An Experimental Study of Microscopic Spray Characteristics of a GDI Injector Using Phase Doppler Interferometry

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Abstract

Gasoline Direct Injection (GDI) engine is known for its higher power and higher thermal efficiency. Researchers are steadily determining and resolving the problems of fuel injection in a GDI engine. In order to meet the stringent emission norms such as PM and NO_x emitted by a GDI engine, it is necessary to investigate the microscopic spray characteristics and fuel-air mixing process. This paper aims to share the fundamental knowledge of the interacting mixture preparation mechanisms at the wide range of fuel injection pressures. The investigations were carried out at five different fuel injection pressures viz: 40, 80, 120, 160, 200 bar, for 24 mg fuel per injection. A high speed CCD camera was used to determine the macroscopic spray characteristics of the GDI injector. It was found that spray penetration length increased with increasing fuel injection pressure. Phase Doppler Interferometry (PDI) was used to determine the droplet size and droplet velocity for different test fuels. In the end, Sauter Mean Diameter (SMD) and Probability Density Function (PDF) and diameter verses velocity curves were plotted, which gave better understanding of the behavior of fuel injection pressures responsible for improved fuel-air mixture. In the PDF, the shifting of the peak towards left was found to be desirable for better fuel-air mixture. It was observed E15 is better fuel for pressure range of 40-160 bar and gasoline for 200 bar pressure. Droplet sizes with different injection pressures in turn helped in minimizing stringent emission norms.

Introduction

Gasoline direct injection is not a new concept. Foundation of today's GDI technology was put long back during the World War II. It is expected that GDI engine will replace MPFI engine as the scientist make advancement in this field. Researchers around the world are trying to benchmark GDI technology with diesel engine such that it should have higher fuel economy and higher power with lesser engine noise. Today's modern GDI engines work on both, homogenous and stratified mode, with the help of advanced electronic control unit. Injector plays vital role in achieving the right amount of fuel injection at right time and correct pressure. It becomes necessary to understand the fundamental of GDI spray at various engines operating condition. The need of research in this field was found as GDI engine has difficulties in the mixture preparation at wide operating range. A novel spray concept needs to be developed at various operating conditions. Moreover, fuel injection plays a important role for example at high engine load where fuel has to be injected at early stage. Again, stringent emission norms also need to be fulfilled.

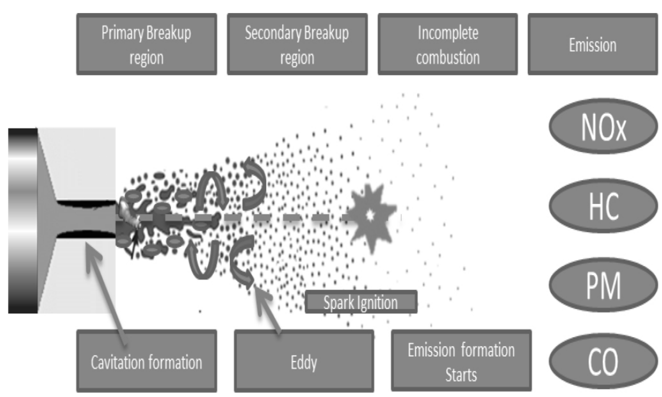


Figure 1. Schematic of primary and secondary break-up from a GDI injector.

Figure 1 shows the schematic of the spray coming out from a GDI injector. This sketch clearly distinguishes between the primary and secondary breakup region. As the atomized fuel is injected from the injector, the fuel in the immediate vicinity of the injector does not have spherical shape. But as the distance of the fuel from the injector increases, the fuel tends to form smaller droplets. Eddies are part of the transition region from primary breakup to secondary breakup. Once the spark is applied inside the combustion chamber, the fuel gets ignited. Figure 1 also shows that due to incomplete combustion emissions are formed. Cavitation plays important role in deciding the droplet size of the atomized fuel as it results of the formation of bubbles in a gasoline spray.

Many researchers are trying to study GDI spray characteristics since past few years and have contributed to the literature with similar work as done in this paper [1, 2, 3, 4]. Yamakawa et al. performed 2D and 3D

PIV technique on GDI injector to understand the behavior of spray structure [5]. The focus of this paper was on the effect of injection pressure on spray and swirl groove geometry. Authors found that the inner structure of the spray is composed of hollow cone and a solid jet. Also, there exists a negative pressure region in between the solid jet and hollow cone. It was found that the irregular structures of GDI spray are due to high ambient pressure. Natti et al. performed experiments to find the effect of high injection pressure of upto 300bar on engine performance and emission [6]. Extensive experiments were carried out by varying the injection pressure, exhaust gas recirculation, start of injection. Effect of these parameters on particle size distribution and total number was investigated. Author found that, with increase in injection pressure from 200 bar lower smoke and constant NO_x level was noticed. It was also found that with increase in injection pressure, the fuel consumption decreases with same level of NO_x and smoke. Köpple et al. mentioned the important parameters and conditions influencing the spray-wall interaction [7]. On the basis of these important parameters the validation of the model was performed. Results were validated using infrared thermography techniques. Author performed detailed numerical analysis and presented results using parameter such as spray cooling, evaporation and wall film formation. Author performed experiments on effect of parameters such as injection pressure and start of injection on the particulate emissions. Surface temperature had strong influence on GDI spray wall interaction as with decrease in temperature the time needed to evaporate the wall film was fund to be increased. Abe et al. investigated the droplet size of the fuel coming from GDI engine [8]. Authors found that it is possible to predict the droplet by refereeing the size of the geometry of the injector nozzle. Author related the velocity of the droplet with droplet size and a co-relation was found between the velocity and nozzle geometry. Direct injection nozzle with narrow seat gap was fabricated and experiments were performed on droplet size. It was found that if outlet velocity is known than droplet size can be predicted. Also, droplet size was found to be proportional to the exponential velocity. Passage area ratio helped in making such co-relation. Matsumoto et al. applied Schlieren and Mie scattering techniques in the pressurized chamber and the optical research engine[9]. Injection strategies and ambient condition was varied and two injectors were used to perform experiments using ethanol as a fuel in the GDI engine. Author also performed numerical simulation and later results were compared with experimental work. As fuel-air mixture plays a vital role for GDI engine, therefore attempts were made in this paper to spray characteristics with optical engine under homogeneous and stratified charge conditions. In the end, the performance of injector A with injector B was compared. Pielecha et al. used E85 and pure gasoline as a fuel in a high-pressure gasoline direct injection constant volume combustion chamber [10]. Author studied the influence of various fuel injection pressures (5 and 20 MPa) with different fuel temperature. Author performed these experiments to find linear and radial spray penetration from different injection pressure along with velocity of the spray. Spray images were captured in the constant volume combustion chamber using high speed camera. It was found that different fuel has different spray characteristics. Different size was noticed for both the fuels. With E85 the droplet size was found to be lower as compared with gasoline. Penetration length was found to be affected by fuel temperature.

