Formation and Structure of the Supercritical Fuel Flash-boiling Spray

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Abstract

The optimization of fuel injection is one of the key technologies to achieve cleaner and more efficient engines. Extensive studies have demonstrated that the flash-boiling of superheated fuel would dramatically improve the atomization, mixing and combustion process. Further increasing the fuel temperature can make the fuel at a supercritical state, the flash-boiling spray of which has rarely been noticed in existing studies. The relevant data and analysis of the behavior and characteristics of supercritical fuel flash-boiling spray are still lacking. In this study, the supercritical flash-boiling injection was achieved by heating the fuel inside the injector, and its spray behavior was examined by high-speed backlit imaging. This study found that the supercritical fuel flash-boiling spray has a transient formation process different from common sprays due to the supersonic effect during the initial injection. The spray structure was carefully analyzed based on its thermodynamic state and hydrodynamic state. The characteristic of the supercritical fuel flash-boiling spray is very similar to that of the highly under-expanded jet.

Keywords: Supercritical; flash boiling; under-expanded flow; supersonic spray; Mach disk

Introduction

Supercritical injection is a novel way for fuel delivery. The viscosity, surface tension and diffusion coefficient of supercritical fuel are close to vapor, which is good for fuel atomization, evaporation, dispersion and mixture formation [1]. Meanwhile, compared with vapor fuel, the supercritical fuel has a relatively high density, which can ensure the fuel delivery efficiency. There is no common definition of supercritical injection in existing studies. Generally, if the fuel thermodynamic state either before or after injection is in the supercritical region, the injection can be regarded as a supercritical injection. Therefore, it can be categorized into three types according to the fuel thermodynamic states before and after injection.

The first type is the fuel injection from the supercritical state to the supercritical environment, which is also called the strict supercritical injection. The second type is the fuel injection from the subcritical state to the supercritical environment. The third type is the fuel injection from the supercritical state to the subcritical environment. Gerber et al. [2] systematically investigated the injection of supercritical hydrocarbon fuel into the environment at room temperature and a wide range of pressure. It was found that the spray behavior sensitively changes with the environment pressure, and four injection regimes were well summarized. Liu et al. [3] and Gao et al. [4] examined the injection of sub- and supercritical fuel into the atmospheric environment. The supersonic-flow-induced Mach disk can be clearly observed, and its location is in good agreement with the literature results of the under-expanded gas jet, suggesting that the spray behavior of supercritical fuel is quite similar to that of the gas jet in the aspect of shock structure. Compared with the other two types of supercritical injection, the injection of supercritical fuel to the subcritical environment is most likely to be achieved in GDI engines. De Boer et al. [5] developed a supercritical injection system and used it in a single-cylinder GDI engine, which was realized by heating the fuel up to 320℃ inside the injector. In comparison with the common injection, the supercritical fuel injection reduced over 90% of PN, up to 61% of PM emissions and up to 4% of part-load BSFC in their experiments. Furthermore, Liu et al. [6] investigated the spray and droplet characteristics of supercritical gasoline injection with fuel temperature up to 376℃. It's reported that the supercritical fuel spray disperses more widely, and the SMD (Sauter Mean Diameter) of the spray reduces to lower than 3μm under supercritical conditions, which is crucial for the better subsequent combustion.

Besides the supercritical injection, the flash-boiling injection has been proposed as a low-cost method to produce better-atomized sprays. Although very extensive studies have been conducted on the phenomenon [7, 8], characteristic [9, 10] and mechanism [11, 12] of flash-boiling spray, few studies link the flash-boiling with the supercritical injection. This is because the fuel temperature used in most studies of flash-boiling spray is below 120°C, while the supercritical temperatures of common gasoline surrogates such as n-heptane and isooctane are above 200°C. Therefore, to achieve supercritical fuel flash-boiling spray, it is only needed to elevate the initial fuel temperature of general flash-boiling injection to exceed the supercritical temperature. Combining the advantages of flash-boiling and supercritical injection, the supercritical fuel flash-boiling spray is very potential to be used in GDI engines to enhance fuel atomization, vaporization, and improve combustion. However, existing knowledge on the fundamental behavior of the supercritical fuel flash-boiling spray is very limited.

