THE EFFECT OF FUEL PROPERTIES ON THE START OF INJECTION AND ENERGY RELEASE OF A COMPRESSION IGNITION ENGINE FUELED ON DIMETHYL ETHER

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The research reported here is concerned with the replacement of diesel oil with dimethyl ether (DME) as a fuel for an unmodified compression ignition engine. The different physical properties of these fuels were found to impact on the fuel injection process and on combustion. A standard, naturally aspirated four-stroke compression ignition engine was fueled on diesel oil and then on DME. All testing was performed at the injection timing and injector opening pressure as recommended for diesel fueling. Constant load tests at increasing engine speeds were performed on diesel and then on dimethyl ether. Analysis of the results shows that as a result of the lower bulk modulus of DME, the rate of pressure rise of DME in the fuel line and the maximum pressure prior to injection were lower than those attained with diesel fueling. It was also found that the start of injection with DME fueling occurred later than with diesel fueling, with the result that less energy was released before top dead center.

KEY WORDS: bulk modulus, start of injection, energy release, rate of pressure rise

1. INTRODUCTION

The properties of a fuel for use in a compression ignition engine are very important, as these will determine the overall performance and emissions of the engine. Since diesel oil is still the base fuel used in compression ignition engines, new fuels are compared to diesel in terms of performance and emissions. Another factor to consider is that alternative fuels must be adaptable to existing engines and their fuel injection systems. Thus physical or chemical properties that are considerably different from those of diesel may require different methods of delivering the fuel to the engine, as well as different injection timing and injector opening pressures (Bhana and Cipolat, 2006; Yu and Bae, 2003; Suh and Lee, 2008). In addition the rate of pressure rise in the fuel line results in a different spray pattern, which in turn affects the performance of and the emissions from the engine (Cipolat, 2007; Seong et al., 2004).
Alcohol fuels, such as methanol and ethanol, have been extensively investigated as possible replacements for diesel. These fuels have been used, for instance, as blends with diesel fuel (Rakopoulos et al., 2007, Sayin et al., 2008). The results reported indicate that the performance is similar to that of diesel fueling. The emissions, particularly NO$_x$, were found to be higher in certain cases and lower in others, when compared to those of diesel fueling. The reason for this was due mainly to injection timing, fueling methods, engine settings, injector geometry, load, speed, and percentage ethanol in the blend. Alcohol fuels have also been used as complete replacements for diesel fuel, but these then require an ignition promoter, for example, dimethyl ether (Brook et al., 1984; Cipolat, 1999; Cipolat, 2005; Murayama, 1992).

The present research, however, is concerned with the use of dimethyl ether as a total replacement for diesel fuel in a conventional unmodified compression ignition engine. DME, however, has properties that differ considerably from those of diesel fuel. These include cetane number, density, viscosity, bulk modulus, autoignition temperature, and calorific value. Some of these properties are discussed in this paper. At present, the cost of DME is greater than that of diesel, and is thus a drawback. In the literature it is recommended by researchers that the injection pressure should be reduced to account for the lower bulk modulus of DME compared to that of diesel. Reductions in emissions have also been reported by researchers fueling a compression ignition engine on DME.

In the present research, the injector opening pressure was the same as that recommended for diesel fueling. This was undertaken in order to investigate the feasibility of interchanging fuels by simply switching from one fuel to the other while the engine was running. This would make the use of DME more practical.

2. PROPERTIES OF DME

Table 1 shows some selected properties of DME and diesel which are pertinent to the process of pressure buildup in the fuel line, the injection process and combustion.

Certain properties of DME are desirable in a fuel for compression ignition engines. The higher cetane number promotes ignition, resulting in a shorter ignition delay, and the presence of the lower carbon and higher oxygen contents has a favorable impact on emissions. Some of the other properties present problems. It can be observed from Table 1 that the bulk modulus of DME is about one third that of diesel fuel. Furthermore, the density of DME is about 80% that of diesel, while the viscosity is about one twentieth that of diesel fuel. Furthermore the bulk modulus and density of DME are functions of temperature and pressure (Seong et al., 2004; Sato et al., 2004). Thus, the speed of propagation of the pressure waves in the fuel line is affected by the conditions present in the fuel line. The amount of DME delivered per pump stroke is less than that of diesel fueling and consequently, the injection characteristics produced by DME will differ from those of diesel fueling. The injection and ignition points will also be affected by the lower
bulk modulus and viscosity of DME. These differences would ultimately lead to different injection spray characteristics. Research on injection spray characteristics using diesel and DME on the same type of injectors used in the present engine have been undertaken (Cipolat, 2006). This is, however, beyond the scope of this research. Spray formation is an area in which considerable research is continuously being undertaken. The challenge here is to make use of the current injection system to fuel engines on DME with few modifications, if any.

