Fuel 236 (2019) 1–12

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Experimental investigation on GDI spray behavior of isooctane and alcohols at elevated pressure and temperature conditions

Rakesh Kale, R. Banerjee*

Department of Mechanical & Aerospace Engineering, Indian Institute of Technology Hyderabad, Kandi, Sangareddy, Telangana 502285, India

ARTICLE INFO

Keywords:
Liquid penetration
Vapour penetration
GDI
Alcohols
PDPA

ABSTRACT

In this study macroscopic spray characteristics and droplet size distribution were measured for spray emanating from a six-hole solenoid GDI fuel injector. Three test fuels namely Isooctane, ethanol and n-butanol were used in this study. Macroscopic spray characterization was performed using Mie scattering and Schlieren Shadowgraph technique along with high speed videography. Liquid and vapor penetration length and along with the liquid/vapor spray cone angle was determined using these techniques. Phase Doppler Particle Analyzer (PDPA) was used to determine droplet size distribution. Results showed that thermo-physical properties such as saturation temperature, latent heat of vaporization, surface tension, density and viscosity of a fuel play a very important role in the spray plume penetration. Isooctane showed the least penetration lengths for all pressure and temperature conditions that were evaluated in this study, whereas butanol showed the highest penetration length. Due to the higher values surface tension, viscosity and latent heat of evaporation, alcohol sprays consisted of droplets of larger diameter.

1. Introduction

Global energy demand is rising significantly and expected to continue so in the coming decades. Since transportation is one of the most important aspects of modern society, automotive sector has become one of the largest consumers of fossil fuel. This is leading us to the twin problems of fast depletion of fossil fuel and environmental degradation. Considering these issues, the development of advanced engine technology plays a very crucial role.

In the last one decade, Gasoline Direct Injection (GDI) has attracted significant interest as an alternative Spark ignition (SI) engine technology. It has many advantages over conventional Port Fuel Injection (PFI) engine, such as higher thermal efficiency due to higher compression ratio, higher volumetric efficiency and greater power output etc. [1]. In addition, stratified charge operation is not possible without the direct injection (DI) of a fuel. During stratified mode of operation, fuel is injected in the vicinity of a spark plug when the piston is under compression stroke [2,3]. This Stratified mode of operation is also referred as a late injection strategy. On the other hand during homogeneous mode of fuel injection, or early injection strategy, fuel is injected during the suction stroke. These two modes of operation have entirely different in-cylinder thermodynamics. For the stratified case, fuel spray is subjected to high pressure and temperature conditions due to compression of the incylinder air, whereas during homogeneous mode, fuel injection occurs at near ambient pressures and temperatures. Such a varying in-cylinder gas condition greatly affects the fuel spray characteristics [4]. As the overall engine performance of the engine is strongly dependent on the fuel spray and air-fuel mixture preparation, therefore precise knowledge of the spray behavior plays a very important role in the successful engine performance.

Flash boiling occurs in the GDI engines when it is operated under homogeneous charge mode. Flash boiling is defined as sudden phase change of a fluid from liquid phase to vapor phase. Heat from the engine, increases the fuel temperature inside the injector. When this heated fuel is injected into the sub-saturation pressure condition; vapor bubbles are formed inside the liquid. These vapor bubbles expands during the decompression process upon the nozzle exit. Explosion of the vapor bubbles result in sudden evaporation and catastrophic disintegration of the liquid jet. Therefore spray emanating from the nozzle results in finer atomization and improved evaporation effect [5]. Aleiferis and Romunde [6] performed series of experiments on isooctane, gasoline and other alcohols (ethanol and butanol) at different injector body temperature for 1 and 0.5 bar ambient pressure. It was reported that, at lower temperature all the test fuels showed similar nature, but spray collapse was observed at the higher injector body temperature. Spray collapse due to the flash boiling, reduces the overall droplet size

---

* Corresponding author.
E-mail address: rajabanerjee@iith.ac.in (R. Banerjee).

https://doi.org/10.1016/j.fuel.2018.08.153
Received 5 April 2018; Received in revised form 12 July 2018; Accepted 30 August 2018

compared to the non-flashing condition. Similar experiments were also performed by Chan et al. [7] in an optically accessed spark ignition DI engine. Macroscopic spray parameter such as liquid penetration length was observed to be higher for the flash boiling condition than the non-flashing condition. Similarly, the overall plume area under flashing condition was found to be higher than non-flashing condition.

In case of late injection or the stratified regimes of GDI engine operation, high temperature and pressure of the in-cylinder ambient gases affect the macroscopic spray structure. Reduction in the liquid penetration of the fuel is attributed to the increased drag force due to higher ambient density and the higher evaporation due to higher sensible heating of the liquid droplets [8]. It was also reported that ethanol sprays showed higher drop size compared to the isooctane and gasoline [9]. This was mainly due to the greater evaporation of isooctane and gasoline at higher temperature, but in case of ethanol this evaporation of the droplets was actually suppressed due to its large latent heat of evaporation.

