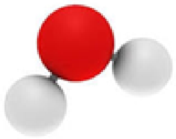

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Revision Final

Nature of the Deliverable: Report
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Contributors:
National Technical University of Athens (NTUA)
MAN Energy Solutions (MAN ES)
Wärtsilä Finland Oy (WFI)
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Work Package Leader Responsible: Nikolaos P. Kyrtatos (NTUA)

Start date of Project: 01/05/2015 Duration: 42 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020
The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 Summary

This Deliverable Report provides an overall review presentation of the HERCULES-2 Project results at the end of the Project. Following a short introduction, the main results of the Project are briefly presented on a per-Work Package basis, preceded by a brief description of the work done within each WP.

2 Introduction

In the year 2004, the Integrated Project HERCULES-A (High Efficiency Engine R&D on Combustion with Ultra Low Emissions for Ships) was initiated by the major engine makers MAN & WARTSILA, which together hold 90% of the world market. It was the Phase I of the HERCULES R&D programme on large engine technologies. The HERCULES-A, involved 42 industrial & university partners, with a budget of 33M€, partly funded by the European Union. The project was broad in the coverage of the various R&D topics and considered a range of options and technologies in improving efficiency and reducing emissions.

HERCULES-B was the Phase II of the Programme, from 2008 to 2011, with 32 participant organisations and 26 M€ budget, partly funded by European Union. The general targets for emissions and fuel consumption were retained in HERCULES-B. However, based on the developed know-how and results of HERCULES-A, it was possible to narrow down the search area, to focus on potential breakthrough research and to further develop the most promising techniques for lower specific fuel consumption (and CO2 emissions) and ultra-low gaseous and particulate emissions.

The HERCULES-C project was the Phase III of the HERCULES programme and addressed this challenge by adopting a combinatory approach for engine thermal processes optimization, system integration, as well as engine reliability and lifetime. In this way, HERCULES-C aimed for marine engines that are able to produce cost-effectively, the required power for the propulsion of ships throughout their lifecycle, with responsible use of natural resources, and respect for the environment. The project had a budget of 17M€ and was funded with 9M€ by the E.U. within FP7.

The HERCULES-2 is the next phase of the R&D programme HERCULES on large engine technologies. The project HERCULES-2 is targeting at a fuel flexible large marine engine, optimally adaptive to its operating environment.

The HERCULES-2 project takes into account: a) the increasing availability of alternative fuels and their potential contribution to the environmental and economic performance of vessels through their use in fuel flexible engines, b) the societal target of economic production of ship propulsion power with near zero emissions, c) the importance of lifetime performance optimization for new and existing ships, in the changing operational environment of global waterborne transport.

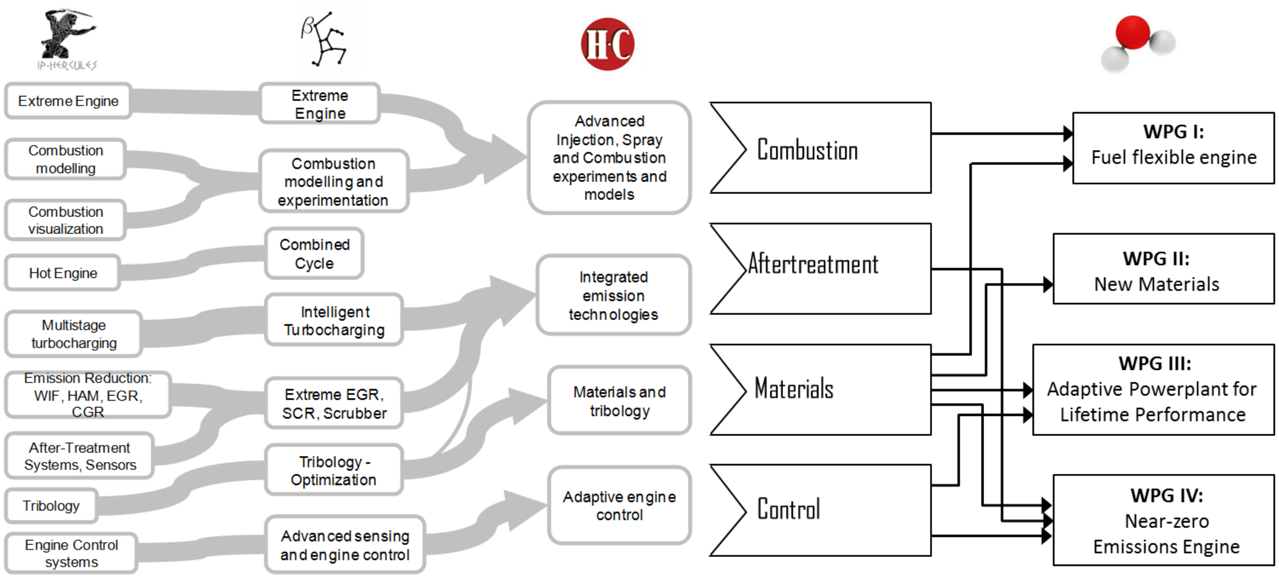


Figure 1: Links from H-A, H-B and H-C to H-2

3 General Objectives of the H-2 Project

Of all ships worldwide, 99% are powered by diesel engines ranging from 1.000 kW to 85.000 kW. Engine design and development is a multi-disciplinary activity involving thermo-fluids, combustion, mechanics, materials, dynamics and control. The main issues in marine diesel engine design and operation have always been Reliability, Fuel economy and (since 2000) Emissions. With the ongoing R&D efforts, the issue of emissions will be mitigated in the coming years, with combinations of exhaust gas after-treatment, advanced combustion techniques, new fuels and control systems. Improved engine performance, operational optimisation, health monitoring and adaptive control over the lifetime of the powerplant, are further R&D issues to ensure lifelong reliability and economy.

The objectives of the HERCULES-2 project are associated to 4 areas of engine integrated R&D:

- Improving fuel flexibility
- Formulating new materials to support high temperature applications
- Developing adaptive control methodologies to retain Lifetime powerplant performance
- Achieving near-zero emissions

The project HERCULES-2 comprises 4 R&D Work Package Groups (WPG):

- WPG I: Fuel flexible engine
- WPG II: New Materials (Applications in engines)
- WPG III: Adaptive Powerplant for Lifetime Performance
- WPG IV: Near-Zero Emissions Engine

Figure 2 is an overview of the R&D thematic areas and respective Work Package Groups.

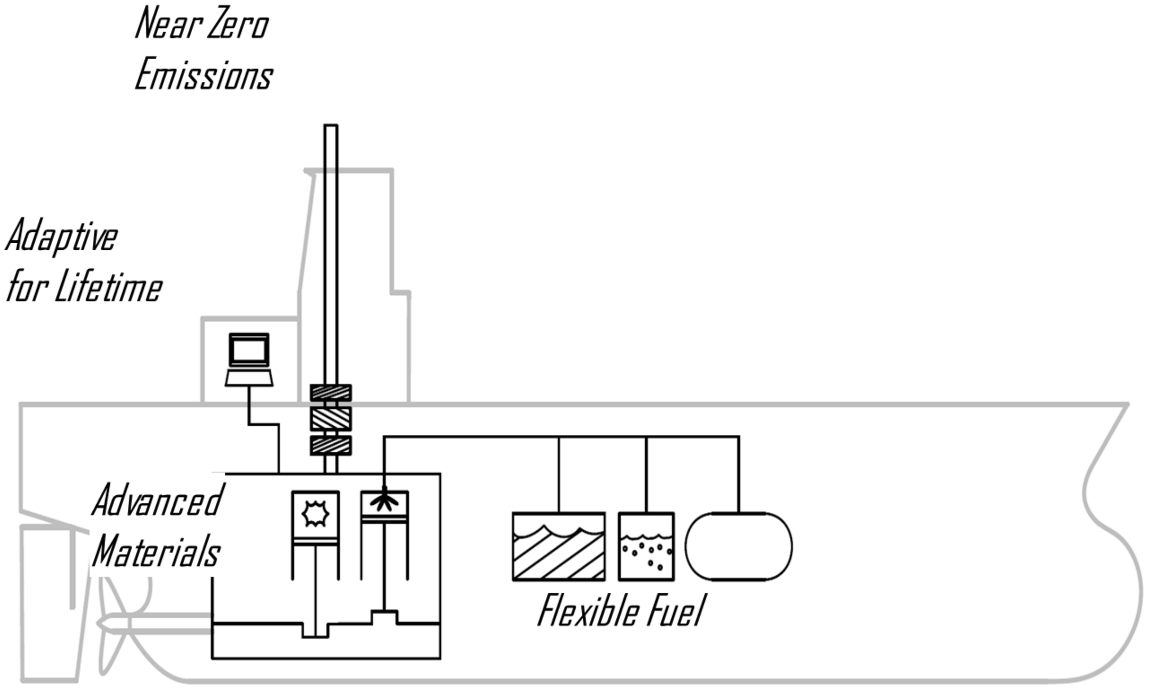
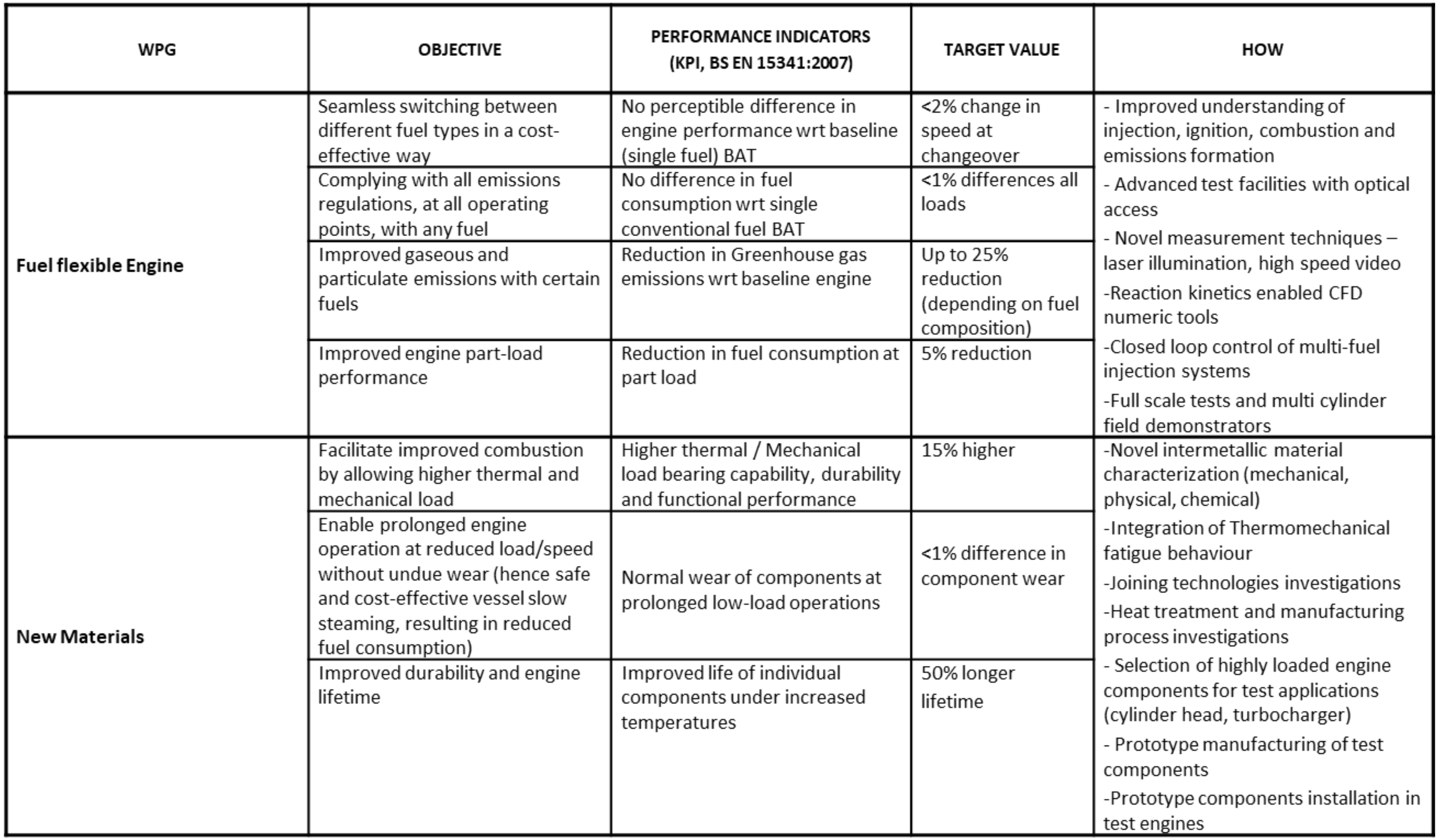


