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Microscopic and Macroscopic Spray Characteristics of Gasohols Using a Port Fuel Injection System

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Abstract

Depleting fossil-fuels and increasing harmful emissions by the combustion of fossil fuels in IC engine is a matter of great concern. It is necessary to explore solutions complying with the prevailing emission norms in different sectors. Methanol has the potential amongst all primary alcohols for widespread use in transport sector due to its clean-burning, high octane rating, sources of production like high ash coal, and biomass. The addition of methanol to gasoline can significantly reduce engine-out emissions. Gasoline-Methanol blends (Gasohols) can be used to reduce dependence of the transport sector on fossil fuels. This study deals with investigation of spray characteristics of methanol-gasoline blends as it affects engine performance and emissions characteristics to a great extent. Macroscopic and microscopic spray characteristics of different gasohols such as M15 (15% methanol blended with 85% gasoline, v/v), M85 (85% methanol blended with 15% gasoline, v/v), M100 (100% methanol), and G100 (100% Gasoline) were experimentally investigated using a port fuel multi-hole solenoid injector. A Constant Volume Spray Chamber (CVSC) having glass windows was used for the experiments at a chamber pressure of 1 bar. The fuel injection pressure was maintained at 3.5 bar. The results showed that addition of methanol in gasoline does not have significant effect on macroscopic characteristics like spray penetration length and spray cone angle. On the hand, methanol addition in gasoline has considerable effect on microscopic characteristics. Gasoline showed better atomization behavior compared to other test fuels. Methanol addition shifted the droplet distribution towards the region of higher droplet diameter and velocity.

Keywords

Spray Characteristics, Methanol, Sauter Mean Diameter (SMD), Spray penetration length, Cone Angle

Introduction

Since last few decades, stringent norms and depleting sources of fossil fuels are the main motivations for the use of alternatives fuels in internal combustion (IC) engine. Partial replacement of conventional fossil fuel by alternative fuels in one potential method of this issue, which needs to be evaluated for compatibility along with acceptable engine performance and lower impact on the environment. Alcohols are one of the possible alternative fuel for spark ignition (SI) engine with minor modifications. Different alcohols have been tested and commercialised for automotive applications in many countries. Brazil and North America are using high alcohol content gasoline blends to power automotive [1,2]. Blending of alcohol in gasoline reduces combustion knocking due to its higher-octane number and more latent heat of vaporization. Methanol is produced from environment-friendly resources likes high ash Indian coal, municipal solid waste, low-value biomass, etc. which makes it a comparative green and indigenous fuel. Methanol contains inherent oxygen, which helps in complete combustion of air-fuel mixture. Higher enthalpy of vaporization of methanol compared to gasoline reduces the in-cylinder temperature, leading to lower NOx emissions. Its higher-octane rating allows increased compression ratio of gasoline engine without excessive knocking. Apart from this, methanol is convenient to blend in gasoline [3]. Few experimental studies found that the addition of methanol to gasoline fuel significantly reduced CO and HC emissions, however, formaldehyde emission increased [4, 5, 6, 7].

Better atomization of fuel droplets improve the combustion process and minimize the emissions from the engine. Atomization of fuel increases total surface area of spray. Thus, the rate of evaporation of fuel droplets increases. Fuel spray characteristics also plays critical role inengine performance. Therefore, it is necessary to study fuel spray characteristics and optimize the combustion for different alternative fuels [8]. In depth understanding of spray characteristics is required for developing spray models, spray injection process andinjector calibaration. Fundamental physics of spray can be understood from microscopic and macroscopic characteristics. Macroscopic spray characteristics include spray cone angle and spray penetration length analysis. Spray penetration length gives idea about fuel-air mixing, which is further used to study momentum exchanges of fuel and air. Spray cone angle depend on injector orifice dimensions and operating conditions. Microscopic spray characteristics such as droplet size distribution provide information about atomization, vapourization, and air - fuel mixing. Relatively finer droplets form homogenous mixture which reduces PM emissions and improve engine performance as compared to coarser droplets. It is well known that velocity distribution plays role in understanding rebound and consolidation.

