Haldor Topsøe A/S - TI-Plastics - TI-Engine - Nordhavn A/S

Final report on"Clean and efficient heavy duty diesel running on 2nd generation Bio-ethanol"

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Brief summary

Projektet forløb planmæssigt med hensyn til de fleste work packages. Uheldigvis har problemet omkring smøring vist sig at være væsentligt mere kompleks ind ventet. Det har været nødvendigt at restrukturere projektet, således at det var muligt at dedikerer de nødvendige ressourcer til smøringsproblemet. Dette har haft en effekt på projektets fremdrift. Smøringsproblemet viste sig at være for stort til, at det kunne håndteres indenfor projektet; hvor projektets formål var at demonstrere teknologien i pilotskala. Ydermere er markedet forværret gennem projektets forløb, da en række andre teknologier er kommet frem, og har fået fodfæste. Projektet kunne ikke gennemføres til den planlagte demonstrationsfase. På trods af dette er følgende nøglepunkter afsluttet tilfredsstillende: fuel upgraders design, buffer tank materialeanbefalinger, nødvendige motormodifikationer for en OBATE motor samt containerdesign.

The project progressed as planned for a majority of the work packages. Unfortunately the issue regarding fuel lubrication proved to be significantly more complex than anticipated. It was necessary to restructure the project in order to dedicate the necessary resources to the lubricity issues and this naturally affected project progress. The lubricity issue proved to be too complex to handle within the project bearing in mind that the main goal of the project was to demonstrate the technology in pilot scale. Furthermore, during the project the market conditions worsened significantly as multiple other technologies surfaced and gained traction. Even though the project did not progress to the final demonstration phase, the main deliverables include the design of the fuel upgrader, material recommendations for the buffer tank, engine modifications necessary to run the OBATE fuel optimally in a diesel engine, and the container unit design.

Abstract

The project has achieved considerable results before being terminated prior to the actual demonstration. The project was terminated due to a) lubricity issues where a solution is currently not in sight and b) non-favourable market developments which significantly reduced the market size. Materials suitable for the buffer tank, thermal insulation and gaskets for the OBATE™-E fuel upgrader have been identified. The prototype of the fuel upgrader has been designed in two versions – a light and compact one for which further work is needed in order to satisfy material requirements, and a larger and more robust one which is easy to control. For the larger upgrader which was planned to be used in the demonstration, all of the components have been specified and procured. A trip diagram for the control of the system has also been developed. On the engine side, significant work has been done on modifying the ECU in order to allow optimal run of the diesel engine with its new OBATE™-E fuel. A list of mechanical alterations was also made and the engine was fully ready to start running on the fuel. One of the results of the engine work is however a strong recommendation to switch to a common rail injection system in the future. The 20'container which was to host the engine and the OBATE™-E fuel upgrader was also designed prior to project termination. Overall, the project achieved significant part of the milestones however before proceeding to the actual long term demonstration and the post mortem of the components involved the project was assessed to be redundant considering the distant prospect of fuel commercialization.

Introduction

Below is given a description of the progress in the different work packages that describe the progress in the "Clean and efficient heavy duty diesel running on 2nd generation Bio-ethanol" partly financed by EUDP.

The work has been divided between four different partners, Teknologisk Plastics, Teknologisk Engines, Nordhavn A/S 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. Nordhavn A/S has provided needed support to Teknologisk Engines for the engine that they have supplied to the project.
The work and results achieved, split into Work Packages as given in the project application, is detailed below. The report is a product of collaboration between all partners and **in appendices further descriptions are given, for the use by EUDP and no public distribution.**

WP 1 Catalyst for liquid conversion (HTAS)

The catalytic upgrader system from ethanol to OBATE™-E fuel has at its heart a catalytic converter. Due to the requirements related to energy efficiency, simplicity of design and maintenance as well as compactness, it became imperative to conduct the reaction in liquid phase. This meant finding a catalyst with high activity and stability for the ethanol to OBATE™-E reaction in liquid phase (temperature up to 250°C and pressure of 65bar) which is easy to produce and has good mechanical stability. The temperature and pressure were chosen in order to have a catalyst that is active beneath or on the boiling point (boiling point of ethanol is about 240°C at 64 bar).The activity optimum for the catalyst was set at 72% conversion since it is the highest conversion giving a one-phase product. For any higher conversion, dilution is needed, but for conversions lower than 72% the quality of the fuel drops.
The catalyst development for the liquid phase reaction has been done at Haldor Topsøe A/S. The catalysts screened were all acid catalysts, most some type of zeolites. Furthermore, a few sulfonated polymers, and a few superacidic oxide materials were tested.
The experiments were performed in a once-through U-tube powder SS reactor (2 or 4 mm ID), see Figure 1. Syringe pump is utilized as liquid feed reservoir. Reactant is typically preheated in a heat box (kept at 190°C) upstream of the reactor. Nitrogen flow is added to the heated reactor effluent to evaporate liquid products by lowering their vapor pressures. Part of the stream (50-100 mL/min@65 barg) is depressurized through a series of inert alumina-packed and capillary columns before entering a Gas Chromatographer for analysis. Another part is vented out to a condenser (15°) to control the system pressure.

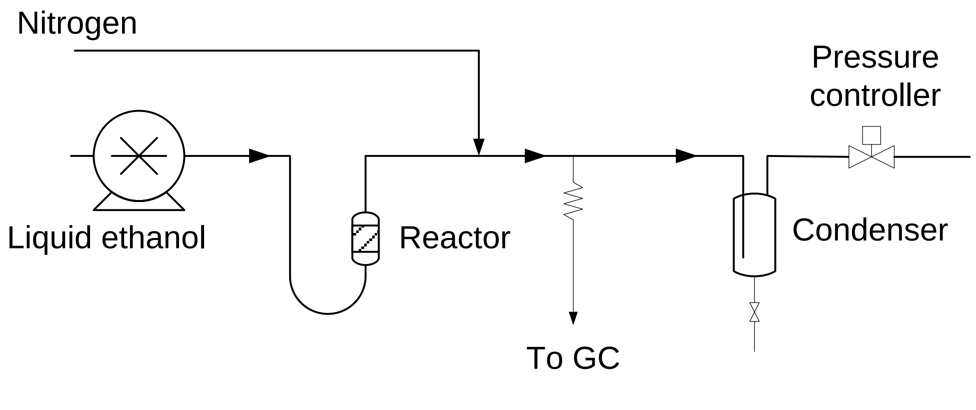

Figure 1. Schematic overview of the configuration of the reactor equipment for measurement of the conversion of ethanol to diethyl ether (DEE) in the liquid phase

