ABSTRACT This research analyses the spray pattern resulting from a diesel injector used for fuelling a compression ignition engine on dimethyl ether (DME). Spray visualization tests were performed with diesel and then with DME in order to compare the patterns. This information was used to provide possible explanations for the difference in NO\textsubscript{X} emissions from an engine fuelled on diesel and then on DME. From testing it was noted that with diesel fuel, the typical diesel spray pattern was present. As the injector pressure was increased the spray became narrower, dispersed more rapidly and the duration of the spray was shorter. When DME was tested, it was noted that it took longer to build up the pressure in the line and as the injector pressure was increased a wider spray pattern was observed than in the case of diesel, and a greater penetration was achieved. Engine tests were then performed on both diesel and dimethyl ether fuelling. The results indicate that specific NO\textsubscript{X} emissions for DME were higher than those from the corresponding diesel tests at lower speeds, but these were found to decrease as speed increased. At the higher speeds, however, emissions for DME fuelling were less than those of diesel fuelling. This pattern was found to occur at all loads tested.

Keywords: Emissions, DME, NO\textsubscript{X}, Injector spray

1. INTRODUCTION

The use of DME as a replacement for diesel fuel has been well established. In early research on the use of methanol as a fuel for compression ignition engines, DME was used as an ignition promoter [1,2]. Having established the potential of DME as a fuel the next step was to use DME as a total replacement for diesel [3]. The physical properties of DME are, however, such that certain changes are required in order for DME to be used in the conventional injection system. One modification is that the injector opening pressure should be reduced when fuelling on DME. In the research reported here, one of the objectives was to be able to fuel the engine on diesel and then to simply turn to DME without making any adjustments to the fuelling system. In previous research, tests had been carried out with DME fuelling where the injector opening pressure had been reduced. It was reported that the emissions were generally much lower when compared to those attained under the same engine conditions with diesel fuelling, where the injectors were set for correct diesel functioning [3]. Therefore, the next step was to perform tests on DME at the same injector pressure as recommended for diesel fuelling, and to analyse and compare the resulting performance, combustion characteristics and emissions of the two fuels. The results achieved showed that in terms of performance, similar results were obtained with both fuels. The levels of NO\textsubscript{X} attained with DME were, however, higher than those previously reported at lower injector pressures. Furthermore, these emissions were higher than their diesel counterpart at low speeds. As the speed was increased, while the load was maintained constant, the NO\textsubscript{X} specific emissions of DME were also noted to decrease to levels below those of diesel. Furthermore, as the load was increased the specific NO\textsubscript{X} emissions decreased with both fuelling methods.

In order to better understand the reason for these higher than expected NO\textsubscript{X} emissions, a facility was set up to visualize injector spray patterns from both diesel and DME, and analyse and compare their behaviour.

2. OBJECTIVES

The objectives of this research were to perform tests on a compression ignition engine fuelled on diesel and then on DME with injector opening pressure set at that required for diesel fuelling as well as to compare:

i) NO\textsubscript{X} emissions from both fuels with increasing speed at various loads.

ii) The spray patterns of both fuels.

iii) Provide possible explanations regarding the levels of NO\textsubscript{X} emissions attained from both fuels.

3. LITERATURE REVIEW

The study of spray patterns from fuel injector nozzles is important as it sheds light on events as they occur in the combustion chamber leading up to the combustion of the fuel. It also contributes to the understanding of the formation of various species found in exhaust gases. Each fuel used for an internal combustion engine has its own physical and chemical properties with the result that each has its own characteristics. The work reported here considers only diesel oil and DME. Each fuel has its own property, as shown in the table below, and hence it is expected to behave differently when injected. A short review of the literature shows that considerable research has been and is still underway in an effort to gain a better understanding of the behaviour of a fuel when injected into a combustion chamber. Recent works, of interest to the
research reported here, are discussed below. The available literature on this topic is extensive.

In a study of DME flow in a diesel nozzle it was shown that DME spray spreads widely with a short penetration [5]. This was noted using a nozzle with a larger orifice diameter than that required for diesel fuel injection. Furthermore, the spray was observed to be made up of both liquid and gaseous phases. The liquid portion was found to have a shorter penetration than that of diesel. In another comparative study of diesel and DME sprays, it was found that because the DME injection pressure was lower than that of diesel, longer injection duration was required to allow the diesel-equivalent amount of DME [6]. This results in a longer penetration of DME compared to that of diesel. This study was also performed on a nozzle with a larger orifice diameter than that used for diesel injection. In addition since DME is less dense and more volatile than diesel, it has a higher gas-to-liquid density ratio in the spray which tends to increase the spray angle.

