Study on the Spray Dynamics and Sectional Spray Distribution using Spray Pattern Measurement of Multi-Hole GDI Injector

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Abstract

In a gasoline direct injection (GDI) engine, fuel is directly injected into a combustion chamber. The fuel spray in such engines plays a critical role in combustion and emissions. In particular, the uniformity of air–fuel mixture in the combustion chamber is an important factor affecting the complete combustion and formation of exhaust emissions. Various types of studies on the spray characteristics have been extensively conducted over a long period to improve combustion efficiency and reduce emissions. However, identifying the individual spray characteristics of a multi-hole GDI injector is difficult owing to the interference of spray plumes. Additionally, there are few studies related to the individual spray plume.

In this study, the spray pattern was acquired through the cross-sectional visualization of the fuel spray injected by the injector. The data on the movement of the spray plume center, spray area, and injection angle were analyzed. In addition, the uniformity of the individual spray plume and the spray dynamics were measured and analyzed. A visualization of the spray pattern of a multi-hole GDI injector was obtained using a sheet-beam formed by a Nd:YAG laser, optic sets and high-speed camera. The visualized spray patterns were analyzed using an in-house image processing program that was based on MATLAB. n-heptane was used for this experiment.

As the distance from the nozzle tip to the cross-sectional area of the spray plume increased, the deviation of the spray center increased. The further away from the nozzle tip, the further away the center of the spray plume was from the spray axis owing to the decrease in the spray momentum. On the other hand, an increase in the injection pressure was shown to improve the uniformity of the individual spray plume owing to the increase in spray momentum caused by the increase in injection velocity. In addition, the spray was developed along the spray axis. The combined results indicate that the location of the spray target in the combustion chamber can be predicted with greater accuracy and that the injection strategy can be established to minimize collisions with the combustion chamber and the piston wall.

Keywords

Spray pattern, Individual spray plume, Spray center, Spray momentum, Spray dynamics

Introduction

Direct injection engines from gasoline engines have become more popular, such as diesel engines. Therefore, controlling their fuel spray has become a subject of increasing interest.[1-4] Direct injection engines require precise control of the air–fuel mixture for optimal combustion, and the shape and type of the injector nozzle are two of the primary factors affecting the air–fuel mixture. In internal combustion engines, a variety of injector nozzles types such as pintle, slit, outwardly-opening and multi-hole type injectors have been developed for the efficient mixing and atomization of the fuel supplied to the combustion chamber. Among them, a multi-hole type injector, possessing excellent characteristics such as fuel distribution, mixture formation, and atomization, is the most widely adopted and supplied type in modern commercial vehicles. The multi-hole injector has been adopted both as a GDI engine as well as a diesel direct injection engine owing to the convenience of fuel distribution and the economic advantages of using the shape and arrangement of the orifice. [5, 6]

Therefore, studies on controlling the spray of multi-hole injectors to achieve optimum combustion have been conducted worldwide. Mohan et al. [7] proposed a spray rate measurement method based on the momentum flux method to determine the hydraulic characteristics of a multi-hole injector under high pressure conditions. In addition, Zhang et al. [8] observed the flash boiling phenomenon of propane with a multi-hole GDI injector using a schlieren and backlight method. Furthermore, Wang et al. [9] analyzed the effect of deposit on the spray of the multi-hole GDI injector by using CFD and verified their results by using PLIF. It has been reported that, owing to the deposit, the spray structure is deformed, the velocity of droplets is increased, and the SMD is increased.

Presently, active research on multi-hole injectors using these various methods is underway. However, multi-hole injectors with multiple orifices exhibit different internal and external flow characteristics for fuel injected from each orifice depending on the design arrangement. Therefore, understanding the flow characteristics of individual spray plumes injected from each orifice is crucial to understanding and controlling the macroscopic spray characteristics of the fuel injected by the multi-hole injector.

