Experimental Improvements to a Constant Volume Combustion Chamber for Fuel Spray and Ignition Studies

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Experimental Improvements to a Constant Volume Combustion Chamber for Fuel Spray and Ignition Studies

by

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April 24, 2023
DECLARATION OF ORIGINALITY

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

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ABSTRACT

The primary objective of this thesis is to improve optical setups of a constant volume combustion chamber to better understand the vaporization and spray characteristics of various fuels. The schlieren imaging technique is utilized to visualize phenomena that are challenging to observe directly. In this thesis, the schlieren imaging is used to observe the spray and ignition characteristics of DME and diesel fuels under high injection pressure.

First, various optical techniques are discussed and compared under the same test condition including schlieren, shadowgraph, and direct imaging. The advantages for these techniques are presented and the most appropriate technique for different testing scenarios is proposed.

Second, the spray and ignition characteristics of DME and diesel are compared. The inert spray for both fuels are observed and compared using schlieren imaging technique. The reactive spray for both fuels are observed and compared using direct imaging and shadowgraph imaging system.
DEDICATION

This work is dedicated to beloved family
ACKNOWLEDGEMENT

It is my honor to express the sincere gratitude to my supervisors, Dr. Ofelia A. Jianu and Dr. Ming Zheng, for their inspiration, guidance, and encouragement throughout my work in the MASc. program.

I would also like to thank my committee members Dr. Xiang Chen and Dr. Xiao Yu for their precious time and guidance on my thesis.

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## ABBREVIATIONS/SYMBOLS

### Abbreviations

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CI</td>
<td>Compression ignition</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>DBI</td>
<td>Diffused back-illumination</td>
</tr>
<tr>
<td>DI</td>
<td>Direct injection</td>
</tr>
<tr>
<td>DME</td>
<td>Dimethyl ether</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
</tr>
<tr>
<td>FC</td>
<td>Flame chemiluminescence</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbons</td>
</tr>
<tr>
<td>HP</td>
<td>High-pressure</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>Oxides of nitrogen</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>RT-FPGA</td>
<td>Real-time field-programmable gate array</td>
</tr>
</tbody>
</table>

### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n)</td>
<td>Refractive Index</td>
</tr>
<tr>
<td>(k)</td>
<td>Gladstone-dale coefficient</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density</td>
</tr>
<tr>
<td>(C_0)</td>
<td>Speed of light in vacuum</td>
</tr>
<tr>
<td>(C)</td>
<td>Speed of light in medium</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>Excess air ratio</td>
</tr>
</tbody>
</table>
CHAPTER 1    INTRODUCTION

1.1 Research Background

Compression ignition (CI) engines have inherently high thermal efficiencies because of the high compression ratio and fuel lean operation. The high compression ratio produces the high temperatures required to achieve the auto-ignition of the fuel, and the high expansion ratio reduces energy loss to the exhaust [1]. However, the reduction of pollutant emissions from CI engines is challenging.

For CI engines, hydrocarbons (HC) and carbon monoxide (CO) emissions are typically low, particulate matter (PM) and oxides of nitrogen (NOx) may be produced in significant quantities [2]. Localized regions of heterogeneous air-fuel mixture in CI engines leads to low levels of oxygen surrounding fuel droplets at the start of combustion, which consequently prevents complete combustion and leads to increased unburned carbonaceous particles (soot) [2].

The additional oxygen in the cylinder is required to facilitate complete combustion as well as to compensate for the inhomogeneity in the fuel distribution. However, high flame temperatures predominate because local stoichiometric air-fuel ratios prevail in such heterogeneous combustion processes [1,3]. As a result, the high flame temperature in the presence of abundant oxygen and nitrogen causes diesel engine combustion to produce significant levels of NOx [1,4,5].

In other words, the primary source of NOx emissions from diesel engines comes from the high flame temperatures that occur locally in the near-stoichiometric auto-ignition area, whereas the primary source of soot generation comes from the mixing-controlled burning
of the bulk fuel. Hence, lowering the combustion temperatures reduces NOx emissions, and increasing the homogeneity of the air-fuel mixture reduces soot production [6].

The use of exhaust gas recirculation (EGR) helps reduce NOx emissions by lowering the local flame temperatures. The process works by recirculating a portion of the engine's exhaust gas back into the combustion chamber, where it mixes with the incoming air, hence, EGR reduces NOx emissions by reducing the peak combustion temperature and diluting the oxygen content in the combustion chamber. However, diffusion-controlled combustion struggles to find oxygen at the late stages of combustion and in this case, the dilution of oxygen concentration increases the difficulties of burning smoke-free [1].

Resolving the trade-off between NOx and soot emissions in diesel engines is challenging as diesel combustion is hindered by a balance between low combustion temperatures and mixture homogeneity. One approach is to use alternative fuels like Dimethyl ether (DME) which has suitable chemical properties for use in CI engines and physical properties to realize a low tendency to produce soot.

1.2 Alternative Fuels

Renewable energy has been attractive because of the gradual exhaustion of fossil fuels and the environmental concerns of burning such fuels. Alternative fuels are considered as energy sources with great potential to reduce particulate emissions in CI engines. Moreover, alternative fuels are often produced from renewable sources, which render the net carbon impact negligible and improves energy security [10]. From environmental conservation and energy security perspectives, DME is an attractive alternative to conventional diesel fuel for CI engines [11].
1.2.1 Dimethyl Ether

DME has the chemical formula CH$_3$-O-CH$_3$. DME can be produced from various energy sources such as natural gas, crude oil, and coal. On the other hand, many renewable energy sources can be converted to DME such as biomass, crop residual, and renewable power.