It has also been suggested that the air mixing process may be poor in the DME spray due to the insufficient penetration [7]. This may be caused by the rapid vaporization of DME in the spray. This seems to explain the poor combustion occurring at higher loads, whereas at light and medium loads, good combustion of DME was reported. Rapid vaporization of DME should enhance air-fuel mixing, because evaporation is the first physical stage for the formation of a combustion gaseous mixture from a liquid fuel.

4. PROPERTIES OF DME

Table 1 below shows selected properties of dimethyl ether and diesel fuel, which are particularly relevant to dimethyl ether as a fuel for compression ignition engines.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>DME</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Heating Value</td>
<td>MJ/kg</td>
<td>28.8</td>
<td>42.5</td>
</tr>
<tr>
<td>Liquid Density</td>
<td>kg/m³</td>
<td>668</td>
<td>840</td>
</tr>
<tr>
<td>Liquid viscosity</td>
<td>kg/m³</td>
<td>0.15</td>
<td>2 – 4</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>% wt</td>
<td>&gt;&gt;55</td>
<td>38 – 53</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>°C</td>
<td>-25</td>
<td>180 – 360</td>
</tr>
<tr>
<td>Auto ignition Temp</td>
<td>°C</td>
<td>235</td>
<td>250</td>
</tr>
<tr>
<td>Carbon Content</td>
<td>% wt</td>
<td>52.2</td>
<td>87</td>
</tr>
<tr>
<td>Hydrogen Content</td>
<td>% wt</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Oxygen Content</td>
<td>% wt</td>
<td>34.8</td>
<td>0</td>
</tr>
</tbody>
</table>

From the above table it can be seen that DME has certain properties that are desirable in a fuel for compression ignition engines. The higher cetane number has the effect of reducing the ignition delay, while the lower carbon and higher oxygen contents have a favourable impact on emissions. There are, however, also certain properties that are not as effective as those of diesel fuel, such as the lower viscosity of DME which presents a problem with lubricity in the pumps and injectors. Fuel injection systems have been designed taking into consideration the properties of dimethyl ether [8]. It should, however, be emphasised that the fuel injection system used on the engine for this research was not modified or altered in any way. The rationale for this was to investigate the possibility of fuelling compression ignition engines with dimethyl ether using their original fuelling systems.

5. EXPERIMENTAL EQUIPMENT

5.1 Engine and fuelling system

The engine used for the experimental work consisted of a naturally aspirated, four-stroke, direct injection, air-cooled of the compression ignition type. The engine was instrumented to measure combustion chamber pressure, fuel line pressure, crank angle and top dead centre. The engine specifications are given in Table 2.

Table 2: Engine specifications

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore (mm)</td>
<td>87.74</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>110.00</td>
</tr>
<tr>
<td>Continuous power rating @ 2000 rpm (kW)</td>
<td>12.2</td>
</tr>
<tr>
<td>Displacement (cm³)</td>
<td>1330</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16.5:1</td>
</tr>
<tr>
<td>FUEL INJECTION RELEASE PRESSURE</td>
<td></td>
</tr>
<tr>
<td>900 to 1099 rpm (bar)</td>
<td>137/152</td>
</tr>
<tr>
<td>1100 to 2000 rpm (bar)</td>
<td>197/217</td>
</tr>
<tr>
<td>FUEL INJECTION TIMING</td>
<td></td>
</tr>
<tr>
<td>Up to 1650 rpm &quot;BTDC</td>
<td>24</td>
</tr>
<tr>
<td>1651 to 2000 rpm &quot;BTDC</td>
<td>28</td>
</tr>
</tbody>
</table>

The standard fuel system of the engine consisted of a fuel pump and injector combination for each cylinder. The injector opening pressure was maintained at the recommended value of 21 MPa for both diesel and dimethyl ether fuelling. The injection system used on this engine was specifically made for diesel oil. When tests were performed on DME fuelling no lubricity improver was added. In the long term, however, injector seizure could occur due to the low lubricity of DME.

The fuel was supplied to the engine from a bottle pressurized at 400 kPa. The DME was extracted from the bottle in the liquid phase, and was then further pressurized to 2 MPa, to prevent vaporization in the lines before it reached the fuel pumps of the engine. The mass rate of flow of DME was measured by a rotameter fitted at the outlet of the bottle. An additional rotameter was used to measure the DME overflow from the injectors.

5.2 Emissions monitoring

A number of exhaust species were recorded using exhaust monitoring equipment. These included CO, CO₂, NOx, THC and O₂. The concentration of each specie was displayed in real time on a PC monitor. This information was also used to ensure that engine conditions were stable before taking a test.

5.3 Spray visualization

This test rig consists of three main components: the image capturing, the fuel delivery system and the test chamber with injector. These are now briefly discussed.