Unlike diesel direct injection injectors, gasoline direct injection injectors are designed to have a relatively small spray angle to reduce wall wetting due to rapid injection timing.[10] Because the small injection angle of the gasoline injector causes interference and collisions between neighboring spray plumes, visualizing and analyzing each individual spray plume from the spray image is difficult. Recently, a spray pattern visualization method has been developed to analyze the flow characteristics of an individual spray. Data acquisition for individual spray plumes facilitates for a more accurate interpretation of the fuel distribution and atomization characteristics according to the nozzle orifice arrangement. Wu [11], Wood [12] et al. observed spray collapse due to flash boiling conditions in the multi-hole injector by using a spray pattern. They reported that the strong interaction between the fuel plumes leads to severe spray collapse and major alterations in the spray structure, resulting in a long spray tip penetration and a small spray angle[11]. Befrui et al. [13]used CFD to verify the possibility of analyzing the fuel behavior inside the injector and the spray targeting using a spray pattern (liquid foot print).

Therefore, this study visualizes and analyzes the cross-section of the spray to understand the behavior characteristics of individual spray plume of the multi-hole injector with six holes. Spray pattern experiments were conducted to measure the cross section of the spray and obtain information on spray area, spray center, and spray angle. Additionally, the spray uniformity and momentum of each orifice were analyzed using these data.

Experimental apparatus and analysis methods

In this study, n-heptane, which has similar physical properties to gasoline, was used; detailed physical properties are shown in Table 1.[14-16] n-heptane not only has similar physical properties to those of gasoline, but also has uniform spray characteristics as a single component fuel and provides the advantage of easy data analysis. In addition, SAE recommends n-heptane as fuel for spray experiments.[17] A side-mounted 6-hole GDI injector driven by a solenoid was used as the fuel injector. Table 2 shows the experimental conditions for this study.

Table 1. Properties of test fuel [14-16]

Fuel	Gasoline	n-heptane
Molecular formula	-	n-C_7H_{16}
Molecular weight	-	100.2
Density [g/cm^3@20℃]	0.746	0.682
Viscosity [cSt]	0.55	0.689
Surface tension [mN/m]	21.3	20.53

Table 2. Experimental conditions

Conditions	Value
Test injector	6-hole GDI injector
Energizing duration [ms]	1.5
Injection Pressure [MPa]	10, 20
Ambient Pressure [MPa]	Atmospheric
Measuring distance from injector tip [mm]	20-80(increase by 5)
Shoot timing after start injection [ms]	0.2-2.6

Figure 1 is a schematic diagram illustrating the spray pattern measurement system. The spray pattern measuring device consists of a fuel supply unit, an image acquisition unit, and a signal control unit. The pressurization of the fuel in the fuel supply unit was performed using a pneumatic pump (Haskel, DSF-60), and the fuel was stored in the accumulator to maintain the fuel pressure. Injectors were controlled using a compactRIO controller (NI, cRIO-9030), differential digital input (NI, 9411) and an injector controller (NI, 9751). The image acquisition unit comprised a high speed camera (FASTCAM, Mini AX100), a macro lens (SIGMA, 105mm f / 1: 2.8 DG MACRO HSM) and a 532nm Nd: YAG laser (Continuum, SL2-100). Lenses were combined to produce plane light and obtain the cross-sectional image of the spray. A pulse generator (Berkeley Nucleonics Corps, model 577) was used for signal control and the synchronization of ultra-fast cameras, injectors and lasers in the signal control unit. Quantitative data such as the spray area, the spray center, and the spray angle of the individual spray plume can be extracted using the acquired spray pattern image and a program based on MATLAB. First, the spray pattern image is post-processed and changed to suit the data format. The spray image is subjected to background removal, black-and-white, binarization using the threshold value, and filtering, and finally the image is displayed as '1' where the spray is present and as '0' when there is no spray. Using the final post-processed image, ROI (Region of interest) is set according to each spray plume size, and information about the area, center, and spray angle of the individual spray plume is obtained using the coordinates of the area where the spray exists have.

