File No.: S-02251, PG/SFM, 28 March 2012

Final report on

”Diesel Vehicles Running on 2nd Generation Bioethanol” EUDP08-II

Sammenfatning på dansk

I projektet er der udviklet er reaktorsystem hvor ethanol omdannes til diethylether og vand. Det er vist at omdannelsen kan ske energieffektivt. Den dannede blanding af ethanol, diethylether og vand er et glimrende dieselbrændstof, som vi kalder OBATE-brændstof. OBATE står for Om Bord Alkohol Til Ether. Brændstoffet er blevet testet på en 4 cylindret HDI dieselmotor, hvor brændstofindsprøjtningen er optimeret med en programmerbar styringsenhed. Der er kørt test hvor der er målt på effektivitet og emissioner både ved konstant belastning og omdrejninger men også ved transiente driftscykler. Systemet bestående af kemisk reaktorsystem og motor har været koblet sammen i Aarhus, så hele processen fra ethanol over omdannelse til OBATE-brændstof og videre til motoren har kørt samlet. Der er kørt med varierende belastning, mens der blev målt på emissioner fra motoren, der som forventet var meget lave både på NOx og partikler, vel at mærke uden efterbehandling på udstødningsgasserne.

Abstract

In the project, a chemical reactor system, called OBATE reformer, has been developed to convert ethanol to diethyl ether and water in order to make it into a diesel fuel. It is shown that the conversion can be made with high energy efficiency. The product after the reactor system is a mix of ethanol, diethyl ether and water and is an eminent diesel fuel with a high cetane number. The fuel mix is called “OBATE fuel”, where OBATE stands for On Board Alcohol to Ether. The fuel has been tested in a four-cylinder HDI passenger car diesel engine, for which the fuel injection has been calibrated and optimized for the OBATE fuel using a programmable electronic control unit. Test runs have been made, where the efficiency and emissions have been measured, not only at constant load and revolution but also during transient operation in passenger certification cycles. The complete system consisting of OBATE reactor and engine was combined for test at Teknologisk Institut in Aarhus, in order to demonstrate the entire process from converting ethanol to OBATE fuel which then was used in the engine as one unit. Runs were made with varying loads, where emissions from the engine were measured, and it was demonstrated that the level of both NOx and particles was low, and that future emission requirement could possibly be reached without aftertreatment of the exhaust gasses.

Introduction

Below is given a description of the progress in the different work packages that describe the progress in the “Diesel Vehicles Running on 2nd Generation Bioethanol” partly financed by EUDP.

The work has been divided between the different partners, Teknologisk Plastics, Teknologisk Engines and Haldor Topsøe A/S. Teknologisk Plastics has been developing the first prototype and Teknologisk Engines has worked on the engine modification and testing. Haldor Topsøe A/S has developed the catalytic system and been the project manager for the project. The project has been a success regarding progress and results and has continued in a second phase, where the design of a compact OBATE unit is one task, and trying the system on a heavy duty diesel engine the second main task.

WP1&2 Fuel Handling System development and Test of Fuel Handling system

Since the OBATE fuel possesses some challenging properties when operated on a standard Diesel engine, it was planned in WP1 that a fuel handling system needed to be considered. Through preliminary experimental tests, it was illustrated that the OBATE fuel needed to be pressurized and cooled more than standard Diesel fuel. Furthermore, the reactor system is able to produce different qualities of the OBATE fuel producing two phase mixtures which needed stirring in order to operate the engine. Since the target for the OBATE technology is the existing market for Diesel engine, the objective was to create a simple fuel handling system that in the future could be used on a vehicle. The developed fuel handling system could be shortly described as a system using the air-conditioning compressor to cool the fuel, a standard fuel pump for stirring the OBATE fuel in the buffer tank, mechanical valves for controlling fuel pressure in the feed and return lines in combination with pressure pumps to increase fuel pressures to adequate levels. Since the initial project involved testing of several fuel compositions, it could be operated without the reactor system itself. The size of the system is larger than a production ready OBATE fuel handling unit would be. The developed fuel handling system is shown in Figure 1. The system was used for testing different fuel qualities of the OBATE mix as well as combinations of different other alcohols and hydrocarbons. These mixes were made just by blending the different ingredients to get started with the engine testing while the so-called OBATE reformer was developed.

