

Flash Boiling: Easy and Better Way to Generate Ideal Sprays than the High Injection Pressure

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ABSTRACT

When heated fuel is injected into an ambient environment below its saturation pressure, the fuel could reach superheated state and experience flash boiling. Comparing with the non-flash boiling spray, namely the single phase liquid spray, flash boiling spray is characterized by its nature of two phase flow, due to vapor bubbles constantly generating inside the liquid phase. The behavior of those microscopic scale bubbles could introduce prompt spray atomization and vaporization, resulting in dramatically different spray characteristics. Comparing with the sprays generated via a high pressure injection system, the flash boiling spray has much shorter penetration, wider spray angle, more uniformly distributed mass, quicker evaporation, and smaller drop sizes, etc., which are ideal for the direct-injection (DI) gasoline and diesel engine applications without the hassle and the high cost associated with the high pressure injection system. This new approach provides new opportunities for the DI engine combustion system design. Understanding the physical mechanisms involved in the flash boiling spray formation is crucial to achieve its full potential. In this study, the flash boiling spray from a multi-hole DI injector was investigated in a constant volume chamber using various laser diagnostic techniques. The macroscopic spray structure, flow field, droplet size and vapor concentration were obtained under typical conditions encountered in the DI engine operations. Non-dimensional analysis was used to correlate the spray characteristics under the wide range conditions. The results show that the dimensionless numbers governing the liquid spray formation, which include Reynolds number (Re) and Weber number (We), are no longer important and adequate to describe flash boiling spray formation process. It is found that the ratio between ambient pressure and liquid saturation pressure (P_a/P_s) plays an important role during the spray flash boiling with good correlations to the spray characteristics. Based on those correlations, a phenomenological model consisting of a set of empirical equations is proposed to quantitatively describe the flash boiling spray characteristics. Those equations reveal the unique mechanism related to the flash boiling spray formation, and explain why the flash boiling spray behaves so differently from the liquid spray.

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INTRODUCTION

High pressure injection systems are widely used in spark-ignition direct-injection (SIDI) gasoline engines to atomize liquid fuel to small droplets. Those atomized small droplets can greatly enhance the liquid-air interface and promote the vaporization and mixing. The high pressure injection enables accurate control of fuel delivery and atomization, resulting fast engine transient response, good efficiency and reasonable level of emissions [1, 2]. However, there are also some critical issues associated with the method that utilizes high injection pressure to atomize liquid fuel. First, when the liquid fuel is propelled by the high pressures, the liquid momentum is normally very high. The fast-travelling liquid fuel could over penetrate in the small engine cylinder and impinge the cylinder wall and/or piston surface. The fuel

adhering with the wall surface is hard to evaporate, easy to escape into the crankcase to dilute the lubricant, and could have abnormal combustion (such as pool fire), leaving high level of unburned hydrocarbon (UHC) and soot emissions [3, 4, 5]. Second, as the emission regulations get increasingly stringent, small droplets are needed to achieve desired combustion so that those regulations can be met. Corresponding to this demand, the injection pressure in currently SIDI engines will be elevated to increasingly high level. However, reducing the droplet size by increasing the fuel pressure becomes inefficient when the injection pressure is already high. The effects of injection pressure on droplet size reduction decline or even diminish as the injection pressure further increases [6]. Continuing to increase injection pressure to achieve small droplets degrades the cost-

efficiency. Finally, high injection pressure systems place great demands on manufacture quality for the injection system components such as high pressure pump, rail, injector, controller, etc. The core technologies are controlled by a few companies.

There are other ways to get small droplets and fast vaporization rather than solely increasing the injection pressure. Injecting the fuel with pressure and temperature beyond its critical point has been demonstrated recently to achieve instant vaporization. An 80% engine emission reduction and 10% efficiency improvement were reported [7]. However, how to manipulate the fuel to beyond its critical point under normal engine operation conditions still remains a big challenge.

Superheat injection, on the other hand, is easier to achieve with SIDI engines than supercritical injection. As a matter of fact, the superheat injections have been observed by several researchers both in port-fuel-injection (PFI) and direct-injection (DI) engines [8, 9, 10]. When the fuel is heated to high temperature and subsequently discharge into a low pressure environment, the temperature of the fuel can easily exceeds its boiling point to reach superheat conditions and the spray is flash boiling. In today's SIDI engines, the temperature of fuel in the injector is normally high due to the heat transfer from the engine coolant and combustion gases. When such hot fuel is injected during the intake stroke with low in-cylinder pressure, the fuel temperature could exceed its boiling point and trigger flash boiling.

