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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Development of Experimental Apparatus to Analyze Diesel Spray Characteristics

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DOI: https://doi.org/10.30880/ijie.2020.12.03.003
Received 20 May 2018; Accepted 20 September 2018; Available online 27 February 2020

Abstract: Diesel engine performance and emission rely greatly on the diesel spray. A lot of researches conducted to study the diesel spray characteristics in a closed chamber. However, it cannot describe in detail about the phenomenon since the chamber condition such as pressure and size play a role in spray characteristics. It would be beneficial to conduct an experiment in open chamber. Hence, this research would develop a new experiment apparatus and analyze the diesel spray characteristics in open chamber. In this research, common-rail injector tester is used to simulate the actual common-rail injection diesel engines. The injection pressure is varied from 100MPa to 180MPa. A high speed camera with 3,000 frames per second is used to capture the diesel spray formation using direct photography technique. From the result, spray development angle, and fully developed spray angle is studied. The results revealed early at the injection, the spray angle increased swiftly before slowly decreased as reaching fully developed spray phase. At the fully developed phase, spray angle proved to be decreased as the injection pressure increased.

Keywords: Diesel, common-rail, fuel injection, spray characteristics, spray angle.

1. Introduction

Diesel engine is often valued by its fuel consumption, performance, and emission. One of the most contributing factors is the diesel fuel injection, atomization, and combustion. In order to improve the engine fuel consumption, performance, and emission, most modern diesel engines are using common-rail fuel system [1]. The common - rail system is capable of regulating fuel injection pressure with engine timing over a broad scale. After diesel fuel being pressurized in common-rail system, it is injected into the combustion chamber via fuel injector [2-4]. Fuel injector has 3 different kinds of nozzle which are conical sac hole, cylindrical sac hole, and valve covered orifice [5-7]. The nozzle has been identified as one of the most critical parts in an injector as it affects combustion performance. Spray characteristic measurement can be divided into two. They are macroscopic characteristic, and microscopic characteristic [8]. Some of the macroscopic characteristics of fuel spray are spray tip penetration, spray cone angle, and derivatives of both as shown in Fig. 1.

On the other hand, microscopic characteristic examples are droplet velocity, droplet distribution, and air fuel ratio distribution. In previous years, there is a lot of research have been done to study the diesel spray characteristics. A study on the diesel spray characteristics have been done experimentally or by simulation. From the previous experimental research, it shows that the spray angle increases with an increment of injection pressure [9-15]. However,

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these researches cannot elaborate in detail the spray characteristic since the chamber condition also plays an important role affecting the spray characteristics. Hence, this research will develop a new device for conducting diesel spray experiments for open chamber. Next, diesel spray characteristics at different injection pressure parameters will be studied. The experiment was done in an open chamber with the surrounding pressure of 1atm. The injection pressure was varied from 100MPa to 180MPa.

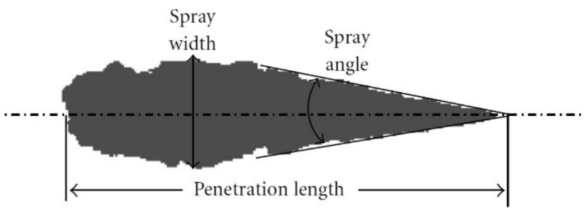


Fig. 1 - Macroscopic characteristics of fuel injection [8]

2. Methodology

This experiment was divided into three stages. The first stage is developed. The spray chamber is designed and fabricated to cater the needs of this experiment. The second stage is a test run to ensure the spray chamber is ready to use or needs some improvement. The final stage is experiment to analyze diesel spray characteristics. The experiment setup from previous studies are analyzed, compared, and adapted to be used as the experimental setup. Fig. 2 shows the methodology of this research.