A zeolite-based material emerged as the best candidate both pure and when extrudated with a binder and then crushed for testing. This means that the upscaling to the extrudate catalyst form

was successful. This zeolite material is commercially available and making of the paste and extrusion are some of HTAS core competencies. The production of the catalyst does not pose a challenge and the catalyst can be produced in several production lines in our factory in Frederiksssund. The catalyst extrudes have then be tested for mechanical stability – both at HTAS shaker facility and at Delta shaker in Hørsholm. Typically, in automotive applications the vibrations are strong and the catalyst needs to be held in place by balls or grids put at the bottom and/or top of the reactor. The vibrations can cause wear, grinding, and crushing of the catalyst. Therefore, two representative mock reactors were made and tested at each of the shaker facilities. The shaker test setups are shown in Figure 2.
For tests at HTAS shaker, a small mock reactor has been made and mounted on the shaker plate. A holder was attached at the bottom of the reactor tube with the purpose of collecting the catalyst dust which would enable us to determine the catalyst loss of mechanical stability simply by weighing.
A sine sweep test considered representative for automotive applications was conducted within the frequency range of 6-100 Hz and the sine profile was swept at 1 oct/min starting from 6Hz and repeated 10 times. The duration of the test was 40 minutes. The test was run twice, with the total test duration time of 80 minutes. No dust has been collected during each of the tests.
For tests at Delta shaker, a mock reactor based on industrial reactor setups for DME production was made and tested for automotive-like vibrations at a shaker facility at Delta, Hørsholm. The test setup designed consisted of a plexiglass pipe inserted in a stainless steel pipe with “windows” at top and bottom. The bottom “grid” was glued to the plexiglass tube so that the pipe could be pushed up. This ensured that after the test, the potential migration of catalyst could be seen, even if it occurred below the top window. The test pipe had same vibration amplitude at the middle as at fixation points and the vibration test was planned so that it ran for 4 hours.
Following the test, the top and bottom flanges were dismounted and the plexiglass pipe pushed upwards so that the level of the catalyst could be inspected. No drastic settlement was seen (settlement approximately 3 mm) – therefore it was concluded that the catalyst was not affected by the vibrations it experienced.
Overall, the two tests proved good mechanical stability of the catalyst extrudates tested.

Figure 2. Test setup at HTAS (left) and at Delta shaker (right)

WP 2 Fuel upgrade system (TI-Plastics and HTAS)

The work on the fuel upgrader was split in such a way so that the contribution from TI-plastics came to focus on materials for the fuel upgrade system (especially materials for its light version), whereas HTAS took charge of the system development. The first edition of the system was to be made in stainless steel and the later systems with new light components.
The fuel upgrade system was broken down into following components:

1. Light reactor vessel and materials for it
2. Materials for intermediate tank and fuel lines/tubing
3. Thermal insulation
4. Gaskets for reactor and intermediate (i.e. buffer) tank.

Light reactor vessel

The aim was to develop a system for use on heavy duty vehicles and one of the main requirements for such a system is being light and compact. In addition to the weight and space restrictions being a major guideline in the vehicle industry, a light system would also have a lower heat capacity and thereby require less energy and time to go from cold stand-still to hot operating condition.
From the system point of view, in order to have the liquid-phase process and avoid energy unfavorable primary fuel evaporation and product fuel condensation, it was necessary to set the reactor pressure to 65bar and temperature tolerance to up to 270 °C. This meant that quite advanced composite materials had to be used to replace the conventional stainless steel reactor. Contact was established with Falck Schmidt Advanced Composites Engineering who were willing to commit to making a light carbon fiber reactor vessel to the desired specifications. Formal legal agreements were made and meetings were held on the technical solution. However, this solution proved too costly considering the project budget and therefore a decision was made to proceed with a stainless steel solution for the first reactor in the system prototype.

Intermediate tank and fuel lines

The fuel consumption in an engine varies rapidly with the road conditions and traffic. To lower the demand on the catalytic reactor, an intermediate or buffer tank was planned between the reactor and the engine. A search for materials capable of withstanding the conditions and with a reasonable price was made. The requirements for the buffer tank were set to 65 °C, up to 10 bar pressure tolerance and of course good compatibility with the OBATE™-E fuel comprising of diethylether, ethanol and water.
Two kinds of tests were made in order to screen the materials: durability in heated OBATE™-E fuel, and testing for permeability to DEE, the most challenging fuel component. The materials tested were all technical plastics. Bags of granulate were purchased and it was then processed by injection molding into ‘dog bone’ (see Figure 3) or plate test samples. The ‘dog bones’ were used for tensile testing following periods of exposure to OBATE™-E, while the plates were used for permeability tests.
The materials chosen for tests were:

1. PA6 (Polyamide aka Nylon)
2. PBT (Polybutylene Terephtalate)
3. HDPE (High Density Polyethylene)
4. PPS (Polyphenylene Sulfide)
5. POM (Polyoxymethylene)
6. PES (Polyethersulfone)
7. Vectra (A liquid crystal polymer)

Figure 3: 'Dog bone' samples for tensile test

To investigate the durability of the materials in OBATE™-E fuel, 'dog bone' samples were submerged in OBATE™-E for different periods of time and subsequently the mechanical properties were tested with a tensile test machine. In ageing of plastics, it is common to store them at elevated temperature to increase the speed of the degradation processes. DEE has a boiling point at atmospheric pressure of 36 °C, so subjecting of the samples to elevated temperatures had to be done in pressure vessels.

To contain the OBATE™-E fuel permeability is a highly important property which was investigated with a purpose-built permeation setup (see Figure 4) capable of handling pressurized liquid and of heating the permeation cells individually. When in use, this setup is placed in a suitable fume hood. The concentration of permeate was measured with a gas chromatographer. The results of permeability tests are shown in Figure 5 below.