Figure 1 Fuel handling system

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WP3 Fuel Composition Experiments

One of the main objectives in the early stages of engine testing was to increase the patent portfolio in the OBATE area. Therefore, a broad matrix of fuel mixtures was set up including different alcohols, biodiesel and mixtures with normal Diesel fuel in order to illustrate the flexibility of the OBATE technology and to document the boundaries of the fuel. The fuel mixtures all have different properties, which means that the combustion timing needs to be changed. So to compensate for the differences in the combustion properties, the engine electronic controls were completely altered and modified to an open system, where fuel injection timing and pressures could be adjusted accordingly.

Parallel with these engine tests, other studies were carried out concerning the lubricity performance of the fuel mixtures. The different fuel mixtures were tested with different commercially available additives according to known test procedures using diesel as reference fuel. Some modifications to the test procedure had to be considered, since the normal test procedures are performed at ambient temperatures. Using ambient temperatures is not possible with the OBATE fuel, since diethyl ether is evaporating at 36℃ a t atmospheric pressure. Hence the complete test apparatus was put to a climate chamber and cooled to sub-zero temperatures. Results are presented in Figure 2.

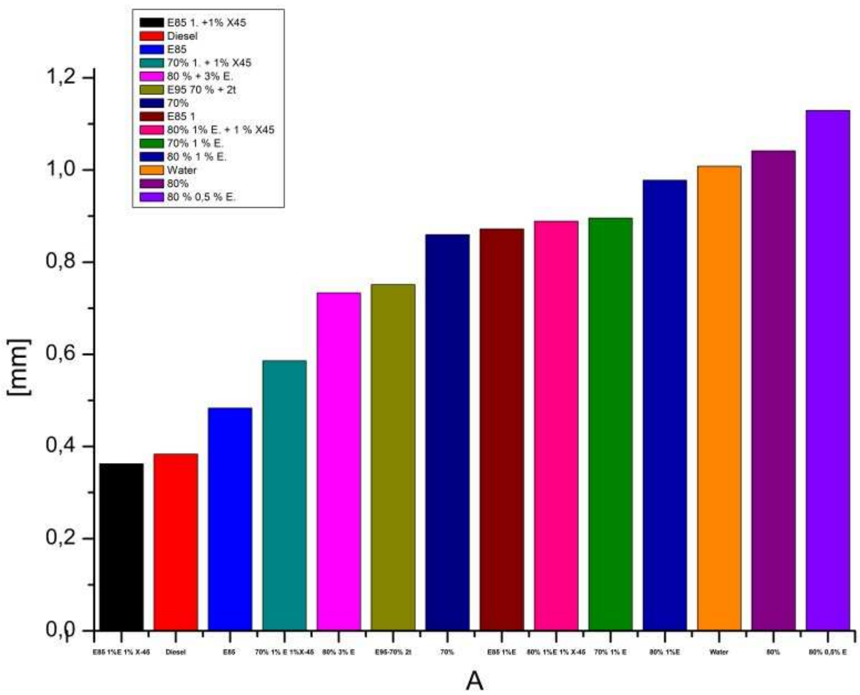

Figure 2 Lubricity tests with different additives

Examining Figure 2, it can be seen that Diesel (red bar) has a good performance concerning lubricity. However, through the aid of additives, the OBATE fuel can obtain similar results where the blue bar is a typical OBATE mixture being one of the mixtures chosen for further engine testing. One problem with the tested additives was the 10000-20000 parts per million treat rate used to obtain adequate performance. Compared to the additives used in standard Diesel fuels, there is commonly used around 50-300 parts per million*. Thus, further research is needed to find or develop additives for the OBATE fuel. This is currently being investigated in the ongoing project EUDP 11-I, Clean and efficient heavy duty diesel engine running on 2nd gen. bio-ethanol.
* SAE paper: 2009-01-0848

