Annual Technical Report
on

**Dimethyl Ether (DME)-Fueled Shuttle Bus
Demonstration Project**

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ABSTRACT

The objectives of this research and demonstration program are to convert a campus shuttle bus to operation on dimethyl ether, a potential ultra-clean alternative diesel fuel. To accomplish this objective, this project includes laboratory evaluation of a fuel conversion strategy, as well as, field demonstration of the DME-fueled shuttle bus. Since DME is a fuel with no lubricity (i.e., it does not possess the lubricating quality of diesel fuel), conventional fuel delivery and fuel injection systems are not compatible with dimethyl ether. Therefore, to operate a diesel engine on DME one must develop a fuel-tolerant injection system, or find a way to provide the necessary lubricity to the DME. In this project, we have chosen the latter strategy in order to achieve the objective with minimal need to modify the engine. Our strategy is to blend DME with diesel fuel, to obtain the necessary lubricity to protect the fuel injection system and to achieve low emissions. Our laboratory studies have included work with a Navistar V-8 turbodiesel engine, demonstration of engine operation on DME-diesel blends and instrumentation for evaluating fuel properties. Our field studies have involved performance, efficiency and emissions measurements with the Champion Motorcoach "Defender" shuttle bus which will be converted to DME-fueling. Our results include baseline emissions, performance and combustion measurements on the Navistar engine for operation on a federal low sulfur diesel fuel (300 ppm S). Most recently, we have completed engine combustion studies on DME-diesel blends up to 30 wt.% DME addition.

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EXECUTIVE SUMMARY

The objectives of this research and demonstration program are to convert a campus shuttle bus to operation on dimethyl ether, a potential ultra-clean alternative diesel fuel. To accomplish this objective, this project includes laboratory evaluation of a fuel conversion strategy, as well as, field demonstration of the DME-fueled shuttle bus. Since DME is a fuel with no lubricity (i.e., it does not possess the lubricating quality of diesel fuel), conventional fuel delivery and fuel injection systems are not compatible with dimethyl ether. Therefore, to operate a diesel engine on DME one must develop a fuel-tolerant injection system, or find a way to provide the necessary lubricity to the DME. In this project, we have chosen the latter strategy in order to achieve the objective with minimal need to modify the engine. Our strategy is to blend DME with diesel fuel, to obtain the necessary lubricity to protect the fuel injection system and to achieve low emissions. Sponsorship comes from the National Energy Technology Laboratory (Project Managers Mike Nowak and Jenny Tennant, and Program Manager John Winslow), the Pennsylvania Department of Environmental Protection Alternative Fuel Incentive Grant Program (Program Manager Susan Summers) and Air Products and Chemicals, Inc. (Program Manager Peter Tijm (now with Renntech) and Ed Heydorn).

To date, our activities have covered two areas: laboratory investigations and field investigations. The laboratory studies have included work with a Navistar V-8 turbodiesel engine, demonstration of engine operation on DME-diesel blends and instrumentation for evaluating fuel properties. The field studies have involved performance, efficiency and emissions measurements with the Champion Motorcoach "Defender" shuttle bus which will be converted to DME-fueling.

Within the Diesel Combustion and Emissions Laboratory in the Penn State Energy Institute, we have installed and equipped a Navistar V-8 direct-injection turbodiesel engine for measurement of gaseous and particulate emissions and examination of the impact of fuel composition on diesel combustion. We have also reconfigured a high-pressure viscometer for studies of the viscosity, bulk modulus (compressibility) and miscibility of blends of diesel fuel, dimethyl ether and lubricity additives. Our results include baseline emissions, performance and combustion measurements on the Navistar engine for operation on a federal low sulfur diesel fuel (300 ppm S). Most recently, we have completed engine combustion studies on DME-diesel blends up to 30 wt.% DME addition.

We have also performed viscosity measurements on diesel fuel, DME and blends of DME in diesel. These tests have verified that DME has a much lower viscosity than the diesel fuel and that the viscosity of the blended fuel is also much lower than the diesel base fuel. This has implications for the injection and atomization of the DME/diesel blends.

EXPERIMENTAL

This project is driven by Air Products' interest in the development of markets for the Liquid Phase Dimethyl Ether process technology, the state's interest in development of transportation fuel usage from Pennsylvania resources (e.g., coal) and the Department of Energy's interest in ultra-clean transportation fuels. In this project we (Penn State Energy Institute and Air Products and Chemicals, Inc.) have determined how to effect the conversion of a shuttle bus equipped with a Navistar DI turbo-diesel engine to operation on Dimethyl Ether (DME). To accomplish this goal, we have been examining the co-firing of the engine on diesel fuel and dimethyl ether, using the diesel fuel as a lubricating agent to protect the fuel pump and fuel injection system from excessive wear. Dimethyl ether has no natural lubricity, making it antagonistic to fuel system components.

The work consists of two parallel efforts. One is an evaluation of the performance, emissions and efficiency of a shuttle bus equipped with a diesel engine and operated on dimethyl ether. That work is relying on the bus testing facilities and portable emissions analysis equipment of the Pennsylvania Transportation Institute (PTI). The other is the development of a conversion process to operate a diesel engine on dimethyl ether using conventional fuel injection equipment. PTI is evaluating the in-service performance, emissions and efficiency of the shuttle bus (Champion "Defender" model) that serves as a faculty/staff shuttle on the University Park campus. Initially, the bus is being operated on diesel fuel to provide baseline information. Tests have been performed since break-in of the vehicle and will be performed at several intervals after the conversion to dimethyl ether operation.

Meanwhile, we have been working on the development of a conversion strategy to operate a Navistar T444E turbodiesel engine, identical to the one in the shuttle bus, to operation on blends of DME and diesel. We have demonstrated that the laboratory engine can be operated effectively on the blended fuel.

At the same time, we have designed a large scale, dedicated DME fueling station for delivery of DME-diesel blends. The cost of the initial design, however, was well beyond the level of funding available for the fueling station. Instead, we have developed a simpler plan that involves a two-stage fueling process. The driver of the shuttle bus will use the existing diesel fuel pumps for University service vehicles to fill the bus' main tank with diesel fuel. This diesel fuel will be transferred to the DME-diesel mixture tank. Then, the driver will back up to an adjacent storage location for the DME tank to add the DME to the shuttle bus.

The objectives of the laboratory testing have been to determine the compositions of fuel and additive blends that will permit long term operation of the T444E engine on dimethyl ether. We have successfully operated the laboratory engine on blends with up to 30 wt.% DME. Based on these tests, we have determined that the optimal blend ratio for the field vehicle is 25 wt.% DME in diesel fuel.

Through collaboration with the Tribology Laboratory in Penn State's Chemical Engineering Department, we are characterizing the viscosity, compressibility and miscibility of blends of DME, diesel fuel and the additives under pressures and temperatures relevant to the fuel

injection system. These tests are using a high pressure viscometer adapted to these specific experiments. In addition under a new project with support from NETL, we will construct an injector durability experiment to determine the time to failure and boundary of the of fuel composition which can lead to injector failure. Also, we will modify an existing pin-on-ring apparatus to investigate the lubricity of DME blends with diesel fuel and lubricity additives.

At present, we are selecting and designing fuel system hardware for use on the shuttle bus to convert it to DME-diesel operation. The conversion is now planned to occur during May and June of 2001. Then PTI will perform the emissions, performance and efficiency tests on the converted vehicle at several intervals over an 18-month period. The diesel engine in the laboratory will continue to be operated on DME for continuing studies of fuel system durability and optimization.

Several companies have been willing to participate in this project. Navistar International has contributed funds to purchase the laboratory engine, provided technical guidance during the laboratory studies, and a cost share on the shuttle bus. Champion Motorcoach provided a cost share on the purchase of the shuttle bus. Lubrizol and Ethyl Additives have provided samples of lubricity agents. Caterpillar (manufacturer of the HEUI fuel injectors on the Navistar T444E turbodiesel engine) has agreed to participate in a new, related project on injector durability which will lead to more DME tolerant fuel injector design. Dupont Fluorocarbons have provided over 500 lbs of DME for use in the engine studies. We are presently negotiating with DuPont Fluorocarbons regarding their providing DME at a discounted price for the field vehicle demonstration.

