Annual Technical Report
on

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

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by
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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. Within the Combustion Laboratory of 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 examined blends of an oxygenated fuel additive (a liquid fuel called CETANERTM) produced by Air Products, for comparison with dimethyl ether blended at the same weight of oxygen addition, 2 wt.%. While we have not operated the engine on DME yet, we are now preparing to do so. A fuel system for delivery of DME/diesel blends has been configured and initial investigations at low DME blend ratios (around 5-10 vol%) will begin shortly. We have also performed viscosity measurements on diesel fuel, DME and 50-50 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.

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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 Manager Mike Nowak 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).

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 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 Combustion Laboratory of 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 examined blends of an oxygenated fuel additive (a liquid fuel called CETANER™) produced by Air Products, for comparison with dimethyl ether blended at the same weight of oxygen addition, 2 wt.%. While we have not operated the engine on DME yet, we are now preparing to do so. A fuel system for delivery of DME/diesel blends has been configured and initial investigations at low DME blend ratios (around 5-10 vol%) will begin shortly.

We have also performed viscosity measurements on diesel fuel, DME and 50-50 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.

In addition, the Champion "Defender" shuttle bus that will be converted to DME operation has been in service at Penn State since the fall of 1998. During 1999, the shuttle bus was tested for performance, efficiency and emissions by the Pennsylvania Transportation Institute on their test track. While their testing procedures do not follow any industry standard strategies, such as the heavy-duty transient test cycle, their procedures produce a rigorous and consistent basis of

evaluation of vehicle performance and durability for comparative purposes between different vehicles and different configurations of the same vehicle.

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.) will determine 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 are 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 before the conversion to dimethyl ether operation.

Meanwhile, a dimethyl ether fueling station is being designed and will be constructed on the University Park campus. Tanker trucks will deliver fuel to this station from the Alternative Fuels Development Unit (AFDU) in LaPorte, Texas. This fuel grade dimethyl ether (a mixture of DME and methanol) will be blended with diesel fuel either on-site in LaPorte for transport to State College, at the University Park fueling station, or on-board the vehicle.

During the baseline operation period of the shuttle bus, we are determining how to perform the conversion of a Navistar T444E turbodiesel engine to DME through laboratory testing with a stand-alone engine. This work is being accomplished in a new engine test cell in the Combustion Laboratory at the Penn State Energy Institute. This cell consists of a 450 hp Eaton eddy current dynamometer, a Nicolet FTIR spectrometer, an HP 6890 Gas Chromatograph, Horiba on-line emissions analyzers, an R&P Series 5100 Diesel Particulate Analyzer, a Sierra Instruments BG-1 Microdilution test stand, a California Analytical HFID hydrocarbon analyzer and in-cylinder pressure sensing equipment for emissions and combustion analysis. The objective of the laboratory testing is to determine the compositions of fuel and additive blends that will permit long term operation of the T444E engine on dimethyl ether. Three additives will be considered, a Lubrizol lubricity agent, an Ethyl Additives lubricity agent and methyl soyate. Fuel blends will range from very low DME composition in the initial phase of tests, to as high a DME content as the engine can tolerate. Wear of the fuel injection system components will be used to judge the tolerance of the engine to DME fueling and to judge the effectiveness of the additives and diesel fuel for protection of the fuel system components.

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. We are now also planning to construct an injector durability experiment to determine the time to failure and boundary of the of fuel composition which can lead to injector failure.

Two expected outcomes of the laboratory testing are determination of the maximum DME concentration that can run in conventional engine hardware and what additives and additive concentrations are necessary to ensure fuel system integrity. The goal will be to maximize DME utilization, without sacrificing long term durability of the fuel system. Once this information is in hand, Air Products and Penn State will develop fuel system hardware for use on the shuttle bus and install the conversion equipment on the shuttle bus. The conversion is expected to occur in late summer 2000. 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) have expressed a willingness to provide specially modified injectors for the project. Dupont Fluorocarbons have provided over 500 lbs of DME for use in the engine studies.

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. There may be supercritical fluid behavior to contend with in the fuel injection system resulting in an increase in fuel compressibility (which can impact fuel injector needle lift), and phase separation of the components of the fuel blend (which may bring the lubricity additive out of solution with the DME).