In this work, the morphology of the supercritical fuel flash-boiling spray was studied using a single-hole injector. The typical spray formation process and spray structure were analyzed.

Experimental Details

As shown in Figure 1, a constant volume chamber with four optical windows was used in the experiments. The chamber was filled with nitrogen during the tests, and its internal pressure, denoted by the ambient pressure (p_a), was regulated by the vacuum pump and the pressurized nitrogen. The ambient temperature was at 25℃. The tested injector was mounted on the top of a constant volume chamber. It has a vertical single-hole with a diameter (d_0) of 143 μm and length (L) is 800 μm. A high-pressure fuel supply system delivered the test fuel to the injector and the injection pressure (p_{inj}) can be regulated by the pressure regulator. An electric heater controlled by a PID controller was used to heat the fuel through heating the injector nozzle, and the fuel temperature (T_f) can reach 300℃.

Backlit high-speed imaging was used to capture the spray behavior. The back illumination was provided by the Xenon lamp. A high-speed camera was used to record the spray backlit images. With a lens of 50 mm focal length, the macroscopic spray images were taken. Its sampling frequency is 40 kHz, the resolution of each image is 0.117 mm/pixel and the corresponding image size is 30 mm (width) × 60 mm (height). To observe the detailed structure of the initial spray, a microscopic lens was used to take the nozzle near-field spray images. The near-field imaging frequency is 20 kHz, the resolution of each image is 0.0176 mm/pixel and the corresponding image size is 7.2 mm (width) × 9 mm (height). A high-speed synchronizer was used to synchronize the injection and high-speed imaging system. During the tests, the injection duration was set to 1500 μs, and the injection frequency was set to 1 Hz. To mitigate the measurement error, 20 cycles of images were taken for each case.

In all the experiments, n-pentane was used as the test fuel. Its critical temperature is 197℃ and pressure is 3.37 MPa (data from NIST). The ambient temperature was kept at 25℃. The injection pressure was fixed at 350 bar. The fuel temperature was ranged from 169℃ to 290℃ and the ambient pressure was ranged from 5 kPa to 100 kPa. Specifically, Figure 2 depicts the thermodynamic state change that the fuel experiences during the injection and spray process in a *p*-*T* diagram (data from NIST).

The red marks represent the initial state of the fuel inside the injector, covering the subcritical liquid and supercritical state. The blue marks represent the ambient state in the test chamber. After the fuel is injected, its pressure suddenly drops to around the ambient pressure. Due to the very limited time for heat transfer, the fuel temperature still keeps a high value. Such a situation causes the fuel in an unstable thermodynamic state for all test conditions, which is marked in yellow in Figure 2. Subsequently, the fuel passes through a series of processes including flash-boiling from an unstable state to the environmental state shown by the blue marks. This process is the focus of this study.

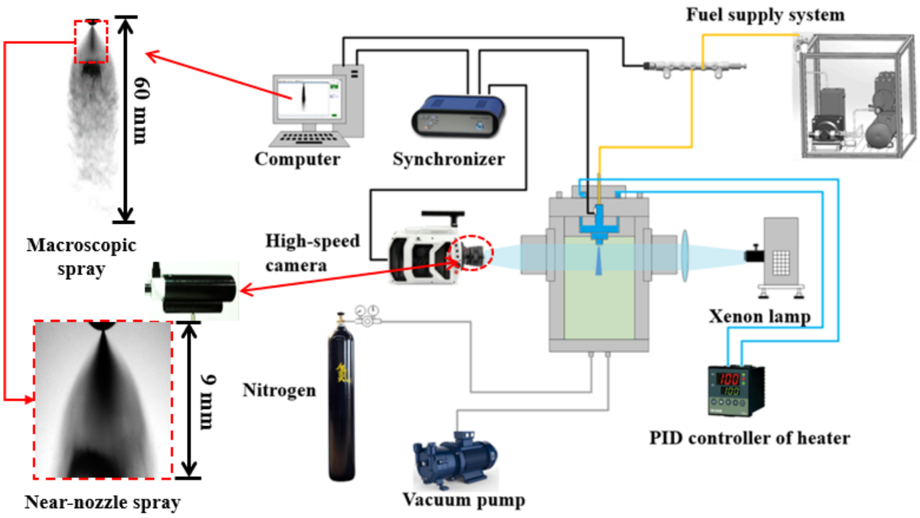

Figure 1. Schematic of the experimental setup.