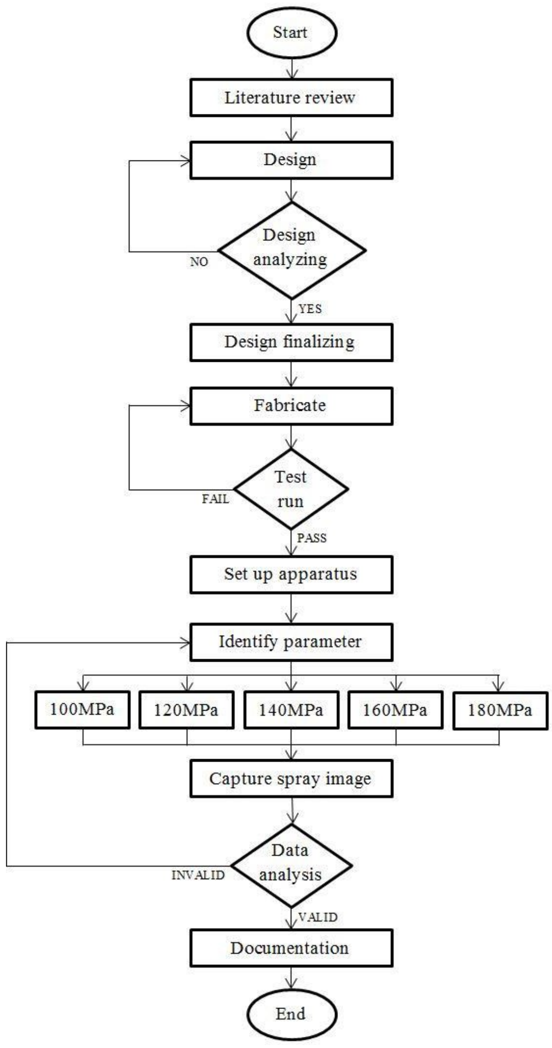
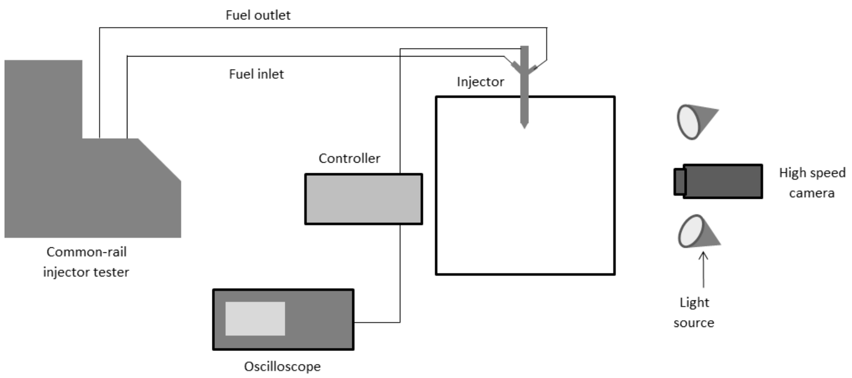


Fig. 2 - Research methodology

2.1 Sample and Apparatus

The experiment was conducted in a newly developed spray chamber. The spray chamber was made to conduct experiments in atmospheric condition. It was made from mild steel with the dimension of 500mm in height, length, and width. The inner part of the chamber was coloured black to avoid any light reflection during recording. The spray chamber could only support 1 injector at a time. At the front part of the spray chamber, a controller box was installed. The controller box was equipped with switching power supply, and electronic diesel controller. To simulate the high pressure fuel injection in a diesel engine, a common-rail injector tester will be used. The common-rail injector tester used was PQ1000 model. Injection pressure was varied here. The pressure was raised from 100MPa to 180MPa with 20MPa interval. An air compressor is coupled to the common-rail injector tester to supply the necessary air to build up high pressure injection.

A diesel fuel injector is connected to the common-rail injector tester via a high pressure fuel line. Fuel injector will be used to inject fuel into the spray chamber. There is a variety of injector brand in the market, but this research will use fuel injector from Denso. There are also many types of injectors, but this injector is a solenoid type. It requires electrical energy to control its timing and duration which can be controlled from the controller box. The fuel used in this experiment was not a biodiesel blend, but a conventional diesel fuel found at any gas station. However, diesel from BHPetrol with Euro 5 compliance was used. To record the swift diesel spray, a DITECT HAS-LI digital high speed camera was used. The high speed camera was set at its highest frame rate setting at 3,000 frames per second (fps), with direct photography technique applied. The lens paired together with the camera is from Fujian China TV Lens GDS-35 with a focal length of 35mm and magnification ratio of 1:1.7 with no extension tube used. Sufficient lighting was also equipped.



