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Gane fuel and Infineum additives – a single fuel methanol solution

Fuels - Alternative & New Fuels

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ABSTRACT

Gane Energy has developed a methanol-based fuel, called "Gane fuel", which can be received by end-users as a single liquid fuel for use in a wide range of newbuild or retrofitted heavy duty diesel engines in many applications, including maritime. The fuel comprises methanol and water. Combustion is achieved through the approach of taking a small amount of Gane fuel, passing it across a catalyst, and creating di-methyl ether (DME) on demand for injection into the inlet manifold of the engine while using the engine's modified high-pressure fuel system for injection of Gane fuel into the combustion chamber.

In tests undertaken on a 12-litre series production non-road diesel engine, diesel-like CI diffusive combustion was achieved across the full engine map. With 10% water content in Gane fuel as tested, emission outcomes were on average 80% lower in NOx and particulate matter and 99.5% lower in particulate number, when compared with diesel, while matching or exceeding the equivalent diesel efficiency.

Changes to the base engine are modest. Methanol appropriate injectors and high-pressure pump must be used for the liquid fuel injection system. Low-pressure port injection of DME can be supplied by the on-demand DME production unit. These changes can be applied to retrofit existing engines, enabling customers to accelerate the transition of their fleets to carbon neutrality.

A prototype DME production unit has been developed by Gane Energy using a catalyst developed by BASF. By making DME available on demand at the engine, this unit enables end-users to receive a single, liquid methanol-based fuel to power their engines. This avoids the need for using a diesel pilot fuel and the necessity for two fuel supply chains.

The adoption of a methanol/water fuel requires acceptable outcomes on lubricity and corrosion along the supply chain and in the engine. Additive treatment of methanol/water fuels has been investigated as part of a collaboration between Gane Energy and Infineum, the results of which will be presented.

1 INTRODUCTION

It is normal for an oil refinery to produce a range of fuel components in the form of rundown streams with distinct qualities, a selection of these being blended to make a particular product. Computer models operate with many variables and constraints to determine on a per product basis, what the cost of product quality giveaway (quality produced minus quality required) is on a particular specification point. It is not common for a single rundown stream to be partitioned from the rest and sold to market, because such an approach in most cases does not provide the best economic solution for the refinery.

Gane fuel comprised of methanol, water and DME is a methanol-based diesel alternative fuel formulation and follows a similar approach, recognizing that 100% chemical grade methanol with its strict quality specifications set by the chemical industry may not be the best solution for a fuels market where quality requirements for compression ignition internal combustion engines in particular, are very different.

Methanol is growing in the market as a diesel fuel substitute, typically ignited by a diesel pilot fuel. It is natural that for the significant change in fuel quality, from bunker fuel to methanol, an ingredient which is available and of known high quality such as chemical grade methanol, would be a one of first contenders as a substitute for diesel fuel.

This transition to methanol based fuel has achieved success, with a significant and growing number of methanol fuelled ships in the market and on order.

The methanol with diesel pilot approach for marine applications has some drawbacks:

- Two fuel supply chains are required from supply point to end user
- Exhaust quality remains impacted by the use of diesel fuel
- The proportion of diesel can be highest when the ship enters emission control areas, forcing owners to take an expensive abatement step

Gane fuel by contrast represents an opportunity for a single fuel supply chain to the customer, with lower exhaust emissions reducing or in some cases eliminating the need for expensive exhaust after-treatments in order to meet regulated emissions limits.

The motivations behind the development of a methanol based alternative fuel were to utilize methanol for HD ICE to at least match diesel fuel engine performance with improved emissions, and which could provide the capability to meet progressively tightening emissions standards. In addition to these primary motivations identified at an early stage of fuel development, other important aspects have been gaining prominence

- A potential for the fuel to be fully renewable, i.e. carbon neutral to reduce the contribution of HD ICE fuel use to global warming
- The possibility to significantly reduce or completely eliminate black carbon emissions normally associated with production and combustion of higher carbon transport fuels such as diesel and bunker fuel and their associated global warming impact
- The capacity to retrofit existing engines to immediate begin to reduce exhaust emissions - this being facilitated by fuel system changes such as fuel pump and injectors, not structural change to engine block or cylinder heads of heavy duty or other commercial CI engine in the market
- The opportunity for enhanced engine performance and emissions improvements as CI engine designers find ways to make best use of methanol based alternative fuel's physical, thermodynamic and chemical properties
- The reduction of peak combustion temperatures using nil carbon-carbon bond Methanol, water and DME leads to reduced NO2, particulate and soot emissions.

The fuel components working together that have the ability to enable Gane fuel to meet the foregoing objectives, are methanol, water, dimethyl ether, and additives, each playing an essential though different part in the overall performance of the fuel. The discussion which follows is focused on Gane fuel producing lowest emissions, with engine performance and BTE equal to or better than with diesel fuel.

Cleaner fuels for CI engines are more of a necessity today, than ever before, with a variety of options being examined by industry. Gane fuel is one such fuel option. The ignition of Gane fuel is achieved by taking a small proportion of fuel and passing it over a catalyst to generate dimethyl ether (DME), a high cetane component, and water. The DME is directed to the inlet air of the CI engine, with co-produced water being used by the engine as part of the high-pressure fuel injection. The unit that carries out the conversion of methanol to DME is the DME production unit (DPU), an integral part of the combustion of Gane fuel in various "on-board" diesel applications. The combination of Gane fuel with DPU offers the following benefits to diesel engine users.

- Single fuel delivery
- Renewable fuel capable of high GHG reduction
- No change to base engine required
- No by-products to deal with
- Diesel-like combustion performance
- Viable operation across full engine map
- Soot free, low NOx low particulates exhaust, no soot-efficiency trade-off
- Can be used in a wide variety of diesel engine applications
- Methanol, due to its low carbon content per unit of energy, produces less GHG at the same efficiency compared to other alcohol fuels

The combustion sequence is HCCI combustion of DME followed by diffusive combustion of the high pressure injected Gane fuel. This mode of combustion respects the principles of diesel fuel combustion, which is one reason why engine performance using Gane fuel is able to at least match the performance of diesel fuel.

