EXPERIMENTAL STUDY ON EMISSION CHARACTERISTICS OF DIESEL ENGINES WITH DIESEL FUEL BLENDED WITH DIMETHYL CARBONATE

C. S. CHEUNG, a* M. A. LIU, a S. C. LEE, b and K. Y. PAN c

a Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong SAR

b Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong SAR

c School of Energy and Power Engineering, Xian Jiaotong University, China

In the present study, dimethyl carbonate (DMC) was blended with ultra-low sulphur diesel oil at different proportions, up to 30% by volume, and tested on a single cylinder direct-injection diesel engine, a 4-cylinder indirect-injection diesel engine, and a light-duty diesel vehicle to assess the effect of %DMC on fuel consumption and exhaust emissions. With an increase in %DMC, there was an increase in fuel consumption or a decrease in power output. Particulate emissions were measured with a scanning mobility particle sizer and an aerodynamic particle sizer. DMC was found to significantly reduce particulate emissions, both sub-micron and micron, but the reduction was not proportional to the %DMC in the blended fuel. Within addition to the reduction in particulate emissions, there was a slight decrease in NOx and a slight increase in CO. For HC, there was a reduction at 5%DMC but an increase at higher %DMC. A lug-down test on the light-duty diesel vehicle showed a significant reduction in smoke emission coupled with a reduction in power output of the vehicle. It can be concluded that dimethyl carbonate-blended diesel can effectively reduce particulate emission.

Keywords: Diesel engine; Oxygenated fuel additive; Dimethyl carbonate; Diesel particulate; Pollution control

INTRODUCTION

In recent years, diesel vehicles have been widely recognized as one of the major sources of air pollution in urban areas. The reduction of soot and particulate emitted by diesel engines and vehicles has been an active area of research with increasingly stringent emissions standards being imposed (Herzog, 1998;
Scarnegie et al., 2003). Some of this recent research has concentrated on the number concentration and size distribution of particulates emitted from diesel engines (Carberry et al., 1998; Richards et al., 1998). New technologies, such as high-pressure fuel injection (Chikly, 2000) and split fuel injection (Choi and Reitz, 1999), alternative fuels (Gardner et al., 2001), and oxygenated fuel additive (Huang et al., 2001), are used to reduce particulate emission. Dimethyl carbonate (DMC) is one of the oxygenated fuel additives investigated for application to diesel and petrol engines (Murayama et al., 1995; Pacheco and Marshall, 1997; Miyamoto et al., 1998; Zhang and Reader, 1999; Wang et al., 2000; Huang et al., 2003). DMC is miscible with diesel fuel and the blended fuel can significantly reduce the smoke level of the exhaust gas. However, there is little understanding of the effect of DMC on particle emission characteristics, including number concentration, volume concentration, and particle-size distribution.

In the present study, experiments were carried out on a single cylinder direct-injection diesel engine and a 4-cylinder indirect-injection diesel engine, on an engine test bed; and on a light-duty diesel vehicle, on a chassis dynamometer, with ultra-low sulphur diesel oil (50 ppm by weight of fuel sulphur) blended with different proportions of DMC. The %DMC affects the fuel and injection properties, and hence the combustion process and the emissions level.

**TEST FUELS**

The diesel fuel used in the present study is ultra-low sulphur diesel with the following properties: maximum sulphur content 50 ppm by weight, minimum cetane number 51, viscosity 2.0–4.5 mm²/s at 40°C, and maximum density 0.835 kg/liter at 15°C. DMC is a chemical with a molecular formula of C₃H₆O₃. Under atmos-