The results presented in this research article can be useful in determining GDI injector characteristics. Novelty of this work lies in the fact that there is limited work carried out to study the fundamentals of spray through PDI. Although, many researchers have carried out work in the field of LDV or other laser based techniques but this advance technique may be necessary to answer other question which cannot be answered by other laser based techniques. With the advancement of the gasoline direct injection technology, higher injection pressure of up to 300 bar may be desirable in the future. It becomes really important to answer certain critical questions for such injectors. The aim of the study was to find out the mechanism of the fuel air mixture preparation for gasoline like fuels such as ethanol and methanol through GDI injector. The investigations were carried out at five different fuel injection pressures viz: 40, 80, 120, 160, 200 bar. A high speed camera was used to find out the measurement point of the single plume of a GDI injector. The behavior of ethanol and methanol blended with gasoline is investigated to determine the Spray penetration, Sauter mean diameter (SMD), and spray plume shapes.

Experimental Setup

PDI is a tool used to extract information related to droplet size and droplet velocity of any liquid spray such as water, diesel, gasoline and biodiesel. In this paper real-time, non-intrusive characteristics of gasoline and its blend are found to understand the fundamental of the fuel-air mixture. When atomized droplet travel in a combustion chamber, PDI can be used to determine three components of velocity based on the known laser light wavelength and diameter of that particular droplet. Detailed experimental set-up is shown in figure 2.

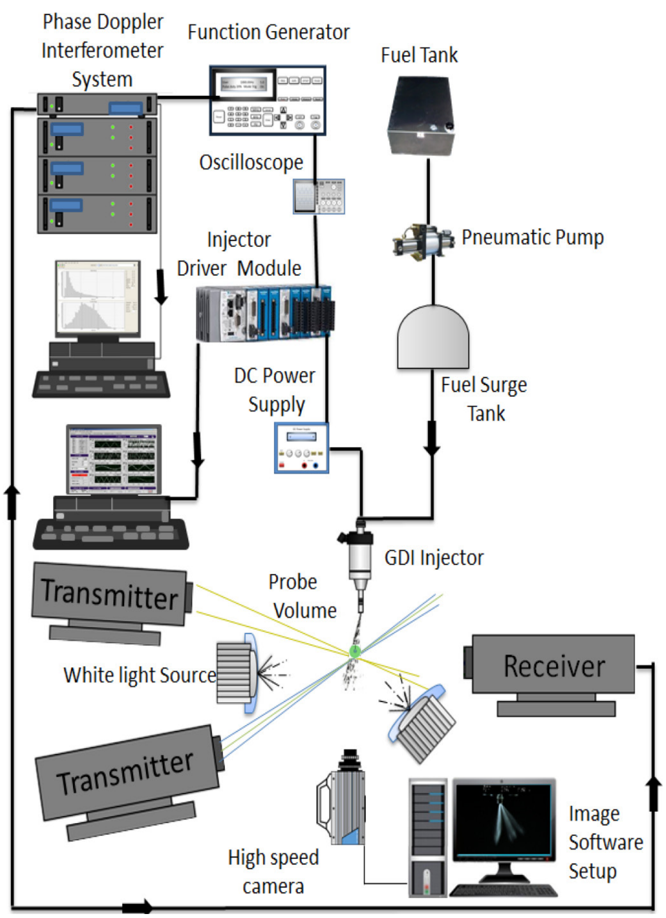


Figure 2. Experimental set for Phase Doppler Interferometry using high speed camera

Experimental setup consists of two transmitters and one receiver. Through transmitter one, two laser beam comes out. One laser beam of green color (532 nm) and other is blue color (491 nm). Through transmitter number two, only one laser beam of yellow color with wave length of 561 nm comes out. The point where all the three laser beam intersect is called probe volume. A signal processing software was part of the experimental setup. Gasoline direct injection injector is placed in such a way that the spray is orthogonal to the probe volume. Moreover, a cap is placed on the injector tip such that only one plume comes out of the injector. A fuel surge tank is placed in the fuel like in order to damp the pressure oscillation. NI injector module is use to drive peak and hold injector. Also, PDI setup was synchronized with injector driver module such that readings are captured only when spray plume passes through the probe volume. In order to find the primary and secondary breakup of the GDI injector a high speed camera was used. Figure 3 shows the point of measurement for downstream of the plume.

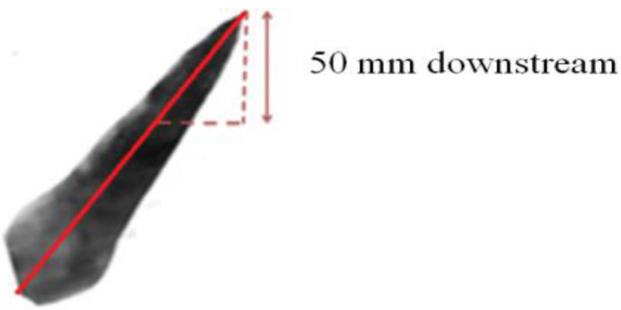


Figure 3. Downstream point, 50 mm, where measurement was taken for PDI

It was found that 50 mm downstream of the injector is the optimum position to find the droplet size and droplet velocity. Also, data was taken at various downstream positions but only the optimum data is reported in this paper. Injector was calibrated for 24 mg fuel quantity for different test fuel and for 5 injection pressure. In order to make correct comparison, it was ensured that 24 mg fuel is injected from the injector at all the test condition. Oscilloscope and function generator had their specific assigned role. The high power, diode pump solid state laser systems used in the PDI experiment was class 3B lasers. The function of the three channels shown in the experimental setup was to collect the raw data signal and to perform the necessary mathematical calculation to find out the accurate droplet size and droplet velocity of the atomized drop. In this experiment 500 mm focal length for transmitters and 350 mm focal length of receiver were used. The optics of the transmitters and receiver such as the angle between the two transmitters, collection angle of the receiver and correct focal length was ensured. Sauter mean diameter, arithmetic mean diameter and weber number used in the results are given below.

$$\text{Sauter Mean Diameter (D32)} = \frac{\sum i^{n_{c(i)}} d_i^3}{\sum i^{n_{c(i)}} d_i^2}$$

$$\text{Arithmetic Mean Diameter (D10)} = \frac{\sum i^{n_{c(i)}} d_i}{\sum i^{n_{c(i)}}}$$

$$\text{Weber number} = \frac{\rho v^2 L}{\sigma}$$

The velocity and diameter of the droplet isgiven by:-

$$v = f_d \times \delta \quad (1)$$

$$f_d = f_r - f_s \quad (2)$$

$$d = \frac{f \times \delta}{s \times \Lambda} \quad (3)$$

Where,

v - velocity of fuel droplet

f_r - raw signal is a combination of Doppler signal and frequency shift

f_s - frequency shift generated by Bragg cell which is used for the resolution of direction ambiguity of droplet whether in positive and negative direction.

Two white light sources were used to illuminate the single plume from the GDI injector. Throughout the experiments, the test cell was maintained at ~20 degree c. Experiments matrix is shown in the table 1. Table 2 shows instrument specification.