Emissions of particulates are improved due to the nil carbon-carbon bond structure of methanol and DME. The high oxygen content of Gane fuel of >50% wt. may also play a role in the nil soot in the exhaust at all points of the engine map. Contributing to the reduction of high carbon species in the exhaust is the lower peak combustion temperature of Gane fuel compared to diesel.

Methanol has a cetane number so low that it cannot be measured with standard methods. That makes the use of methanol by itself unsuitable for compression ignition in a traditional CI engine. To use it as a replacement for diesel fuel with CI and keeping the advantages of diffusive lean combustion, a method to support the ignition is needed. In Gane fuel, that is realized by using DME as fumigant. The fumigant is mixed in small quantities into the inlet air. The DME concentrations required to enable compression ignition of the Gane fuel were tested and remain below the lower explosion boundary in all engine operating points. The role of the fumigant is to enable the CI combustion of methanol and not to deliver a significant share of the heat release during combustion. Therefore, the rate of DME injection was minimized for the given combustion system depending on the operating point of the engine.

Fuel operability across the widest range of engines and applications can be enhanced by the addition of additives to the fuel mixture. Lubricity improver additives have become mainstream in diesel fuel since the introduction of widespread and stringent sulfur limits. The desulfurization process of diesel removes naturally occurring lubricating compounds from the fuel which traditionally prevented wear of the fuel system. The purpose of these additives is to lubricate parts of the fuel delivery system of an engine where metal-on-metal contact exists, that cannot be lubricated with engine oil, for example, fuel pumps and injectors. Poorly lubricated fuel can have catastrophic effects to the injectors and pumps, as severe wear will eventually cause engine failure. Lubricity improvers are typically ambiphilic, the non-polar component allows solubility in the fuel, while the polar constituent adheres to the metal surfaces of the system, providing protection from wear. Methanol fuels are expected to have poorer lubricating characteristics than diesel as the (dynamic) viscosity of methanol is much lower (1.6-3.8 vs 0.545 mPas [1] at 25 ^{o}C), therefore it is expected that lubricity improvers are required to prevent damage to the engine and ensure protection from wear in the long-term. The Lubricity Improver used within this study is a bio-derived surfactant, developed by Infineum for use specifically with methanol fuel.

Lubricity test results of various combinations of methanol, water and lubricity additive were determined, along with diesel fuel using an identical method. A variety of fuel compositions with lubricity improver additive were tested for phase stability over a range of temperatures which included severe freezing conditions.

2 GENERAL DISCUSSION

2.1 Fuel Considerations

The components of Gane fuel as tested and reported below comprise methanol, water, DME and lubricity improve (LI) additive. The impact of the components of Gane fuel and how they contribute to the overall fuel performance is described,

Table 1. Fuel properties of the tested blend

Property	Unit	Result
UHV	MJ/kg	20.4
LHV	MJ/kg	17.7
Density@15C	kg/l	0.8256
Density@20C	kg/l	0.8214
Density@25C	kg/l	0.8171
%Carbon	%m	33.7
%Hydrogen	%m	12.4
MW	g/mol	29.7

Water	%m	10.2
Methanol	%m	89.7
Lubricity Gane fuel@25C HFRR	um	220
Lubricity Diesel fuel@25C HFRR	um	250
Lubricity Diesel fuel@60C HFRR	um	440
NACE Rust Test TM-01-72	Rating	B++

2.1.1 DME

The presence of DME is central to the performance of Gane fuel, due to its excellent ability to trigger ignition of high pressure injected low cetane methanol/water, even under conditions of extreme dilution at high lambda high rpm and low load. Bench testing on a turbocharged 12-liter Liebherr series production diesel engine for Gane Energy by IAV GmbH in Berlin demonstrated the efficacy of DME in meeting its task to ignite a 90/10 methanol/water mix across the full engine map. (refer Fig 1)

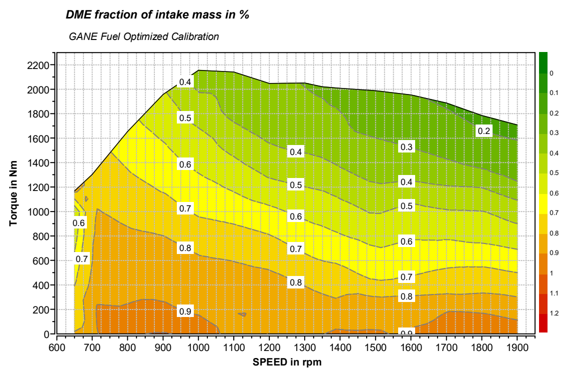

Figure 1. DME mass as a percentage of the total mass intake into the engine

The above chart demonstrates the capability of DME to ignite Gane fuel which included 10% water across the full map, points of note being

- The DME as a proportion of total mass flow into the engine was less than 1.0% mass. at any point of the map
- On the full load curve, the % DME required was approximately 0.2% m from 1500 to 1900 rpm, 0.3% m from 1000 to 1400 rpm and from 0.8% m to 0.5% m. from 650 rpm to 900 rpm
- Stable combustion was achieved at all load points tested on the map
- The highest DME flow was required at high RPM and low load
- The % of DME required to achieve ignition is well below the lower flammability limit of DME in air of 3.4% [2] vol or 5.3 % m.

A second fuel composition was tested with 82%m methanol and 18%m water using DME as ignitor with no difficulty experienced.

In addition to the points listed above, DME can contribute to improved diesel engine operation as follows

- Low toxicity
- Ability to enable cold start of Gane fuel down to freezing temperatures
- Requires a minimum concentration to initiate combustion in each cylinder.
- For single point DME injection, e.g. into the air path upstream of the air inlet manifold, the total DME required will be set by the weakest igniting (e.g. coolest) cylinder.
- For multipoint injection of DME, with an injector for each cylinder, tuning of injected quantities can reduce oversupply to hotter cylinders, minimizing the overall DME consumption of an engine.
- As an ignitor of Gane fuel, DME, can be produced from a small portion of the methanol in Gane fuel.
- For transient engine operating conditions some additional DME is required compared to steady state DME requirements, with no loss of performance compared to diesel. Severe transients such as seen in the WHTC emissions cycle can be met using DME as ignitor.
- DME use as fumigant may be further reduced compared to what is shown in Fig 1 by incorporating additional steps as follows:
    - Using air temperature adjustment under appropriate load conditions to reduce DME flow into the engine, in some cases to zero.
    - Injecting as fumigant an appropriate mixture comprising DME and methanol to reduce the engine's need for DME

The DME can be added to the intake air as gas or liquid, for the test results reported herein gas phase injection was used. This choice was made mainly due to restrictions concerning the available flow metering hardware for DME and to decrease the effort of modifying the engine.