<table>
<thead>
<tr>
<th>Properties</th>
<th>DMC</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular formula</td>
<td>C₃H₆O₃</td>
<td>C₁₀–C₂₁</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>90.1</td>
<td>190–220</td>
</tr>
<tr>
<td>Cetane number</td>
<td>35–36</td>
<td>40–55</td>
</tr>
<tr>
<td>Lower calorific value (MJ/kg)</td>
<td>15.78</td>
<td>42.5</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1079</td>
<td>840</td>
</tr>
<tr>
<td>Viscosity (mm²/s)</td>
<td>0.625</td>
<td>4.4</td>
</tr>
<tr>
<td>Surface tension (N/m)</td>
<td>0.0319</td>
<td>0.031</td>
</tr>
<tr>
<td>Heat of evaporation (kJ/kg)</td>
<td>369</td>
<td>250–290</td>
</tr>
<tr>
<td>Stoichiometric air–fuel ratio</td>
<td>4.6</td>
<td>14.6</td>
</tr>
<tr>
<td>Boiling point temperature (°C)</td>
<td>80</td>
<td>180–360</td>
</tr>
<tr>
<td>Auto-ignition temperature (°C)</td>
<td>220</td>
<td>250</td>
</tr>
<tr>
<td>%wt of carbon/hydrogen/oxygen</td>
<td>40/6.7/53.3</td>
<td>86/14/0</td>
</tr>
</tbody>
</table>
pheric temperature and pressure, it is a colorless, non-toxic, and non-corrosive liquid. It can be blended with diesel fuel in any proportion. In the molecular structure of DMC, there are C–H and C–O bonds, but no C–C bonds. It contains 53% by weight of oxygen. The high oxygen content of the DMC can help reduce smoke and particulate in the engine exhaust. The DMC used in the present study has the following properties: maximum DMC content 99.99% by weight, minimum cetane number 35, viscosity 0.62–0.63 mm²/s at 20°C, and maximum density 1.079 kg/liter at 20°C. The major properties of diesel oil and DMC are compared in Table I.

Because of the property differences between DMC and diesel fuel, its blending in diesel will modify the chemical-physical properties and the injection properties of the original fuel. When the proportion of DMC is increased, there is an increase in density and surface tension, and a decrease in viscosity, cetane number, lower calorific value, and the stoichiometric air–fuel ratio.

**EXPERIMENTAL SET-UP**

In the present study, a diesel engine was operated at different steady states on an engine test bed, with blended fuel containing different percentages of DMC. In each case, the engine was run for a period of 20 minutes to reach the steady state before measurements were carried out. Tests were performed with a direct-injection single-cylinder and an indirect-injection 4-cylinder diesel engine. Specifications of the engines are given in Table II. The single-cylinder diesel engine was coupled to an electrical dynamometer, while the 4-cylinder diesel engine was coupled to a hydraulic dynamometer. The engine speed was indicated by a tachometer and fuel consumption was measured by a fuel meter. The particulate number concentration and size distribution were measured with a scanning mobility particle sizer (SMPS, TSI 3934) in the range of 0.015 micron to 0.75 micron and

<table>
<thead>
<tr>
<th>Engine</th>
<th>Single-Cylinder</th>
<th>4-Cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model and Type</td>
<td>Nanyang TY1100, 4-stroke, direct-injection, natural aspirated</td>
<td>Nissan TD23, 4-stroke, indirect-injection, natural aspirated</td>
</tr>
<tr>
<td>Maximum power</td>
<td>11 kW at 2300 rpm</td>
<td>52 kW at 4300 rpm</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>60 Nm at 1600 rpm</td>
<td>147 Nm at 2200 rpm</td>
</tr>
<tr>
<td>Bore and stroke / mm</td>
<td>100 × 105</td>
<td>89 × 92</td>
</tr>
<tr>
<td>Displacement / cm³</td>
<td>903</td>
<td>2289</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>18</td>
<td>21.9</td>
</tr>
<tr>
<td>Fuel injector</td>
<td>Multi-hole nozzle</td>
<td>Pintle nozzle</td>
</tr>
<tr>
<td></td>
<td>4 holes × 0.3 mm dia</td>
<td></td>
</tr>
<tr>
<td>Injector/nozzle opening pressure</td>
<td>18 MPa</td>
<td>9.8 MPa</td>
</tr>
</tbody>
</table>
with an aerodynamic particle sizer (APS, TSI 3310A) for larger particles. The SMPS classifies the particles based upon their electrical mobility, reporting the number of particles per unit volume (#/cm$^3$) versus the electrical mobility diameter, using an electrostatic classifier and a condensation particle counter. The volume fraction (nm$^3$/cm$^3$) is calculated by assuming spherical particles at the measured mobility diameters. Exhaust gas was diluted through a mini-dilution system before passing to the SMPS or the APS.