The critical properties of DME and Diesel are listed in Table 1.1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Diesel</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td></td>
<td>C$<em>{10}$H$</em>{20}$~C$<em>{15}$H$</em>{28}$</td>
<td>CH$_3$OCH$_3$</td>
</tr>
<tr>
<td>Cetane number</td>
<td></td>
<td>43</td>
<td>55-60</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>g/mol</td>
<td>~170</td>
<td>46</td>
</tr>
<tr>
<td>Stoichiometric air/fuel ratio</td>
<td>by weight</td>
<td>14.6</td>
<td>8.95</td>
</tr>
<tr>
<td>LHV</td>
<td>MJ/kg</td>
<td>43</td>
<td>28.4</td>
</tr>
<tr>
<td>Oxygen content</td>
<td>wt%</td>
<td>0</td>
<td>34.8</td>
</tr>
<tr>
<td>Liquid kinematic viscosity</td>
<td>cSt</td>
<td>&gt;3</td>
<td>0.184</td>
</tr>
<tr>
<td>Liquid density @15°C</td>
<td>kg/m$^3$</td>
<td>840-880</td>
<td>667@5bar absolute</td>
</tr>
<tr>
<td>Auto-ignition Temperature</td>
<td>°C</td>
<td>180-285</td>
<td>350</td>
</tr>
<tr>
<td>Heat of evaporation</td>
<td>kJ/kg</td>
<td>316.6</td>
<td>465</td>
</tr>
<tr>
<td>Surface tension @ 25°C</td>
<td>N/m</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>Lubricity, HFRR WSD*</td>
<td>μm</td>
<td>300 @60°C</td>
<td>Poor</td>
</tr>
<tr>
<td>Vapor pressure @ 20°C</td>
<td>kPa</td>
<td>&lt;&lt; 10</td>
<td>510</td>
</tr>
<tr>
<td>Boiling Temperature</td>
<td>°C</td>
<td>180-360</td>
<td>-25</td>
</tr>
</tbody>
</table>
The boiling point for DME at 1 bar absolute is 248K. Therefore, DME is gaseous under ambient conditions. For liquid fuel management, the low boiling point of DME necessitates a closed-loop pressurized fuel system [10]. The tendency to vaporize increases the chance of cavitation which prevents stable fuel injection operation and challenging on the pump hardware [10]. To account for the heating and safety factors of the DME fuel during operation, a closed-loop fuel system under about 30 bar absolute is considered adequate [8,10,11]. Lee et al. [12] studied the injection rate characteristics of DME fuel and reported that the pressure in the tube was kept at 30 bar during fuel injection to prevent DME vapour generation in the tube. DME is reactive with most elastomers due to its corrosiveness. Thus, unique material such as polytetrafluoroethylene (PTFE) is necessary for the sealing of DME fueling systems [10]. The DME has a much lower viscosity than diesel, meaning that DME can cause wear problems to the injectors. Therefore, a lubricity enhancer is often suggested during operation.

The high oxygen content (34.8 % by mass), the absence of C-C bonds in the molecular geometry and the quick evaporation of the fuel allows DME has near-zero-smoke combustion products [9,10]. The proportion of fuel carbon forming soot precursors had been found to decrease with increased oxygen content in the fuel and decreased number of C-C bonds [13,14]. Sidhu et al. [15] found that DME had much lower PM (0.026%) with the DME engine, NOx was reduced by 40% compared to compared to diesel combustion under the same conditions, and HC was maintained at an extremely low level [16,17].

1.3 Schlieren and Shadowgraph Imaging

Schlieren and shadowgraph imaging techniques are utilized to visualize phenomena that are challenging to observe directly. Robert Hooke [18] first introduced schlieren and
shadowgraph imaging techniques in the 17th century. They became a standard laboratory tool in observing shock waves until the 19th century owing to reinvention by August Toepler [18,19]. Kamimoto et al. [20] investigated the characteristics of diesel spray and flame as a function of fuel injection pressure using the schlieren technique under quiescent atmospheric condition. The atomization and air entrainment of non-evaporating spray was observed with the aid of the schlieren imaging system. Pastor et al. [21] performed a parametric study on the schlieren setup to optimize the optical arrangement and the quality of the resulting image. The diameter of the light source and the collection angle in the Fourier plane (knife edge) is varied to optimize the images. They reported that the schlieren visualization was an appropriate technique to obtain spray penetration length under reactive and non-reactive conditions.

Refraction is the change in phase speed when light passes through a transparent medium. The refractive index \( n \) of a medium describes the change in phase speeds and is given by [19]:

\[
\frac{n}{C_0} = \frac{C}{c}
\]

(1)

where \( C_0 \) is the speed of light in vacuum and \( C \) is the speed of light in the medium.

For gas, the refractive index is linearly proportional to the density of the gas, given by the Gladstone-Dale relation [19]:

\[
n = 1 + k \rho
\]

(2)

where \( k \) is known as the Gladstone-Dale coefficient, \( \rho \) is the density of the media gas.
When light travels orthogonally through a transparent medium with a change in refractive index, the speed of the light is affected but the light keeps travelling in the original direction. When light intersects the change in refractive index obliquely, the light is deflected to the region with a greater n value, or a denser region. These deflections could be visible with the aid of schlieren or shadowgraph imaging systems.

Figure 1.1 Diagram of the schlieren system [19]

The classical schlieren system is depicted in Figure 1.1. This system contains the illumination section and the collection section [22]. The light path starts from a point light source, and the light is collimated by the concave lens 1 and brought to focus by lens 2. A camera is placed after the focus point to capture the image. A knife edge is placed at the focal point of lens 2, blocking part of the light. These gradient disturbances of inhomogeneous transparent media are frequently termed “schlieren” [19].

As depicted in Figure 1.1, the collimated light rays that do not pass through the schlieren (red lines) propagate along their original light path. The light rays that pass through the schlieren are reflected away from their original path. Two such reflected ray paths are presented, one bent upward, the other downward. Both refracted rays do not pass the focal
point of the lens 2. The light ray refracted downward by the schlieren is blocked by the knife edge or land outside the projecting screen, thus corresponding to a dark image point, while the light ray refracted upward brightens a point on the screen [22].

The setup of schlieren imaging and shadowgraph imaging systems differ mainly in that the former uses a knife edge to enhance contrast by blocking some of the light at the focal point.

The turbulence flame kernel generated by air and fuel mixture ignition are observed by shadowgraph and schlieren imaging are shown in Figure 1.2. These two images are captured under the same test condition but not simultaneously. Significant differences could be observed in these two images. 1. Shadowgraph imaging indicates the location of the density variation and 2. Schlieren imaging is sensitive to the density variation and even the flow of the background mixture could be observed in schlieren imaging.