Figure 2: Schematic overview of HERCULES-2 Work Package Groups

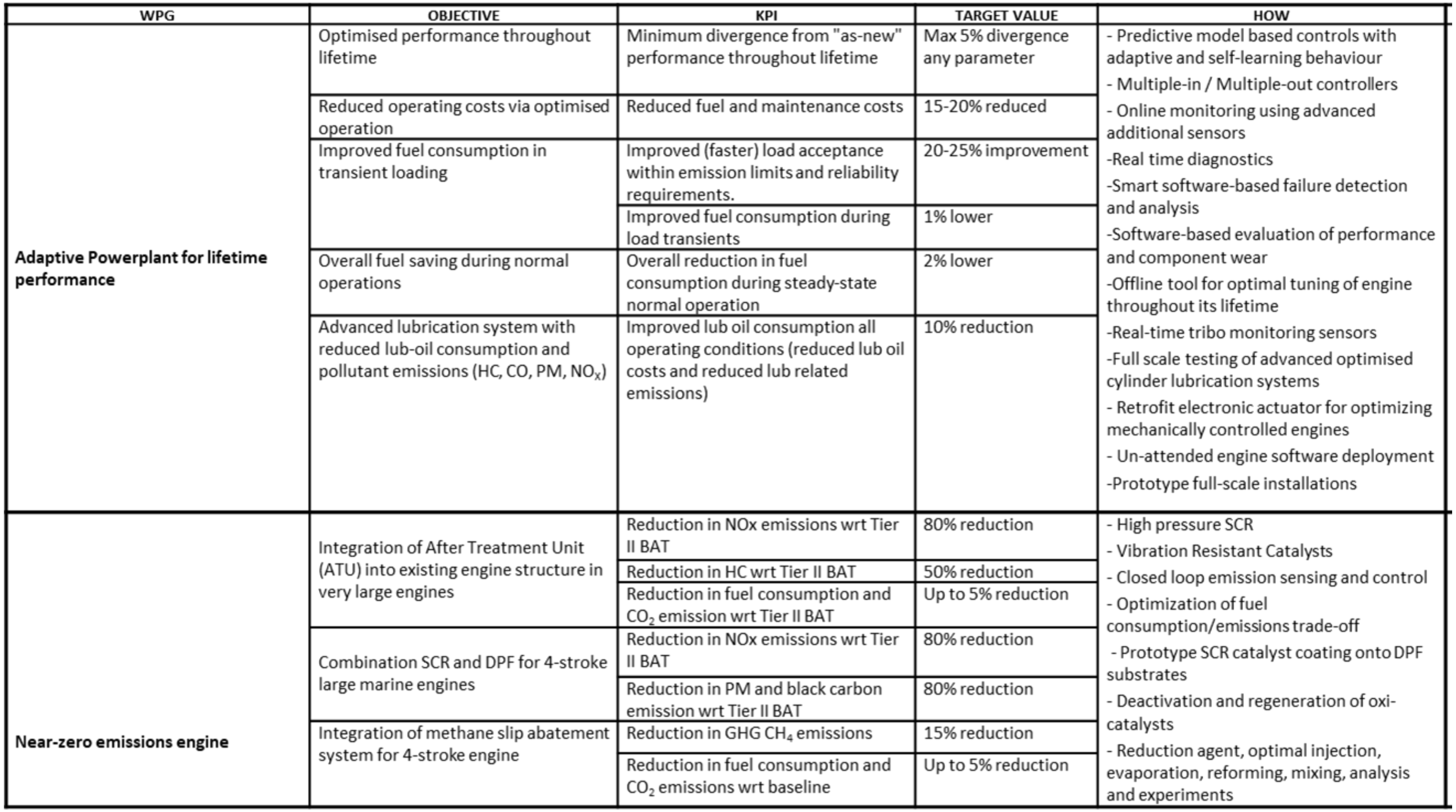
For each R&D Work Package Group, specific Objectives, related Performance Indicators, Target Values, actions How to achieve Targets and contributions to “Expected Impacts” of the specific topic MG.4.1-2014-Towards the energy efficient and very low emissions vessel, are provided.

The HERCULES-2 project Objectives are presented in Table 1.

Table 1: WPG, Objectives, KPI’s, Targets (2 pages)



WPG	OBJECTIVE	PERFORMANCE INDICATORS (KPI, BS EN 15341:2007)	TARGET VALUE	HOW
Fuel flexible Engine	Seamless switching between different fuel types in a cost-effective way	No perceptible difference in engine performance wrt baseline (single fuel) BAT	<2% change in speed at changeover	- Improved understanding of injection, ignition, combustion and emissions formation - Advanced test facilities with optical access - Novel measurement techniques – laser illumination, high speed video -Reaction kinetics enabled CFD numeric tools -Closed loop control of multi-fuel injection systems -Full scale tests and multi cylinder field demonstrators
	Complying with all emissions regulations, at all operating points, with any fuel	No difference in fuel consumption wrt single conventional fuel BAT	<1% differences all loads	
	Improved gaseous and particulate emissions with certain fuels	Reduction in Greenhouse gas emissions wrt baseline engine	Up to 25% reduction (depending on fuel composition)	
	Improved engine part-load performance	Reduction in fuel consumption at part load	5% reduction	
New Materials	Facilitate improved combustion by allowing higher thermal and mechanical load	Higher thermal / Mechanical load bearing capability, durability and functional performance	15% higher	-Novel intermetallic material characterization (mechanical, physical, chemical) -Integration of Thermomechanical fatigue behaviour -Joining technologies investigations -Heat treatment and manufacturing process investigations - Selection of highly loaded engine components for test applications (cylinder head, turbocharger) - Prototype manufacturing of test components -Prototype components installation in test engines
	Enable prolonged engine operation at reduced load/speed without undue wear (hence safe and cost-effective vessel slow steaming, resulting in reduced fuel consumption)	Normal wear of components at prolonged low-load operations	<1% difference in component wear	
	Improved durability and engine lifetime	Improved life of individual components under increased temperatures	50% longer lifetime	



WPG	OBJECTIVE	KPI	TARGET VALUE	HOW
Adaptive Powerplant for lifetime performance	Optimised performance throughout lifetime	Minimum divergence from "as-new" performance throughout lifetime	Max 5% divergence any parameter	- Predictive model based controls with adaptive and self-learning behaviour - Multiple-in / Multiple-out controllers - Online monitoring using advanced additional sensors -Real time diagnostics -Smart software-based failure detection and analysis -Software-based evaluation of performance and component wear -Offline tool for optimal tuning of engine throughout its lifetime -Real-time tribo monitoring sensors -Full scale testing of advanced optimised cylinder lubrication systems - Retrofit electronic actuator for optimizing mechanically controlled engines - Un-attended engine software deployment -Prototype full-scale installations
	Reduced operating costs via optimised operation	Reduced fuel and maintenance costs	15-20% reduced	
	Improved fuel consumption in transient loading	Improved (faster) load acceptance within emission limits and reliability requirements.	20-25% improvement	
		Improved fuel consumption during load transients	1% lower	
	Overall fuel saving during normal operations	Overall reduction in fuel consumption during steady-state normal operation	2% lower	
	Advanced lubrication system with reduced lub-oil consumption and pollutant emissions (HC, CO, PM, NO_X)	Improved lub oil consumption all operating conditions (reduced lub oil costs and reduced lub related emissions)	10% reduction	
Near-zero emissions engine	Integration of After Treatment Unit (ATU) into existing engine structure in very large engines	Reduction in NOx emissions wrt Tier II BAT	80% reduction	- High pressure SCR - Vibration Resistant Catalysts - Closed loop emission sensing and control - Optimization of fuel consumption/emissions trade-off - Prototype SCR catalyst coating onto DPF substrates - Deactivation and regeneration of oxi-catalysts - Reduction agent, optimal injection, evaporation, reforming, mixing, analysis and experiments
		Reduction in HC wrt Tier II BAT	50% reduction	
		Reduction in fuel consumption and CO_2 emission wrt Tier II BAT	Up to 5% reduction	
	Combination SCR and DPF for 4-stroke large marine engines	Reduction in NOx emissions wrt Tier II BAT	80% reduction	
		Reduction in PM and black carbon emission wrt Tier II BAT	80% reduction	
	Integration of methane slip abatement system for 4-stroke engine	Reduction in GHG CH_4 emissions	15% reduction	
		Reduction in fuel consumption and CO_2 emissions wrt baseline	Up to 5% reduction	

4 Overall Review of Project Results

In the following pages, the Project results are presented on per Work Package basis. A short description of the specific objectives of each Work Package is followed by an outline of work.

The HERCULES-2 WorkPackages are shown below.

WP 1:	Systems for increased fuel flexibility
WP 2:	Multi-Fuel combustion
WP 3:	Intermetallics and advanced materials for marine engines
WP 4:	New materials for higher engine efficiency
WP 5:	Lifetime performance control
WP 6:	Model-based control and operation optimization
WP 7:	On-engine aftertreatment systems
WP 8:	Integrated SCR and combined SCR and filter

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Input from **WP1:Systems for increased fuel flexibility**

Final

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Contributors:	Winterthur Gas & Diesel AG OMT S.p.A. University of Applied Sciences North-western Switzerland Paul Scherrer Institute (PSI) Wärtsilä Finland Oy University of Vaasa Aalto University
Work Package Leader Responsible:	A. Schmid (WinGD)

Start date of Project: 01/05/2015 Duration: 42 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020
The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 WP1 Objectives

The objective of work package 1 was *to build engines, able to switch between fuels whilst operating in the most cost effective way and complying with the regulations in all sailing regions*. The work package was divided into two focus areas:

- Two-stroke engines (handled by Winterthur Gas & Diesel AG) on the one hand
- and Four-stroke engines on the other (handled by Wärtsilä Finland Oy).

1.1 Two-stroke

On the two-stroke side the objectives for the project were:

- To identify possible fuel alternatives
- Design and manufacture a fuel injection system, capable of handling alternative fuels
- Setup of injection test rigs for the validation of injector operation under worst conditions
- Modification of the Spray Combustion Chamber for the new injector design
- Evaluation of Spray and Combustion for different fuel compositions

1.2 Four-stroke

The first objective of the pre-study was to gather information about the suitability of gas condensate fuels to engines. Basic physical and chemical properties of four to five condensate fuels are collected. Propane (C_3H_8) and hexane (C_6H_{14}) were studied, as well as additional condensates from the carbon number groups of 7 to 14 and 15 to 20.

Based on the fuel property results, fuel admission, mixture formation, ignition and combustion phenomena were further investigated, and the experimental setup was designed for the engine tests. The data was also used for simulation and combustion analyses.

Additionally, the requirements for a flexible injection system have been specified to be able to operate the engine with various gas condensate fuels. Issues like fuel spray penetration into the combustion chamber and the effects of fuels on the injection nozzles and injection needle operation had to be clarified.

The continuous determination of the fuel is also important to be able to operate the engines on an optimal level even though the fuel quality fluctuates. The objective for this task was to compare different gas quality measurement systems and to evaluate their applicability.

2 Outline of work performed

2.1 Two-stroke

In the literature review at the beginning of the project possible fuel candidates were identified. It showed quickly that there is not one single fuel which could replace HFO in the future. WinGD expects several possible solutions, depending on the individual case, like ship type, route, cargo etc. Hence a high fuel flexibility is expected to be asked for by the customer. Ethanol and diesel have been chosen to represent this broad fuel spectra.

Therefore, a system was developed, able to switch between fuels whilst operating in the most cost effective way and complying with the regulations in all sailing regions.

To do so, a Common Rail system with activation close to the nozzle, made of stainless steel to withstand ethanol and other fuels and with variable flow area (two-step FAST) was developed.

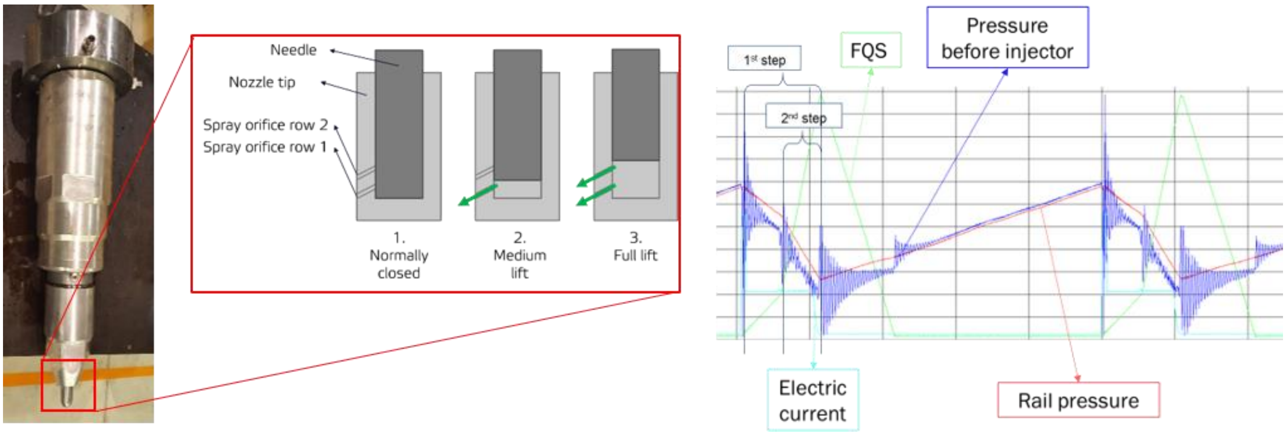

Figure 1 Fuel Flexible Injector

The system was tested on the injection rig to understand the hydraulic behaviour before it was put on the test engine. It performed according to the expectations. Later the injector was taken onto the Spray Combustion Chamber where it was tested to understand spray, ignition and combustion of the injector. Special focus was set on the interaction between pilot and main injection to get the perfect timing and hence reduce testing time on the RTX-6 test engine.