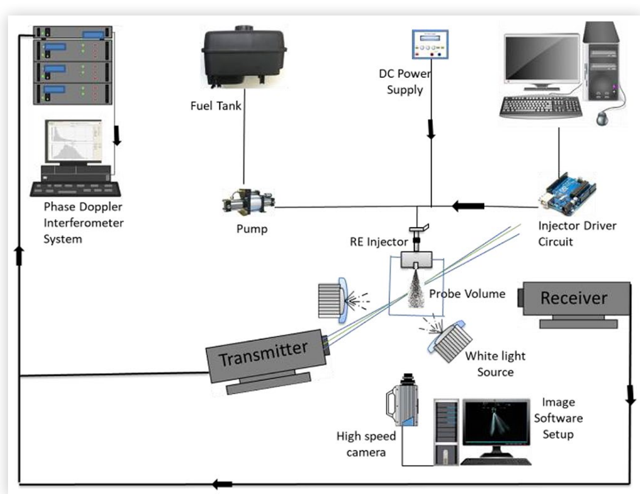
Various studies have shown that fuel properties such as viscosity, surface tension and density influences the spray characteristics to a great extent. Feng et al. [9] studied spray characteristics and atomization of diesel/gasoline/ethanol blends using high pressure common rail injection system. Results showed that as percentage of gasoline in diesel-gasoline blend increased, spray tip penetration and average droplet size reduced. This was mainly due to lower viscosity and surface tension of blends, which promoted spray breakup. Ethanol has higher viscosity and surface tension compared to gasoline. Therefore adding ethanol in diesel-ethanol blend increased fuel droplet size however it is still smaller compared to conventional diesel spray. Similar observations were also presented by Park et al. [10]. Tang et al. [11] studied macroscopic spray characteristics of ethanol-gasoline fuel under gasoline direct injection engine conditions. The addition of less viscous fluid such as ethanol changes spray breakup characteristics. It was observed that breakup length shortens and cone angle increases with an increase in alcohol content in blends [12]. Butanol is very competitive alcohol for use in SI engine due to its properties like less hydrophilic nature, higher heating value and good miscibility than ethanol and methanol with conventional fuels. Li et al. [13] investigated spray characteristics of butanol and gasoline by varying fuel injection pressure (FIP) from 60 to 150 bar, whereas spray chamber pressure range was 1 to 5 bar. They observed a reduction in Sauter mean diameter (SMD) for gasoline and butanol with increase in chamber pressure. Liu et al. [14] varied oxygen content (21%, 16%, and 10.5%) using EGR. Results found that with increase in oxygen content, spray penetration decreased. Higher amount of oxygen reduced the auto-ignition timing for the fuel. Thus allowed less penetration compared to less oxygen presence. Lee et al. [15] carried out fundamental research on Acetone-butanol-ethanol (ABE) spray characterization and combustion and found content of Acetone, butanol, and ethanol are critical parameters to study spray characterization and combustion of whole mixture. Kale et al. [16] used ethanol, iso-butanol, and n-butanol as test fuels for macroscopic and microscopic spray study. Spray penetration length of all alcohols was found to be higher than iso-octane due to higher latent heat of evaporation. Similar experimental and simulation results were observed for heavy fuel oil blend with methanol, ethanol, and butanol [17]. The n-pentanol-diesel blends have more spray cone angle and less penetration length and spray area compared to pure diesel. Hence atomization of n-pentanol-diesel blends was better than pure diesel. The addition of 50% n-pentanol in diesel reduces soot formation by 77.15% with a slight reduction in (~1.8%) brake thermal efficiency (BTE) [18]. Mathieu et al. [19] studied spray characteristics of different potential fuels such as alcohols, alkanes, etc. They concluded that fuel properties affect total injection quantity and hence the droplet size and liquid penetration length. Also, fuel properties play an essential role in primary atomization which generates small mean diameter droplets. This effect is dominant along the spray axis and at high fuel injection pressure [20].

From literature, it was observed that alcohol addition significantly affects the spray characteristics and has the potential to reduce emission and improve combustion with little modification in the existing engine. In PFI engine, emissions are mainly formed due to inferior atomization of fuel spray, wall wetting and inhomogeneity of mixture [21]. The novelty of this study will be to investigate spray characteristics of methanol-gasoline blends as fuel for PFI engines. It includes comprehensive study of macroscopic and microscopic spray characteristics. For this purpose, PFI injector of Royal Enfield (500cc) was mounted on constant volume spray chamber (CVSC) and fuel spray characterization was performed at atmospheric conditions.