Figure 2 shows the shape of the spray and schematic diagram of the GDI injector used in this study. The number of holes is specified clockwise from 1 to 6. The spray plumes interfere with each other, which makes it difficult to acquire an image of individual spray patterns according to the orifice arrangement. The image of an actual spray pattern is taken as shown on the bottom right in 2D and 3D; the green dot is the injector tip; the red dot, the center of each spray. In addition, the spray cone angle of the individual spray plume can be calculated using the spray pattern image. The individual spray cone angles can be obtained using the nozzle tip and both end points of the spray zone, which meet the nozzle tip and the line passing through the center of the spray plume. Using the position information of each of the three points, the distance between the points is calculated and the angle of the individual spray plume can be obtained by applying the second law of cosine.

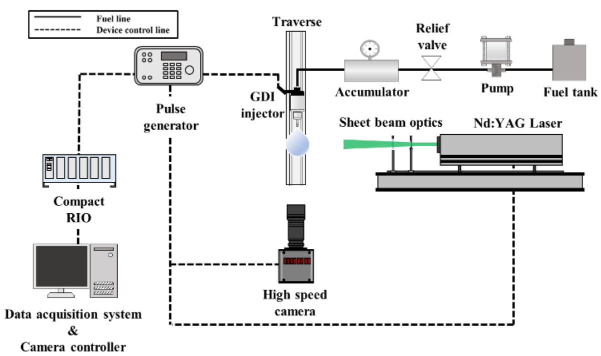


Figure 1. Schematic diagram of spray pattern image measurement system

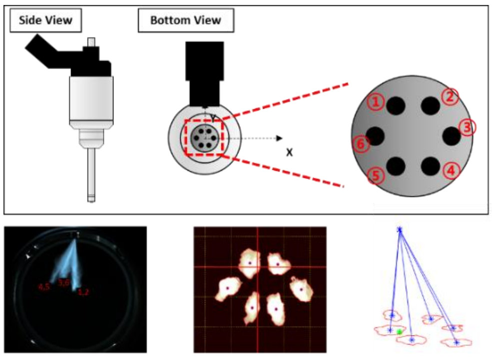


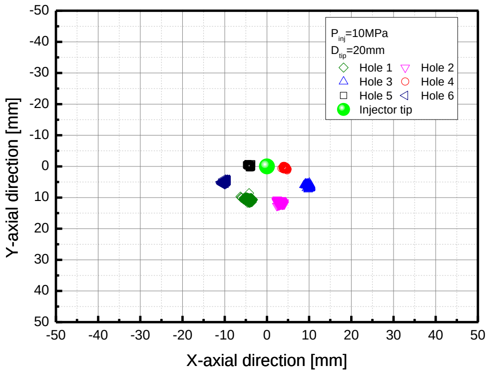
Figure 2. Schematic diagram of test injector and position of the spray plume according to the specified hole number

Results and discussion

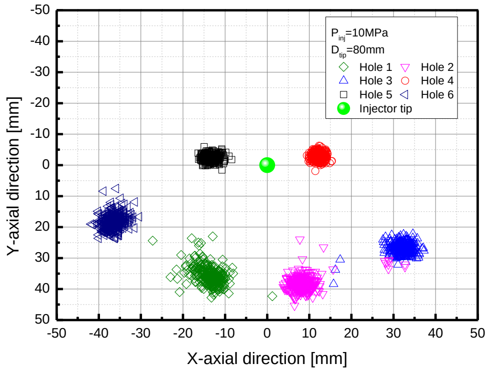
The sheet beam, produced by the combination of the Nd: YAG laser and lens, was lighted along the vertical direction of the spray. The experimental results of the visualized spray pattern are shown in Figs.3–5. Figure 3 shows the centers of each spray plume using an image processing program, and the spray pattern is observed 200 times for each experimental condition. For a side-mount 6-hole GDI injector, each spray plume is asymmetric with respect to the injector nozzle tip. As the nozzle orifice is designed and manufactured asymmetrically, the internal flow and cavitation characteristics of each hole change, and the behavior of the spray plume injected from each hole also differs. Further, the spray area of the large-angle holes 5 and 6, inclined from the center axis of the nozzle tip, can be exaggeratedly measured. However, the position of the spray center is assumed to be at the center of the spray plume regardless of the spray area. When the distance between the nozzle tip and the measuring cross section was short, the center of spray was observed to reach the designed position relatively because the spraying droplets have a large momentum; however, as the distance increases, the center of each spray plume moves away from the injector nozzle tip, and the deviation of the spray center becomes larger owing to scattering of the spray and loss of momentum of the droplets.