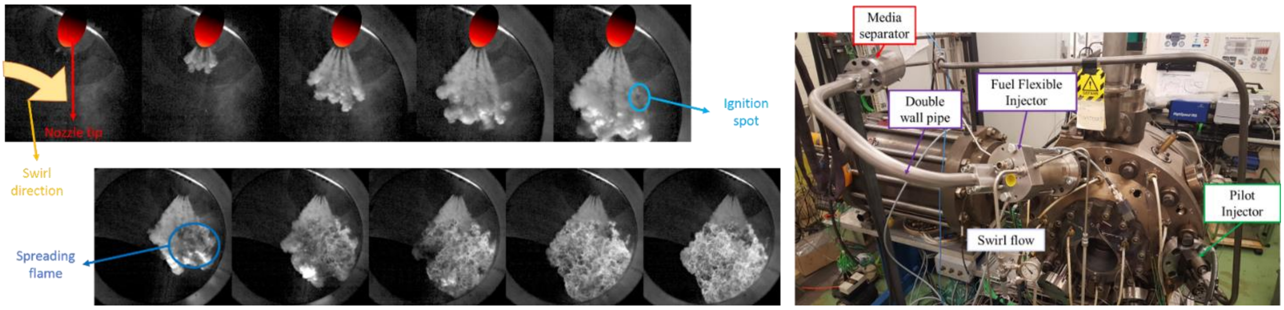

Figure 2: Fuel Flexible Injector on the Spray Combustion Chamber

The next step was to take the system on the RTX-6 and proof the concept under real conditions. As the system is a prototype and not a serial application yet, and to allow for maximum flexibility on the test engine, the design was made such that the fuel flexible rail was put on top of the existing gallery. An application on a production or serial engine would integrate the system into the gallery floor, where it would replace the standard system.

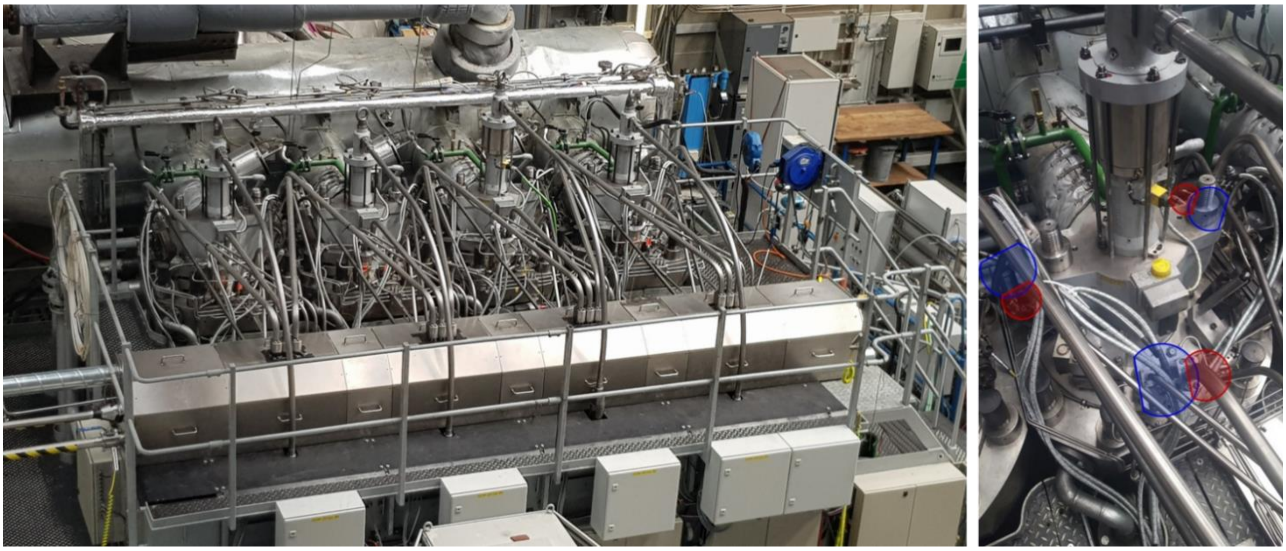

Figure 3: Fuel Flexible Injection System on the RTX-6 test engine

2.2 Four-stroke

The outline of the work from the three partners on the four-stroke part was divided into three areas. Wärtsilä´s part was to develop new measurement techniques and sensor technology for gas online measurement. The University of Vaasa (VY) was studying possible fuel combinations for marine engine applications, by doing experiments and safety improvement with high volatility and low flash point fuels. Ignition studies for non-auto-igniting fuels was also in the program. VY was also setting up test facilities for in-cylinder combustion studies with single-cylinder engine and potential fuels like liquid bio-fuels, methanol, DME, or gas. At Aalto University the work was concentrating on development of combustion control devices (valve trains, EGR, control and fuel injection valves) as well as numerical modeling and spray combustion chamber studies for liquid bio-fuels, methanol, or DME to be used as diesel pilot for DF engines.

During the first part of the project, Aalto University (Aalto) and the University of Vaasa (VY) concentrated on the analytic side of the fuel. Aalto performed high level simulations by utilizing spray chamber test results and optical in-cylinder measurements. VY made a screening on different alternative fuels were anlayzed in depth and compared with marine diesel oil. After the analyses were ready, 5 different fuels were chosen to be tested on the engines.

The second part of the project was concentrating on practical measurements. Concept development for optimized engine performance with controls based on gas online quality measurement was carried out at Wärtsilä. VY tested and analysed the engine performance with different fuels both on a high-speed engine as well as on the Wärtsilä 4L20 engine, that was installed and taken into operation in a new testing facility called Vaasa Energy Business Innovation Centre (VEBIC).

3 Achievements and Final Results

3.1 *Two-stroke*

The system was tested with diesel and ethanol as fuel which went smoothly. Due to budget and time constraints the nozzle tips could not be optimised, yet. The RT-Flex injectors which were used to pilot, could not be operated with their optimum performance, as they are not designed for such small quantities. There is still a high potential to reduce emissions and fuel consumption: The consumption was higher compared to the standard system. The reason for this is still investigated as there was a problem with a flow sensor. The values shown here are including the values from the problematic sensor (conservative calculations). NOx shows a similar trend for the new system, whereas the ethanol doesn't seem to reduce the NOx emissions. All over good results could be achieved and the testing was successful.

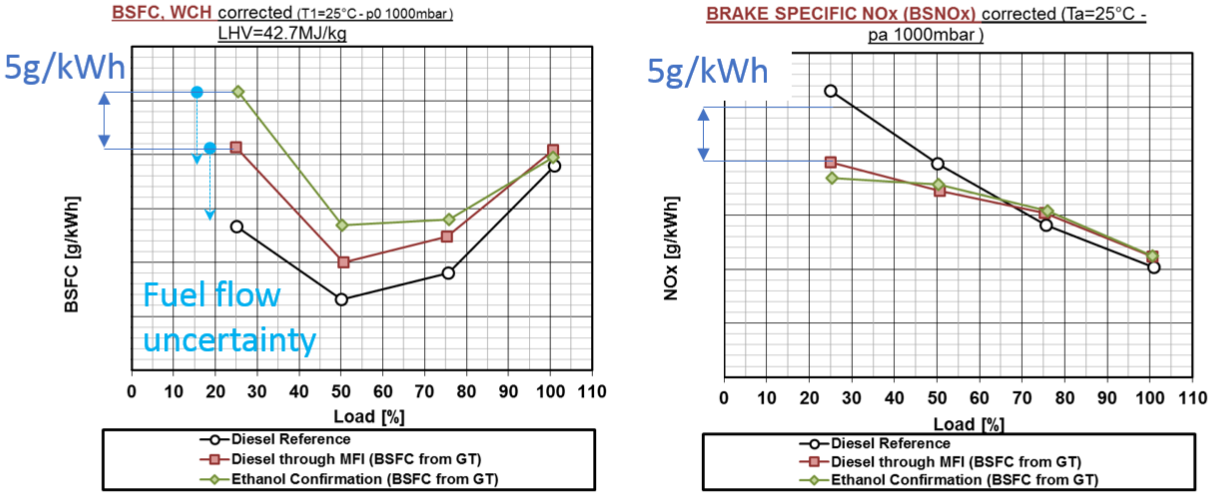

Figure 4: Results from the first engine tests

A changeover from diesel to alternative fuel is very smooth. If this happens drastically, for example in case of problems with the fuel supply of the alternative fuel system, the engine would automatically trip to diesel mode.

The loss in engine speed caused by the "hard" changeover from alternative fuel to diesel was within reasonable limits: At low loads the change in engine speed is around ten percent, and at 50% load it is maximal 7% of the according engine speed.

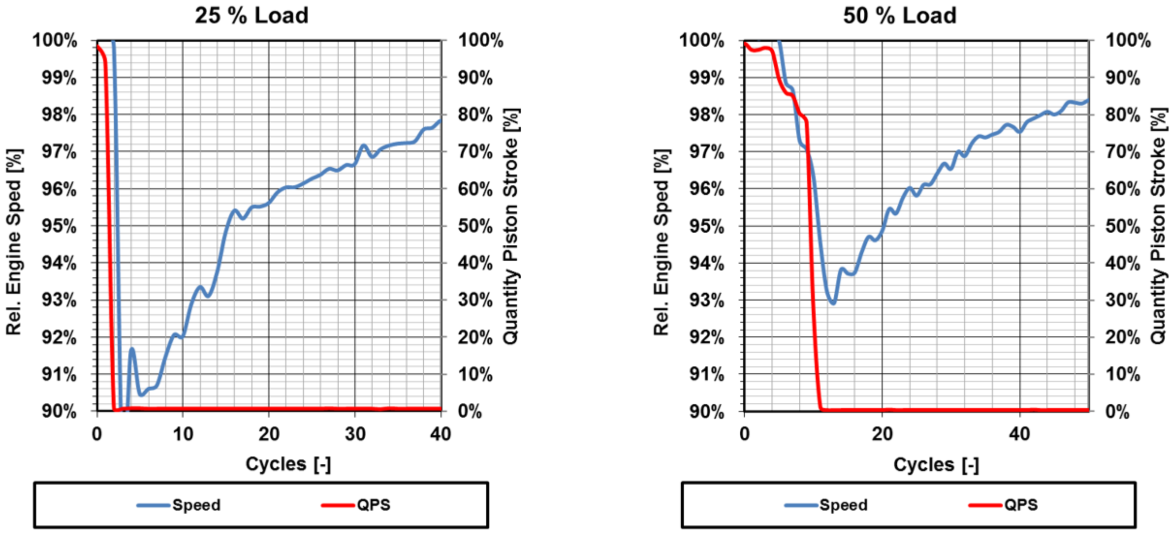

Figure 5: Behaviour under sudden fuel change

3.2 Two-stroke, sub project 1.2 Feasibility study RCEM

In a sub project, WinGD and its partners investigated the development of a rapid compression and expansion machine. In a feasibility study the rough outline – technically and financially – should be made. During the feasibility study which was mainly conducted by our partners, FHNW and PSI, an extensive investigation was made with very good results: Such a system would technically be possible to build. It would allow for very good optical accessibility and could run on both, Otto and Diesel cycle. A founding in the range of 2-3 million € would be necessary (only the main parts, without building etc. operation etc)

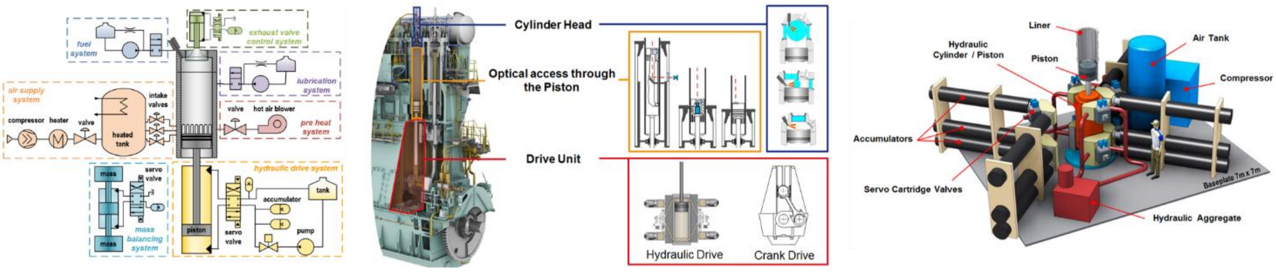

Figure 6: Possible layout of a rapid compression expansion machine for 2-stroke applications

3.3 Four-stroke

Aalto made successful measurements on droplet sizes for methanol sprays and the impact on the injection pressure and chamber density on the Sauter Mean Diameter (SMD) was compared between diesel and Methanol.