3. OBJECTIVES

A standard compression ignition engine was fueled on diesel and on DME while maintaining the injection timing and injector opening pressure as recommended for optimum diesel performance. Since these fuels have different properties, the objectives of this research were to analyze the effects of some of these properties on certain aspects leading to combustion. The following were chosen for analysis:

1. The rate of pressure rise in the fuel line prior to injection;
2. The start of injection;
3. The cumulative energy release.

4. EXPERIMENTAL EQUIPMENT AND PROCEDURE

4.1 Engine and Fueling System

The engine used was a naturally aspirated, four-stroke, direct-injection, air-cooled, two-cylinder compression ignition engine. The engine was instrumented to monitor transient measurements, namely, combustion chamber pressure, fuel line pressure, crank angle, and top dead center. Steady-state parameters that were monitored in-

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Diesel</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid density</td>
<td>kg/m³, 20ºC, 2MPa</td>
<td>824</td>
<td>668</td>
</tr>
<tr>
<td>Liquid viscosity</td>
<td>Pa-s, 20ºC, 2MPa</td>
<td>3790</td>
<td>184</td>
</tr>
<tr>
<td>Boiling point</td>
<td>ºC, 1 atm</td>
<td>180–370</td>
<td>–25.1</td>
</tr>
<tr>
<td>Autoignition temperature</td>
<td>ºC</td>
<td>250</td>
<td>235</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>N/mm², 20ºC, 2MPa</td>
<td>1549</td>
<td>553</td>
</tr>
<tr>
<td>Stoichiometric A/F ratio</td>
<td></td>
<td>14.6</td>
<td>9</td>
</tr>
<tr>
<td>Cetane number</td>
<td></td>
<td>40–55</td>
<td>55–60</td>
</tr>
<tr>
<td>Lower heating value</td>
<td>MJ/kg</td>
<td>42.5</td>
<td>28.8</td>
</tr>
<tr>
<td>Carbon content</td>
<td>%wt</td>
<td>87</td>
<td>52.2</td>
</tr>
<tr>
<td>Oxygen content</td>
<td>%wt</td>
<td>0</td>
<td>34.8</td>
</tr>
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cluded air intake, exhaust and engine temperatures, fuel and air flow rates, load, and engine speed. The engine specifications are supplied in Table 2.

The fueling system of the engine consists of a mechanical jerk-type fuel pump and injector combination for each cylinder. The injector configuration recommended for this engine is of a three-orifice type, each with a diameter of 0.26 mm and a spray angle of 130, operating at an opening pressure of 21 MPa. This condition was maintained for both diesel and dimethyl ether fueling. Although the viscosity of DME is considerably lower than that of diesel, no lubricating agent was added.

Diesel fuel was gravity fed to the engine and the flow rate measured using an electronic flow meter. DME was supplied from a container pressurized at 400 kPa and was extracted in the liquid phase. This fuel was then pressurized to 2 MPa to prevent vaporization from occurring in the fuel lines. The DME flow rate was measured using a rotameter at the exit of the container and a second rotameter measured the overflow from the injectors.

4.2 Experimental Procedure

Baseline diesel tests were first performed at loads of 25, 40, and 55 Nm, with engine speed varying from 1100 to 1800 rpm in increments of 100 rpm for each load. At each condition of load and speed transient and steady-state data including combustion chamber pressure, fuel line pressure, load, speed, and fuel and air flow rates were recorded. Upon completion of the diesel tests, DME fueling tests were undertaken. Before recording any data, the engine was allowed to run for a period of time to ensure that no diesel was present in the fuel lines and injection system. Thus the engine was allowed to run while all the engine parameters were monitored to ensure that steady-state conditions were achieved. Emissions were also

