Characteristics of Diesel Spray Under High Injection Pressure

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Abstract
Increasing injection pressures can improve combustion efficiency in direct-injection diesel engines attributing to enhanced atomization. In this work, a high pressure experimental setup was established to generate ultra-high fuel pressures. An intensification system was used to magnify the pressure by about 10 times and provide an injection pressure of up to 10000 bar (1000MPa). Preliminary testing of the high pressure system produced a peak pressure of about 8700 bar (870MPa). Since there is no available commercial fuel injector that can handle such a high pressure, relatively low pressure levels were used to perform the preliminary test for a commercially available piezoelectric diesel fuel injector. High pressure diesel fuel was injected into atmospheric pressure (1 atm) and temperature (298 K). The injection activation pulse duration was 1 millisecond. The fuel injection event was synchronized with the instruments for high-speed imaging by using a pulse generator, and spray images were taken by a high speed camera for spray analysis. The penetration velocity of the spray increases with the increase of the injection pressure, while the spray starts to appear at the nozzle exit a little bit later for higher injection pressures due to the operation mechanism of the injector. The spray angle decreases by a small amount during the injection. Due to the design of the fuel injector, the maximum pressure used in the preliminary testing was 2500 bar (250MPa). In order to achieve fuel injection under even higher pressures, new injection devices or modifications on existing fuel injectors are needed for further studies.

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**Introduction**

High-speed (supersonic) liquid jets have wide applications in engineering, particularly in propulsion and power generation systems [1-5]. For fuel injection application, especially direct injection diesel engine, improving spray atomization is important and higher injection pressure usually means better atomization and mixing, which can help improve combustion efficiency. Studying and optimizing the combustion process is becoming more and more important for reducing fuel consumption and pollutant emissions.

The study of high-speed diesel jets has attracted significant interest due to their potential to achieve better performance for diesel engines [6-8]. For a diesel engine, the injection pressure is one of the most influential factors on its performance and particulate emissions. With the elevated injection pressure, the velocity of the diesel jet increases, especially when it is higher than sound speed, then a supersonic jet could be generated and a shock wave phenomenon could appear, which would further enhance the atomization and evaporation process.

Series of investigations were done on supersonic liquid jets by different groups of researchers [10-12]. They adopted a projectile impact method to generate a liquid jet with Mach number higher than 5.3, leading to significant shock waves around the jet. The spray structure of these supersonic jets is significantly different from the diesel jets observed in diesel engines operated in normal working ranges.

In most of the above-mentioned supersonic liquid jet investigations, however, because the supersonic liquid jet was generated by a projectile impact method, the liquid dispensing process was not directly controllable. In this study, a high pressure experimental system was built in order to generate ultra-high fuel pressures. An intensification system was used to magnify the pressure by about 10 times and provide up to 10000 bar (1000MPa) injection pressure. Preliminary testing of the high pressure system produced a peak pressure of about 870 bar (870MPa). The main objective of this study is to investigate the important characteristics of the diesel spray, such as spray angle, penetration, etc. With these information, we can better understand the effect of high injection pressure on diesel sprays. This will ultimately lead to enhanced engine performance with reduced fuel consumption and pollutant emissions.

**Experimental setup**

The high pressure experimental setup mainly consists of a fuel supply system, an intensification system, a high-speed imaging system, and a control unit, as in Figure 1. The fuel supply system can provide up to 1800 bar (180 MPa) fuel injection pressure. In this study, the pressure of up to 1000 bar is used and the intensification system can magnify the pressure by about 10 times. A pulse/delay generator is used to control the fuel injection duration and trigger the fuel injector and the high-speed camera. This way the fuel injection event can be synchronized with the other instruments. The rising edge of the triggering pulse is used for all the devices. Figure 2 shows the schematic of the whole fuel supply system. It mainly consists of a low pressure pump, a high pressure pump, a fuel common rail, and a commercial fuel injector (which is used to drive the medium pressure side of the intensifier). The fuel injector is controlled by a piezo injector driver from Drivven Company. The high pressure pump is driven by a 3 horse power electric motor. After the fuel passes through low pressure pump, the high pressure pump pressurizes the fuel which then goes into common rail and injector. There is a pressure sensor on one end of the common rail and a pressure control valve on the other end. The rail pressure is controlled by a Labview program using a PID control scheme. Thus, the injection pressure can be controlled and maintained.

Figure 3 shows the schematic of the intensification system. On the higher pressure side, there is ultra-high pressure cross which connects ultra-high pressure check valve, ultra-high pressure sensor (0-200,000 psi), the injector body and the intensifier. On the lower pressure side, there is a high pressure tee which connects the fuel supply line, the intensifier and the fuel return valve. During experiment, the fuel first passes through the check valve and fills the higher pressure side with fluid. At this time, the return valve is closed. When the fuel supply line is operated, high pressure fuel (up to 1000 bar) goes into the tee and the lower pressure side of the intensifier, pushing the piston inside the intensifier. Due to the balance of force and the area ratio of the piston on both sides, the pressure on higher pressure side will become about 10 times of the lower pressure side. Meantime, the ultra-high pressure check valve prevents the fuel from going back. This ultra-high pressure fuel is then injected out from the injector body, while the ultra-high pressure sensor measures the pressure and output a voltage signal to data acquisition board. The injector driver which can generate a voltage up to 175V to drive the piezo stack in the injector. It can be triggered both internally and externally. In this study, fuel is injected into atmospheric pressure (1 atm) and temperature (298 K). A Stanford pulse/delay generator (Model No.DG535) is used to trigger the injection in order to acquire accurate and precise control and synchronize the timing with the high speed camera. The rising edge of the triggering pulse is used for all the devices.