(a)

(b)

Fig. 3 - Experimental setup. (a) Schematic diagram; (b) Common-rail injector tester, spray chamber, and high speed camera setup

2.2 Experiment Setup

Fig. 3 above shows the experimental setup for this experiment. To get the best result, the camera was mounted on a tripod. The neck of the tripod was adjusted so that the height of the camera was at the same height as the injector nozzle. With a guide of a water level, the camera was made sure facing straight with no elevation. The camera was placed nearly 2m from the spray chamber. Next, the shutter speed of the camera was configured to get the best spray motion. In this case, the frame rate is 3,000 hence the shutter speed was around 1/6,000. This complied with 180° shutter angle rule. Choosing the 3,000fps setting would only offer one output resolution, which is 160 x 120 pixels. The video obtained would be small but still able to analyze.

From the video taken by high speed camera, it was then converted to images. Videos were played frames by frames before each frame was saved as pictures. The photos were then being enhanced in photo editing software. The photos were enhanced to get better and clearer images to obtain more accurate measurements. The images of fully developed spray are then analyzed with ImageJ software to measure their spray angle. From the ImageJ software, the average spray angle from all readings could be calculated directly.

3.0 Results and Discussion

With the 3,000fps high speed camera, it is possible to study the spray development. This is due to the fact that with 3,000fps setting, the camera captured 3,000 pieces of image in 1 second. Hence, with high frame rate, more detailed and smooth spray movement can be captured and analyzed. Besides, high speed setting also enabled to study the fully developed spray angle when the injection is fully stable.

3.1 Spray Development

Spray development is the early stage of injection. The condition of early injection at the nozzle is shown in Fig. 4. From the images obtained, at the early injection, the spray angle appeared to be puffier than the rest of the injection. The angle of each spray development was measured and analyzed. Fig. 5 shows the result of spray angles of each injection pressure.

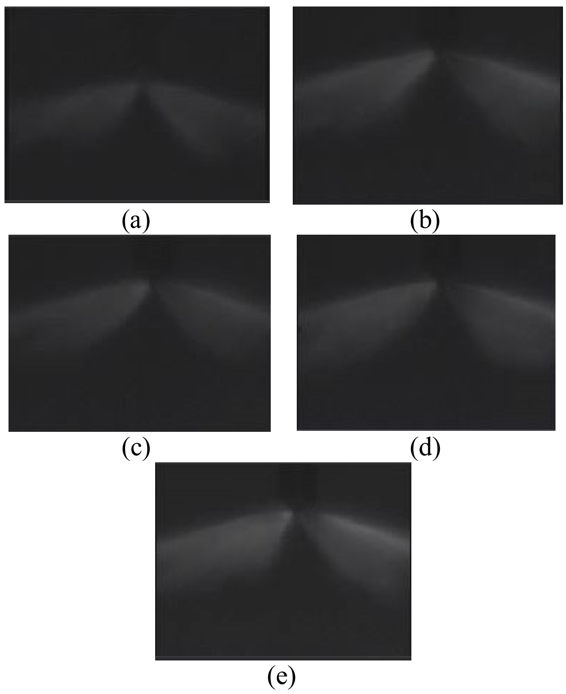


Fig. 4 - Spray development images. (a) 100MPa; (b) 120MPa; (c) 140MPa; (d) 160MPa; (e) 180MPa