$\text{NO}_x$ concentration was measured with a heated chemiluminiscent analyzer (HCLA). HC was measured with a heated flame ionization detector (HFID). CO was measured with a chemical cell. The analyzers were calibrated with standard gases before conducting the measurements.

In addition, a light-duty diesel vehicle was used in carrying out tests on a chassis dynamometer. In this case, the particle size was not measured. Instead, the smoke opacity was measured with a Dieseltune smokemeter.

**EXPERIMENTAL RESULTS**

**Particulate Emission**

Figures 1 and 2 show the particle number concentrations and size distributions of the 4-cylinder diesel engine operating with pure diesel, under different engine loads. The %load refers to the percentage of the maximum torque of 147 Nm. Figure 1 shows the results as measured by the SMPS. There was an increase in the sub-micron particle concentration with an increase in engine load, coupled

![FIGURE 1 Distribution of sub-micron particles of 4-cylinder diesel engine on pure diesel.](image-url)
with a shift of the peak value of the sub-micron particle concentration to the right; that is, there was an increase in the average diameter of the sub-micron particle with an increase in engine load. Figure 2 shows the results as measured by the APS. There was an increase in the number concentration with an increase in engine load. There were significantly fewer micron-sized particles than sub-micron ones.

Figures 3 and 4 show the change of size distribution of the sub-micron particles owing to different %DMC added to the diesel fuel for the 4-cylinder diesel engine.
engine at two different operating conditions. Figure 3 shows the case of the engine operating at 2200 rpm and 0% load. Basically, there was a significant decrease in the number of particles when DMC was added into the diesel fuel. However, the reduction was not proportional to the %DMC added. For example, there were more small particles emitted with 30%DMC or 20%DMC in the fuel than that with 5%DMC and 10%DMC. Figure 4 shows the case of the engine operating at the same engine speed, but at 75% load. In this case again, there was a significant decrease in the number of particles when DMC was added into the

![Graph showing particle diameters and concentrations for different DMC percentages at 2200 rpm, 75% load.]

FIGURE 4 Effect of %DMC on sub-micron particulate emission: 4-cylinder diesel engine, 2200 rpm, 75% load.

![Graph showing particle diameters and concentrations for different DMC percentages at 2200 rpm, 0% load.]

FIGURE 5 Effect of %DMC on micron particulate emission: 4-cylinder diesel engine, 2200 rpm, no load.
diesel fuel, and the reduction was not proportional to the %DMC added. It can be concluded that DMC-blended diesel can lead to a significant decrease in sub-micron particles in the engine exhaust.

Figures 5 and 6 show the corresponding changes in the micron-sized particles. We can see that DMC can effectively reduce the micron-sized particles in the exhaust gas but, again, the reduction was not proportional to the %DMC in the blended fuel.

FIGURE 6  Effect of %DMC on micron particulate emission: 4-cylinder diesel engine, 2200 rpm, 75% load.

FIGURE 7  Effect of %DMC on sub-micron particulate emission: single-cylinder diesel engine, 1800 rpm, 6 Kw.
Figures 7 and 8 show, respectively, the distribution of the sub-micron and micron particles for the single-cylinder diesel engine. In these cases, only two %DMC were considered. Again, there was obvious reduction in the sub-micron and micron particles in the exhaust gas under different operating conditions. It can be concluded that DMC-blended diesel is effective in reducing particulate in the exhaust gas of both engines.