2.1.2 Methanol

Of the alcohol fuels, methanol has some unique properties that distinguish it from C2 and heavier alcohols.

- Methanol is the most polar alcohol, with a strong affinity with water. This interaction results in shrinkage of the overall volume when water is added to methanol to a point of maximum shrinkage, after which shrinkage declines as additional water is added. The shrinkage effect increases the fuel density compared to what may be expected from linear blending considerations.

- When DME of lower polarity is added to the methanol water mixture, the ternary solution is less accommodating of DME in the liquid, increasing vapour pressure of the mixture nonlinearly with respect to DME.

- Has high octane sensitivity, demonstrating its stability and resistance to ignition under low and medium stress while showing increasing willingness to ignite and combust as thermal and free radical stressors gain strength under compression. Such behaviour is a good match with Gane fuel HCCI combustion of DME controlling ignition, with mild ignition of dilute DME acting as ignitor of the high pressure injected fuel late in compression stroke. Such an approach should enable high or low compression ratio engines to be used with appropriate dosage and purity of DME as ignitor

- Methanol has s favourable carbon intensity (at the same efficiency) compared to Diesel fuel. see Table 2 below.

Table 2. Non-renewable fuels vs diesel

Fuel		MeOH	Diesel 1)	Gane fuel 10%wt 1)
carbon fraction	wt/wt	0.375	0.859	0.337
LHV	GJ/t	20	42.74	17.7
carbon %/LHV	%/GJ	1.88	2.01	1.90
Carbon comparison (Diesel = 100)		93.3	100.0	94.7
CI reduction % vs diesel		-6.7	0.0	-5.3

1) Carbon fraction, LHV from lab analysis.

Table 2 shows that at the same BTE non-renewable methanol with 6.7 carbon intensity reduction and Gane fuel with 10% water has a 5.3 % carbon intensity reduction, compared to EN590 B7 Diesel fuel as the zero baseline.

Table 3. Renewable fuels vs MDO

	MeOH	EtOH USA	EtOH cellulosic	MDO
Renewable gCO2/MJ fuel	13 [3]	63 [4]	31 [4]	78 [3]
Carbon comparison (Diesel = 100)	16.7	80.8	39.7	100.0
Carbon reduction % vs diesel	-83.3	-19.2	-60.3	0.0

Table 3 shows that when a highly renewable alcohol such as methanol substitutes non-renewable MDO diesel the carbon reductions is 83.3%. Based on the similar carbon%/LHV ratios shown in Table 2, there is minimal difference in carbon reduction between pure methanol as a fuel and Gane fuel including 10% water.

2.1.3 Water

Water and methanol have a high degree of compatibility at all concentrations, each molecule though small, has high polarity with correspondingly high boiling points. The result is a mixture that does not require pressurisation or refrigeration to remain a liquid under ambient conditions.

It may be expected that water would have a negative effect on engine efficiency at all concentrations, soaking up sensible and evaporative heat out of the combusting fuel air mixture and lowering in-cylinder combustion temperature. Such expectations of negative impact on efficiency are true in many circumstances but not all.

Gane has found that introducing water with fuel under high pressure and igniting the mixture along with DME fumigant leads to definite reduction in NOx and can simultaneously lead to an increase in BTE.

While some applications such as ships have ready access to water using desalination techniques, some other applications do not, being remote from any water source. Such cases will obtain their water for Gane fuel by other means including recovery of dehydration reaction water or use of co-produced water with fuel methanol production. It may not be economical to create a separate purified water supply chain to blend with methanol.

2.1.4 Additive

Refer to section 5.1

3.1 DME Production Unit (DPU)

The DME Production Unit is a gas phase unit for conversion of the methanol in Gane fuel to DME. It enables customers to receive a single methanol-based fuel, without requiring a diesel pilot fuel. The DME produced by the DPU may be injected into the air path in the gas or liquid phases as single point or multipoint injection, to achieve ignition of the high pressure injected main fuel.

The key features of the DPU design are

- Robustness of the design to maximise longevity of the catalyst, enhancing unit reliability.
- Heat to drive the unit will preferably come from exhaust gas waste heat.
- Lower peak temperature of less than 250 °C and maximum operating pressure of 10 bar targeted.
- Varying conversion rates of DME acceptable.
- Tolerant to a wide range of climatic conditions.
- Use of non-precious metal conversion catalyst, with lower conversion temperature targeted.
- Providing means to incorporate the co-produced water from the dehydration reaction into the fuel supplies to the engine.

3.1.1 DPU design overview

The design of the unit takes account of the following considerations:

- The supply of DME to the engine must have high reliability in terms of quality and reliability of supply.
- Varying conversion rates for DME acceptable.
- Providing means to incorporate the co-produced water from the dehydration reaction into the main fuel supply to the engine.
- Being capable of producing high quality DME. A stable and consistent DME quality will provide a good platform for reliable engine ignition.
- Separating a variety of species present in the feed using difference in boiling point, and injecting those species into the high pressure fuel supply to the engine. One such species is lubricity additive which is discussed in Section 5.1.

3.1.1 DPU Schematic

The schematic for the DPU is shown if Figure 2.