After the permeability with DEE was measured, the permeation was measured with the OBATE™-E fuel mixture for the most impermeable materials. The measured permeation was close to that measured with pure DEE. Measurements with the mixture are more challenging as one has to take care that the mixture does not change due to evaporation of one or more of the components. A short report detailing the work on permeability measurements further is given in Appendix 1.

Figure 4: Setup for measuring permeability

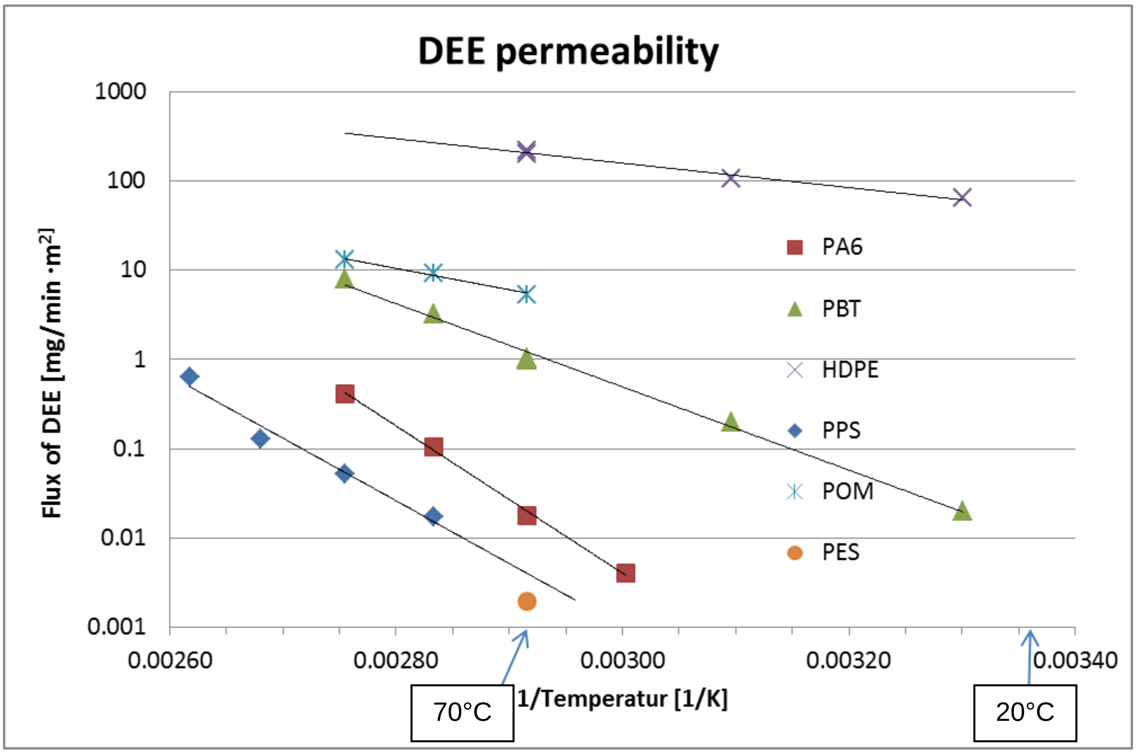

Figure 5: Plot of measured permeability of diethylether vs. 1/temperature in Kelvin

The conclusion of the material test is that PPS with or without glass fibers would be the best candidate for the intermediate tank. Glass fibers give higher strength and can be injection molded; a container should then be made by welding the parts together. PPS without glass fibers is weaker but can be processed by rotation molding and a container capable of withstanding OBATE™-E at 10 bar and 65 °C can be made. Further references have been found indicating that the partial degradation of the strength of PPS with glass fibers in OBATE™-E is suggested to be due to degradation of the interface between PSS and glass fiber; consequently pure PSS should be degraded less. However, it is important to state that despite the observed degradation of mechanical properties of PPS with glass fibers it would still be a good material for the application.

Insulation for reformer system

In order to build an energy efficient system it is important to keep heat losses to the minimum. The desired insulation material should be cheap, light and well insulation as well as capable of withstanding use on a vehicle. Four materials were chosen: Light and Heavy rockwool (both 15x15cm), Skamol V-1100 (475) (Vermiculite) and Skamol Super-1100E (Calcium silicate) (both 30x30cm). All samples had a thickness of 20mm. The samples were subjected to standardized ISTA 2A test, corresponding to transport on ‘really bad roads’ which they all survived without loss of mechanical or insulation properties.
Two short reports on this work can be found in Appendix 2.

Gaskets for reactor and system

To prove whether a proposed gasket for the reactor consisting of steel reinforced graphite would be suitable for the reactor it was subjected to 300 °C and 65 bar for 14 days. Both maximum and break stress was reduced by 27 % in the exposed samples as compared to the non-treated ref-

erence samples. The conclusion was that the gaskets can be used but a biweekly inspection can be recommended as a safety measurement.
Gasket materials for the buffer tank part of the system were also tested. The materials chosen were PTFE (Teflon), Klinger Sil and a Graphite gasket, all from Klinger. The samples were subjected to OBATE™-E at 110°C for 29 days and no significant degradation of mechanical properties was found.
Two short reports on this work are given in Appendix 3.

Complete System Development

The complete system was first designed with a prototype that could go directly to an on road vehicle in mind. The key design targets were compactness, lightness and easiness of maintenance. This system is shown in Figure 6. Alcohol comes from the feed tank and is heated up in the heat exchanger and enters the reactor vessel. The hot product from the reactor vessel is again heat-exchanged with the cold feed in a feed-effluent heat exchanger. After a pressure relief, the cold product is stored in the buffer tank which is connected to the fuel injection system on the vehicle.
Once the system was designed and the procurement phase was about to start, a couple of challenges were identified. The main challenge was the task of identifying a suitable material for the reactor tank. This tank would have had to be custom made, complemented by a high cost and long delivery time. The other challenge was the uncertainty of controlling efficiently such a system at a first attempt given the time line of the project.
Therefore, it has been decided to resize the equipment making the buffer tank larger in order to ease the control issues and to go with a stainless steel reactor vessel. The components have been procured in the course of the project, and it was succeeded in finding the standard components for the whole system. The system still had a very convenient feature of a feed-effluent micro heat exchanger that used the heat from the fuel product to heat the alcohol going in the reactor. The reactor size was also kept small at 9L. The final system design that was planned for the demonstration is shown in Figure 7. Its footprint is c $5m^2$.
The complete Process Flow Diagram for the system is given in Appendix 4. The control system for the upgrader is also available upon request but is not included here due to confidentiality reasons.