Experimental Setup

The experimental setup for present research consisted of a cubic glass chamber (15′′×15′′×15′′) with port-fuel injector (16-hole injector) used in Royal Enfield 500 cc motorcycle, which was mounted on the top of the chamber, as shown in figure 1. Injector driver module using micro-controller (Arduino) was customized for controlling the injection pulse width of test fuel by controlling the pulse to the solenoid PFI injector. This was done to ensure that fixed amount of fuel (10.5 mg per injection) was injected from injector. The macroscopic and microscopic spray characteristics of different gasohols blends namely, M15 (15% methanol blended with 85% gasoline, v/v), M85 (85% methanol blended with 15% gasoline, v/v), M100 (100% methanol), and G100 (100% Gasoline) were investigated. The spray chamber pressure and temperature were maintained at 1 bar and 22° C respectively. The fuel injection pressure was maintained at 3.5 bar. These

FIGURE 1 Experimental setup for spray characteristics



conditions were chosen to simulate the similar condition of port injection during wide open throttle. The experimental matrix is shown in the Figure 2.

To study macroscopic spray characteristics, a high-speed CCD (Photron, SA-1) camera was used. White light sources were used to illuminate the fuel spray to capture the spray images. The images were captured at a rate of 5400 frames per second. ImageJ software was used for post-processing of spray images.

The microscopic spray characteristics of different test fuels were evaluated using Phase doppler interferometry (PDI). PDI works on principle of light scattering. The PDI system comprises of two transmitters and one receiver, which was used for detecting the constructive and destructive interference of fringes of the lasers and then further analyzed to determine the spray droplet size and velocity distributions. As droplet passes throught the probe volume, it scatters light and receiver collects the signals and transfers them to Advance Signal Analyser (ASA) signal processor for further calculation. Depending on the wavelenght of laser and phase shift, fuel spray droplet size and velocity distributions (2D and 3D) are calculated. For this study, 2D PDI system was used. PDI experiments were performed at distance of 40 mm downstream of the injector nozzle in the centre of a spray cone for all test fuels [22]. This distance was found suitable for optimum number of counts recognition by the PDI system. The technical specification of the PDI instrument is given in Table 1.

Table 2 shows the important properties of test fuels used in the experiments.

FIGURE 2 Experimental test matrix

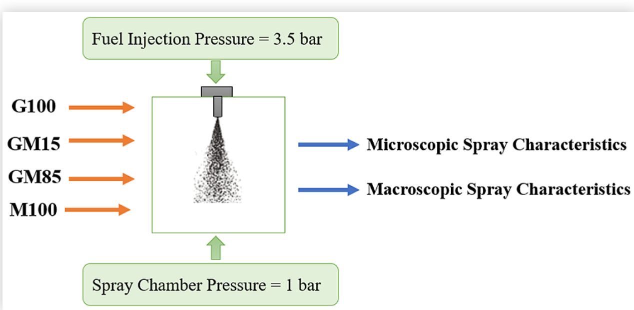


TABLE 1 PDI instrument specifications

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 mm
Transmitter focal length	500 mm
Laser type	Diode Pumped Solid State (DPSS)
Wavelength of lasers	Green - 532 nm, Blue - 491 nm

TABLE 2 Test Fuel Properties

Fuel properties	Gasoline	Methanol
Molecular formula	C_4-C_{12}	CH_3OH
Density @20 °C (g/cm^3)	0.745	0.796
Kinematic viscosity (mm^2/s at 40 °C)	0.494	0.596
Surface tension @ 27 °C (10^{-3} N/m)	18.93	22.18
Molecular weight (Kg/Kmol)	110	32.042
Oxygen content (% w/w)	< 0.05	50
Lower heat value (MJ/kg)	43.50	19.66
Vapour pressure @ 27 °C (MPa)	0.045-0.09	0.032

Results and Discussion

The present study involved the understanding of spray characteriscics of multi-hole PFI injector of RE500 (Royel Enfield) using gasoline-methanol blends. The experiments were performed using M100, GM15, GM85 vis-à-vis baseline gasoline (G100). Spray images were taken using high speed CCD camera to evaluate the macroscopic characteristics such as spray evolution, spray penetration length and cone angle. PDI system was employed for obtaining microscopic characteristics such as droplet size and velocity distribution. Experimental readings were acquired at atmospheric pressure and temperature conditions.