Table 1. Experimental matrix

Pressure (bar)	Macroscopic experiments (Quantitative only) (24 mg per injection)		Microscopic experiments (24 mg per injection)	
	Test Fuel		Test Fuel	
40	G100	E15	G100	E15
80	x	✓	✓	✓
120	x	✓	✓	✓
160	x	✓	✓	✓
200	x	✓	✓	✓

Table 2. PDI Specification

Instrument Specification	
Droplet size range	0.5 to 2000 µm
Estimated accuracy	± 0.5 µm
Estimated resolution	± 0.5 µm
Velocity measurement range	-100 to 300 m/s
Velocity accuracy	± 1%
Volume flux accuracy	± 15%
Receiver focal length	350, 500, 750, 1000 mm
Transmitter focal length	350, 500, 750, 1000 mm
Laser Type	Diode Pumped Solid State (DPSS)
Wavelength of Lasers	Blue-492 nm, Green- 532 nm and Yellow- 660 nm

Result and Discussions

The experiments were performed on two fuels namely E15 (15% ethanol blended with gasoline) and G100 (pure gasoline) at five different injection pressure. Droplet size and droplet velocity were the main findings from this study. Result and discussion have been divided into the following sections: counts with axial velocity and radial velocity for gasoline and E15, variation of Pulse time with axial velocity and radial velocity for gasoline and E15, Variation of axial velocity with diameter for E15 and gasoline fuel, statistical analysis, Mean particle diameters at different injection pressure and macroscopic spray images for E15 fuel.

Counts with axial velocity and radial velocity for gasoline and E15: Figure 4,5,6,7 shows the variation of Counts with axial velocity and radial velocity for gasoline and E15 fuel for 24 mg fuel per injection. It is found that for both the test fuel, axial velocity is more on the positive side for all the fuel injection pressure. On the other hand, radial velocity is uniformly distributed on both the positive and negative side of the origin for both the test fuel and all the fuel injection pressure. As the velocity marches away from the origin, the number of counts decreases for both the test fuel and all fuel injection pressure. Another point to be noted is that highest counts are observed on the positive side of the origin (close to origin) for every condition.

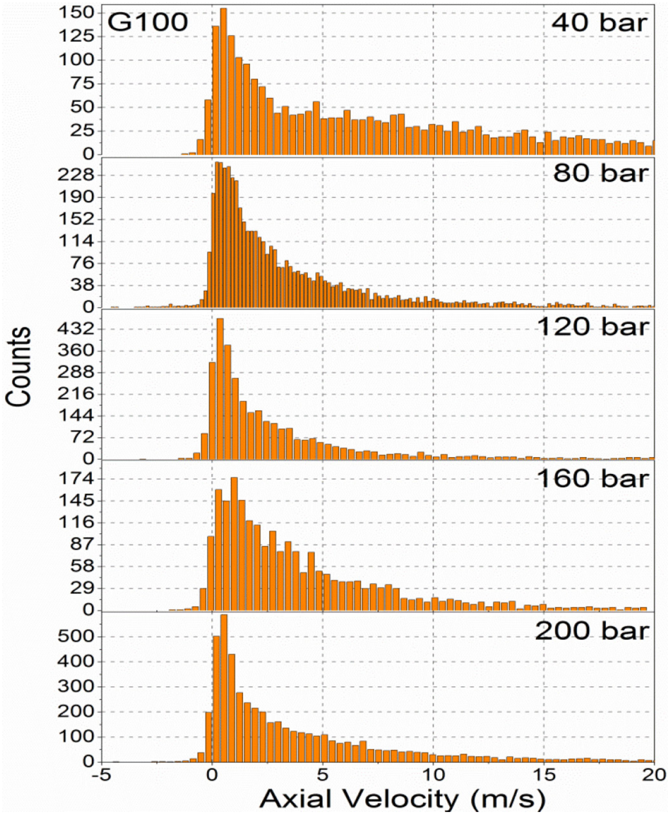


Figure 4. Variation of counts with axial velocity for G100

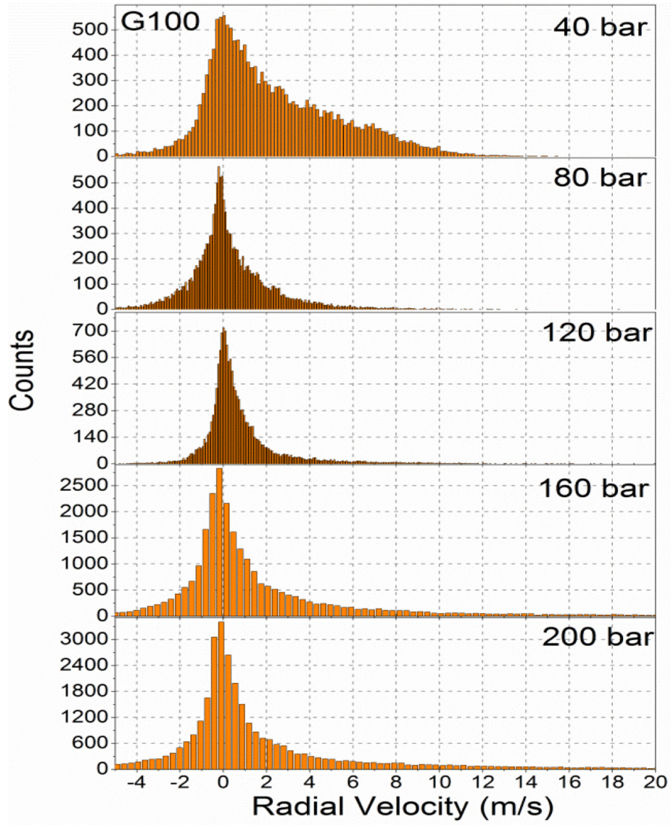


Figure 5. Variation of counts with radial velocity for G100

Negative velocities signify the opposite direction of the velocity which may be due to eddies generated in the fuel injection. Also, negative velocity indicates the re-circulation zone created by the swirl flow. Recirculation zone is dependent on the injection pressure, ambient condition and drag experienced by the fuel droplet. The significance of these eddies lies in the fact that they are responsible for improved mixing in the immediate vicinity of the recirculation zone created by the injector. G100 graphs are shown in orange color and E15 are shown in red color.

Variation of Pulse time with axial velocity and radial velocity for G100 and E15: Figure 8 shows ensemble average, multiple injections, axial velocity of 40 millisecond pulse time for five different injection pressures for gasoline fuel, 50 mm downstream distance from the injector and 24 mg fuel quantity in one injection. Each dot in the graph represents the individual droplet injected from the injector in the atomized form. It is noticed from the graph that as the fuel injection pressure increases velocity of the droplet increases. For a lower injection pressure, majority of the droplet are ensemble at a point less than 10 m/s axial velocity. The droplets did not ensemble after 28 millisecond for 40 bar fuel injection pressure. The ensemble particles in the immediate vicinity of the y-axis forms a tail like structure. Now, as the fuel injection pressure increases, this tail tends to be thinner and longer. Similarly, the tail like structure in the immediate vicinity of the x-axis also tend to become thinner and longer. This signifies that as the fuel injection pressure increases, the greater number of particles tends to reach 80 m/s velocity.

