Chapter 8
Development of an Optical Measurement Test Rig for Fuel Spray Characteristics Study of a Diesel Direct Injection System—An Experimental Approach

Megat Mohd Amzari Megat Mohd Aris, Shahril Nizam Mohamed Soid, and Ishak Abdul Azid

Abstract Optical measurement techniques have been proven by many researchers in obtaining fundamental spray and combustion characteristics either in a real engine combustion chamber or in a constant volume combustion chamber (CVCC). This technique can be used to observe the spray development and flame behaviour during the combustion process. Few renewable energy resources were extensively studied by various researchers. However, the measurement of its performance is not focusing to their fundamental characteristics especially on the spray characteristics such as tip penetration and cone angle. In this work, an experimental setup was designed to investigate the spray and combustion characteristics at various injection pressures. To examine the effect of different injection configurations, an optical measurement technique in a CVCC was used. The experimental setup consisted of a constant volume combustion chamber, sensors, and high-speed camera. The results were compared at various injection pressures in terms of spray development. The experimental setup was successfully developed to obtain the spray characteristics such as tip penetration and cone angle.

Keywords Diesel · Spray · Injection · Tip penetration · Cone angle

M. M. A. M. M. Aris · S. N. M. Soid (✉) · I. A. Azid
Engineering Section, Universiti Kuala Lumpur Malaysian Spanish Institute, Kulim Hi-Tech Park, 09000 Kulim, Kedah, Malaysia
e-mail: shahrilnizam@unikl.edu.my

M. M. A. M. M. Aris
e-mail: megatamzari@unikl.edu.my

I. A. Azid
e-mail: ishak.abdulazid@unikl.edu.my

M. H. Abu Bakar et al. (eds.), *Progress in Engineering Technology V*, Advanced Structured Materials 183, https://doi.org/10.1007/978-3-031-29348-1_8

8.1 Introduction

Various researchers have employed optical measurement techniques in engine fuel injection and combustion studies (Ghiji et al. 2017; Munsin et al. 2013; Soid and Zainal 2014). As the fundamental combustion characteristics are very important in ensuring better engine performance and emissions, various attempts have been made to understand the combustion process in the internal combustion engine. In some of the optical measurement techniques, few modifications have been carried out to obtain further details of the process, for example by using particle image velocimetry (PIV), laser-induced fluorescence (LIF), and phase Doppler particle anemometry (PDPA) techniques (Soid et al. 2012).

The research related to fuels and engine performance in internal combustion engine (ICE) can be generally classified into three broad areas: fuel and its preparation, engine geometries and features, and engine performance and emissions. To narrow down the studies, scopes of improvement are made by customizing certain existing engine components with different strategies and configurations such as introducing various types of fuels and blends to analyse characteristics and factors affecting engine performance and emission (Alagumalai 2014; Martins and Brito 2020).

Furthermore, phenomenon behavioural interaction between fuel and air towards combustion has also been studied by replicating the engine cylinder to visualize spray and combustion development. There are numbers of researchers that are involved in the development of optical measurement test rigs for fuel spray, whereby the design is made according to their different scope of studies. Optical measurement is usually focusing on two categories: macroscopic and microscopic parameters. The macroscopic parameters such as spray tip length and cone angle can be obtained through direct visualization methods. Meanwhile, microscopic parameters such as velocity, droplet size, and scalar field can be obtained by using PIV or PDPA techniques (Algayyim et al. 2018; Bohl et al. 2017; Tan et al. 2017).

Understanding the fundamentals knowledge of fuel spray development is essential towards achieving the optimum performance for the internal combustion engine. The engine's performance is influenced by the characteristics of the fuel and the quality of the air–fuel mixture; thus, it is critical to ensure that the injection process is as efficient as possible. As a result, it is crucial to analyse the fuel injection characteristics, as they will reveal solutions to improve the process.

In this paper, the development of an experimental setup used is presented based on the objective to measure the fuel spray characteristics. The optical measurement techniques were used to investigate the fundamental diesel fuel spray characteristics in a CVCC. Several experiments were carried out to see how diesel performs when the injection pressure is altered. A CVCC was developed with an optical window in order to accommodate a space for a camera to capture the fuel injection process. The optical window was made of fused silica, which could withstand high temperatures and pressures during combustion. A high-speed camera was used to record the spray development process. At various injection configurations, the spray tip penetration and cone angle were observed. This setup could also be used to determine the combustion performance of various fuels.