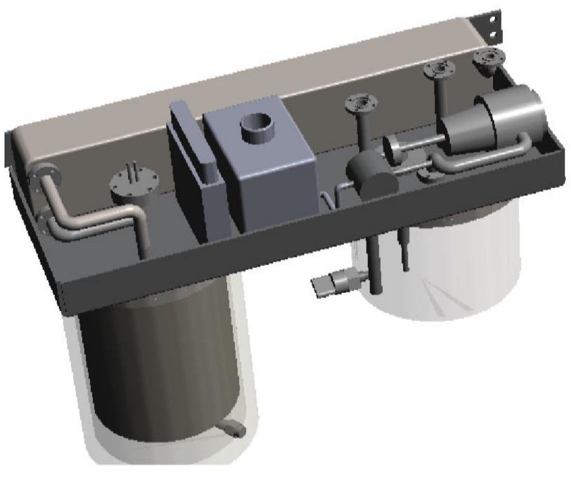

Figure 6. Design of very compact and light fuel upgrader for the on board application

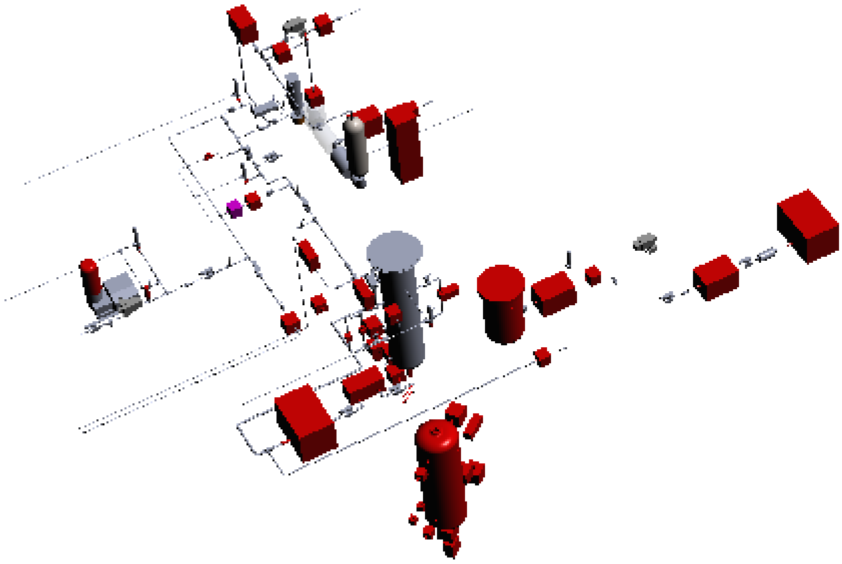

Figure 7. Complete final design for the fuel upgrader planned for the fuel demonstration

WP 3 Engine analysis and development (TI-Engines with support from Nordhavn)

The engine selected for this project was a 9-liter engine with five cylinders from Scania. The engine was turbocharged and had EGR for NO_x reduction. This version of the engine was used for power generation. It has a rated power of 226 kW at 1500 RPM. The engine was chosen given that a comparable 'sister' engine was available for running on ethanol fuel – the motivation was the availability of spare parts that would be interchangeable and ethanol-compatible.
The engine was installed at the engine dynamometer (at TI Aarhus) which is a powerful and controllable electric generator that converts the shaft power from the engine to electricity. This installation is shown in Figure 8.

Figure 8: Scania engine coupled to the dynamometer at TI-Engines

In order to have the engine running smoothly on the OBATE^{TM}-E fuel, certain mechanical modifications needed to be made. The main modifications were done in the fuel system, consisting of injectors, fuel supply and fuel line. In addition to mechanical modifications, the electronic control

of the engine was completely adapted to work with its new fuel. This is considered a major step forward from the first project ("Diesel Vehicles Running on 2nd Generation Bioethanol", EUDP08-II).
In the sections below both the mechanical and electronic control modifications are discussed and the recommendations for the future are given. Finally, a section on the work done on lubricity of the OBATE™-E fuel is given and this challenge is discussed in detail.

Mechanical modifications

The engine was equipped with unit injectors (PDE, Pumpe Düse Einspritzung). This injector technology combines the high-pressure pump and injector in one body. The high-pressure pump is actuated by the camshaft, like the valves.
The unit injectors were changed from the version used with the diesel fuel to the version used on the 'sister' ethanol engine. The injector was modified slightly to work with ethanol which has a lower lubricity than diesel. The main difference was a DLC (diamond-like-carbon) coating on the piston, which decreases demand for lubricity (see Figure 9). Since OBATE™-E fuel has lower lubricity than diesel, the ethanol injectors were found suitable to replace the standard diesel injectors. Addition of a lubricant was however also required in order to increase the fuel lubricity. The choice of unit injectors over the more modern common rail injection technology meant that there was no need for a separated high-pressure pump (the standard solution for pressurizing the fuel distribution rail). The traditional high pressure pumps are susceptible to extensive wear when fuels with lower lubricity than diesel are used, since most mechanical parts of a normal pump are lubricated and cooled by the fuel. In the unit injector however, the only moving part, which is exposed to the fuel, is the cylinder and plunger, whereas the actuating external parts are lubricated by engine oil. Thus, in terms of wear resistance the unit injectors are likely superior to standard common rail pumps.

