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Study of Shock Wave Characteristics of Supersonic Diesel Fuel Jets Using a Shadowgraph Technique

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Abstract

In this paper, a technique for the generation of supersonic liquid (water and diesel fuel) jets is presented. The supersonic liquid jet is generated by the use of a purpose-developed vertical, single-stage powder gun. With the aid of a shadowgraph technique, the characteristics and behaviour of supersonic liquid jets have been visualised. The visual evidence of supersonic diesel fuel jets (velocity around 2000 m/s) generated from a variety of nozzle types is presented. The effects of various nozzle parameters on the jet behaviour are determined. It is found that the characteristics of the leading edge shock wave and jet shape are significantly related to its nozzle geometry. The jet characteristics and its leading edge shock wave are also assessed to determine the potential for auto-ignition.

Introduction

For a few decades, the characteristics of high-speed liquid jets have been widely studied. These can be of benefit to a number of technological and scientific applications such as cleaning and cutting technology, mining and tunnelling. It has been recently conjectured that the characteristics of high-speed liquid jets may be beneficial in improving combustion in such applications as direct injection diesel engines and SCRAM jet engines. It should be noted that there are practical limitations on the usable maximum jet velocity. Nevertheless, a fundamental study of the auto-ignition possibility is important. Important potential benefits are increased combustion efficiency and enhanced emission control from improved atomisation. A special technique is needed to generate such a high-speed liquid jet. A ballistic range method has been successfully used to provide a highly pulsed impact to accelerate a liquid jet to the supersonic range [1, 7, 10]. Its main advantages are repeatability and controllability. This method typically uses a projectile to accelerate a packet of liquid through a converging nozzle. In such a process, the pressure in the front region of the liquid is rapidly increased. The liquid then moves with a velocity which may be in the supersonic range itself forming a supersonic liquid jet on emergence from the orifice. The mechanism of such high-speed liquid jets has been previously described [3, 4]. Recently, it has been suggested that auto-ignition of a light oil jet at a velocity of 2-3 km/s occurs, when injected into a normal ambient environment [3, 10]. This is suspected because of the high temperature and pressure behind the shock wave ahead of the supersonic jet.

For such high-speed liquid jets, effective flow visualisation is necessary to investigate characteristics of the flow. It is widely recognised that optical flow visualisation is the most suitable method to observe the shock wave in a compressible flow study. The shadowgraph is the simplest optical visualising procedure, and it is especially convenient for clearly indicating shock wave location. The related shadowgraph technique has been applied to many areas; high-speed liquid jets [10], interaction of a turbulent round jet with a free surface [5], unsteady jet characteristics in a stratified fluid [11] and aerodynamic characteristics of annular impinging jets [6].

In this paper, the generation of supersonic liquid jets is briefly described. The shadowgraph method is used to visualise the characteristics of a supersonic diesel fuel jet and its shock wave. Many nozzle geometries have been tested in order to investigate their effect on jet velocities, jet shapes and shock wave characteristics. The shadowgraph can effectively capture supersonic diesel fuel jets and their shock wave characteristics. Also the possibility of auto-ignition, induced by the strong leading edge shock wave, of supersonic diesel fuel jets is investigated

Experimental Setup

To generate supersonic liquid jets, the required strongly pulsed impact is achieved by using a single stage powder gun firing a projectile of diameter 8.0 mm. The projectile is made from polycarbonate, is cylindrical in shape and 10 mm long. Nozzles used in this experiment are made from mild steel. The nozzle assembly and liquid set-up is shown in figure 1. The projectile is fired downwards through the pressure 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 well 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 and of low strength compared to the impact momentum from the projectile. Therefore, it is reasonable to neglect the momentum loss of the projectile due to the strength of this plastic. After the impact, the projectile is brought to rest in the nozzle cavity. Projectile and fuel jet velocity are measured using the laser beam interruption method. The accuracy in the measured velocity is high, with an error of only 1-3 %.