The high speed imaging system mainly consists of a Phantom V4.3 camera from Vision Research Inc, a light source and an image acquisition computer. A light source (PAR64 1000 W lamp) was used to volumetrically illuminate the spray. A 50 mm fixed focal length lens was used. The F8 was set at 5.6 and the exposure time was 10 μs. The camera was set at 10000 fps with a resolution of 64×600. The corresponding physical image
resolution is approximately 0.375 mm/pixel. The camera can be triggered externally by the trigger pulse from the pulse generator.

Results and Discussion

During the preliminary test, the pressure on low pressure side was increased gradually. The pressure on high pressure side was boosted up and the ratio between these two remained at 10 when the pressure was not too high, as shown in Figure 4. When the pressure is higher than 6000 bar (600 MPa), the ratio decreases by a small amount. Eventually, when there is 1000 bar (100MPa) on the low pressure side, the pressure on the high pressure side is able to reach about 8724 bar (872.4 MPa). Since there is no available commercial fuel injector that can handle such a high pressure, relatively low pressure levels were used to perform the spray test for a commercially available piezoelectric diesel fuel injector. In this experiment the fuel injector is not able to produce injection when the pressure goes beyond 2500 bar (250 MPa), due to the design of the fuel injector. In order to achieve high pressure fuel injection, new injection devices or modifications on existing fuel injectors are needed for further studies.

Spray image processing program was developed and used to read the original video frames and detect the spray edge. The background is subtracted and images are further enhanced by adjusting the intensity and contrast. A threshold is then used for spray edge detection. This method proved to be effective for detecting the visible edge. Next operation was to use an algorithm to find the left and right edges of the spray for each image. Then a linear fitting was applied to the spray edges to calculate the spray angle at each time step. A similar edge-finding method was used to obtain the penetration of the spray front. The velocities of the spray tip was calculated based on the penetration and the frame rate of the camera. The calculation continues for up to 2.5 ms, well beyond the end of fuel injection.

To demonstrate the development of the spray, a typical set of images under 1500 bar and 2500 bar (250MPa) is shown in Figure 5 and Figure 6. In the images, besides the spray signal other added information includes a time stamp showing the time of the image after the activation of the injection pulse, a white thick bar showing the scale of the image.

From the spray images, it is observed that the spray develops very fast at the beginning. The cone angle stays rather stable during most of the injection process. For this case, the spray angle is calculated up to after the injection stopped. There exist some vortices on the edge of the spray after the spray developed, which might also cause the linear fit for spray angle to change slightly.

The spray penetration length is shown in Figure 7. When the pressure increases from 1500 bar to 2100 bar, the penetration increases earlier and faster. However, when the pressure is beyond 2100 bar, the penetration appears later, especially for the case of 2500 bar. At around 1.6 ms, the penetration front touches the wall for cases of 1500 bar, 1700 bar and 1900 bar. When the injection pressure is higher, the time it takes to reach the wall shortens by a small amount. The tip penetration velocity is shown in Figure 8. In general, the penetration velocity increases with the increase of injection pressure. When the injection pressure is 2500 bar, the top velocity can reach about 320 m/s, which is close to the speed of sound. Further increasing the injection pressure could probably cause the tip speed to be even higher.

Figure 9 shows the spray angle development with time. For all the cases, after there is observable spray, the spray angle appears as a relatively big value. This might be caused by the large amount of fluid which is pushed out of the nozzle in the beginning of injection. The shape of this early amount of fluid is closer to an ellipse than a jet. Thus the linear fit of the right and left edges will result in a bigger angle value. After that, the spray angle is relatively steady and decreases by a very small amount throughout the injection process. After the spray tail leave the nozzle, the calculation of spray angle is continued by defining the angle from the spray tail. The spray angle gradually increases with the developing of the spray shape. It is noted that with a higher injection pressure, the speed of spray angle increase becomes higher. This might be due to a higher velocity at the spray center.

Conclusion

An ultra-high pressure injection experimental system is built. The intensification system can magnify the pressure by about 10 times. Preliminary testing of the high pressure system produced a peak pressure of about 8700 bar. Relatively low pressure levels is used to perform the test for a commercially available piezoelectric diesel fuel injector. Some important characteristics of the diesel spray are studied.

The spray penetration increases earlier and faster when the pressure increases from 1500 bar to 2100 bar, and appears later when the pressure is beyond 2100 bar. The spray reaches the wall earlier when the injection pressure is higher. The penetration velocity increases with the increase of injection pressure. The top velocity can reach about 320 m/s. The spray leaves the nozzle at around 2.1 ms and then develop into the ambient environment.

The spray angle first appears as a relatively big value, then decrease by a small amount throughout the injection process. The time averaged angle is about 10 degrees. After injection ends, the spray angle gradually increases with the developing of the spray shape. The extent of spray angle increase becomes bigger with a higher injection pressure.
In order to achieve even high pressure fuel injection, new injection devices or modifications on existing fuel injectors are needed for further studies.

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References
Figure 1. The component systems in the set up

Figure 2. Schematic of the fuel supply system
Figure 3. Schematic of the intensification system

Figure 4. Relationship between pressure on the high pressure side and low pressure side
Figure 5. Development of fuel spray (1500 bar) at different time steps after the trigger signal.
Figure 6. Development of fuel spray (2500 bar) at different time steps after the trigger signal.
Figure 7. Spray penetration length with time.

Figure 8. Spray penetration velocity with time

Figure 9. Spray angle with time