Spray Characteristics of Multiple Fuels from a Gasoline Direct Injection Injector under Different Ambient Pressures

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Abstract
This study explores the spray characteristics of light naphtha (LN), primary reference fuel (PRF) and neat gasoline under different ambient pressures with GDI fuel injector. Gasoline (E10) (AKI (anti-knock index) = 87) used in this study was obtained from three different local gas stations to account for the variation of fuel properties. The AKI is an average of the research octane number (RON) and the motor octane number (MON). Naphtha is a less processed petroleum stream with gasoline-like boiling range. Normally, the naphtha fuels have lower octane number (research octane number ~65) than normal gasoline. PRF is a gasoline surrogate mixture comprising iso-octane and n-heptane. PRF95, the blend of 95% iso-octane and 5% n-heptane by volume, was used in this study as a surrogate for high-octane gasoline. Five different ambient pressure conditions were selected from 1 bar to 10 bar. The spray is visualized using a high-speed camera with Mie-scattering technique. The spray structure, spray angle, spray penetration length and spray front fluctuation are discussed. The result shows that higher ambient pressures generally lead to larger spray angle for all three fuels. Neat gasoline always has the largest spray angle at each ambient condition, while the spray angle of PRF95 is the smallest. For each fuel, spray penetration length and spray penetration velocity decrease with increasing ambient pressure. All three selected fuels have similar penetration length and penetration velocity under each ambient pressure condition. A two-stage spray front fluctuation distribution is remarked for all three fuels. Stage one begins from the start of the injection and ends at 450 μs to 500 μs ASOIT with slow fluctuation increasing for all ambient conditions. The spray front fluctuation increases rapidly to a certain level and then becomes stable in stage two.

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Introduction

Currently, solenoid-actuated inwardly opening multi-hole injectors and piezo-electrically actuated outwardly opening injectors are predominant injectors in GDI engines. Solenoid injectors are more economical than piezo injectors by sacrificing the precision and repeatability [1]. Piezo injectors draw attentions because of their sensitive and fast response, which are significant for small quantities or closely spaced multiple injections [2]. Spray from a piezo injector has a hollow-cone structure with visible striations and filaments. Unlike hollow cone pressure-swirl sprays, no collapse arises with the spray development [3], and this spray pattern is quite repeatable [4]. Studies have been done on both types of injectors in GDI engines in the past few years. Smith et al. [5] conducted a systematic performance comparison of two spray-guided, single-cylinder, spark-ignited direct-injected (SIDI) engine combustion system designs with both solenoid and piezo injectors and found that the two kinds of injectors have comparable combustion stability and smoke emissions. Achleitner et al. [6] demonstrated the possibility to develop a spray-guided combustion system to meet the requirements to the maximum possible extent by using a piezo injector. Skogsberg et al. [7] and Wang et al. [8] explored the atomization of sprays generated by a piezo injector. It was shown that a leading edge vortex is formed at the outer periphery of the spray. The location of the leading edge vortex depends on back pressure. Zhang and co-authors [9] demonstrated that the cone angles at the developed phase for alcohol fuels and iso-octane are consistently stable for a solenoid swirl GDI fuel injector. Higher injection pressure helps reduce droplet size. The outwardly opening hollow cone piezo injector has also been numerically modeled using commercial computational fluid dynamics (CFD) code [10].

Along with the research interests in piezo injectors, researchers also paid attention to naphtha fuels due to their high volatility and stronger resistance to auto-ignition, which potentially could be used for high efficiency compression-ignition combustion with low emissions. Naphtha is a kind of fuel with less processed refinery stream in the gasoline boiling and carbon number range, lower octave number and higher heating values compared to commercial gasoline. Producing naphtha is significantly simpler in a refinery compared to gasoline [11]. According to the refining process, naphtha fuels generally can be categorized as heavy naphtha (HN) and light Naphtha (LN) [11]. Investigations have been performed on the thermal efficiency, combustion and emission characteristics of naphtha. Chang et al. [12] demonstrated that naphtha can be used in a modern diesel vehicle without compromising comfort, drivability, emissions or power requirements. Won et al. [13] evaluated low cetane number (CN) naphtha fuels (CN from 20 to 35) with different bowl and nozzle designs. It turns out that diesel CI engine can run with low CN naphtha fuels without major modifications. CN 35 naphtha fuel was recommended for its better robustness and lower HC and CO emissions.

While studies of piezo injectors and naphtha fuels have been undertaken, little study was done on the fuel spray characteristics of naphtha fuels with a GDI piezoelectric outwardly opening hollow-cone fuel injector under different back pressure conditions. Therefore, light naphtha (LN), PRF95, and E10 gasoline sprays using a GDI piezo fuel injector are studied and compared in this study. The spray angle, spray front penetration length and spray front fluctuation were calculated and discussed.