<table>
<thead>
<tr>
<th>TABLE 2: Engine specifications</th>
</tr>
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<tbody>
<tr>
<td>Bore (mm)</td>
</tr>
<tr>
<td>Stroke (mm)</td>
</tr>
<tr>
<td>Continuous power rating @ 2000 rpm (kW)</td>
</tr>
<tr>
<td>Displacement (cm³)</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Fuel injection release pressure</td>
</tr>
<tr>
<td>900 to 1099 rpm (bar)</td>
</tr>
<tr>
<td>1100 to 2000 rpm (bar)</td>
</tr>
<tr>
<td>Fuel injection timing</td>
</tr>
<tr>
<td>Up to 1650 rpm Before Top Dead Center (°BTDC)</td>
</tr>
<tr>
<td>1651 to 2000 rpm °BTDC</td>
</tr>
</tbody>
</table>
monitored and when these were steady for some time, it was taken as an indication that no diesel was present in the fueling system. Furthermore, the engine was allowed to run until the speed had stabilized before testing commenced. The same testing procedure was used with DME fueling. The same loading and engine speed conditions applied as for diesel fueling. At each condition of speed and load, nine consecutive cycles were captured and averaged. Furthermore at least five sets of tests were recorded at each condition and were then used to obtain an overall average to ensure repeatability and a reduction in possible errors.

5. RESULTS AND DISCUSSION

The discussion below consists of an analysis of the pressure in the fuel line leading up to injection, the start of injection and the cumulative energy release. Comparisons between these aspects of the two fueling methods are then made.

5.1 Fuel Line Pressure

This analysis is based on a load of 40 Nm which represents some 70% of full load and a mid-range speed of 1500 rpm. Figure 1 shows the fuel line pressure variation versus crank angle for diesel fueling, at the above conditions.

The pressure in the fuel line has an initial value of 12.3 MPa and remains steady until the pressurization process starts at 330.2°CA. From this point the line pressure increases quite uniformly to a maximum value of 30.2 MPa at 346°CA. This represents a rate of pressure rise of 1.12 MPa/°CA over this interval. As the injection process starts the pressure falls to 6.5 MPa, representing a rate of pressure decrease of 1.4 MPa/°CA. This is followed by pressure fluctuations diminishing in intensity as the cycle proceeds. The residual pressure in the fuel line at this point

FIG. 1: Fuel line pressure versus crank angle for diesel fueling at 1500 rpm and 40 Nm
is 12 MPa. The injection pulse width measured at a pressure of 12.3 MPa, which is the point at which the rise starts, is 27.6°CA.

Figure 2 represents the same conditions as illustrated in Fig. 1, but represents what occurs with DME fueling. The starting and residual pressures are about 15.2 MPa, some 3 MPa higher than in the case of diesel fueling. The maximum pressure reached before injection started was lower than that of diesel fueling at 25.4 MPa occurring at 357.3°CA. The rate of pressure rise was considerably lower than that of diesel fueling, at 0.47 MPa/°CA, while the rate of pressure decrease was 0.88 MPa/°CA, which is almost double that for the pressure rise. The pulse width was wider at 34.7°CA, as a result of the lower bulk modulus of the DME, where more crank angle degrees are required to compress the fuel. This effect is also noted in the greater fuel line pressure fluctuations prior to the start of presurization than is the case with diesel fueling, but less after injection.

Fuel-line pressure graphs at a load of 55 Nm with diesel and DME fueling at the same speed as above were also analyzed. This load represents the maximum recommended by the manufacturers. The rate of pressure rise of diesel fueling changes by a small amount to 1.18 MPa/°CA, while the rate of pressure decrease from the injection point was 3.34 MPa/°CA, some 2.4 times greater than at 40 Nm. The pulse width was found to increase by 1.6°CA to 29.2°CA. The average rate of pressure rise with DME fueling was unchanged at 0.47 MPa/°CA, while the rate of pressure decrease was slightly less at 0.71 MPa/°CA. The pulse width in this instance was found to increase by 2.6°CA to 37.3°CA.

The rate of pressure rise of the fuel in the line and the volume of fuel injected are two of the factors which determine the injection point of a particular fuel. This is clearly noticeable in the graphs illustrating the start of injection, which is discussed below. Another consideration regarding the injection point is the viscosity.
of the fuel, the effect of which can be better appreciated by analyzing injector spray patterns. A separate study on the spray formation of DME from the same injectors as those used in the engine was undertaken. It was shown that some DME leaks from the injector during the pressurization process occurred (Cipolat, 2006). In the engine tests, this was noted on the fuel line pressure trace as a small drop before the maximum pressure was reached. This was noted to occur particularly at the lower speeds. Similar findings were also reported in the literature where injectors were operated at pressures well below those recommended for diesel fueling (Sorensen and Mikkelson, 1995; Yu and Bae, 2003; Seong et al., 2004).