Large Eddy Simulations (LES) was carried out with different fuels and significant differences in the local equivalence ratio fields within the sprays could be shown. These results will be used for further combustion optimisation.

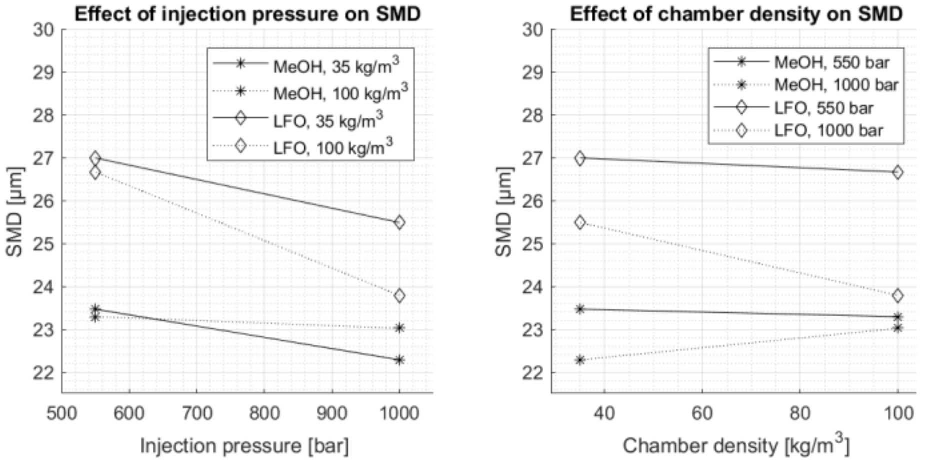

Figure 7. Experiments: Effect of injection pressure and chamber density on SMD between Diesel and Methanol.

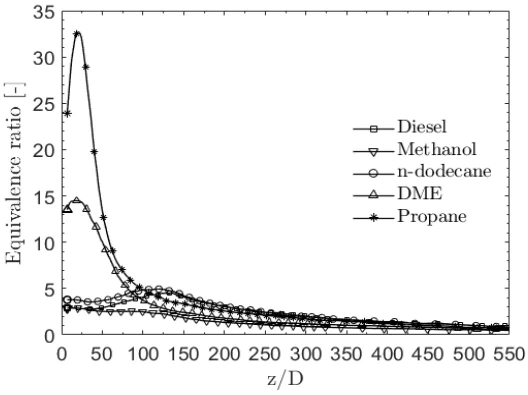

Figure 8. Simulation: Effect of fuel on the spray centerline equivalence ratio (z/D=500 is about 4.5cm from the nozzle)

The medium-speed engine at VEBIC worked favourably with MGO, Kerosene, the blend of naphtha and LFO, and neat LFO. The experiments created new information about the heat release process of the engine. The fuel conversion efficiency of the engine was almost equal independent of the fuel. Kerosene generated slightly higher NOx emissions than the other fuels. Concerning particle number emissions, MGO and naphtha-LFO blend seemed to be more beneficial than the other fuels. Novel data were also obtained of so far unregulated exhaust compounds.

Based on the tests, all fuels seemed to suit to the medium-speed engine. The low flash point of naphtha and its blends must be taken into account when planning the safety issues of the engine applications. Next, the injection system must be designed suitable for the studied fuels

The combustion and engine tests at VY showed that MGO and Naphta- LFO blend had more favourable results regarding the particle numbers than LFO and Kerosene.

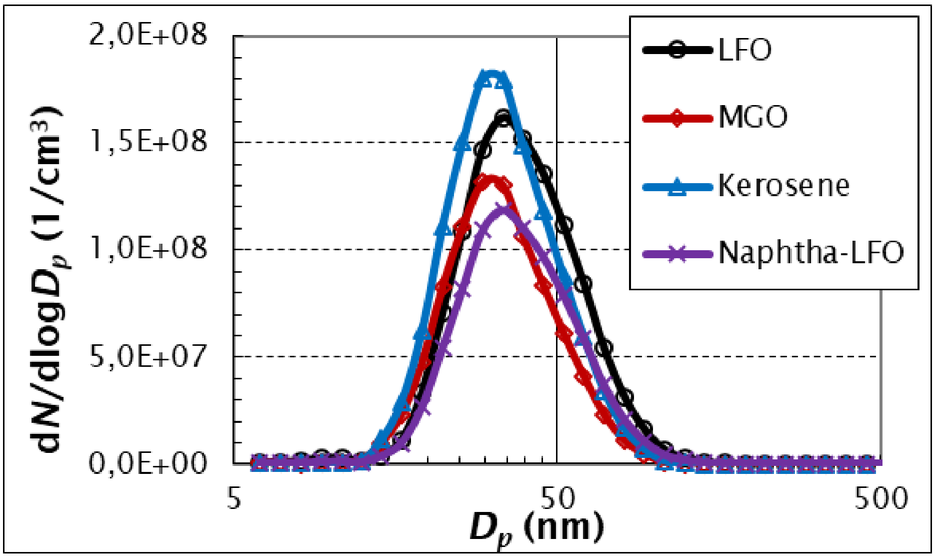

Figure 9. Particle number comparison between different fuels.

The gas online measurements with a variating gas quality showed that there is a clear impact on the engine performance as the composition of the gas is variating. The results also show that these impacts can be manged by engine optimisation and continuous control.

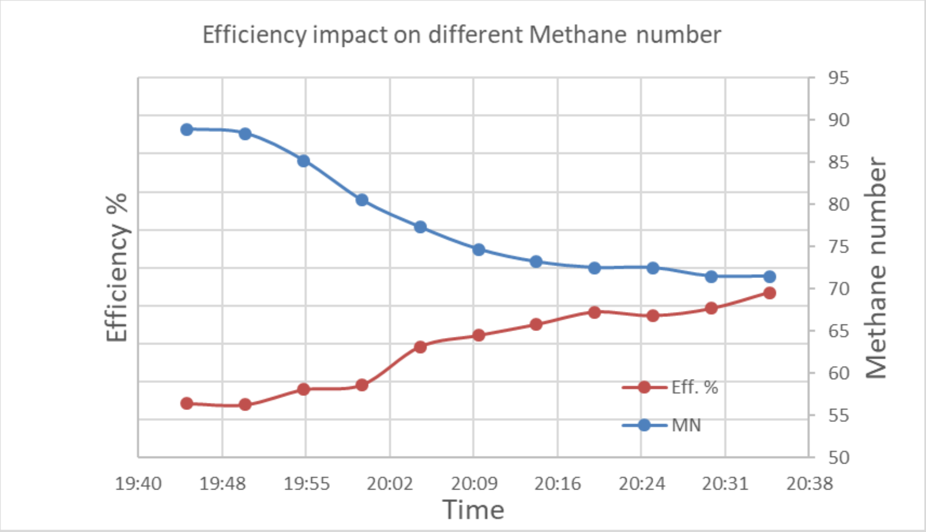

Figure 10. Engine efficiency impact with variating methane number of the fuel gas

4 Conclusions

4.1 *Two-stroke*

During the past 3.5 years WinGD and its partners designed, manufactured and tested a complete new injection system. The results are promising, that such a system could be used in the future to operate a variety of fuels on WinGD engines. The prototype built during the HERCULES-2 project allows WinGD the investigation of a broad spectrum of fuels and fuel qualities to develop a fuel flexible injection system for serial engines. Therefore WinGD will use it in the near future to learn more about different fuels.

4.2 Four-stroke

During the Hercules-2 project Wärtsilä has together with the partners analysed and tested various liquid and gaseous fuels for future use in medium speed diesel and dual fuel engines. The results show that the engine is capable of operating on a big spectrum of different fuels.

The DF combustion was characterized in an optical engine using various methane lambda's and intake temperatures. Large differences can be observed in the flame propagation between the different intake conditions.

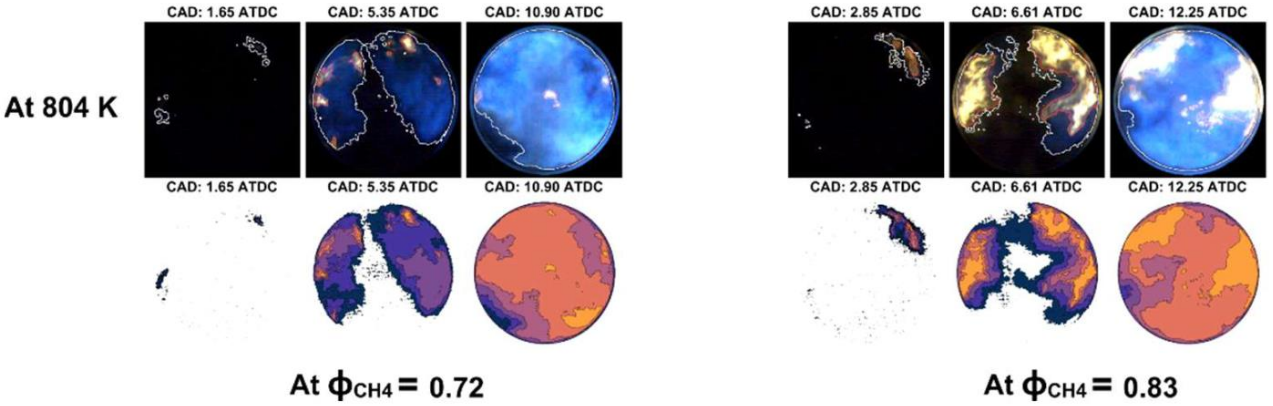

Figure 11. DF combustion characterization

Diesel, methanol, hexane, kerosene, DME, and propane were analysed numerical and experimentally yielding ground-breaking new picture of their behaviour.

The full-scale engine tests with different liquid fuels show almost equal efficiency with all fuels. The kerosene has slightly higher NOx emissions. The PM emissions were very similar for all fuels. Regarding the low flash point of the naphtha-LFO blend, the security of the handling can be an issue.

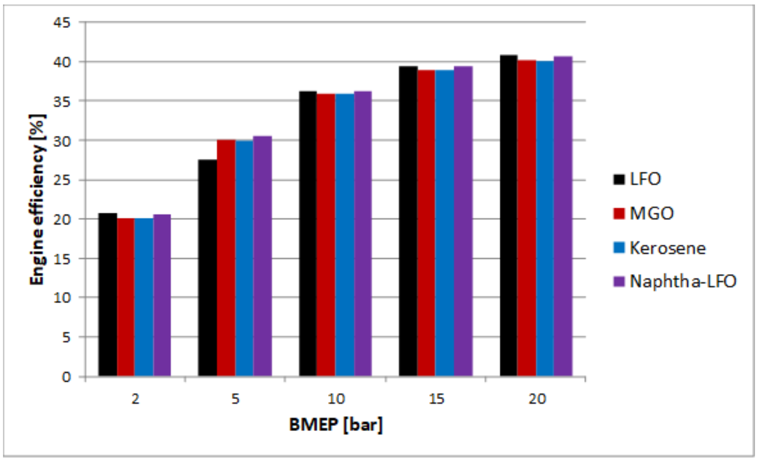

Figure 12. Engine performance comparison between different liquid fuels.

The efficiency and emission optimisation and flexible operation of the engine need to be and can be controlled by optimized injection systems and continuous controls. The project has also contributed to the setup of a new testing facility at Vaasa University called VEBIC,that will provide possibilities for future development.

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Input from **WP2: Multi-Fuel Combustion**

Revision Final

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DTU
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MTU

Work Package Leader Responsible: Johan Hult (MAN Energy-Systems)

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HORIZON 2020
The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 WP 2 Objectives

The overall objective of WP2 has been to enable further improvement of fuel-flexibility of marine engines. In order to operate efficiently on a larger variety of fuels we need an increased understanding of injection, ignition, combustion and emissions formation of novel fuels or mixed operation on several fuels. For this purpose we have developed experimental facilities with optical access for tests under conditions relevant to low- and medium-speed engines. Numerical tools have also be developed and applied for furthering understanding of ignition and emission formation. Finally, novel engine control strategies have been developed to fully exploit potential benefits of such fuels.

