet size in the near nozzle region is nearly independent on the fuel properties but dependent on injection pressure. Although the radial propagation is more prominent under raised injection pressure, smaller proportion of fuel is seen in the periphery when compared with the low pressure case (Figure 10). It is worth noting that the plume becomes obviously narrower at 50μs ASOI under raised injection pressure.



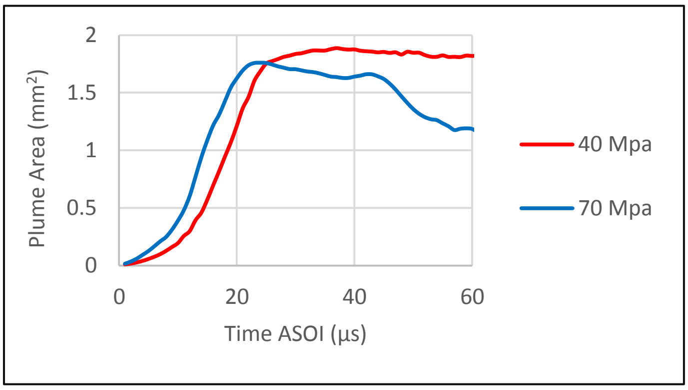
0μs 4μs 8μs 12μs 20μs 30μs 50μs

Figure 13. Spray morphology development during initial injection stage under 70 MPa injection pressure, 0.2 bar back pressure and 100℃ ambient temperature

The comparison of the spray characteristics between high and low injection pressures is shown in Figure 14. It is quite sensible to find higher penetration under higher pressure due to raised inertia. Larger plume area and cone angle are also expected with the rise of injection pressure because of enhanced dispersion. However, surprisingly observed is the two quick step reductions of the cone angle for the high pressure case (Figure 14 (c)). The first reduction, namely stage A, is due to the aforementioned further injector opening and the consequent higher axial velocity (thereby limited time for radial expansion and propagation). The disappearance of the well dispersed droplets produced when injector opens is also responsible for the first reduction of the cone angle. Stage A is not shown under low injection pressure (40 MPa) in this time range due to limited storage of the employed ultrahigh speed camera (102 images maximum). However, it should be pointed out that this stage still exists although not captured because the cone angle for quasi steady state (Figure 12 (b)) is obviously smaller than the cone angle during the initial stage. The second reduction is caused by the movement of the initially well dispersed fuel located in the tip of the plume, the C part shown in Figure 14 (c).



(a)



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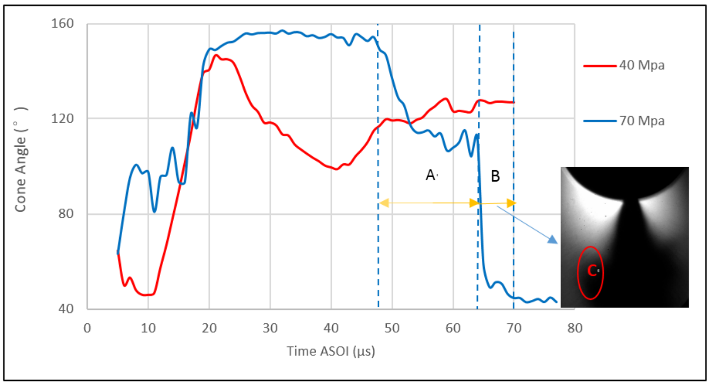


(c)

Figure 14. Influence of injection pressure on (a) penetration, (b) plume area and (c) cone angle during initial injection stage under 0.2 bar back pressure and 100℃ ambient temperature

4.3.2 Steady state injection

The high injection pressure case surprisingly presents both smaller plume area and cone angle than the low injection pressure case after the full open of the injector, as presented in Figure 15. This can be verified through the morphology shown in Figure 8 (e). Generally, higher injection pressure results in better dispersion and larger cone angle, which conflicts the results shown in this study. Two facts are likely to be responsible. The first one is the limited time for radial propagation due to high axial velocity, as mentioned before. The other is the transfer of the flow regime from cavitating flow to flipping flow in the nozzle hole. Under cavitating condition, the spray is dispersed completely at the very outlet of the injector. The cavitation mode shows a large cone angle due to the good dispersion and this is generally reported under high injection pressure [17]. However, further increase of the injection pressure results in the flipping flow, showing a detachment between the fuel flow and the nozzle wall. The appearance of the detachment results in a decrease of the cone angle.

Sou et al. [25] quantified the boundary value for cavitating flow and flipping flow with a 2D transparent injector. It was reported that when Reynolds number (Re) is higher than 68000, the flow is cavitating while when Reynolds number (Re) is higher than 76000, the flow is flipping. The two values are employed as the reference in the present study due to various experimental similarities.