WP4 Prototype System Design

In collaboration between DTI Plastics and Haldor Topsøe A/S, the process specifications were determined (WT 4.1) Several different process layouts were reviewed, where energy flow under different modes of operation were modelled, i.e. startup and continuous conversion (WT 4.2). Complexity in operation and use was discussed and held up against energy efficiency. Safety was also carefully considered, and input from the engine tests was used to specify the necessary degree of conversion of ethanol to ether. The first process considerations were all on systems with a gas phase reaction at low pressures. The catalytic reaction took place at elevated temperature and, to make an energy-efficient system, waste heat from the vehicle was used. The gas phase reaction requires heat for evaporation of the ethanol and energy that can be taken from the engine exhaust gas. Since the reaction is slightly exothermic it would be obvious to heat exchange the inlet with the outlet in a so-called feed-effluent heat exchanger, but in this case it is not possible, since the condensation point of OBATE-fuel is below the boiling point of ethanol and, therefore, will not work in this specific case. With a high certainty, it would be possible to find a catalyst for the gas phase reaction that would work, and, therefore, it also became the first choice for the development of the OBATE-fuel upgrader. Based on gas phase reaction, a laboratory system design was developed (WT 4.3). Later it was, however, decided to move over to a another process window .The new condition meant that now the feed and the product could be efficiently heat-exchanged. As a consequence, the need from taking energy out of the exhaust disappeared, which made the overall system less complex.

The development of the system was followed by thorough considerations on necessary safety systems and precautions. Prior to operation of the modified system, it was leak-tested first by filling with nitrogen to ensure that it can hold the pressure and then by filling the system with an easily detectable gas and detecting leaks from the outside. In choosing parts for the system, it was important that they with high certainty would be able to withstand both the chemicals and the heat. Special steel and seals were therefore chosen to avoid corrosion and chemical decomposition (WT 4.4). Prior to all startups, the system is filled with inert gas (nitrogen). A special consideration when working with ether is the formation of peroxide crystals that may self-ignite. In the system ether is not in contact with oxygen from the air, and there has not been observed signs of peroxide formation (e.g. by use of designated test kit).

WP 5 Reformer Unit Development

Different reformer and system designs were modelled. As mentioned, it was known that the reaction could take place in gas phase with high enough conversion so that was the starting point for the development.

The first laboratory reformer unit was running at low pressure. With this system, safe operation was established and the process was demonstrated, catalytic dehydration of ethanol to ether was shown. It was also shown that a diesel engine could run on the produced ether-ethanol-water mixture, the OBATE-fuel. Inefficient heat exchage at these operating conditions lead to the decision to go to other reaction conditions at higher pressures.. One idea was to utilize the hot exhaust gasses from the engine, a suitable heat exchanger was received and pressure tested, making it a viable solution.

Changing to the other reaction parameters lead to a more simple system not involving the engine exhaust or other sources of heat.

The reactor system was developed and the reactor vessel was changed to allow the higher pressure, several different new catalysts supplied from Haldor Topsøe A/S were tested for performance and usability. The reactor was changed to one with a larger volume to get higher conversion at low temperature. Different optimization steps made the system more compact (WT 5.5). Figure 3 shows the prototype setup.