2 Outline of work performed

- A fuel-flexible test facility for controlled studies of fuel injection, ignition and combustion under realistic conditions designed.
- Optical tests on several fuels (diesel, LNG, ethane, LPG) performed on two-stroke test-engine. Optical methods for multi-camera 3D imaging, lube-oil visualisation and Schlieren prepared.
- Detailed chemical kinetic models for alternative fuels developed. CFD of single and multi-fuel combustion performed.
- Realisation and successful testing of a concept to measure 3D in-cylinder mixture formation on a dual fuel medium speed single cylinder engine.
- Fuel-specific engine-control strategy developed on a single cylinder engine and successfully validated on a MAN-ES medium speed full-scale dual-fuel engine.
- Development and validation of an efficient numerical model to predict NO_2 formation in a dual-fuel medium-speed engine.

3 Achievements and Final Results

MAN has designed a test rig for creating representative conditions (for a 2-stroke marine engine) for studies of fuel injection and combustion. As reported previously component design and construction was postponed (due to limited engineering resources). Instead we have run a series of optical tests on diesel and on alternative fuels (LNG, ethane and LPG) on the test engine in Copenhagen. The optical techniques were first prepared in Lund, and then applied on the engine. In Fig. 1 an example of imaging with 3 high-speed cameras, to allow triangulation of the spatial position of the flame in the cylinder (useful for CFD validation and for ignition studies), is shown.

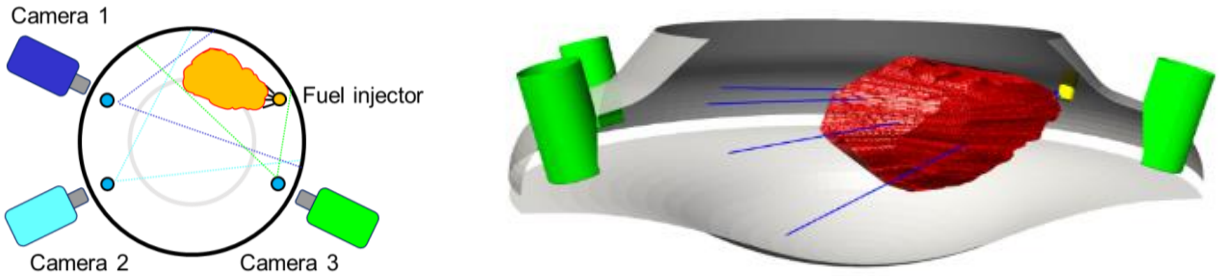

Fig 1. Spatial mapping of flame shape using multi-camera imaging.

The numerical work on two-stroke engines was in two stages. First a detailed chemical kinetic model for new fuels was completed and validated at DTU (includes LNG, ethane, methanol and LPG). The mechanism has been implemented in tools for calculating ignition delays and flame speeds. Secondly, CFD tools for dual-fuel operation have been developed in collaboration with the partners in Lund and Milano. The work has focused on dual-fuel operation (high-pressure injection of LNG + diesel pilot). An example of mixture fraction from gas injection and the associated temperature is shown in Fig. 2.

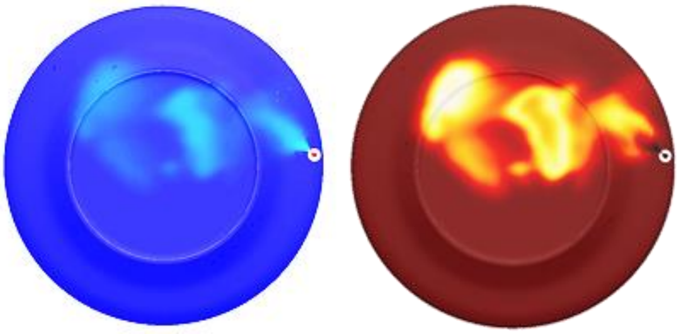

Fig 2. Mixture fraction (left) and temperature (right) for dual-fuel low-speed engine (CFD).

An optical cylinder head for a single-cylinder medium speed test engine was designed in collaboration between MAN and TUM. It was built, installed, and successfully tested up to full load. It allows optical views both from the top and from the sides (see Fig. 3). With vertical access one can cover up to 140 mm in diameter. For fuel mixing studies a tracer system was installed, for adding a fluorescing tracer either to the natural gas or to the air. This was then used to visualise the fuel distribution within the cylinder.

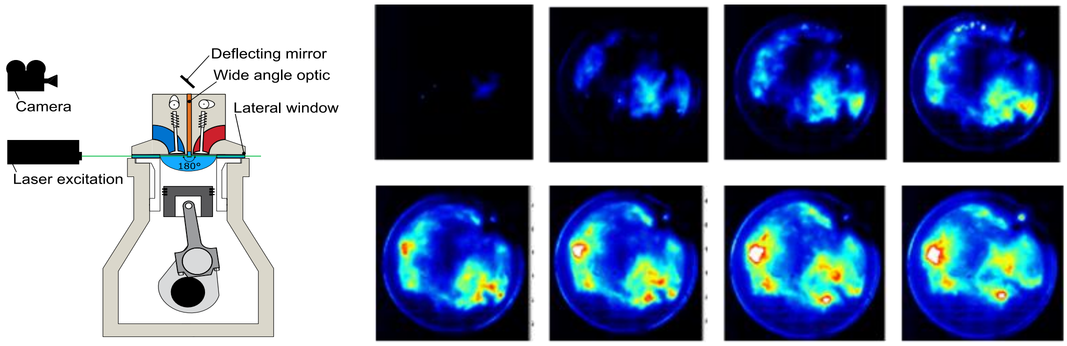

Fig 3. Measurement of flame luminescence with vertical access.

A fuel specific engine control strategy was also developed. First different fuels were tested in a spray chamber and in a single-cylinder engine, and the fuel properties which affect combustion and emissions were identified. Then the negative impacts of HFO (compared to DMA) were compensated for by changing injection strategy. This successful control strategy was then tested on a full-scale medium-speed engine. Finally, the conditions than can lead to NO_2 formation have been investigated by TUM. It was found that it makes sense to split model into an exhaust and an in-cylinder part. The exhaust duct model was successfully validated against tests, see Fig. 4. An in-cylinder model was also built up and validated, but to achieve good predictions it would need improvements in the combustion model.

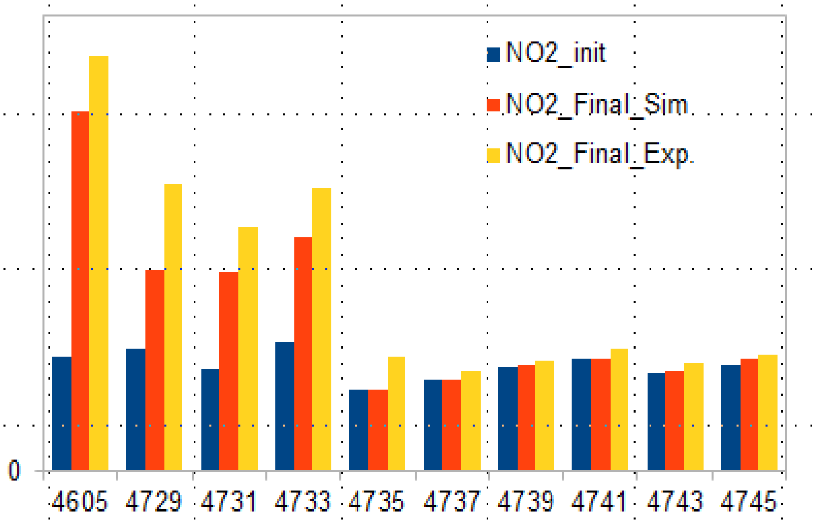

Fig 4. Comparison of NO2 in exhaust duct model: simulation (red) experiment (yellow).

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Input from **WP3: Intermetallics and advanced materials for marine engines**

Revision Final

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Contributors:	Max-Planck Institut für Eisenforschung Deloro Wärtsilä Finland WinGD ABB
Work Package Leader Responsible:	Monika Damani (WinGD)

Start date of Project: 01/05/2015 Duration: 42 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020
The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 WP 3 Objectives

The objective of WP3 is to examine the feasibility of using novel materials, which are capable to withstand higher temperatures to enable higher engine loads. Hereby increasing efficiency and lower emissions by providing more freedom to optimize combustion and/or use new fuels. WP3 consists of two sub-projects (SP3.1 and SP3.2). SP3.1 aims to identify new materials (as well as to examine their manufacturing routes) for different engine components and SP3.2 is focused on materials (and topological) optimisation of turbocharger casings.

2 Outline of work performed

2.1 Sub Project 3.1: Novel materials for engine applications.

In the beginning the boundary condition were set and promising candidate materials were chosen. New, no- commercially available reference materials were produced via different manufacturing routes (casting, hot isostatic pressing, thermal spraying, plasma transferred arc welding) . Extensive investigations of the new materials were performed in order to assess their mechanical, thermal and corrosive properties. Rig Testing of coatings was done. Prototypes of Alloy 2 were successfully produced via casting route for 4-stroke test parts and from HIP-material for 2-stroke application. Missing material data and characterisation of the HIPped material was conducted .4-stroke and 2-stroke prototypes have been tested on the respective test engines and post analysis of the components was performed.

2.2 Sub Project 3.2: Novel materials for turbine casing.

Initially, material selections for application up to 800 ° based on existing material data was done. Set-up of preliminary material design datasets for a first design approach was conducted. It was decided to go on with a heat resistant austenitic cast steels and white spots of missing data were identified. Casting simulations including development of a proper casting system was done and prototypes of the steel cast were produced. Non-destructive and destructive examination of the prototype casings including LCF and TMF testing was conducted. Reconsidering the life-time calculations with the revised material design data was made. Finally, functional engine testing was successfully done.

3 Achievements and Final Results

3.1 Sub Project 3.1: Novel materials for engine applications.

Insights into new, i.e. no-commercial available materials, could be gained and generation of valuable new material data was achieved. Investment casting of Alloy 2 showed the potential of fabrication near net shape components. For 2-stroke application the prechamber made of Alloy 2 passed the engine test. However, for 4-stroke application an increased ductility of the intermetallic alloy is required.

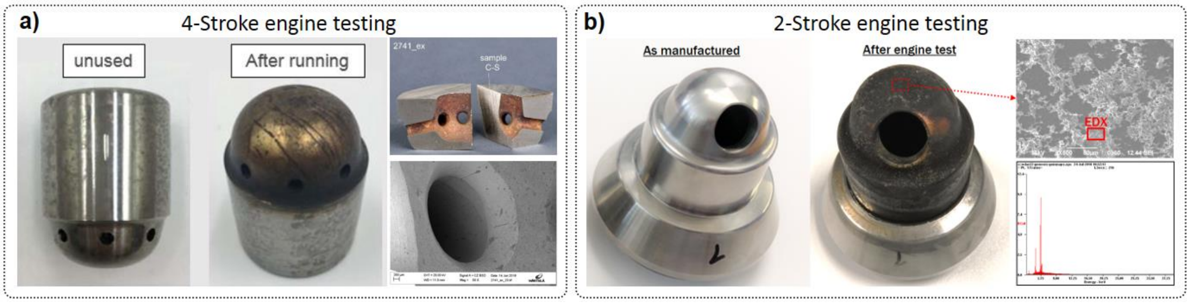

Figure 1. Prototypes of Alloy 2 prior and after engine testing for a) 4-stroke b) 2-stroke applications

3.2 Sub Project 3.2: Novel materials for turbine casing.

For sub-project 3.2 the work has shown that the casting of a turbine casing made of the austenitic cast steel is possible. The prototype passed the standard thermal cycle test The lifetime analysis showed that the so-called “tongue” is critical and further geometrical optimization of the casing for serial production is recommended. Valuable material design data of the austenitic cast steel could be evaluated, which is a benefit for ABB Turbo Systems.

