Shock Tube Based Diesel Spray and Methane-Air Ignition Testing

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1 Introduction

Modern diesel engines use common rail injectors, splitting the fuel addition into a short duration pilot injection followed by a longer main fuel injection, to reduce the shortcomings of traditional diesel engines [1]. Dual-fuel engines use diesel pilot injection to act as an ignition source for a premixed fuel-air primary charge [2]. Dual-fuel engines are increasingly receiving attention because of the low cost of natural gas and their low emissions compared to diesel engines. There are many studies on diesel spray ignition and methane-only ignition, but very little on diesel spray ignition in a premixed methane-air mixture. Fu and Aggarwal showed through numerical simulations that the presence of methane mixed in with cylinder air affects the diesel spray ignition delay time since the methane takes the place of some of the oxygen and can interfere in the diesel ignition kinetics [3].

Traditionally, a heated constant volume chamber is used to investigate diesel spray ignition under engine conditions. However, for the dual-fuel engine application a heated spray chamber is not applicable since the methane-air mixture undergoes chemical reaction while the mixture heats up in the chamber. The objective of this study is to use a shock tube approach, where the premixed methane-air is shock heated before diesel injection, to get around this limitation. Diesel fuel was injected via a commercial injector at the endplate of a shock tube optically accessed test-section following shock reflection. Experiments were carried out with diesel spray injected into air-only, and premixed methane-air with no diesel injection are reported. These provide baseline ignition delay time data that can be used to determine the effect of methane on diesel spray ignition. High-speed regular and schlieren photography were used to capture the fuel spray formation and ignition processes. The results are discussed in the context of the goal of performing experiments involving diesel injection into methane-air.

2 Experimental Details

All experiments were conducted with a double-diaphragm shock tube with optical access just ahead of the end wall, a schematic of the apparatus is provided in Figure 1**Error! Reference source not found.**. The shock tube has a 2.85 m long, 76 mm square cross-section driven section and a 1.83 m long, 102 mm diameter cylindrical driver section. The driver and driven sections are connected via a 762 mm long circular-to-square cross-section transition section that maintains the planarity of the shock wave. The two diaphragms were made from 1.6 mm thick 1100 aluminum sheet that was stamped with a cross-shaped indentation to promote "petaling" upon opening. An inert gas mixture consisting of 21% argon and 79% nitrogen was slowly injected from immediately after the diaphragms to form a buffer between the driver gas and the test gas. This buffer gas reduced the length of the test gas slug at the end wall so that pressure rise associated with heat release is minimized during ignition and combustion. . This pressure rise produces a temperature rise that results in a reduction in the ignition delay. Minimizing this effect produces a process closer to the constant pressure and enthalpy condition typically used to model ignition phenomenon.

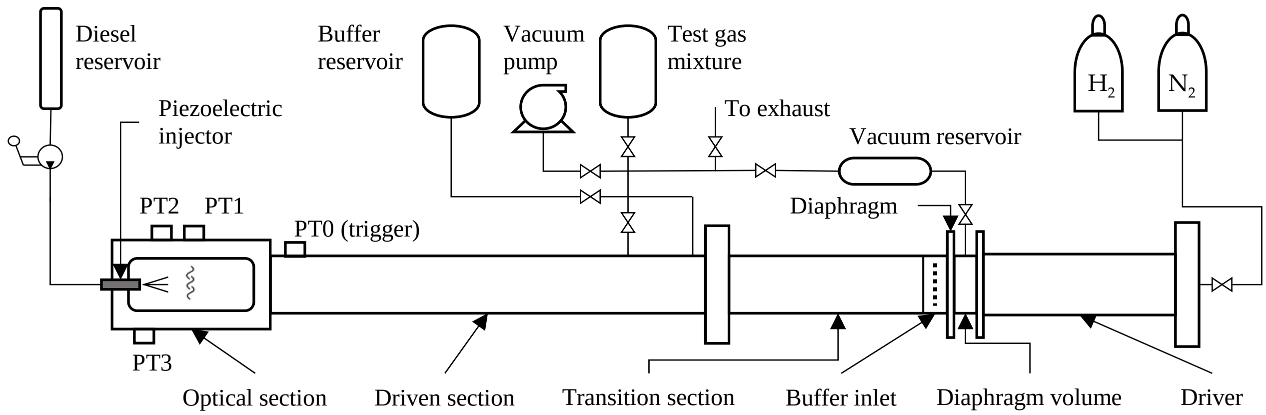

Figure 1: Experimental schematic of the shock tube, illustrating the optical section, buffer inlet and injector assembly.