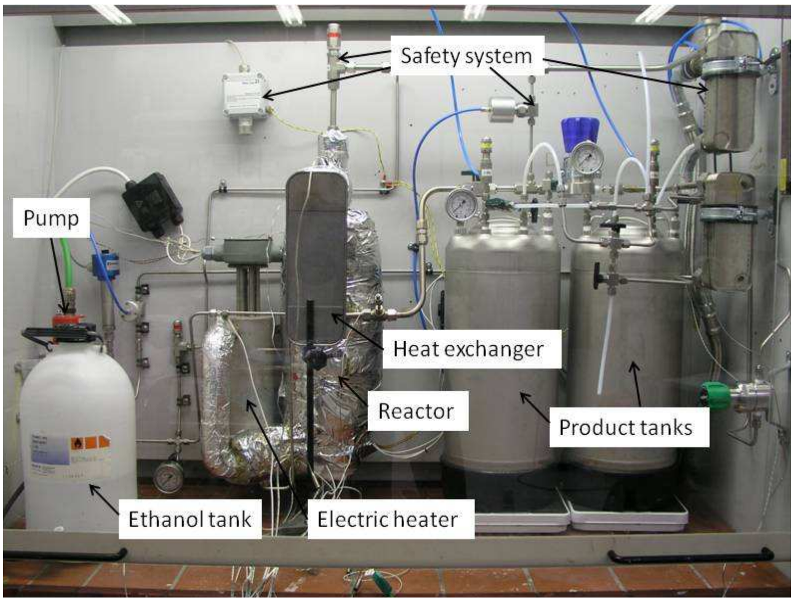

Figure 3. Reformer prototype at Teknologis in Tåstrup

The catalyst development at Haldor Topsøe A/S (WT 5.1) has been crucial to the progress of the project. Engine tests have shown that there is a minimum amount of the ethanol that must be converted to ether to obtain a product mixture that can be used as a diesel fuel. As the reactor size can only be a few litres and the fuel consumption of the engine is given, this conversion requirement implies that the catalyst must have a high activity. This has been an important challenge in the project, since a too low activity leads to either a product mixture with a too low cetane number, a too large reactor, or insufficient fuel production; either way, the concept of the on-board conversion of ethanol will fail.

Clearly, the catalyst converting the ethanol to diethyl ether is the heart of the reformer system. The conversion of ethanol to diethyl ether is an acid assisted reaction. In the project, we have therefore performed a screening of a large variety of acidic materials, for the catalytic performance for the conversion of ethanol. The present catalyst of choice possess a sufficient activity and stability in the right temperature range, where the conversion of ethanol to ether can be run in an energy-efficient way.

With the knowledge from the prototypes and the test run, a more compact unit was designed (WT 5.4). The more compact unit was made with the assumption that it should be mounted on a vehicle, e.g. heavy duty truck. The design has been patented and is not shown here, since the patent still is in the examination phase. The same design is now used in the EUDP 11.1 project, which is a prolongation of this specific project.

WP 6 Test Bench Prototype

In order to show the OBATE technology, an experimental setup was made at Technological Institute's engine test facility. The modified engine was built up with combustion analysis equipment, emission measurement equipment and additional measurement equipment. This was combined with the reactor system and fuel handling system to demonstrate the complete system (WT 6.1). Results were obtained and the engine was operated together with the other systems producing and conditioning continuously as engine emissions and parameters were monitored, see Figure 4 (WT 6.2).

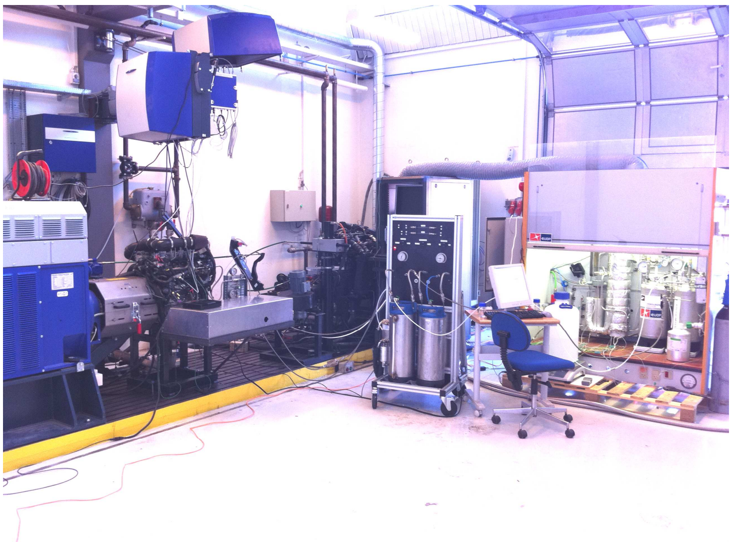

Figure 4. Final system test with OBATE reformer and engine working as one unit.