In holes 1 and 2, the spray developed is almost perpendicular to the measuring cross section and the deviation of the center of the spray plume is reduced. However, the spray centers of holes 4 and 5 that are designed to have the largest spray angle have a relatively large deviation along both the X and Y directions. In addition, the increase in the injection pressure (10 MPa → 20 MPa) did not significantly affect the deviation of the spray center. However, the deviation of the center of the spray plumes increases with the distance between the nozzle tip and the measuring cross section, even at an injection pressure of 20 MPa because the momentum of the spray droplets is reduced.

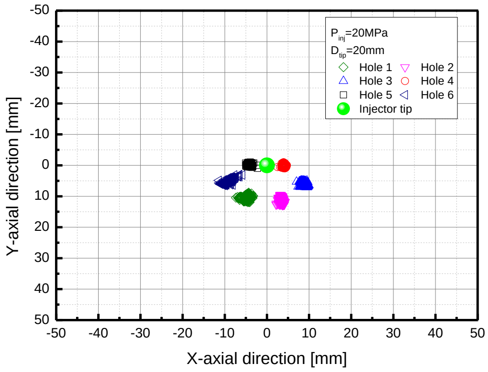
Figure 4 shows the deviation of the spray center quantitatively. The deviation of the center of the spray was calculated by dividing the center of the spray along the X and Y directions. The deviations of the spray center according to the distance between the nozzle tip and the measuring cross section are shown in Figs. 4 (a) and (b), and the deviations of the spray center along each hole are shown in Figs. 4 (c) and (d). As the distance between the nozzle tip and measuring cross section increases, the deviations along both the X and Y directions increase considerably, and the deviation of the spray center varies considerably from a minimum of 0.22 mm to a maximum of 3.76 mm. As the distance between the nozzle tip and the measuring cross-section increased from 20 mm to 80 mm at an injection pressure of 10 MPa, the uniformity of the spray decreased and the deviation of the spray center increased 5.85 times along the X direction and 3.89 times along the Y direction. The deviation was small when the injection angle of the spray center of the holes 1 and 2was designed to be small; further, the deviation was relatively large when the when the injection angle of the spray center of holes 4 and 5 was designed to be large. This is because the spray angle and the momentum of the droplets along the horizontal direction increases compared with those along the vertical direction, resulting in a greater deviation of the spray center. Further, the deviation of the center of the spray increases rapidly at a distance of 70 mm or more from the nozzle tip, which is considered to be a critical point where the spray droplet loses its initial momentum considerably and shakes at an injection pressure of 10 MPa.



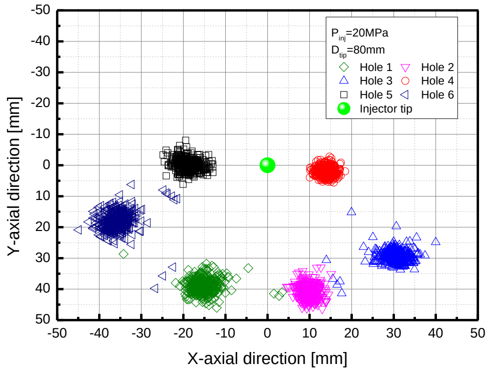
(a)Spray center at P_{inj} =10MPa and D_{tip} =20mm