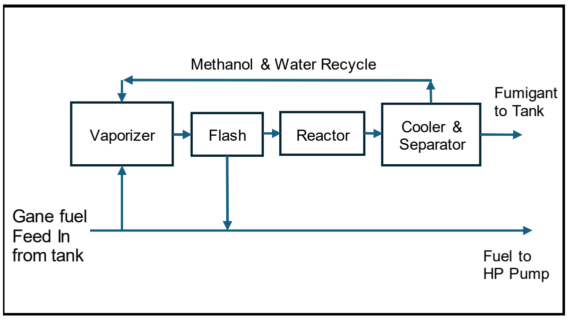

Figure 2. DPU Main Equipment Items

The DPU functions as follows:

- A small stream of ~5% of Gane fuel to engine is fed to the DPU.
- A heat exchanger heats up this stream to vaporise it.
- The vaporised stream enters a flash vessel to separate light overheads (predominantly methanol) from heavy bottoms (predominantly water & additive).
- The overheads stream enters the reactor containing the catalyst, where the methanol is converted to DME and water.
- The water-rich bottoms are fed to the engine's HP pump and integrated with the HP injection of the main fuel.
- The output from the reactor goes through a cooling and condensation process to maximise DME percentage in the final product stream.
- The DME-rich output stream is then cooled to liquid phase and injected into the engine or stored in a separate tank which is used for start-up and transient accommodation.

The recycle stream in Figure 2 shows the pathway for unreacted methanol to return to join the fresh Gane fuel feed from storage.

3.1.2 DPU Fumigant Composition

The design requirement of any DPU would include targets including fumigant production rate and DME purity.

The injected fumigant may not need to be a high purity DME and there are various means provided in the DPU design which enables an increase in the proportion of methanol relative to DME, and also have some impact on the water content of the fumigant.

- Lowering conversion in the reactor in order to increase the proportion of methanol in the fumigant
- Adjustments withing the cooling and separation step to allow more methanol into the DME-rich product stream used for fumigation and/or
- Combine Gane fuel from the tank with the DME-rich stream for use as fumigant

Table 4. Fumigant composition options for ignition of Gane fuel

Fumigant Purity	DME range %	Water range %	MeOH range %
High	90 - 97	0.5 - 4	2.5 - 6
Medium	75 - 89	4 - 10	7 - 15
Low	60 - 74	10 - 20	16 - 20
Reactor Out 80% conversion	52	30	18
Reactor Out 64% conversion	42	26	32

Fumigant purity required to be confirmed by test/simulation based on application and relevant operating conditions

Table 5. 97% DME - Base Fumigant Properties

% Conversion		80	64
H_2O	mass%	0.5	0.3
MeOH	mass%	2.8	3.5
DME	mass%	96.7	96.2
Lubricant	ppm mass	0.0	0.0
Mass Density	kg/cum	673.4	674.0
Molar Density	kmol/cum	14.9	14.9
Bubble point temperature	C	17.7	17.7
Dew point temperature	C	43.6	43.0
Critical temperature, mixture	C	134.3	134.6
Critical pressure, mixture	bar	56.7	56.5
Critical volume, mixture	cum/kmol	0.2	0.2
Critical compressibility factor, mixture		0.3	0.3
Net heating value	kJ/kg	28.4	28.4
Bubble point pressure	bar	4.9	4.9
Dew point pressure	bar	1.4	1.5
Reid vapor pressure, ASTM method	bar	7.8	7.7
Molecular weight, mixture		45.2	45.1

From Table 5 it is evident that a consistent and high-quality fumigant is produced from the simulation model

3.1.4 DPU Process Simulation results

The qualities the DPU input and output streams achieved during simulation runs are shown in Tables 6 and 7.

Table 6. High DME Conversion (80%)

Stream	MeOH %m	Water %m	DME %m	RVP (kPa)
Fuel Feed ex Tank	91.9	8.0	0	32
DME fumigant to Engine	2.8	0.5	96.7	
Fuel to Engine High Pressure Pump	88.8	11.1	0	31

Table 7. Low DME Conversion (64%)

Stream	MeOH %m	Water %m	DME %m	RVP (kPa)
Fuel Feed ex Tank	91.9	8.0	0	32
DME fumigant to Engine	3.5	0.3	96.2	
Fuel to Engine High Pressure Pump	88.8	11.1	0	31

It can be seen that the DME fumigant quality changes to a small extent falling from 96.7% to 96.2%, and water decreases from 0.5 to 0.3%. At lower conversion the methanol content of fumigant increased by 0.7%, from 2.8% to 3.5%.

Other points of note from the above tables are

- The water content of feed to the high-pressure pump increased by 3% compared to the Gane fuel feed, rising from 8 % to 11% wt. This water increase was due to
    - A concentration of water in feed to the high-pressure pump due to the concentrating effect of removing an essentially water free fumigant stream
    - Recovery of dehydration reaction water to HP pump feed
- The RVP of feed to the HPP was a little lower than Gane fuel feed due to
    - Displacement of methanol by water due to inclusion of dehydration water
    - Effective removal of DME from dehydration water prior to its inclusion with HPP feed

As a result of the process simulations, the following points can be a stated regarding the Gane DPU design

- Variable catalyst conversions levels can be accepted while producing the required fumigant without the production of unwanted by products
- The fuel volatility into the high-pressure pump can be reduced to a small extent due to the added presence of catalyst dehydration water in fuel to the HPP with accompanied by trace amounts of DME

4.1 Engine Testing

To test the properties of Gane fuel on a complete engine, a suitable Diesel engine was chosen and tested under steady state and transient conditions with Diesel fuel as reference. Subsequently the same engine was retrofitted to operate on Gane fuel. The target was to match the power density of the Diesel engine and compare emissions and thermal efficiency of both fuels. Additionally, the mechanical wear and corrosion on the engine were assessed after testing in a tear-down analysis to identify the potential weak points in operation with Gane fuel.

The tested blend of Gane fuel has a lower heating value significantly less than half of Diesel fuel. As reference Diesel fuel EN590 B7 was chosen as standard EU pump quality. To keep the power density and thermal efficiency on the level of the Diesel combustion system, the injection rates with Gane fuel need to be significantly raised. To achieve that, a modified set on high pressure injectors was installed on the engine with high flow capacity. The design target for the nozzle flow of the high-flow injectors was to match the duration of combustion with Diesel fuel at rated power. At the same time, the maximum injection pressure was lowered in Gane fuel operation to 1000 bar. That resulted in a nominal nozzle flow raised by roughly factor 3.5 compared to the standard injectors of the engine. The engine's series standard and the modified injection system were supplied by Liebherr-Components Deggendorf GmbH.