An early 2010s Volkswagen TDI piezoelectric diesel injector was mounted behind the end wall so that the nozzle protrudes minimally into the centre of the optical section, comparable to an engine cylinder. The nozzle has 8 orifices 0.18 mm in diameter arranged in an included angle of 160° and is energized by a NI-cRIO FPGA module. Fuel is supplied by a hand crank pump up to an injection pressure of 90 MPa. The schlieren system developed is a 150 mm single pass folded z-type assembly with a Photron camera capable of up to 65000 frames per second (fps) video and 576 x 288 pixel resolution. Four PCB piezoelectric pressure transducers were mounted along the optical section: three near the end wall and one slightly further upstream to act as a trigger. The trigger transducer was connected to a custom-built comparator logic assembly connected to all the equipment while the rest were used to simultaneously calculate incident shock speed via time-of-arrival and provide pressure traces for ensuing combustion. In addition to testing with schlieren, regular photography was used to observe the spray event and ignition from an oblique angle, shown in Figure 2.

Ignition delay for both diesel and methane was separately measured via high-speed schlieren video to obtain baseline data. For diesel, the time of the first video frame with visible spray from the injector until the first frame of the sudden and rapid expansion of the fuel-air region was used. Methane testing was similar; however the beginning of delay was measured from the shock reflection. Because the beginning of delay measurement is focused on different steps of the test it is crucial to begin fuel injection into the cylinder as early as possible after shock reflection during dual fuel testing.

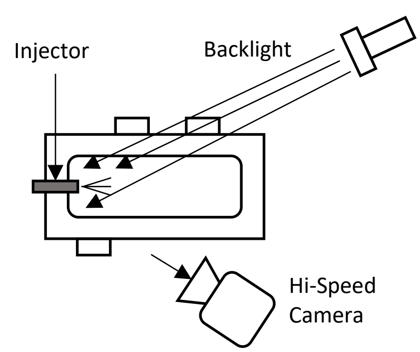

Figure 2: Schematic of the optical section in the regular photography configuration.

Two sets of tests were performed: diesel spray into synthetic air and pre-mixed methane-air.. Experimental parameters are shown in Table 1. Argon was used in place of nitrogen in the test gas to avoid bifurcation of the reflected shock and the associated boundary layer separation. This minimizes the degradation of the schlieren imaging and temperature inhomogeneity in the test-section. De Vries and Peterson showed that the ignition delay for methane is not affected by replacing the nitrogen in air with argon [4].

Table 1: Summary of experimental parameters.

	Diesel spray	Premixed methane-air
T_5 [K]	880-1490	900-1400
P_5 [bar]	10 ± 1.6	10 ± 1.6
P_f [bar]	900 ± 20	Disabled
t_{dur} [ms]	0.15 ± 0.015	Disabled
Test Gas	21% O_2, 79% Ar	2.5% CH_4 with O_2/Ar-air

For each test the driven section was evacuated to at least 0.15 mbar before filling with pre-mixed test gas. . The equilibrium post-reflected shock condition was calculated using known initial conditions and the measured incident shock velocity. In order to achieve the desired shock Mach number the initial pressure of both the driver and driven section were varied, as well as the ratio of hydrogen to nitrogen in the driver. Hydrogen was used in the driver because of the unavailability of helium.