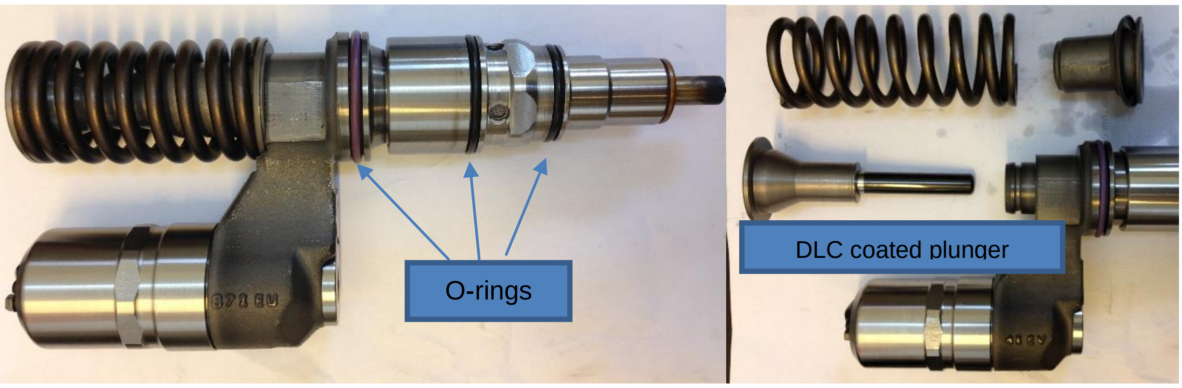

Figure 9: Unit injector complete and disassembled

The fuel passages for the injectors pass through the cylinder head before entering the injectors. Three O-rings on the outside of the injector provide the seal between the fuel passages and the internal area of the engine. Due to ether being very aggressive towards normal O-ring materials, teflon-coated Viton O-rings were used. The sealing of the new O-rings were confirmed intact during extended periods of use at elevated pressure with OBATE™-E fuel.
OBATE™-E fuel contains a little over 50 % of the heating value per unit volume compared to diesel. The high-pressure pump however has identical displacements in the diesel and ethanol injectors. This means that injection durations are required to be twice as long with OBATE™-E fuel to obtain the same fuel input. This can ultimately limit the peak power of the engine, since an

extended injection duration will also result in an extended duration of the combustion and hence a reduction in efficiency. Also, it was not possible to test at high loads, since the test bench was not capable of absorbing more than 50 % of the rated power of the engine, or approx. 110 kW at 1500 RPM.

Another disadvantage of the unit injector technology is that the quantity that is delivered during the starting of the engine is only adequate for starting on diesel. The pump in the unit injector follows the engine speed, while the electrical activation of the injector has a fixed maximum of approx. 13 milliseconds due to hardware limitations in the ECU. This means that the maximum quantity injected per cycle is much smaller during starting (200-230 RPM) than at nominal speed. Further adding to this problem is the fact that the OBATE™-E fuel mixture is more compressible than diesel, which delays the pressure buildup when the injector is activated. Finally, the heat of vaporization is quite significant for OBATE™-E fuel, which causes an extensive ignition delay as the fuel is allowed to evaporate before igniting. Again, this problem is worst during starting when the in-cylinder temperature is at its lowest.

Based on the aforementioned issues, the overall recommendation would be to use common rail injection technology instead. This would require further development of the high-pressure pump for increased capacity and wear resistance, but it would be much easier to control the fuel injection. It would also enable multiple injection strategies, such as using pilot injections to reduce ignition delay of the main injection, which further helps to control the formation of pollutants such as NO_x and particulates.

The fuel supply system to the injectors is shown in Figure 10. The OBATE™-E fuel components (DEE, ethanol and water) were first mixed in a large pressure vessel standing on a scale. The pressure vessel was then pressurized with nitrogen, which pushed the fuel through the fuel line to the engine. The fuel pressure for the injectors was further increased using a boost pump. The higher pressure was required to ensure that the ether did not boil when reaching the cylinder head and injectors, which could have a temperature of more than 100°C.

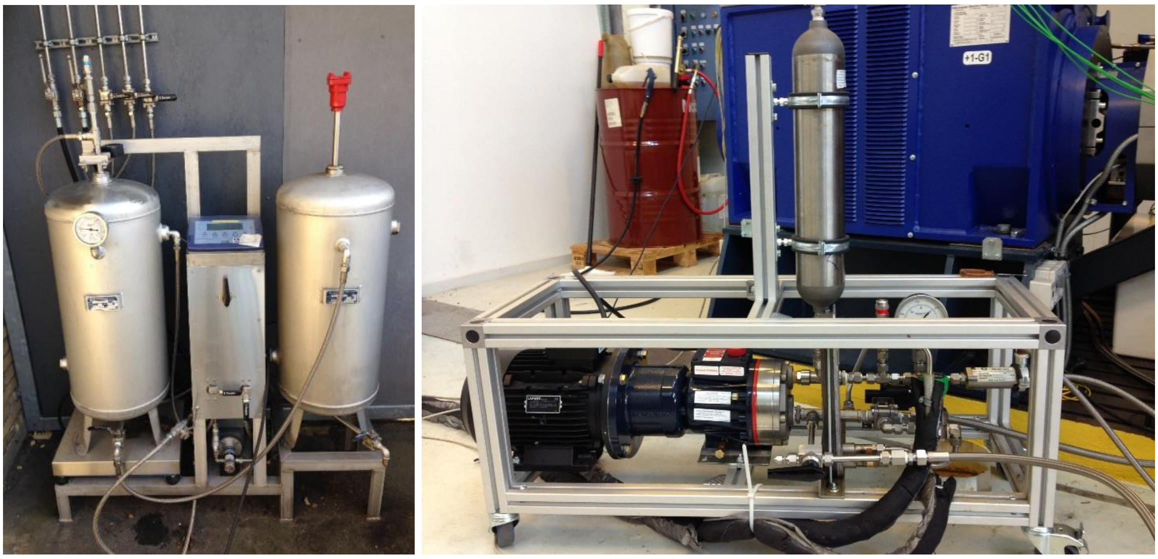

Figure 10: Fuel mixing station (left) and the boost pump rig (right)