Macroscopic Spray Characteristics

For all test fuels, evolution of spray is shown at three different time intervals from the start of fuel injection. The raw spray images were processed using ImageJ software. Steps used for processing of raw images included contrast and brightness enhancement, noise removal, conversion to 8-bit grayscale type and finally binarization. The images were converted into binary format, where lighter spray region was represented as '1' and darker background region was represented as '0'. The threshold value used for converting images into binary format was 94.77%. Table 3 shows the processed spray images for different test fuels, which were used for evaluating the macroscopic spray characteristics, namely spray penetration length and spray cone angle. The spray penetration length was measured by obtaining the centre to centre distance from injector tip to farthest spray edge. Similarly, spray cone angle was determined by measuring the angle between two extreme edges of spray. The measurements were done by 2D binary images using ImageJ software. The length in the image can be calculated by calibrating the pixel of image by some known distance.

Figure 3 shows the maximum spray penetration length and cone angle of fully evolved spray at 5 ms. It represents the average data values, however the uncertainty in the measurements was greater than the differences between values of different test fuels. Hence, any significant conclusion cannot be drawn from the results of macroscopic spray characteristics. Also, it had been shown in a study [23] that the varying fuel properties have hardly any effect on vapour penetration length of spray while liquid penetration length is very much

TABLE 3 Macroscopic shadowgraph images at an injection pressure of 0.35 MPa under evaporating condition.

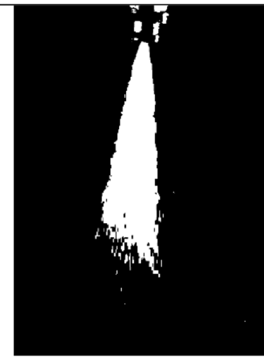
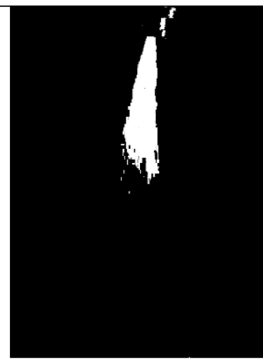
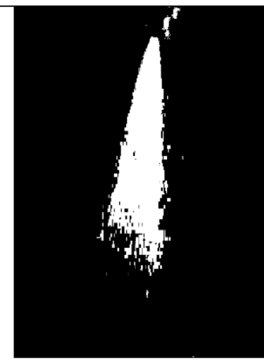
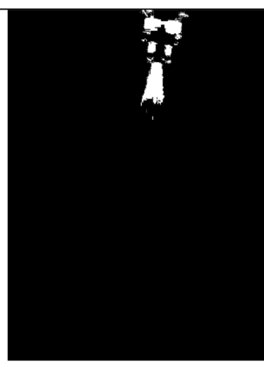
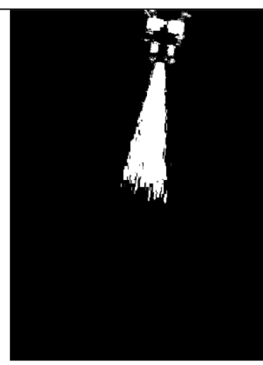
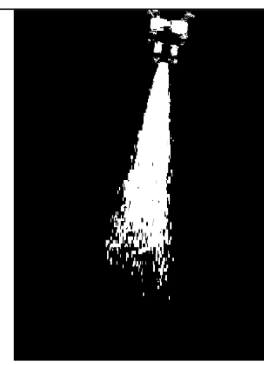
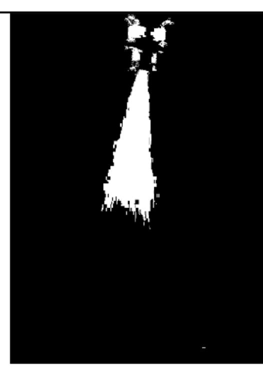
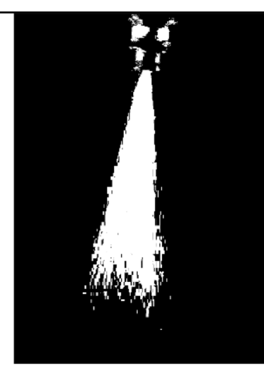
Test fuel	0.926 ms	2.963 ms	5 ms
G100			
M15			
M85			
M100			

FIGURE 3 Spray penetration length and Cone angle variation of M15, M85, M100, G100

