Fuel 235 (2019) 782–794

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Experimental study on the spray characteristics of an air-assisted fuel injection system using kerosene and gasoline

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ARTICLE INFO

Keywords:
A2FI
Spray characteristics
Working parameters
Kerosene
Gasoline

ABSTRACT

Spray characteristics play a key role in affecting combustion performance of piston aero engines. In this study, spray characteristics of two types of fuel, kerosene and gasoline, were investigated with an air-assisted fuel injection (A2FI) system under different working parameters, which included air and fuel injection duration, fuel-air interval, ambient pressure, fuel pressure and fuel temperature. The macroscopic spray characteristics were observed by high speed imaging technique. The main difference is that the elevated ambient pressure or depressed fuel pressure reduces the spray angle of kerosene while the gasoline's spray angle is basically constant. It is attributed to the joint effects of air disturbance and compressed air expansion. Phase doppler particle analyzer (PDPA) was utilized to study the microcosmic spray characteristics. It indicates that the droplet size is significantly influenced by air and fuel injection duration, ambient and fuel pressure and fuel temperature. The droplet velocity increases when ambient pressure decreases or fuel pressure rises, which can explain the performance of macroscopic spray characteristics accordingly. There exist evident differences as well as similarities on spray characteristics between kerosene and gasoline with A2FI system. The study is beneficial for combustion chamber optimization and fuel matching.

1. Introduction

Spark ignition engines are widely used on piston aero engines for it's high power to weight ratio [1–3]. Gasoline is the main fuel used for these engines. Recently, piston aero engines for small general aviation aircrafts are currently facing a transition from being powered by aviation gasoline (AVGAS) to being powered by heavy fuels (diesel or kerosene) considering the high volatility, low viscosity and storage/transportation problems of gasoline [4–6]. However, general injection scheme like carburetor and port fuel injection (PFI) is tough to form ideal kerosene droplet size, which influences the spray quality dramatically. A series of studies have been conducted in order to elevate the kerosene atomization quality [7–9].

A2FI system is recognized as an effective way to improve atomization quality and achieve higher efficiency and cleaner combustion of engines [10,11]. In the process of work, the fuel is injected into a premixed chamber filled with compressed air, then the mixture of fuel and air is directly injected into the combustion chamber by an air injector. The sauter mean diameter (SMD) of the fuel spray can even reach approximately 5 µm, meanwhile the low pressure of A2FI system (often fuel injection pressure is 0.8 MPa) needs low costs and ensures the security [12–14]. However, the thermal conditions inside the combustion chamber are complicated. The absolute ambient pressure varies from 0.02 to 0.5 Mbar, and can be even higher in turbo-charged engines, while the fuel temperature varies from below 0 °C at cold-start conditions to 150 °C at high loads [15,16]. What's more, under different working conditions, working parameters like fuel and air injection duration vary a lot. Therefore, it is essential to acquire a thorough understanding on A2FI system with kerosene and gasoline under different conditions in consideration of either the potentiality to improve atomization quality or the frequent appearance in engine working process.

Boretti et al. [17] investigated the transient behavior of the fuel spray from an air assisted fuel injector numerically and experimentally in a constant volume chamber and an optical engine, and found a good atomization of the spray with the SMD of droplets of order 10 µm. C Jang et al. [18] investigated the spray characteristics of an intermittent A2FI system for a four-stroke gasoline direct injection engine, and found that droplet size varied from 9 to 30 um throughout all experimental conditions. The most influential factor to the fuel spray SMD is fuel injection pressure, followed by fuel viscosity [19,20].

The spray characteristics with A2FI system vary a lot under different conditions. S H Jin et al. [21,22] found that the characteristics of the injector varied weakly with several particular injection parameters,

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https://doi.org/10.1016/j.fuel.2018.08.083
Received 14 June 2018; Received in revised form 11 August 2018; Accepted 20 August 2018
0016-2361/ © 2018 Published by Elsevier Ltd.

notably the fuel-air interval, and the effect of the ambient pressure on the spray penetration of the air-assisted fuel injector was determined. What's more, they conducted the experimental study using laser induced fluorescence (LIF), which could capture the transient characteristics of the spray injected by air-assisted system. They found that spray penetration was significantly influenced by the injection pressure and chamber backpressure. Diwakar et al. [23] performed the experiment of liquid and vapor fuel distributions from an air-assisted injector. They analyzed and found that spray cone was strongly dependent on flow field near the nozzle outlet. Macinnes et al. [24] studied the transient spray characteristics of an air-assisted injector. They concluded that spray width and penetration have a close connection with the structural design. Longfei Chen et al. [25–27] studied the collapse mechanism, cavitation formation and primary breakup of the fuel, they found that high injection pressure could effectively improve the dispersion quality, and the fine droplets detached rapidly from the main spray. The spray angle at the near nozzle was almost linearly increasing at the initial breakup stage with the increase of fuel injection pressure.