The testing chamber consists of a cube of sides 90mm x
90 mm x 110 mm. These dimensions represent the size of the actual combustion chamber. The injector was mounted in the centre of the top surface. The nozzle of the injector protrudes into the testing chamber by the same amount as it does in the engine.

The fuel delivery system consists of a hand pump used to set diesel injectors. A gauge was fitted so as to be able to see the pressure at which the injector was set and opened during the tests.

The visualization and image capturing set up consists of a Schlieren system. The camera used to capture the images was capable of taking 1000 frames per second. The images taken by the camera were then stored in a computer for later processing and analysis.

6. EXPERIMENTAL PROCEDURE

6.1 Engine emissions tests

The tests performed in order to collect emission samples were made up of two parts. Firstly diesel baseline test were performed at four loads, namely 25, 35, 45 and 55 Nm. The engine speed was increased from 1100 to 1800 rpm in stages of 100 rpm for each load tested. The injector opening pressure was set at 21 MPa as required for diesel fuelling. For each test all relevant readings such as combustion chamber pressure, fuel line pressure, load, and speed, fuel and air flow rates were taken. Emission species monitored were CO, CO$_2$, NO$_X$ and O$_2$. Once the diesel tests were completed the procedure was repeated with DME fuelling.

6.2 Spray visualization tests

The injector opening pressure was checked to ensure that it was set at the desired value. The Schlieren system was activated and the fuel line in the hand pump was pressurized. The computer program was set up so that 2000 frames could be recorded once the image capturing process was initiated. Thus when all was ready the hand pump and the image capture were started simultaneously. The injector released one spray of fuel and the camera recorded the entire event.

The tests were performed first with diesel fuel to give a reference against which to compare the DME spray patterns. The procedure was repeated using DME supplied from the same bottle that had been used for the engine tests.

7. TEST RESULTS AND DISCUSSION

7.1 Emissions

Tests were performed at four loads, namely at 25, 35, 45 and 55 Nm. This was done to obtain a good spread from low load to close to the maximum of 60 Nm which is allowed by the manufacturers for continuous operation.

The trends of NOX emissions against speed and load are first discussed for both fuels. This is then followed by an overview of some of the factors which could have an influence on the production of NOX.

Figure 1 depicts the graph of specific NOX emissions against engine speed for diesel fuelling at the four loads tested. NOX increases slightly initially reaching a maximum at 1300 rpm, and then decreasing steadily as the speed is increased to 1800 rpm. Although the 35 Nm shows the least emissions almost across the speed range, the difference between the NOX concentrations at the various loads is small.

![Figure 1: Specific NOX emissions versus engine speed for diesel fuelling](image-url)

The surface plot of specific NOX emissions for diesel fuelling, with both speed and load is shown in Figure 2. The general trend shows that for a given load, the concentration first increases with increasing speed, followed by a decrease as speed increases. The lowest emissions are achieved at a load of 35 Nm and 1800 rpm. The maximum concentration of specific NOX was recorded as 0.279 ppm/W at 25 Nm at an engine speed of 1300 rpm. The surface average was 0.203 ppm/W. As indicated above, the reactions forming NOX are very temperature dependent, thus NOX emissions scale proportionally to the engine load. The results for diesel fuelling confirm this trend, showing an increase with speed and reaching a maximum. Furthermore, since the chemical rates are non linear functions of temperature [9], the concentrations reach a maximum and then begin to fall off somewhat.

Figure 3 shows the corresponding graph of specific NOX emissions versus engine speed for DME fuelling. The results show that emissions are inversely proportional to engine speed. There is a distinct pattern in which the specific emissions decrease with increasing load and with increasing speed. These all converge at speeds above 1600 rpm. There is little difference in emissions between diesel and DME from 1600 rpm onwards.
The surface plot of specific emissions versus load and speed for DME fuelling is given in Figure 4. The highest concentration was achieved at low speed and load, where 0.792 ppm/W was recorded. The average surface value is higher than that of diesel at 0.555 ppm/W. As both speed and load were increased, a flatter surface emerged. An almost uniform concentration can be noted at speeds of 1600 rpm and above, while the load was increased.

The overall picture emerging from Figure 4 is that in the range in which the engine is more likely to operate the specific concentrations of DME fuelling are comparable to those of diesel fuelling. This is a positive result in that this was achieved without any changes to the settings of the fuelling system. Thus the objective of being able to switch from one fuel to the other is met.

7.2 Spray visualization

The nozzle used for the spray visualization research was of the three-orifice configuration as recommended by the engine manufacturer, with a spray angle of 130° and a 0.26mm orifice diameter. The injector was tested at four opening pressures, namely 100, 150, 200 and 250 bar for both diesel fuel and DME.