The most significant technical challenge in this project is accounting for the lubricating quality of the fuel and additive mixtures. This involves two considerations of the mixtures: (1) the lubricating quality of the mixtures; and (2) the phase behavior of the mixtures, given that advanced diesel fuel injection systems use injection pressures that exceed the critical pressure of DME. At higher DME blend ratios, we have observed some instability in the laboratory engine, perhaps due to generation of excessive amounts of DME vapor. This is one aspect of engine operation on DME-diesel blends that we will need to monitor closely during the field evaluation.

The rest of this report consists of a section for each of the major activities under the project.

- Laboratory Engine Progress Summary
- Electronic Controls of the Navistar T444E Turbodiesel
- Viscometer Progress Report
- Fuel Station and Bus Conversion Design

RESULTS AND DISCUSSION

Laboratory Engine Progress Summary

The laboratory engine, a Navistar T444E 190hp V-8 Turbodiesel has been operational since October 1999 in our engine test cell. The engine is outfitted with numerous thermocouple sensors, an in-cylinder pressure sensor (in Cylinder #1) and the exhaust system has a number of ports for sampling particulate emissions, gaseous emissions (including total hydrocarbons) and particulate composition (via thermal analysis). The figure below shows a digital photo of the engine in the test cell prior to the fuel system conversion.

Figure 1. Photo of the Navistar T444E Turbodiesel Engine in the 450 hp Engine Test Cell Prior to Conversion to DME-Diesel Blends

The AVL steady state 8 mode test had been selected to do the emissions comparison studies for different fuel additives and blend ratios of DME to diesel. During previous tests, a comparison of exhaust emissions was made with two different oxygenates, the CETANERTM fuel additive and

Dimethyl ether (DME). These were blended with a federal low sulfur diesel fuel that will also serve as the baseline fuel. The oxygenates were blended such that the oxygen content of the mixture will be 2% by mass. The Appendix includes a copy of a Society of Automotive Engineers technical paper that was written on this work.

Modifications Based on Initial Engine Tests

Based on the engine operation for the 6% DME operation (2wt % oxygen) (see Appendix), minor modifications to the fuel system cooling were completed. This included adding additional heat exchanging capability via increased surface area in the cooling bath, and by increasing heat removal rate with a larger bath chiller unit. This allowed for the bath to cool the fuel below the critical temperature for the particular pressure being used in fuel system.

Figure 2. Navistar T444E View showing cooling bath and chiller unit.

Low DME/Diesel Concentration Tests

Testing was performed for 5 and 10 wt % oxygen, which is roughly 12.5 and 25 % DME in diesel respectively. Data was collected on the engine operation, emissions, and engine control parameters which are governing the engine during operation. At present, that data is being analyzed and tabulated. The following chart provides a preliminary impression of the data. Further work will need to be done to correlate the data to the brake horse power from the engine for each mode. However, the preliminary information does confirm what would be expected from the data. With increasing DME content addition, there is a decrease in particulate emissions. In Figure 3 below, the first two bars are the baseline diesel results. The second two are the 5 and 10 wt % oxygen respectively. It is evident here that the general trends expected are consistent. Also, what can be seen are missing bars from some modes. At these engine conditions, it was not possible to control and stabilize and run the engine for extended lengths of time. It is believed that the engine control had reached its maximum fuel capability at these points. Further work will be performed to confirm that this is the case, and to optimize the engine so that these modes can be analyzed. Optimization will include tuning the fuel quantity and the injection timing based on the ignition delay for the fuel to permit the engine to perform over the entire rated range, and to reduce emissions. The pressure trace analysis for this data will help to support the direction of the research. This data has been collected, and is now in the process of being analyzed.

Figure 3. Particulate Matter Emissions from Baseline Diesel, Converted Diesel and DME-Diesel Blend Operation

Electronic Controls Of The Navistar T444e Turbodiesel

What has been accomplished and learned

In the initial purchase of the engine, the electronic control module (ECM) was purchased from Navistar, and had been programmed with a base calibration of software. This was not immediately realized, as we had asked for the engine to be programmed with the same calibration as the bus.

Engine Debugging

In the process of debugging the engine, it was necessary to purchase the Service Technician Tool which would allow for the failure modes of the engine to be observed. The tool allows for communication across the ATA (American Trucking Association) Communication lines per one of the established communication protocols to the electronics. The tool does allow for additional engine parameters to be monitored and for small portions of that information to be logged into the tool itself. The tool has served a great purpose in allowing for the engine to be easily debugged during the start up phase and while operating. It has allowed for us to understand what common failure modes to look for, and has allowed for us to easily move past them on a daily operation basis. It has also allowed for us to check out the bus, during the verification of the ECM software part number. It will definitely be a good tool to have and use during the future phases of the project, so that we can observe what may be occurring when the engine will not operate.

In addition to the tool being purchased, any associated wiring and connectors were also purchased so that the tool could be used to communicate correctly with the ECM.

Automotive Electronic Communication Protocols

In the past, there have been many different types of communication protocols used by automotive and truck manufactures. Over the past 10 years, a conscious effort has been made to standardize these methods so as to reduce the proliferation of Service Technician tools, and the amount of software which needed to be programmed into the ECM for the manufacturing facilities test equipment. This in turn helped to reduce the overall cost and complexity of the product by using the least memory necessary. The protocol which is gaining wide acceptance in the industry is called CAN (Controller Area Network). The important aspect of the protocol is that with the correct IC within the ECM, software can be transmitted serially to the product through the ECM connector. In comparison, in the past, if an ECM needed to be reprogrammed, this was accomplished by sending it back to the factory and programming occurred by probing on the microprocessor pins.

Communicating with the Navistar T444E Control Module

Working with Navistar, we reached a compromise to permit us access to the signals within the ECM, including both the ability to read and reprogram engine operating conditions. Navistar suggested that we use the CAN communication protocol as described above, and over the last year we have acquired a National Instruments CAN instrumentation board. We have developed programs to use the CAN board in the Labview environment. The CAN board allows us to communicate via the ATA bus with the ECM and obtain essential information such as fuel injection timing.

Engine Parameter Programming

To permit us to perform engine parameter programming, Navistar has provided us with a “developmental” version of their ECM, To be able to modify certain parameters ourselves via the CAN bus, or to “flash” the new set of software Navistar provides us via the CAN bus. (Navistar has also provided us with some custom ECM software to allow for us to do this.)

Parameters Needed for Pressure Trace Analysis

The injection timing is a little more difficult to measure since it is calculated from a few tables and is only an internal variable in the ECU. Navistar has provided us with software to read or reprogram injection timing over the CAN or diagnostic bus. Injection timing cannot be measured because the injector fires earlier than the actual timing depending on oil temp, and injection pressure so the only easy way is to get the value from the ECU.

Viscometer Progress Report.

High Pressure Viscometer Setup

To optimize the performance of a fuel injection system for a particular fuel or fuel blend, it is very important to have a good estimate of the physical properties of those fuels. It is equally important to know the change in properties with change in pressure and temperature. An experiment was configured to measure the viscosity of diesel, DME and their blends at various pressures. The high pressure viscometer apparatus used for this work was designed and built at The Pennsylvania State University in 1962-63. This apparatus was modified to allow for charging of a pressurized liquid sample, as is necessary when dealing with compressed liquids. Robert Johnson in his Master's thesis, gives a detailed description of the design and use of the apparatus. The thesis presents an excellent overview and a summary of the work done in the field of high pressure viscometry up to 1962. The equipment very simple in design, is nevertheless extremely accurate in viscosity measurement up to a pressure of 10,000 psig.

Description of High Pressure Viscometer

A schematic diagram of the apparatus setup is shown in Figure 4. The setup consists of a pressure intensifying system, a pressure measurement system, a constant temperature bath and the viscometer pressure vessel.

Figure 4. High Pressure Viscometer Setup

Pressure Supply and Measurement Equipment

Pressurized Helium produces the high pressure required for this equipment. Initial studies were carried out with Nitrogen as the pressurizing gas. It was found, however, that Nitrogen is highly soluble in DME. Soluble gases present in a liquid increase the error of viscosity measurement. For this reason it was decided to use Helium, which is less soluble in DME as compared to

Nitrogen. Pressures up to 2500 psig can be attained by simply connecting a commercial Helium gas cylinder to the system. For higher pressures, the air operated pressure intensifying pump is used. This system consists of an Aminco Dehydrogenation Bomb with a volumetric capacity of 4.5 liter. This bomb is filled with Helium from the gas bottle at the available pressure. This Helium is further compressed by pumping oil into the bomb. A SAE30 oil was used in this case. For higher pressures a SAE50 oil is recommended. The oil is pumped by an air driven pump made by Teledyne Sprague Engineering (Model # S-216-J-150). The 150 in the model number, indicates the factor by which the pressure of oil can be raised as compared to the pressure of the supplied driver air.

