

Measurements of Attenuation and Penetration of Pulsed Supersonic Liquid Diesel Fuel Jets - the Possibility for Use in Diesel Engines

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Abstract

Characteristics of pulsed supersonic liquid diesel fuel jets (velocity of around 1500 m/s to 1800 m/s) have been examined. In this paper, measurements of the attenuation and the penetration distance of the liquid jets are presented. Series of six laser beams are placed downstream of the jet for measuring jet velocities and penetration distances. It was found that the attenuation is relatively high in the first 300 μ s of the jet flight. The penetration distance is around 300-500 mm, this depending on the initial velocity, the nozzle geometry and the properties of liquid. The experimental results agree well with the estimation using conventional diesel spray formula. The high-speed camera and shadowgraph technique is used to visualize the jet shock wave and jet structures. With multiple pulses and cavitating nozzle orifice, they tend to enhance atomization and combustion. The possibilities to apply such jets for use in conventional diesel engines are also discussed. However, further examination of their atomization related to the jet attenuation and penetration distance is required.

1. Introduction

In diesel engines, fuel injection pressures have been increased substantially during the last decade. Injection pressures

have risen from about 70 to 110 MPa to currently about 150 MPa in common rail systems and some electronic unit injectors of the mechanical (EUI) or hydraulic (HEUI) types have reached 230 MPa. The higher fuel spray velocity enhances atomization, air entrainment and mixing due to the intense shear layer, which then leads to improved combustion. An increase in engine efficiency, improvement in fuel economy and, particularly, a reduction in smoke emissions occurs [1-2]. However, because of the high temperature operating conditions in diesel engines, the highest pressure conventional jet has a Mach number which is likely to be either in the high subsonic range of 0.5 to 1.0 [3] or just supersonic. At even higher injection pressures, the fuel spray or jet is likely to travel at a supersonic speed with the accompaniment of a leading edge (bow) shock wave. In addition to more rapid mixing, other possible phenomena resulting from this would be shock wave heating which may enhance the use of poor cetane number fuels, allow compression ignition (CI) engines to operate at lower compression ratio or, in extreme cases, provide fuel auto-ignition from the jet itself. However it is important to note that there are still many practical limitations on the usable maximum jet velocity. Nevertheless a fundamental study on the characteristics of high-speed liquid fuel jets, especially in the supersonic range, is important.

Some researchers [4-5] have investigated the characteristics of a 250 MPa, single hole nozzle fuel spray giving a jet velocity of

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about 600 m/s injected into a high pressure vessel at ambient temperature where the acoustic velocity is about 340 m/s. Here, the jet is definitely supersonic at a Mach number approaching 1.8. Shock waves were noted around the jet. With increasing injection pressure and hence the strength of the accompanying shock wave, it was found that the Sauter Mean Diameter (SMD) of droplets in the spray became smaller with a corresponding decrease in the ignition delay time [6-7]. Nishida et al. [8] also studied the spray angle, spray shape, penetration velocity and the SMD of diesel fuel sprays at an ultrahigh injection pressure (up to 300 MPa). This study confirmed that the SMD and spray angle decreased with an increase in injection pressure.

Higher velocity, intermittent jets are more difficult to create and, at present, fuel jets in this range are available only from specially designed experimental apparatus. The most common method, a single-shot projectile driving the liquid by impact, has been used by several researchers instead of a high-pressure pump [9-10]. The injection pressures have exceeded 2 GPa, depending on the impact velocity and the projectile material. At such pressures, the liquid compressibility cannot be neglected and densities well above normal will exist within the nozzle sac.

As well as diesel engine combustion, supersonic ram (SCRAM) jet engines are currently of great interest. In these, the mixing and heat release must be extremely rapid if combustion is to occur within the very short residence times in the combustion chamber. This is a significant engineering challenge. Supersonic fuel injection could enhance this process. Some fundamental studies of high-speed liquid jets have shown the importance of the leading edge shock wave to this case. However, for both SCRAM jets and diesel engines, further studies of supersonic liquid fuel jets are needed. These include examination of the shock wave structure around the jet, the mixing and atomization and the velocity attenuation and jet penetration. This paper examines all these but concentrates on the last two areas.