8.2 Methodology

The quality of the air–fuel mixture, which is dependent on the fuel injection into the combustion chamber, has a significant impact to the combustion performance. As a preliminary study, diesel fuel spray characteristics were studied at different fuel injection pressures. The experimental setup for measuring spray characteristics is shown in Fig. 8.1. This experimental setup has been prepared to analyse significant parameters that contribute towards effective condition for spray and combustion development. With regards to the spray development, the setup can be segmented into three stages of experimental processes which are (1) fuel preparation; (2) fuel injection; and (3) image capturing. This setup consists of A: fuel tank with filter, B: controller, C: electric motor, D: fuel pump, E: optical cylinder, F: injector, G: high-speed camera, and H: backlight source.

Focusing on the spray development, the experiments were carried out by supplying fuel from the tank into the fuel pump through a filter to ensure that unintentional particles would not pass through the fuel system. An electric motor was coupled to a fuel pump to pressurize the fuel to the required injection pressure. As pressure built up in the pump section, a signal was sent to the motor driver to give input on further rotation to keep a sustainable pressure within the fuel line. A pressure regulator controlled the required fuel pressure needed to supply the injector where the close/open valve was regulated by a switch box. This switch box was also linked

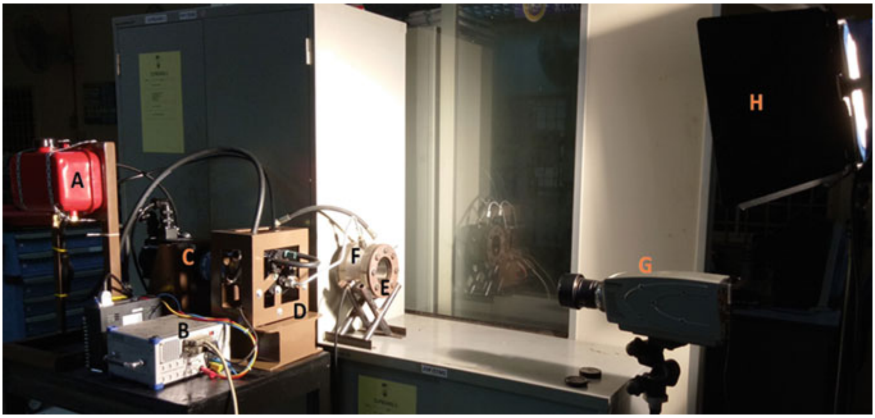


Fig. 8.1 General layout for experimental setup

to the high-speed camera which was put in a ready mode as the valve opened a required pressure for injection stage.

If the pressure regulator valve was kept closed, the fuel would keep circulating within the pressure pump. Once the pressure built up in the fuel line was at the required pressure, the pressure regulator would release a certain amount of fuel to an injector where a needle inside it would push backwards to allow the pressurized fuel to burst through the nozzles of holes from the injector which was attached to an optical cylinder. Figure 8.2 shows the schematic of experimental layout that consists of the fuel injection system, optical cylinder, and high-speed camera.

Meanwhile, the five holes injector (Delphi EJBR04601Z) was used to spread spray inside the cylinder. The holes approximate diameter of 0.19 mm was evenly positioned at angle 72°, and the injection-enclosed angle was 156°. Figure 8.3 shows the close-up view of the injector tip. To open the injection tip nozzles, the injector required approximately 120 bar of pressurized fuel to allow the needle push backwards by a spring effectively. The pressure built up within the fuel line indicated by a pressure gauge ensured the required fuels pressure before being released to the injector. An optical cylinder was prepared to visualize the spray characteristics at certain variables conditions. This cylinder having an inner diameter of 70 mm was made of stainless steel grade 304 and end closed with sight glasses at both ends. The optical cylinder had also an inlet valve port to supply pressurized air at 2 bar inside the cylinder. For this study, injection pressures chosen were 30 MPa, 40 MPa, and 50 MPa, respectively.