![Figure 8](image1.png)

**FIGURE 8** Effect of %DMC on micron particulate emission: single-cylinder diesel engine, 2200 rpm, no load.

![Figure 9](image2.png)

**FIGURE 9** Effect of %DMC on total number of sub-micron particulate emission of 4-cylinder diesel engine.
Figure 9 shows the total number of sub-micron particles, as measured by the SMPS for the 4-cylinder diesel engine under different engine loads and %DMC in the blended fuel. Figure 10 shows the corresponding total volume of the sub-micron particles, assuming that the particles are spherical in shape. We can see that, in both cases, 5%DMC and 10%DMC are effective in reducing both the total number and total volume of sub-micron particles in the exhaust gas. A higher percentage of DMC in the fuel would not guarantee further improvement in sub-micron particulate emissions. For example, at 25%load, the total number of sub-micron particles in the exhaust gas with 20%DMC was higher than the case with 5%DMC. Because of the reduced energy content of the blended fuel, the engine failed to deliver 75%load with 30%DMC.

Gaseous Emissions

Figures 11, 12, and 13 show, respectively, the effect of %DMC on HC, NO\textsubscript{x}, and CO emissions of the 4-cylinder diesel engine. Figure 11 shows that there was a decrease of HC emission with 5%DMC in the blended fuel at the loaded conditions. HC emissions increased with higher %DMC in the blended fuel. Figure 12 shows a slight decrease of NO\textsubscript{x} emissions with %DMC in the blended fuel. Figure 13 shows an increase in CO emissions with %DMC in the blended fuel. The effect of %DMC on the gaseous pollutants was far less significant than its effect on the number of particles. It can be concluded that the adverse effects of %DMC on the gaseous pollutants in the exhaust gas, if any, are insignificant in comparison with the advantages gained in reducing the particulate emission.
FIGURE 11  Effect of %DMC on HC emissions of 4-cylinder diesel engine.

FIGURE 12  Effect of %DMC on NOₓ emissions of 4-cylinder diesel engine.

FIGURE 13  Effect of %DMC on CO emissions of 4-cylinder diesel engine.
Smoke Emissions

A light-duty diesel vehicle, which has an engine of 2,779 c.c. capacity and a maximum power of 60 kW, was used for lug-down tests on the chassis dynamometer with different %DMC. The lug-down test is the mandatory procedure in Hong Kong for testing the smoke opacity of in-service diesel vehicles. During the test, the vehicle, with fixed fuel pump setting, is operated on the chassis dynamometer to find out its maximum horsepower and the corresponding maximum engine speed attainable under the maximum horsepower. The test then proceeds continuously in three stages: first, with the vehicle operating at maximum power and the maximum engine speed; subsequently, with the vehicle operating at maximum power and at 90% of the maximum engine speed; and finally, at maximum power and at 80% of the maximum engine speed. The test period for the lug-down is about 40 seconds. Throughout the test period, the smoke opacity of the exhaust gas is measured continuously with a smoke meter. In our tests, the same lug-down procedure as is required by Hong Kong law was adopted. Figure 14 shows the measured results of smoke opacity during the lug-down period. The sections marked 100%, 90% and 80% in the figure correspond, respectively, to the test sections at 100%, 90% and 80% of the maximum attainable engine speed at maximum power. From Figure 14, we can see that there was a decrease in smoke opacity with an increase in %DMC. Again, the decrease was not proportional to the %DMC in the blended fuel. The maximum power output of the vehicle dropped from 42 kW with pure ultra-low sulphur diesel fuel to 35 kW with 20%DMC, primarily because of the reduced heat value of the blended fuel.

FIGURE 14 Effect of %DMC on smoke emissions of a light-duty diesel vehicle.
Hence, it is not justified to use a higher %DMC in diesel fuel to reduce the smoke emission of a vehicle.