Engine electronic control modifications

The engine management is provided by the Engine Control Unit, commonly referred to as the ECU. The main purpose of the ECU is to control the fuel injection, in terms of duration and position relative to the piston. This control is particularly important for maintaining the desired speed

when load is changed. Furthermore, the engine has to be able to start when commanded to. This implies that the engine management must control the fuel injection in such a way that the engine will transit from cranking speed to 1500 RPM, where it will be ready to synchronize the generator to the 50 Hz power grid.
Since the standard ECU on the Scania engine could not be modified, it was decided to purchase an engine control that was designed for development projects. The ECU chosen for this project was the Bosch MEDC 17 FLEX ECU for diesel applications. It was a fully programmable unit, for which the specific engine software was programmed. The ECU was delivered by ETAS in Sweden, a company specialized in custom ECU applications.
In order for the engine to operate as desired, a software model needed to be programmed and loaded to the FLEX ECU. The model containing the controlling algorithms and monitoring functions was programmed in Simulink, a visual programming language supplied by Math Works. The model for this project was developed by South West Research Institute in Texas, USA.
With the software loaded onto the FLEX ECU, the engine was tested with the OBATE™-E fuel. In order to manipulate the model parameters, tables etc. in the loaded model, software called INCA was used. INCA was installed on a regular computer and it connected to the ECU on the engine using the CAN bus. With this, it was possible to make changes to parameters with immediate responses, such as changing load, injection timing and engine speed.
The ECU underwent extensive development to adapt it to the Scania engine. All of the functionalities were implemented, except for the automatic load control, which was required when the engine was operated as a generator.
The connectors used on all cables leading to the original ECU were replicated in the front panel of a box, which was mounted in the same position as the original ECU. From this box, all connections were cabled to the FLEX ECU in two connectors (see Figure 11a).
The Scania engine ECU was programmed to send and receive information during operation. The relevant input and output to and from the ECU was collected and transmitted together in digital format through the CAN bus between the ECU and the generator control. The generator control was named ICAMS and functions as the interface between the generator and the control panel from where the generator is remotely operated (see Figure 11b). The CAN communication followed the SAE J1939 standard protocol, and communication was by an RS 485 serial interface.

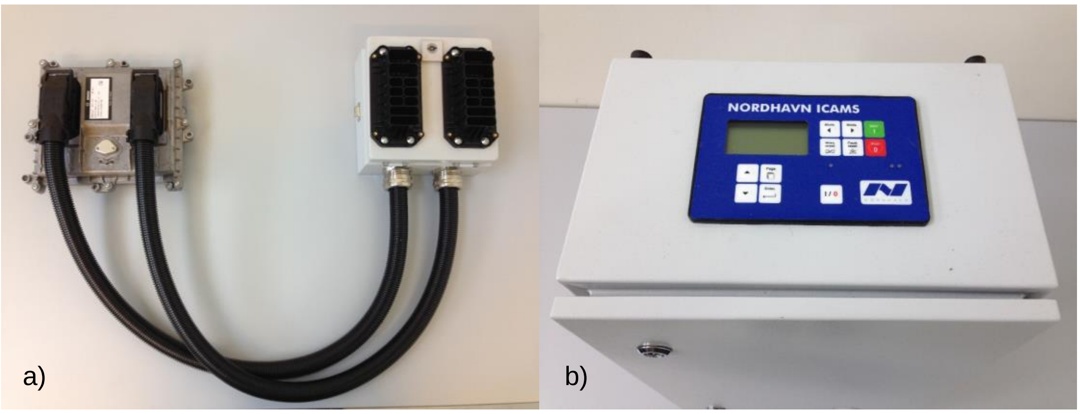

Figure 11: a) FLEX ECU (left) connected to adapter box (right) for the standard connectors on the Scania engine, and **b)** Nordhavn's generator control ICAMS

The CAN bus communication interface was not a standard feature in the BOSCH MEDC17, but was required for communication between the ICAMS module on the Nordhavn generator and the ECU. It was mainly due to safety reasons that ICAMS was used for monitoring and safety shut-

down of the engine. The most important communication included ICAMS commanding the ECU to start the engine, increasing or decreasing speed for synchronization and stopping. The ECU also communicated the information about the engine back to ICAMS, which could then take action if a shutdown was required. The CAN communication was implemented in the ECU software, and the functionality was extensively tested.
The engine management can be designed to control the engine when it is connected to the electricity grid or in synchronized operation with other engines. The first application requires only that the fuelling rate can be controlled (since the engine will not be able to change the grid frequency) while the latter requires that the various engines can cooperate and share the load evenly. The most common load sharing principle is called Droop Speed Control (see Figure 12). The control is a software model of the traditional mechanical governors, which operates by adjusting the fuel quantity according to minor changes in engine speed, such that the engine can absorb sudden load changes with a minimum change in actual speed. It also prevents the engine from excessive speeds if the load is dropped, and protects the engine from overloading if the load exceeds the engines power rating.
Synchronization is however required before the engine can deliver power to the grid. When the engine has started and reached 1500 RPM, the speed must be adjusted to a speed providing a frequency slightly higher than the grid, e.g. 50.1 Hz or so. This allows the generator to be switched in when the phases are aligned, with very little speed change when the generator is locked to the grid frequency. Once synchronized, the engine load can be controlled manually simply by changing the fuelling rate.
The procedures for synchronizing, loading and decoupling of the engine were tested by manual operation of the fuelling rate. It was also tested on a similar engine (same base model, but a 13L displacement SCANIA engine) equipped with our ECU, onboard the ferry Scanrail owned by Stena Line. The test showed that it was possible to control the engine synchronization and loading in the same way as in a permanent installation, with the only exception that speed was controlled through the FLEX ECU interface (INCA) instead of a remote control panel.