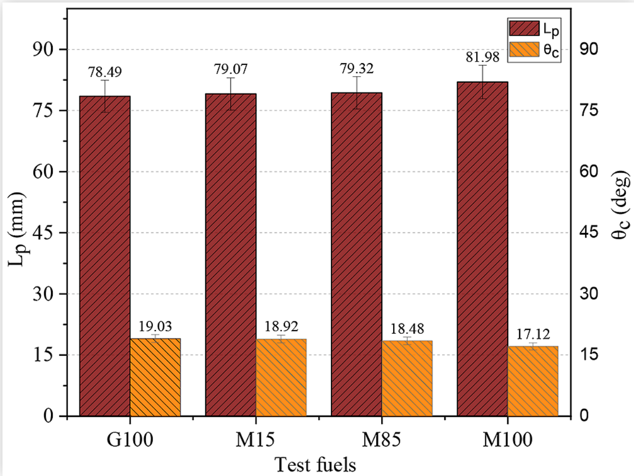
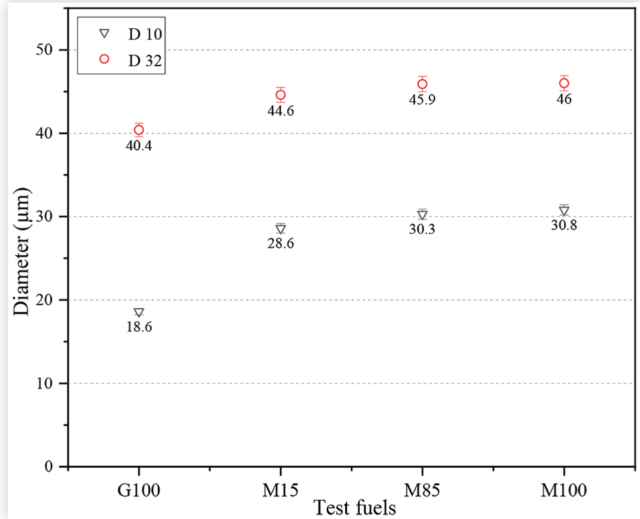


FIGURE 4 Mean particle diameters of spray droplets for all test fuels



dependent on fuel properties. This could be the probable reason for obtaining the insignificant differences in the results.

Although the average data values indicated that the spray penetration length increased with increasing percentage of methanol in test fuels however the cone angle decreased. This is due to higher viscosity and surface tension of methanol which slowed down the spray breakup. Hence, it led to higher penetration length and narrower plume of the spray. Other studies [24,25] have also justified the similar interpretations. However viscosity has more dominant effect than surface tension on in spray penetration.

In few studies, it has been reported that the volatility of fuel also affects its spray penetration length [26]. Due to slightly higher vapour pressure of gasoline as compared to methanol, gasoline has more volatile character, thus its penetration length is marginally higher. Kook Pickett [27] tested nine different fuels and found vapour penetration length fell within experimental uncertainties while liquid penetration were dependent on density and volatility of fuels. The correlations obtained from the experiments by Siebers [28] concluded that spray penetration length increases for fuel having higher specific heat and latent heat of vapourisation, which is higher for methanol. Further, higher density fuel results in higher penetration length as it requires entrainment of more surrounding air to evaporate completely [29]. Hence, the conclusions from these studies are similar with the inferences drawn from this study.

From the images taken at 0.926 ms (early evolution), it was observed that spray penetration length of M85 and M100 was reduced slightly as compared to M15. The probable reason for this could be the delayed opening of needle of injector due to presence of higher viscous fuel. However, the later evolution of M85 and M100 spray resulted in more penetration.

Microscopic Spray Characteristics

Droplet diameter is considered as an important parameter to decide the quality of fuel spray. For better atomization of fuel, droplet diameter should be small. Smaller droplet size leads to higher vaporization rate and improves fuel-air mixing, resulting in homogeneous mixture. It enhances the quality of combustion and reduces the exhaust emissions from the engine.

Figure 4 shows the variation of Sauter mean diameter (SMD, D32) and Arithmetic mean diameter (AMD, D10) for different methanol-gasoline blends. AMD signifies the comparative length of fuel spray, thereby indicates the idea of spray penetration. SMD refers to volume to surface area ratio of droplets which corresponds to mass transfer property, i.e. evaporation of droplets. These statistical mean diameters demonstrate the comparative averaged droplet diameter related to various phenomenon in spray evolution. From the experimental results, it could be inferred that gasoline had minimum AMD and SMD. With the increase in methanol fraction in the blends, AMD and SMD of the fuel spray increased. Higher surface tension and kinematic viscosity of methanol compared to gasoline resulted in delayed spray breakup due to the presence of large vanderwaal forces, leading to bigger fuel droplets. Fuel viscosity increases the internal friction forces in the fuel jet, thereby restricts the disintegration into fine ligaments and hence, coarser droplets are formed. However, the effect of surface tension of fuel is less significant to that of fuel viscosity. As soon as fuel jet emerges out of spray orifice, the fuel jet gets deformed into fine ligaments and on entering the gaseous medium in high velocities, the action of aerodynamic and surface tension forces on fuel stream results in surface disturbance and breaking down into finer droplet. The droplets get detached from fine ligaments of fuel thread only after attaining a definite size and its size gradually increases. This happens when surface tension forces overcome the aerodynamic and gravity forces. Thus, fuel having higher surface tension have inferior spray atomisation and results in coarser droplets.

