Fuel 190 (2017) 113–128

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Characteristics of spray from a GDI fuel injector for naphtha and surrogate fuels

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HIGHLIGHTS

- Spray from a GDI piezoelectric fuel injector was tested.
- Macroscopic and microscopic features were measured for naphtha fuels and their surrogates.
- Naphtha fuels and their surrogates show similar macroscopic characteristics.
- Complicated features were observed for droplet size and size distribution depending on fuels and measuring locations.

ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form 31 October 2016
Accepted 2 November 2016
Available online 18 November 2016

Keywords:
Gasoline direct injection (GDI)
Naphtha
Surrogate
Spray penetration
Spray angle
Particle size distribution

ABSTRACT

Characterization of the spray angle, penetration, and droplet size distribution is important to analyze the spray and atomization quality. In this paper, the spray structure development and atomization characterization of two naphtha fuels, namely light naphtha (LN) and whole naphtha (WN) and two reference fuel surrogates, i.e. toluene primary reference fuel (TPRF) and primary reference fuel (PRF) were investigated using a gasoline direct injection (GDI) fuel injector. The experimental setup included a fuel injection system, a high-speed imaging system, and a droplet size measurement system. Spray images were taken by using a high-speed camera for spray angle and penetration analysis. Sauter mean diameter, Dv(10), Dv(50), Dv(90), and particle size distribution were measured using a laser diffraction technique. Results show that the injection process is very consistent for different runs and the time averaged spray angles during the measuring period are 103.45°, 102.84°, 102.46° and 107.61° for LN, WN, TPRF and PRF, respectively. The spray front remains relatively flat during the early stage of the fuel injection process. The peak penetration velocities are 80 m/s, 75 m/s, 75 m/s and 79 m/s for LN, WN, TPRF and PRF, respectively. Then velocities decrease until the end of the injection and stay relatively stable. The transient particle size and the time-averaged particle size were also analyzed and discussed. The concentration weighted average value generally shows higher values than the arithmetic average results. The average data for WN is usually the second smallest except for Dv90, of which WN is the biggest. Generally the arithmetic average particle sizes of PRF are usually the smallest, and the sizes does not change much with the measuring locations. For droplet size distribution results, LN and WN show bimodal distributions for all the locations while TPRF and PRF shows both bimodal and single peak distribution patterns. The results imply that droplet size distribution is skewed to the larger side for locations close the axis and is skewed to the smaller side for distance away from the axis.

1. Introduction

Liquid fuels, with the advantages of high energy density and easy transportability, have been playing an irreplaceable role in industrial and commercial applications. More than 90% of the global transportation energy demand is currently expected to be supplied by the petroleum-based liquid fuels such as gasoline, diesel, jet and heavy fuel oil fuels [1]. However, petroleum, the most important source for liquid fuels, is estimated to be in shortage in the near future. Total world proved oil reserves reached 1697.6 billion barrels by the end of 2015, which is only sufficient to cover 50.73 years of current global oil production rate [2]. In addition, the utilization of fossil liquid fuels in internal combustion

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http://dx.doi.org/10.1016/j.fuel.2016.11.015

(IC) engines generates pollutant emissions, including carbon monoxide (CO), unburned hydrocarbon (UHC), sulfur dioxide (SO_2), nitrogen oxides (NOx), particulate matter (PM), and greenhouse gases (i.e., CO_2). Due to the fact that the majority of greenhouse gas emission is related to combustion of fossil fuels [3], understanding and optimizing the combustion process in IC engines is important to achieve better efficiency, reduce fuel consumption and pollutant emissions.

Liquid fuel atomization is critical to combustion and emissions in diesel and direct injection gasoline engines. Characterization of the spray angle, penetration, and droplet size distribution is important to analyze the spray and atomization quality of fuel injectors. Studies of the fuel spray behavior can be on either macroscopic or microscopic scales. Macroscopic parameters, such as spray penetration length and spray cone angle, can be measured by direct visualization methods, usually with a high-speed camera. Microscopic parameters such as droplet velocity, droplet size and size distribution can be measured through particle image velocimetry (PIV), phase Doppler particle analyzer (PDPA) or laser diffraction particle analyzer (LDPA) systems [4]. Lee and Park [5] conducted spray visualization and PDPA experiments to study the spray characteristics of a group-hole nozzle and compared them with the characteristics of a single-hole nozzle as reference. Yokoi et al. [6] investigated the effect of fuel injection pressure (200–800 bar) on atomization and combustion characteristics and found that spray tip penetration and spray width increased, while the Sauter mean diameter (SMD) of droplets decreased with an increase in the fuel injection pressure. Many spray modeling studies are also available in literature for different injectors. One of particular interest to the current work is the recent study of Sim et al. [7], where they modeled the outwardly opening hollow cone injection which is similar to the one investigated here.

