



Droplet dynamics of DI spray from sub-atmospheric to elevated ambient pressure



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HIGHLIGHTS

- Time-resolved development of droplet velocity during spray process was described.
- Bifurcation of jet was observed at sub-atmospheric and atmospheric pressure.
- The modes of droplet velocity distribution are determined by the ambient pressure.
- Increase in injection pressure advances and enhances the deviation of jet.

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ABSTRACT

In this study, one of the five jets issued from a 5-hole Direct Injection (DI) injector was studied in detail using Phase Doppler Particle Analyzer (PDPA) and high speed imaging techniques. The tests were carried out in a constant volume vessel with absolute ambient pressures ranging from 0.05 to 0.5 MPa and injection pressures ranging from 6.0 to 15.0 MPa. Throughout the test conditions, the jet trajectory deviation of the target jet is observed due to the gas pressure imbalance between the inner and outer sides of the target jet. Both the results from spray morphology and the time-resolved droplet velocity have demonstrated the bifurcation of the target jet during the spray process at sub-atmospheric and atmospheric ambient pressures. It is attributed to the joint effects of the pressure imbalance between the two sides of the target jet and the velocity distribution change at the nozzle exit which relates to the vapor pressure of gasoline. The increase in injection pressure advances and enhances the deviation of the jet trajectory due to the larger jet speed. The deviation and/or bifurcation of the target jet also changed the size distribution.

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1. Introduction

Nowadays, multi-hole injectors have been widely used in DISI engines due to the ability to control jet targeting and fuel distribution, which can be designed to transport the fuel to where it is needed, e.g. towards the spark plug. However, the spray behaviors are dramatically affected by the complicated thermal conditions inside the combustion chamber at the time of injection. The absolute ambient pressure can be varied from 0.02 to 0.5 MPa, even higher in turbo-charged DISI engines and the fuel temperature can be varied from below zero at cold start to 150 °C at high loads [1].

The wide range of working conditions forces researchers and engineers to fully understand how the spray develops in different

thermal conditions and it places an emphasis on understanding what parameters affect the spray process, in order to achieve combustion chamber optimization. Zeng et al. [2] experimentally investigated the effect of fuel properties, fuel temperature, injection pressure and ambient pressure on spray characteristics in non-flash-boiling conditions and they proposed correlations for spray penetration and spray angle using dimensionless analysis. Zigan et al. [3,4] investigated the effect of fuel properties on spray characteristics and the results indicate that the internal nozzle flow, the injected mass and the spray droplet size distribution are different due to viscosity. Befrui et al. [5,6] and Shost et al. [7] numerically studied the effect of nozzle geometry on jet structure and primary breakup. Skogsberg et al. [8] found that changing the length/diameter (l/d) ratio is a potential way to control the local air/fuel ratio and cross-flow velocity at the spark plug.

The co-existence of high fuel temperature and sub-atmospheric in-cylinder pressure is normal in DISI engines. In these conditions,

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flash boiling may occur if the vapor pressure of gasoline exceeds the local pressure. In recent years, the flash boiling process of fuel spray has been extensively investigated by a number of researchers and it has been recognized as a promising way to enhance fuel evaporation and reduce droplet size [1,9–13], but its application in real DISI engines still needs further exploration. One of the phenomena of flash boiling covered in most studies using multi-hole DI injectors is the collapse of the jets, which prevents the objective of transporting fuel to desired positions with good jet orientation from being achieved. The occurrence of flash boiling would lead to the failure of the fuel to reach the spark plug in a proper way with the correct timing, and the deterioration of engine performance and even misfire in extreme cases.

Recently, new-generation multi-hole DISI injectors have been used and one of their features is the non-axisymmetric nozzle configuration in order to reduce the spray impingement on the wall. The resultant jet-to-jet interactions in this kind of DISI injector have been of concern [8,14–18]. Due to the compact arrangement of injector holes, the development of a normal recirculation of gas in the two sides of the spray jet cannot be achieved and consequently the gas surrounded by the jets has to move downwards, causing the low pressure zone under the nozzle to be filled with small droplets [16]. The jet-to-jet interaction would change the jet trajectory and such behaviors could lead to partial or even full collapse of the sprays at certain conditions. It would also disrupt the designed fuel distribution, leading to a deteriorated performance in combustion and emissions, even though the full collapse of the sprays may reduce the droplet size (in fact, the fuel collapse of flash boiling in multi-hole DI injectors is a special case of jet-to-jet interaction). Therefore, the fundamental understanding of jet-to-jet interaction is of paramount importance in modern multi-hole DISI injectors.