![Figure 1.2 Air and fuel mixture ignition observed by shadowgraph and schlieren imaging](image)
1.4 Research Objective

In this work, the spray characteristics for DME and diesel fuel are captured by different imaging systems under high-pressure inert and reactive sprays. The specific research objectives are:

- Improve the constant volume combustion chamber system to be suitable for fuel spray studies under engine like working fluid conditions.
- Set up a schlieren imaging system to the constant volume combustion chamber and find the appropriate imaging system to observe the fuel spray characteristics under chemically inert and reactive conditions.
- Investigate the atomization and ignition process of DME and diesel fuel, compare DME fuel spray characteristics with that of diesel fuels under inert and reactive conditions.
1.5 Thesis Outline

There are five chapters in this thesis.

- Chapter I introduces the research background, associated challenges, and related literature.

- Chapter II describes the experimental setups. Detailed experimental apparatus and procedures are presented in this section. The schlieren and shadowgraph imaging systems are used to observe the fuel spray under inert and reacting conditions.

- In Chapter III, a simultaneous schlieren and shadowgraph optical arrangement is used to observe the fuel spray characteristics. The images from these two techniques are compared and discussed.

- In Chapter IV, DME and diesel fuel sprays are recorded under room temperature and reacting conditions. The reacting spray requires pre-combustion to create high-pressure and high-temperature conditions.

- Chapter V summarizes this research with a conclusion and future work.
CHAPTER 2  Experimental Setup and Methodology

In chapter 2, the experiment apparatus and research methodologies are introduced. In this study, a constant volume combustion chamber system with optical accessibility has been used to study the characteristics of chemically inert and reactive spray. Optical measurements via direct, shadowgraph, and schlieren imaging were applied to visualize the spray characteristics under various conditions.

2.1 Constant Volume Combustion Chamber

A constant volume combustion chamber shown in Figure 2.1 was used as the testing platform. Five orthogonal ports gave optical access to the combustion chamber, hence the fuel spray and ignition characteristics inside the chamber could be observed. A spark plug was mounted at the top of the combustion chamber to generate a spark event if a combustion event inside the chamber was necessary, whereas the bottom side of the chamber was connected to an exhaust line to evacuate the exhaust gases after the combustion. The left view was blocked and equipped with an injector, and the rest three ports were equipped with quartz windows for optical measurements. The specifications for the chamber are listed in Table 2.1.
Figure 2.1 The optical constant volume combustion chamber platform: (a) shows the appearance of the chamber and (b) shows a section view which shows the interior details of the chamber.
### Table 2.1 Chamber specifications

<table>
<thead>
<tr>
<th>Chamber dimension</th>
<th>Width 312mm x Depth 312mm x Height 305mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber material</td>
<td>Stainless Steel SS 304</td>
</tr>
<tr>
<td>Chamber inside volume</td>
<td>2.95 liters</td>
</tr>
<tr>
<td>Chamber maximum operating temperature</td>
<td>200°C</td>
</tr>
<tr>
<td>Chamber maximum operating pressure</td>
<td>150bar</td>
</tr>
<tr>
<td>Heater power</td>
<td>6 kW (cartridge heater x 6)</td>
</tr>
<tr>
<td>Insulation material</td>
<td>Mineral wool rated @ 650°C</td>
</tr>
<tr>
<td>Optical quartz window diameter</td>
<td>110mm</td>
</tr>
<tr>
<td>Optical access diameter</td>
<td>90mm</td>
</tr>
</tbody>
</table>

Six cartridge heaters were installed in the chamber body for heating purpose. It took approximately 60 minutes to heat the combustion chamber from room temperature to 200°C. Two thermocouples were installed to monitor the combustion chamber wall and gas temperature, respectively. The gas charging and discharging processes were controlled via pneumatic valves. Prior to each experiment, the chamber was purged by compressed nitrogen and then vacuumed to minimize the impact of residual exhaust gases.

2.2 **Fuel Delivery and Injection Systems**

In this section, the fuel delivery and injection systems are described. As discussed in section 1.2, because DME is in gaseous phase at ambient conditions (1 bar absolute, 25°C), fuel delivery and storage are very important to safely operating the fueling system. The procedures for fueling and handling are presented in the following part. The DME fueling line is depicted in Figure 2.2.
A portable fuel cart with a 1-US-gallon tank was used to store the DME in liquid phase for experiments. Compressed nitrogen gas was supplied to the tank via a top valve at 10bar absolute pressure to keep DME in liquid phase. The liquid DME flowed to a high-pressure (HP) pneumatic pump via a bottom valve, to raise the fuel pressure. A Maximator LSF 100-2 pneumatic pump was utilized to pressurize the fuel [23]. Another compressed nitrogen gas cylinder was connected to the HP pneumatic pump. The fuel injection pressure was adjusted by a regulator on the HP pump. The pressure ratio of the HP pump between the inlet and outlet was fixed at 1:226, by the piston area ratio of the pump, whilst the outlet pressure was rated at 1600bar. The HP pump was sealed with Viton O-ring, a material that does not react with DME. A common rail plenum (commonly used in diesel engines) was connected to the HP pump outlet to stabilize the fuel injection pressure.

![Diagram of DME fueling line](image)

**Figure 2.2** DME fueling line for high pressure injection application

Two fuel injectors were used in this work. A six-hole gasoline direct injection (GDI) injector was operated under inert spray condition with 300bar injection pressure. Under reactive spray condition, an engine-like working fluid conditions were mimicked inside the constant volume chamber. For direct injection compression ignition engines, injection
pressure is usually extreme high. Because the GDI injector was not designed to operate at high injection pressure, a piezoelectric diesel injector with higher pressure rating (2000bar) was used under reactive spray condition [24]. Five of the six nozzle holes were plugged by laser welding to render a single plume. The diameter of the nozzle hole is 180μm. The injection commands were generated using a real-time field-programmable gate array (RT-FPGA) controller, and the signal was sent to an injector power driver (IPoD/ EFS 8370) [25]. An in-house designed LabVIEW program was applied for precisely controlling the spark discharge, fuel injection, and camera recording commands, the detailed information will be presented in the following section.

Figure 2.3 Single-hole laser welded piezoelectric injector

2.3 Testing Scenario of the Reactive Spray

An engine-like ambient condition was mimicked physically inside the combustion chamber, to study the reactive spray. A mixture of ethylene(C\textsubscript{2}H\textsubscript{4}), oxygen(O\textsubscript{2}), and nitrogen(N\textsubscript{2}) was charged into the chamber, spark ignited and combusted to reach elevated background pressure and temperature that are compatible to engine like working fluid conditions suitable for fuel spray studies. The general testing procedures for reactive spray
are presented, along with detailed methodologies and approaches presenting in the following subsections. Along the timeline, a flow diagram for the testing procedure is depicted in Figure 2.4.

