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Full Length Article

Effect of ambient fuel vapour concentration on the vapour penetration of evaporating n-hexane sprays

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ABSTRACT

Ambient gas properties like pressure, temperature, density etc. play an important role in spray evaporation and hence influence the spray properties like penetration, cone angle and liquid length. The concentration of fuel vapour in the ambient gas was seen to influence the liquid length in an earlier work by the present authors. A method was also reported to study spray parameters at constant pressure, temperature and density but at different fuel vapour concentration in the ambient. In the present paper, the vapour penetration of evaporating n-hexane sprays have been studied by means of a shadowgraph technique at different mass fraction of fuel vapour in the surrounding ambient gas. The results revealed that the ambient vapour concentration has an effect on vapour penetration and cone angle at low ambient densities. But, at higher densities, this effect is absent, although the liquid length is influenced even at higher densities.

1. Introduction

Liquid fuel injection is the primary source of fuel supply to a number of applications such as oil-fired boilers and furnaces, gas turbines and automotive engines. The injected liquid jets breakup into small droplets and as a result fuel surface area increases which leads to increase in vaporization, proper mixing with surrounding gas and efficient combustion. In case of direct injection engines (like diesel and gasoline direct injection), liquid fuels are injected into the combustion chamber. The pressure, temperature and density inside the chamber at the time of injection vary over a wide range. The spray development process significantly influences the air-fuel mixture inside the cylinder and as a result, controls the combustion and emission formation. So spray characteristic study at different ambient conditions and the effect of different ambient parameters on spray properties are of prime importance. Optically accessible test rigs like optical engines, rapid compression machines and high pressure high temperature constant volume chambers are developed worldwide for spray investigations. Spray tip penetration, spray cone angle, spray tip velocity etc. are considered as macroscopic parameters, whereas droplet size distribution, liquid-vapor distribution inside an evaporating spray etc. are considered as microscopic spray parameters [1,2]. Parameters like projected spray area and spray volume are also used for characterizing sprays [3]. In case of an evaporating spray, the liquid phase fuel penetrates up to a certain axial distance, and after that, the tip of the liquid region stops penetrating further and starts to fluctuate about a mean axial location, though the fuel injection and vapour phase penetration continues [4–6]. For an evaporating spray, penetration of the liquid region is known as liquid length (*LL*). It is defined as the distance from the nozzle to the maximum liquid phase fuel penetration inside an evaporating spray. Naber and Siebers [7] experimentally studied the effect of gas density and evaporation on spray penetration and spray cone angle in a constant volume spray chamber. The results revealed that the spray penetration decreased and cone angle increased with increasing ambient density. They also showed that evaporation reduced penetration and cone angle at lower density. However, this effect decreased with increase in ambient density. Huang et al. [8] studied spray characteristic of the ethanol-diesel blend at non-evaporating and evaporating conditions. Their results showed that evaporation had no effect on spray penetration, but increased the spray spreading angle and spray projected area. Presence of low boiling point fuel like ethanol in the fuel mixture might be a reason for this. Similar results were reported by Ma et al. [9], where cone angle at evaporative condition decreased for diesel but increased for a mixture of diesel and n-pentanol. Payri et al. [10] studied three different fuels in evaporating condition at three ambient densities (15.2, 22.8, and 30.4 kg/m^3), three different ambient temperatures (800, 900, and 970 K) and four different injection pressures (60, 90, 150, and 200 MPa). They found that at a fixed ambient density, the liquid penetration depends on ambient temperature while the vapour penetration does not. Again at constant ambient density, the vapour penetration depends on injection pressure while the liquid penetration does not. No significant difference in vapor

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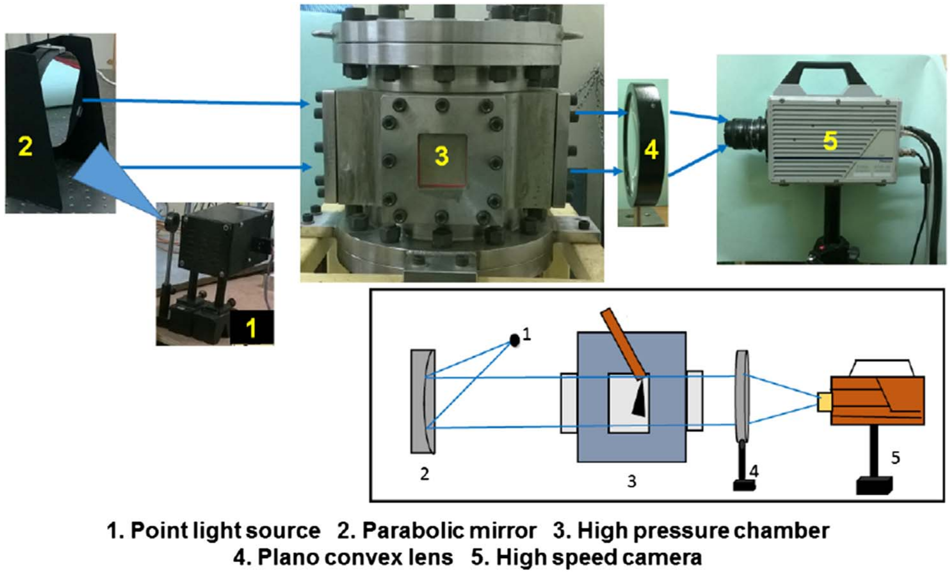