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

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.

Photo of the Navistar T444E Turbodiesel Engine in the 450 hp Engine Test Cell

The AVL steady state 8 mode test has been selected to do the emissions comparison studies for different fuel additives and blend ratios of DME to diesel. During the current test sequence, a comparison of exhaust emissions will be made with two different oxygenates, the CETANERTM fuel additive and Dimethyl ether (DME). These will be blended with a federal low sulfur diesel fuel that will also serve as the baseline fuel. The oxygenates will be blended such that the oxygen content of the mixture will be 2% by mass.

At this point, data have been taken for the baseline as well as the CETANER™ fuel additive. The data presented here is for the baseline fuel and 2 wt.% CETANER™ addition to the baseline fuel.

CO emissions per unit fuel consumed

Fuel Consumption

All data for gaseous emissions are presented on a dry exhaust basis. These results show several expected trends that demonstrate that the engine, dynamometer system and emissions analysis instrumentation are performing well. A decrease in PM emissions is observed over most of the 8 modes of the AVL test. Fuel consumption and air consumption increase slightly on a mass flow rate. Carbon monoxide and NO_x emissions increase for some operating modes and decrease for others. These trends and observations are consistent with our previous observations with CETANERTM and will form an important comparison with DME fueling.

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 known, 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 year, 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 have gained an initial understanding of the electronics and the complexity of being able to make changes to software calibrations. After numerous communications, we realized that the path we were taking to be able to modify the calibration for the DME/diesel fuel blend optimization would give Navistar a great deal of liability. In addition, the potential method was putting us in a position to potentially struggle with procuring and building a great deal of expensive hardware for only needing to modify a few parameters.

A compromise was suggested from Navistar which would allow for us to accomplish our goals, as well as for Navistar to be involved with monitoring our modifications and assisting us in the development. The suggested course involves using the CAN communication protocol as described above. Navistar encouraged us to purchase a National Instruments CAN instrumentation board, as well as, Labview. The CAN board will allow for us to communicate via the ATA bus with the ECM. Labview is the National Instruments software for data acquisition. It is great for creating visual instruments, as one programs the software like putting together simple electrical circuits with inputs and outputs.

Example of Labview from the National Instruments Website

Together with these two products, we will be able to do the following:

Engine Parameter Programming

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 will provide 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 could make some software to send it over the CAN or diagnostic bus. It 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.

Next Steps

Because of the throughput on the existing computer at the test cell, another lab computer will be reallocated to the test cell to serve as the support for the National Instruments CAN card. The process of putting the hardware in place should be rather easy. A Labview data acquisition program will be written with the support of Navistar so as to send and receive data to the ECM. This may involve a few weeks of work.

Viscometer Progress Report.

The high pressure viscometer is on loan from the Tribology Group in Penn State Department of Chemical Engineering. It is capable of measurements up to 10,000 psi and for the purposes of the present work will be used at pressure of up to 5000 psi. The figure below shows a digital photo of the viscometer.

Photo of the High Pressure Viscometer Housing. The Capillary Tube Sits within this Housing.

At this point, the viscometer capillary has been calibrated using a calibration standard made by Cannon Instruments. The data has been taken and it is being reduced to get an appropriate calibration curve. We are not being able to reproduce the linear curve that was recorded for the earlier experiments (in 1962). The earlier curve, though, was for a different apparatus and this aspect is being looked into.

New capillaries were designed and made to deal with the extremely low viscosity of pure DME.

Blends of DME and Diesel have been examined for viscosity along with the pure substances. This was done in the older capillary, though and will have to be redone in the new capillary.

The calibration curves for the new capillary are shown in the following figure.

The viscometer pressure vessel has round glass windows. The three sets of points represent three different liquid levels as seen through three adjacent windows. The measurement of diesel DME blends can be made using the window that has the best calibration curve. As seen in the above figure, it will be Window 1.

The pressure intensifier has been repaired and is in working condition. This will now be used to build up the pressure required for making high pressure measurements.

CONCLUSION

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 viscosity measurements on diesel fuel, DME and 50-50 blends of DME in diesel 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.

REFERENCES

None.

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