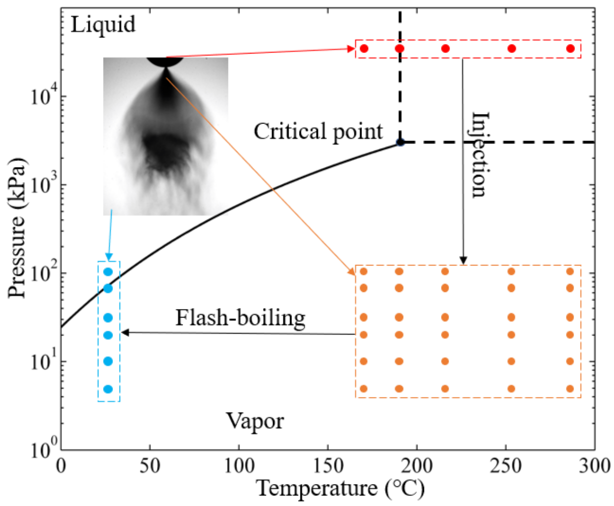

Figure 2. Schematic illumination of fuel thermodynamic state before and after injection in the *p*-*T* phase diagram.

Results and discussions

The main findings of our investigation on the supercritical fuel flash-boiling spray are presented in this section, and the transient spray formation process, the spray structure in quasi-steady state, the characteristic of spray axial penetration, radial expansion and Mach disk location are analyzed and discussed.

Figure 3 illustrates the transient formation process of supercritical fuel flash-boiling spray and related characteristics. At injection pressure of 350 bar and initial fuel temperature of 252℃, the fuel is in a supercritical state inside the nozzle before injection. When the supercritical fuel is injected into an environment with an ambient pressure of 30 kPa, the supercritical fuel flash-boiling spray is generated, and its presence is obviously different from the superheated fuel flash-boiling spray that has been extensively studied before.