Emissions are of great interest when introducing a new fuel. Since the OBATE fuel has some known properties such as increased oxygen, alteration in ignition quality (cetane no.) and 3.5 times higher latent heat, it will result in changes in the combustion properties. It was anticipated that particle emissions should be significantly reduced due to the high level of oxygenates as combustion occurs. Furthermore, from theoretical calculations on flame temperature with changes in specific heat values compared to Diesel, it was expected that combustion temperatures would be decreased. However, in order to obtain significant results, it is mandatory to do experimental work. The combustion process in internal combustion engines is highly complex, and mathematical modelling of the combustion process is still a state of the art research field within the automotive industry. The engine set up is seen in Figure 5.

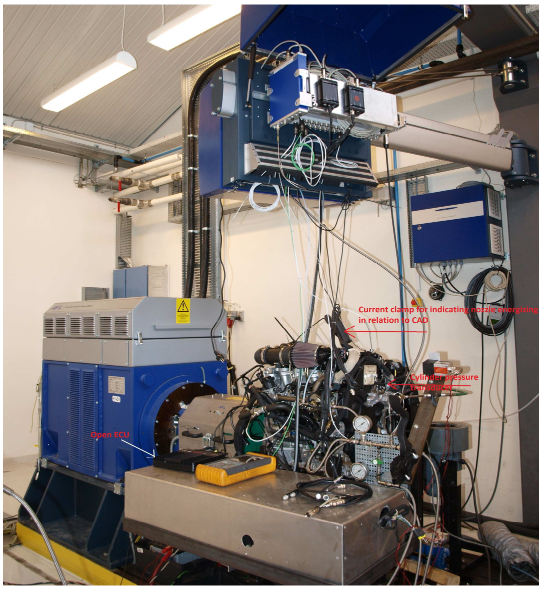

Figure 5. Test engine at Teknologisk in Århus

Some of the key results from the comprehensive engine/fuel testing are described in the following section. If a more detailed explanation is needed, the published Society of Automotive Engineers (SAE) paper number 2012-01-0859* can be read. The paper will be presented at SAE World Congress 2012 in Detroit, see Appendix 1.

Since emission legislations increasingly have become more stringent concerning particle emissions and NO_x, the need for exhaust aftertreatment system has become predominant, expensive and fuel consuming. The OBATE fuel has in this project showed that particle emissions are reduced by almost 100% and leaves out the need for using particle filters. Two of the particle sampling filters are shown in Figure 6 and clearly illustrate the effect on reducing particle emission using the OBATE fuel.

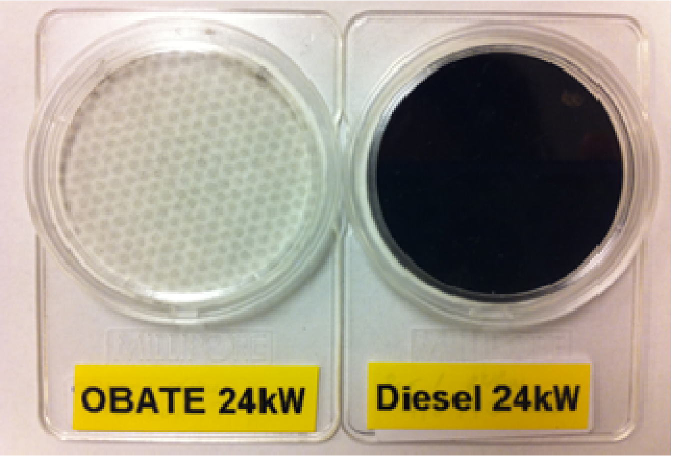

Figure 6 Particle sampling OBATE fuel compared to standard Diesel fuel

In recent years, much attention has been given to reducing NO_x emissions, since it effects the promotion of smog in urban areas and secondly affects the respiratory system of humans.

Some of the commonly observed NO_x emissions are shown in Figure 7. Examining Figure 7, it can be seen that NO_x emissions are significantly reduced using the OBATE fuel compared to Diesel fuel. During the engine test, the engine was operated at different load settings, and the engines electronic fuel control unit (ECU) was calibrated for each fuel with and without exhaust gas recirculation (EGR) in order to reduce NO_x emissions even further. When the engine was operated without EGR, the NO_x reduction was approximately two to three times lower than that of Diesel fuel. Results obtained when using EGR showed up to five times higher reduction of NO_x. Since calibration of the ECU is a time-consuming issue, more experimental work is needed to obtain even lower NO_x emissions and the outcome of further research might eliminate the need for NO_x aftertreatment systems, thus, reducing fuel consumption.