(b) Spray center at P_{inj} 10MPa and D_{tip} 80mm



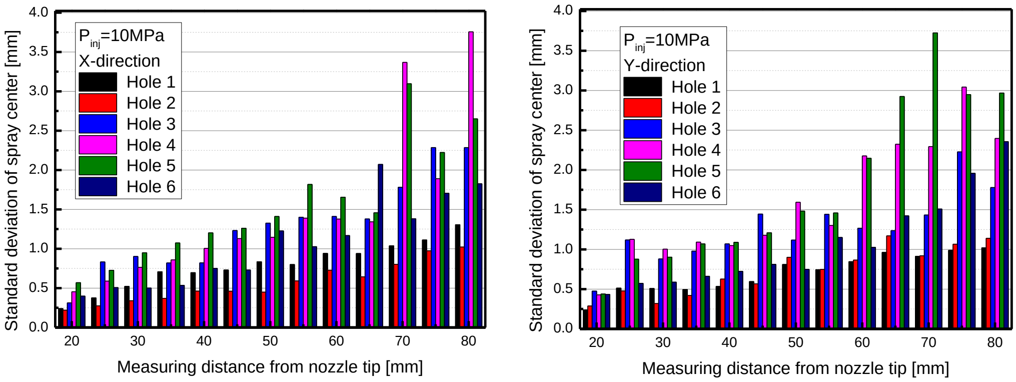
(c)Spray center at P_{inj}=20MPa and D_{tip}=20mm



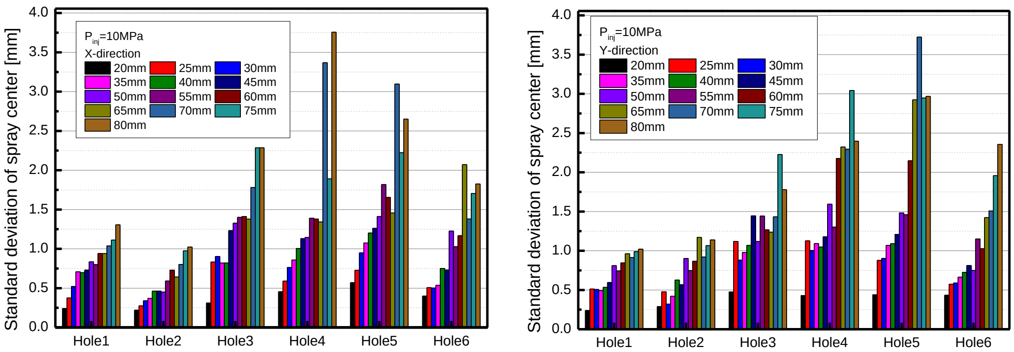
(d) Spray center at P_{inj}=20MPa and D_{tip}=80mm

Figure 3. Injector tip and the spray center of each spray plume at each condition

For each condition, the straight line distance from the injector tip to the spray center is divided according to the injector holes, as shown in Figure 5. The spray center and the fitting line is indicated in black, and the spray center prediction obtained using the initial center of spray is represented in red. It is observed that the spray plume develops differently according to the spray angle of each designed hole and varies from approximately 10.6° to 26.6° degrees. Although the injection pressure has doubled, the spray center has not significantly changed. At an injection pressure of 10MPa (Fig. 5(a)) for 1 and 2 holes, it is observed that the spray center is lower than the predicted spray center line; however, when the injection pressure increases to 20MPa (Fig. 5(b)), the spray angle reaches the forecast line obtained using the initial spray center. This is because the spray droplets descend in the vertical direction owing to the influence of gravity at a low injection pressure. It is thought that the spray droplets injected from the nozzle at a high injection pressure possess sufficient momentum to overcome the effect of gravity and maintain the initial spray angle.