2. Experimental procedure

To generate supersonic liquid jets, a high velocity impact from a projectile is required. This has been achieved by using a vertical two-stage light gas gun (VTSLGG), shown in Fig. 1, firing a projectile which impacts on the liquid retained in the nozzle cavity (sac). The projectile is made of polycarbonate (PC), is cylindrical in shape with diameter of 15 mm and is 20 mm long (weight of 4.45 g). The piston, made from high density polyethylene (HDPE), has a diameter of 50 mm and length of 75 mm (weight of 137 g). In this study, only one projectile impact velocity was used i.e. 700 m/s. This is the maximum currently

obtainable and the most consistent velocity produced by this VTSLGG. The piston or the first stage projectile is driven by 2.5 MPa nitrogen (N_2) when the quick release valve is operated (a piston moves and opens the nitrogen gas port). The light gas used in the pump tube is helium of initial pressure 0.16 MPa. The thickness of the mylar diaphragm is 188 μ m. The high pressure coupling was originally a straight-step adapter to reduce the tube diameter from 50 mm to 15 mm [11]. To increase the projectile velocity, it has now been modified to a converging section as shown in Fig. 2.

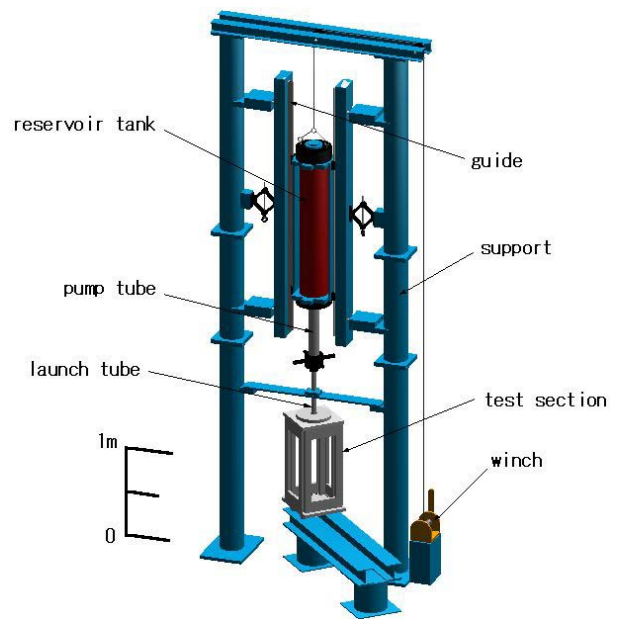


Fig. 1 Vertical two stage light gas gun

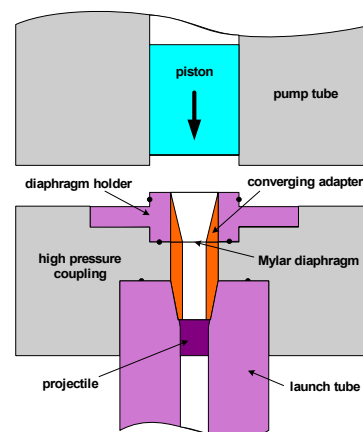


Fig. 2 High pressure coupling with converging section

The test setup is shown in Fig. 3. Mild steel nozzles were used in these experiments. The projectile is fired downwards from the entrance of the launch through the pressure or blast relief section, which is designed to diminish the blast wave in front of the projectile. The nozzle is directly connected to the exit of the