The pressurization procedure can be explained as follows with reference to Figure 4:

- Valve B, the return valve is closed and valve A is opened. The outlet oil pressure gauge will read the pressure of the Helium in the bomb.
- Driver air is supplied to the pump at a pressure of about 25 psig. An air lubricator is installed upstream of the pump. If the air inlet valve to the pump is open, it will cause the pumping plunger to pump oil into the hydrogenation bomb. The addition of oil increases the pressure of Helium already present in the bomb. There is a flowcheck valve in the oil supply line, which prevents the oil from flowing back into the pump. The pressure of the Helium in the bomb is read by an accurate pressure gauge.
- When the desired pressure is reached, the air inlet valve to the pump can be closed to stop the pump. The valve A is then closed. High pressure after the pump is relieved slowly by gradually opening the valve B.
- The bomb is now ready to supply pressurized Helium to the viscometer apparatus. The pressure of Helium is always kept a bit higher than the required pressure in the viscometer.
- The amount of oil in the bomb can be estimated by observing the oil level in the oil reservoir.
- Care should be taken to prime the pump with oil. This can be achieved by gravity feeding the oil.

High pressure gauges are used to measure the pressure in the system. These gauges have a maximum readability of 5,000 and 10,000 psig and have a rated accuracy of 0.5% of full scale. For the present study, the gauge with a capacity of 5,000 psig was used for its higher resolution.

Constant Temperature Bath

For the present study, the viscometer housing was kept at a constant temperature of 100°F. Water was used as the bath fluid. It was maintained at 100°F, using a temperature controller by Omega Engineering (Model CN9000A). This controller reads the temperature by means of a K-type thermocouple. This feedback loop controls the electric immersion heater. Using this system, the temperature in the bath can be maintained to within 0.1 deg F. The bath is made out of a glass jar

12 inches in diameter. The water level in the bath is maintained at a certain height so that the viscometer pressure vessel is fully immersed in water. A simple submersible pump is used for water circulation, which helps maintain a constant temperature throughout the water bath. The bath temperature control is typically kept ON continuously to assure a stable operating temperature.

Viscometer Operation Procedure

The operating procedure for the viscometer is described with respect to Figure 4. Prior to beginning the viscosity measurement, the sample for viscosity measurement is prepared in the sample cylinder and maintained at a pressure of about 500 psig. The sample cylinder is then kept immersed in the water bath for a couple of hours to ensure correct temperature of the fluid. This step drastically reduces the stabilization time. The AMINCO hydrogenation bomb is charged to the required pressure by operating the pressurizing equipment. The viscometer capillary is assembled in the pressure vessel and is brought up to the operating pressures. The bath is brought up to the operating temperature of 100°F. The following steps are then taken to charge the viscometer capillary with the fluid and measure its viscosity:

1. The 5,000 psig pressure gauge is used to measure the pressure in the viscometer housing. At this point valves 1, 3, 4, 6, 9 and 12 are open and valves 2, 5, 7, 8, 10, 11, 13 and 14 are shut off. At this point, the viscometer housing is at the desired pressure.
2. The sample cylinder is connected to the viscometer housing at valves 2 and 5. Valve 2 is opened to equalize the pressure between the sample cylinder and the viscometer housing. Valve 5 is used to introduce the desired amount of sample into the viscometer housing. The level of the sample is observed through the glass windows on the housing. As soon as the desired level is reached, the valve 5 is closed. The sample cylinder can then be disconnected from the viscometer housing.
3. As the test fluid is already at the operating temperature, the viscometer capillary can be immediately filled with the sample. To accomplish this, valves 3 and 4 are shut off. Helium is then vented very slowly to the atmosphere through valves 1 and 2. Valve 2 can be left fully open and the rate of capillary filling can be controlled by modulating valve 1. It is very important to fill the capillary very slowly. Rapid filling may cause boiling and separation of the sample. A rule of thumb is to allow the same time for filling as it takes for drainage. The liquid level in the capillary should be a little above the uppermost etched line above the degasification bulb as shown in Figure 5. At this point valves 1 and 2 are closed. Valves 1 and 4 are then opened slightly to equalize the pressure between the top of the capillary and the reservoir. Valve 3 is then opened so as to read the correct pressure in the viscometer housing. Valve 1 is then closed immediately to maintain the level of the liquid in the capillary. The filling process can reduce the pressure in the system to a great extent because of venting. It is important to begin with a pressure higher than desired. With sufficient practice, the desired level in the capillary can be reached at the desired pressure.
4. At this time the viscometer is left to equilibrate for a couple of hours. This is to ensure that the entire system has reached a constant desired temperature.

5. After about two hours, the viscometer is ready for the viscosity measurement. Care should be taken that the liquid level hasn't changed significantly in the capillary. Starting drainage from different liquid levels may introduce errors as will be discussed later. Valve 1 is now opened to allow the liquid to start flowing down. The stop watch is started as soon as the lower liquid meniscus comes in line with the top etched line on the efflux bulb. The time is stopped when the lower meniscus reaches the lower etched line at the bottom of the efflux bulb. The time is measured with a resolution of 0.01 seconds. The measured efflux time along with the characteristic distance are the only two observations required of the viscosity test run. The characteristic distance is the distance between the liquid level at the bottom of the viscometer housing and the bottommost etched line on the capillary. This distance is measured by a cathetometer with a resolution of 0.005 cm after the drainage of the sample is completed and the entire sample is at the bottom of the housing.

Sample Preparation

The samples tested for viscosity were blends of Diesel and DME in various proportions. A schematic of the apparatus used for sample preparation is shown in Figure 6. It consists of a transparent pressure vessel used to hold the mixture under a pressure of about 90 psig. The pressurizing gas is Helium, which is chosen for its lower dissolution in DME. The following steps describe the preparation of a homogeneous sample and its transfer into the sample cylinder.

1. About 100 gm of DME are introduced into the sample cylinder. The sample cylinder is then pressurized to about 90 psig. The difference in mass of the sample cylinder with and without DME gives the exact amount of DME present in the cylinder.
2. The observation vessel is pressurized with Helium to about 90 psig. The sample cylinder filled with DME is attached in the circuit 1. The valves connecting the sample cylinder to the observation vessel are opened. Under the influence of gravity, DME flows down into the observation vessel. The circuit 1 helps in equalizing the pressures in the two connected vessels. Sufficient time is allowed for all the DME in the sample cylinder to drop down into the observation vessel. The sample cylinder is disconnected and weighed. The difference in mass is the mass of DME introduced into the observation vessel.
3. This known mass of DME dictates the mass of Diesel fuel to be put in to get the desired Diesel-DME blend ratio. The required amount of Diesel is then introduced into the observation vessel in a similar manner. The velocity of the Diesel fuel entering the observation vessel helps in forming a homogeneous mixture instantly.
4. This mixture is then introduced into the sample cylinder through circuit 2. The mixture blend ratio is calculated by taking the actual mass numbers as observed.

Figure 5. Viscometer Capillary

Figure 6. DME Diesel Mixture Preparation

Miscibility Studies of Diesel – DME Blends

To ensure stable operation of a direct injection diesel engine, it is imperative that the fuel blend is always maintained in a homogeneous liquid state. The miscibility of the fuels is therefore an important aspect in any fuel blend.

The miscibility tests of Diesel-DME blends were carried out in a pressure vessel with a transparent window for observation. Blend ratios were varied in steps of 25% by mass. Thus 0, 25, 50, 75 and 100 were the percentages of DME in a blend comprising of DME and Diesel. Diesel has a density that is higher than that of DME. To separate the effect of gravitation on the mixing process, diesel formed the lower layer in the observation vessel. DME, which was introduced from the top as a liquid under pressure, formed the upper layer. The pressure was maintained at about 90 psig. This same pressure was later to be used in the pressurized fuel tanks. The mixture was then left undisturbed and the quality of the mixture was observed at various time intervals. This process ensured that the mixing would be because of molecular diffusion and not because of any physical mixing via agitation or density difference. It was observed that irrespective of the blend ratio, the blend became a homogeneous mixture in about 6 hours.