Table 8. Engine properties

Parameter	Value	Unit
Engine type	Diesel D946 A7-04	-
Cylinder	6	-
Cycle	4 stroke	-
Displacement	11.95	Liter
Stroke	150	mm
Con rod length	237	mm
Bore	130	mm
Compression ratio	17.5	-
Power	334 / 354 / 404	kW
Rated Speed	2,100 / 1,900	1/min

To ensure proper mixture of the DME with the inlet air a static mixer was installed downstream of the DME injection point and upstream of the intake manifold. The DME was injected gaseous and with continuous flow.

The testing setup underwent several modifications. The final setup with exhaust after treatment is shown in Figure 3. The catalysts of the exhaust after-treatment system were supplied by BASF. The emission quality was assessed with a wide range of measuring equipment consisting of a standard exhaust analyzer rack, partial flow dilution tunnel, condensation particle counter, and an FTIR analyzer.

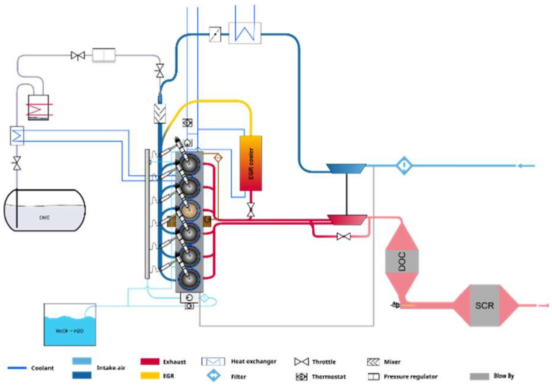

Figure 3. Engine testing setup

The calibration of the combustion and after-treatment relevant parameters of the engine's ECU was fully optimized for Gane fuel operation. The DME injection control was realized with a separate ECU that communicated with the engine's ECU via J1939 CAN bus protocol.

4.2. Engine Test Results

4.2.1 Combustion

The DME burns with homogeneous charge compression ignition (HCCI) and its start of combustion cannot be controlled independently. Its combustion phasing depends on the thermal conditions in the cylinder. The directly injected main fuel, consisting of a blend of methanol, water, and the lubricity additive, burns with (assisted) compression ignited lean diffusive combustion like Diesel fuel. That makes it robust against irregular combustion like knocking or premature ignition. Figure 4 shows the in-cylinder pressure traces as well as the heat release for Diesel and Gane fuel combustion at rated power. The reference data from Diesel combustion was taken from the high-efficiency operating mode of the engine in its Tier 4 configuration without EGR.

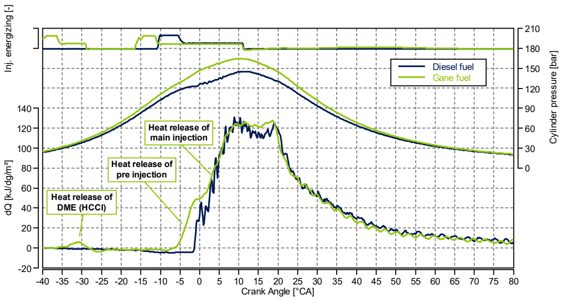

Figure 4. Combustion at rated power

As can be seen in Figure 4, the injection pattern was adapted for Gane fuel operation, using a pilot injection, while the Diesel engine ran with a single injection in the same operating point. The heat release rates of both fuels are well matching, showing that the design goal for the injector nozzles was achieved. The fumigant shows a heat release far ahead of top dead center, raising the pressure and temperature in the cylinder assisting the ignition of methanol. Additional to its low cetane number, the much higher injection quantity and enthalpy of evaporation of the methanol/water blend leads to a longer combustion delay. With an advanced injection timing compared to the Diesel baseline this could be countered to have a similar start of combustion. The calibration with Gane fuel was optimized for efficiency at a target NOx emission of 2 g/kWh engine out which is roughly 20% of the Diesel engine's value in the same operating point.

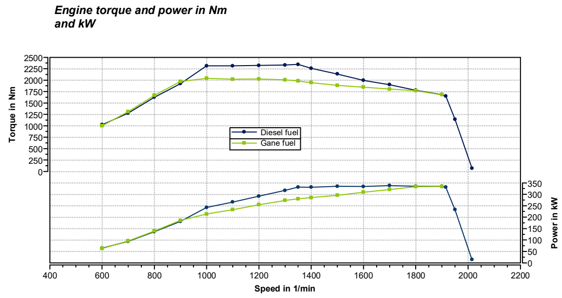

Figure 5. Full load curves with both fuels

Figure 5 shows that the rated power of the Diesel engine at 1900 1/min could be matched with Gane fuel while the torque plateau was lower. At engine speeds below 1800 1/min the capacity of the high-pressure pump was not sufficient to deliver the required flow with Gane fuel. Therefore, the injection quantities needed to be limited to suitable levels with some reserve for transient pressure control. Typical boundaries limiting the torque like exhaust temperature, peak firing pressure, turbocharger speed and others were not touched so it is expected that the full load curve could be matched with a higher capacity high-pressure pump.

Figure 6 shows that the BTE could be increased or matched in major areas of the engine map with Gane fuel. In general, the combustion settings optimized for Gane fuel were very similar to the Diesel calibration. That shows that the combustion system, which was carried over from the Diesel engine, works similarly well with Gane fuel making retrofitting of Diesel engines or producing variants with the same engine hardware simpler.

The areas with reduced BTE suffer from a higher DME share at low load and slower combustion. The optimization of the DME injection system with more precise metering could help to raise the BTE in that area.