When the fuel is superheated, the thermodynamic instability will trigger the vapor nucleation inside the liquid. The nucleation can be homogeneous or heterogeneous depending on the fluid flow and boundary conditions [11, 12]. Those large number of vapor nucleus will fiercely grow and eventually burst as the liquid pressure sharply drops to low ambient during the discharge process. The explosion of those bubbles will effectively break the liquid into fine droplets. The release of the fuel vapor in the bubble makes the fuel vaporization almost instantaneous. Comparing to higher pressure injection atomization system where atomization and vaporization occurs only on the liquid-air interference, the liquid atomization and vaporization takes places inside the liquid spray under superheat conditions. The atomization and vaporization efficiency is expected to be greatly improved. Smaller droplet size and faster vaporization could be achieved using flash boiling sprays even with relatively low injection pressure. The shortcomings associated with high injection pressure are expected to be solved.

Flash boiling sprays have been discovered and studied by some researchers in the past. Brown and York [13] first found the flash boiling phenomena and provided an initial description. Since then many optical diagnostic techniques were used to characterize flash-boiling sprays under various conditions [14, 15, 16], illustrating that fluid type, temperature and ambient pressure influence the spray characteristics. The effects of injector configuration on flash

boiling sprays were investigated using various types of injectors. The sprays from a single-hole nozzle show wider spray angle, reduced penetration length and smaller droplet size as the fuel gets more superheated [17]. The sprays from high pressure swirl injectors and multi-hole injectors were found having a collapsing feature as the fuel got superheated [9, 18-19].

More specifically, the spray angle has been shown to initially increase with increasing superheated degree. When continuing to increase the superheated degree, the multiple spray plumes (for multi-hole injector) and the liquid sheet (for swirl injector) were found to collapse into a single-plume structure. Evaporation studies of the multi-hole flash boiling sprays [20] have illustrated that both the liquid and vapor phases collapse with increasing superheated degree, where the vapor structure collapsed more rapidly compared to the liquid plumes. These experimental investigations unveiled the important spray structural changes under flash-boiling conditions by providing visual descriptions of the spray transformation.

Although the flash boiling spray has been widely investigated in various aspects, a complete understanding and description of flash boiling spray characteristics and its formation process are still missing. Flash boiling is a complicated process where heat and mass transfer between phases are constantly occurring. Such a complicated process is normally coupled with liquid atomization, flow, vaporization. Any one single diagnostic technique could hardly capture all characteristics of flash boiling sprays. Only a full characterization that collects all the needed information could possibly provide insight to reveal flash boiling spray formation mechanism. In this paper, various laser diagnostics were applied to investigate the flash boiling sprays. The spray macroscopic structure, droplet size distribution, spray particle flow field and liquid/vapor distribution were investigated thoroughly. By combining all the information, the mechanism of the flash boiling spray becomes much clearer.

EXPERIMENT TECHNIQUES AND APPARATUS

Spray characteristics were investigated under a wide range of superheat conditions. The characterization techniques and laser diagnostics applied include:

- The global macroscopic spray structures were investigated using white light imaging technique. The sprays were illuminated using an instantaneous white light source and the scattering light was collected by a CCD camera.
- The spray inner structures were investigated using laser sheet imaging technique where a cross sectional plane of the spray was illuminated by a thin laser sheet. The scattered light was captured by a CCD camera. Both axial plane coinciding with the injector axis and radial plane perpendicular to the axis were imaged [18].
- The droplet size distribution was measured using laser sheet drop sizing (LSD) technique. To avoid the large measurement

errors associated with the traditional LSD technique when it was applied to vaporizing sprays such as flash boiling sprays, a new LSD technique was developed [21].

- The 2D flow field of the spray particles was studied using high speed particle image velocimetry (HS-PIV) technique where the velocities of the spray particles were calculated based on two shortly separated image frames [22, 23].

- Laser induced exciplex fluorescence (LIEF) was applied to separately image the spray liquid phase and vapor phase. Quantitative vapor concentration measurement was achieved through a series of calibration and image correction methods [20].

The experiment setup was shown in Figure 1. A high pressure optical accessible chamber was used to provide the ambient pressure. The chamber was connected to a high pressure nitrogen supply and a vacuum pump so that both the high pressure and vacuum conditions could be achieved. An 8-hole DI injector was mounted at the top of the chamber. A high pressure nitrogen cylinder and a piston accumulator were used to provide the various injection pressures. To control the fuel temperature, a water jacket was designed around the injector. An external heat exchanger circulated the water in the jacket to condition the fuel temperature to desirable level. The fuel spray was illuminate by the light source. Depending on the characterization objective, the light source could be a flash lamp or an Nd: YAG laser. A combination of CCD camera and image intensifier was used to collect the scattered light from the spray. The injection system, light source and image acquisition system were synchronized using a programmable timing unit (PTU).