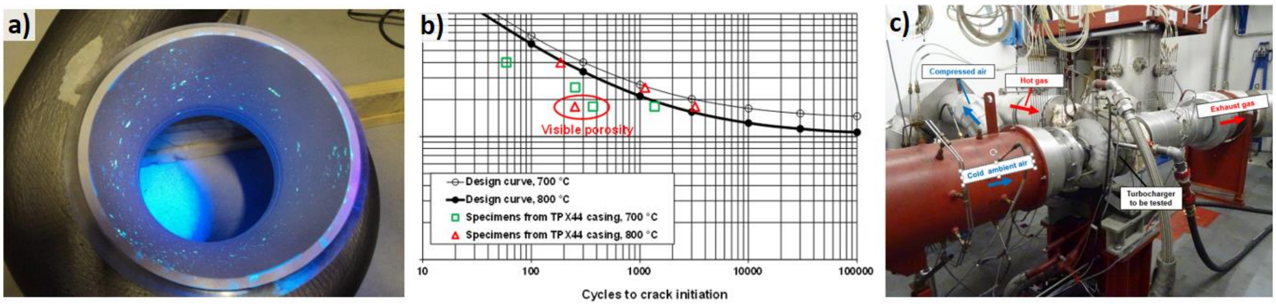

Figure 2. a) Prototype of the turbocharger made of the newly applied austenitic cast steel b) TMF data generated from samples cut out of prototype castings, c) test rig with assembled turbocharger;

Overall, promising materials for use in marine engines could be identified and proven. Valuable material data were generated. Hence, setting a profound basis to enable the application of the newly identified materials in serial products.

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Input from **WP4: New materials for higher engine efficiency**

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Work Package Leader Responsible:	Rayk Thumser (MAN ES)

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HORIZON 2020
The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 WP 4 Objectives

Thermodynamic concepts of exhaust gas treatment, reduction of specific fuel oil or intensified usage of exhaust gas energy go along with higher component temperatures and mechanical loads. The objective of this Work package is to develop the use of appropriate material for optimized combustion engines. The components are the cylinder head and the turbocharger turbine casting. These components are cyclic loaded by mechanical and thermal loads.

The objective of this work package is to increase the fatigue resistance for cylinder heads (WP 4.1) and turbocharger inlet casing (WP4.2).

2 Outline of work performed

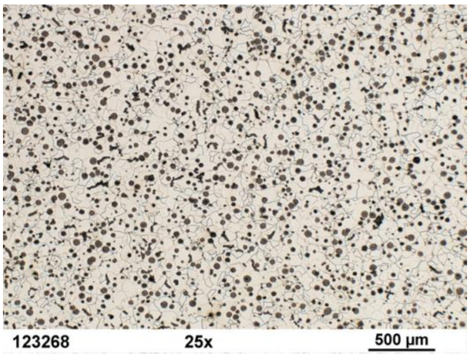
2.1 Subproject 1 - WP 4.1

The aim of the first part of this project is to find an appropriate material candidate for further investigations and prepare the work packages required for the second half project time. The selection of appropriate material for pilot study was done in cooperation with MDT-AUG and IWM. Five materials where selected. At the foundry at MDT-AUG different plates and sleeves (fig. 1) where produced. There was a multiple step process to optimize the different foundry process in dependency of the material composition, e.g. inoculation tests. The material characterisation for the pilot study was a shared work between MDT-AUG and IWM. At MDT-AUG a huge amount of ultrasonic tests where done to see the influence of casting thickness. Further, the basic tests according to delivery standard where done at Augsburg. At IWM the basic characterization was performed for the materials at the pilot study:

- Tensile tests from room temperature (RT) up to 500°C,
- isothermal fatigue tests at RT, 400°C and 500°C and
- thermophysical properties (coefficient of thermal expansion, density, thermal diffusion, thermal conductivity, heat capacity).

With all partners (IWM; ICT; HSO, MDT-AUG) the decision for the final material for the investigation was done based on the thermal shock resistance parameter.

Within FHG-IWM there were done intensively investigations on the selected material. There were done isothermal tensile static test, isothermal complex LCF tests, TMF tests as well as metallographic investigations.



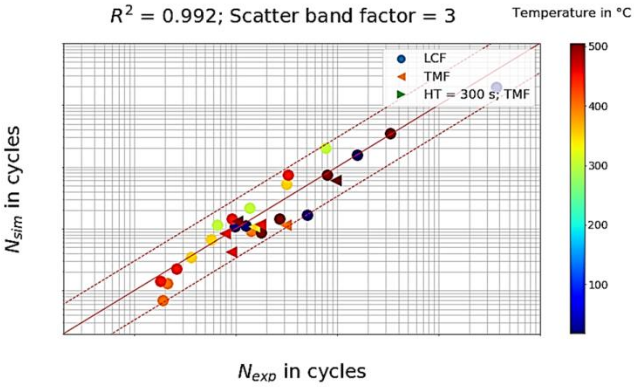
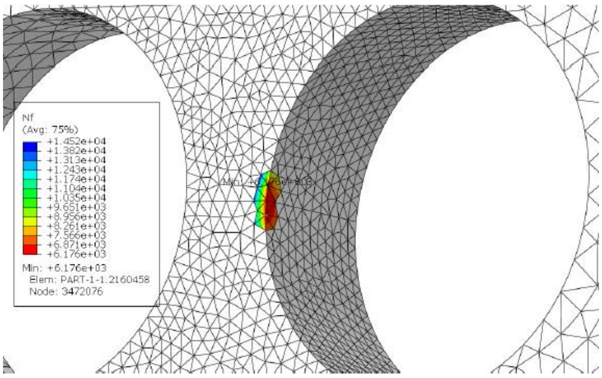


Figure 1: Ferritic matrix of selected Material

Figure 2: Predicted vs. experimental cycles

The modelling of the uniaxial damage behaviour was done by CTOD fracture mechanics concept. This concept was extended by intergranular embrittlement. The prediction of the experiment shows a good agreement of the fatigue lives. The HSO worked on the different levels of modelling deformation behaviour. The CLCF stress-time curves show a notable better description using the advanced model. Especially during the dwell times, the second simplified model is not able to describe stress relaxation appropriately due to the missing static recovery term in the kinematic hardening law. However, the models show less deviation at the TMF experiments.



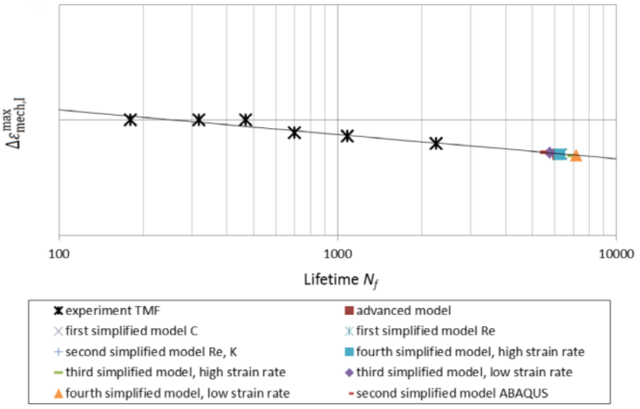


Figure 3: Finite-element model of the cylinder head specimen

Figure 4: Wöhler curve with calculated lifetimes of the different models

The cylinder head specimen (see Figure 9) is used to compare the models regarding their prediction accuracy. The slope of the Wöhler curve is quite low. Thus, even small deviations of maximal principal mechanical strain range can lead to large deviations in the determined lifetime.

The FHG-ICT was working on a component test rig for cylinder head equivalent specimen is designed for combined stress of both thermomechanical and high cycle fatigue.

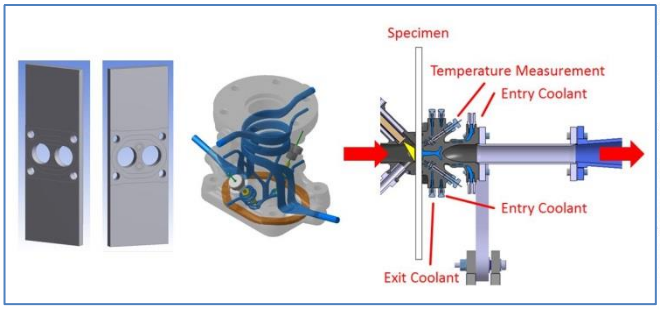


Figure 5: Adaption of specimen, design of cooling adapter

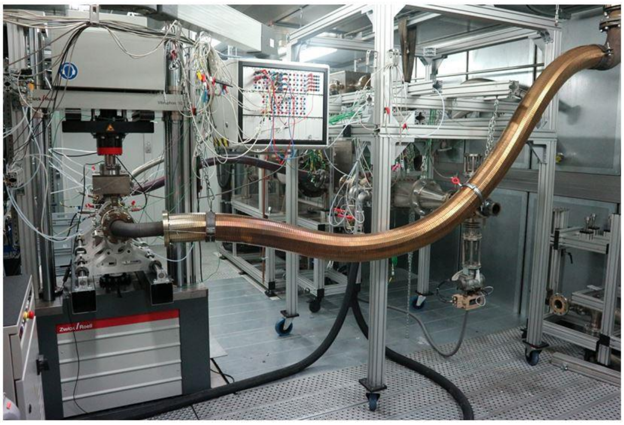


Figure 6: Test rig

With the actual test conditions a crack initiation could not be evoked. First failure analyses indicate that the mechanical load applied by the ram didn't comply with the required loads. Further failure analyses are being conducted. At MDT–AUG was responsible for the optimisation of the cylinder head.

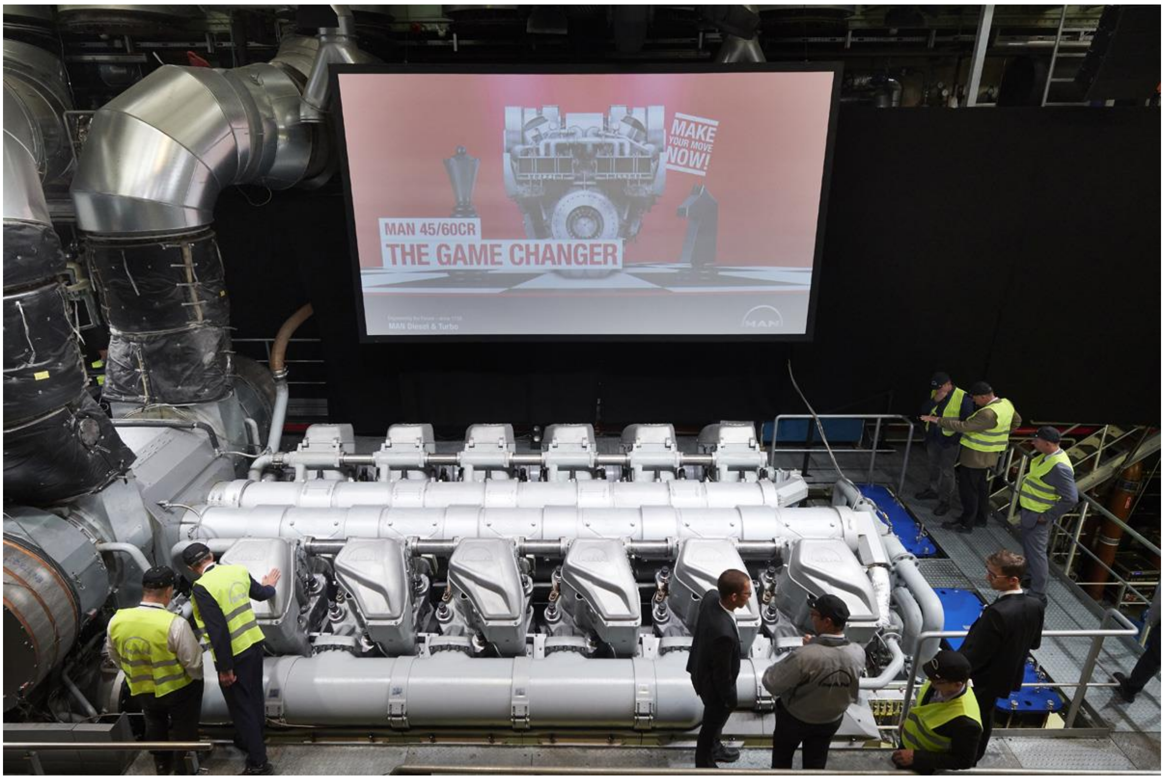


Figure 7: One official engine test in Augsburg with optimized cylinder head

Finally, the release of the "new" cylinder head cannot be achieved only by numerical simulations. A short in house test with the new component has been carried out. An intermediate design of the cylinder head is used for the first engine tests in Augsburg. Analysing the cylinder head after the test run is absolute necessary to confirm its reliability.

2.2 Subproject 1 - WP 4.2

In the frame of this Work Package 4.2 the focus is on cyclic marine applications like ferries (see fig.1), offshore supply vessels, dredgers, etc. Introduction of new materials for the use on marine engines requires a thorough assessment in order to mitigate all possible risks which may arise from it. As part of this risk mitigation process material tests are performed.

