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Research article

Experimental study on non-vaporizing spray characteristics of biodiesel-blended gasoline fuel in a constant volume chamber

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A B S T R A C T

Detailed investigation of the spray phenomenology of liquid fuel injection is the primary step to understand better and predict the physical characteristics involved in fuel spray and atomization process. This study focuses on non-vaporizing transient spray characteristics of neat gasoline (GB00) and biodiesel addition (10%, 20% and 40% by volume) to gasoline in three different ratios under low load and different injection pressure conditions. Different ambient gas densities and injection pressures were tested, which ranged from 10 to 20 kg/m^3 and 40 to 120 MPa respectively, with a fuel temperature of 323 K. A z-type shadowgraph was utilized as an optical method to capture the highly transient spray development at 40000 frames per second and a modified image processing algorithm was implemented to determine the spray characteristics. The image processing results revealed that an increase in injection pressure significantly accelerates the spray development process while penetration length increases with the increment of biodiesel fraction. Differences in penetration lengths were much significant under lower injection pressure; however, a further increase in injection pressure diminishes the differences in tip penetration. The spray cone angle was increased for higher gasoline content which promotes a larger spray width and as a consequence, neat gasoline exhibited a larger spray area and volume. However, after a certain period of injection start, spray area and volume of neat gasoline and 10% biodiesel-blended gasoline were surpassed by 20% and 40% biodiesel-blended gasoline. In contrast, a decrease in droplet size was observed according to breakup regimes under high injection pressure and low ambient density. These results imply that the higher biodiesel blending fraction has poor air-fuel mixing capability compared to neat gasoline, and the risk of liquid impingement on the cylinder wall becomes higher if the blended-gasoline contains higher biodiesel percentage.

1. Introduction

Cleaner combustion technology with high thermal efficiency is the key pathway to meet increasingly stringent emission regulations and future energy demands. Over the past century, diesel fuel has been widely used in compression ignition (CI) engines to achieve low fuel consumption and high-power output. CI engines are facing more stringent emission regulations around the globe due to harmful tailpipe emissions such as carbon monoxide (CO), nitrogen oxides (NOx), unburned hydrocarbon (HC), soot and particulate matter. As a result, after treatment techniques e.g., LNTs (lean NOx traps), DPFs (diesel particulate filters), and SCR (selective catalytic reduction) are necessary to meet the Euro VI and upcoming emission legislation. But, implementing these methods to mitigate emissions in existing and future diesel vehicles will be costly [1]. So, diesel combustion-based advancements have undergone a noticeable shift in attempts to achieve future emission legislation and outstanding fuel economy. However, the diesel engine developments are directly challenged by the complex nature of NOx-PM trade-off [2]. All of those CI engine-based advancement relies on the concept of low-temperature combustion (LTC), which depends on two major targets: a comparatively low in-cylinder combustion temperature and avoidance of fuel-rich mixture [3]. Recently, the noticeable focus has been drawn towards the use of low cetane fuel in LTC mode, and recent studies [4–6] have shown that gasoline-like fuel with a low cetane value (CN) having high volatility is more appropriate for CI engines in terms of efficiency and emissions. As a further milestone, researchers have started to explore low cetane fuel in partially premixed compression ignition (PPCI) mode, which is advantageous for increasing the ignition delay compared to diesel fuel [7]. Gasoline-based PPCI was introduced by Kalghatgi [8] and experimented by Johansson [9]. Experiments have been performed on diesel engines using different gasoline-like fuel by Kalghatgi et al. [10], Manente et al. [11],

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Weall and Collings [12], Ra et al. [13] and Ciatti et al. [14]. Gasoline has poor self-ignitability but high volatility which is easy to vaporize and can potentially help to increase the local air-fuel mixing time. Engine designers have become interested in using gasoline fuel in CI engines due to high thermal efficiency and significant pollutant reduction compared to traditional diesel engines. Researchers have shown that the gasoline compression ignition (GCI) based dual-fuel blending concept is more potential than PPCI and HCCI. The advantage of GCI relies on the low-temperature combustion regime in the CI engine, which helps to obtain high thermal efficiency while maintaining lower NOx and soot emissions. However, attaining LTC over an extensive range of conditions is somewhat challenging because diesel fuel has lower volatility and is highly chemically reactive. Gasoline-like fuel has been experimentally examined in the aforementioned combustion strategies by utilizing the poor self-ignitable property of gasoline, which enhances the air-fuel mixing time similar to HCCI mode. In spite of that, applying gasoline in the conventional common rail is questionable due to lower lubricity [15] and higher vapor pressure [16], which can lead to problems in the fuel injector and high-pressure pump. As a result, researchers have investigated gasoline-diesel dual-fuel blending over diesel to minimize droplet size, increase ignition delay, and reduce smoke. Thus, the direct mixing of diesel and gasoline (termed as dieseline) was recommended to avoid stratification in the engine cylinder, along with the advantage of nominal modification in the current common rail system [17]. Won et al. [18] demonstrated dieseline fuel (10 vol% of 56 CN diesel and 90 vol% of 95 RON gasoline) and summarized that the lower fuel injection pressure and larger orifice diameter are better to reduce hydrocarbon and carbon monoxide in gasoline-based PCCI. Beside this summary, few dissimilarities still exist in the spray morphology between diesel and gasoline. Payri et al. [19] demonstrated similar macroscopic tip penetration and momentum flux for both gasoline and diesel at non-vaporized conditions, while Kim et al. [20] pointed out that gasoline could result in shorter tip penetration but wider cone angle at the same condition in constant volume chamber. Han et al. [21] concluded that decreasing diesel percentage of dieseline fuel increases the rate of injection due to the lower kinematic viscosity and density of gasoline fuel. They also inferred that blended fuel with higher gasoline percentage greatly enhances the break up process towards the ambient environment and exhibits decreasing fuel droplet size. However, they suggested the similar conclusion with Payri et al. [19] in case of tip penetration length for pure diesel and dieseline fuels. According to Kook and Pickett [22], the density and viscosity of gasoline are lower than that of diesel, which allows an increase in air entrainment and the decrease in tip spray penetration length compared to diesel spray. Also, their findings comprehended that the distillation temperature of diesel is around 50% higher than gasoline, which quickens the fuel evaporation and air/fuel mixing process.