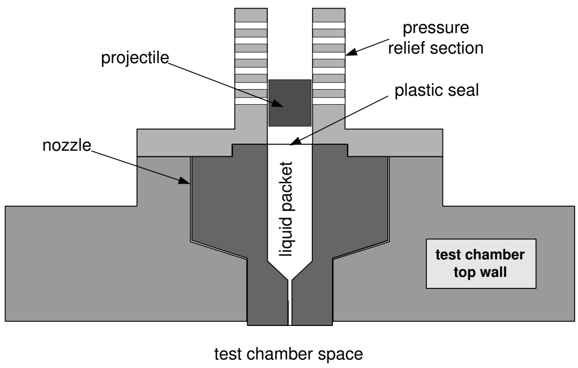

Figure 1: Nozzle assembly and liquid setup

The schematic arrangement of the shadowgraph system is shown in figure 2. The trigger signal for the argon jet light source is from a high temperature pressure transducer (PCB 112A05), which is located between the exit of the launch tube and the entrance of the flight tube. The signal from the pressure transducer is magnified by the signal amplifier before passing through the signal retarder where the signal delay is preset to trigger the argon light source. The argon light source operates with the power to spark gap of 3 J, 0.2 μs light duration, and 0.07 μs rise time. Two lenses are used in this system. They basically collimate the light beam from the light source through the test section. The test section window is a transparent polymethyl methacrylate (perspex). The film holder is placed on the other end of the test section which is 25 cm away from the target object. High-speed Polariod, 3000ASA, was used in this test. Its advantages are quick development and adequate resolution. The condition in the test chamber is atmospheric (25 °C).

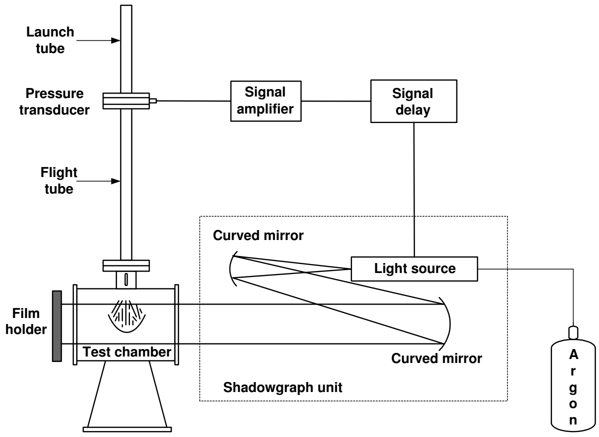

Figure 2: Schematic arrangement of shadowgraph system

Results of Jets Visualization

The generation, velocity measurement and velocity maximisation of supersonic liquid jets were presented in previous work [8]. In this study, the goal is to attempt to capture the appearance of the supersonic diesel fuel jet and its shock wave. The shadowgraph technique can successfully capture a shock wave and jet image at various stages of its progress through quiescent air. Figure 3 shows two stages of a typical water jet travelling at 600 m/s, from the initial impingement into the quiescent air until the disintegration of the core jet into droplets. These jets were generated from a 5.0 mm orifice diameter and a 450 m/s projectile impact velocity. The early stage, Figure 3(a), shows a bulbous characteristic, "mushroom" effect caused by the high density behind the shock manipulating the jet front. It does not have enough energy to push through the increasingly dense medium ahead of it and therefore remains detached from the shock. The shock standing away from the liquid head is expected to occur at speeds of between Mach 1 and 2 (or slightly higher). The later stage, figure 3(b), shows parallel jet sides as the shock wave diminishes and the tail becomes increasingly prominent. The head is still rounded but probably contains more atomised liquid than the core jet. The generation of liquid jets by impact momentum transfer generally results in a repeated reflected shock pattern within the liquid in the nozzle internal geometry. This would cause the emerging jet to pulsate, forming a rippled shock front. The clean shock in these experiments suggests that there is little, if any, significant shock reflection of this type within the nozzle.

Figure 4 shows two stages of development of a much higher supersonic velocity water jet emerging from a straight cone nozzle with 1.0 mm orifice diameter. At an early stage, figure 4(a), the shock wave is attached (rather than detached as found in the low supersonic velocity jet) to the front of the jet whilst the jet itself stays intact. At a later stage, figure 4(b), the core jet is surrounded by fine particles of atomised water. Alongside the body of the jet, a second shock wave is clearly observable. This implies that multiple shock wave reflections occur within the nozzle cavity during the injection process.