1. The constant volume chamber was evacuated by a vacuum pump. The premixed C₂H₄, O₂, and N₂ mixture was charged into the chamber to the pressure of 8 bar absolute through intake lines.
2. The spark plug ignited the mixture to create a combustion event to elevate the temperature and pressure inside the chamber.
3. At desired background temperature (~1237 K), the liquid fuel for spray study was injected into the chamber and auto-ignites.
4. After the end of combustion, the exhaust line was open to discharge the combusted gases. After the burned gases were released, nitrogen was supplied through intake lines to purge the chamber.
2.3.1 Mixture preparation

The residual oxygen concentration after the “first-stage” (spark-generated) combustion is a crucial parameter because fuel oxidation under high temperature is dependent on the oxygen presence surrounding the fuel spray. The oxygen remaining in the combustion products was controlled by adjusting the initial mixture composition. An initial lean mixture is required to ensure some oxygen is left over for “second stage” (spray-generated) combustion. The excess oxygen ratio determines the ignitability of the premixed air-fuel mixture. In this study, the targeted residual oxygen concentration was kept at 15% which was near the moderate EGR level in the engine chamber, and the oxygen-fuel ratio was kept at 2.
Assume ideal combustion, the oxygen concentration for products can be approximated by using a theoretical chemical reaction balancing:

\[ a \, C_2H_4 + b \, O_2 + c \, N_2 \rightarrow d \, CO_2 + e \, H_2O + f \, O_2 + g \, N_2 \]  

(3)

With a known excess oxygen ratio before combustion, a desired oxygen concentration \( \left( \frac{f}{d+e+f+g} \right) \) after combustion, all the coefficient \( a, b, c, d, e, f, \) and \( g \) can be calculated by balancing the carbon, oxygen and hydrogen atoms between reactants and products.

The ignitability of the premixed mixture for spark ignition depends on the excess oxygen ratio. The stoichiometric \( O_2 \) to \( C_2H_4 \) ratio is 3 by mole (3 moles of \( C_2H_4 \) consume 1 mole of \( O_2 \) under stoichiometric combustion), thus the \( O_2 \) to \( C_2H_4 \) ratio should be 6 to keep the excess oxygen ratio at 2. The reactant mixture composition in Table 2.1 was calculated based on the desired residual oxygen concentration of 15% and the excess oxygen ratio prior to spark ignition of 2.

<table>
<thead>
<tr>
<th>Reactants</th>
<th>Mixture</th>
<th>( C_2H_4, N_2, O_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.56kg/m(^3)</td>
<td></td>
</tr>
<tr>
<td>Excess oxygen ratio</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>( C_2H_4 ) concentration</td>
<td>5% by mole</td>
<td></td>
</tr>
<tr>
<td>( O_2 ) concentration</td>
<td>30% by mole</td>
<td></td>
</tr>
<tr>
<td>( N_2 ) concentration</td>
<td>65% by mole</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Products</th>
<th>( O_2 )</th>
<th>15% by mole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( CO_2 )</td>
<td>10% by mole</td>
</tr>
<tr>
<td></td>
<td>( N_2 )</td>
<td>65% by mole</td>
</tr>
<tr>
<td></td>
<td>( H_2O )</td>
<td>10% by mole</td>
</tr>
</tbody>
</table>
A high-pressure reservoir (premixing chamber) with 5L volume stores and supplies the premixed charge to the intake lines, as shown in Figure 2.5. In this study, the premixing chamber was charged to 48bar absolute with the premixed mixture. Due to lack of active internal stirring, the mixture was kept at room temperature for 24 hours to enhance the mixing of the premixed charge. Because the vapor pressure for C₂H₄, O₂, and N₂ are much higher than 48bar, all the three gases are considered to be ideal gas. The volume concentration of each gas in the premixing chamber was controlled by the partial pressure of each component that is added, a pressure gauge is mounted on the chamber to monitor the pressure inside the chamber. Each gas was separately added to the premixing chamber. For safety concerns, the order to fill the premixing chamber was C₂H₄, N₂, and lastly O₂. It is vital to fill the chamber with N₂ before charging O₂. The presence of N₂ the fuel concentration and reduced the potential safety hazards. The detailed procedures for preparing the mixture in the premixing chamber are as follows:

- Empty the premixing chamber by a vacuum pump to ~0.1bar.
- Charge the premixing chamber with C₂H₄ first to desired pressure (48 bar×5% = 2.4 bar)
- Charge the chamber with N₂ to desired pressure (33.6 bar)
- Charge the chamber with O₂ to 48 bar
- Wait for 24 hours to enhance the homogeneity of mixture inside the chamber
2.3.2 Pressure Measurement

To produce the reactive spray condition, the premixed mixture was ignited by a spark plug to create a combustion event that elevates the temperature and pressure, while lowers the O\textsubscript{2} concentration inside the chamber transiently. Figure 2.6 shows the pressure measurement and the calculated bulk-gas temperature calculation history of the combustion event. The pressure was measured with an AVL GU24D piezoelectric pressure transducer. The charge output was conditioned with a Kistler 5010 charge amplifier. The bulk temperature was calculated using the ideal gas law based on the measured pressure. The pressure inside the chamber rose as the premixed fuel burned and released energy.

A peak pressure of ~48bar was achieved around 113ms. After the “first-stage” combustion, the pressure decayed because of heat transfer to the chamber walls. When the desired temperature was reached inside the chamber, the fuel for spray combustion study was injected into the chamber and to be subjected to the auto-ignition in the “second-stage” combustion. The background temperature further decreased as the injection was further
retarded. Under the presented test conditions, the postponing of fuel injection beyond 1400ms caused unsuccessful “second-stage” combustion. This constrained the background temperature range for reactive spray studies from 1091K to 2063K. In this work, the fuel for spray study was injected at 1000ms with a background temperature of 1236K in the chamber, which was close to the background temperature inside an engine cylinder at top dead center of a compression stroke i.e. the engine like condition for spray and ignition.