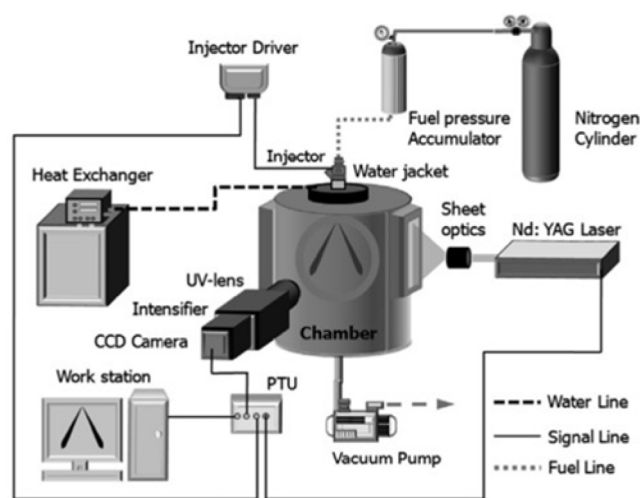


Figure 1. Experimental setup for spray imaging

The experimental conditions were listed in Table 1. An 8-hole high pressure DI injector was used through this study. The injection duration was fixed at 1.2ms. The injection pressure ranged from 3MPa to 15Ma to cover typical injection pressure level in today's SIDI injection system. The

ambient pressure was between 20kPa and 200kPa absolute. To lower the boiling point of the fuel thus achieving superheat conditions, most of the experiments were carried out below the atmospheric. The fuel temperature was set between 25°C to 90°C. The ambient temperature was kept consistent at 25±1°C.

Table 1. Experimental conditions

Injector	8-hole
Fuel	Gasoline, ethanol, methanol, n-hexane
Injection duration	1.2ms (7.5mg n-hexane @ 10MPa injection pressure)
Injection pressure	3~15MPa
Ambient pressure	20kPa~200kPa
Fuel temperature	25°C~90°C
Ambient temperature	25±1°C

RESULTS AND DISCUSSIONS

In this section, the characterization results of the flash boiling sprays from the 8-hole injector using the diagnostic techniques discussed above are reported. The spray structure, atomization, flow field and vaporization are discussed.

Global Spray Structure

The global spray structure under various superheat conditions are shown in Figure 2 and Figure 3. Injection pressures are 4MPa and 10MPa respectively. The superheat state of the fuel is dependent on both the fuel temperature and local boiling point. Actually, superheat degree (SD), which is defined as the difference between liquid temperature and boiling point ($T_f - T_b$), is widely used to indicate fuel superheat state. Since the boiling point of the fuel is a function of ambient pressure, superheat degree can be altered by either varying the liquid temperature or the ambient pressure. Another way to represent the superheat heat state is to use the ambient-to-saturation pressure ratio (P_a/P_s). This definition of superheat degree is dimensionless and easier to use for dimensionless analysis. In fact, the two definitions are linearly correlated, hence have the same meaning [18]. Therefore, only P_a/P_s will be used in this paper.

Figure 2 shows the spray white light images under various ambient-to-saturation pressure ratios and two different injection pressures. The ambient-to-saturation pressure ratios ranges from 1.56 to 0.31 by lower the ambient pressure from 100kPa to 20kPa at a fixed fuel temperature of 55°C. When the ambient-to-saturation ratio is above 1, the sprays are in liquid regions. Plumes from different injector holes are widely separated and can be clearly identified. When the pressure ratio decreases to 0.63, wider plumes are observed due to the bubble expansion in the liquid jets. When further decreasing the P_a/P_s to 0.31, not only the plumes get even wider, the spray starts to merge into the injector centerline to form a solid-cone spray. This trend is especially obvious

under the lower injection pressure where the individual plumes are hardly seen. The spray angle starts to shrink due to the collapsing. Under both injection pressures, the spray penetration gets shorter as ambient-to-saturation pressure decreases.

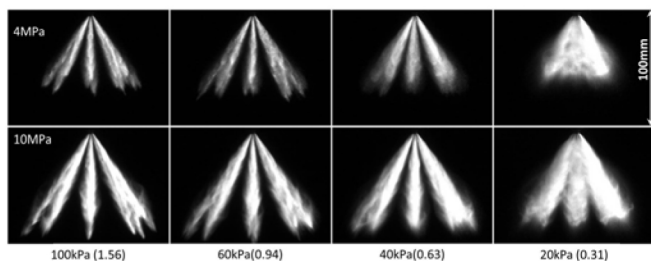


Figure 2. Spray images under various ambient pressures and 55°C fuel temperature (*n*-hexane, 0.8ms after start of injection (ASOI), numbers in the brackets indicating ambient-to-saturation pressure ratios)