The theoretical Reynolds number (Re) can be calculated through Equation 3

$$\mathrm{Re} = V_{th} * d_0/v \tag{3}$$

Where V_{th} is theoretical flow velocity in the nozzle, d_0 is hole diameter and v is fuel viscosity.

V_{th} can be obtained through Bernoulli's equation, shown in Equation 4

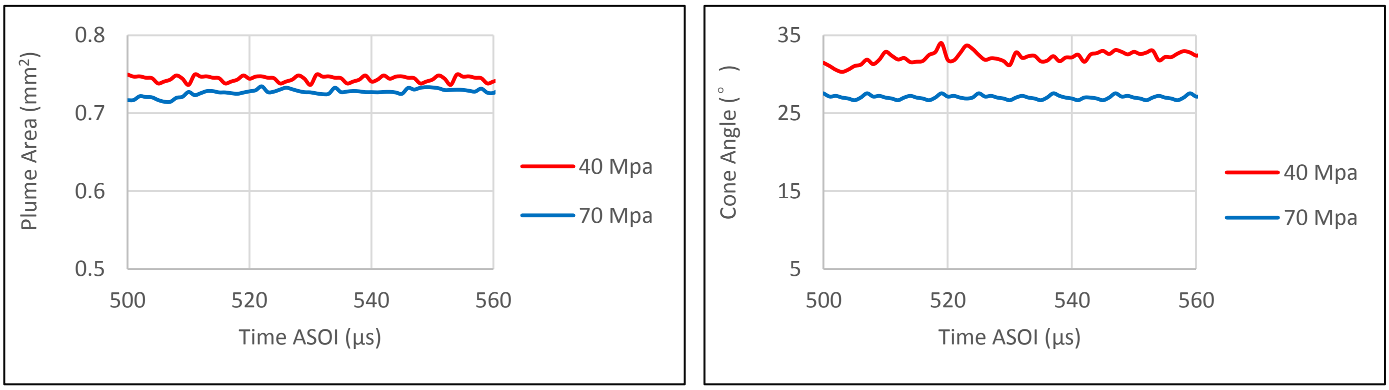
$$V_{th} = \sqrt{\frac{2\Delta p}{\rho_l}} \tag{4}$$

Where Δp is effective injection pressure and ρ_l is liquid fuel density.

Thus, Re can be expressed as:

$$\mathrm{Re} = \frac{d_0}{v} * \sqrt{\frac{2\Delta p}{\rho_l}} \tag{5}$$

In the present study, the Reynolds number is 112610 under 70 MPa and 85125 under 40 MPa, indicating that the flows in both cases are flipping but the detachment under 70 MPa is more significant than that under 40 MPa. This explains the smaller cone angle under 70 MPa than under 40 MPa during the steady stage. If the initial stage is also considered, it can be expected that the flow in the nozzle experiences several stages with the opening of the injector, namely, laminar flow, turbulent flow, cavitating flow and flipping. The influence of flash boiling on the spray behavior is remarking during the initial stage when the flow is mainly laminar, turbulent and possibly cavitating, by contrast, the influence is quite weak during the steady stage when the flow is mainly the flipping.



(a) (b)

Figure 15. Influence of injection pressure on (a) plume area and (b) cone angle during quasi steady stage under 0.2 bar back pressure and 100℃ ambient temperature

Conclusion

The primary breakup characteristics of isooctane spray in the near field were investigated under flash boiling condition which represents the part load operation condition for GDI engine. The spray morphology was recorded with an ultrahigh speed camera complete with a highly resolved long distance microscope. A single-hole diesel injector was used so that the interference from other plumes can be eliminated. A common rail injection system was also applied to study the impact of high injection pressure. The following conclusions can be drawn.

Flash boiling can significantly alter the spray pattern because of the collapse of vapor bubbles produced through phase transfer and cavitation. This considerably improves the primary breakup, producing a large amount of well dispersed droplets at the periphery of the spray. The strength of flash boiling is mainly governed by two factors, ambient temperature and ambient pressure. The increase of ambient temperature (before the inception of flash boiling) leads to the reduction of spray area and cone angle for both initial stage and stable stage by accelerating the evaporation. However, under high ambient temperature, the reduction of back pressure greatly improves the atomization of the spray (thereby considerable increase of spray area and cone angle) by substantially boosting the flash boiling. Besides, under flash boiling condition, the radial propagation of spray during the injector opening stage is more obvious than the quasi-steady stage which is governed by the hydraulic force. In addition, the increase of injection pressure causes better dispersion for both injector opening stage and steady stage. However, the rise of injection pressure results in the decrease of cone angle and spray area during the steady stage because of the dominance of the hydraulic force.

Flash boiling condition is beneficial to spray atomization, producing small droplets and favorable air/fuel mixture. When calibrating the injection timing for GDI engine, the advantageous effects of flash boiling could be employed. However, the pumping loss caused by vacuum for flash boiling condition should be considered because some energy will be wasted due to pumping loss.

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