The situation described above is the worst case scenario in terms of assistance to mixing of the fuels. Introduction of one fuel into the other at some velocity greatly helps the mixing process.

Separation of the two fuels is also an important issue. Once a homogeneous mixture is formed, the fuels do not separate until DME starts boiling. Boiling may occur due to a reduction in pressure or an increase in temperature. Boiling is very likely to occur in the fuel rail of a diesel engine due to elevated temperatures. During the test run with a 2% O₂ content Diesel-DME mixture, unsteady operation of the engine and a loss of power was observed. This could have been due to the boiling of the DME present in the blend. The resulting fuel blend entering the fuel injectors was a mixture of liquid and DME vapors. This is thought to be the cause of power loss and unsteady operation. The temperature of the fuel in the rail was measured at 53 °C, which is higher than the boiling point of DME at the rail pressure of 150 psig

Viscosity of Diesel – DME Blends

The high pressure viscometer capillary was calibrated using a CANNON Certified Viscosity Standard N 1.0. Figure 7 shows the calibration curve obtained for the capillary used. The procedure followed to obtain the calibration was similar to the procedure for data taking. The calibration curve is typically a straight line.

Mass was used as the controlled variable in determining the composition of the samples. Table 1 shows the samples used for viscosity measurement.

Table 1. Samples for Viscosity Measurement

Sample number	Percent of DME by Mass
1	100
2	74
3	50
4	26
5	0

The remaining portion of the sample was made up by the 49 State Reference Diesel fuel. Figure 8 shows the effect of ambient pressure on the viscosity of the various liquid samples. The kinematic viscosity is plotted on a logarithmic scale. R.H. Johnson notes that a plot of the logarithm of the kinematic viscosity versus the pressure results in a straight line. The slope of this line can be used to extrapolate to higher pressures with a fair amount of accuracy.

Figure 7. Viscometer Capillary Calibration Curve

Figure 8. Pressure-Viscosity Relationship for Diesel-DME Samples @ 100 F

The line representing the 49 State Reference Diesel fuel starts from ambient pressure. For the remaining samples with DME as a constituent, the starting point was 500 psig to ensure that the samples remain in a liquid state. The pressure range in which the viscosity measurements are made are typical in the low pressure circuit of a diesel engine. Previous studies, done with pure DME as the fuel, state that lower injection pressures can be used for DME as the condition in the cylinder just before the firing TDC allows a very rapid vaporization of DME.

Another use of the viscosity versus pressure relations for the various blends is to choose or design a fuel injection system for the optimized blend ratio. There are two ways in which the fuel system can be designed for an engine running on a Diesel-DME blend. The first one is to examine the capability of an existing fuel systems. The deciding factor in this case will be the minimum viscosity than an existing fuel injection system can handle. The other way would be to optimize a blend ratio for a particular engine considering the exhaust emissions benefits and the energy density tradeoffs and to use the viscosity data of this particular blend to design a fuel injection system.

Figure 9 shows the response of the kinematic viscosity to the ratio of DME in the blend. This graph shows the effect of pressure on the viscosity of a particular blend.

Figure 9. Viscosity – DME Content Relationship at Different Pressures @100 F

Fuel Station And Bus Conversion Design

Fuel Station Design

Initially an in depth research and design project was undertaken for a large-scale permanent DME fueling station. The fueling station consisted of two DME storage tanks, one diesel tank, and one tank for the mixed fuel. The station was designed to utilize two transfer pumps: the DME/mixed fuel pump to perform at 10 gallons per minute (GPM) and the diesel transfer pump to perform at 100GPM. Extreme attention was given to the material of the inner seals/O-rings in the DME/mixed transfer pump. The system was designed to utilized helium as the gas to provide the necessary over pressure in the DME/mixed tanks.

A full diagram of the design including necessary controls and valves can be seen on the next page. Following the development of this drawing an extensive safety analysis was undertaken with the aid of Dr J. Hansel of Air Products and Chemicals Inc. Allentown PA. The results of this safety analysis are also contained in the pages that follow. This analysis also served as a beginning for a rough outline of a fueling procedure.

The final and much less expensive design of the fueling station requires only that we make the refueling process more elaborate. By switching to a two step process, we will be eliminating the need to have a dedicated fueling station. Instead, the driver of the shuttle bus will use the existing diesel fuel pumps for University service vehicles to fill the bus' main tank with diesel fuel. This diesel fuel will be transferred to the Then, the driver will back up to an adjacent storage location for the DME tank to add the DME to the shuttle bus.

Failure Modes Effects Analysis (FMEA) for Fueling Station

Also shown in the following pages is the result of a Failure Modes Effects Analysis performed in collaboration with Air Products and Chemicals, Inc.

Node 1

**Air Products/Penn State
DME Node/T103-T104**

**DME Fueling Station
6/30/2000**

NODE 1

Deviation	Cause	Consequence	Safeguards	Recommendations
1. No Flow No Flow No Flow	V109 closed P102 off	Normal most of the time. Operator present when P102 is operated. P102 overheats vaporizes diesel fuel. T104 must be vented to handle vapor from P102.	Insure T104 has vent for pressure relief.	
2. Low Flow	No level in T103	Generated vapor must escape; pump burnout.		
3. High Flow	Causes similar to no flow. Break in pipe between T103 and T104.		Acceptable risk tank is diked.	
4. Reverse Flow	V108 leaks and P102 is off.	Transfer of mix back to T103 (contamination) Potential for overflow of T103.	V109 closed by operator. T103 vented.	None
5. Loss of Dent.	Leak T103 Leak T104 Any piping Pump seal Pump seal life considered as well as resistance to blowout.	Leak of diesel fuel and/or mix flammable mixture present and environmental concerns.	Operator present when P102 is running to observe leakage.	Important for operator to understand environmental and flammability issues.

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Node 1

Deviation	Cause	Consequence	Safeguards	Recommendations
6. Pressure Low	See low flow.			
7. Pressure High	Only exists downstream of P102.	See no flow Reverse flow High flow		
8. Temp. Low	Normal in cold ambient temp.	Low flow Not safety problem		
9. Temp. High	See no flow. See high pressure.			
10. Level Low	T103 empty	Operational problem not software problem.		
11. Level High in T103	Overfilling of T103 from diesel distributor. Backflow from T104 through leaking V108 and open V109.	Acceptable risk within diked area and with trained operator. Could produce/release operator training on V109.		
In T104	Inaccurate sonic sensor. Operator error.	Overflow of T104 releasing causing flammable gases.	Periodic checking (including proper procedure for overflow of T101 and T102) of gauge and operator checking Relief valve or T104 must be sufficient to maintain safe pressure in T104.	

Node 1

Deviation	Cause	Consequence	Safeguards	Recommendations
12.-16. Composition Diesel (T103)	Wrong product delivered.	Gasoline/kerosene/off-road diesel risk acceptable proving tank in labeled.	Proper labeling on tank.	Relief valve sizing on T104 and related station equipment or business equipment has to assume worst case of pure DME.
DME (T104)	Wrong % of DME and diesel in tank.	Mal operation of engine (not addressed here)		
17.-19. Mixing	DME and Diesel appear to be soluble with each other and mix well. Mixing should not be a issue. All down _____ equipment will be used for _____ case if each DNE.			
20.-23. RXN	No RXN between Diesel and DME.			
24.-29a. Procedure Steps	All issues covered above.			
30. Phase Or Slate	See above.			
31. See No Flow.				
32.-33. NA				
34. Start-up T104 and all subsequent piping should be purged with He.				

Node 1

Deviation	Cause	Consequence	Safeguards	Recommendations
35. Shutdown DME Flam. Effluent should be made to maintain all DME equipment under (t) pressure to reduce ingestion of air.				
36. No apparent problem; but if long term operator should be reviewed.				
37. Erosion.	None.			
38. Maintenance	Pumps seals need to be checked on P102, V109 and level gauge on T104.			
39. Fire	Fire in vicinity of T103.	Overpressure in T103.	UL approval of vent.	
Fire T104	Relief valve sizing must be adequate.			