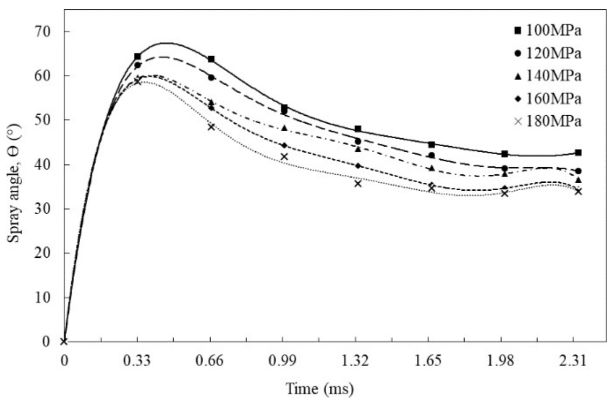


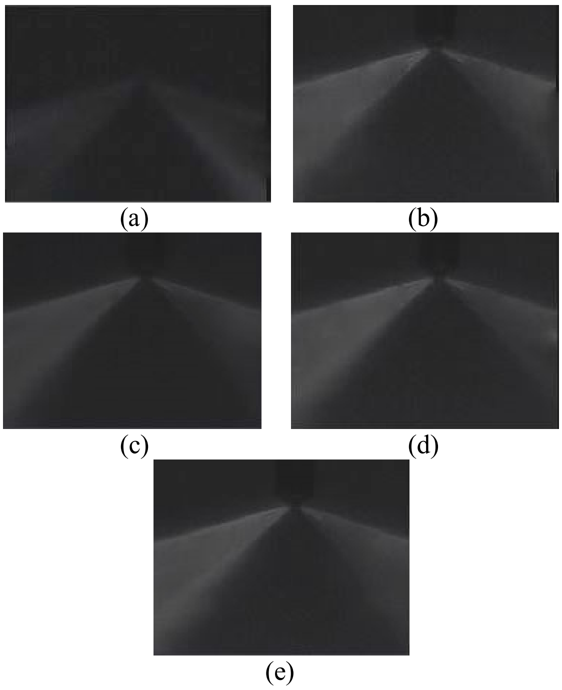
Fig. 5 - Spray development angle at different injection pressure.

From Fig. 5, the spray development for each pressure parameter appeared to be in the same pattern. During the early stage of injection, the spray angles were bigger than the rest of the spray. All of the sprays were at the biggest angle during 0.33 milliseconds. Then, the spray angle started to get smaller seconds by seconds. The drop in spray angles are very gradual, compared to the sudden spike at the early phase of injection. From the figures above, the spray in term of its maximum angle, and time taken to be fully developed can be analyzed. During the 100MPa injection pressure, the spray reached its maximum angle of 65°. When the injection pressure is increased to 120MPa, the spray reached 62°. For the 140MPa injection pressure, it nearly reached 60° spray angle. This shows a decreasing trend and applied to injection pressure of 160MPa and 180MPa which reached 59° and 58° respectively. Despite the development angle decreased as the injection pressure increased, all of the early development angles are bigger than their full development form by an average of 20°.

The time taken for 100MPa injection pressure spray to be fully developed was slightly before the 2 millisecond mark. The injection pressure was then increased to 120MPa and the result shows quite the same time as 100MPa. However, 140MPa and 160MPa injection pressure took an even shorter time to be fully developed at 1.7 milliseconds. 180MPa injection pressure took the shortest time with only 1.3 milliseconds to develop fully. This shows that the higher the injection pressure, the shorter the time taken for the diesel spray to develop fully. These results were proven by having similarity with research done by Lee [16]. From the result, it is proven that diesel spray went through its early stage of injection which called spray development. Spray development angle appeared to be bigger than the fully develop due to inflation from the upstream fuel. Once the fuel is injected, the orifice is set open. The high pressure caused the fuel to inflate as it leaves the spray nozzle. At the tip of the nozzle, it has to go against its surface tension and caused its angle to grow. Once the fuel went through the nozzle, it is then stabilized by surface tension of the fuel itself [17-20].

3.2 Spray Angle

Figure 6 shows the sample of fully developed spray images at 2.3ms. For each pressure variable, three trials were made. Hence, three images for each pressure setting were obtained and measured. From three values, an average reading was calculated. The result of spray angle for each pressure variable is shown in Table 1. The results from Table 1 can be plotted into graph as shown in Fig. 7 to gain a better understanding and analysis. From Table 1 and Fig. 7, results showed that 100MPa of injection pressure produced the biggest spray angle of 42.3°. The spray angle reduces as the injection pressure increases. Hence, 180MPa produced the smallest spray angle of 33.6° compared to other injection pressure.