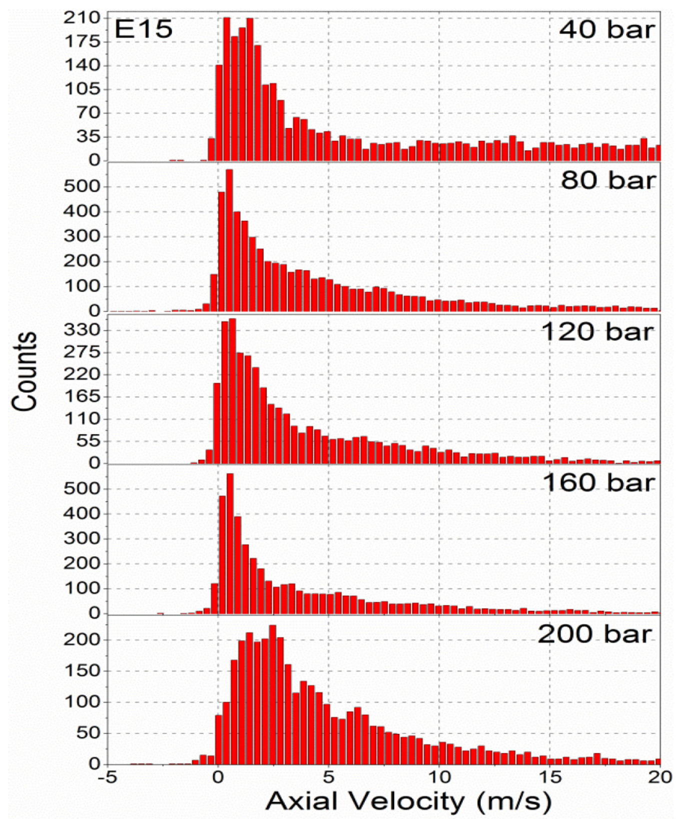


Figure 6. Variation of counts with axial velocity for E15

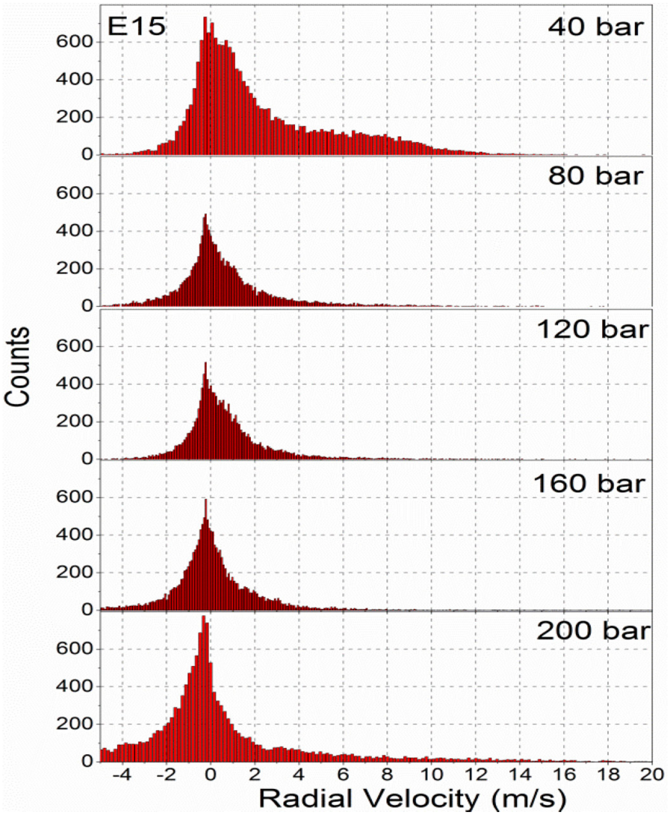


Figure 7. Variation of counts with radial velocity for E15

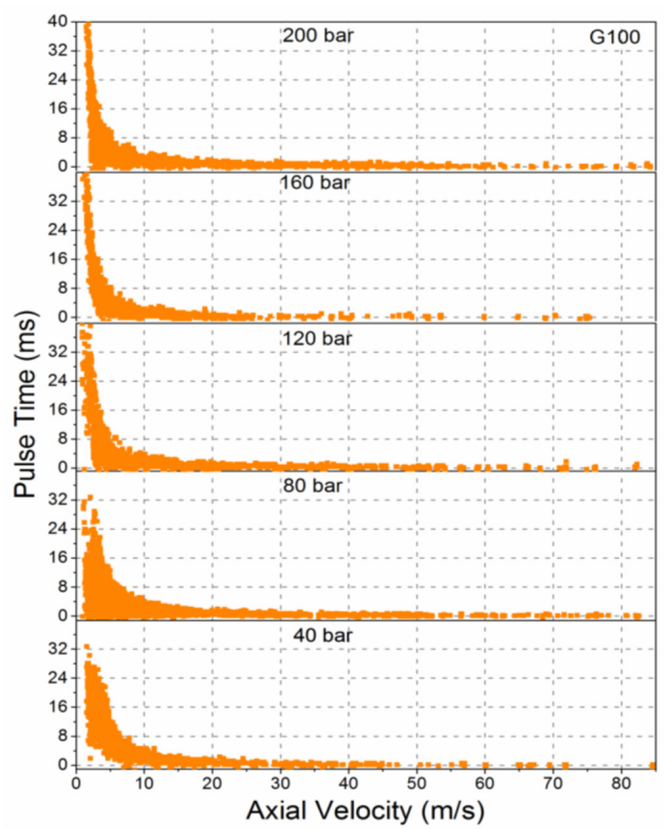


Figure 8. Variation of Pulse time with axial velocity for G100

Figure 9 shows ensemble average, multiple injections, radial velocity of 40 millisecond pulse time for five different injection pressures for gasoline fuel, 50 mm downstream distance and 24 mg fuel quantity in one injection. It is noticed here that radial component of the velocity ensemble here in a much less pulse time duration as compared to axial component of the velocity. On the other hand, tail like structure on x-axis and y-axis tend to grow longer as the injection pressure increases. At 200 bar fuel injection pressure, maximum pulse time is about 28 millisecond for radial velocity, which is same as axial velocity at 40 bar fuel injection pressure. Similar to axial velocity, radial velocity also increases with pressure. The bulk of the droplets are collected in less than 10 m/s velocity for all the injection pressure and both the test fuel. Pulse time for both the fuel increases with increase in fuel injection pressure. But, this increase is less for radial velocity in comparison to axial velocity. The observation noticed above is entirely dependent on kinematic viscosity. Another reason could be that E15 has higher viscosity and surface tension, compared with gasoline.