pressure relief section and is firmly seated in the top wall of the test chamber. The liquid is retained in the nozzle using a plastic diaphragm seal at the top and bottom of the nozzle. This diaphragm is very thin (around 40-50 μm thick) and of low strength for the impact momentum of the projectile. Its purpose is only to hold the weight of the liquid and therefore it is reasonable to neglect any projectile momentum loss due to it. After the impact, the projectile is brought to rest in the nozzle cavity (note that occasionally it bounces back and rests in the blast relief section). Projectile and liquid jet velocities are measured using a laser beam interruption or time of flight method, two laser beams, 30 mm apart being used for the projectile velocity. For the liquid jet velocity measurement, six laser beams are employed. This allows assessment of the jet penetration and jet velocity attenuation. The stand-off distance of the first beam to the nozzle orifice is 5 mm while the preset distance between each laser beam is 60 mm. Time differences of jet passage on each laser beam are recorded by a digital oscilloscope.

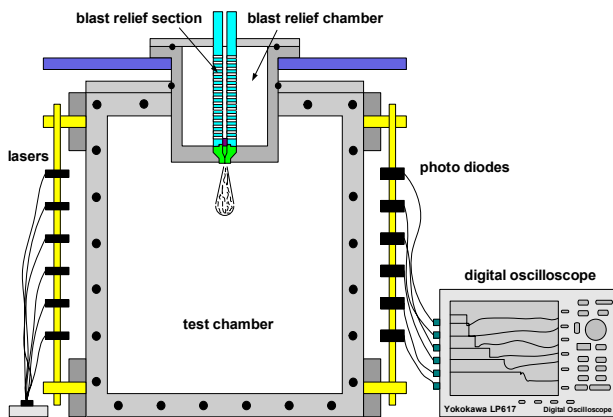


Fig. 3 Nozzle assembly and jet velocity measurement

3. Results

In current study, two nozzle geometries were used. The first is a straight conical nozzle with cone angle of 47° . The second is a stepped nozzle [12]. Both of these have a nozzle orifice of 1 mm and are made from mild steel. The entrance of the nozzle cavity where the projectile impacts is very slightly bigger (diameter of 15.1 mm) than the projectile diameter. This is to ensure the proper impact and maximum momentum transfer between the projectile and liquid package. An example of the results of the flight time recorded by the digital oscilloscope is shown in Fig. 4. From the intensity drop, the time duration which the jet tip passes each laser beam can be determined. Knowing the preset distance between each laser beam (60 mm) and assuming the jet velocity is constant in each laser beam interval

(e.g. beam no.1 and beam no.2), the tip velocity of the jet can be estimated. Then, in the next interval, another jet tip velocity is similarly determined. Therefore, the relationship between the changes in jet tip velocity against the flight times and also the penetration distance can be investigated at the same time in a single experiment.