### 5.2 Start of Injection

As reported in Table 1, diesel has a bulk modulus some 3.25 times greater than that of DME and a density almost 1.3 times greater than that of DME. The effect of these two properties reveals itself in differing aspects which relate to the start of injection (SOI) of the two fuels tested.

From the discussion above and inspection of Figs. 1 and 2, it is clear that the start of injection with DME fueling occurs later than with diesel fueling. The bulk modulus and density of diesel and DME are functions of both temperature and pressure as mentioned above. The general trend is that as temperature increases, the bulk modulus and density decrease. The temperature of the fuel measured at the fuel line pressure transducer was noted to vary from about 34 to 48°C across the loads and speeds tested. This represents approximately 12% decrease in the bulk modulus of diesel and about 31% decrease in that of DME at a pressure of 21 MPa. For the same temperature range the density of DME decreases by some 6% while that of diesel decreases by about 1% (Teng et al., 2004).

For each of the loads tested, the SOI was plotted against speed. Each value of SOI shown in the graphs represents an average value of many tests taken at each load and speed. Figure 3 shows the graph of the crank angle position for the start of injection versus speed for a load of 25 Nm. A gradual increase in the crank angle position is noted for both fuels. The SOI for diesel fueling occurs at 344.35°CA and increases gradually to 347.39°CA, an increase of about 3°CA, while that of DME starts at 351.11°CA and increases to 354.71°CA, an increase of 3.6°CA. The SOI for DME occurs, on average, about 7.5°CA later than with diesel fueling.

Figure 4 shows the graph of SOI crank angle position for both fuels versus speed for a load of 40 Nm. Diesel displays a similar pattern to that of the 25 Nm load but with slightly higher values. The SOI with diesel fueling occurs at 345.3°CA, while that of DME is 4°CA higher at 349.3°CA. At the maximum speed, the values are 347.7°CA for diesel fueling and 356.6°CA for DME, representing a difference of about 9°CA. Diesel SOI rises by 2.4°CA over the speed range, while that of DME rises by about three times at 7.3°CA. Thus DME SOI is closer to that of diesel at the lower speeds but diverges as the speed is increased. The average difference is marginally greater at 7.6°CA.
Figure 5 shows the start of injection crank angle position versus speed for a load of 55 Nm. Once again, diesel displays a similar trend to that shown above, where the start of injection crank angle position gradually increases from 344°CA by 3.2°CA to 347.2°CA as speed increases from 1100 to 1800 rpm.

The pattern produced by DME is somewhat different to that achieved at the lower loads. The most noticeable aspect is that SOI values are higher than for the previous two loads, and all lie in the region between 356°CA and 360°CA. The graph shows two almost distinct sections, one from 1100 rpm to 1400 rpm and the other from 1500 rpm to 1800 rpm. In the lower speed range the SOI rises from

FIG. 3: Start of injection crank angle position versus speed at a load of 25 Nm

FIG. 4: Start of injection crank angle position versus speed at a load of 40 Nm
355.9°CA to close to 360°CA for the next three tests. At 1500 rpm a drop to 356.5°CA is noted, followed by a gentle rise to 358.2°CA, with a trend similar to that of diesel fueling. The higher values of the SOI below 1500 rpm are the result of the DME leaking past the needle, as discussed above. This would be expected at a higher load where more fuel is admitted into the pump. Since the speed is low there is a greater likelihood that DME will leak before the maximum pressure is reached. The differences in the SOI of the two fuels at this load vary between about 11°CA and 15°CA with an average value of 12.6°CA. Thus, on average, the SOI with DME fueling at the highest load occurs about 5°CA later than at the loads of 25 and 40 Nm.

An overall view of the SOI crank angle position at all three loads shows that as the load is increased, the SOI moves closer to top dead center, and as the engine speed increases the SOI crank angle position also increases. This increase is more evident with increasing load. In order to achieve a higher load, more fuel is supplied to the pump thus requiring more time to compress this greater volume of fuel to reach the injector opening pressure. The bulk modulus of a fuel is indicative of the space available between the molecules (Bridgman, 1958). DME has a bulk modulus of more than three times less than that of diesel, as shown in Table 1. Thus more time is required to close the spaces between the fuel molecules, before the fuel can be pressurized to the required injector opening pressure. The result is that injection occurs later when compared to that of diesel fueling. This is confirmed in the trends shown in the three figures relating to the SOI shown above, whereby as more fuel is supplied to the injection pump, more time is required to compress the fuel and the later the injection occurs.