In addition, weber number is considered as an important dimensionless number which influences the spray breakup. It is the ratio of inertia force to surface tension force used for studying flows involving the interface of two different fluids.

Higher weber number results in faster breakup in spray regime. Figure 7 shows the droplet count-velocity distributions, in which the blends having higher fraction of methanol resulted in higher average velocity of droplets compared to gasoline. This might lead to greater inertia force for blends with higher fraction of methanol, however simultaneous increase in their surface tension could possibly reduce weber number of respective sprays. The results showed that gasoline spray could possibly have greater weber number, hence led to faster spray breakup and relatively smaller droplet size compared to other blends. Moreover, higher vapor pressure of gasoline than methanol increased the volatity of the fuel spray, which further supported the outcome. However, kinematic viscosity has been considered as the most influential parameter in determining the droplet sizes, according to many studies [30,31].

Figure 5 shows the droplets count distribution w.r.t. droplet diameter. The results showed that gasoline spray had the maximum number of smaller size droplets, which indicate the superior atomization of gasoline than other test fuels. The droplet distribution curve of gasoline indicated sharp and high peak in small size range of droplets due to its low viscosity, surface tension and density, and gave homogeneous distribution. On the other hand, methanol showed the wide droplet distribution curve with the peak at higher droplet size and having inhomogeneous distribution. Generally Weber number influences the spray breakup when it reaches a critical value, and it is directly related to fuel properties. Hence, low viscosity, surface tension and density of fuel resulted in more readily spray breakup and this is also validated with the current experimental results. M15 has the least droplet counts in the region of particle size of ~ 20 microns diameter. This could be due to coalescence of colliding droplets. Considering large size droplets, M85 and M100 spray had significant share in the distribution.

Droplet velocity is also considered as an important characteristic in determining the spray evolution. Higher droplet velocity indicates higher inertial forces, hence leads to greater penetration of spray. Figure 6 shows the variation of average velocity and maximum velocity for different test fuels. Gasoline spray occurred with the lowest mean droplet velocity

FIGURE 5 Droplet count-size distribution for all test fuels

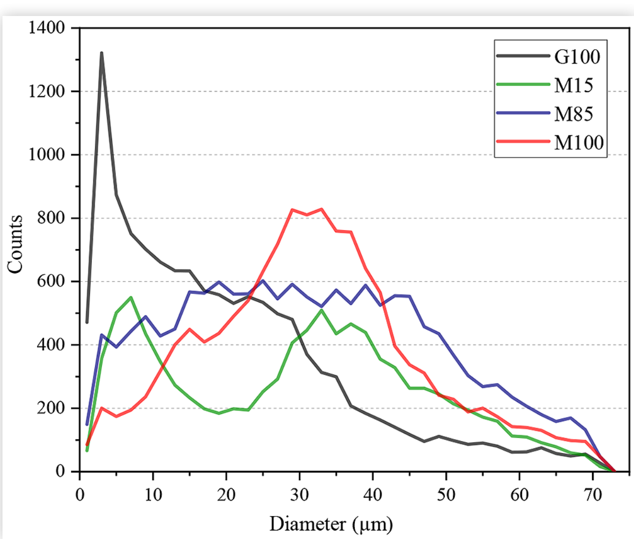
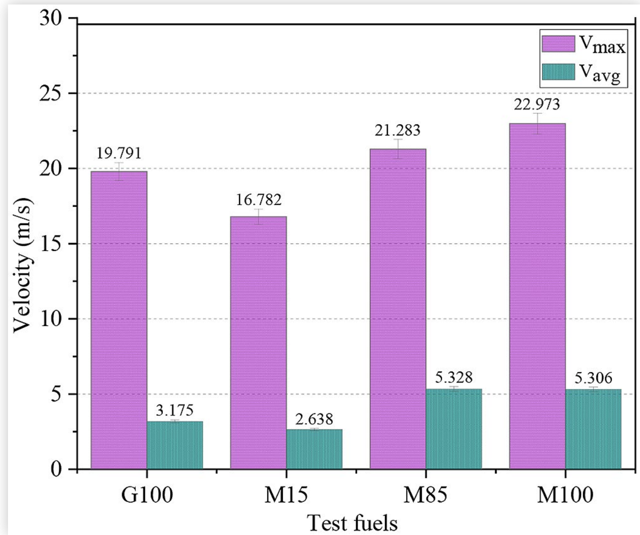