Node 2

NODE 2 (TRANSFER MODE)

Assuming some pressure control on discharge of P101 at least on circuit that feeds T104 to better control mixing ration (problem is vapor pressure curve of DME). Also assuming the level sensor in T104 can be made to shut down P1-01 and/or V107. And pneumatic valves V103 and V107 are fail close on loss of power and He. Place two relief valves on T104 due to large apparent demand, i.e., operator error in filling with diesel/DME, and flow through "closed valves" → two 100% valves!

Deviation	Cause	Consequence	Safeguards	Recommendations
1. No Flow.	Normal most of time. V102, V103, V107 closed. P101 off.	Operator error failed solenoids. Can overheat Resulting vapor must be able to get out or pressure will rise.	Apparently P101 can handle vapor.	Check to see that P101 has internal relief valve that can vent to outside as V107 and V105 could be closed (relief device must be between P101 & V107) (must go to safe location (inside containment area).
	DME low or none in T101/T102	No product delivered.		
	Regulator "X" closed. Error or failure.	Overheat of P101. See P101 off above relief valve "y." Overheat P101 off above relief valve "y."		

Node 2

Deviation	Cause	Consequence	Safeguards	Recommendations
2. Low Flow	Low temperature. See no flow.	Low pressure in T101 and T102 to transfer liquid to pump.	Helium supply. See no flow case for P101 with vapor.	HLZ function checked and logged once per year. HLZ (high level switch on T104) shuts down P101, V103, V107. If this fails relief device on T104 will function.
3. High Flow	High Pressure in T101 and T102. Pressure Reg. X fails open.	Incorrect DME/Diesel mix (Operational not safely). High flow into T104 incorrect mix. T104 overfilled		
4. Reverse Flow	Not normally possible because T104 is at lower pressure than T101 or T102.			
5. Loss Cont.	Piping leakage P101 leakage See no or low flow.	See comment under Node 1 pump seals.	Operator is present under most of flow conditions for tank or bus.	
6. Low Pressure				
7. High Pressure.	High pressure from the He supply. High summer lime temperature (high vapor pressure). Incorrect blend in T104.		Pressure device y will help with pressure downstream of pump. Pressure relief valves on T101 and T102 will have to be sized for DME (including density difference from propane and fire exposure). Pressure regulator x will help minimize blending error.	
8. Temperature Low	Normal	See low ambient temperature above.		

Node 2

Deviation	Cause	Consequence	Safeguards	Recommendations
9. Temperature High	See high pressure.	Firecase below will control.		
10. Low Level	T101 and T102 operational. Not safety issue.		Level sensor will exist on T101/T102.	
11. Level High (T101 & T102	Overfilling by bulk truck.	Liquid binding of T101 and T102. Can overpressure and can exceed burst pressure.	Operator training and tricocks. Relief device on T101 and T102 must be able to handle full flow from delivery truck and taken to safe location (DME is flammable).	
12.-16.	Potential for LPG driver to fill tanks because of operator error and connector is same.		No reason for LPG truck to be in area. Tanks and area are well marked.	Signs also say "NO LPG," "DME ONLY." Investigate type of fitting on DME delivery truck (possible to LPG). (Call Air Products; Jim Hansel.)
17.-19.	Contaminated feedstock	Unknown	APCI Analysis.	None except driver should be able to supply analysis sheet.
20.-23.	N/A			
24.-29a.	N/A			
30.	See above deviations.	Proper opening of valves between T101/T102 and T104 is important to ensure flow.		Procedure for valve opening will have to be developed and there may be a preferred order of valve opening.

Node 2

Deviation	Cause	Consequence	Safeguards	Recommendations
31.		P101 not function valves fail close.		
32.	N/A			
33.	Valves fail close.			
34.	See start-up Node 1.			
35.-37.	See Node 1.			
39.	T101 and T102 and adjacent piping must have adequate fire protection.			

Node 3

NODE 3

Deviation	Cause	Consequence	Safeguards	Recommendations
1. No Flow	P101 not running. V105, V105, valve on bus closed. T104 empty.	See description of P101 Node 2.		None. Flow meter feed to P101. Low flow alarm cut off pump.
2.	Same as No Flow.		T104 limited by relief device.	
3.	High Pressure T104.		Check valves on bus.	In absence of check on bus back flow could occur if P101 is down.
4.	Bus tank at higher pressure than T104.		Consider putting a check valve on bus if connector on bus will not be used to defuel bus. With check valve order of opening of valves becomes immaterial.	
5.	Loss of cont.		Ensure that relief setting on T104 is set to handle backflow from bus if bus is at higher pressure.	
6.	Low Press	Flammable gas.	Strength rating of hose.	By highest pressure rating practical. Hose should be replaced if program exceeds 2 year life span.

Node 3

Deviation	Cause	Consequence	Safeguards	Recommendations
7. High Press	High ambient temperature. Wrong mix in T104.	Potential overpressure of T104 and/or bus. Flammable gas.	Pressure relief valve "y." Pressure regulator "x." Pressure relief valve "z."	Consider relief devices on bus for fire exposure only and not from overpressure by overfilling which would have to be controlled from station. *Overpressure filling from station not addressed here.*
8. Temperature Low	Normal			
9. Temperature High	See pressure high above.			
10. Level Low	Must be controlled on bus.		Sonic sensor.	
11. 10. Level High	Must be controlled on bus.		Sonic sensor.	
12.-16. Comp.	See comp. In Node 1 and 2.			
17.-19. N/A				
20.-23. N/A				
24.-29a.	See reverse flow above. Written manual for safety.			
11. See Node 2.				
31.-33. See Node 2.				
34.-35. See Node 2.				
36.-39. See Node 2.				

NODE 4

Node 3

Deviation	Cause	Consequence	Safeguards	Recommendations
1. Now Flow	He tanks empty.	Pneumatic valves won't work.	Gauges on He tanks. Delivery confirmation. Valves fail close.	Relief loop for T101-T102 so check valve can be put on line into T101-T102 or Isolated header (protected header) (keeps pressure isolated. He solenoids at high pressure. He tank at lower pressure or Use N ₂ for valves.
2. Low Flow	Low level in He tanks.	Pneumatic valves won't work.	Gauges on He tanks. Delivery confirmation. Valves fail close.	
3. High Flow	Regulator on He tanks malfunctioning.	Pressure relief device is required for high pressure circuit. Sized for failure of He (do not rely on relief valve on regulator.	Flow must be taken to safe location.	
4. Reverse Flow				
5. Loss of Contamination	N/A	All locations out doors.		See comment above concerning continuation from back flow of DME vapor.
6. Low Pressure	See low or no flow.			Operator training to include risks of asphyxiation.
7. High Pressure	See high flow.			
8. Temperature High	N/A			
9. Temperature Low	N/A			

Node 3

Deviation	Cause	Consequence	Safeguards	Recommendations
10.-38.	N/A			
39. Fire				
Miscellaneous	<p>Portable CO₂ fire exiting at various locations.</p> <p>2 exits in each area opens both before entering.</p> <p>Emergency kill switch on control panel another in parallel should be located some distance away.</p> <p>Eye wash near by (Consider).</p> <p>Shower (Safety).</p> <p>Mix operators trained and periodically retrained.</p> <p>Consider checklist for securing site upon termination of mixing operation.</p> <p>Lighting</p> <p>Right to know information posted. Emergency number posted.</p>			

CONCLUSION

On-going research continues in testing and reviewing the affects of oxygenates on the composition of emissions from diesel engines. Optimization of the pressurized fuel system for DME-diesel blends is underway. The development of this fueling system is a significant advance toward practical use of DME as a diesel fuel. The results in this report lead to the following conclusions:

- The emissions results with CETANERTM addition are consistent with previous work and shown significant particulate emissions reductions in a DI diesel engine. NO_x emissions were moderately lower, while HC emissions were unchanged and CO emissions increased at low load.
- Results with the pressurized fueling system yielded scattered emissions results, with and without DME addition to the base diesel fuel. These difficulties may stem from an inability to properly cool the fuel that resides in the rail.
- The strategy outlined here for combining DME and diesel fuel under pressure can provide an effective means of fueling an engine with DME without excessive modifications to the engine.

REFERENCES

None.