Figure 2.6 The timeline of the chamber pressure for reactive fuel spray

Since the time domain for the pressure measurement is in “second” level, a medium time constant was applied to the charge amplifier under this condition. A short time constant caused inaccurate pressure measurement because of fast decay rate.

2.3.3 Flame Arrestor

To prevent damage to the equipment from the combustion, a flame arrestor was placed directly after the exhaust port of the chamber as shown in Figure 2.7. A filter with 7-micron pore size was filled with stainless balls to quench the flame.
2.4 Optical Arrangement

In this section, direct imaging, shadowgraph imaging, and schlieren imaging techniques were set up for optical investigation of the fuel spray and ignition characteristics.

2.4.1 Simultaneous Shadowgraph and Schlieren Imaging System

A simultaneous high-speed schlieren and shadowgraph imaging system was conducted to visualize the fuel spray characteristics. When comparing the images captured from the above mentioned two imaging techniques, the uncertainty owing to the randomness of spray events was minished since two images were captured at the same time for the same spray event. A pair of parabolic mirrors with a diameter of 152.4mm and a focal length of 1524mm were used in the setup. The diameters of both mirrors are larger than the diameter of the optical window to secure all the accessible sights that could be captured. A Luminous Devices CBT-90 white LED was used as the light source and a programmable power supply with adjustable output voltage and current powers the LED. The LED was operated at its rating current (3A) to achieve the maximum light intensity.

The optical arrangement for the system is depicted in Figure 2.8. A pinhole with a diameter of 0.4mm was placed right after the LED to create a point light source. The pinhole needs
to be located at the focal point of the parabolic mirror to ensure a collimated beam passes through the window. Along the optical pathway, the second parabolic mirror was placed downstream of the combustion chamber to re-focus the beam toward the camera. A knife-edge at the focal point of the second parabolic mirror was used to block a part of the image to intensify the density contrast of the imaging, which is critical for a schlieren imaging system. A shadowgraph imaging technique will be presented without the knife edge.

A high-speed camera (camera 1) was positioned after the knife edge. The distance between the focal point and the camera determines the size of the captured image. A beam splitter was placed between the knife edge and the second parabolic mirror to capture shadowgraph imaging simultaneously. In this work, the beam splitter has a reflection/transmission ratio of 50%, meaning 50% of the light that comes from the parabolic mirror is reflected, and the rest 50% of the light transmits through the beam splitter.

Another high-speed camera (camera 2) was used to capture the shadowgraph images as depicted in Figure 2.8. The size of the image depends on the location of the beam splitter, and the distance between the beam splitter and the camera. The orientation for the beam splitter also needs to be adjusted precisely. The beam splitter was positioned at an angle of 45° to the light path. The camera and the beam splitter were also installed at an angle of 45°. Since the shadowgraph imaging system did not have a knife edge to block half of the light, the image brightness of camera 2 would be higher than that of camera 1. The views for both cameras were focused to infinite. The specifications for both cameras are listed in Table 2.2.
2.4.2 Direct Imaging System

Another setup is a direct imaging system with diffused back-illumination (DBI). The light source to illuminate the sprays was a halogen light bulb. Diffusion sheets were placed in between the optical window and the halogen light to create a uniformly illuminated background [26]. For inert spray studies, the high-speed camera was placed as opposed to the halogen light as depicted in Figure 2.9 to have the same direction of view as schlieren and shadowgraph imaging.
For reactive fuel spray studies, the high-speed camera was placed as opposed to the injector as depicted in Figure 2.10. Two halogen light sources were used to illuminate the spray. Light emitted from the ignition of fuels (flame) could also be used as the light source, such a system is called direct imaging system with flame chemiluminescence (FC) in this study. The setup for the direct imaging system with FC can be achieved simply by removing the halogen light and diffusion sheets in Figure 2.10. For all the direct imaging systems, the camera views were focused on the injector tip.
2.4.3 Summary of Experimental Improvements to the Constant Volume Chamber

In this section, the improvements to the constant volume combustion chamber platform are summarized.

Table 2.3 Summary of the experimental improvements

<table>
<thead>
<tr>
<th>Improved Components</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation</td>
<td>New insulation material was used to insulate the constant volume chamber to reduce heat loss to the surrounding. It took approximately 60 minutes to heat the combustion chamber from room temperature to 200°C, while it used to take approximately 120 minutes before the improvements.</td>
</tr>
<tr>
<td>Imaging system</td>
<td>Schlieren imaging and shadowgraph imaging systems were set up to the constant volume chamber.</td>
</tr>
<tr>
<td>Flame arrestor</td>
<td>A flame arrestor was added directly after the exhaust port of the chamber to prevent the equipment (exhaust and vacuum pneumatic valves) from being damaged because of the combustion.</td>
</tr>
</tbody>
</table>
CHAPTER 3  IMAGING SYSTEMS

This chapter compares the images from schlieren, shadowgraph, and direct imaging techniques. The three imaging techniques can help analyze different aspects of the fuel spray such as spray cone parameters, liquid and vapor penetration, and fuel vaporization. The appropriate imaging techniques for each spray stage under different conditions are proposed.

3.1 Direct, Schlieren and Shadowgraph Imaging Comparison under Inert Spray Condition

A comparison of the three imaging techniques on an inert spray condition is presented in Figure 3.1 The background condition is at 1bar absolute background pressure, 23°C background temperature, and injection pressure of 300bar absolute.

Test Conditions:
Background Temp: 25°C  Background Pressure: 1 bar abs Injection Pressure: 300 bar

Figure 3.1 Comparison of direct, shadowgraph and schlieren imaging techniques under room temperature: (a) direct imaging, (b) shadowgraph, and (c) schlieren
The direct image of the spray presented in Figure 3.1 (a) is appropriate to capture the liquid fuel spray (represented by the dark area in front of the injector) as the background light in the spray area is blocked by the liquid spray plume. However, fuel evaporation could not be observed clearly as the fuel vapors allow the light to pass through, which is subsequently captured by the camera. Shadowgraph and schlieren imaging techniques are capable of detecting the density gradients in the fluids, making the two techniques ideal for studying the fuel vaporization and mixing process. The fuel spray entrains the surrounding gas and vaporizes as it penetrates the background gas. Gaseous fuel has a lower density than liquid fuel, allowing more light to pass through and causing a brighter image. This means the gaseous fuel appears relatively brighter than the liquid fuel in shadowgraph images. The black triangle-shaped area in the direct, shadowgraph and schlieren images represents the liquid region. The slightly brighter, greyscale area surrounding the contour of the liquid fuel in the shadowgraph images (Figure 3.1 (b)) represents gaseous fuel. The schlieren imaging uses the change in the refractive index of the gaseous media with its density to represent the density gradient. The light deflected by the relatively denser fuel vapors (compared to background air) in the lower part of the fuel spray in Figure 3.1 (c) can be clearly observed using schlieren imaging. Although, the vaporization or density gradient observed by schlieren imaging is “sharper” than shadowgraph imaging, the difference between the two imaging techniques is largely insignificant under these background conditions.