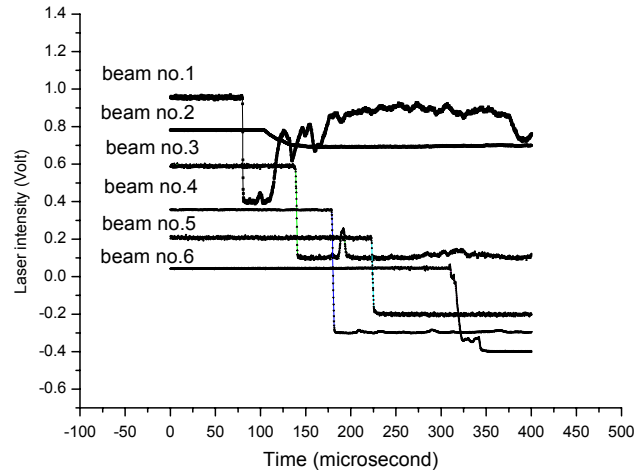


Fig. 4 Time traces of jet flight through six laser beams

Fig. 5 shows results of liquid (water and diesel fuel) jet velocities and penetration distances plotted against time using a 47° conical nozzle. At the impact velocity of 700 m/s, the velocity of the diesel fuel jet is slightly higher than that of water, the values being 1863 m/s and 1714 m/s respectively. This means that the diesel jet has a slightly longer penetration length at the same flight time and so usually has a longer penetration distance (i.e. overall distance). Both water and diesel exhibit the same trend for both attenuation and penetration. This graph shows that the velocity attenuation is significantly high during the first 300 μs . Note that, in the experiment, the maximum detectable penetration distance is only 300 mm, this being where the sixth laser beam is placed. However, in Fig. 5(a) the plot is approximately extended up to a time of 2000 μs . A comparison can then be made with the estimation in Pianthong *et al.* [3] of jet velocity attenuation and penetration distance obtained from the use of conventional diesel fuel spray formulae. This is shown in Fig. 5(b). The initial velocity of the diesel jet used in Fig. 5(b) is 1800 m/s. Note that the current experiments and the estimations from the formula show a similar trend especially for velocity attenuation, however their penetration is quite different. This depends on many factors i.e. nozzle geometry, nozzle orifice diameter, driving condition, and the liquid properties.

For a stepped nozzle, the initial velocity of a diesel fuel jet of around 1500 m/s is obtained. This is slightly lower than that from

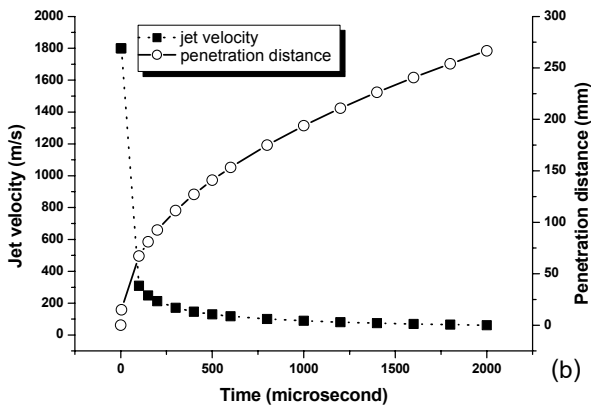
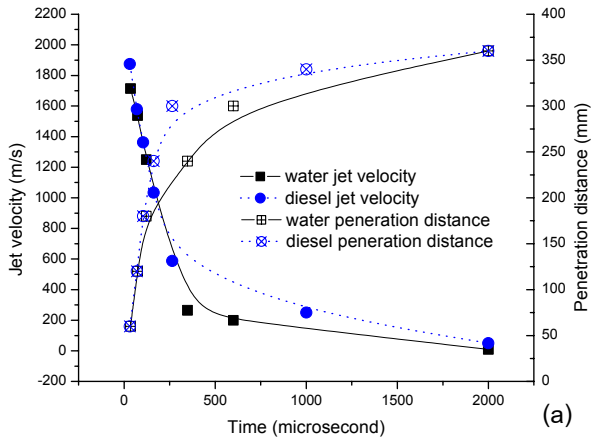


Fig.5. Plots of jet velocity attenuation and jet penetration distances against time (a) experimental (b) estimation

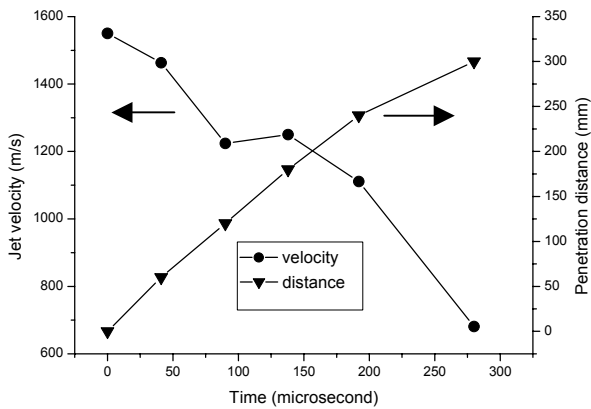


Fig.6. (a) Plots of velocity attenuation and penetration distance of stepped nozzle