A high-speed camera (Olympus i-SPEED TR) was deployed and positioned perpendicular to the plane of the sight glass to capture the image of fuels' spray spreads. The focus length between the camera lens and injection sprays was set up towards plane of optimum images sharpness. As the image captured perpendicular to the tip of the injector but slanting 78º (injection-enclosed angle 156°), the true length of the spray had to be calculated with respect to centre axis of the injector

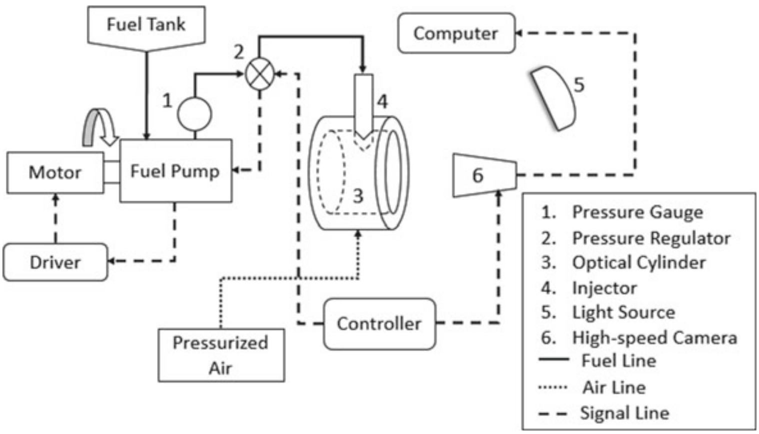


Fig. 8.2 Schematic of experimental layout

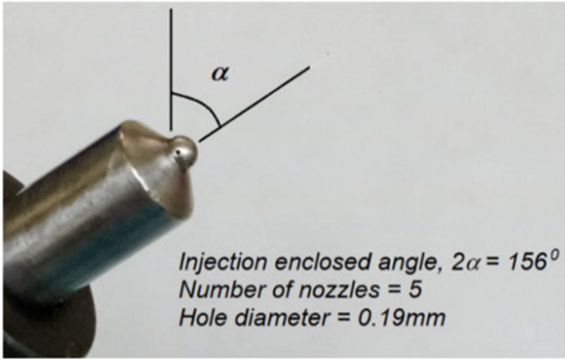


Fig. 8.3 Close-up view of injector tip

tip. After start of injection (SOI), the fuel spray was observed for a duration of up to 5 ms as further time would result the spray to reach to the wall of the cylinder. After that, the images were transferred to the i-SPEED Viewer software, and the spray measurements were performed using the SolidWorks CAD software. This technique was also described in the previous study in determining the spray characteristics by visualization (Soid and Zainal 2014).

8.3 Results and Discussion

The development of test rig has enabled fuel characteristics investigation for replication of a diesel direct injection system. Figure 8.4 shows macroscopic views of the injection spread recorded by a high-speed camera setting at certain image focus length over period of milliseconds. Instead of having visual results, these views enabled further investigation on spray characteristics which integrate to properties and condition of injection fuel such as fluid density and viscosity, effects of temperature and pressure, performance of injector, as well as in different types and blends of fuel.

To determine the performance of the fuel spray, there are three indicators that exhibit characteristics of the tested fuel: (1) tip penetration (unit: mm length), (2) cone angle (unit: degree angle), and (3) spray velocity (unit: metre per second). In the current study, these parameters were obtained by processing the image of the spray using the CAD software to measure the length and angle of sprays. Meanwhile, spray speeds were calculated from data of the tip penetration length over time. Figures 5a and b show the plotted data of the standard diesel tested at different injection pressures. In general, a good characteristic of a spray was obtained as indicated by the large cone angle size and speed of penetration, whereby the fuel dispersed widely into the ambient to atomize with air within shorter duration. Conversely, a bad characteristic of spray was happened when a narrow cone angle was produced and not able to disperse into the air but impingement to the cylinder side wall.