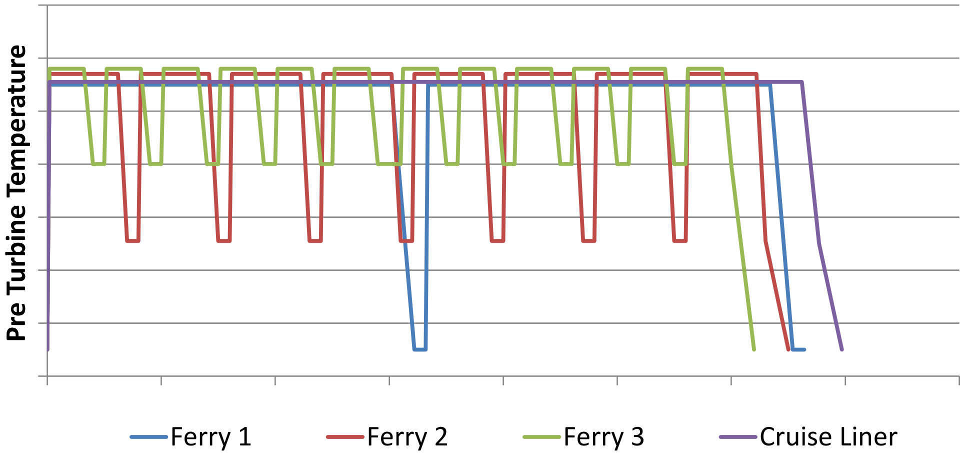


Figure 8: Typical Load Spectra Ferry vs. Cruise Liner

The selection of the material was performed based on previous experience gained at MDT in relation to corrosion and material fatigue. The target is to find a material with similar strength and fatigue characteristics at elevated temperatures compared to the now used materials at current application temperatures.

The material selected is expected to have approx. 25% higher corrosion resistance compared to current materials for the turbine inlet casing. If the amount of corrosion resistance is sufficient to meet the target has to be assessed in this workpackage.

The test plan consists of

- 28 low cycle fatigue tests (constant temperature, cyclic load),
- 54 thermomechanic fatigue tests (cyclic temperature and cyclic load) and
- 11 creep tests (constant temperature, constant load).

The production of test specimens was performed in accordance to the specified test plan. It was considered to produce some reserve specimens to be able to find the correct settings at the testing equipment. The drawings for the production of the specimens were provided by the BAM.

During production it was observed that the misalignment tolerance of the probes could not be met. The inherent bending of the specimens is not acceptable because it affects the test results. After repeated testing of different manufacturing techniques it was found that by a special heat treatment the bending of the probes is inhibited. However, the issues in the sample manufacturing lead to a delayed delivery of the specimens to BAM of approx. 6 months.

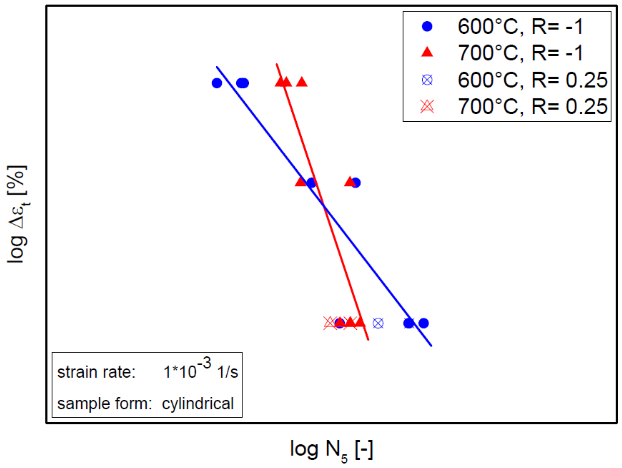


Figure 9: : LCF tests

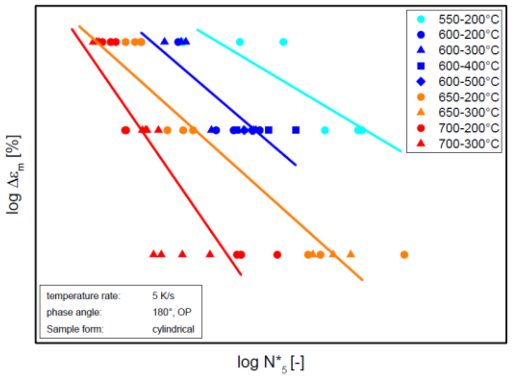


Figure 10: TMF Tests

The derived material model by MDT-AUG is based on the material tests performed by the BAM. Derivation of the material model consists of two main parts. On the one hand the attainable fatigue and creep lifetime are determined; on the other hand the constitutive equation that permits to model realistic deformations in a finite element analysis is derived.

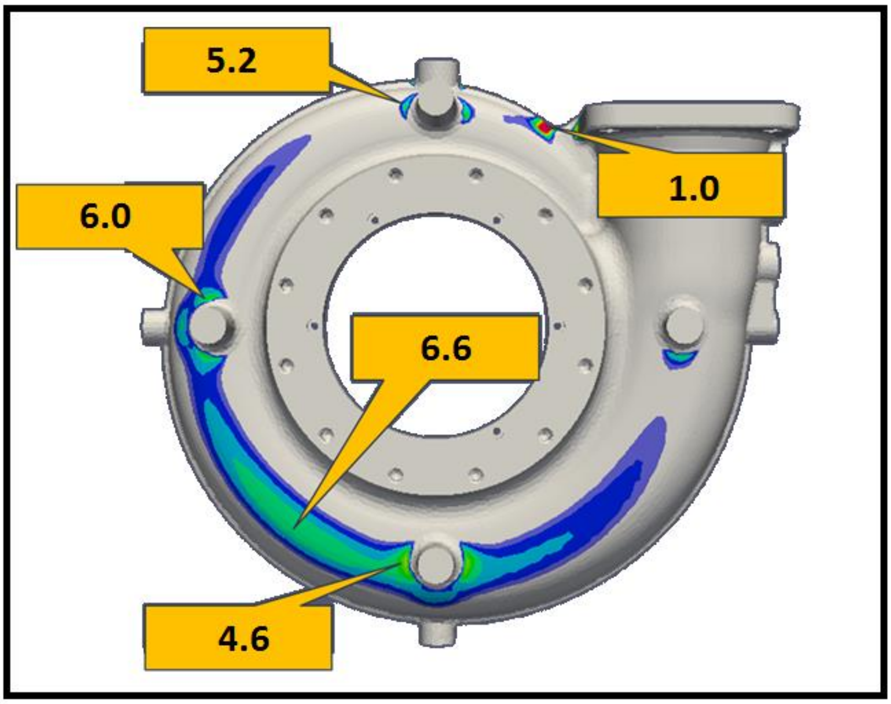


Figure 11: Computed TMF hot spots

Validation of the present material model was performed by comparing finite element results to test results. The test results were gained in an in house development project where an accelerated TMF lifetime test was conducted with a radial turbocharger. In the accelerated lifetime test the turbocharger is cyclically loaded in a burner rig and cycling is stopped at constant intervals for crack inspection.

The finite element analysis considers all relevant components for a sufficiently accurate computation of temperature distribution, turbine casing deformation and finally lifetime. Figure 11 shows the computed lifetime of the different TIC locations as a colour plot on the TIC. From red to blue the lifetime increases. In the graph the lifetime ratios of some locations are shown normalized to the hot spot with the smallest computed lifetime, which is in way of the casing inlet. Overall a good agreement between test and computation was achieved with a maximum non-conservative bias in lifetime of 23% which is good considering usual material variations and typical safety factors for fatigue design.

3 Achievements and Final Results

3.1 WP 4.1

The final efficiency with regard to the design can be found primary in the normalized weight of the cylinder head and additionally in the assembly space which is needed by the component. It would be a serious mistake to compare the weight of cylinder heads with nearly the same bore directly. It is advisable to normalize the weight of the head by the main driver of the acting loads.

Unfortunately the functional requirements and the interface connection to adjacent structural components prevent the reduction of the assembly space.

- The weight reduction is more as acceptable for MAN. Whereas the normalized weight of the cylinder head can be reduced by 16%. This is a dramatically decrease of the weight especially due to increased fatigue performance.
- The calculated mechanical strength regarding thermomechanical fatigue has been be improved by a factor of 3. It was really reasonable to change the material with regard to the thermomechanical strength. Due to other actions the increased temperature was not needed to achieve the overall diesel engine performance.

Additionally it should be mentioned that all other requirements about costs, manufacturing and feasibility etc. are achieved as well.

3.2 WP 4.2

Thermo-mechanic fatigue tests performed by BAM were used to derive a TMF lifetime model. The TMF lifetime model was verified by computing the TMF lifetime of a tested turbine casing. Computation results show good agreement with test results considering usual statistical uncertainties inherent to fatigue lifetime.

The derived thermo-mechanic fatigue tests indicate that the new material is comparable to the actual standard material used in the marine environment. The increased corrosion resistance of the new material has little impact on the TMF lifetime of the material. The creep resistance, however, is higher compared to the standard material. This means that increased corrosion resistance correlates to the increased creep resistance. Contrary to the expectations this finding is an indicator that the new material is more suitable for stationary applications than for cyclic ones.

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Input from **WP5:Lifetime Performance Control**

Revision Final

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Contributors:	The university of Sheffield Universita del Salento ETH NTUA Aalto University University of Vaasa Politecnico di Milano WinGD Wärtsilä
Work Package Leader Responsible:	Jonatan Rösgren (Wärtsilä Finland Oy)

Start date of Project: 01/05/2015 Duration: 42 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020
The EU Framework Programme for Research and Innovation

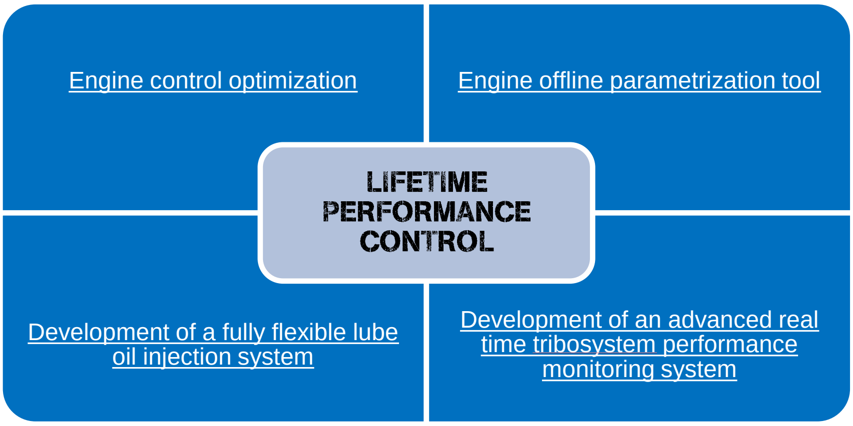
TABLE OF CONTENTS

1 WP 5 Objectives

The objective with the work package is to develop methods, systems and processes allowing a continuous optimized performance of the power plant throughout its lifetime.

2 Outline of work performed

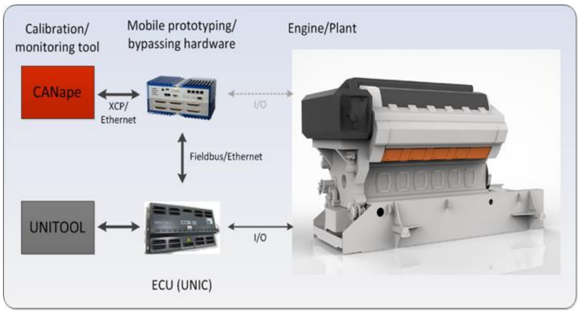
The structure of the work package can be seen in the picture. To achieve lifetime performance, the work has been divided into engine control optimization (5.1), offline parametrization tool (5.2), development of a fully flexible lube oil injection system (5.3) as well as development of an advanced real time tribosystem performance monitoring system (5.4).

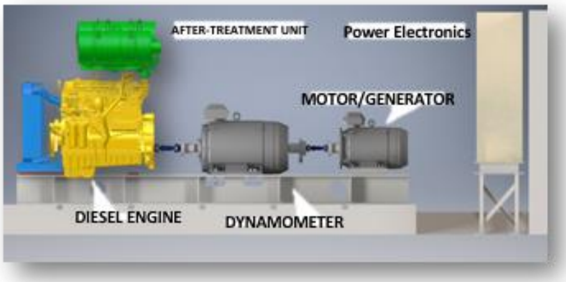


3 Achievements and Final Results

3.1 Sub projects 5.1 and 5.2

In sub-projects 5.1 and 5.2, the work has been developed and driven into demonstrators utilizing rapid prototyping systems on Wärtsilä engines at Wärtsilä as well as University of Vaasa premises as well as a hybrid system setup at NTUA. Furthermore, test engines has been utilized at Aalto university as well as ETH.