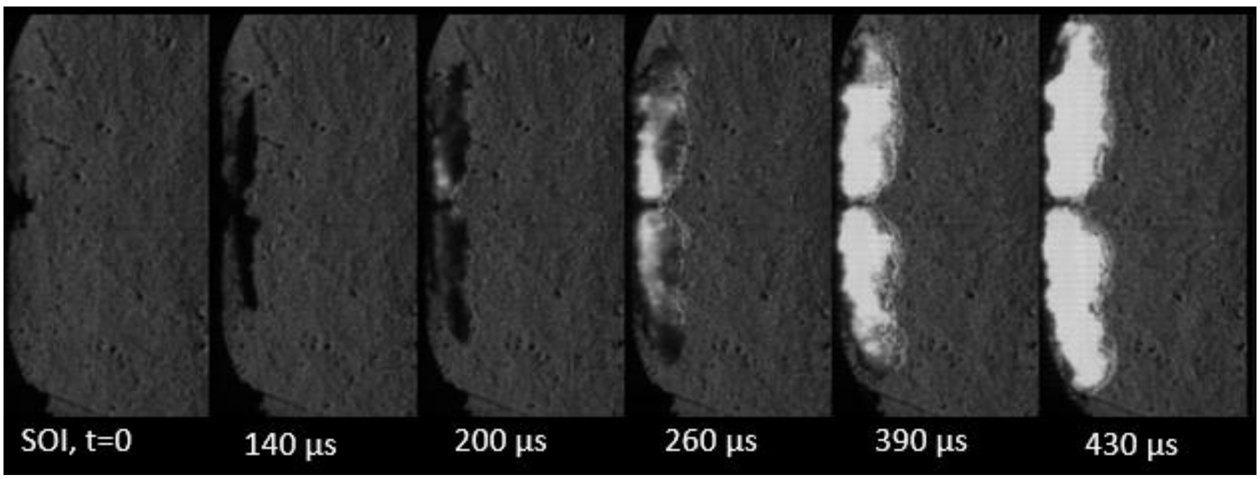

Figure 3: Schlieren images of diesel spray ignition at 10 bar, 1490 K. SOI denotes start of injection.

3 Results & Discussion

Results for reflected shock conditions of roughly 10 bar and 900 K to 1480 K are reported. The schlieren images from a higher temperature diesel-air test are shown in Figure 3. The penetrating liquid spray and surrounding vapor is observed in the first two images. The first sign of ignition is observed in image 3. Because of the very small amount of diesel injected (typical of pilot injection) there was no detectable pressure rise associated with the diesel combustion. At temperatures higher than 1300 K light was emitted from the spray and captured in the schlieren video, as seen in the images in Figure 3.

A limitation of the schlieren imaging is that individual diesel jets are superimposed on each other in the image, and as a result there is no clear image of a single jet igniting. This makes the identification of the ignition location difficult from the schlieren images. Non-schlieren images captured from the camera in the orientation shown in Figure 2 are provided in Figure 4, the oblique angle permitted the observation of the individual jets. The lighting produced multiple images of the individual jets. One image was the shadow of the jet cast on the end wall, and the other jet image was the shadow produced by the reflection of the light off the highly reflective aluminum end wall. Note, light reflected off the liquid fuel spray was not observed, but the intense light from the combustion was. It was found that the spray ignites upstream of the liquid penetration tip at the relatively high temperature of this test, which is consistent with the findings of Gopalakrishnan et al. [5].

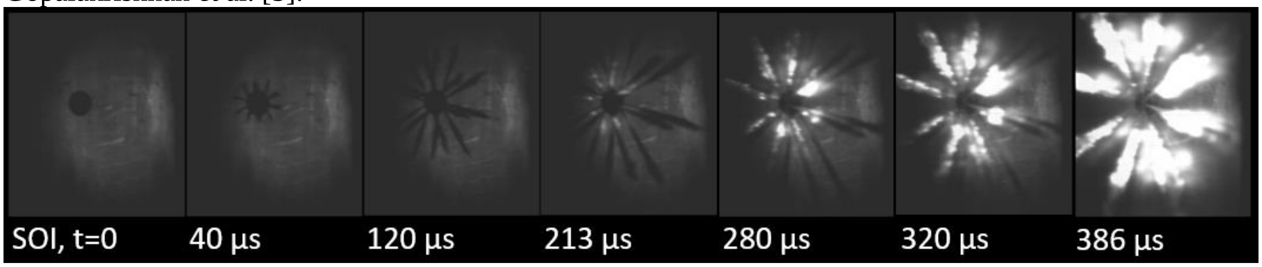

Figure 4: Video frames of ignition location testing for 1300 K, 10 bar initial conditions. It is worth noting the shadow of the spray on the end wall can be seen in addition to the real spray due to the angle of the camera and light source.

The measured ignition delay is presented in an Arrhenius-style plot in Figure 5, along with data obtained by other researchers using different experimental techniques. There is good agreement between the present data with that reported from other shock tube testing with fuel injectors [5-7]. Since ignition is based on the video images, there is an uncertainty of 15.4 μs in the ignition delay time associated with the inter-frame time. The ignition delay of the diesel spray decreases with increasing reflected temperature, over the range of 900 K to 1480 K. Diesel fuel chemistry has traditionally been studied using homogeneous mixtures consisting of single-component surrogates that show complex ignition phenomena including multi-stage ignition and negative temperature correlation (NTC). There was no evidence of two-stage ignition and the temperature range tested at in this study is mostly higher than the 800-900K NTC temperature range for the diesel surrogate n-heptane [3]. Furthermore, Fu and Aggarwal proposed that fuel evaporation and other two-phase flow effects tend to dampen the temperature effects even in the NTC region. This is evident when comparing the present data with the data obtained by Haylett et al. [8] in an aerosol shock tube where it is assumed that the diesel is completely evaporated and perfectly mixed with the air following the passage of the incident shock. Therefore, one can conclude that the longer ignition delay observed in the present study is governed by the effect of fuel atomization and evaporation.