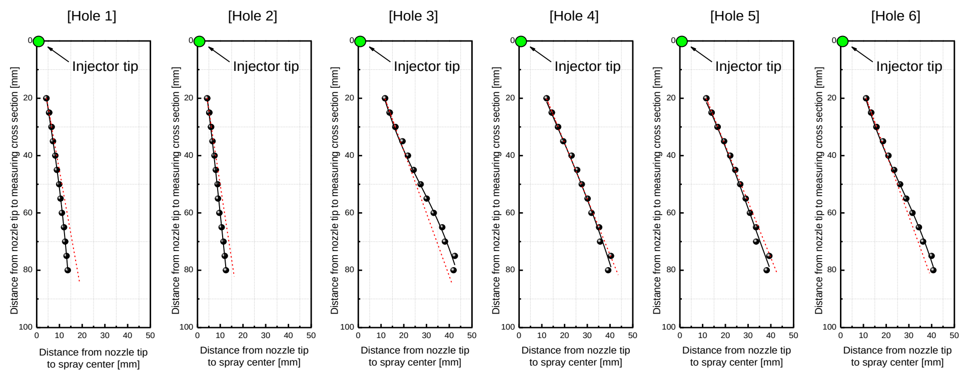


(a) X-direction depending on distance from nozzle tip (b) Y-direction depending on distance from nozzle tip

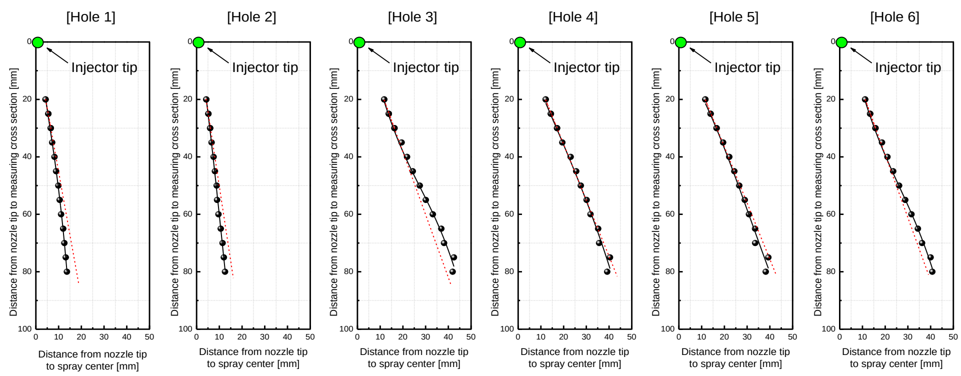


(c) X-direction depending on each holes (d) Y-direction depending on each holes

Figure 4. Standard deviation of the spray center along distance from nozzle tip to measuring surfaces and each holes in the X and Y directions



(a) Injection pressure 10MPa



(b) Injection pressure 20MPa

Figure 5. In each condition, the distance between the spray center and the injector tip (black point and line) and the predicted distance using the initial spray center

Conclusions

In this study, a spray pattern experiment was conducted to take the cross-sectional measurements in order to analyze the spray characteristics of the individual spray plumes of a multi-hole injector. Data on the center and deviation of each spray plume were assessed using the spray pattern, and the uniformity and momentum of the spray were analyzed using this data. The primary findings were as follows.

1) The GDI multi-hole injector exhibits different spray behaviors for each hole depending on the designed orifice arrangement. The characteristics of each individual spray plume, which are difficult to separate using the macroscopic spray image, were obtained using the spray pattern.

2) The deviation of the center of spray, which can be considered as a measure of the uniformity of each spray plume, increased in the X and Y directions owing to the scattering and evaporation of the spray as the distance from the nozzle tip to the measured cross section increased. Additionally, the deviation rapidly increased after approximately 70 mm for an injection pressure of 10 MPa.

3) The spray droplets were affected by gravity for an injection pressure of 10 MPa, and the spray center was closer to the nozzle tip axis than the initial spray angle. However, when the injection pressure was increased to 20 MPa, the momentum of the spray droplets increased, and it was confirmed that the spray droplets approached the initial spray angle.