When diesel fuel was tested, the injector opening pressure was set accurately by pressurizing the hand pump and adjusting the spring stiffness until the desired pressure was attained. However, when the injector was set for DME, it was found that as a result of its compressibility, it was necessary to use short strokes in quick succession to ensure that the injector would open at the desired pressure. This problem was overcome to some degree by cooling the fuel line with ice and water. It is also recognized that these tests were performed in an environment that was quite different from that occurring in an engine. It is however hoped that some insight can be gained by studying the effects of varying the injector pressure, and analyzing the behaviour of the DME sprays.

Figure 5 below shows the spray patterns resulting from diesel fuel at the pressures indicated. Analysis of the four photographs indicates that the sprays are uniform and well directed as they appear to narrow as the opening pressure is increased. The diesel remains in the liquid form throughout the duration of the spray, and also remains as individual sprays with no overlapping.
Figure 5: Diesel nozzle sprays at 100, 150, 200 and 250 bar.

Figure 6: DME nozzle sprays at 100, 150, 200, and 250 bar.
Figure 6 shows the same nozzle but with DME as the fuel. The sprays are not as well defined as in the case of diesel. It is also noted that more vapour is formed, which is expected since the boiling point of DME is some – 25°C. As the pressure was increased, it was noted that the DME remained in the liquid phase for longer. DME sprays spread widely with a longer spray depth, thus larger spray angles were observed than in the case of diesel fuelling.

The above tests were performed in a chamber at atmospheric conditions and with no swirl, as would occur in the actual engine. If the swirl effect is added, more effective mixing occurs and therefore better combustion can be expected.

Injection of DME forms a cloud as the fuel leaves the nozzle tip producing a spray that is much wider than that of diesel and it has a greater penetration. Since mixing of the air-DME mixture is required for good combustion to occur, this appears to be taking place at the higher speeds. Here the specific NOx emissions were observed to be at their lowest for both fuels. The vaporization process would also occur faster thus permitting a more thorough mixing of the fuel and air. This would satisfy the conditions of the first stage for the formation of a combustion gaseous mixture as suggested in [7]. Thus it may be expected that at the lighter loads and speeds, this mixing process is not as effective, resulting in higher NOx emissions, as reported.

As a result of the compressibility of DME injection and ignition occur later than in the case of diesel, and closer to top dead centre. Thus the temperature of the trapped mass in the combustion chamber is higher than it would be in the case of diesel fuelling. Analysis of the temperature graphs showed that at a speed of 1500 rpm, for example, the temperature of the trapped mass at the point of ignition was always more than 100°C higher in the case of dimethyl ether. Higher temperatures, to a certain extent, favour the formation of NOx resulting in greater concentrations being present. Furthermore, as the speed increases, so does the swirling action, with the result that the DME and air mix more thoroughly, thus producing the desired gaseous mixture. The higher speed, however, also brings about a higher temperature in the combustion chamber. This in turn affects the ignition delay, discussed below.

A comparison of the ignition delay shows that in the case of diesel fueling it is always higher than that of DME, at all loads. At all the loads tested, as the speed is increased the ignition delay of diesel decreases slightly, while that of DME increases, but always remains less than that of diesel. At higher speeds, more DME is injected into the combustion chamber and therefore more time is required for the DME to ignite, resulting in a small increase in ignition delay. This shorter ignition delay of DME is the result of the partial vaporization of the fuel as it is injected, as shown in figure 6, as well as the higher temperature of the combustion chamber at the point of ignition. As the speed is increased the combustion chamber temperature increases but the specific concentrations decrease, for both fuels. The reversal in the trend is assisted by the non-linear relationship of the rate of formation of NOx with temperature, where the rate of formation of NOx reverses its trend and begins to decrease [9].

The above factors are not the only causes for the higher concentrations reported with DME fuelling. There are several other factors influencing the formation of NOx. The focus of this research was, however, to analyse the spray patterns of DME resulting from a nozzle made for diesel injection.

8. CONCLUSIONS

Although the injector spray test facility may not be fully representative of events in the combustion chamber, it reveals information regarding the behaviour of the spray of both diesel and DME.

The results from the emissions tests show that the specific NOx emissions decrease with increasing load and speed. At low speeds the concentration of NOx is higher with DME than with diesel fuel. The spray patterns of DME reveal that DME vaporizes partially when exiting the nozzle and that these have a wider angle with a longer spray depth. Diesel sprays are better defined with a narrower angle and remain in the liquid phase. At higher speeds mixing of dimethyl ether and air and the higher combustion temperature appear to have a dominant effect on the reduction of NOx. This pattern was also observed to occur at the higher loads.

There are many factors affecting the formation of NOx in the exhaust gases. A number of these have been analysed as possible contributors to the promotion of NOx.

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10. REFERENCES