**Engine Performance**

For the single-cylinder diesel engine, the in-cylinder pressure was measured and the heat release rate analyzed. Table III shows the summarized results for the case with the engine operating at 1800 rpm and 11 kW, and a typical heat release rate diagram is shown in Figure 15. Figure 15 shows a delay in ignition, coupled with an increase in the peak heat release rate, with an increase in %DMC. Table III shows a slight decrease in the combustion pressure, but an increase in the percentage of fuel burned in the premixed mode. The percentage of fuel burned in the premixed mode is defined here as the energy released during the premixed mode divided by the energy of the fuel consumed. The increase in ignition delay of the blended fuel is because of the lower cetane number and higher heat of evaporation of the blended fuel. The increase in ignition delay with %DMC caused a larger amount of fuel burned in the premixed mode and also a

<table>
<thead>
<tr>
<th>%DMC</th>
<th>Peak value of pressure (MPa)</th>
<th>Fuel burned in premixed mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.52</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>8.31</td>
<td>19</td>
</tr>
<tr>
<td>10</td>
<td>8.27</td>
<td>26</td>
</tr>
<tr>
<td>15</td>
<td>8.22</td>
<td>29</td>
</tr>
<tr>
<td>20</td>
<td>8.10</td>
<td>34</td>
</tr>
</tbody>
</table>

**FIGURE 15** Effect of %DMC on heat release rate.
higher peak heat release rate. We know that the formation of the particulate matter emitted from the exhaust gas of a diesel engine has mainly to do with the diffusion combustion process. The increase in the percentage of fuel burned in the premixed mode partially explains the decrease of particulate in the exhaust gas. However, it fails to explain the higher number of particles in the exhaust gas at 20%DMC than at 5%DMC, in certain operating conditions.

With an increase in %DMC, the increase in ignition delay and drop in peak pressure are favourable conditions for reduction of NO\textsubscript{x}. However, the oxygen content of the blended fuel could lead to an increase in NO\textsubscript{x} formation. Hence, there are reported cases of NO\textsubscript{x} emission higher than base fuel in using DMC blended fuel (Murayama et al., 1995; Wang et al., 2000).

Figure 16 shows the specific fuel consumption, at a different %DMC, of the single-cylinder diesel engine operating at 1800 rpm. When the %DMC was increased, the blended fuel consumption increased because of the lower heat value of the blended fuel. The increase was higher where the original specific fuel consumption was high, for example, in the lower power range. For maintaining the same power output, there will be a longer spray period that will affect the subsequent combustion process. The increase in fuel consumption is a disadvantage in the application of DMC blended fuel.

**CONCLUSION**

From the present study, the following conclusions can be made:

1. Blending DMC in diesel fuel can significantly reduce both the sub-micron- and micron-sized particles in the exhaust of the 4-cylinder and single-cylinder diesel
engine. However, the reduction is not proportional to the %DMC in the blended fuel.

2. DMC can efficiently reduce the smoke opacity emitted from the light-duty diesel vehicle. Again, the reduction of smoke opacity is not proportional to the %DMC in the blended fuel.

3. DMC has little impact on gaseous pollutants. With an increase in the %DMC, there is a slight increase in both CO and HC emission, but a slight decrease in NOx emission.

4. DMC has an impact on the combustion process of the diesel engine. With an increase in the %DMC, there is an increase in ignition delay, a reduction in the combustion pressure, and an increase in the percentage of fuel burned in the premixed mode.

5. The major adverse effects of DMC are the reduction in power output of the engine or the vehicle and the increased fuel consumption, both owing mainly to the lower heat value of the blended fuel.

It can be concluded that DMC can be used as a fuel additive to diesel engines or diesel vehicles for reducing smoke and particulate emissions. The appropriate application of DMC as a fuel additive to in-service vehicles can help in reducing air pollution.

Acknowledgments

This project is supported by a research grant from the Research Grants Council of the Hong Kong SAR (Project No. PolyU 5156/01E).

References