straight conical nozzle. However, the most interesting phenomenon found in this experiment is that the jet velocity decreases at the beginning and then increases (by around 50-100 m/s) after leaving the nozzle orifice for 120 μ s as shown in Fig. 6. This is suspected to be caused by the second pulsed of the jet overtaking the first pulse. The former is believed to be faster than the first jet pulse as has been confirmed by the analysis developed in this program [12]. Multiple pulsing has

usually been found when the conical angle of the nozzle is very wide, example shadowgraphs of such a jet being shown in Fig. 7. Those are series of images of supersonic diesel fuel jets taken by high-speed camera and shadowgraph optical setup [13]. At least three jet tips and leading shock waves are observed. These certainly prove that the jet is leaving the nozzle orifice as multiple pulses caused by the shock wave reflection inside the nozzle cavity.

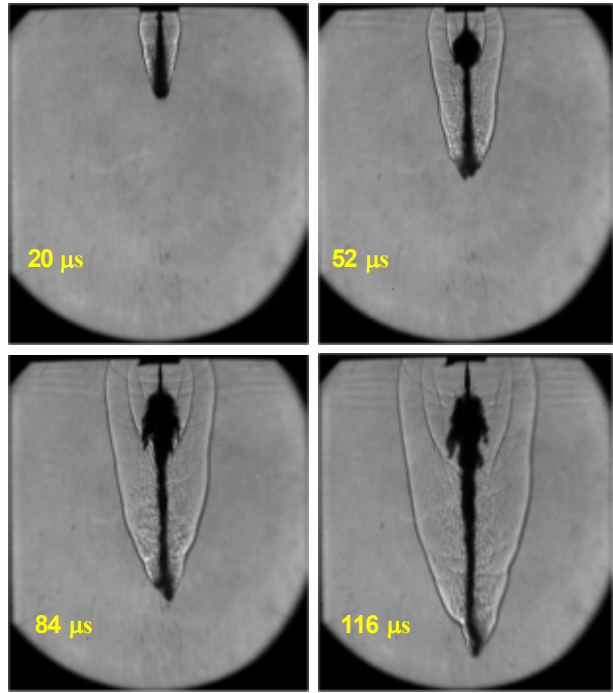


Fig. 7 Multiple pulsed supersonic diesel fuel jets

4. Discussion

Very high pressure diesel fuel injection has substantial benefits but some disadvantages. Current technology uses jets which have a velocity such that they are likely to have a high subsonic Mach number at the conditions of the air in the engine at the time of injection. When the injection pressures are further increased to values sufficient for the jets to become supersonic, some interesting phenomena appear which have the potential to further improve the combustion characteristics. Of particular note is the bow shock wave that forms ahead of the jet. The entropy rise across the shock increases the air temperature by a significant amount which will shorten the ignition delay of the fuel.

Using a specially designed apparatus which provides a single pulsed jet, the shock wave phenomenon has been studied. Injection pressures of nearly 5 GPa have been obtained with corresponding jet velocities up to 2000 m/s or more. The apparatus uses impact to drive the jet and hence some phenomena in the nozzle sac may be different from either a

common rail or HEUI system if they could reach such a high pressure. With impact driven jets, a shock wave reflection pattern forms in the liquid inside the nozzle cavity. This provides secondary shocks around the body of the jet as it emerges into the air. It should be noted that the sudden application of such a high pressure in any driving system is likely to cause a similar liquid shock pattern although the details may be different.

The tests using the present apparatus have examined jets at very high velocities (1500 m/s to 1800 m/s) in atmospheric air. Note that these Mach numbers are equivalent to velocities of 2530 and 3036 m/s at diesel injection conditions. The shock is attached and the tip of the jet has been reshaped to a more conical profile. It is not clear at this stage which provides the best atomization and mixing although the shadowgraph photographs seem to show that the high speed jet is better. This would be expected.