Experimental Setup

Experiments were conducted in a constant volume spray chamber (CVSC) with six ports, as shown in Fig. 1. Optical access was enabled by quartz windows installed in two ports. The other four ports were sealed by solid stainless steel plugs fitted with a gas inlet, an outlet, a fuel injector, a spark plug, a pressure sensor, and other necessary components. More details of the chamber can be found in previous publications [14, 15]. The inner diameter of the quartz window is 100 mm, and the total chamber inner volume is 0.95 L. An outwardly opening piezoelectric fuel injector was employed in this study. Five different ambient pressure conditions including 1, 3, 5, 7, and 10 bar were generated by using compressed air in the constant volume chamber. Three fuels were selected including light naphtha (LN), primary reference fuel (PRF), and E10 gasoline (10% ethanol and 90% neat gasoline by volume). LN was obtained from Saudi Aramco, with an AKI value of 64. AKI is defined as the average of the research octane number (RON) and the motor octane number (MON). PRF is a binary mixture of iso-octane and n-heptane that used as a surrogate for gasoline. PRF used in this work was PRF95, a blend of 95% iso-octane and 5% n-heptane by volume. The AKI of PRF95 is 95 [16]. The E10 gasoline (AKI = 87) was obtained by mixing fuels with equal volume ratios from three different local gas stations. The injection pressure was maintained at 100 bar by a gasoline common rail fuel injection system, and the injection duration was set as 0.3 ms for all experiments. The fuel quantity per injection was around 10 mg. The injection parameters are listed in Table 1. Fuel temperature was the same as the ambient, namely 298 K. Selected fuel properties are listed in Table 1 [8, 17, 18].

The spray development during the fuel injection process was visualized by applying a Mie-scattering technique. A high-speed camera (Phantom V4.3 from Vision Research Inc.) was employed to capture the spray images of each selected fuel. Experiments were repeated.
In this section, the spray macroscopic features of LN, PRF95, and gasoline are presented and analyzed, respectively. The spray structure, spray angle, spray front penetration length, spray front, and the spray front fluctuation were calculated and discussed.

A set of spray images of three fuels with marked spray edges and front under different ambient pressures are presented in Fig. 2-4. It is seen that the spray develops smoothly with a clear filamentary hollow-cone structure at the atmospheric condition. A reducing spray dimension or size is also noted with increasing ambient pressure. The spray front stays quite evenly during the injection process for all investigated fuel. In order to better understand the ambient pressure effect on the spray development, the spray structure is evaluated with contour-plots at selected ambient pressure conditions, as shown in Fig. 5. Martin et al. [19] described a parallel moving string shape at the spray front with GDI fuel injectors. A similar phenomenon is observed in this study for all the selected ambient conditions, which indicates a relatively uniform velocity distribution at the spray font. However, the filamentary structure gets blurred when the ambient pressure is higher than 1 bar, and a noticeable toroidal recirculation vortex is observed at the downstream region of the spray, which deforms the hollow-cone shape. The edge vortex does not appear until the spray penetrates a certain distance from the exit plane. The location of the vortex moves to the injector nozzle and becomes stronger with increasing ambient pressure conditions for all investigated fuel. In addition, this string shape is getting more inconspicuous with increasing ambient pressure. As a result, the spray front fluctuation may become weaker under a high ambient pressure environment.

Spray angle

In order to calculate the spray angle, the spray edges were detected and marked with colored lines for all transient images in each single injection using a Matlab code developed in-house. The spray angle is defined as the average angle between the whole detected spray edges. Because the spray developed freely and had no definite angle after the end of the injection (around 430 μs after the start of injection trigger (ASOIT)), the transient spray angle was calculated from the beginning to the end of each single injection. The spray angle results of each fuel were presented in Fig. 6 (a). Generally, the spray angle of each fuel slightly increases with time all investigated ambient pressures. For the first half of injection process (0-200 μs ASOIT), the effect of ambient pressure on spray angle is almost negligible for all three fuel. The spray angles of each fuel under different ambient pressure conditions are quite close within this time interval, except for the 1 bar condition of gasoline. However, the effect of ambient pressure on spray angle becomes significant after 200 μs ASOIT. In this stage, a higher ambient leads to a larger spray angle for all three fuels. This may be caused by the stronger vortex under a higher ambient pressure. In order to evaluate effect of the fuel properties on spray angle under investigated ambient pressures, spray angles of three fuels were compared at 1 bar, 5 bar and 10 bar condition, as shown in Fig. 6 (b). Overall, gasoline always has the largest spray angle for the whole injection process and for all investigated ambient conditions. LN has slightly higher or close spray angle compared with PRF95. The lower spray angle of PRF95 may be caused by its higher viscosity than LN and gasoline. Gasoline has the lowest viscosity among three fuels, which may be a reason for the largest spray angle of gasoline for all the investigated ambient conditions.