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Emission Characteristics of a Navistar 7.3L Turbodiesel Fueled with Blends of Oxygenates and Diesel

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ABSTRACT

Several oxygenates have been proposed and tested for use with or as diesel fuel. This paper examines two such oxygenates, CETANER™ and dimethyl ether (DME), partially or wholly produced by Air Products and Chemicals, Inc's Liquid Phase Technology. In previous studies on a single cylinder compression ignition engine and a Volkswagen TDI four cylinder engine, significant reductions in particulate matter emissions were observed with blends of CETANER™ in diesel fuel. In this study, experiments were performed on a multi-cylinder Navistar 7.3L Turbodiesel engine confirmed and extended the observations from the earlier studies. This is an important step in not only showing that the fuel does perform on each type of engine in similar fashion, but also in showing that DME and its derivatives can give consistent, significant results in lowering emissions. The oxygenated fuels were blended to achieve a net addition of 2 wt.% oxygen in the blended fuel. A pressurized fueling system was developed to deliver mixtures of DME-diesel at up to 1 MPa (150 psi). With the DME-diesel blend, less consistent emissions results were obtained owing to an inability to sufficiently the fuel in the rail.

INTRODUCTION

Demand for cleaner burning diesel fuels is growing worldwide, as governmental regulations make emissions reductions necessary. In the U.S., future regulations that take effect in 2004 and 2007 will require diesel

engine and vehicle manufacturers to review all aspects of the vehicle system design. To achieve substantial reductions in emissions, it is thought that reformulated diesel fuels will play an important role. The reformulation of diesel fuels could include lowering the sulfur content, lowering the aromatic content, or potentially the addition of oxygen within the fuel.

A solution to affect emissions reductions for future and current diesel vehicles on the road is to modify the fuel without the need for modifying the engine hardware. It has been shown that many oxygenates are effective at reducing particulate emissions from diesel engines [1-20]. Therefore, much research has focused on screening of oxygenated fuel additives, including alcohols, esters, and ethers. Of particular interest are the glycol ethers, which have been shown to be very effective as blends and as neat fuel.

Over the last ten years, many researchers have begun to evaluate the performance of blends of glycol ethers with diesel fuel, and have observed decreases in particulate matter emissions. Liotta and Montalvo [5] measured the effects of several different oxygenated fuel additives, including several glycol ethers. From the tests performed in a DDC Series 60 diesel engine, their results indicated that particulate matter reductions of 4-10% could be achieved for each 1% of oxygen blended into diesel fuel, through incorporation as a glycol ether. Specifically, the results indicated that oxygen addition via glycol ether addition was more effective than oxygen addition via alcohol. Ullman and coworkers [6,7] also

evaluated the addition of several glycol ethers to diesel fuel, specifically, monoglyme (1,2-dimethoxyethane) and diglyme (diethylene glycol dimethyl ether), at 2 wt.% and 4 wt.% oxygen. A DDC Series 60 engine and a Navistar DTA-466 engine were used for the testing. Their results indicated that particulate matter reductions of 6-7% were reached for each 1% of oxygen blended into diesel fuel.

Higher molecular weight glycol ethers blended with diesel fuel have also been effectively used to reduce particulate matter emissions. Tsurutani and coworkers [8] blended several glymes, including monoglyme, diglyme, triglyme and tetraglyme, at levels up to 12 wt.% oxygen in diesel fuel. They observed that combustion of the glycol ether blends in an IDI engine yielded a particulate matter emission reduction of 3-5% for each percent of oxygen blended. Additional studies completed by Hess et al. [9] as well as by Litzinger and coworkers [10,11] have shown that higher molecular weight glycol ethers are also effective in reducing particulate matter emissions, although to a lesser extent than monoglyme or diglyme.

Beatrice and coworkers [12-15] as well as Miyamoto and coworkers [16,17] have evaluated the use of diglyme as both an oxygenated blend component and as a neat fuel. Both research groups have reported that smokeless combustion is possible with pure diglyme. Heat release rates have shown that combustion of diglyme results in shorter combustion duration, with a shift towards the diffusion phase of the combustion process.

Although it has been shown that glycol ethers effectively reduce particulate emissions, the fundamental mechanisms of the reduction have not been clearly identified. There has been some work in simulating the ignition and rate mechanism behavior of dimethyl ether in comparison to dimethoxy methane [18]. Also, oxidation mechanisms have been proposed for gaseous forms of DME [21-23]. Limited data is available for many of the liquid oxygenates under consideration.

Hence, the objectives of the experimental work reported here are to further evaluate the effects of glycol ethers, specifically CETANER™ on the diesel combustion process, as well as to compare this data to another oxygenate, dimethyl ether (DME), utilizing the same engine condition. In different engine configurations, CETANER™ has been shown to reduce particulate emissions over a range of blend ratios in diesel fuel [24]. CETANER™ is an oxygenated diesel fuel additive developed as a coal-derived syngas product by Air Products and Chemicals, Inc., and is a mix of glycol ethers, namely monoglyme and diglyme. As a diesel fuel additive, CETANER™ has been shown to exhibit high cetane number, roughly 125 [25]. This work is also intended to demonstrate fueling of a commercial turbodiesel engine on DME-diesel blends through the

use of a pressurized fueling system. The long term objective is to apply this fueling strategy to a shuttle bus on the Penn State University Park campus.

For this experimental work, blends of a Federal Certification diesel fuel with CETANER™ and dimethyl ether were evaluated in a multi-cylinder direct injection (DI) engine. A simplified mixture of 20% monoglyme and 80% diglyme was chosen for the experimental work, to represent a potential CETANER™ formulation. In-cylinder pressure measurements provided information about the impact of the oxygenated fuel on the combustion process. In addition, fuel property tests were performed on the base fuels as well as the fuel blends. These measurements included calorific value, flash point, and viscosity, and were used to understand and describe the combustion behavior. Since dimethyl ether is a vapor at 1 atm., the fuel property tests for the fuel blends were performed under pressure so that the dimethyl ether and diesel remained in the liquid state. Therefore, the fuel system of the engine was redesigned to accommodate the pressurized fuel delivery.

EXPERIMENTAL

TEST ENGINE

For the purpose of studying the effects of fuel additives on light-medium duty diesel combustion, a Navistar T444E 7.3L Turbodiesel engine was coupled to a 450 horsepower Eaton (Model AD-1802) eddy-current dynamometer for testing. The specifications for the engine are given in Table 1. Pentium PCs with Kiethly Metrabyte DAS-1800 data acquisition cards were connected to the engine to log real-time engine parameters. These parameters included engine speed, torque, and power from the engine. A Modicon PLC was used to record temperatures from the engine, as well as, for the entire experimental system monitoring. Intake airflow rates were determined via an electronic flow sensor, which was calibrated from a laminar flow element. Fuel consumption was monitored using a precision Sartorius Industrial Scale (Model EA60EDE-1), with an accuracy of ± 2 grams. Figure 1 shows the test cell set up, and additional equipment used for emissions monitoring.

Figure 1. Multicylinder Engine Test Cell Navistar T444E 7.3L Turbodiesel

TEST PROCEDURE

In this work, an AVL 8-mode test procedure has been utilized as a model for diesel emissions tests. The AVL 8-mode tests was designed to correlate to the U.S. Federal Heavy-Duty Transient Test procedure through a weighted 8-mode steady state test procedure. The 8 modes are a combination of speeds and loads, to produce the same emissions output as would be recorded for a transient cycle [26]. For our engine, the test procedure included the speed and load settings, shown in Table 2.