Malaguti et al. [19] experimentally and numerically studied jet-to-jet interaction using a 6-hole GDI injector, and they found that the spray jets surrounded by other jets have a faster penetration rate due to the lower ambient pressure (as well as the lower drag resistance) in the zone surrounded by the other jets. It was also found that their present model cannot accurately predict the spray development due to the jet-to-jet interaction. Montanaro et al. [20] also observed the jet surrounded by the other jets has longer penetration. Skogsberg et al. [8] produced images of the jet-to-jet interaction and found the vapor accumulation inside the spray cone experimentally using the LIEF method. A stagnation point was found by Khan et al. [15] in the zone surrounded by the spray jets which moved downwards as the spray developed. The appearance of the stagnation point was caused by two airflows with opposite velocity: one is the downstream airflow entrained near the nozzle and the other is the upstream airflow from the far field of the spray. At the stagnation point, a strong radial velocity appeared which forced the spray jets deviating from the original path towards to the external side. Nishida et al. [17] using two-hole nozzles with different hole angles found that hole-axis angle (HAA) has a strong impact on fuel penetration development, e.g. the longest spray penetration was observed at a HAA of 10 and the shortest one was observed at a HAA of 15. They attributed this to the coalescence and local pressure difference. Dahlander and Lindgren [18] reported that nozzle configuration provides ways to control fuel distribution. A smaller jet-to-jet angle would lead to the interaction of fuel jet sprays; the individual jet develops independently when the holes are axisymmetric.

Furthermore, it is worth noting that most of the previous studies were carried out at atmospheric or elevated pressure, and the studies carried out with fuel heated at sub-atmospheric conditions are mainly focused on the sprays in flash boiling conditions. The test results of tests carried out at the conditions of low fuel temperature (below the temperature that the sprays can achieve

flash boiling) and/or sub-atmospheric conditions is much less. In fact, injections at low fuel temperature (e.g. cold start) and/or sub-atmospheric conditions (absolute ambient pressure can be as low as 0.02 MPa during the intake stroke) are quite normal in DISI engines. Due to the high volatility of gasoline, fractional composition of gasoline can be immediately vaporized if the fuel is injected during intake stroke, and this will greatly change the process of mixture formation. In addition to the effect of jet-to-jet interaction, this process will be more complicated. Therefore, the in-depth understanding how the sprays develop in these conditions will be of great help for spray atomization and combustion chamber design.

In this work, in order to clarify the effect of ambient and injection pressure on the fuel spray process at atmospheric fuel temperature and in order to understand further how spray jets develop with the existence of the jet-to-jet interaction, especially in the sub-atmospheric pressure conditions (where the light fraction of gasoline can be rapidly vaporized in the hole passage or during the spray process) the time-resolved development of spray morphology and droplet velocity was analyzed using high-speed imaging and Phase Doppler Particle Analyzer (PDPA) using a 5-hole DI injector with non-axisymmetric hole configuration. A wide range of absolute ambient pressures from 0.05 to 0.5 MPa and injection pressures from 6.0 to 15.0 MPa were used. In the following sections, the experimental setup and test conditions are firstly introduced. Then follows a description of how the spray develops based on spray morphology and time-resolved droplet velocity and size; then the effect of ambient and injection pressure on the spray process is examined followed by the explanation of the jet bifurcation; Finally, the conclusions are made.

2. Experimental setup

Fig. 1 shows the schematic diagram of the test bench. The tests were carried out in a constant volume vessel specially designed for the application of PDPA. Two observation windows were mounted at the side of the vessel with an intersection angle of 110° in order to obtain the best signal/noise ratio. Both the high-speed imaging and PDPA techniques were used. During the imaging tests, one window is used to illuminate the spray, and the other is for the camera imaging. During the PDPA measurements, the incident lights from the transmitter accessed into one window, and the scattered signal came out from the other window and was captured by the receiver.

The ambient gas was allowed to flow continuously while the ambient pressure inside the vessel was kept constant at elevated pressures. This was done to remove the residual droplets from the previous injections, avoiding the fouling of the windows and interference of scattered light on the experiment results. The ways to adjust the ambient pressure are as follows: for the elevated ambient pressure conditions, the ambient pressure was realized by a needle valve (outlet) and for the sub-atmospheric pressure conditions, an additional vacuum pump and inlet valve were used. The gas flow rate inside the vessel is between 1 and 3 m/s and its effect on the spray development can be ignored. In order to provide sufficient time for the purging of the residual droplets, the injection frequency was set at 0.5 Hz.

A 5-hole DI injector with non-axisymmetric hole configuration was mounted on the top of the vessel and the footprint of the spray jets at the distance of 30 mm is shown in Fig. 2(a). Jet 2 was selected as the target jet. With the deliberate adjustment, Jet 2 was perpendicular with the imaging direction and incident lights from PDPA. In addition, with this arrangement, there is few interferences from the adjacent jets, e.g. few projection and light scattering. The fuel pressure was realized by a gas–liquid pressure

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