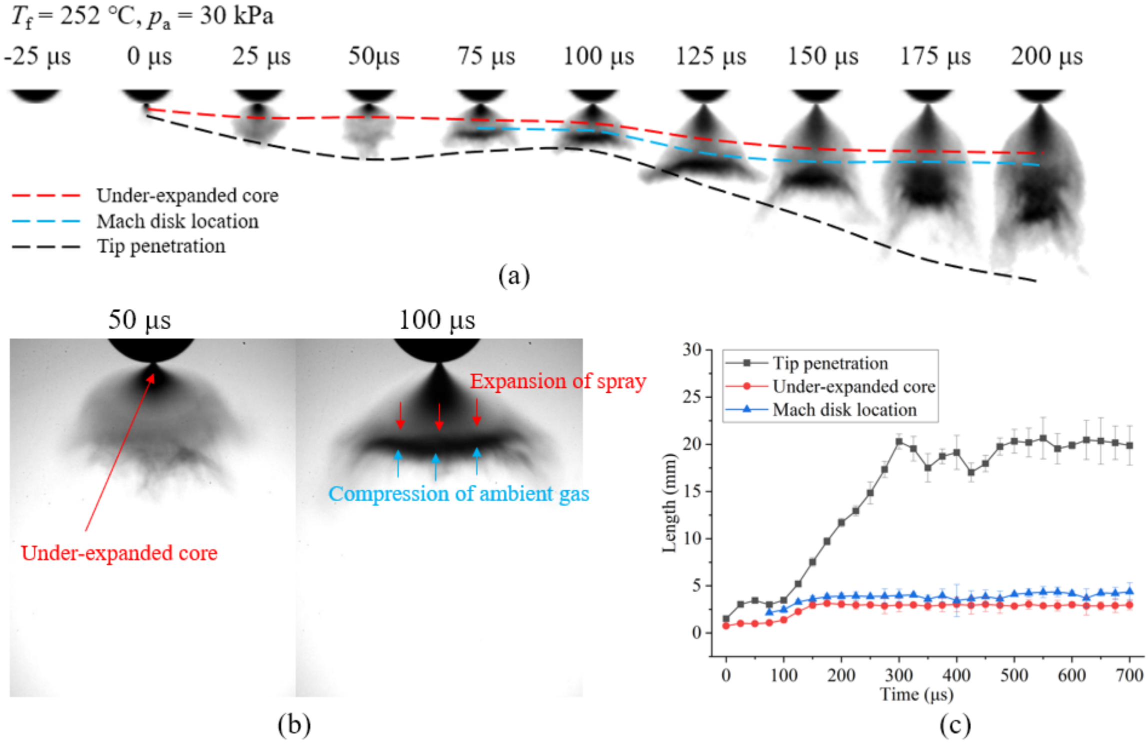

Figure 3. The formation of the supercritical fuel flash-boiling spray (T_f = 252℃, p_a = 30 kPa): (a) macroscopic images of initial spray; (b) nozzle near-field images of initial spray; (c) Development of tip penetration, under-expanded core and Mach disk location with time ASOF.

A series of spray images are shown in Figure 3(a), which were taken by the high-speed backlit imaging and the sampling interval is 25 μs. These images can reveal the transient formation process of the supercritical fuel flash-boiling spray during the first 200 μs ASOF. It is easy to notice that from Figure 3(a), the tip penetration of supercritical fuel flash-boiling spray grows to about 3 mm from 0 to 50 μs ASOF, then remains about this stable value to about 100 μs ASOF, and after that, it continues to grow with time. This is quite different from a general spray, of which the tip penetration should linearly grow with time in the nozzle near-field. It can be seen more clearly from the penetration curve shown in Figure 3(c) that the spray penetrating is delayed from 50 μs to 100 μs ASOF. This transient process is a unique phenomenon of supercritical fuel flash-boiling spray since it was rarely observed and mentioned in existing studies.

To further explore the mechanism that results in this phenomenon, the internal structure of supercritical fuel flash-boiling spray should be noticed, which is also significantly different from that of a general spray. As shown in Figure 3(b), at 50 μs ASOF, there is only one dark area in the spray image at the exit of the nozzle hole. For the backlit image of real spray, although the image opacity does not have strict correlation with the fuel density, the dark area generally means that the local fuel density is high and light is difficult to pass through. Therefore, the dark area just out of the exit of the nozzle is similar to the “liquid core” observed in low-pressure spray studies. For the supercritical fuel flash-boiling spray, a large amount of fuel vaporizes through flash-boiling after being injected, and its volume would expand rapidly and greatly. Therefore, the just-injected fuel can also be considered to be in an under-expanded state, and the dark area near the nozzle on the spray image can be defined as the under-expanded core. The discharge of injection pressure provides the fuel with a large axial velocity, and the rapid volume expansion outside the nozzle further accelerates spray. However, because the ambient air is still quiescent at the same time, it would be compressed by the quick penetrating spray head, which consequently causes the local pressure of the spray/air interface to rise greatly and forms a high resistance to the spray head. A large number of fuel droplets are decelerated and stayed on the spray/air interface and even condensation might happen due to the rising local pressure, showing the phenomenon that the dark area on the spray head is formed and the spray tip penetration was stagnant as the spray images at 100 μs ASOF shown in Figure 3(b). This internal structure of supercritical fuel flash-boiling spray is very similar to the shock wave structure caused by the under-expanded supersonic jet, and the upper surface of the local compression area is defined as Mach disk. After 100 μs ASOF, as the injection continues, more fuel is delivered to the local compression area, the ambient air is gradually accelerated, the compression area begins to expand downward, the spray tip return to penetrate, and the near-field spray structure tends to balance. As shown in Figure 3(c), the length of the under-expanded core and the Mach disk location reaches a quasi-steady state around 200 μs ASOF, and the tip penetration distance also reaches a quasi-steady state around 300 μs ASOF due to the mass vaporization. The structure of the supercritical fuel flash-boiling spray in the quasi-steady state is very similar to that of the under-expanded jet.

The typical structure of the supercritical fuel flash-boiling spray is quite complicated because the spray process involves the change and coupling of the thermodynamic state and the hydrodynamic state. Figure 4(b) presents a supercritical fuel flash-boiling spray image in its quasi-steady-state (the imaging time is 800 μs ASOF). Its initial fuel temperature is 252°C and the ambient pressure is 30 kPa. Combining the p-v phase diagram shown in Figure 4(a) and the illustration of a highly under-expanded jet shown in Figure 4(c), the spray process and structure can be analyzed and discussed.