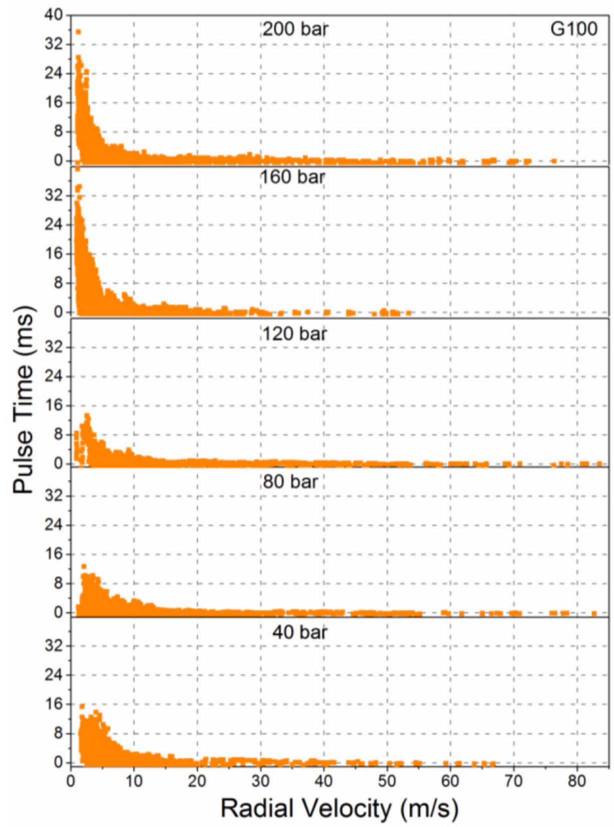


Figure 9. Variation of Pulse time with radial velocity for G100

Figure 10 shows ensemble average, multiple injections, axial velocity of 40 millisecond pulse time for five different injection pressures for E15, 50 mm downstream distance from the injector and 24 mg fuel quantity in one injection. It can be observed from graph that as the fuel injection pressure increases, the velocity of the atomized fuel droplet increases except for 200 bar. It seems that the droplet with E15 fuel get evaporated quite early than gasoline fuel at 200 bar. Similar to G100, more number of droplets is concentrated at the origin. As the fuel injection pressure increases, the droplet tends to move away from the origin. The ensemble particles in the immediate vicinity of x-axis and y-axis forms a tail like structure. Now, as the fuel injection pressure increases the tail like structure become thinner and thinner. Figure 11shows ensemble average, multiple injections, radial velocity of 40 millisecond pulse time for five different injection pressures for gasoline fuel, 50 mm downstream distance and 24 mg fuel quantity in one injection. It can be concluded that radial component of the velocity ensemble here in a lesser pulse time duration as compared to axial component of the velocity.

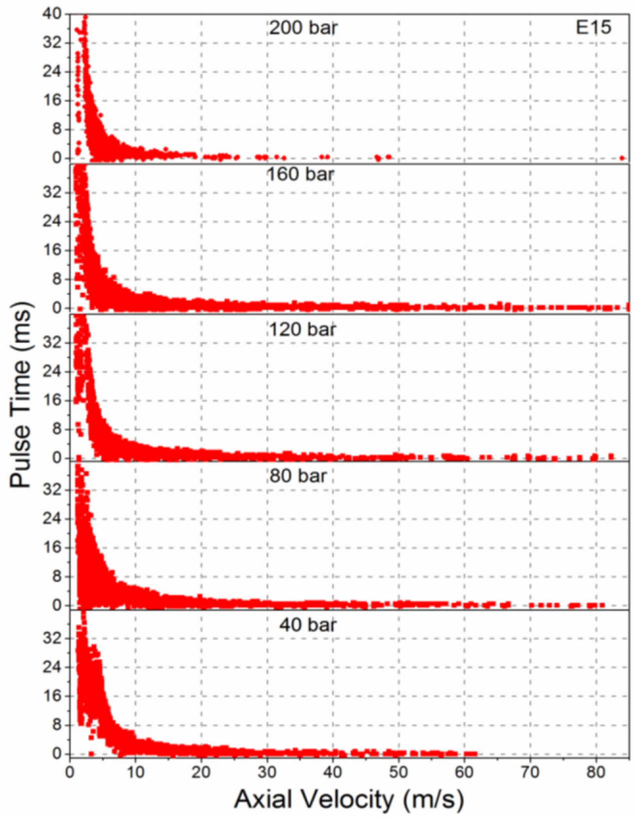


Figure 10. variation of Pulse time with axial velocity for E15

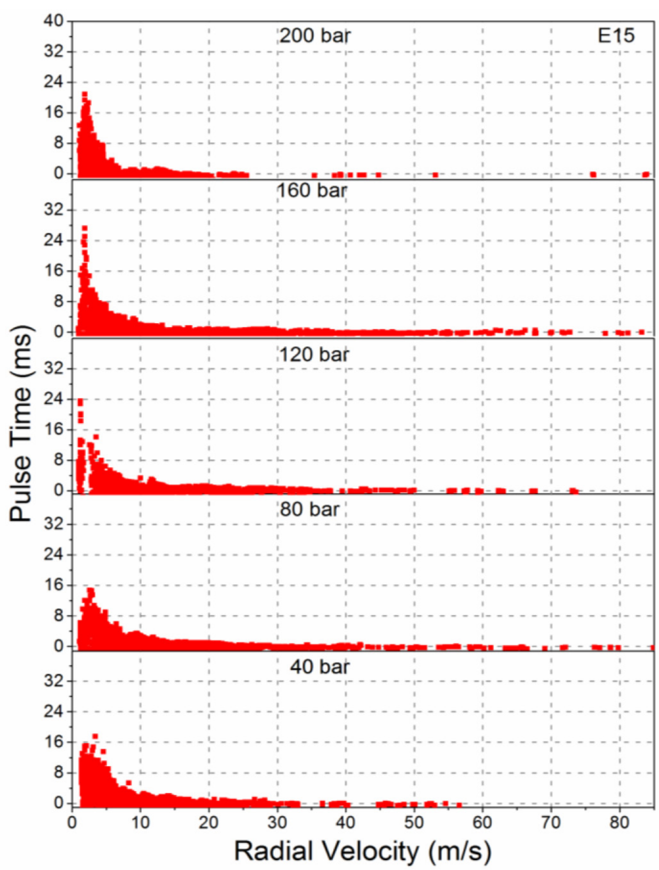


Figure 11. Variation of Pulse time with radial velocity for E15

Variation of axial velocity with diameter for E15 and gasoline fuel: Figure 12 shows the multiple injections, ensemble average, and distribution of axial velocity with diameter for G100, for 24 mg fuel per injection. It is noticed that as the fuel injection pressure increases, axial velocity tend to increase. For a less fuel injection pressure, higher droplet size is seen. But as the fuel injection pressure increases, droplet size decreases. The maximum axial velocity is about 30 m/s for 40 bar fuel injection pressure. As the fuel injection pressure increases maximum velocity becomes about 80 m/s for 200 bar injection pressure. The bulk of smaller droplets have velocities in the range of less than 20 m/s and bulk of droplet size is about 25 micrometer. It is observed that as the fuel injection pressure increases the bulk of the smaller droplet velocity decreases. The droplets with lesser injection pressure are less scattered and as the fuel injection pressure increases, the droplets tend to scatter in all the directions. This is because with increase in pressure, velocity of the droplet increases and mass of the particles decreases. In another way, smaller particles have lesser surface area and may they get evaporated at higher injection pressure.