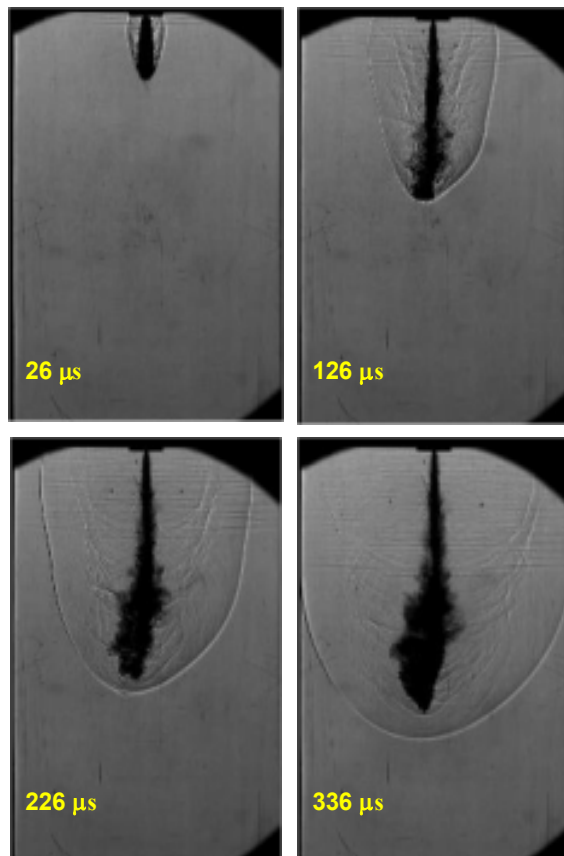


Fig. 8 Supersonic diesel fuel jet from the cavitating orifice

It should be noted that the current experiments have been carried out on smooth, conical, single-hole nozzles. There is substantial evidence that a multi-hole diesel nozzle with more complex internal passages around its needle produces cavitating flows which alter the emerging jet, shorten the breakup length and noticeably increase the rate of atomization and mixing. For

example, a preliminary study on cavitating the jet leaving the nozzle has been carried out. The visualization of the diesel jet is shown in Fig. 8. The nozzle orifice is modified by preparing it as a thread (M1.2x0.25) instead of being a smooth orifice. From the visualization, the jet has much slower velocity and shorter penetration distance. The mixing and atomization seems to be better than those of the jet from smooth nozzle.

In all diesel engines, the jet penetration is important. Because of the ignition delay, which is likely to be at least 1 ms, a high velocity jet may penetrate a considerable distance before ignition. A reasonable penetration at the time of ignition should be less than the distance the jet travels from the injector to the wall. For a central injection about 15° below horizontal and additional distance due to swirl, this approaches the cylinder bore size. Using conventional formulae, they have been estimated [3]. At 1 ms, 600, 1200 and 1800 m/s jets have penetrated about 117, 161 and 194 mm respectively. These are moderately large distances and may place a limitation on the use of extreme pressure injection in smaller engines depending upon whether the shock waves can further shorten the ignition delay. Also, from the visualization in Fig. 7 and Fig. 8 the penetration distance of both jets are considerably too long (around 40-50 cm) for using in diesel engine.

5. Concluding Remarks

Supersonic liquid diesel fuel jets in the range of 1500 m/s to 1800 m/s have been produced and examined. The main purpose is to investigate the attenuation and the penetration distance of the liquid jets. Six laser beams have been used and installed in series downstream of the jet. It is found that the attenuation is relatively high during the first 300 μ s. The penetration distance is around 300-500 mm but this depends on many factors. The experimental results agree quite well with the estimation from subsonic formulae. Using high-speed camera and shadowgraph technique, photographs show the shock wave structures and phenomena during the jetting process which tend to enhance the atomization. The possibility to apply such high speed diesel fuel jet for use in the diesel engine is discussed. It was found that at such injection pressures and velocities the fuel jets might be too long for the conventional diesel engine unless the cavitating or shortening the penetration length of the jet. This needs further study in detail.

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