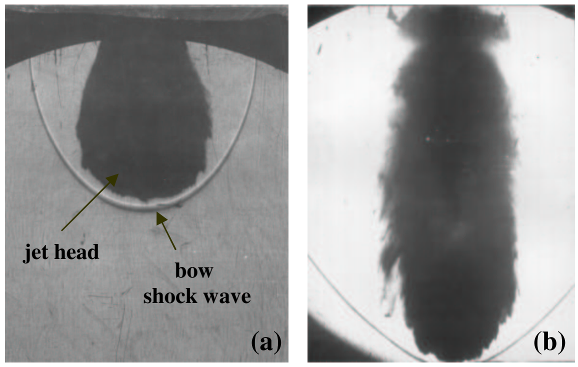

Figure 3: Low supersonic water jets,mm, 600 m/s (a) initial stage: showing bulbous characteristic at jet head and (b) later stage: showing parallel jet body and more atomisation

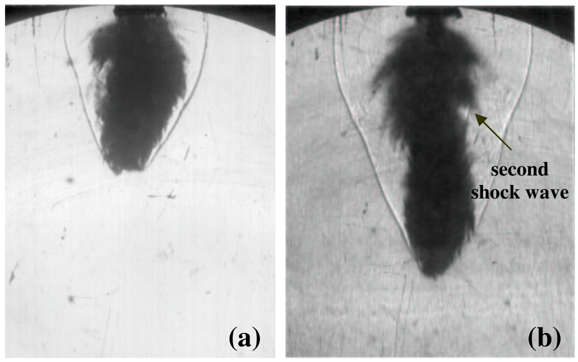

Figure 4: Supersonic water jets, d = 1.0 mm, 1800 m/s (a) at early stage and (b) at later stage

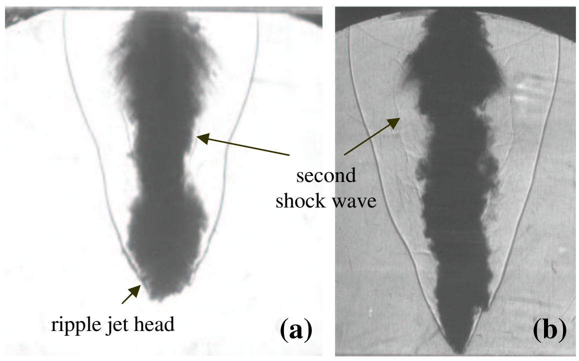

Figure 5: Supersonic diesel fuel jets, d = 1.0 mm, 1800 m/s

Figure 5 presents shadowgraphs of diesel fuel jets at a late stage. The jet head is not a classical "mushroom" or bulbous shape; instead, it is sharp and rippled. Its leading shock wave is oblique and attached to the jet head rather than bow and stand away (or detached). The second shock wave is clearly seen in figure 5(a). In figure 5(b), the second shock wave is starting to dissipate. A fine droplet shroud covers the main core and jet body before dispersing in the test chamber. Supersonic diesel fuel jets from smaller diameter orifice nozzles (e.g. 0.7 and 0.5 mm) are presented in figure 6. The jet from the 0.5 mm orifice has a significantly smaller core jet and provides better atomisation and a smaller droplet size. However, in the experiment, the jet velocity from the 0.5 mm orifice is always slower than that from the 0.7 mm orifice. Again, figure 6 shows signs of multiple

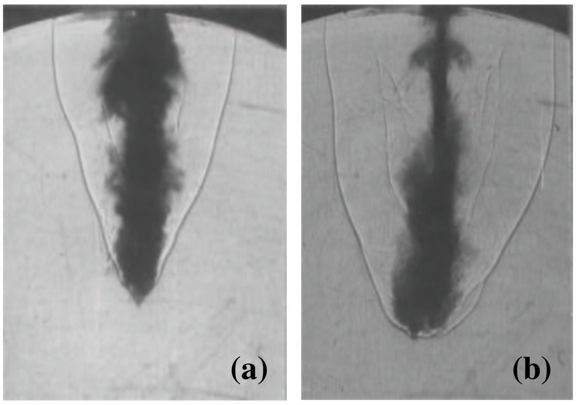

Figure 6: Supersonic diesel jets from a small orifice: (a) d = 0.7 mm, 2000 m/s (b) d = 0.5 mm, 1850 m/s

pulsed jets similar to those in figure 5. Some of the supersonic jet heads are neither round nor mushroom shaped, but rippled. Also, a non-smooth front shock wave is formed. This implies that, during the period when the liquid package is being accelerated inside the nozzle, multiple reflections of a liquid shock wave occur between the projectile and nozzle wall. This then propels the liquid jet so that it exits from the orifice as a series of jet pulses which are discrete but at a very high frequency.