Acknowledgements

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References

[1] Reddy, A. A., and Mallikarjuna, J. M., 2017, "Parametric Study on a Gasoline Direct Injection Engine - A CFD Analysis," SAE Technical Paper 2017-26-0039.
[2] Zhao, F., Lai, M.-C., and Harrington, D. L., 1999, "Automotive spark-ignited direct-injection gasoline engines," Progress in Energy and Combustion Science, 25(5), pp. 437-562.
[3] Storey, J., Barone, T., Thomas, J., and Huff, S., 2012, "Exhaust Particle Characterization for Lean and Stoichiometric DI Vehicles Operating on Ethanol-Gasoline Blends," SAE Technical Paper 2012-01-0437.
[4] Bonatesta, F., Chiappetta, E., and La Rocca, A., 2014, "Part-load particulate matter from a GDI engine and the connection with combustion characteristics," Applied Energy, 124, pp. 366-376.
[5] Zhao, F., David, L., Harrington, D. L., and Lai, M.-C. D., 2002, Automotive Gasoline Direct-Injection Engines, SAE International.
[6] Moon, S., Komada, K., Sato, K., Yokohata, H., Wada, Y., and Yasuda, N., 2015, "Ultrafast X-ray study of multi-hole GDI injector sprays: Effects of nozzle hole length and number on initial spray formation," Experimental Thermal and Fluid Science, 68, pp. 68-81.
[7] Mohan, B., Du, J., Sim, J., and Roberts, W. L., 2018, "Hydraulic characterization of high-pressure gasoline multi-hole injector," Flow Measurement and Instrumentation, 64, pp. 133-141.
[8] Zhang, Z., Li, Y., Ma, X., Ding, H., Xu, H., Wang, Z., and Shuai, S., 2018, "Characteristics of trans-critical propane spray discharged from multi-hole GDI injector," Experimental Thermal and Fluid Science, 99, pp. 446-457.
[9] Wang, B., Badawy, T., Jiang, Y., Xu, H., Ghafourian, A., and Zhang, X., 2017, "Investigation of deposit effect on multi-hole injector spray characteristics and air/fuel mixing process," Fuel, 191, pp. 10-24.
[10] Mitroglou, N., Nouri, J. M., Yan, Y., Gavaises, M., and Arcoumaniks, C., 2007 "Spray Structure Generated by Multi-Hole Injectors for Gasoline Direct-Injection Engines," SAE Technical Paper 2007-01-1417.
[11] Wu, S., Yang, S., Wooldridge, M., and Xu, M., 2019, "Experimental study of the spray collapse process of multi-hole gasoline fuel injection at flash boiling conditions," Fuel, 242, pp. 109-123.
[12] Wood, A., 2014, "Optical investigations of the sprays generated by gasoline multi-hole injectors under novel operating conditions," Doctoral Thesis, Loughborough University.
[13] Befrui, B., Corbinelli, G., D'Onofrio, M., and Varble, D., 2011, "GDI Multi-Hole Injector Internal Flow and Spray Analysis," SAE Technical Paper 2011-01-1211.
[14] Wang, L., Badra, J. A., Roberts, W. L., and Tiegang, F., 2017, "Characteristics of spray from a GDI fuel injector for naphtha and surrogate fuels," Fuel, 190, pp. 113-128.
[15] Aleiferis, P. G., Serras-Pereira, J., van Romunde, Z., Caine, J., and Wirth, M., 2010, "Mechanisms of spray formation and combustion from a multi-hole injector with E85 and gasoline," Combustion and Flame, 157(4), pp. 735-756.
[16] Li, T., Moon, S., Sato, K., and Yokohata, H., 2017, "A comprehensive study on the factors affecting near-nozzle spray dynamics of multi-hole GDI injectors," Fuel, 190, pp. 292-302.
[17] Hung, D., Harrington, D., Gandhi, A., Markle, L. et al., 2009,"Gasoline Fuel Injector Spray Measurement and Characterization - A New SAE J2715 Recommended Practice," SAE Int. J. Fuels Lubr. 1(1):534-548.