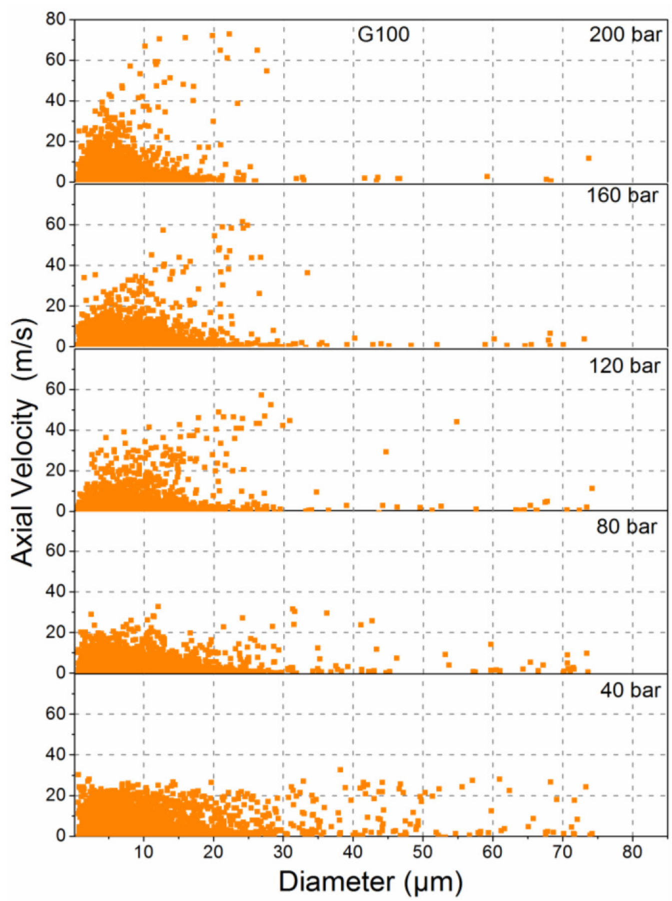


Figure 12. Variation of axial velocity with diameter for G100

Figure 13 shows the multiple injections, ensemble average, and distribution of axial velocity with diameter for E15 blend, for 24 mg fuel per injection. Similar trend is seen in the case of E15 as was seen for G100. The maximum velocity for G100 is 30m/s whereas maximum velocity for E15 is 20 m/s at 40 bar fuel injection pressure. At point to be noted at 40bar fuel injection pressure is that droplets are more scattered forE15 test fuel and les scattered for G100 test fuel. For all the fuel injection pressure diameter range is same for both the test fuel. For intermediate fuel injection pressure that is 80 bar, maximum velocity of droplet is found to be 40 m/s for G100 and 30 m/s for E15. For 120 and 160 fuel injection pressure there is no significant change in trend, maximum velocity and largest diameter as they lie in the same range. For 200 bar fuel injection pressure G100 is more scattered than E15. The observation noticed above is entirely dependent on kinematic viscosity. As depicted from the figure, smaller droplet is concentrated towards the origin with lesser velocity. The reason for decrease in droplet size is the interaction of these droplets with ambient air. Droplet with larger momentum may experience larger drag force. Momentum exchange of these droplets with air becomes more dominant than the decrease in the droplet size due to increase in fuel injection pressure is another possible reason for such a behavior of test fuel.

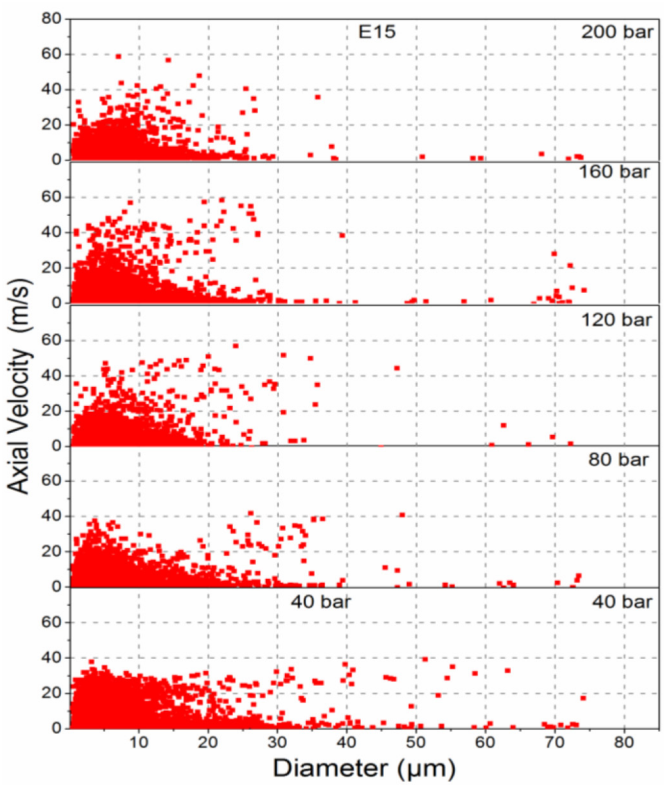


Figure 13. Variation of axial velocity with diameter for E15

Statistical analysis: To understand the above results in a better way, it become necessary to show statics of the above data in terms of probability density function, and cumulative distribution. Distribution of G100 and E15 droplet fall in a narrow range of x-axis. Figure 14 shows the probability density function (log-normal fit) for G100 and E15 fuels and cumulative probability density function for volume and diameter is shown in figure 15. It is noticed from the graph that maximum number of droplet for both gasoline and E15 fall in the narrow range of zero to 15 micrometer. For all the fuel injection pressure except 200 bar G100 had lower peak as compared to E15. The reason for such a trend is that E15 had higher viscosity and surface tension, compared with gasoline. It is observed from the figure that the peak of E15 fuel is higher for all the fuel injection pressure except 200 bar. This signifies that higher numbers of droplets of E15 are in the range of 5 micrometer, whereas, gasoline droplet peak is lower in comparison to gasoline. The shifting of the peak towards left is desirable for better fuel-air mixture. It is observed E15 is better fuel for pressure range of 40-160 bar. For 200 bar fuel injection pressure, the peak of gasoline is higher which depicts that the gasoline had higher droplets of smaller size which is again desirable for better combustion. As the fuel injection pressure increases, the peak of G100 fuel increases and peak of E15 fuel decreases. The possible reason for such a behavior of both the test fuel could be that E15 has higher viscosity and surface tension, compared with gasoline. A similar trend is noticed in the cumulative distribution. E15 has higher peak than gasoline for all the fuel injection pressure expect 200 bar. This is in agreement with figure 14. Starting and ending point of the cumulative density function is same but there is a significant difference in the lines between the diameter range of 10-40 micrometer. An important fact about the cumulative distribution obtained from the graph is that steepness of the line increases with increase in fuel injection pressure. Also, as the fuel injection pressure increases the slope shifts towards left side.