The difference between schlieren and shadowgraph images becomes even more pronounced as the background temperature increases to 160°C and fuels become more
prone to vaporize. The two images captured by schlieren, and shadowgraph imaging system are shown in Figure 3.2.

**Test Conditions:**
Background Temp: 160°C  
Background Pressure: 1 bar abs  
Injection Pressure: 300 bar

![Shadowgraph and Schlieren Images](image)

Figure 3.2 Comparison of shadowgraph and schlieren imaging techniques at 160°C:

(a) shadowgraph, and (b) schlieren

Increased vaporization of fuels at higher temperature makes it more challenging to distinguish the vapor and liquid region from the figures. However, the schlieren imaging is relatively more sensitive to the fuel vapor characteristics as compared to shadowgraph imaging.

In conclusion, direct imaging with DBI is an appropriate method to observe the liquid sprays, while shadowgraph and schlieren imaging techniques are appropriate to observe vapor sprays. Under the current test conditions, schlieren imaging shows better capability to observe the vapor fuel. Since evaporation effects are a key focus when comparing DME and diesel fuels, for the upcoming test under inert condition, the schlieren imaging will be adopted to observe the vaporization behavior of both fuels.
3.2 Shadowgraph and Schlieren Imaging under Reactive Spray Condition

This section compares shadowgraph and schlieren imaging techniques under the reactive spray condition. The background temperature is around 1230K, and the injection pressure is 600bar absolute. As shown in Figure 3.3, the density gradient in the background is caused by the spark-generated flame. For the shadowgraph imaging, only a small portion of the area near the bottom extremity is dark. The injector tip, fuel spray, and flame could still be observed. As the schlieren imaging is more sensitive to the density gradient, most of the area is black for the images captured by schlieren imaging. The injector tip and fuel spray cannot be observed clearly. Therefore, because of the presence of extreme density gradients in the background, shadowgraph imaging is more appropriate under reactive spray conditions to observe the fuel spray and ignition characteristics.

Figure 3.3 Comparison of shadowgraph and schlieren imaging techniques under pre-combustion condition: (a) shadowgraph, and (b) schlieren
The high intensity of the flame causes the image to become oversaturated which affects the observation of the flame structure. Even after adding a neutral filter with 1.0 optical density (10% transmittance) and reducing the exposure time to 0.25μs, saturation persists. Additionally, the camera view is not focused near the fuel spray which also affects the observation of the flame structure. A possible solution may be to use direct imaging at low exposure time without any external illumination. Since direct imaging system of flame chemiluminescence does not require other light source, it can be coupled with shadowgraph imaging system to achieve a simultaneous shadowgraph and direct imaging system.

3.3 Simultaneous Shadowgraph and Direct Imaging with Flame Chemiluminescence under Reactive Spray Condition

In this section, shadowgraph and direct imaging are coupled to observe the spray and ignition characteristics. A time-based spray history for diesel is shown in Figure 3.4. The corresponding details of test conditions and camera settings are listed in Table 3.1. The two sets of images are captured simultaneously.
Table 3.1 Spray conditions and camera settings corresponding to Figure 3.4

<table>
<thead>
<tr>
<th>Test condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Background temperature</td>
<td>~1230K</td>
</tr>
<tr>
<td>Fuel</td>
<td>Diesel</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>600bar</td>
</tr>
<tr>
<td>Injection duration</td>
<td>300μs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Camera setting</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame rate</td>
<td>Direct imaging: 20000fps</td>
</tr>
<tr>
<td></td>
<td>Shadowgraph imaging: 20000fps</td>
</tr>
<tr>
<td>Exposure time</td>
<td>Direct imaging: 0.5μs</td>
</tr>
<tr>
<td></td>
<td>Shadowgraph imaging: 1.99μs</td>
</tr>
<tr>
<td>Resolution</td>
<td>Direct imaging: 512×512pixels</td>
</tr>
<tr>
<td></td>
<td>Shadowgraph imaging: 512×512pixels</td>
</tr>
<tr>
<td>Light source</td>
<td>Direct imaging: Flame chemiluminescence</td>
</tr>
<tr>
<td></td>
<td>Shadowgraph imaging: LED</td>
</tr>
</tbody>
</table>

Figure 3.4 Diesel spray and ignition images under 1230K background temperature:

(a) direct imaging, and (b) shadowgraph
Several perspectives could be drawn from Figure 3.4. For the images captured from shadowgraph imaging:

- Vapor penetration and evaporation could be observed. At 0.75ms, the liquid and vapor penetration can be observed, the black plume near the injector tip represents liquid fuel and the gray region near the extremity of the window represents the vapor fuel region.
- The start of the ignition could be observed clearly. At 1ms, a white area inside the vapor fuel region could be observed clearly. Simultaneously, a weak flame plume is observed in the image captured by direct imaging.
- Flame saturates the camera. At 1.3ms and 1.5ms, the combustion (extreme white region) emits abundant light and saturates the camera. The reduction of the exposure time and addition of a neutral filter result in no significant improvement to the captured intensity.

For the images captured from direct imaging:

- Flame could be observed without saturation which makes it easier to observe the structure of the flame.
- Because of the low exposure time and the absence of back light, liquid fuel spray could not be observed.
3.4 Direct Imaging with Diffused Back-illumination under Reactive Spray Condition

In this section, to observe the liquid spray simultaneously with the flame chemiluminescence, direct imaging with DBI and higher exposure time is adopted. The corresponding test conditions and camera settings are listed in Table 3.2.