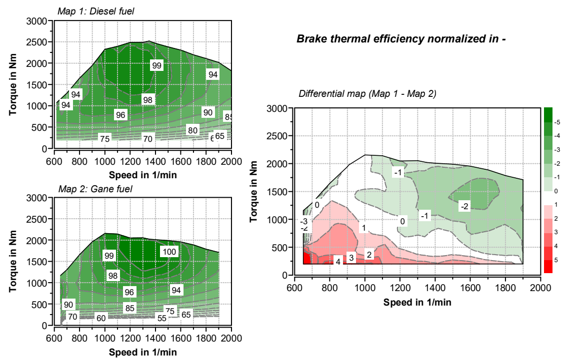

Figure 6. Normalized BTE across the engine map

4.2.2 Emissions

The emissions with both fuels were measured and assessed regarding regulated criteria pollutants, non-regulated pollutants specific to alcoholic fuels, and greenhouse gases. Gane fuel showed a strong reduction in NO_x and PM emissions at the same time. While NO_x output was reduced by roughly 80% in average across all engine operation, black carbon soot could not be detected. PM measured gravimetrically was significantly reduced and is likely consisting of unburned hydrocarbons due to the absence of soot. Additionally, the installation of an oxidizing catalyst further reduced the PM values towards the detection limit. The particulate numbers were reduced by almost a factor of thousand with Gane fuel. The absence of soot was also used to optimize the transient load response of the engine as temporary low air-fuel-ratios did not lead to soot emission peaks. The achieved transient load response was equal and partially better compared to Diesel operation. Figure 7 shows the typical spread between transient and steady state PM emissions in various legislative emission cycles for a Diesel engine. The transient PM penalty is not visible with Gane fuel.

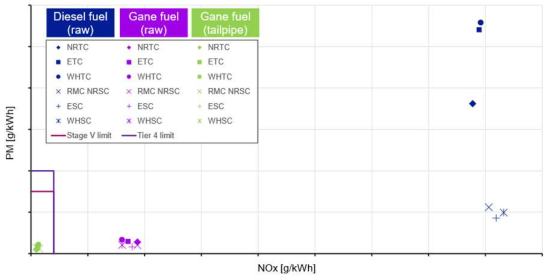

Figure 7. PM and NOx emissions in various legislative emission cycles

Other emissions of incomplete combustion such as CO and THC are higher with Gane fuel engine out. The trend is towards higher CO and THC emissions at low load and almost complete combustion at full load. It could be tested that a large part of the CO emissions results from HCCI combustion of DME. Both emissions could be treated close to detection limit with the oxidation catalyst similar to a Diesel engine.

Methane emissions, which cannot be treated by a catalyst in the exhaust temperature range of a Diesel engine, are of special interest as methane is a high-impact greenhouse gas. With Gane fuel very low levels of methane could be detected at low engine load and in overrun conditions. That makes it likely that similar to CO also methane is mostly a product incomplete DME combustion and oxidized at higher in-cylinder temperatures by the combustion of the main fuel. Methanol-specific emissions such as unburned methanol and formaldehyde can be seen measured in a hot NRTC cycle in Figure 8. The engine out and tailpipe concentrations are plotted showing that the OC was able to almost completely convert the low level of raw emissions to virtually zero emissions at tailpipe.

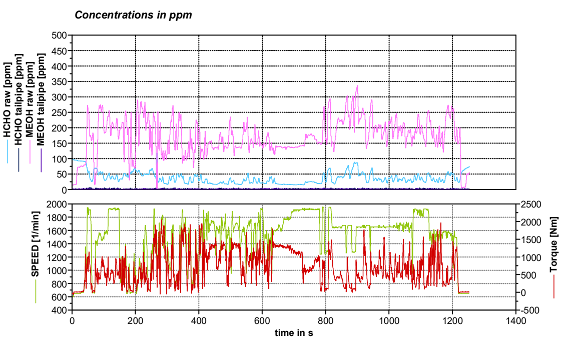

Figure 8. Alcohol-specific emission concentrations

5.1 Lubricity Improver Tests

5.1.1 Stability Test

The evaluated material was stored at selected temperatures over a period of time and examined at prescribed intervals for signs of product instability. Measurements were a visual assessment of the sample. Volumetrically graduated glass centrifuge tubes of 100 ml capacity were used, with the first graduation not exceeding 0.05% vol. The centrifuge tube must be of such quality that the graduations are distinguishable enough to be read (the most important graduations being at the bottom of the tube) with the tube in a clean condition without deposits. Stoppers of cork or rubber were used to prevent water ingress from condensation. Test temperatures of 20, 0, -15 and –30 °C were used in this test with calibrated refrigerator(s) or freezer(s) capable of maintaining the selected temperatures to ±5°C throughout the 28-day test period. 100 ml of the prepared sample for testing was poured into a glass stability tube and placed in the refrigerator at the desired temperature. For samples at 20 °C these were placed on a bench in a dark, dry room, maintained at 20 °C +/- 5 °C. Observations of the conditions of the sample were taken after 24 hours, 7 days, 14 days, 21 days, and 28 days at the specified temperature. If a sample was observed as “C &B”, this denotes “Clear and Bright” meaning the markings on the opposite side of the stability tube were clearly visible under natural light. “Sed” or “Sediment” refers to hard, solid particles which have collected at the very bottom of the stability tube.

5.1.2 HFRR Test

A test method to determine the lubricity of various methanolic fuels was developed based on ISO12156 (Assessment of lubricity of diesel fuel). Modifications were made for use with methanol fuels, due to its toxicity, volatility, and flash point. A gasoline conversion kit was needed to reduce evaporation, and the rig was moved into a well-ventilated area. The test parameters are shown in Table 9.

Table 9. Parameter Table for the modified methanol HFRR test used in this paper.

Parameter	Value
Fluid Volume, ml	15 ± 0.2
Stroke Length, mm	1 ± 0.02
Frequency, Hz	50 ± 1
Fluid Temperature, oC	25 ± 2
Test Mass, g	200 ± 1
Test Duration, min	75 ± 0.1

Reservoir Surface Area, mm2	1470 ± 100

Further information on the lab air conditions, apparatus, sampling, preparation, and calibration can be found within the energy institute publication, IP PM FK: Methanol fuel – Assessment of lubricity using the high-frequency reciprocating rig (HFRR). Samples were prepared and measured in accordance with this method. The method used herein this paper complies with IP PM FK and its test duration and test mass are consistent with the original well-established diesel test method ISO12156.