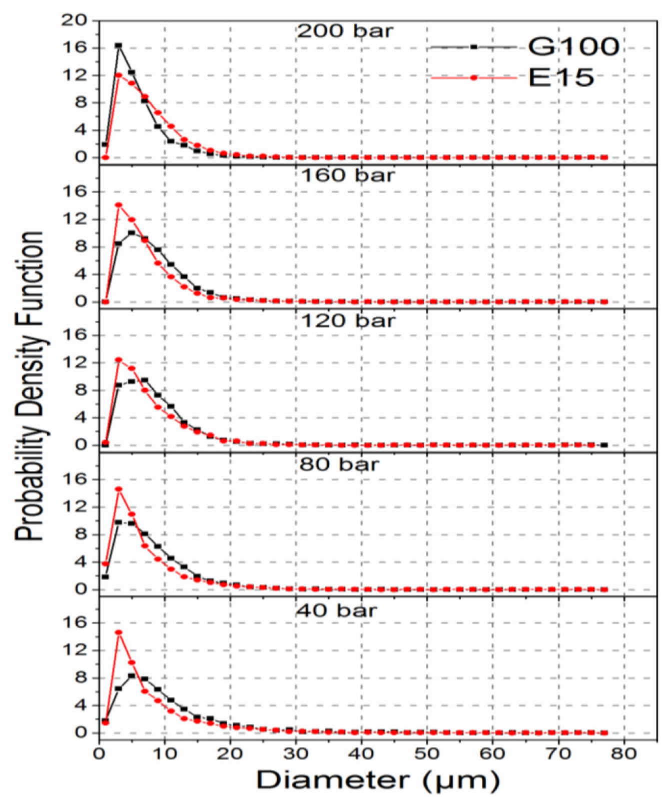


Figure 14. Probability density function v/s Diameter

Mean particle diameters at different injection pressure:

Figure 16 shows the Mean particle diameters at different injection pressure for test fuel. Fuel atomization through high fuel injection pressure forms smaller droplet, which forms the heart of the spray characteristics. Droplet size effects performance, emissions, and noise characteristics of the gasoline direct injection engine to a greater extent. Different droplet size injected vaporizes and participates in the combustion process. Those droplets which have sufficiently high droplet size burn poorly and are the major part of emission. Stringent legislation demands reductions in emissions of pollutants and at the same time increase in efficiency. D10 plays a vital role in compression of the length of the droplets. Average mean diameter (D20) signifies surface area controlling and volume mean diameter (D30) has application in controlling the column. Absorption f the droplet can be compared with surface area length mean diameter (D21). Evaporation of the droplets and molecular diffusion of the atomized fuel can be compared with (D31). Mass transfer of the gasoline fuel droplets can be compared with Sauter mean diameter (D32). D43 is the De Brouckere Herdan and application lies in the combustion equilibrium. It is observed from the graph that as the fuel injection pressure increases both the fuels tend to decrease in its diameter for the entire mean diameters. It is also observed that gasoline had less mean diameters for all the fuel injection pressure as compared to blended fuel. The reason for such a trend is that E15 had higher viscosity and surface, compared with gasoline. Now, as all these parameters lead to highest weber number, therefore, gasoline had the smallest SMD. For the tested range of fuel injection pressure, the profile shows good linearity for all the test fuels. It is clearly observed that as the fuel injection pressure increases most of the mean diameters decreases

Macroscopic spray images for E15 fuel:

Table 3 shows the spray images of GDI injector at three pulse time of 1ms, 2ms and 3ms for E15 test fuel. In the present study, only quantitative data for macroscopic spray visualization is presented. It is noticed from the table that, for particular millisecond duration, as the fuel injection pressure increases the penetration length also increases. A cap was designed such that only single plume comes out of the injector without any intersection. The sole purpose to show this table is to give reader a fair idea of the experiment procedure.

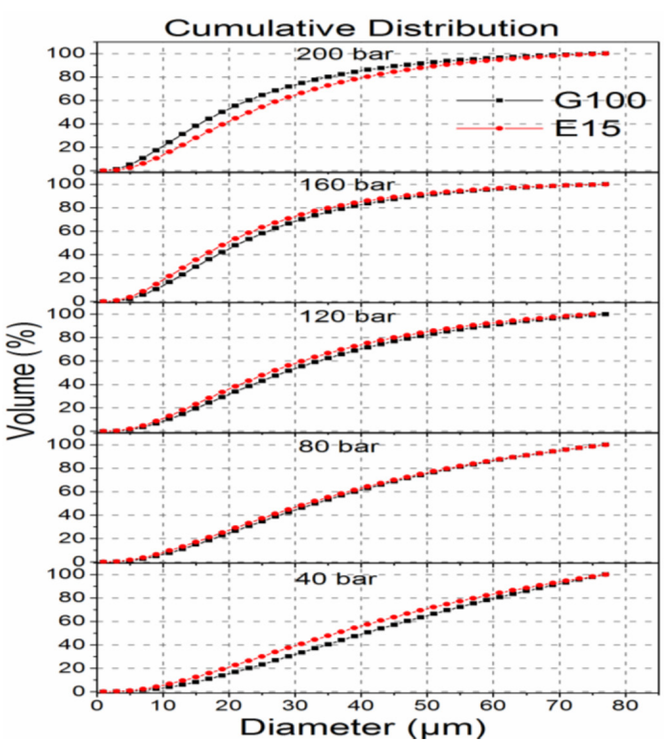


Figure 15. Cumulative distribution of volume v/s diameter

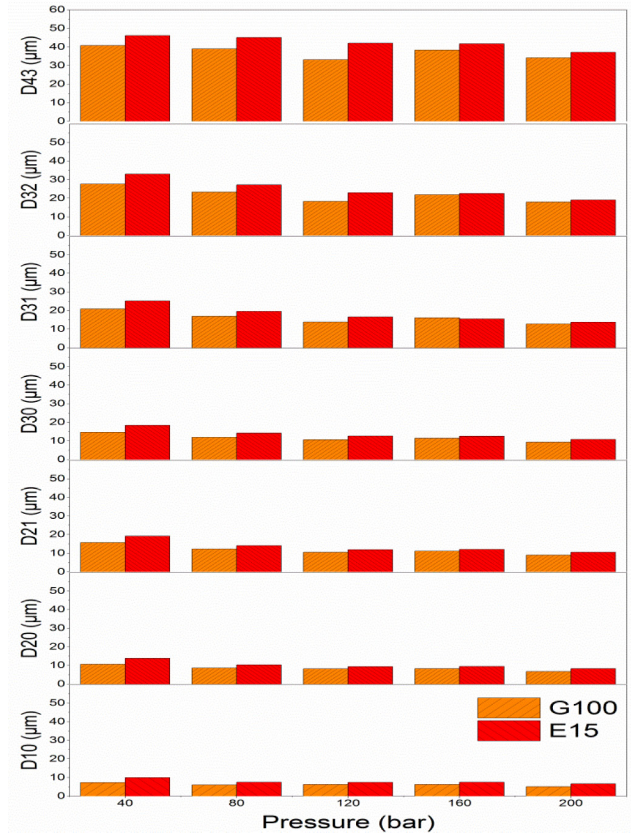
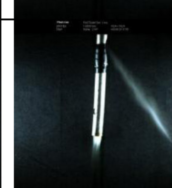
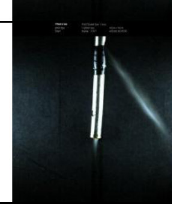