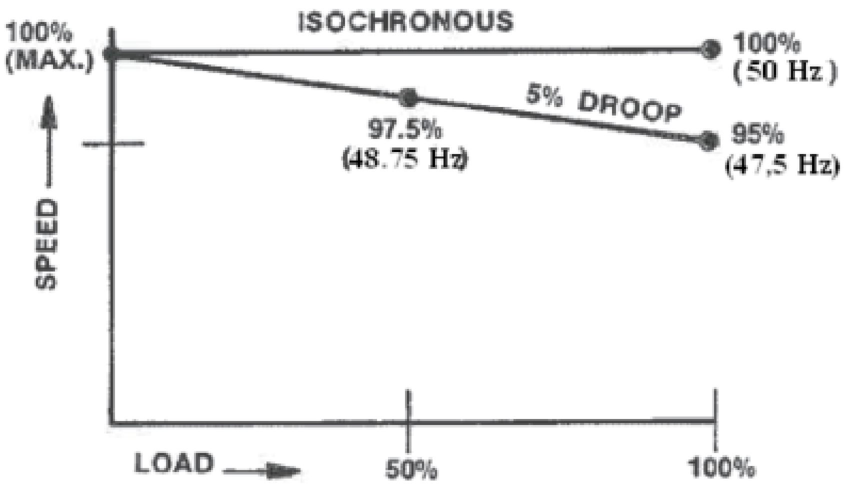

Figure 12: Illustration of Droop Speed principle: the 'isochronous' line shows that speed is maintained disregarding load while the 'droop' line shows that a small reduction in speed is allowed at increased load

OBATE™-E lubrication studies

The basic idea of the project was to use OBATE™-E fuel in a standard diesel engine with only minor changes. The combustion properties of OBATE™-E fuel are good but the lubricating properties of the ether, ethanol and water mixture became a concern during the project and both HTAS and towards the end also TI-Plastics have been working on it.
As the fuel is burned in the cylinder, it is not lubrication of the engine itself that raised the concern but the lubrication of the high-pressure fuel pump. The high pressure is desired to spray the fuel fast in to the cylinder and get it evaporated. The choice of unit injectors over the more modern common rail injection technology meant that there is no need for a separate high-pressure pump, which is the standard solution for pressurizing the fuel distribution rail. The traditional high pressure pumps are susceptible to extensive wear when fuels with lower lubricity than diesel are used, since most mechanical parts of a normal pump are lubricated and cooled by the fuel. In the unit injector, however, the only moving part, which is exposed to the fuel, is the cylinder and plunger, whereas the actuating external parts are lubricated by engine oil. Thus, in terms of wear resistance the unit injectors were likely to sustain the demonstration time planned, but for the future applications a strong recommendation is to use the common rail injection system (see Mechanical Modifications section above) and that is why an extensive search for the lubricant was conducted.
Given that a lubricity additive for the OBATE™-M fuel (fuel comparable to OBATE™-E which is produced by dehydration of methanol and is a corresponding mixture of Dimethylether (DME), methanol and water) was known and worked really well at doping rates as low as 200ppm, it was initially not assumed that finding the lubricant for OBATE™-E would pose a big challenge.
At HTAS, works have been conducted, together with tribology expert, Prof. Ion Sivebæk from DTU, in the course of 8 months. The samples for testing were collected based on the previously published work, and also obtained through a large contact network established with lubricant companies. The tests were conducted at DTU at a MFPRR (Medium Frequency Pressurized Reciprocating Rig) which is a test stand adapted especially to low boiling point fuels. The regular setup used for diesel and gasoline fuels is called HFRR (High Frequency Reciprocating Rig) and has been discarded for testing with OBATE™-E fuel since the amount of fuel taken for test is 2ml, all of which evaporated under a test conducted at the temperature of 25°C.
The MFPRR was developed in 1999 and the apparatus consists of a pressurized tank holding the rig driven by a magnetic coupling. The result is that no dynamic sealing is used causing leaks and no elastomers are present in the tank as these are vulnerable to ethers for example. The rig consists of a ball carrying arm which is reciprocating as the shaft is rotating. The disk is situated on the weight arm that provides the pressure in the ball disk contact (shown in Figure 13). The principle in a lubricity test is to slide a steel ball against a steel disk immersed in fuel for a given period. The ball disk contact is loaded by a preset load and the frequency of the reciprocating motion is also given. After the test the wear scar on the ball is measured and compared to a chosen reference value (that of diesel oil was chosen for this project). The Wear Scar Diameter (WSD) is expressed as the average of the major and minor axes of the scar (see Figure 14). The WSD is reflecting the lubricity of the fuel and is given in microns.

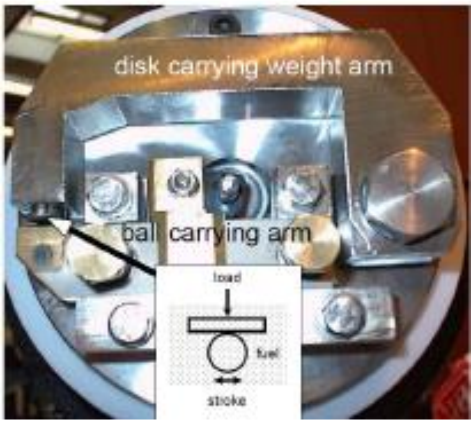

Figure 13. MPFRR test setup at DTU

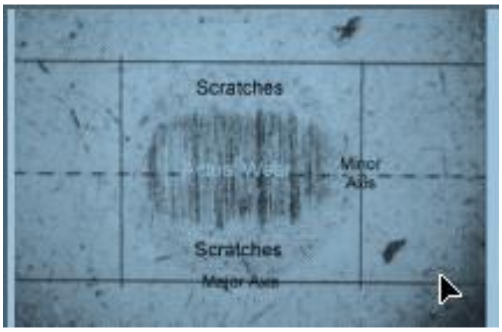

Figure 14. The principle of measuring the major and minor axes of a wear scar

In total, 32 tests were run but no lubricant blended with OBATE™-E fuel gave the same lubricity result as that of pure diesel oil. The closest candidates were still those that perform optimally with the OBATE™-M fuel but the resulting lubricity was still not close to the diesel oil level, and the doping rates used were considerably higher compared to those needed to lubricate the OBATE™-M fuel (up to 2% of lubricant addition was tried).

Given the discouraging results and the competence in surface chemistry that was available at TI-Plastics, it has been decided in November 2013 to attempt to supplement the work done on the lubricant by HTAS with the support of TI-Plastics. The first round of works was to build a test set-up which would allow higher throughput of experiments compared to that at DTU and to confirm its suitability for qualitative screening of candidates. Then, works were to be done on selecting lubricants and lubricant mixtures based on the surface chemistry competence in the group at TI-Plastics.