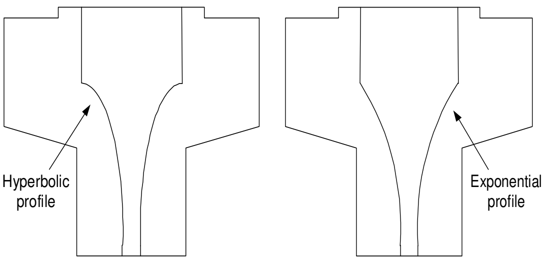

Figure 7: Hyperbolic and exponential profile nozzles

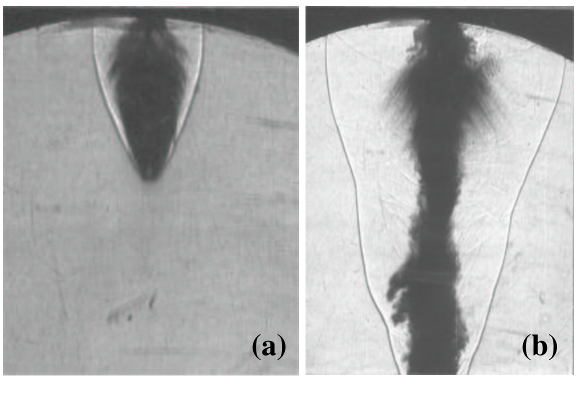

Figure 8: Various stage of supersonic diesel fuel jets from exponential profile nozzles, d = 1.0 mm, 1850 m/s

To maximise the liquid jet velocity, curved profile nozzles (i.e. exponential and hyperbolic nozzle) have been tested. Edney [2] has shown that exponentially and hyperbolically curved nozzle profiles (figure 7) produce higher jet velocities than straight-walled nozzles. However, our attempts to take advantage of curved nozzle profiles in this way have increased jet velocities by only 50-100 m/s. Figure 8 presents visualisation of supersonic jets from exponential profile nozzles. In the early stage, figure 8(a), the supersonic diesel fuel jet looks similar to that

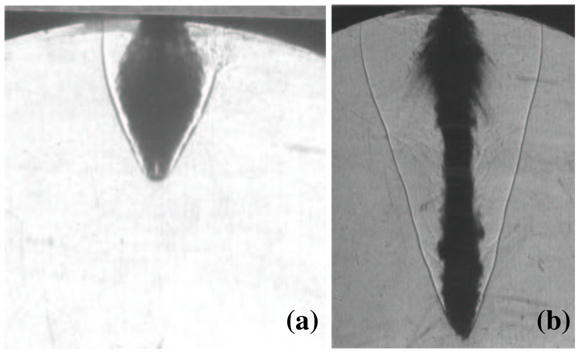

Figure 9: Various stage of supersonic diesel fuel jets from hyperbolic profile nozzles, d = 1.0 mm, 1850 m/s

from the straight cone nozzle. However, at later stages, the jet remains more intact with strong penetration but less atomisation. Similar characteristics are found in jets from hyperbolic profile nozzles (figure 9). This suggested that it is more appropriate for application to jet cutting or penetration than to engine injection. Surprisingly, there is no sign of a second shock wave occurring in most of the curved profile nozzle experiments, suggesting that there is no multiple shock wave reflection during its generation process.

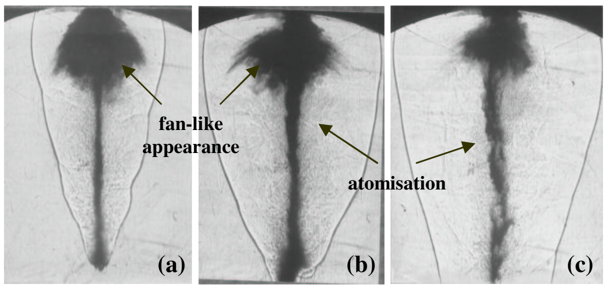

Figure 10: Various stage of hypersonic diesel fuel jets from hardened nozzle: (a)–(b) d = 1.0 mm, 2300 m/s (c) d = 0.7 mm, 2500 m/s

All the above jets were generated within mild steel nozzles. Hardened high carbon steel nozzles, with a straight cone profile were also tested. With these, diesel fuel jets from 1.0 mm and 0.7 mm orifice diameters are shown in figure 10. These have a unique characteristic, being long and thin and surrounded by very fine atomisation and vapour. Immediately at the nozzle exit, a “fan-like” flow appears. The jet head emerges from the nozzle at very high velocity. This behaviour is close to that of the “shape charge” phenomena, which generates very high speed jets. The fan may be caused by the strong impact of the projectile into the tapered cone at the point where the projectile stops within the nozzle. This creates a large shock reflection pressure in the nozzle wall, which may be transferred to the fuel package. Both the 1.0 mm and 0.7 mm orifice diameter hardened nozzles give similar jet characteristics. Note that each shadowgraph is of a different shot, with some variance or uncertainty in its appearance being possible.