Countries such as Brazil and the United States of America have replaced large percentage of gasoline by the ethanol blended fuel [10]. E85 (blend up to 85% ethanol and 15% gasoline) compatible vehicles are commonly available in the USA, whereas flex fuel vehicles are common in Brazil. Thermo physical properties of a fuel play a major role in the designing of the new generation SI engines. For an effective operation of the stratified engine, it is desirable to have the precise control over fuel metering and the timing of fuel injection process. Fuel stratification largely depends upon incylinder aerodynamics, piston geometry and the thermo-physical properties of a fuel. If the charge motion and the piston geometry are considered to be invariant, then choosing different fuel will result in significant variation in the engine performance and emissions. Compact spray structure is always favorable because it avoids the problem of the wall wetting, which may eventually lead to excess un-burnt hydrocarbon emission [11], however, it also restricts the air entrainment and can affect the mixture quality.

Significant amount of research is going on in the field of bio-fuels and their effect on internal combustion engines. Therefore it is of prime importance to study the spray characteristics of alcohols under engine like evaporating spray conditions. Series of publications can be found discussing gasoline and alcohol spray behavior under normal atmospheric conditions [12–14]. However the spray behavior under evaporating conditions may be entirely different. Additionally, different thermo-physical properties of alcohol fuels are expected to show some interesting observations. Furthermore, this kind of experimental data can be very useful for the CFD model validations. Therefore current work is focused on the spray characterization of the GDI injector using isooctane and two alcohols. The alcohol fuels used in this study are ethanol and n-butanol due to their increasing popularity as a renewable fuel for the SI engines. Although, homogeneous regime of engine operation is also important for the flash boiling spray studies, however current work is mainly focuses on understanding the spray behavior under the stratified mode of GDI engine operation. For comparison of these fuels, four macroscopic parameters i.e. vapor and liquid penetration lengths; and vapor and liquid spray cone angles are selected. Particle size data is obtained for some experimental conditions using Phase Doppler Particle Analyzer (PDPA).

2. Experimental setup and procedure

2.1. Constant volume combustion chamber

A constant volume combustion chamber was fabricated to create engine like elevated pressure and temperature conditions. Total internal volume of the chamber is approximately 2.5 L. It has four optical windows for the spray visualization. The transparent windows were made of Sapphire that are 20 mm thick and the optical diameter is about 60 mm. The fuel injector and the spark plug were located at the top wall of the cubical chamber. Pressure gauges were attached to the chamber to meter the required amount of reacting gases (acetylene and air) for pre-combustion. In order to measure the in-cylinder pressure history, a dynamic pressure transducer (BERU Germany) was attached at the top wall of the chamber. The historical data was then recorded using a high speed data acquisition system (HBM Germany, model no.-QuantumX MX410B). The time evolution of the spray was recorded using a high speed camera (Phantom v12.1) which was operated at a frame rate of 10,000 fps.

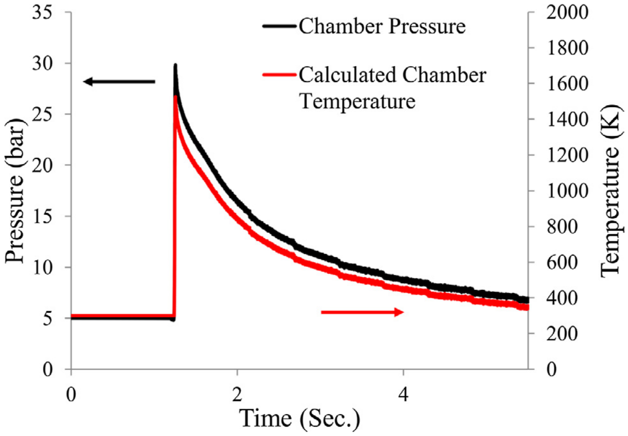

Fig. 1. Pressure and temperature history inside the chamber.

To start the experiment, the chamber was initially filled with a predefined amount of acetylene and air (Equivalence ratio ~1.3). The combustible mixture was then ignited with the spark plug which was placed inside the spray chamber. This helped to create a high temperature and pressure environment inside the chamber. As the products of combustion cool down due to heat transfer to the vessel walls, the pressure and temperature inside the spray chamber also decreases. When the desired experimental conditions were reached, the electronic control unit gave the signal to the fuel injector, which then injects the fuel inside the chamber. Typical pressure data inside the chamber is shown in Fig. 1.

2.2. Optical setup

Schlieren shadowgraph or focused shadowgraph technique was adopted to track the vapor phase of the spray and Mie scattering was used to track the liquid portion of the spray. The liquid and vapor lengths were determined separately by conducting two different set of experiments. Experimental setup for the Schlieren shadowgraph is as shown in Fig. 2. A High intensity white LED was used as a light source in this experiment. A 1 mm diameter iris was placed in front of the LED source such that the iris acted as a point light source. The diverged light from the point source was allowed to fall on a 160 mm diameter parabolic mirror (Edmond Optics, focal length 91 cm). Since the distance between the iris and the parabolic mirror was equal to the focal length, the reflected light from the parabolic mirror was a parallel beam of light. This parallel beam of light was again reflected by a plain mirror and allowed to pass through the transparent spray chamber wall. After passing through the chamber, light beam was then converged by the second parabolic mirror towards the high speed camera. Since the technique is very sensitive to the change in the density of the medium [15], it can easily capture the vapor phase of the fuel spray.

Fig. 3 shows the experimental setup for the Mie-scattering where a high intensity 532 nm (500 mW power) continuous laser was used to flood the entire combustion chamber. The laser beam was passed through a set of cylindrical lenses and a diffuser to create a diffused light beam. Scattered light from the spray plume was then captured by the high speed camera. In front of the camera lens, a 532 nm band pass