In order to advance the start of injection, various approaches may be considered. For example, the pump timing may be advanced so that the pressurization of the
fuel starts earlier, thus advancing the start of injection. The injector opening pressure could be reduced to account for the lower bulk modulus of DME. Injector opening pressures of 80 and 100 bar have been tested successfully (Sorensen and Mikkelsen, 1995; Sato et al., 2001). In this research, however, the intention was not to modify the engine in any way, and to show that it can be fueled on diesel or DME while maintaining injection and injector settings. It may be possible to find a compromise, in terms of injection timing and injector opening pressure, which would be quite suitable for both fuels, without causing too much loss in power and without increasing emission levels.

5.3 Energy Release

The cumulative energy release of diesel fueling for a load of 40 Nm at 1500 rpm is shown in Fig. 6. Injection and ignition points occur at 347.3°C and 352.1°C, respectively, with an ignition delay of 4.8°C. Between the injection and ignition points a drop in energy release can be observed. This represents the vaporization of the diesel fuel as it is injected, after which the fuel ignites. This process absorbs energy from the compressed trapped mass of air and residuals so that the injected fuel spray can vaporize. This leads to the ignition of the fuel where a steady rise in the cumulative energy is observed. From the figure it is also noted that some 350 J of energy are released when Top Dead Center (TDC) has been reached. The remaining energy is released in some 40°C after TDC, followed by a gentle rise until the exhaust valve opens. The temperatures at injection, ignition, and at maximum were 987 K, 1032 K, and 2143.4 K, respectively, while the exhaust temperature was 508.5°C.

The cumulative energy release of DME fueling at the same load of 40 Nm and speed of 1500 rpm is shown in Fig. 7. The injection and ignition points occur at

![FIG. 6: Cumulative energy released versus crank angle for diesel fueling, at 1500 rpm and 40 Nm](image-url)
351.5°CA and 354.1°CA, respectively, with a shorter ignition delay of 2.6°CA. The injection occurring 4.2°CA later than in the case of diesel fueling, is a result of the lower bulk modulus of DME. Between the injection and ignition points there is no drop in the cumulative energy released, as observed in Fig. 6. As DME is injected it vaporizes as it leaves the nozzle (Yu and Bae, 2003; Cipolat, 2006; Suh and Lee, 2008) and ignites with a much shorter ignition delay than is the case of diesel fueling. DME has a much lower boiling point than diesel oil, and thus vaporizes promptly. DME also has a greater cetane number than that of diesel fuel, thus igniting more readily. By the time TDC has been reached, some 225 J of energy have been released. The remaining energy is released after TDC, and the total cumulative energy is attained some 70°CA after TDC. This means that the greater part of the energy is released as the piston is on its downstroke. A gentle drop is observed in the last 40°CA before Exhaust Valve Open (EVO). The injection, ignition, and maximum temperatures were all lower than in the case of diesel fueling at 936 K, 973 K, and 1912.4 K respectively, while the exhaust temperature was 433.1°C.

6. CONCLUSIONS

Tests were performed on a compression ignition engine fueled on diesel and then on DME in order to analyze the effects of the differences in properties of the two fuels on the rate of pressure rise in the fuel line, on the start of injection and on the cumulative energy released. It was found that the rate of pressure rise with DME fueling was about 40% that of diesel fueling and that the maximum fuel line pressure with DME was about 15% lower than that of diesel. This consequently produced a delay in the start of the injection crank angle position. For both fueling methods the start of injection crank angle position was observed to increase with increasing engine speed and load. In terms of energy release, it was found that at
TDC, DME released some 35% less energy compared to that released by diesel fuel. The remaining energy is released over some 30°CA more than in the case of diesel fueling. The present research was undertaken without altering fuel injection settings from those recommended for diesel fueling. This forms a base for comparison in future research where ways of improving the performance of the engine would be investigated. The specific areas for future investigation are reducing injection pressure, advancing injection timing, and changing injector geometry. A comparison of emissions is also to be undertaken.

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