In an overview of the test, a sample of the fuel under investigation was placed in a reservoir maintained at a constant temperature of 25°C. A steel ball, fixed within a vertically mounted chuck, was pressed against a horizontally mounted stationary steel plate using a predetermined load. The steel ball was subjected to oscillatory motion at a fixed frequency and stroke length, ensuring that the interface between the ball and the plate remained fully immersed in the test fluid throughout the experiment. The metallurgies of the ball and plate, test fluid temperature, load, frequency, stroke length, and the ambient air conditions of temperature and humidity during the test are specified. The wear scar generated on the test ball was measured digitally using a microscope post-experiment and used as an indicator of the lubricity of the fuel sample. One instance of this test will record the wear scar components in the X and Y direction on the ball bearing, then average them to get one result. The values in this paper are averages of at least 2 instances of the test.

5.2 Lubricity Improver Results

5.2.1 Stability Results

10 methanol fuels were prepared to investigate the effects of varying amounts of methanol (0-80%), water (0-20%), inorganic chloride (0-10 mg/kg), and lubricity additive (0-1000 ppm) in the fuel. Table 10 below shows the contents of each of the fuels. The inorganic chloride was added to samples 5 and 5a using a chloride solution of known concentration.

Table 10. Fuel compositions for this study

Fuel No.	MeOH %m	Water %m	Cl – mg/kg	Lubricity Improver ppm
1	>99.85	0.021	<0.3	-
1a	>99.8	0.021	<0.3	1000
2	80.5	19.5	<0.3	
2a	80.5	19.5	<0.3	1000
3	90.2	9.75	<0.3	
3a	90.2	9.75	<0.3	1000
4	95.2	4.75	<0.3	
4a	95.2	4.75	<0.3	1000
5	90.3	9.675	10.2	
5a	90.3	9.675	10.2	1000

[a]Methanol results are estimates based on the remaining content of the fuel, and as a result are accurate to +/- 0.2%.

[b]Water % is measured using ASTM E1064,

[c]Inorganic Chloride content is measured using IMPCA 002 method.

The full stability results for the 10 fuels can be found in Table 11.

Table 11. Stability sedimentation test results by temperature, in mL of a 100 mL fuel sample

Fuels (1-5a)	Temp. deg C	Day 7	Day 14	Day 21	Day 28
All	20	0	0	0	0
All	0	0	0	0	0
All	-15	0	0	0	0
1-2 & 3-5a	-30	0	0	0	0
2a	-30	<0.05	<0.05	<0.25	<0.25

'0' means Clear & Bright appearance without deposition. Numbers given are mL in 100 ml sample.

Firstly, at test temperatures of 20, 0, and –15 ^{o}C, all samples remained “clear and bright” over the 28-day test period. No observable dropout, phase separation or haziness in the fuel was observed for these samples. At –30 ^{o}C, all but 1 sample remained “Clear and Bright” for the full 28-days. Fuel sample **2a**, containing the additive with the highest water content of 20%, showed <0.25 ml sediment after 28-days. The solid sediment is thought to be the lubricity additive, although further testing was not carried out to determine this conclusively. The results show that methanol fuels with a water content of 20%, containing lubricity additive with treat rates up to 1000 ppm, are stable at temperatures down to –15 ^{o}C, however the fuels should not be stored or handled below this as the lubricity improver will precipitate from the fuel. Samples with water contents between 0-10% have no compatibility issues with the fuel additive and can be stored at –30 ^{o}C for 28 days without any observable change. Finally, it was noticed that high chloride contents of 10 ppm made no observable impact to the stability performance of the fuel, both in the presence of the additive and without. Therefore, high chloride content methanol fuels have the same low temperature stability performance as low chloride content methanol.

5.2.2 HFRR Results

The lubricity of Fuels 1 to 5 were tested using the HFRR test described in Section 5.1.2. The composition of these fuels is repeated in Table 12 below, along with the average HFRR result obtained for each fuel.

Table 12. Fuel compositions for this study

	Methanol	Water	Cl -	Lubricity Improver	HFRR	HFRR Reduction
	%m	%m	ppm	ppm	µm	%
1	>99.85	0.021	<0.3	0	461	
1a	>99.8	0.021	<0.3	1000	200	56.6
2	80.5	19.5	<0.3	0	579	
2a	80.5	19.5	<0.3	1000	235	59.4
3	90.2	9.75	<0.3	0	684	
3a	90.2	9.75	<0.3	1000	232	66.1
4	95.2	4.75	<0.3	0	656	
4a	95.2	4.75	<0.3	1000	260	60.4
5	90.3	9.675	10.2	0	609	
5a	90.3	9.675	10.2	1000	239	60.8

[a]Methanol results are estimates based on the remaining content of the fuel, and as a result are accurate to +/- 0.2%.

[b]Water % is measured using ASTM E1064,

[c]Inorganic Chloride content is measured using IMPCA 002 method.

To compare the lubricity results of the methanol fuel samples with that of an on-spec diesel fuel, representative sample **SC-1** was analysed using the HFRR test (see experimental), yielding a wear scar of 466 µm, using ISO 12156-1, a standing marine fuel lubricity test. This result is below the target of 520 µm for marine distillates, set by ASTM D975, however, is on the boundary of the EN590 ULSD specification for on-road diesel fuel, which is 460 µm. This indicates a fuel sample with the maximum wear-scar to still comply with all diesel fuel lubricity specifications. The same sample of **SC-1** was then examined in the modified HFRR test described in Section 2. used for all methanol fuels in this study, giving a wear scar result of 242 µm. This indicates that to achieve 'diesel-like' lubricity in the modified HFRR test, a wear scar of 242 µm or less is required and will accordingly be used as a benchmark for lubricity additives in methanol fuel.

With a standardized method developed, fuels **1-5** were examined using the modified HFRR (Table 12). The fuels can be split into 2 categories, those without the Infineum lubricity additive, and those with. As expected, the former category did not meet the target lubricity measurement of ≤242 um) with wear scars ranging between 461-684 µm.