Auto-ignition Investigation

A few researchers [10, 3] have claimed that auto-ignition occurred for a 2000 m/s fuel oil jet injected into a low temperature and pressure atmosphere. Theoretically, auto-ignition is possible because of the high temperature and pressure behind the bow shock. With high injection pressure and intense shear layer of the jet, the droplet mean diameter is much smaller than that of a typical fuel spray which reduces ignition delay time. However, these high temperature and high pressure conditions only exist in the region directly behind the normal part of the shock wave. The ignition delay time of the fuel jet at these conditions (gas phase equivalence ratio, temperature, pressure) must be less than the shock wave dissipation time. Correlations of the important physical properties on ignition delay have been reviewed [9]. The ignition delay time was estimated (for normal shock wave condition) giving the minimum time that the conditions behind the leading edge shock wave must be maintained for ignition. Although it is quite short, in the order of 40-50 μs, auto-ignition of the supersonic fuel jets may be possible. However, the question remains as to whether the gas phase equivalence ratio of 1.0 used in the estimation exists and whether gas flow to the cooler region behind the oblique shock negates these factors.

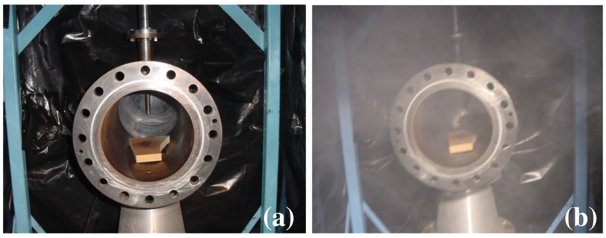

Figure 11: Photographs of area around test chamber: (a) before (b) after the experiment

The experimental investigation showed that a blanket of smoke always covers the test chamber after every diesel fuel jet injection at a velocity around 2000 m/s. Figure 11 shows the region within the test chamber before and after the experiment. The smoke throughout the test chamber after the injection is clearly visible. However, the smoke does not confirm that auto-ignition has occurred, as this might be fuel vapour or pyrolysed fuel. Thus, in these experiments, the test chamber gas was analysed using an exhaust gas analyser. Combustion gases (i.e. CO_2, CO) have not been found, although a small amount, about 10 ppm, of HC and NO existed in the test chamber after each test. Diesel fuel has a cetane number of about 50. To investigate further, fuels with a cetane number up to 100 (n-hexadecane) were tested to improve the ignition quality. Again no CO_2 or CO was found. However, increased HC and NO, around 50-60 ppm, was found with the higher cetane number fuel. From this evidence and the shadowgraphs of figure 5–figure 10, it seems that auto-ignition has not occurred. There are four possible reasons for this. Firstly, the temperature and pressure conditions behind the leading edge shock wave are not uniform and they decrease progressively behind it. Secondly, the normal shock wave is not retained along the jet body where auto-ignition usually starts in spray combustion. Therefore, normal shock wave theory over-estimates the conditions, these existing at the jet tip only. When using oblique shock wave theory (flow over a cone), the temperature and pressure would be only 431 °C and 3.327 atm respectively. Auto-ignition will not then readily occur as the ignition delay would be about 2-3 seconds even at an equivalence ratio of 1.0. Thirdly, the leading edge shock wave dissipates very quickly as the jet velocity reduces, with the temperature and pressure behind it being no longer maintained. Finally, the equivalence ratio in this case might not be appropriate for auto-ignition. Further clarification of the auto-ignition possibility of a supersonic diesel fuel jet is required. This is much more complex than that for a normal injection process because it involves a shock-induced increase in pressure and temperature which is more local and transient than those from compression by a piston. Further investigation at UNSW is in progress. By raising the initial temperature and pressure slightly above ambient, producing a higher jet velocity or a combination of the two, the auto-ignition characteristics are likely to be enhanced. The exact combination of these factors needs to be defined. This will be studied further in the near future.

Conclusions

Supersonic liquid jets (water and diesel fuel) have been generated experimentally using a purpose-developed vertical, single stage powder gun. Their characteristics and behaviour have been successfully studied with the use of a shadowgraph technique. It is found that the liquid jet and its leading edge shock wave characteristics are related to the nozzle geometry and material (hardness). Shock-induced auto-ignition of a supersonic diesel fuel jet at a velocity of 2000 m/s at atmospheric conditions was also investigated. At this stage, auto-ignition was not found for fuels with cetane number between 50 to 100.

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