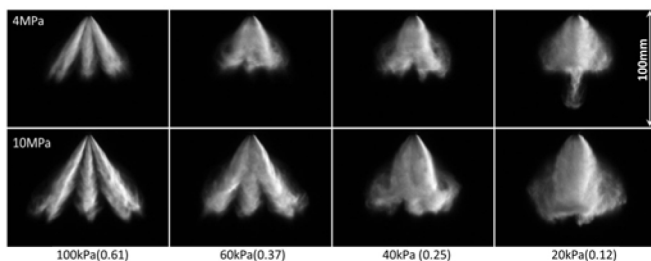


Figure 3. Spray images under various ambient pressures and 85°C fuel temperature

The ambient-to-saturation pressure ratio value is extended to lower region by increasing the fuel temperature to 85°C. The spray images under those conditions are shown in Figure 3. The spray transformation when reducing ambient-to-saturation pressure ratio from 0.61 to 0.37 is similar with those observed under 55°C fuel temperatures. More severe spray transformation is observed when lowering the ambient-to-pressure ratio from 0.37 to 0.25. The sprays under both injection pressures collapse into the injector centerline. Larger vortices are present in front the spray, indicating intense air-fuel mixing. When the ambient-to-saturation pressure ratios reduces to 0.12, the collapsing of the fuel spray is so strong that excessing fuel is pushed out of the spray in the case of 5MPa injection pressure. Such fuel is not observed under 10MPa injection pressure. When the ambient-to-saturation pressure ratio decreases from 0.61 to 0.12, the spray penetration firstly decrease and then increases with a turning point around the ambient-to-saturation pressure of 0.3. This turning point is coincident with the spray collapsing point after which a solid-cone spray is formed.

Comparing the spray images at two different fuel temperatures concludes that the spray structures are similar under ambient-to-saturation pressure ratios. For example, the sprays under 20kPa ambient, 55°C fuel temperature is very

close to those found at 60kPa ambient, 85°C fuel temperature because they have similar ambient-to-saturation pressure ratios. This observation indicates that the spray formation process is dominated by the bubble behavior under superheat conditions. The effects of injection pressure, ambient pressure and fuel temperature become secondary. The mechanisms involving with the flash boiling process are totally different from those in the pure liquid spray [24]. More diagnostics are need to reveal the detail mechanism of the flash boiling formation process.

Inner Spray Structure

The inner spray structures are obtained using laser sheet imaging where a thin laser sheet is guided through the spray to illuminate one spray cross-section. The light scattered from the spray particles is collected using the imaging system.

Figure 4 shows the cross-sectional spray images using laser sheet imaging under various superheat conditions. Both axial plane and radial plane are cut to reveal spray's inner structure. On the injector axial plane, two spray plumes are illuminated by the laser sheet. The perpendicular plans are taken from 10mm, 20mm and 30mm downstream the injector. The spray pattern can be clarified from those images.

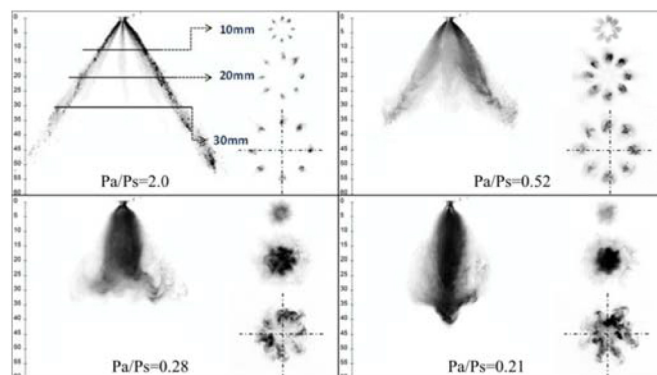


Figure 4. Inner spray structures under various superheat conditions (*n*-hexane, $P_{fuel}=5\text{MPa}$, $P_{amb}=40\text{kPa}$, 0.8ms ASOI)

Under non-flash-boiling conditions, the plumes from different holes are well separated. There is negligible plume-to-plume interaction in this case. Decreasing the ambient-to-saturation pressure ratio to 0.51 makes the fuel moderately superheated. The widen plumes are clear in both directions, which is consistent with the white light images. The spray pattern shows that the plume-to-plume interaction starts to take place as the widened plumes touch their adjacent counterpart. As the fuel gets further superheated, those plumes contact with each other to form a joint structure. The joint structure could act like a curtain to block the pressure balance inside and outside the spray cone, and gradually cause the spray collapsing by the built-up pressure differential. When the ambient-to-pressure ratio decreases to