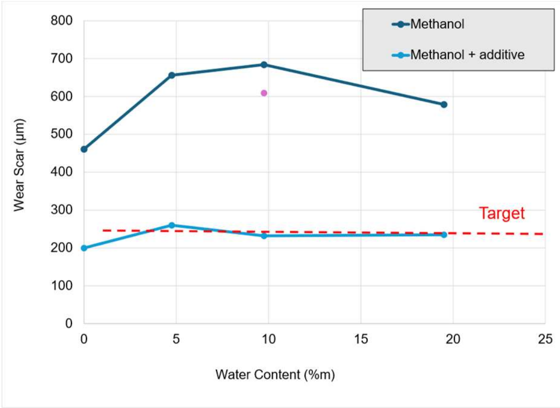

Figure 9. Wear Scar µm vs Water content %m @ 25 °C, without lubricity improver (dark blue), as well as 1000ppm lubricity additive (light blue). The data point in pink is 10 ppm Chloride, without additive. All data was generated using the modified HFRR test.

Of particular note, fuels **2-5** yielded wear-scars more than double the required target indicating poor lubricity, likely to be ascribed to their high water content (5-20%). Furthermore, when comparing the performance of fuels **3** and **5,** a significant reduction of wear scar is observed from 684µm to 609µm by the inclusion of 10 ppm of inorganic chloride. It is known that heteroatoms, such as sulphur and chloride, improve the lubricity of diesel fuels, and these results show the same is true in methanol fuel. Pleasingly, the corresponding HFRR results for all the additised fuels (**1a-5a)** were below the 242 µm target, except for **4a**, which was slightly higher at 260 µm, yet still within error. Increasing the chloride content of the fuel from <1 ppm to 10 ppm, in the presence of the additive had no noticeable effect on the resulting wear scar of the ball bearing with both results being between 230 –240 microns. The significantly improved result in both cases is due to the high concentration of lubricity additive, in relation to the chloride, overriding the small lubricity impact of the chloride species, therefore demonstrating that chloride ions do not impact the ability of the lubricity additive to protect the metal surface. Fuel **1a** had the best lubricity performance, with a wear scar 32 µm smaller than the next best performing additised fuel, suggesting peak lubricity additive performance in high purity methanol (>99.8%) with only residual water content. To summarise, 1000 ppm of lubricity additive is effective at reducing friction in methanol fuel below a standardised baseline, even with up to 20% water content and in the presence of chloride ions.

The effect of the lubricity additive in terms % wear scar reduction was greatest on water-containing fuels, all achieving higher % wear scar reduction compared to the low water fuel 1/1a. The % wear scar reduction was greatest for fuel 3/3a with 9.75% water at 66.1 %, a 9.5% improvement compared to fuel 1 at 56.6%. Figure 9 shows that blend 2 with 19.75% water had the lowest wear scar for non additised fuel blends 2,3,4 and 5. This may be contributed to by the increasing mixture viscosity at higher water concentration in this water concentration range. The wear scar results for 2a, 3a, 4a and 5a were all similar and close to diesel fuel, and seemingly independent of either the non-additised base wear scar result, or the varying water contents in the 5 – 20%m range.

3 CONCLUSIONS

Methanol based Gane fuel has been extensively tested in a 12-liter CI engine with engine performance comparable to diesel fuel.

Emissions of key pollutants such as PM, PN, NOx and soot were substantially reduced or eliminated. Unburnt species were effectively removed with the use of an oxidation catalyst.

DME can be made from a methanol dehydration unit using a portion of the methanol in Gane fuel to ignite the high-pressure fuel injected into the engine. The DPU can deliver high target DME purity.

The DPU does not require chemical grade methanol, and can accommodate high water levels and the presence of other species such as lubricity improver.

Acceptable engine operation was achieved at all load points and in six standard emissions cycles, including three transient cycles.

The extensive engine testing included the use of a lubricity improver which demonstrated its effectiveness over a range of water contents to 20%. Research carried out by Infineum proved that at the 1000 ppm level, Gane fuel can achieve a consistent HFRR result close to or marginally less to that of baseline diesel fuel.

28-day additive stability test demonstrated the lubricity improver was stable in all test blends down to minus 30 deg C, with the excepting of a 20% water blend where phase separation became evident at minus 30 deg C. For the 20% water blend the 28 day stability test was positive down to minus 15 deg C, the 5% and 10% water blends proved to be stable with no separation evident for 28 days at minus 30 deg C.

4 GLOSSARY

Table 13. Acronyms and abbreviations

Acronym	Meaning
ASTM	American society for testing and materials
BTE	Brake thermal efficiency
CA	Crank angle
CAN	Controller area network
CI	Compression ignition
Cl-	Chlorine anion
CO	Carbon monoxide
CO_2	Carbon dioxide
deg	Degree
DME	Dimethyl ether
DOC	Diesel oxidation catalyst
DPU	Dimethyl ether production unit
ECU	Engine control unit
EGR	Exhaust gas recirculation
EN	Euronorm
EN590	EU standard diesel pump quality with 7% biodiesel (ultra low sulfur)
ESC	European steady-state cycle
ETC	European transient cycle
EtOH	Ethanol
EU	European union
GHG	Greenhouse gas
H_2O	Water
HCCI	Homogenous charge compression ignition
HCHO	Formaldehyde
HD	Heavy-duty
HFRR	high-frequency reciprocating rig
HP	High-pressure
HPP	High-pressure pump
ICE	Internal combustion engine
IMPCA	International methanol producers and consumers association
ISO	International standards organization
LI	Lubricity improver
LHV	Lower heating value
%m	Per cent mass
MDO	Marine diesel oil
MeOH	Methanol
MW	Molecular weight
NACE	National association of corrosion engineers
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxide
NRTC	Non-road transient cycle
OC	Oxidation catalyst
PM	Particulate matter
PN	Particulate number
ppm	Parts per million
RMC NRSC	Ramped modal cycle non-road steady state cycle
RVP	Reid vapor pressure
SCR	Selective catalytic reduction
THC	Total hydrocarbon

UHV	Upper heating value
ULSD	Ultra-low Sulphur diesel
WHSC	World harmonized steady state cycle
WHTC	World harmonized transient cycle
wt	Weight
THC	Total hydrocarbon

5 REFERENCES

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