As shown in Figure 3.5, liquid fuel penetration could be captured from the scattering of the back light. Moreover, the “blue color” flame is observed at the early stage of ignition (0.85ms) before it transitions into the second “hot flame” stage (1.3ms and 1.5ms). In published literature, the “blue color” flame is called “cool flame” or low temperature flame[27–29]. The name “cool flame” refers to the fact that the heat released from chemical reactions is relatively small. As a result, cool flame temperatures are relatively low and do not produce large amounts of chemical radicals and ionized species that are responsible for the familiar bright light seen in conventional flames [27].
Figure 3.5 Direct imaging with diffused light of diesel spray under 1237K background temperature: (a) raw images, and (b) images with background subtraction

Table 3.2 Test conditions and camera setting corresponding to Figure 3.5

<table>
<thead>
<tr>
<th>Test condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Background temperature</td>
<td>~1237K</td>
</tr>
<tr>
<td>Fuel</td>
<td>DME</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>750bar</td>
</tr>
<tr>
<td>Injection duration</td>
<td>300μs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Camera setting</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame rate</td>
<td>100,000fps</td>
</tr>
<tr>
<td>Exposure time</td>
<td>4μs</td>
</tr>
<tr>
<td>Resolution</td>
<td>256×256pixels</td>
</tr>
<tr>
<td>Light source:</td>
<td>Diffused halogen light</td>
</tr>
</tbody>
</table>

A summary of the characteristics of the three imaging systems is presented in Table 3.3. Following this preliminary investigation, schlieren imaging system is adopted to observe
fuel spray under inert condition, direct imaging (flame chemiluminescence) coupled with shadowgraph imaging system is adopted to observe spray and ignition characteristics under reactive condition. Direct imaging (DBI) system is adopted to observe the low intensity flame.

Table 3.3 Summary of imaging systems

<table>
<thead>
<tr>
<th>Imaging System</th>
<th>Inert Condition</th>
<th>Reactive Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct imaging (Diffused back-illumination)</td>
<td>Appropriate to observe liquid spray</td>
<td>Appropriate to observe liquid spray and “cool flame”</td>
</tr>
<tr>
<td>Direct imaging (Flame chemiluminescence)</td>
<td>-</td>
<td>Capable of observing the flame and can be coupled with shadowgraph imaging</td>
</tr>
<tr>
<td>Shadowgraph imaging</td>
<td>Capable of observing vapor spray and evaporation</td>
<td>Capable of observing vapor spray and ignition. However, ignition saturates camera, can be coupled with direct imaging to observe the flame</td>
</tr>
<tr>
<td>Schlieren imaging</td>
<td>More sensitive to vapor spray and evaporation. High contrast of density gradient makes the vaporization effects more clearly.</td>
<td>The high contrast of density gradient makes the background disturbance prominent under the test condition, which deteriorates the observation of spray and ignition characteristics.</td>
</tr>
</tbody>
</table>
CHAPTER 4  FUEL COMPARISON

This chapter provides insights into the spray and ignition characteristics of DME and diesel. The high-pressure direct injection fuel spray characteristics of both fuels are investigated at matching conditions. The macroscopic spray characteristics of inert fuel injections are studied using the schlieren imaging technique. Under matching background density yet elevated temperature, the fuel evaporation and ignition characteristics are studied using simultaneous direct and shadowgraph imaging techniques. The images are processed and compiled to analyze the spray development processes of DME and diesel.

4.1 Inert Fuel Spray

Figure 4.1 shows the spray development of diesel and DME fuels under 25°C and ambient atmospheric pressure. The fuel injection pressure is maintained at 300bar. Significant amounts of evaporation cannot be observed for diesel spray. At 0.65ms, a mushroom-like shape can be observed at the tip of the diesel spray. The fuel atomization however can be observed at the downstream of diesel spray.

Generally, fuel spray processes begin with the breakup of liquid core into droplets followed by continued breakup into smaller droplets, often referred as the secondary breakup [ref]. With a decrease in droplet size, fuel atomization increases owing to less surface area of the droplets [28]. As shown in Figure 4.1, the evaporation of DME droplets showed high breakup occurrence. This observation is likely owing to the low surface tension and high Weber number of DME and the vapor pressure for DME is much higher than of diesel fuel. Therefore, the evaporation speed is considered to be faster than the breakup speed [28].
The fuel penetration of DME spray was faster compared with the diesel spray and evaporates without the secondary breakup process. The edge of DME spray plume showed enhanced vaporization throughout the entire fuel spray event. The faster evaporation in the DME fuel sprays indicates that DME is more prone to mix with air and form a homogeneous air-fuel mixture than diesel [9].

Figure 4.1 Schlieren imaging of diesel and DME inert spray at 300bar injection pressure, 1bar absolute background pressure and room temperature: (a) raw images of diesel spray, (b) raw images of DME spray, (c) background-subtracted images of diesel spray, and (d) background-subtracted images of DME spray.
The images of DME and diesel fuel spray at 8bar absolute background pressure are shown in Figure 4.2. Under this condition, the spray penetration speeds for both fuels are close. Similar trend can be observed under this condition, the diesel spray still exhibits liquid-dominant spray behavior. Fuel atomization could be observed at the edge of the spray. The DME spray shape under 8bar background pressure is similar to that under 1bar background pressure. The fuel vaporization can still be observed but are less perceptible than that with 1bar background pressure.

Figure 4.2 shows the fuel spray development of diesel and DME at 8bar absolute background pressure. Under elevated pressure and equivalent density, the sprays show more similarities in spray penetration and plume structure. The penetration speeds for both fuels are close. Similar trend can be observed under this condition, the diesel spray still exhibits liquid-dominant spray behavior. Fuel atomization could be observed at the edge of the spray. The DME spray shape under 8 bar background pressure is similar to that under 1bar background pressure. The fuel vaporization can still be observed but are less perceptible than that with 1bar background pressure.
Figure 4.2 Schlieren imaging of diesel and DME inert spray at 300bar injection pressure, 8bar absolute background pressure and room temperature: (a) raw images of diesel spray, (b) raw images of DME spray, (c) background-subtracted images of diesel spray, and (d) background-subtracted images of DME spray