Fig. 1. Schematic of the optical arrangement for shadowgraph imaging technique.

penetration was found between different fuels at same density and injection pressure. Similar results are reported by other researchers as well [9,11]. Apart from pressure, density and temperature, various transport properties of the ambient gas may influence the penetration and cone angle of the spray. Effect of viscosity of the ambient gas was studied by Dan et al. [12]. They found that higher ambient viscosity led to shorter penetration, larger cone angle and smaller Sauter mean diameter (SMD). Payri et al. [13] studied spray penetration in two different gases, nitrogen and sulphur hexafluoride (SF6). They showed higher penetration in the case of SF6 at same ambient density. This was attributed to the difference in gas compressibility which resulted in different sound speed in two gases, and hence penetration rate changed. In case of a split injection system, a variation in penetration between two consecutive sprays was reported [14–17]. Farrel et al. [18] showed that in case of multiple injection system, the second injection penetrated faster than the first split spray. They also showed that reduced time spacing between the two split sprays led the second split spray to penetrate faster. They explained that the first spray reduced the drag for the second spray and helped to penetrate faster. Apart from this, as the time between the two split injections is very small, the evaporated fuel vapour from the first injection does not get sufficient time to disperse uniformly into the ambient. This may increase the fuel concentration in the surrounding gas around the spray penetration path. So the entrained gas for the second injection contains fuel vapour. Presence of fuel vapour in the entrained gas may influence the evaporation rate of the second spray. As a result, the droplets in the second spray evaporate less, retain the momentum and penetrate faster. The previous work by the present authors [19] showed that maximum liquid phase penetration and different inner zones of an evaporating spray were influenced by the presence of vapour in the ambient gas. The liquid length increases with the presence of fuel vapour in the ambient at the same values of ambient pressure, temperature and density. The present paper attempts to investigate the effect of ambient vapour concentration on vapour penetration and cone angle of an evaporating spray. Although the effect of different parameters on penetration and cone angle have been extensively studied before, the effect of ambient vapour concentration has not been reported so far. The present work attempts to address the influence of this effect.

2. Experimental setup

2.1. Spray visualization chamber and high pressure fuel injection system

Constant volume chambers are widely used for spray visualization due to good optical access with large visualization area and better reproducibility of the thermodynamic conditions. A constant volume, high pressure, and high temperature chamber with optical access is used in the present study to generate different thermodynamic conditions before spray visualization. The chamber is cylindrical in shape with 230 mm inner diameter. Total inner volume is 10.7 l. Three 80 mm × 70 mm quartz windows are placed at 90 degree to each other whereas another 80 mm × 70 mm window is placed at 60 degree angle with the nearest window. High pressure gas cylinders are used to build the pressure inside the chamber. A 4 kW heater is placed at the bottom of the chamber to increase the temperature inside the chamber. A PID controller is used to control the power output of the heater to maintain a constant temperature inside the chamber. Long heating time to reach a desired temperature ensures homogenous temperature of the ambient gas inside the chamber.

A second generation Bosch common rail injection system is used for the high pressure injection. The maximum injection pressure of the system is 160 MPa. A six-hole injector has been taken, and five holes have been blocked by micro welding to make it a single-hole injector. The nozzle hole diameter is 0.149 mm. The spray characteristic of the modified single-hole injector was compared with similar kind of multi-hole injector [20], and the difference was found to be nominal. A National Instrument(NI) 4 channel direct injector driver system module is used to control the injection pressure, timing, and duration. Two different injection pressures, 40 and 60 MPa are adopted for the present study. Injection duration is 1.5 ms for all the cases.

2.2. Optical arrangements

2.2.1. Vapour phase visualization

Shadowgraph or Schlieren imaging has been widely used to detect the vapor-phase boundaries of sprays injected into an environment where temperature (or density) gradients are present [21–25]. In the present experiment, a single-pass shadowgraphy technique is used for spray visualization. A schematic of the optical arrangements is given in Fig. 1. A 150 Watt continuous halogen light is used as light source. Light is passed through a pin hole to make it a point light source and then