As mentioned in Section 3.1, the just-injected fuel is under-expanded due to the instantaneous drop in pressure during injection, and then it would quickly expand all around. Together with the large initial axial velocity caused by the high-pressure injection, the under-expanded core presents a cone shape. Similar to the flow crossing the centered expansion fan in Figure 4(c), the fuel expands through the under-expanded core with the increasing of Mach number (Ma), the decreasing of static pressure and constant total pressure and entropy. Correspondingly, after this expansion, the fuel changes from the supercritical state to the subcritical liquid state due to the static pressure drop. This process is as the isentropic line shown in Figure 4(a).

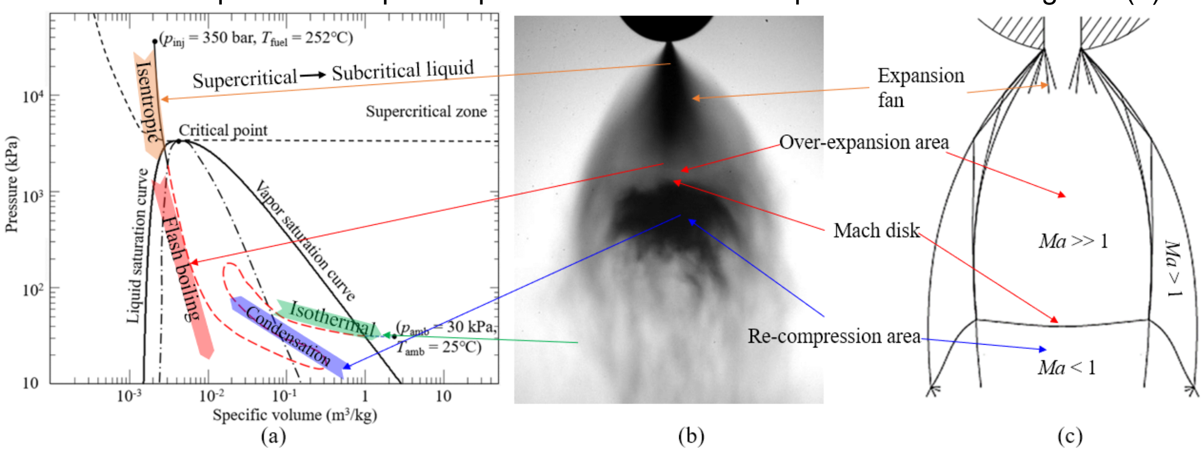

Figure 4. The structure of the supercritical fuel flash-boiling spray (T_f = 252℃, p_a = 30 kPa) at quasi-stable state (800 μs ASOF) in accordance with the thermodynamic and hydrodynamic state.

Along the isentropic line corresponding to the ambient pressure of 350 bar and the fuel temperature of 252°C, the further pressure drop causes the fuel to pass through its liquid saturation curve and the liquid spinodal curve, and enter the two-phase region, where flash-boiling occurs. The thermodynamic path of this process can be roughly shown by the red dashed line in Figure 4(a). In this process, a large amount of fuel vaporizes and the spray volume expands rapidly. From the spray image shown in Figure 4(b), the shadow of this area is lighter than that of the under-expanded area, indicating that the fuel density is relatively low because the backlight can pass through the spray well. Hence, in this area, fuel mainly exists in the vapor phase, and only a small amount of liquid fuel is evenly distributed in the form of tiny droplets. Additionally, corresponding to the structure of highly under-expanded jet shown in Figure 4(c), the spray in this area is rapidly transformed into an over-expanded state due to strong Prandtl-Mayer expansion, and the local pressure is rapidly reduced to even below the ambient pressure. Correspondingly, the local sound speed becomes slower, and the spray velocity is much larger than it ($Ma \gg 1$).