Figure 16. Mean particle diameters at different injection pressure

Table 3. Single spray plume from GDI injector of E15 fuel

Pressure (bar)	1 ms	2 ms	3 ms
40			
80			
120			
160			
200			

Conclusions

Experiments were carried out at five different fuel injection pressure viz: 40, 80, 120, 160, 200 bar for G100 and E15test fuel on GDI injector and 24 mg fuel quantity per injection. A high speed camera was used to find out the point of measurement (50 mm downstream) and quantitative analysis. Some of the important conclusion is as follow:-

1. For the velocity and count variation, axial velocity is more on the positive side for both the test fuel, for all the fuel injection pressure range. Whereas, radial velocity is uniformly distributed on both the positive and negative side of the origin, for all the fuel injection pressure. Negative velocity indicates the recirculation zone created by the swirl flow which is dependent on the injection pressure, ambient condition and drag experienced by the fuel droplet. Another point to be noted is that highest counts are observed in the immediate vicinity of the origin on the positive side, for all the fuel injection pressure. For a lower injection pressure, majority of the droplet are ensemble at a point less than 10 m/s axial velocity.
2. Radial component of the velocity ensemble in a much less pulse time duration as compared to axial component of the velocity. Similar to axial velocity, radial velocity tend to increases with increase in fuel injection pressure. For both the test fuel, the bulk of the droplets are collected in less than 10 m/s velocity for all the fuel injection pressure. The ensemble particles in the immediate vicinity of x-axis and y-axis forms a tail like structure and this structure tend to be thinner with fuel injection pressure.
3. Droplet size tends to decrease with increase in fuel injection pressure for all the test fuels and all the fuel injection pressure.
4. As the fuel injection pressure increases the bulk of the smaller droplet velocity decreases. The droplets with lesser fuel injection pressure are less scattered and as the fuel injection pressure increases, the droplets tend to scatter in all the directions.
5. In the PDF, the shifting of the peak towards left is desirable for better fuel-air mixture. It is observed E15 is better fuel for pressure range of 40-160 bar. For 200 bar fuel injection pressure, the peak of gasoline is higher which depicts that the gasoline had larger number of droplets of smaller size which is again desirable for better combustion. As the fuel injection pressure increases, the peak of G100 fuel increases and peak of E15 fuel decreases. The steepness of the line increases with increase in fuel injection pressure. Also, as the fuel injection pressure increases the slope shifts towards left side.
6. As far as mean diameters are concerned, as the fuel injection pressure increases both the fuels tend to decrease in its diameter, for the entire mean diameters. It is also observed that gasoline had less mean diameters for all the fuel injection pressure as compared to blended fuel. For particular millisecond duration, as the fuel injection pressure increases the penetration length tend to increases and then disappears.

References

1. Postrioti, L., Bosi, M., Cavicchi, A., AbuZahra, F. et al., "Momentum Flux Measurement on Single-Hole GDI Injector under Flash-Boiling Condition," SAE Technical Paper 2015-24-2480, 2015, doi:10.4271/2015-24-2480.
2. Araneo, L., Coghe, A., Brunello, G., and Dondé, R., "Effects of Fuel Temperature and Ambient Pressure on a GDI Swirled Injector Spray," SAE Technical Paper 2000-01-1901, 2000, doi:10.4271/2000-01-1901.
3. Parotto, M., Sgatti, S., and Sensi, F., "Advanced GDI Injector Control with Extended Dynamic Range," SAE Technical Paper 2013-01-0258, 2013, doi:10.4271/2013-01-0258.
4. Badami, M., Bevilacqua, V., Millo, F., Chiodi, M. et al., "GDI Swirl Injector Spray Simulation:A Combined Phenomenological-CFD Approach," SAE Technical Paper 2004-01-3005, 2004, doi:10.4271/2004-01-3005.
5. Yamakawa, M., Isshiki, S., Lee, J., and Nishida, K., "3-D PIV Analysis of Structural Behavior of D.I. Gasoline Spray," SAE Technical Paper 2001-01-3669, 2001, doi:10.4271/2001-01-3669.
6. Natti, K., Sinha, A., Hoerter, C., Andersson, P. et al., "Studies on the Impact of 300 MPa Injection Pressure on Engine Performance, Gaseous and Particulate Emissions," *SAE Int. J. Engines* 6(1):336-351, 2013, doi:10.4271/2013-01-0897.
7. Köpple, F., Jochmann, P., Kufferath, A., and Bargende, M., "Investigation of the Parameters Influencing the Spray-Wall Interaction in a GDI Engine - Prerequisite for the Prediction of Particulate Emissions by Numerical Simulation," *SAE Int. J. Engines* 6(2):911-925, 2013, doi:10.4271/2013-01-1089.
8. Abe, M., Hideharu, E., Masahiro, S., and Ishikawa, T., "Spray Atomization Study on Multi-Hole Nozzle for Direct Injection Gasoline Engines," SAE Technical Paper 2013-01-1596, 2013, doi:10.4271/2013-01-1596.
9. Matsumoto, A., Zheng, Y., Xie, X., Lai, M. et al., "Characterization of Multi-hole Spray and Mixing of Ethanol and Gasoline Fuels under DI Engine Conditions," SAE Technical Paper 2010-01-2151, 2010, doi:10.4271/2010-01-2151.
10. Pielecha, I., Maslennikov, D., and Wislocki, K., "Optical Research of Spray Development of E85 Fuel in High Pressure Gasoline Direct Injection System," SAE Technical Paper 2010-01-2285, 2010, doi:10.4271/2010-01-2285.

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Definitions/Abbreviations

PFI - Port Fuel Injection

MPFI - Multi Point Port Fuel Injection

GDI - Gasoline Direct Injection

PDI - Phase Doppler Interferometry

PDA - Phase Doppler Anemometry

G100 - Pure Gasoline

E15 - 15 % v/v Ethanol blended with 85 % v/v Gasoline

CCD - Charge-Coupled Device

SMD - Sauter Mean Diameter

AMD - Arithmetic Mean Diameter

D10 - Arithmetic Mean Particle Diameters

D20 - Area Mean Particle Diameters

D21 - Surface Area Length

D30 - VolumeMeanParticle Diameters

D31 - Volume Length

D32 - SauterMeanParticle Diameters

D43 - De Brouckere or Herdan

LDV - Laser Doppler Velocimetry

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