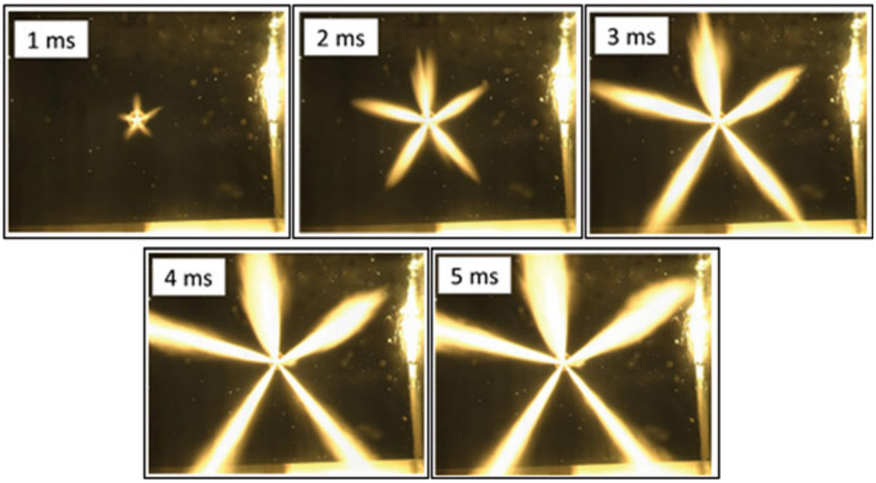
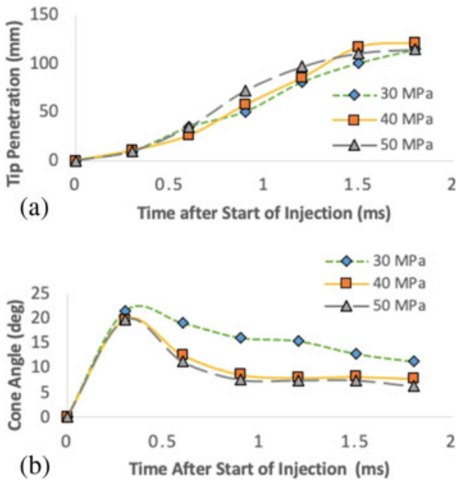


Fig. 8.4 Typical views of the spray patterns from the multi-hole's injector for 30 MPa bar diesel fuel injection pressure at ambient pressure

Fig. 8.5 Diesel fuel **a** tip penetration and **b** cone angle at various injection pressures



8.4 Conclusion

The optical measurement test rig was successfully developed for the measurement of the fuel spray development process in a CVCC. This technique can be used to model the actual fuel spray process in an internal combustion engine. Various injection parameters can be changed, and their effect to the spray development can be observed. This setup can be used to study various alternative fuels such as biodiesel and plant oil. The results from the analysis can be compared to conventional diesel fuel. Increasing the injection pressure might also close the gap between the high-viscosity fuels when compared to diesel at standard injection pressure. It can be concluded that this optical technique can help in understanding the fundamental of fuel spray development in terms of tip penetration and cone angle.

References

Alagumalai A (2014) Internal combustion engines: progress and prospects. Renew Sust Ener Rev 38:561–571

Algayyim SJM, Wandel AP, Yusaf T (2018) The impact of injector hole diameter on spray behaviour for butanol-diesel blends. Energies 11(5):1298

Bohl T, Tian G, Smallbone A et al (2017) Macroscopic spray characteristics of next generation bio-derived diesel fuels in comparison to mineral diesel. Appl Energ 186(3):562–573

Ghiji M, Goldsworthy L, Brandner PA et al (2017) Analysis of diesel spray dynamics using a compressible Eulerian/VOF/LES model and microscopic shadowgraphy. Fuel 188:352–366

Martins J, Brito FP (2020) Alternative fuels for internal combustion engines. Energies 13(16):4086

Munsin R, Chung B, Shing L, Phunpheeranurak K, Phongphankasem T, Laoonual Y, Jugjai S, Chanchaona S (2013) Design of constant volume combustion chamber (CVCC) with pre-combustion technique for simulation of CI engine conditions. In: The 4th TSME international conference on mechanical engineering, vol 16

Soid SN, Zainal ZA (2014) Combustion characteristics and optimization of CPG (compressed producer gas) in a constant volume combustion chamber. Energy 73:59–69

Soid SN, Zainal ZA, Iqbal MA et al (2012) Macroscopic spray characteristics of palm oil-diesel blends in a constant volume combustion chamber. J Sci Ind Res India 71:740–747

Tan YH, Abdullah MO, Nolasco-Hipolito C et al (2017) Engine performance and emissions characteristics of a diesel engine fueled with diesel-biodiesel-bioethanol emulsions. Energ Convers Manage 132:54–64