Gasoline direct injection (GDI), as an emerging technology, has been considered to have the potential to satisfy the stringent emission requirements and becomes more popular in recent spark-ignition (SI) engines. The major advantages of a GDI engine are its increased fuel efficiency and high power output. It was reported that the fuel efficiency or miles per gallon (MPG) of vehicles driven by GDI engines is about 5–10% higher than those using port-fuel injection (PFI) engines, which means less greenhouse gas emissions [8,9]. Zhu et al. [10] compared tailpipe emissions from gasoline direct injection (GDI) and port fuel injection (PFI) vehicles at both low and high ambient temperatures. The results suggested that the gaseous and particulate emissions from the PFI vehicles are higher compared to those from the GDI vehicles especially in a cold environment. The cited gains were achieved by precisely controlling the fuel amount and injection timings according to engine operating loads. Though there are several aspects of GDI engines that need to be further studied and optimized [11], such as carbon build up and particulate emissions, it is still a promising option for future engines.

Another promising engine technology for higher efficiencies and lower emissions by achieving low temperature combustion (LTC) conditions [12] has recently attracted significant attention and is termed gasoline compression ignition (GCI). Recent studies [13–16] reported that GCI combustion occurs as a series of auto-ignition events with minor contributions from flame fronts. The auto-ignition timing is controlled by manipulating the mixture composition and temperature stratification within the cylinder through late injection in the compression stroke, in contrast to homogeneous charge compression ignition (HCCI) [17–20] and premixed combustion [21,22] engines where the fuel and air are fully mixed in the combustion chamber.

In order to facilitate the study of spray and combustion of fuels, reference fuels were often introduced. Edgar [23] first proposed using *n*-heptane and isooctane as reference fuels to measure the knocking characteristics of gasoline, resulting in the octane number. Since then, scientists have tried to use different combinations of fuels as a reference fuel to represent complex liquid fuels. Sturgis et al. [24] used di-isobutylene and benzene to represent the olefins and aromatics, respectively, for antiknock studies of gasoline-like hydrocarbon mixtures. Because of the wide applications in engine study, the demand for surrogates to better represent real fuels is significant. Conventionally, gasoline is represented using a binary mixture, called the primary reference fuels (PRFs): *n*-heptane and isooctane, which represent straight and branched alkanes, respectively [25]. Studies have been done based on PRF [25–27]. More complex surrogates are needed to represent the reactivity of high-sensitivity fuels. Recently, adding an additional component such as toluene, a representative of aromatics, have been considered a better approach to match the reactivity of gasoline [28–31]. This resulting mixture is called three-component toluene reference fuels (TRFs), and some recent work has been done using this surrogate [32–34].

In addition, petroleum naphtha with a low octane number and a high volatility has attracted much research interest [34–38]. Naphtha, mainly comprised of shorter chain hydrocarbons (c5–c7), is a petroleum solvent similar to mineral spirits but with a greater volatility. It may contain sulfuric compounds or other impurities. Naphtha is the least processed product during the refining process and the cost required to produce naphtha is lower than that of gasoline. Light naphtha with a low octane number could be used for low-temperature compression-ignition (CI) or gasoline compression ignition (GCI) engines. The group in Saudi Aramco

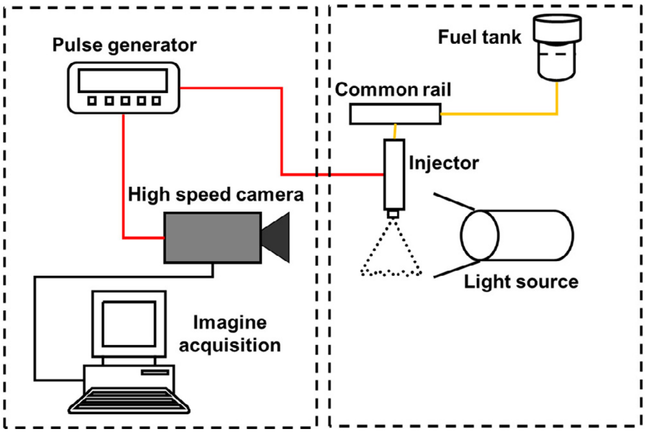

Fig. 1. High speed imaging system and fuel injection system.

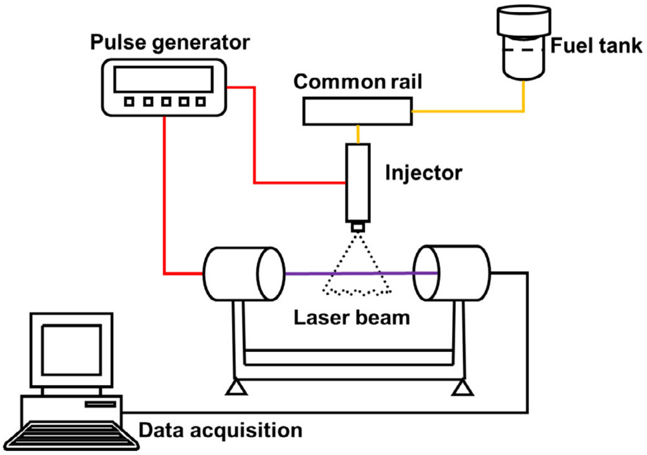

Fig. 2. Droplet size measurement system.