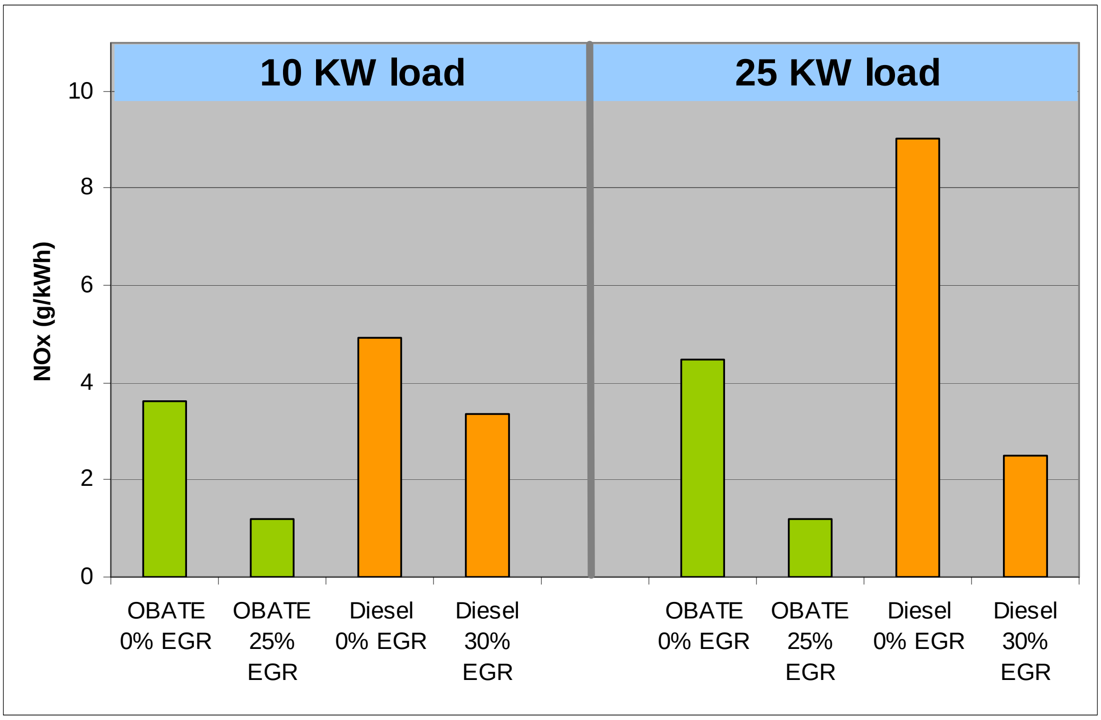

Figure 7 NO_x emissions for the OBATE fuel and ordinary diesel fuel

As mentioned, the project delivered results beyond the original project scope, since the flexibility of OBATE fuel together with open ECU enabled the engine to be operated under real driving conditions powering a transient test cycle according to European test cycle legislation. Results showed that the engine almost obtained EURO 6 emissions legislation, see Figure 8, which will come into force in 2014. This is without NO_x reduction equipment, and with further research it is expected to reach this target.