Table 1. Characteristics of the 1998 Navistar T444E 7.3L Turbodiesel Engine

Displacement	7.3 Liter (444 cu.in.)
Bore	104.39mm (4.11 inch)
Stroke	106.20mm (4.18 inch)
Rated Power	143kW (190 HP)@2300 RPM
Peak Torque	640Nm(485lbf-ft)@1500 RPM
Configuration	Turbo charged, Intercolled (Air-to-Air), Direct Injection
Injection Scheme	HEUI- Hydraulically actuated, electronically controlled unit injectors
Low Idle Speed	700 RPM
Features	Split-shot injection
Compression Ratio	17.5:1

Table 2. AVL 8-Mode Test for the Navistar T444E Turbodiesel engine

Mode	Speed (rpm)	Load (Nm)
1	700	0
2	876	111
3	1036	296
4	1212	472
5	2300	102
6	2220	235
7	2220	405
8	2124	540

EMISSIONS ANALYSIS

An extended warm-up period was used to prepare the engine for testing. The sampling and measurements during each mode commenced when the exhaust temperatures reached a steady state. During this time, RPM and torque were maintained within 1-2% of the target test conditions. Once steady-state operation was achieved, a portion of the exhaust gas was passed through a Sierra Instruments BG-1 micro-dilution test stand with a constant dilution air / sample flow ratio of 8:1 and a total flow of 150 liters/min. These settings were chosen in order to maintain the filter temperature below the EPA specification of 52°C. Particulate collection occurred on Pallflex 90mm filters (Type EMFAB TX40HI20-WW), conditioned in an environmental chamber at 25°C and 45% relative humidity before and after sampling. Five particulate samples were taken for each fuel at each test mode, except for the DME-diesel tests where only one sample was obtained.

Exhaust gas analyses were completed using a Nicolet Magna 550 Fourier Transform Infrared (FTIR) Spectrometer. For each mode, five gas samples were analyzed for CO₂, CO, NO and NO₂. Also, a Rosemont Analytical O₂ sensor was used to monitor the percent oxygen in the exhaust gas. The oxygen readings were used in conjunction with the mass flow sensor to determine and verify the air / fuel ratio. Additionally, total hydrocarbon emissions were monitored using a California Analytical Instruments Model 300 HFID Heated Total Hydrocarbon Gas Analyzer. For the total hydrocarbon measurements, undiluted exhaust gas was collected via a heated sample line, which was maintained to 190°C. Calibration of all equipment was completed prior to each day of testing. Gaseous emissions data are only presented for the CETANER™-diesel blend, as the gaseous sampling system was not functioning correctly during the testing of the DME-diesel blends.

PRESSURE TRACE ANALYSIS

In order to observe the impact of the oxygenated blends on combustion and heat release, the combustion chamber of cylinder 1 of the engine was fitted with a Kistler 6125A pressure probe. The pressure sensor was used with a Kistler 2612 optical crank angle encoder to provide time resolved in-cylinder pressure traces of the combustion event. Pressure, crank angle, and TDC trigger signals were acquired with a Kiethley DAS-1800 data acquisition card operating in a "burst" mode. The pressure traces were analyzed with PTrAn V.02, a software product designed by Optimum Power.

TEST FUELS

Previous work has been completed comparing the increasing percentage of oxygenate mixed with diesel fuels within several types of engines [8-17,24]. For this

testing, comparisons are made between a 2 wt.% addition oxygen of two different additives. The baseline diesel fuel properties, as well as test fuel properties are given below in Table 3. A Federal Certification Fuel (Specified Fuels, Emissions Certification Diesel – Low Sulfur, ECD-LS) was used in these experiments. Because of the difficulty of obtaining the fuel blend properties for DME as a liquid, the properties available in the literature for neat DME are presented.

PRESSURIZED FUEL DELIVERY SYSTEM FOR DIESEL-DME BLENDS

DME is a liquefied gas. At STP, it is a gas, but liquefies under a moderate pressure. The fuel delivery system was designed keeping in mind the following important points:

- The vapor pressure of DME.
- Material compatibility of the various components in the fuel system with DME
- Lack of lubricity of pure DME.

A schematic of the fuel delivery system is shown in Figure 2. The working of the fuel delivery system can be explained as follows:

1. The fuel comes out of the fuel tank at a pressure of about 0.6 MPa (90 psig). This overpressure is necessary to keep the DME in a liquid state. Any inert gas is suitable for this purpose. Helium was used as it has a lower solubility in DME than nitrogen.
2. The pressure is then boosted by a gear pump to about 0.82 or 1.0 MPa (120 or 150 psig), depending on the pressure rating of the fuel rail. The rail pressure is maintained at 0.48 MPa (70 psig) in the original fuel system of the engine.
3. The fuel return line pressure is held at about 0.82 MPa (120 psig) by the backpressure regulator. The regulator is a simple spring loaded valve that regulates the flow to keep the backpressure at 0.82 MPa (120 psig).
4. This fuel then passes through a heat exchanger, where it is cooled down to a predetermined level.
5. After cooling, the fuel is then fed to the inlet of the pump

Table 3. Fuel Properties

Fuel Property	ASTM Method	ASTM Spec.	Base Diesel	5wt.% CETANER	DME
Viscosity, 40°C, cSt	D 445	1.39-4.20	2.2	1.27	.25 [30]
API Gravity	D 287	API 30	35.3	42.5	
Cloud Point (°C)	D 2500	<-18	-16		

Pour Point (°C)	D2500	<-18	<-18		
Flash Point (°C)	D 93	52	74		-41
Calorific Value (MJ/kg)	D2015	46	45	44	28

PRESSURE AND FLOW REQUIREMENTS

At 20°C the vapor pressure of DME is about 0.52 MPa (75 psia). Keeping DME in a liquefied state calls for pressurizing the entire fuel system from the fuel tank up to the fuel injectors. The vapor pressure also changes rapidly with temperature. The pressure of the fuel system is hence dictated by the fuel temperature. The pressure, however, is limited by the pressure rating of the fuel rail. The engine used in the study has a common rail injection system. Each cylinder head has a fuel rail running along its length, which is the source of fuel for the pressure intensifier in the fuel injectors. In the original fuel system of the engine, the pressure in the rail is maintained at 0.48 MPa (70 psig). This facilitates proper filling of the pressure intensifiers. The fuel rails in the cylinder head form a dead head system. This means that there is no fuel return once the fuel enters the fuel rail. It is because of this that the fuel temperature in the rail approaches the engine coolant temperature in the head. This layout of the fuel system was modified to accommodate a fuel return from the cylinder heads.

A study was performed in which the temperature of the fuel in the fuel rail was recorded in conjunction with the fuel consumption of the engine, for the 8 modes of the AVL test. Assuming certain values for heat capacities for diesel and DME, a minimum flow rate value was calculated so as to keep the temperature of the fuel in the rail below 50°C. The vapor pressure of DME at this temperature is about 1.0 MPa (150 psi). This pressure, more or less, dictated the temperature rise allowed. The fuel delivery pump was sized based on the above calculations. In addition to excess flow rate, cooling of the returned fuel was necessary to maintain the required fuel temperature. In these tests, a 500 W chiller was used to chill a bath through which the fuel was passed within stainless steel coils. This fuel cooling was insufficient to maintain the fuel temperature below 50°C under some operating conditions, particularly during Mode 8.

Design Considerations for the Pressurized Fuel System

DME is known to be incompatible with the common gasket materials such as Viton and buna-N, used in diesel service. Data provided by DuPont Inc. indicated Kalrez to be the best material for DME. For economic considerations however, this material was used

sparingly. Other materials such as butyl rubber, Teflon and neoprene have also been found to be compatible, though not to the same degree as Kalrez. Stainless steel was used for the fuel lines as a safeguard against corrosion. All the other components such as valves and regulators were also made of stainless steel.

Selecting a pump for pumping DME was challenging due to the properties of DME such as its low lubricity and low viscosity. Due to the vapor pressure of DME, the pump

Figure 2. Pressurized Fuel System Diagram for the Navistar T444E Turbodiesel Engine.

housing was required to handle pressures up to 1.7 MPag (250 psig). Positive displacement pumps such as vane pumps, diaphragm pumps and gear pumps were considered. Gear pumps were found to be economical as well as convenient to operate. With these considerations, a gear pump made by Tuthill Pump CO, California (model #TXS2.6PPPT3WN00000) was selected. This pump has a magnetically coupled AC motor. This configuration does not have the driveshaft going through the pump housing, which in turn obviates the need for seals, a potential source of leakage. The gear material is Ryton (Polyphenylene sulphide), which was found to be compatible with diesel and DME as per the data by provided DuPont Inc. The pump body seals are made of Teflon.

The fuel filters on the engine could not be used because of the high pressure of the fuel. The minimum pressure in the fuel lines was 0.62 MPag (90 psig). This required the use of special filters, which would withstand higher pressure. A diesel water separator was used as a primary filter. This is rated at 0.69 MPag (100 psig). The final filter was a LPG filter rated at 3.4 MPag (500psig). The mesh size of the filter was 2 micron, very near to the engine specification.