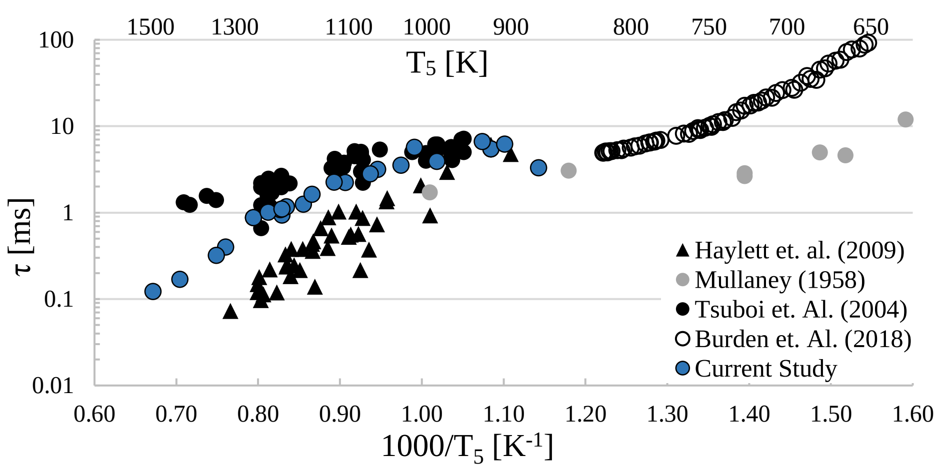

Figure 5: Ignition delay time for diesel spray as a function of reflected temperature for the present study. Results are compared to homogeneous diesel ignition from Haylett et al. [8]*, shock tube diesel spray from Mullaney* [6] *and Tsuboi et. al.*[7]*, and CVSCC spray measurement from Burden et. al.*[9]

In the methane-air tests ignition delay time was measured using the schlieren imaging and verified via pressure measurments. Images from a methane-air test with a reflected temperature of 1130K are provided in Figure 6, and the recorded pressure is shown in Figure 7. The planar reflected shock wave is observed in the first frame traveling from left-to-right. Individual flame kernels start to appear at 0.714 ms. It is not clear if the flame kernals at mid-height are in the channel core, or in the boundary layer of the windows. The slow growth in the flame surface produces a slow rise in pressure starting at roughly 1 ms in Figure 7. An explosion occurs abruptly on the right side of the field-of-view, a blast wave produced by the explosion can clearly be seen propagating towards the end wall in the images at 2.19, 2.21 and 2.36 ms (see arrow). This explosion produces an instantaneous rise in the pressure 2.2 ms post-reflection, see Figure 6.

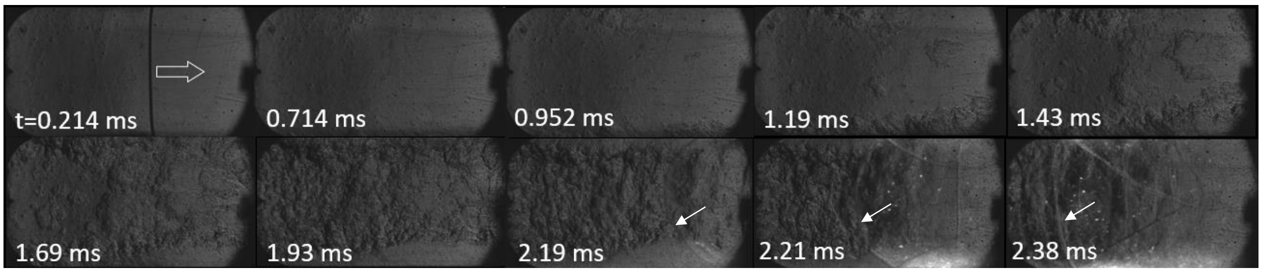

Figure 6: Schlieren images of 2.5% methane ignition at 1130 K, 11 bar. Time-zero corresponds to time of shock wave reflection.