FIGURE 6 Maximum and average velocity of spray droplets for all test fuel



among different test fuels. With an increase in methanol fraction in test fuels, both average and maximum droplet velocity increased. This could be due to greater momentum of their larger droplets. Further, higher density of methanol and its larger spray droplets led to increased inertia forces, hence higher droplet velocity was obtained.

Figure 7 shows the droplet count distribution for different droplet velocity. The results indicated that gasoline spray had the maximum number of spray droplets with lesser velocity. The peak of almost all test fuels fell around velocity of 1 m/s. With increase in methanol fraction, droplets with higher velocities were observed. The reasons have been discussed previously. M15 showed the least number of counts in the distribution possibly due to coalescence and collision of droplets. M85 spray attained maximum number of counts of high-velocity droplets in the range of 5 - 10 m/s.

FIGURE 7 Droplet count-velocity distribution for all test fuels

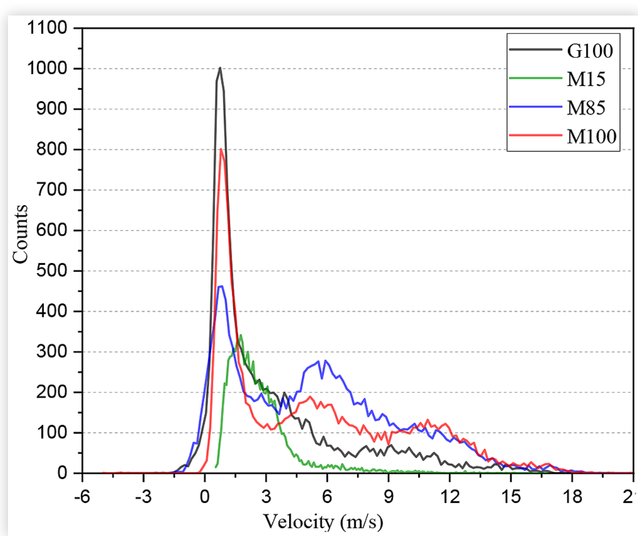


FIGURE 8 Droplet size-velocity distribution for all test fuels

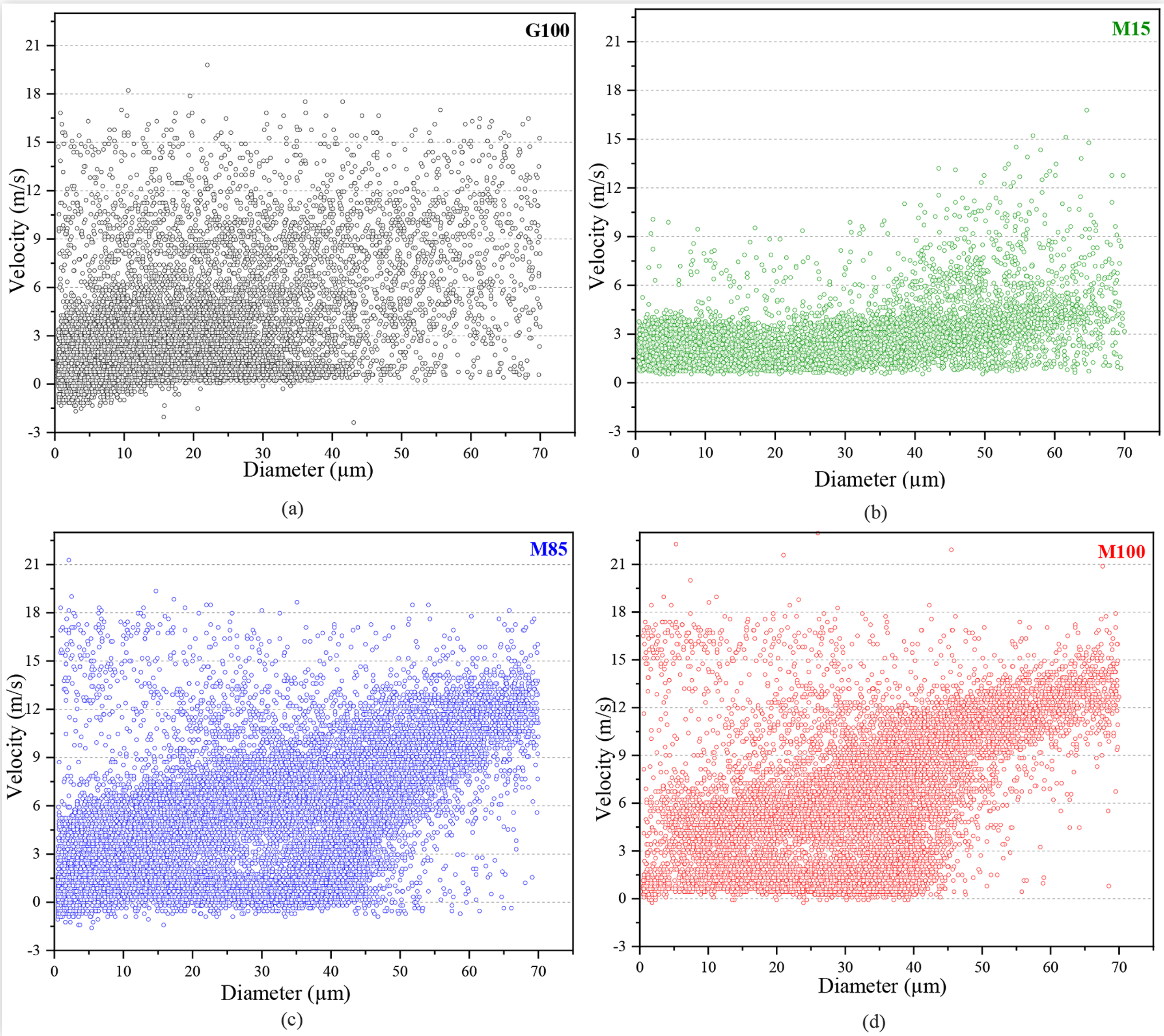


Figure 8 shows the enssemble distribution of droplets velocity w.r.t. their diameters for various test fuels. From figure 8(a), it was observed that bulk of the droplets of gasoline spray were confined to lower velocity-lower diameter regions as compared to other fuel. Although few droplets were found in extreme regions. The distribution showed the maximum velocity up to 18 m/s. Droplet size spanned over 0-70 microns range. Lower kinematic viscosity, surface tension and density of gasoline as compared to methanol resulted in the superior droplets distribution relative to other test fuels. For M15, the distribution indicated that the number of droplets with higher diameter increased as compared to gasoline. However, major portion of distribution was leaning towards lower velocity regions (< 4 m/s). For M85, the droplet distribution was very dispersed. Fuel properties of methanol resulted in significant number of droplets with large diameter (> 40 microns). Further, higher inertia of bigger droplets led to greater droplet velocity. A similar pattern of droplet distribution was observed in M100. The majority of the droplets were distributed in the region of intermediate and larger diameter with greater velocity.