The fuel tank was made out of a modified 45 kg (100 lb) capacity LPG cylinder which was pressure tested prior to

use. This tank was fitted with a 1/2" NPT fitting at the bottom for liquid exchange.

RESULTS AND DISCUSSION

This section presents results from combustion studies of the effect of the CETANER™ additive on emissions compared to the base fuel composition (prior to the fuel system conversion), and the effect of the DME-diesel mixture on emission compared to the base fuel composition (after the fuel system conversion). Fuel property tests were completed to permit comparisons of the combustion data. Through an uncertainty analysis, based on methods described by Moffat, error bars showing the 95% confidence intervals are presented in each figure [27].

PARTICULATES

As noted previously in the discussion, oxygenates traditionally reduce particulate emissions. Shown in Figure 3, the brake specific particulate matter (BSPM) emissions for the 2 wt. % oxygen (5.59wt.% CETANER™ and 5.75wt.% DME) show a decrease in particulate matter emissions for CETANER™ addition, but a mixed result for DME addition. As seen in Figure 4, on a basis of particulate emissions per unit fuel consumed, greater variability in the results is evident. These numbers for the impact of CETANER™ addition correlate well with the particulate emissions observed previously by Hess and coworkers [24], as well as, Ullman and coworkers [6,7]. In their work, particulate emissions decreased as a function of increasing load. This is also seen in the results in Figure 3. For mode 4, even though there is a particulate reduction through using CETANER™ vs. the baseline diesel, the interesting trend is in the engine particulate output for the engine conditions. Mode 4 operates the engine near the peak torque, and the overall emissions conditions change, possibly due to a change in the injection timing.

Figure 3. Particulate Matter Emissions, Brake Specific Basis.

Considering the work here and elsewhere on CETANER™, there seems to be some consistency in the results between different engine configurations, which would lead one to believe that the particulate reductions are more a function of the presence of the oxygen in the fuel, and less a function of number of cylinders and fuel injection type (DI or IDI) [24]. As has been shown in previous work, this particulate reduction is due to a reduction in the soot portion of the emission, and would result in a percentage increase in the soluble organic fraction (SOF) portion [5].

It is evident from Figure 4 (in particular, Mode 4), there is substantially greater variability introduced by the pressurized fueling system with regard to particulate emissions measurements. The variation from the original baseline emissions (before the fuel system conversion) is quite large, and may in part be due to difficulties in maintaining sufficiently low temperatures in the fuel rail. As shown in Figure 2, the pressurized fuel system relies on a heat exchanger to cool the fuel that is rejected from the rail so that this fuel can be recirculated to the rail. However, during these tests it was observed that the heat exchanger capacity was insufficient to maintain fuel rail temperatures below 50°C under some of the operating modes, particularly Mode 8.

Figure 4. Particulate Matter Emissions, g/kg Fuel Basis.

NITROGEN OXIDES

Table 4 reports the weighted brake specific NO_x (BSNO_x) emissions for the CETANER™-diesel blend. Using the AVL 8-mode weight factors, the net NO_x emission reduction was 5.35%. Shown in Figure 5, for modes 4 through 8 a reduction of NO_x per unit fuel consumed was observed. In general, the data follows an expected

trend, in that at higher engine speeds, NO_x is lower, and as the load increased, NO_x increased. For the other three modes, the data does not show significant conclusions. There are conflicting reports in the literature as to whether oxygenates do indeed reduce NO_x [2,4,5,11,15]. The data from this engine, however, shows a reduction in NO_x emissions on a brake specific basis, for most modes. Choi and Reitz [4] observed that there is a small penalty on the NO_x emissions when using a split injection strategy (two fuel pulses) with an oxygenated fuel, which could be affecting the results for mode 1 and 2 for this particular engine. Because the unique multiple fuel injection strategy of the Navistar T444E especially is more pronounced at lower speeds, the NO_x reduction could occur due to greater mixing effect in the cylinder during the combustion event.

Figure 6 presents the particulate matter vs. NO_x tradeoff per mode for the CETANER™-diesel blend. As can be seen for modes 2 through 8 on a brake specific basis, a slight decrease in particulate matter and NO_x occurs for each mode. In each case, the PM-NO_x emissions point shifts toward the origin, which further demonstrates the viability of reducing diesel engine emissions via oxygen addition.

CARBON MONOXIDE

Table 4 reports the weighted brake specific CO (BSCO) emissions. There is no clear trend in this data, although there is an increase in CO for most of the mode positions. If CO per unit of fuel is reviewed, one can see that for each of the lower speed and load modes, a definite increase in the CO for CETANER™ is observed. This is shown in Figure 7. This may again support the rationale that during the low speed and low load conditions, CO formed during early reactions of the fuel are being halted from final conversion to CO₂. This was postulated by Litzinger and coworkers [11]. As explained by Glassman, the conversion of CO to CO₂ would be a function of the size of the hydroxyl radical pool, which does not grow until after all the original fuel and hydrocarbons have been consumed [31]. Since the concentration of hydroxyl radicals is important in the rate of CO oxidation, the additional molecules of oxygen with the monoglyme and diglyme may be playing a role in providing excess CO and CO₂ which continue the creation of the hydroxyl radical pool. In addition, Flynn and coworkers show through kinetic simulations that the addition of the oxygen in the fuel leads to reduced amounts of soot precursors, and larger amounts of carbon leaving the fuel rich premixed combustion zone as CO [28].

Table 4. AVL 8-mode Weighted Gaseous Emissions Results, CETANER™-Diesel Blend, Brake Specific Basis

WEIGHTED EMISSION	BASLINE DIESEL (g/BHP-hr)	2 wt. % OXYGEN VIA CETANER™ (g/BHP-hr)
NO _x	3.31	3.13
CO	1.29	1.30
HC	.252	.238

TOTAL HYDROCARBONS

The weighted brake specific emissions for the CETANER™-diesel blend are reported in Table 4. In general, the HC emissions decrease with higher engine loads, as the engine combustion efficiency increases. In this work for all engine loads, HC emissions remain unchanged as compared to the baseline diesel, as can be seen in Figure 8. These results are consistent with other work by Hess and coworkers [24].

Figure 5. NO_x Emissions per Unit Fuel Consumed for CETANER™ Addition, g/kg Fuel Basis.

Figure 6. Brake-Specific Particulate Emission vs. NO_x Emission Tradeoff.

FUEL CONSUMPTION

Figure 9 reports the brake specific fuel consumption (BSFC) for CETANER™ and DME addition. The general trend shows an increase in the amount of fuel required to maintain the same speed and load. This is due to the slightly lower calorific value of the CETANER™ and DME blends, as shown in the Fuel Properties of Table 3. However, when fuel consumption is calculated on an energy basis, the energy consumption results are not significantly different.

Figure 7. CO Emissions per Unit Fuel Consumed for CETANER™ Addition, g/kg Fuel Basis.

Figure 8. Total Hydrocarbon Emissions per Unit Fuel Consumed for CETANER™ Addition, g/kg fuel

The results from this work are significant in that they confirm previous data for particulate reductions. The reductions correlate well with those of 2 wt.% oxygen addition via diglyme of Liotta and Montalvo [5]. For this data, a NO_x reduction was shown for specific modes and as an overall number, which would be contrary to most work found in the literature. The CO emissions seem to follow the trends as reported [11,24,28]. The mode 4 CO data raises questions, but will be reviewed further.

Figure 9. Fuel Consumption, Brake Specific Basis.

CONCLUSION

On-going research continues in testing and reviewing the affects of oxygenates on the composition of emissions from diesel engines. Optimization of the pressurized fuel system for DME-diesel blends is underway. The development of this fueling system is a significant advance toward practical use of DME as a diesel fuel. The results in this paper lead to the following conclusions:

- The emissions results with CETANER™ addition are consistent with previous work and shown significant particulate emissions reductions in a DI diesel engine. NO_x emissions were moderately lower, while HC emissions were unchanged and CO emissions increased at low load.
- Results with the pressurized fueling system yielded scattered emissions results, with and without DME addition to the base diesel fuel. These difficulties may stem from an inability to properly cool the fuel that resides in the rail.
- The strategy outlined here for combining DME and diesel fuel under pressure can provide an effective means of fueling an engine with DME without excessive modifications to the engine.

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