However, the characteristics comparison between kerosene and gasoline with A2FI system is studied less. Thus, the main objective of the study is to clarify the effect of different conditions on the spray characteristics of kerosene and gasoline. In this work, experiments on spray development under different ambient pressure and fuel temperature have been performed, which would be desirable to obtain and analyze the similarities and differences between kerosene and gasoline, and it is beneficial for combustion chamber optimization and fuel matching. What's more, the comparison of different fuel injection pressure, air injection duration and fuel-interval helps us to optimize the existing system, find the optimal parameter configuration. The PDPA measurements and camera imaging tests of gasoline and kerosene injection are main experiment contents, by which macroscopic and microcosmic spray characteristics are obtained.

2. Methodology

A test bench was built based on a constant volume vessel. An electronic controlled A2FI system was installed in the bench. By utilizing the high speed imaging technique and PDPA, the spray characteristics can be recorded under different conditions. This chapter mainly includes experimental setup, test conditions, and uncertainty analysis of experiment.

2.1. Experimental setup

The schematic diagram of the test bench is illustrated as Fig. 1. The experiments were performed in a constant volume vessel with an air-assisted injector mounted on the top and two observation windows at the side.

The cross angle between the two quartz windows was deliberately designed as 110° to obtain the best signal-to-noise ratio for the PDPA. During the experiment, the ambient gas flowed continuously through the vessel in order to clean out the residual droplets from the prior injection. This was done to avert the stain of windows and the disturbance of scattered light on the experiment results. The air flow velocity inside the vessel was between 1 and 3 m/s so that the influence on the spray could be neglected, and the ambient pressure inside the vessel could be maintained constant.

The A2FI system consisted of a fuel injector, an air injector and an installation block was shown in Fig. 2(a). During the experiment, fuel was firstly injected into the mixing chamber and then the mixture of fuel and air was injected from the air injector. Fig. 2(b) shows the sequential driving signal produced by electronic control unit (ECU), which will form "peak-hold" current in injectors. T1 and T4 are the "peak" signal of fuel injector and air injector respectively. Otherwise, T2 and T5 are the fuel injection duration and air injection duration respectively. T3 is the fuel-air interval. The fuel and air injection pressures are respectively controlled at 0.8 MPa and 0.7 MPa by adjusting pressure regulators, the pressure difference of fuel and air is fixed at 0.1 MPa. The fuel injector is an ordinary hole injector and air injector is an axial needle injector with a toroidal hole. The geometric model of air injector tip is shown in Fig. 3(a), and (b) has shown the spatial measurement positions of droplet size and velocity. The injector axis and radial axis for target jet have been drawn and the target jet is perpendicular with the imaging direction and incident lights from PDPA. The injector axial distances from the nozzle (30, 40, 50, 60, 70, 80, and 100 mm) and radial distances at the injector axis of 50 mm (in a step of 2 mm) have been marked with red circles, which represent the measurement positions.

The fuel droplet size and velocity were simultaneously measured by a set of PDPA. As for macroscopic spray characteristics, a LED light was used to illuminate the spray from the other side of the vessel, and a high speed camera (SA4, Photron) was utilized to visualize the macroscopic spray characteristics by capturing the spray images with a speed of 10,000 frame/s.

In order to get reliable data of spray, 1000 times of injection were controlled by ECU under different parameters every time.

2.2. Test conditions

The experiment conditions are listed in Table 1. The ambient pressure ranges from 0.05 MPa to 0.3 MPa. The fuel and air injection duration, fuel-air interval are controlled by ECU, and the range of value is showed in Table 1. The fuel temperature is achieved by the water jacket around the injector. The reference conditions are listed in Table 2, whose air injection duration is 1 ms, fuel injection duration is 4 ms, fuel-air interval is 0.5 ms, fuel pressure is 0.8 MPa, ambient pressure is 0.1Mpa and fuel temperature is 20 °C. The fuel properties are shown in Table 3.

2.3. Uncertainty analysis of the experiment

Droplet size and droplet velocity were directly calculated by PDPA. However, in order to analyze the macroscopic spray characteristics, the procedure for image processing was specially developed in MATLAB environment, which is displayed in Fig. 4. The penetration and spray angle are explained in Section 3.1.

The measurements obtained with MATLAB were evaluated with the uncertainty analysis [28]. The average of the measurement ($\overline{X}$) is

$$\overline{X} = \frac{\sum X_m}{n} \quad (1)$$

where n is the number of measurements andX_m is the measurement. Standard deviation (SD) is

$$SD = \sqrt{\frac{\sum_{m-1}^{n}(X_m - \overline{X})^2}{(n-1)}} \quad (2)$$

Uncertainty (U) was given in Eq. (3)

$$U = \pm\frac{SD}{\sqrt{n}} \quad (3)$$

The uncertainties of the kerosene measurements were given in Table 4. According to the findings of the uncertainty analysis, it was determined that the obtained results of the measurements were acceptable for the A2FI system. The uncertainties of gasoline measurements were similar and the results were acceptable too.

3. Results and discussion

The spray characteristics performance can be classified into macroscopic and microcosmic spray characteristics. The macroscopic spray characteristics include spray penetration and spray angle. The

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