Fuel 219 (2018) 467–476

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Microscopic behavior of spray droplets under flat-wall impinging condition

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ARTICLE INFO

Keywords:
Fuel spray
Wall impingement
Gasoline engine
Microscopic characteristics
Droplet size distribution

ABSTRACT

The impingement of fuel spray on the wall in direct-injection spark-ignition (DISI) engines affects the fuel-air mixture formation, combustion and exhaust emissions. A detailed understanding of the fuel spray and impingement is required to reduce the undesirable products of combustion whilst maintaining good fuel economy. In this study, the droplet size was measured by particle image analysis (PIA). The microscopic characteristics of impinging spray were obtained using ultra-high-speed imaging. By changing the injection and ambient pressures, the influences of breakup and coalescence on the droplet behavior were investigated. Before impingement, the region near the center of the spray has larger droplets size and lower droplet number density than the edge, which suggests that spray breakup and atomization is poor in the center region. After impingement, the droplet size decreases along the distance from the wall under low ambient pressure. However, large droplets appear in the region far from the wall under high ambient pressure, indicating the existence of a coalescence effect on the droplets.

1. Introduction

Gasoline direct injection (GDI) is very attractive for fuel economy and performance improvements in spark ignition (SI) engines [1]. GDI offers the possibility of multi-mode operation, homogeneous and stratified charges, with benefits respect to conventional SI engines owing to higher compression ratio, zero pumping losses, control of the ignition process at very lean air-fuel mixtures, and good cold starting [2,3]. However, it is difficult to avoid the impingement of liquid fuel on the piston and cylinder surfaces. The wall film caused by impingement affects the air-fuel mixture formation process, which is a possible source of unburned hydrocarbons (UHC) and particulate matters (PM), making it difficult for DISI engines to meet the future requirement of particle number (PN) regulations [4–6]. In particular, with the decrease in the fuel supply and the significant increase in the fuel demand, governmental regulations regarding automobile emissions globally have tightened considerably over the past 20 years [7–9].

It is well known that the microscopic characteristics of fuel spray are very important for atomization and mixture formation. The droplet size and number distributions reveal the quality of spray and atomization, which affect the subsequent combustion and emissions characteristics [10]. Comprehensive experimental investigations have been carried out to deeper understand the microscopic spray characteristics. Both Payri et al. [11] and Lacoste et al. [12] discussed the shear force and coalescence behavior of droplets in diesel free spray. Manin et al. [13] reported direct observations of the liquid structures or droplets in the near-nozzle region of a single-hole injector. Their observations showed that the surface tension of high-grade n-dodecane fuel was evident when fuel was injected into a low-ambient pressure condition, whereas the surface tension decreased significantly under higher ambient-pressure condition as fuel ligaments and droplets breakup. Lee et al. [14] focused on the spray breakup and atomization processes of GDI injectors. Their results showed that an increase in injection pressure led to a decrease in Sauter mean diameter (SMD, also known as D_{32}), but there is a limitation on droplet breakup up to 20 MPa. Guan et al. [10] examined the effect of different fuels on the microscopic spray characteristic during free spray. They reported that lower viscosity and surface tension improved the spray characteristics by comparisons of droplet number density and droplets size distribution. Wang et al. [15] investigated the microscopic characteristics of split injection spray, and their results showed that higher injection pressure led to better dispersion and atomization. Moreover, the strong collision between split injection caused larger droplets than those obtained with single injection. Feng et al. [16] experimentally studied the spray and atomization characteristics of fuels blends in common rail injection system. They found that the droplet size decreased as gasoline blending ratio increased in diesel fuel, indicating that the spray atomization was promoted. Guo et al. [17] visualized the gasoline microscopic spray under

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https://doi.org/10.1016/j.fuel.2018.01.059
Received 13 November 2017; Received in revised form 9 January 2018; Accepted 16 January 2018

idle and wide-open throttle conditions in GDI engine. It was revealed that the SMD decreased on increasing the fuel temperature from 20 to 60 °C, and the reduction in viscosity and surface tension should be the main reasons for that. Liu et al. [18] reported on the droplet characteristics of gasoline spray under high-temperature (up to 376 °C). They found that the droplet size dropped significantly when the fuel temperature approximated the critical point (278 °C), and that large droplets disappeared when the temperature exceeded 173 °C.

A series of studies have been extensively conducted in terms of free spray processes under different pressures, temperatures and test fuels. However, wall-impingement behavior has not been sufficiently studied. After impingement, the fuel spray velocity changes significantly, and the energy interaction between the fuel and air becomes more violent, resulting in the mechanism of spray and atomization becoming more complicated, especially under high ambient and injection pressures. Therefore, more researches are required to clarify the mechanism of wall-impinging spray. Papers in the current literature mainly focus on experimental work, although a few numerical works have also been conducted. Allocca et al. [19] described the spatial and temporal evolution of liquid and vapor phases on a heated wall of GDI spray to investigate the structure of spray–wall interaction. Montanaro et al. [20] studied the spray-wall impact of both GDI multi-hole spray and a single-hole spray over a cold and hot wall to evaluate the droplet behavior after impingement. Piazzullo et al. [21] investigated the heat transfer effect on wall–film formation in GDI spray, and a good agreement was obtained between the experimental and numerical results. Zhao et al. [22] studied the spray morphology before and after impingement of diesel spray, and showed that the larger droplets tend to contribute to the fuel film formation more than the smaller ones. The effects of different injection pressures, ambient pressures, impingement distances and wall roughness on fuel film formation have been reported in our previous papers [23–25].