Spray front penetration length and front fluctuation

Similar to the spray angle, the spray front is detected and marked by green lines for the spray front penetration length calculation. In this study, spray penetration length is defined as the average distance between the entire detected spray front and the exit plane. The spray front penetration length and spray front fluctuation were analyzed in a much longer time interval than spray angle (up to 790 μs ASOIT), and spray front penetration length results of each fuel under different ambient conditions were shown in Fig. 7 (a). Overall, the spray penetration length increases quite linearly until the end of the injection for all the ambient conditions. A higher ambient pressure leads to a shorter penetration length at each time step for all three fuels, which is caused by the increasing drag force experienced by the moving spray droplets with increasing ambient pressure. The difference of the penetration length between two adjacent ambient pressure conditions decreases with increasing ambient pressures. The spray front penetration of three fuels were compared at selected conditions and illustrated in Fig. 7 (b). Unlike the spray angle, the penetration length of the three fuels are nearly the same for all investigated ambient conditions during the injection process. Only tiny differences are noticed at the end of the injection (around 400 μs after the start of the injection) and the end of the whole penetration process (after 700 μs). Gasoline has a slightly longer penetration length than LN and PRF95 at the two periods mentioned above.

The spray front fluctuation is defined as the standard deviation of the entire detected spray front in this study.
The spray front fluctuations of three investigated fuels were shown in Fig. 8 (a). The development of the spray front fluctuation can be divided into two stages for the whole process. Stage one is from the beginning of the injection to around 400-500 μs ASOIT depends on fuel type, during which the spray front fluctuation increases slowly for each ambient pressure, and the fluctuation level is close for all ambient conditions. However, after the end of stage one, the fluctuation firstly increases rapidly and then becomes stable by the end for each fuel. This period is defined as Stage two. In this stage, and a higher ambient pressure gives rise to stronger spray front fluctuation except the atmospheric condition for gasoline, but no clear relationship between the ambient pressure and the highest level of the fluctuation is found for LN and PRF95. The comparison of spray front fluctuation among three fuels were shown in Fig. 8 (b). It is seen that the beginning of the sharp increase is close for the three fuels at each ambient condition. In addition, the timing of the sharp increase shifts forward with increasing ambient pressures. For example, at 1 bar condition, spray front fluctuation has a low increasing rate until around 600 μs ASOIT. When the ambient pressure increases to 10 bar, the timing shortens to 450 μs ASOIT. This may be caused by the stronger spray/air interaction due to the larger drag force experienced by the moving spray droplets under a higher ambient pressure condition.

Summary and conclusions

The spray characteristics of LN, PRF95 and E10 gasoline were investigated under different ambient pressure conditions in a constant volume chamber in this paper. The findings are summarized as follows:

1. A clear filamentary hollow-cone spray structure is observed for all three fuels at atmospheric condition. Toroidal recirculation vortex is noticed at the spray downstream, and a higher ambient pressure leads to a stronger vortex closer to the exit plane.

2. Generally, a slightly larger spray angle is found with a higher ambient pressure for all three fuels. Among the three fuels, gasoline always has the largest spray angle at each ambient condition and PRF95 spray angle is the smallest at most time.

3. The spray front penetration length reduce considerably with increasing ambient pressure for all the fuels. For each ambient pressure and each fuel, spray penetrates nearly linearly until the end of the injection. LN, PRF95 and gasoline have close penetration length under all selected ambient pressure conditions.

4. The spray front fluctuation shows two distinct stages during the spray development. During Stage one the spray front fluctuation is close for all ambient pressures and increases slowly with time. During Stage two, the spray front fluctuation increases rapidly to a certain level and then becomes stable.

Acknowledgement

This research was supported in part by the Saudi Aramco R&D Center through the Clean Combustion Research Center of the King Abdullah University of Science and Technology under the FUELCOM program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the funding agencies.

References


10. Sim, J., Badra, J., Elwardany, A., and Im, H., "Spray Modeling for Outwardly-Opening Hollow-Cone

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<th>Fuel</th>
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Table 1. Selected fuel properties
Figure 1. Experimental system: 1. fuel injector, 2. exhaust line, 3. chamber body, 4. quartz window, 5. plug/window retainer, 6. pressure transducer, 7. intake line, 8. metal plug, 9. spark plug, 10. Combustion chamber, 11. high speed camera (Phantom V4.3). 12 lighting

Figure 2. Spray images of LN, PRF95 and gasoline under 1 bar ambient pressure condition.
Figure 3. Spray images of LN, PRF95 and gasoline under 5 bar ambient pressure condition

Figure 4. Spray images of LN, PRF95 and gasoline under 10 bar ambient pressure condition
Figure 5. Spray structure development under selected ambient pressures

Figure 6. (a) Spray angle of each fuel at different ambient pressures (b) Comparison of spray angle among three fuels
Figure 7. (a) Spray front penetration length of each fuel at different ambient pressures (b) Comparison of spray front penetration length among three fuels

Figure 8. (a) Spray front fluctuation length of each fuel at different ambient pressures (b) Comparison of spray front fluctuation length among three fuels