Subsequently, the spray would be compressed again at the Mach disk. The local pressure is increased, and the thermodynamic path of the spray passes through the vapor spinodal line from the right to the left and enters the two-phase region again. The condensation occurs as the purple arrow shown in Figure 4(a). Correspondingly, it can be seen from the spray image in Figure 4(b) that a high-density compression area is formed below the Mach disk, indicating that a large amount of upstream vaporized fuel has been condensed into a liquid state again. At the same time, the air resistance in this area increases due to the increasing pressure, and the spray tip velocity would drop rapidly. In addition, the local sound speed also increases with the increasing pressure, which together causes the speed of flow to be lower than the speed of sound ($Ma < 1$) as shown in Figure 4(c). After that, the spray again undergoes an expansion process and returns to the ambient condition. Since this process takes a relatively long time and the jet diameter is large, it can sufficiently exchange the heat with a large amount of entrained air. This process can be close to isothermal expansion, as shown by the green arrow in Figure 4(a).

Through the above qualitative analysis and discussion, it can be found that the structure of the supercritical fuel flash-boiling spray is very similar to that of the highly under-expanded jet. Combined with the analysis of the thermodynamic state change of the spray process, a basic understanding of its structure can be developed.

As shown in Figure 5(a), for sprays with relatively high contrast between the re-compression area and the over-expansion area, their boundary can be recognized by image processing. The axial location of the Mach disk (L_{MD}) can be defined as the distance between the nozzle tip and the top of the boundary referring to the existing study [4]. Then the correlation between the dimensionless Mach disc location (L_{MD}/d_0, the ratio of the Mach disc location to the nozzle hole diameter) and the isentropic compression ratio (η) based on the experimental data in this study can be developed as marked in Figure 5(b). Franquet et al. [13] summarized the correlation between the Mach disk location and the compression ratio of the highly under-expanded gas jet in the existing researches, and get the fitting as the red dashed line in Figure 5(b), that is, the dimensionless Mach disk location is proportional to the 0.51 power of the compression ratio, where the compression ratio is directly calculated by the ratio of the injection pressure to the ambient pressure. It can be seen that the experimental results of the supercritical fuel flash-boiling spray in this study are close to that of the under-expanded gas jet, which also shows that characterization method based on ideal gas under-expanded jet can be also modified and used for supercritical fuel flash-boiling spray.

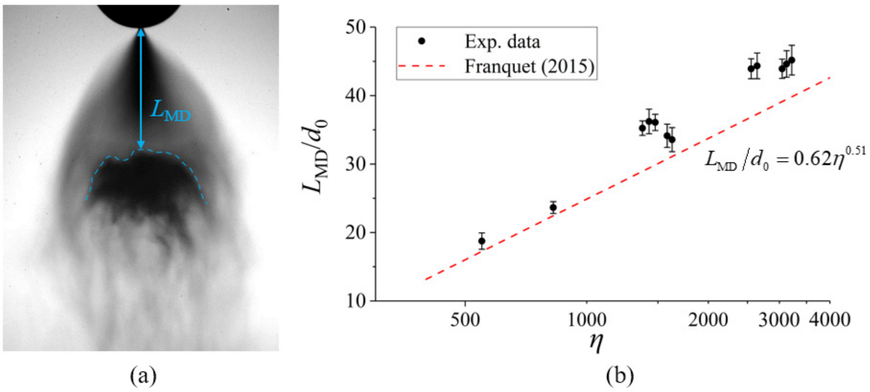

Figure 5. (a) Calculation of Mach disk location; (b) the correlation of Mach disk location and expansion ratio.

Conclusions

In this work, the supercritical fuel flash-boiling spray was studied based on a single-hole injector through high-speed backlit imaging. The findings can be concluded as follows:

1) The transient spray formation process of supercritical fuel injection is different from that of the common injection. Due to the supersonic effect, the Mach disk is generated and suppresses the spray head penetrating during the initial injection in the nozzle near-field.

2) Combining the thermodynamic state and hydrodynamic state of the supercritical fuel flash-boiling spray, the spray process and structure were studied. The supercritical fuel flash-boiling spray has a structure very similar to the highly under-expanded gas jet, and corresponding characteristics such as under-expanded core, over-expansion area, Mach disk and re-compression area can be interpreted well based on the theory of under-expanded and supersonic flow.

3) The location of the Mach disk was calculated according to the upper surface of the re-compression area. The experimental data obtained in this study are in good agreement with data in the existing studies on the highly under-expanded jet.

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