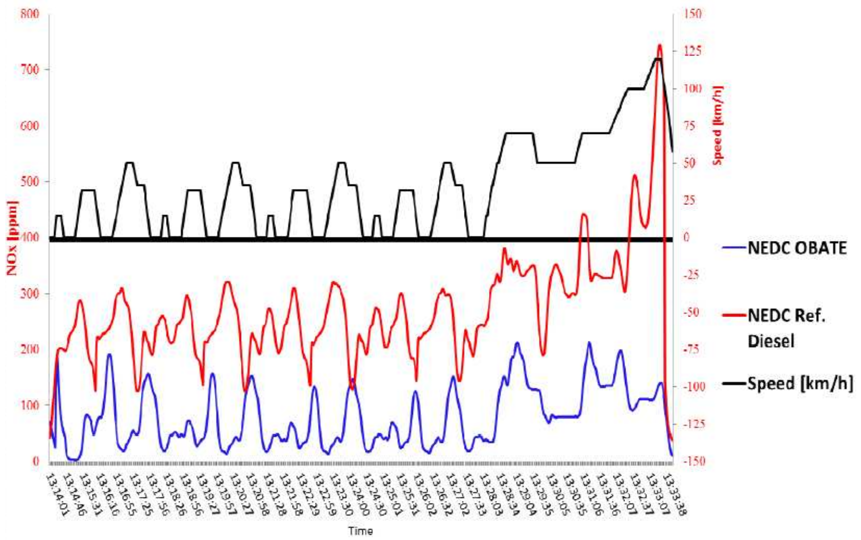

Figure 8 NOx emissions in the NEDC test cycle using ordinary diesel and the OBATE fuel

Also the efficiency of the engine was measured, and the OBATE fuel proved to have the same efficiency as when the engine was operated with Diesel fuel. The brake efficiency was approximately 35-40% for each fuel. The possible elimination of expensive and fuel-consuming aftertreatment systems together with engine efficiency using the OBATE fuel is overall improved vehicle efficiency.

WP7 Control Electronics

The proposed work packaged (WP7) concerning engine electronics in the original project plan was to outsource the electronic engine control to an external company. This was thought to be most feasible in relation to reaching the final target of the project. Early in the project, some basic engine test was performed in order to obtain information on how the standard Diesel engine would combust the OBATE fuel. Indeed, the fuel proved difficult to handle in relation to combustion phasing, thus, it was decided to work with fuel injection electronics internally in the project. This proved to be a good solution and enabled the project to go beyond the intentioned project scope.

WP 8 Vehicle demo project

The project has been carried out in a new project (WP 8) EUDP11-II Journal nr.: J.nr. 64011-0013 “Clean and efficient heavy duty diesel engine running on 2nd gen. bio-ethanol”. Instead of pursuing use of the OBATE technology directly in passenger cars or trucks, it was decided to gain further operational experience from building a larger more compact and efficient reformer system and combining it with a truck size diesel engine. The diesel engine will be coupled to an electric generator, making it a small movable power plant. In this connection, it has fortunately been possible to involve Nordhavn A/S in Randers in this new project. Nordhavn A/S produces and sells gen-sets consisting of truck size industrial diesel engines coupled to power generators and is, thus, a very beneficial expertise to have involved in the development of this new technology as well as in moving it towards commercialization.

Conclusion

According to the partners the project has been at great success. It was demonstrated that ethanol indirectly can be used on a diesel engine by partial conversion of it into a mix of ethanol, diethyl ether and water. It was also demonstrated that the emissions could be significantly reduced. There were virtually no particles, the NOx was reduced to emission levels that will come into force in 2014 without aftertreatment. The project also designed a prototype system which was scaled down from the prototype in order to fit into a vehicle.

The project has now with financial support from EUDP continued into a second part, where the production-like prototype design of the OBATE system is going to be tested with a modified heavy duty truck engine. The target here is to run for 2000 hours, in order to prove the stability of the process and the durability of the OBATE reformer system.

Published patent application

The project has under the project applied for eight different patents and utility patents in the field of OBATE™. Five of those have become public. References are shown below.

1. EMULSIFIED OXYGENATE DIESEL FUEL COMPOSITION AND METHOD OF PREPARING AN EMULSIFIED OXYGENATE DIESEL FUEL COMPOSITION - WO2011154001 (A1)

2. METHOD AND SYSTEM FOR OPERATING A COMPRESSION IGNITION ENGINE ON ALCOHOL CONTAINING PRIMARY FUELS - WO2011120618 (A1)

3. METHOD AND SYSTEM FOR OPERATING A COMPRESSION IGNITION ENGINE ON ALCOHOL CONTAINING FUELS - WO2011120616 (A1)

4. METHOD AND SYSTEM FOR OPERATING A PRESSURE IGNITION ENGINE - WO2011120615 (A1)

5. METHOD AND SYSTEM FOR OPERATING A COMPRESSION IGNITION ENGINE - WO2011120614 (A1)