The work on the alternative testing method was completed succesfully by construcing a machine shown in Figure 15. In the wear test a polished soft steel plate moves under a hard steel ball, wear is measured on the ball and compared. The apparatus was validated through a correct blind ranking of three samples tested previously at DTU sent by HTAS to TI-Plastics without any explanatory details enclosed. Given that no commercial lubricant yielded the desired result, a list of chemicals to be tested for lubricating properties in the ether, ethanol and water mixture has been compiled by TI-Plastics in order to check if any of these would be suitable. It was however decided to terminate the project due to commercial reasons combined with uncertainty on the outcome of the lubricity testing before these chemicals could get tested. It was a hypothesis made by TI-Plastics that one of the keys to the difficulty in finding lubricity additives for OBATE™ -E fuel was that in an ether-ethanol-water mixture the molecules have different polar properties than in the nonpolar diesel oil.

A presentation on the lubricant additive work and the results obtained at both HTAS (in collaboration with DTU) and at TI-Plastics is given in Appendix 5.

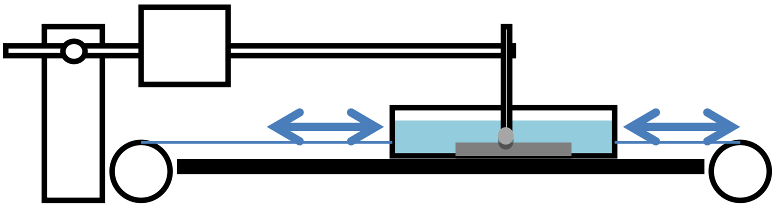

Figure 15: Sketch of the wear test machine constructed at TI-Plastics used in test

WP 4 Generator and complete system (TI-Engine, Nordhavn and HTAS)

This work package should have included work on the integration of the generator set and the OBATE^{TM}-E fuel upgrader in one unit placed in a 20' container. The decision was made to place the container on the TI grounds in Aarhus instead of at HTAS in Lyngby due to the administrative procedures needed for the approval to be able to give the electricity to the power grid in Lyngby. The container was designed (see Figure 16) and it included a separating wall between the upgrader and the engine unit with only the fuel supply and fuel return lines going through. The ventilation principle was also derived with all the necessary ATEX considerations taken into account. Work on the integrated control panel has been started at HTAS, however this task was not carried through before the project termination.
Necessary documentation requested by the municipality and other authorities involved in giving the approval for the demonstration has been collected to a great extent.

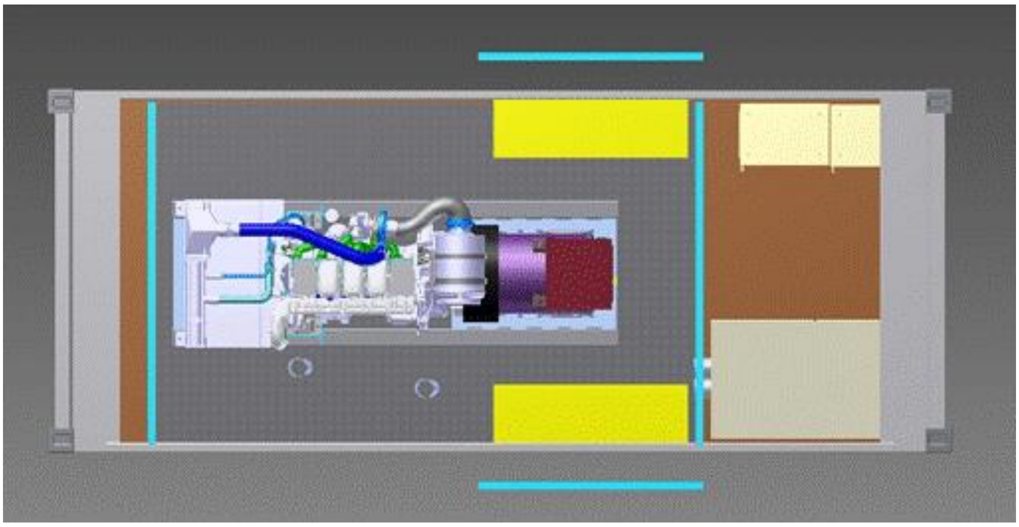

Figure 16. Illustration of the 20' container designed to host the generator (left side of the container) and the fuel upgrader (right side of the container)

WP 5 Pilot tests and post mortem analysis

The project was terminated before the actual fuel demonstration has started. This decision was made based on the commercial situation where the non-favorable market developments combined with the lubricity challenges adversely affected the commercial outlook of the project.
An indication of tolerance of the components used in the engine system to the OBATE^{TM}-E fuel is given in the WP3 section where the plungers and the seals have been inspected regularly while

in use for laboratory testing. A detailed post mortem analysis was planned only for after the demonstration for all of the parts used in the catalytic upgrader and the engine system.

Conclusions

Most of the project milestones have been successfully achieved and the project was progressing satisfactorily and with strong collaboration dynamics between the partners. Works on the upgrader have been nearly completed; however the finally designed system was less compact than previously expected. The engine development work achieved all the necessary targets in order for it to run a demonstration with OBATE™-E fuel as substitute for diesel. The existing engine was however fitted with unit injectors which prolonged the development work and clearly proved to be a non-optimal system solution. It was therefore recommended to rely on the common rail injector systems in any future references and this on the other hand, brought the lubricity of the OBATE-E fuel into focus as the high pressure pump used for common rail injection system is very susceptible to a change in fuel lubricity. The task of finding an adequate lubricant for the fuel unexpectedly came to consume a lot of time and people resources in the project, yet no desired outcome came out of the studies conducted. Combined with an unfavorable market situation, it has been decided to terminate the project, in the interest of reasonable use of time and resources at all partners'.

Published patent applications

The project has under the project applied for one patent in the field of OBATE™-E. The reference is shown below:
PROCESS FOR PREPARING A FUEL FOR AUTOMOTIVE APPLICATIONS, STATIONARY ENGINES AND MARINE APPLICATIONS BY CATALYTIC LIQUID PHASE ALCOHOL CONVERSION AND A COMPACT DEVICE FOR CARRYING OUT THE PROCESS - US 20120247002 (A1)