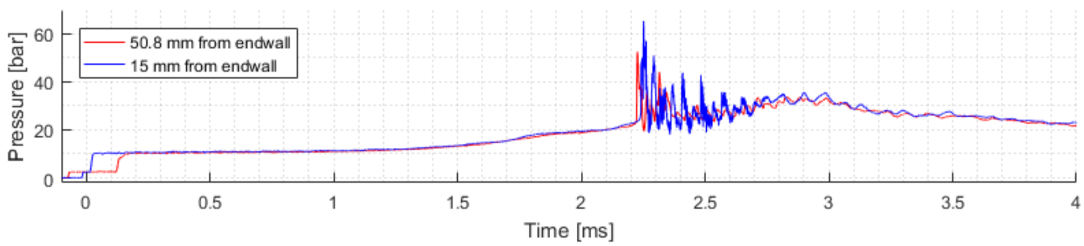

Figure 7: Pressure trace for 2.5% methane at 1130 K, 11 bar.

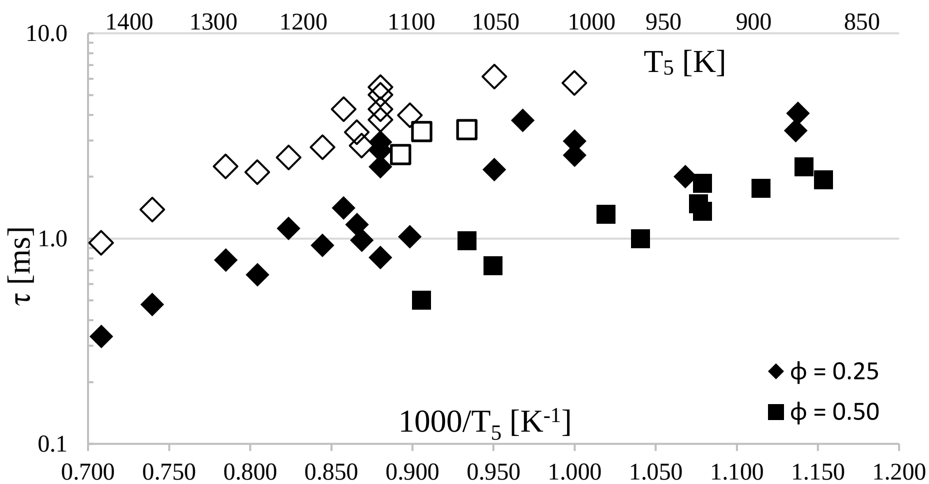

Figure 8: Ignition delay time for premixed methane-argon-oxygen as a function of reflected temperature and reflected shock pressure nominally 10 bar. Solid symbols represent mild ignition and open ones depict strong ignition. The error on the ignition time is 15 microseconds.

Two different equivalence ratios, both fuel lean mixtures, were tested. In the literature, these two observed reflected shock ignition behaviours are typically referred to as mild and strong [10]. Mild ignition is characterised by multiple ignition spots, typically away from the end wall, with merging combustion fronts. A strong ignition involves a more coherent release of energy producing a strong shock wave. For a pressure around 10 bar, a transition from mild to strong ignition for methane-air was reported by Huang et al. [11] at around 1200 K. Pressure traces reported by Huang et al. for strong ignition events are very similar to that shown in Figure 7 from the present study. In this study, mild ignition was followed by an explosion for all temperatures, except for the lowest-temperature condition of 1033 K, suggesting a lower transition temperature than that reported by Huang et al.

Both the flame kernal (mild) and explosion (strong) times obtained in this study as a function of temperature are provided in Figure 8. There is significant scatter in the mild ignition delay time compared to that of strong ignition time, but both show a linear tendancy with temperature. In limited tests performed with diesel spray injected into methane-air, ignition of the methane occurred before the diesel. This is consistent with a comparison of the reported ignition times measured separately, see Figure 5 and Figure 8.

4 Conclusions

A shock tube with optical access was used to measure the ignition delay time for diesel spray into argon-oxygen and premixed methane-argon-oxygen at temperatures from 1000 K to 1480 K. The ignition times are very similar over this temperature range and therefore a dual fuel engine would not operate this high in temperature. In the future, this method will be used to study diesel ignition in a methane-air atmosphere at temperatures more applicable to dual fuel engines. This will require increasing the shock tube test time by tailoring the driver.

References

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