However, the microscopic characteristics of wall-impingement behavior have seldom been reported. The aim of this work is to improve the understanding of the spray–wall interactions under various engine-like conditions. In this paper, the wall-impinging spray behavior is reported in terms of its microscopic characteristics. First, the spray structures before and after impingement are investigated. Next, the droplet size distributions under different conditions are examined. Additionally, the spatial distribution of droplet number and size are compared. Finally, the effects of ambient pressure on droplet breakup and coalescence behaviors are discussed in detail.

2. Experimental setup

The experimental conditions are listed in Table 1. Two injection pressures of 10 and 20 MPa, and two ambient pressures of 0.1 and 0.5 MPa, equivalent to the ambient gas densities of 1.19 and 5.95 kg/m^3, were investigated. This experiment was conducted in a constant-volume chamber filled with nitrogen gas at room temperature. A mini-sac injector with a nozzle hole diameter of 0.135 mm was used. The nozzle was a conventional straight-hole type without a counterbore. The length-to-diameter (L/D) ratio was 4.8. Toluene was employed as a surrogate fuel for gasoline. The injection mass was kept constant at 3.0 mg under different conditions, resulting in different injection durations of 2.4 and 1.65 ms at different injection pressures. The impingement angle was 45° and the impingement distance was 22 mm from the nozzle exit to the impingement point of the flat wall along the spray axis. The flat wall was made of quartz glass (Sigma Koki, DFSQ1-50CO2) with a surface roughness Ra (arithmetical mean deviation of the profile) of 7.7 μm. Moreover, the surface roughness was measured by a portable high-performance surface roughness and waviness measuring instrument (Kosaka Laboratory Ltd., SE300) with a resolution of 0.0064 μm.

Table 1
Experimental conditions.

Injector Conditions	
Injector Type	Mini-Sac, Single-Hole
Hole Type	Straight-Hole without Counterbore
L/D Ratio	4.8
Nozzle Hole Diameter (*d*)	0.135 mm
Injection Conditions	
Fuel	Toluene
Injection Mass (M_{inj})	3.0 mg
Injection Pressure (P_{inj})	10, 20 MPa
Injection Duration (t_d)	2.4, 1.65 ms
Ambient Conditions	
Ambient Gas	Nitrogen
Ambient Pressure (P_{amb})	0.1, 0.5 MPa
Ambient Temperature (T_{amb})	300 K
Ambient Density (ρ_{amb})	1.19, 5.95 kg/m^3
Impingement Conditions	
Impingement Plate	Quartz Glass
Impingement Distance (L_w)	22 mm
Impingement Angle (θ_{imp})	45°
Surface Roughness (Ra)	7.7 μm

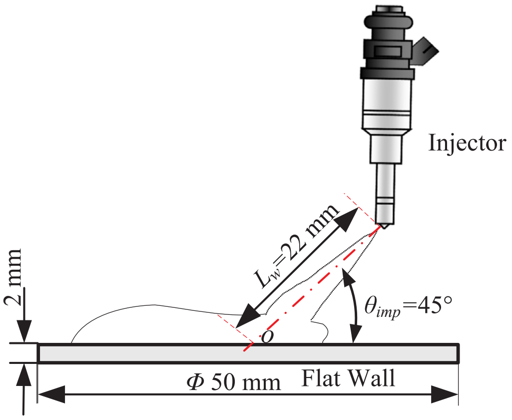

Fig. 1. Schematic of injector and flat wall.

As shown in Fig. 1, the impingement plate with a diameter of 50 mm and a thickness of 2 mm, was set under the injector. The intersection point *o* of the nozzle center axis and the wall was defined as the impingement point. Previously, both Berg et al. [26] and Kashdan et al. [27] certified that particle image analysis (PIA) was a reliable technique to measure the size of spherical and non-spherical droplets. Hence the PIA system was employed to investigate the microscopic spray characteristics. The experimental equipment is shown in Fig. 2. It consisted of a constant-volume chamber, an injection system, and an optical system. Toluene fuel was directed into the mini-sac injector by a high-pressure injection system. An Nd: YAG laser with a wavelength of 532 nm was used as the light source. The energy of the laser pulse was in the order of 10 mJ, and a duration of approximate 6 ns. The light beam was expanded from 8 to 100 mm to provide homogeneous illumination over a sufficiently large area. A charge-coupled device (CCD) camera (Flowtech Research Inc., FtrNPC) with a long-distance microscope was employed to visualize the spray structure. As shown in Fig. 2, two teleconverters (Kenko Tokina, N-AF 1.4X TELEPLUS MC4) were connected with the CCD camera by a bellows to enlarge the spray image. The camera location was collinear with the laser axis. The image was captured at 1200 μs and 900 μs after the start of injection under P_{inj} = 10 and 20 MPa, respectively, when the spray showed the quasi-steady state period. Guan et al. [10] and Feng et al. [16] selected similar periods for image taking in their work. The resolution was approximately 2.008 μm per pixel, and the frame size was 1600 × 1200 pixels.

The measurement regions and coordinate system are shown in Fig. 3. The field of view is 3.2 × 2.4 mm^2. The exit of the nozzle was