* (a) and (b) are raw images, (c) and (d) are images with background subtraction

**4.2 Reactive Fuel Spray**

The evolution of the fuel spray for diesel fuel is shown in Figure 4.3. The corresponding test details are listed in Table 4.1. The first appearance of fuel spray is observed at 0.25ms after the injection command. Electronic, mechanical, and hydraulic delays cause the actual
fuel delivery starts at 0.25ms after the injection command. After penetration, the liquid fuel is atomized with the ambient gases to eventually mix with the surrounding oxygen, apparent at 0.75ms. The first appearance of fuel burning was observed at 1.0ms. The bright chemiluminescence that radiates from the fuel-air combustion is captured with the colored high-speed camera while saturating the shadowgraph imaging. The flame diffuses toward the downstream of the spray and an increase in the area of the flame is observed at 1.3ms. At 1.5ms, only portion of the flame can be observed because the flame propagates out of the optical access. It is imperative to mention that the injection duration is command for 300μs, the actual fuel injection duration observed in Figure 4.3 is longer than 300μs (fuel is still injected even at 1.5ms). The prolonged injection is likely caused by closing delay. The actual injection duration can be obtained if rate of injection is measured on this injector, which is included in the future work.

Table 4.1 Spray conditions corresponding to Figure 4.3

<table>
<thead>
<tr>
<th>Spray condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Background temperature (K)</td>
<td>1237</td>
</tr>
<tr>
<td>Fuel</td>
<td>Diesel</td>
</tr>
<tr>
<td>Injection pressure (bar)</td>
<td>600</td>
</tr>
<tr>
<td>Injection duration (μs)</td>
<td>300</td>
</tr>
</tbody>
</table>
Figure 4.3 Schlieren and direct imaging of diesel reactive spray: (a) direct imaging, and (b) shadowgraph imaging

The evolution of the fuel spray for DME at matching conditon is shown in Figure 4.4. The first appearance of fuel spray is also observed at 0.25ms. As the fuel penetrates, the fuel starts to vaporize shown at 0.75ms. At 1.0ms, flame is not observed in direct imaging and there is no appearance of high intensity spot inside the fuel spray in the shadowgraph imaging. Flame is observed at 1.3ms in direct imaging and the flame saturates the shadowgraph imaging. Flame of DME exhibits a similar trend as diesel, the flame diffuses toward the downstream of the fuel spray and a growth in the flame area are observed at 1.3ms and 1.5ms. However, DME flame has lower luminous than that of diesel.

If direct imaging is used to determine the ignition delay, the ignition delay for DME (1.3ms) is longer than that of diesel (1ms). As mentioned in section 4.1, DME evaporates faster than diesel fuel, which means DME are supposed to have a shorter ignition delay. The possible reason for a longer ignition delay is observed for DME might be that under this test condition, the early stage of ignition for DME is dominated by low temperature flame, and the low temperature flame emits low intensity light that cannot be observed
clearly with current camera setting for colored camera. A set of pictures captured by direct imaging with DBI and higher exposure time in next section is presented to help explain this observation.

Table 4.2 Spray conditions corresponding to Figure 4.4

<table>
<thead>
<tr>
<th>Spray condition</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Background temperature (K)</td>
<td>1237</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>DME</td>
<td></td>
</tr>
<tr>
<td>Injection pressure (bar)</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Injection duration (μs)</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.4 Schlieren and direct imaging of DME reactive spray: (a) direct imaging, and (b) shadowgraph imaging

4.3 Observation under Diffused Back-illumination

Figure 4.5 shows the comparison of DME and diesel spray evolution observed by direct imaging with DBI. The images are processed with false-color method (by mapping different colors to different intensities of light) to observe the low intensity flame more clearly as shown in Figure 4.6. The specific test conditions are listed in Table 4.3.
As shown in Figure 4.5 and Figure 4.6, “cool flame” can be observed in both fuel sprays at this background condition. Shortly after fuel is vaporized and mixed with air, first stage or low-temperature ignition occurs with low-temperature reactions in both DME and diesel combustion[30]. The “cool flame” for DME spray is first observed at 0.85ms, and for diesel spray, the “cool flame” is first observed at 1ms. This may help explain that the longer ignition delay observed for DME in section 4.2 is not true. It is also obvious that DME generates a larger area of “cool flame” than that of diesel, and the “hot flame” for DME is less luminous than that of diesel.

Table 3.3 Spray conditions corresponding to Figure 4.5

<table>
<thead>
<tr>
<th>Spray condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background temperature (K)</td>
<td>1237</td>
</tr>
<tr>
<td>Fuel</td>
<td>DME &amp; Diesel</td>
</tr>
<tr>
<td>Injection pressure (bar)</td>
<td>750</td>
</tr>
<tr>
<td>Injection duration (μs)</td>
<td>300</td>
</tr>
</tbody>
</table>
Figure 4.5 Raw images captured from direct imaging with diffused back-illumination of DME and diesel reactive spray: (a) DME, and (b) diesel

Figure 4.6 False-color images of DME and diesel reactive spray: (a) DME, and (b) diesel
CHAPTER 5  SUMMARY

In this chapter, a summary of the thesis is provided. The different imaging systems are compared and discussed. The appropriate imaging systems for different test conditions are proposed. Under both room temperature and high temperature conditions, DME and diesel spray and ignition characteristics are observed and compared with the proposed imaging systems.

5.1 Conclusion

Based on the results, several points can be concluded:

1. Under inert conditions, schlieren imaging is appropriate to observe fuel vaporization because schlieren imaging has high sensitivity to the density gradient.
2. Under reactive spray conditions, the high sensitivity to the density gradient of schlieren imaging makes the background disturbance apparent and thus affects the observation of the interested focus. Thus, shadowgraph imaging is more appropriate under reactive spray conditions.
3. DME evaporates faster than diesel, thus a shorter ignition delay is observed for DME under reactive spray condition and DME flame is less luminous than that of diesel.

5.2 Future Work

- Further improvement to the optical setup. An optical arrangement of simultaneous direct imaging with diffused light and schlieren imaging will be beneficial to separate the liquid and vapor penetration.
• OH* chemiluminescence will be utilized to indicate the flame structure. Lift off length can also be measured accurately based on the images captured from OH* chemiluminescence.

• Perform the rate of injection of DME on the Bosh long tube test platform. The ROI will quantify the fuel injection amount, the injector opening and closing delay.
REFERENCES


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