On the other hand, biodiesel fuel has lower volatility and superior lubricity that can play an environment-friendly role as an alternative to diesel due to its biodegradable, sulfur-free, oxygenated, nontoxic and renewable nature. Moreover, the biodiesel has abundant feedstock which leads to a different chemical structure and oxygenated content. Biodiesel has already become green and sustainable fuel after the steep increase in fossil fuel consumption. So, high boiling point and cetane of biodiesel counteract with low reactive but high volatile gasoline to prepare a fuel blend which influences superior fuel atomization and autoignition characteristics. The gasoline-biodiesel fuel blends can be served as oxygenated gasoline [23] that will suppress the autoignition and will retard the combustion phasing with increasing EGR concentration. Adams et al. [24] studied partially premixed, split-injection combustion strategy using 5% and 10% biodiesel by mass in gasoline-biodiesel blends and concluded a reduction in intake temperature requirement due to the low-cetane number of gasoline. A very fundamental aspect towards the aim of utilizing gasoline-biodiesel fuel blends (GB blends) in such directly injected compression ignition engine is to thoroughly demonstrate the macroscopic spray behavior and atomization phenomenon [25]. Despite a noticeable physicochemical change in fuel composition, the blended fuel may exhibit a different spray development and atomization level which will influence in-cylinder mixing process, combustion and emission formation [25]. For example, an extra penetration can cause cylinder wall/piston bowl wetting which will increase particulate matter, unburned hydrocarbon and carbon monoxide emission. Experiments on engines can measure combustion relevant parameters, but it fails to quantify atomization and in-depth spray visualization.

In order to relate internal variables, like atomization and spray development, detailed non-vaporizing spray experiments have been carried out in this study to demonstrate the spray morphology of neat gasoline and (GB blends). According to authors, there is not enough detail result on spray development and atomization of GB blends. To demonstrate the injection pressure on low load, spray and atomization characteristics were determined from the spatio-temporal spray images and dimensional analysis. The authors firmly believe that these experimental results will contribute to the future applicability of GB blends in low load gasoline compression ignition and high-fidelity spray simulation.

2. Experimental system and test conditions

2.1. High pressure chamber

Fig. 1 represents a pictorial layout and exploded view of the constant volume chamber (CVC). The cylindrical structure of the CVC contains a length of 335 mm and diameter of 300 mm. In the middle of the cylindrical chamber, a cube-shaped combustion chamber is formed with a characteristics dimension of 105 mm. The optically visible length is approximately 100 mm, which satisfies the requirement for a full spray development. The CVC is a stainless steel (SUS304) vessel that protects against corrosion and oxidation and is suited for extreme conditions like high pressure and temperature. Six sides of the CVC are reconfigurable where four sides are assembled with a solid jig and the remaining two sides have an optical access through a quartz window with a thickness of 50 mm. All the solid and optical sides were assembled with a PTFE-type O-ring using 65 ft-lb of torque. The piezoelectric fuel injector was mounted horizontally in the center of the solid side. A total of eight heater cartridges were installed axially in the chamber body to maintain an accurate ambient temperature of 473 K. Based on previous studies [26,27] the constant volume chamber was improved by several factors to achieve better repeatability during the experiments. The intake and exhaust gas lines were fitted in the CVC using pneumatically actuated ball valves with a combination of check valves and safety valves. An appropriate leakage-free environment was created inside the chamber before performing each experiment. The gas filling procedure was executed through an in-house proportional–integral–derivative (PID) control loop via LabVIEW program. A direct acting solenoid control valve (Burkert type 2875 and control electronics Burkert type 8605) and a piezoresistive type static pressure sensor (Type 4045A50) were installed in the nitrogen gas filling line. A National Instruments (NI) computer (model NI PXI-8106) with a multifunction DAQ (model NI PXI-6251) and a reconfigurable I/O (cRIO 9151) was used for preparing the gas filling program with a combination of NI modules 9237 and 9238. Based on a user-defined partial pressure setpoint, the desired amount of nitrogen gas enters into the chamber for a targeted ambient gas density. This automatically controlled gas filling program will likely give more stable test conditions during the experiment. Two pneumatically actuated double-acting rack and pinion type ball valves (DOW valve type RP-040SD) were installed in the intake and exhaust line to clean the experimental facility after each set of experiments to retain the initial conditions. A single-hole research grade fuel injector manufactured by Bosch was used in this study. A diagram of the nozzle geometry is inserted in the subsection in Fig. 1(c). The rail pressure was monitored and controlled using a