Conclusions

The experimental study was conducted to investigate the macroscopic and microscopic spray characteristics of port-fuel injector used in RE500 motorcycle. The effects of methanol addition in gasoline were studied in spray characteristics. The results were compared for four test fuels, namely gasoline, M15, M85 and M100. The major conclusions obtained in the study are:

- Addition of methanol in gasoline has not shown any significant changes in the spray penetration length and spray cone angle of low pressure PFI injector. The differences in the values for different test fuels were coming under the uncertainties of measurement.

- Among all test fuels, G100 showed the smallest SMD while M100 showed the largest SMD.
- Gasoline showed better atomization due to lower viscosity, surface tension and density as compared to methanol. Lower values of these fuel properties enhance the spray breakup. This leads to formation of larger number of droplets and enhance the vaporization by increasing the effective surface area of spray. Hence, for effective utilization of methanol blends in SI engine, relatively higher fuel injection pressure would be an appropriate measure to improve its spray characteristics.
- The droplet distribution curve of gasoline indicated sharp and high peak in small size range of droplets and gave homogeneous distribution. On the other hand, methanol showed the wide droplet distribution curve having the peak at higher droplet size and having inhomogeneous distribution.
- The addition of methanol in gasoline resulted in higher droplet velocity due to higher momentum of coarser droplets. M85 and M100 resulted droplets having higher velocity.
- As kinematic viscosity and surface tension of test fuel increased due to methanol addition, droplet distribution shifted towards the region of higher droplet diameter and velocity.

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