(a) (b) (c) (d) (e)

Fig. 6 - Fully developed spray images. (a) 100MPa; (b) 120MPa; (c) 140MPa; (d) 160MPa; (e) 180MPa

From 100MPa to 160MPa, the spray angle decreased almost linearly. The difference changed by average of 2°-3° angle decrement per 20MPa injection pressure increment. However, the spray angle between injection pressure of 160MPa and 180MPa did not differ much. This could mean that if exceeding 160MPa, there is no significant spray angle change would occur. Higher injection pressure yielded smaller spray angle due to the increment of the injection pressure itself. From Pascal's law, higher pressure will result in higher force. This high force will then result in higher velocity output and possesses high kinetic energy [21-25]. This high kinetic energy caused the spray to develop smaller in angle as it overcame the friction in the injector nozzle.

Table 1 - Fully developed spray angle reading

Injection pressure, P (MPa)	Spray angle (°)	Average spray angle, Ө (°)
100	42.5 42.2 42.1	42.3
120	39.3 40.4 39.1	39.6
140	37.3 36.4 36.3	36.6
160	33.8 34.9 33.8	34.2
180	33.8 33.5 33.4	33.6

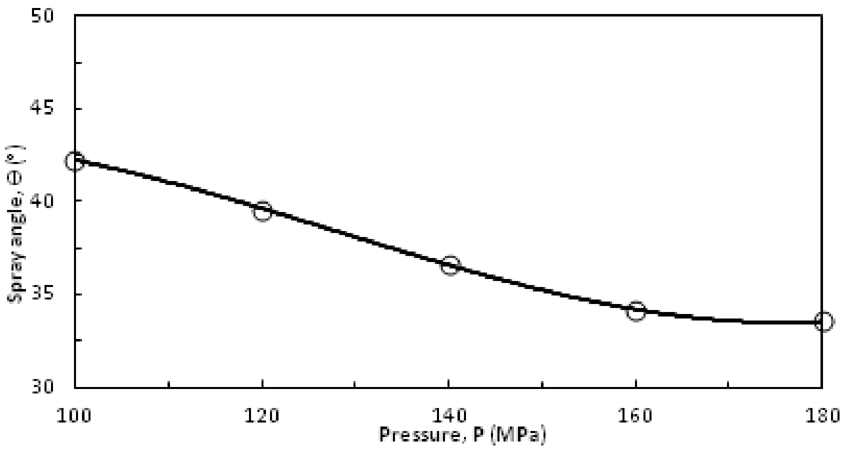


Fig. 6 - Effect of spray angle against injection pressure

4. Conclusion

This research had successfully developed a new experimental apparatus to analyze diesel spray characteristics. The apparatus meant was a rig which includes a spray chamber at atmospheric pressure of 1atm, and follows the surrounding temperature and humidity. The spray chamber includes a controller box that functioned well, allowing the experiment to control the injector duration, delay, and trigger the injection. The spray chamber enabled this research to record the injection characteristic via high speed camera. The effect of the spray characteristics differs as the injection pressure changes. During the early stage of injection, the spray angle was bigger and puffier. This is due to the surface tension of diesel overcome itself. As the spray injection pressure increased, the spray development angle decreased. This resulted in 180MPa injection pressure to have a smaller spray development angle than of 100MPa. The angle increment for every injection pressure parameter was around 50% than the actual fully developed form. Next, the time taken for the fuel spray to be fully developed was shorter as the injection pressure increased. However, the time differences between each injection pressure parameters are very small. During the fully developed spray, the smallest injection pressure parameter showed the biggest spray angle. This proved that as the injection pressure increased, the spray angle decreased. High injection pressure exerted high kinetic energy of fuel, thus overcome the friction inside the nozzle.

Acknowledgment

The authors would like to thank Universiti Tun Hussein Onn Malaysia (UTHM) and Ministry of Higher Education Malaysia (MOHE) for their financial support of the present work through GPPS Grant Scheme (U802).

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