The work has been outlined partly on global system/engine level and partly on the individual cylinder combustion control. On the global control different methodologies has been developed such as

- Physical model based control
- Parametrization tool development for reference parameters as well as
- Model predictive control method for hybrid system control

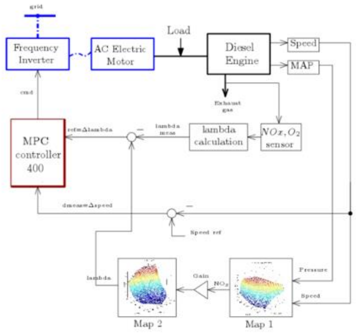


Figure 3.1.1 Hybrid diesel-electric control

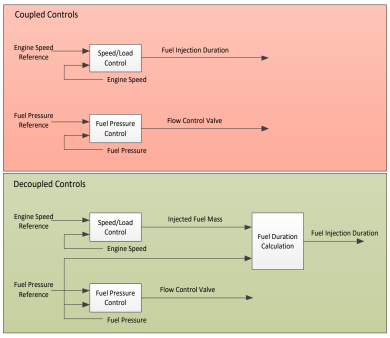


Figure 3.1.2 Physical model based control

On the cylinder-wise side methods has been developed for individual combustion control:

- NOX estimation
- Injector trimming
- Knock margin control
- Cylinder pressure accuracy

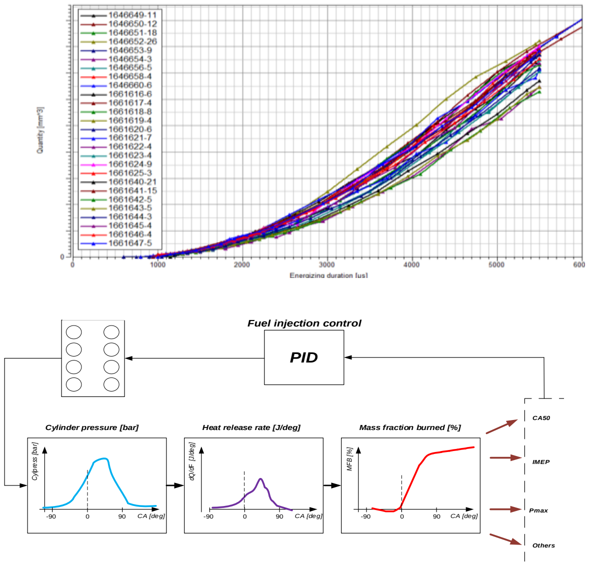


Figure 3.1.3 Injector trimming

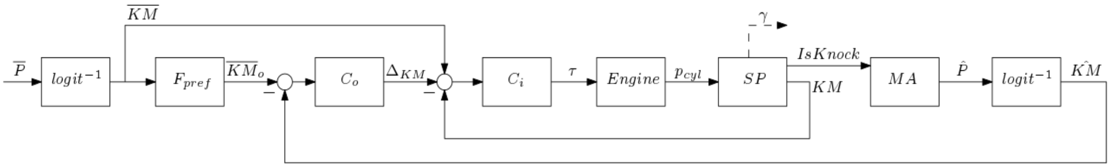


Figure 3.1.4 Knock margin control

A conclusion of the demonstrator tests is that many successful methods for optimizing lifetime performance control has been developed with the aim to minimize divergence from performance parameters throughout the lifetime.

3.2 Sub-projects 5.3, 5.4

The WinGD contribution to WP5 relates to the development of a fully flexible and adaptive lubrication system. Therefore sub-projects 5.3 and 5.4 focus on the „development and simulation of an adaptive lubrication system“ as well as the „development of an advanced real time tribo-system performance monitoring system“ incorporating the development of a lubrication system itself, the application of dedicated monitoring technologies and the establishment of a sound validation base.

Fig.3.2.1 gives a brief overview on key-steps towards the development of an adaptive lubrication system.

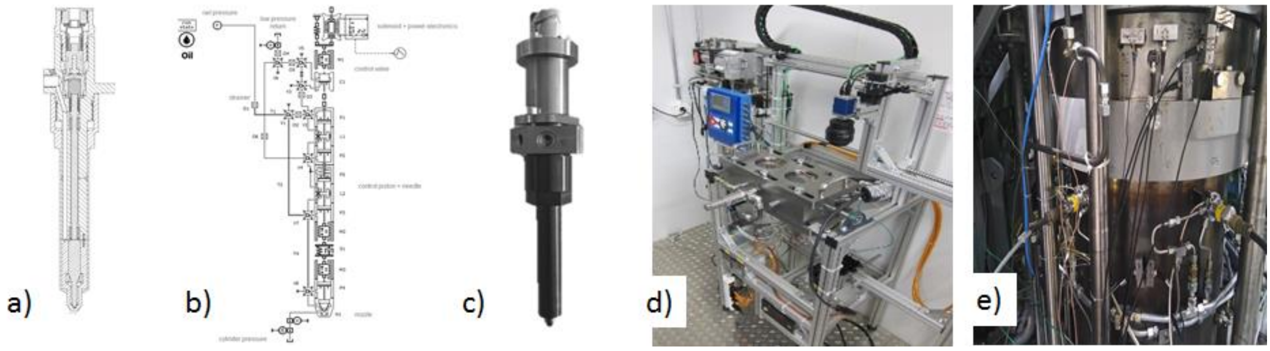


Fig.3.2.1: Key-steps towards the development of an adaptive lubrication system

a) Lubrication system concept study to nominate a suitable lubrication strategy
b) Simulation model development to optimize lubricant spray and injector performance
c) Final prototype injector design
d) Prototype injector testing and performance optimization
e) Full-scale prototype injector performance validation

The first phase of the project focused on the establishment of a sound validation base for simulation tool validation and testing of a prototype monitoring system. *Fig.3.2.2* shows the test bench which was designed to simulate real engine parameters related to the boundary conditions of a lubricant jet.

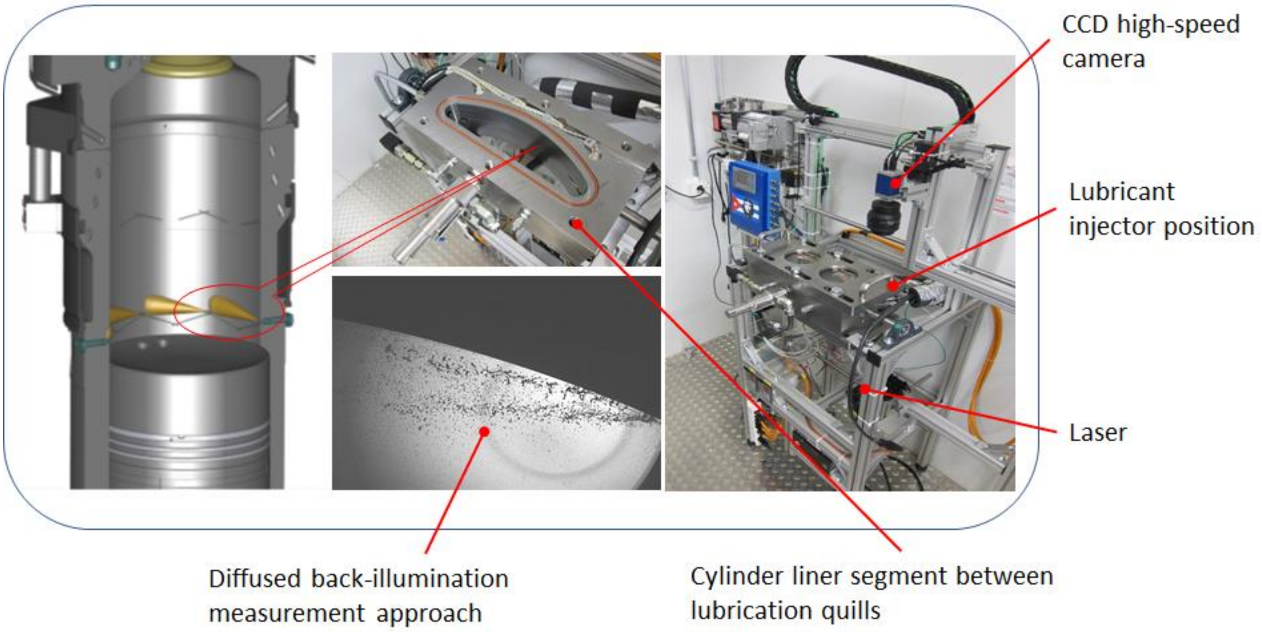


Fig.3.2.2: Experimental setup of the lubrication system validation facility

A major part of this particular investigation yields a statement regarding spray morphology under relevant simulated engine load conditions. *Fig.3.2.3* shows typical results of such an investigation demonstrating relevant effects on spray break up related to different engine load conditions.

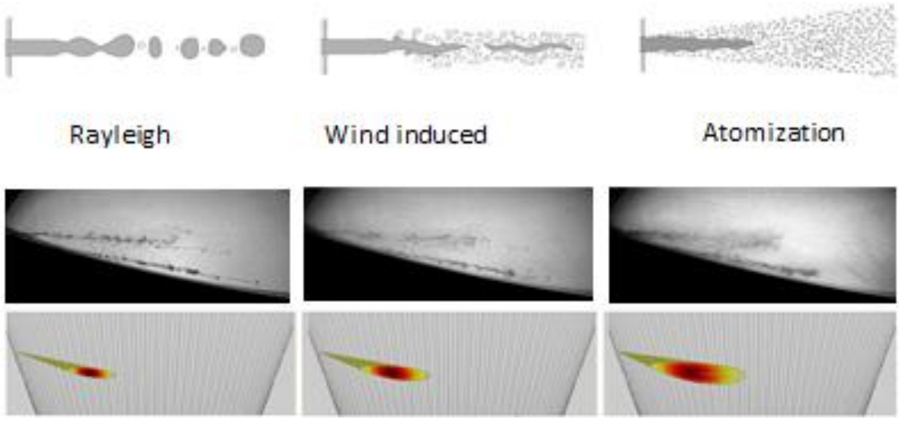


Fig.3.2.3: Typical lubricant spray morphology experimental results

Utilizing the test rig to quantify injected masses of lubricant helps to validate simulation tool developments, which were elaborated in parallel. *Fig.3.2.4* shows a comparison between simulated and measured quantities of injected lubricant.

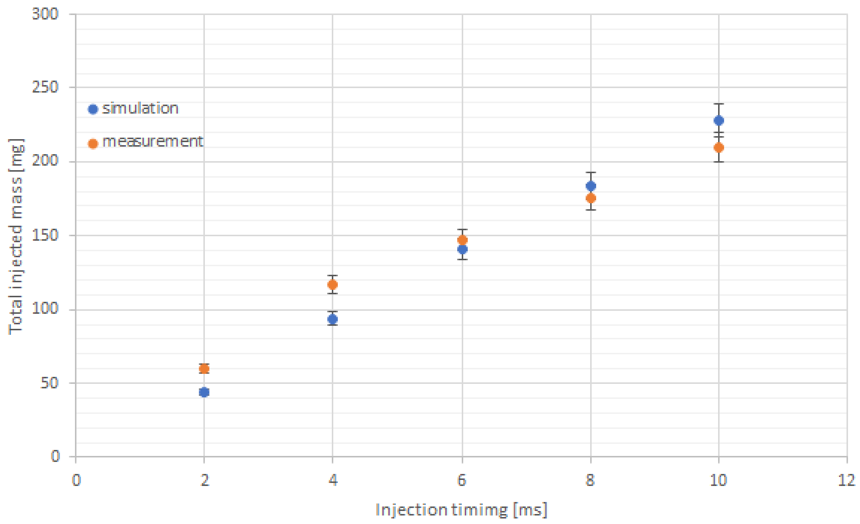


Fig.3.2.4: Comparison between simulated and measured quantities of injected lubricant

Another approach of making use of the test cell relates to the application of monitoring system components. A highly valuable parameter is found in a dynamic signal of viscosity. *Fig.3.2.5.b)* shows a robust prototype of such a novel sensing approach. Another, yet equal important aspect of tribosystem monitoring relates to surface effects on the “cylinder liner – piston ring” interface. A scuffing sensor was developed to address the possibility to detect variations of surface properties induced by thermal stress. *Fig.3.2.5.b* shows a prototype installed on the testing facility.

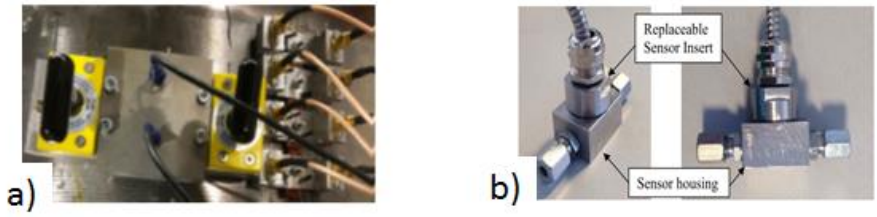


Fig.3.2.5: Prototype of a a) scuffing- and b) viscosity sensor prototypes

The final step of this project leads to the application of all developed prototype on a full-scale engine test. Fig.3.2.6 shows the arrangement of the new lubrication system and monitoring equipment for extended engine testing.

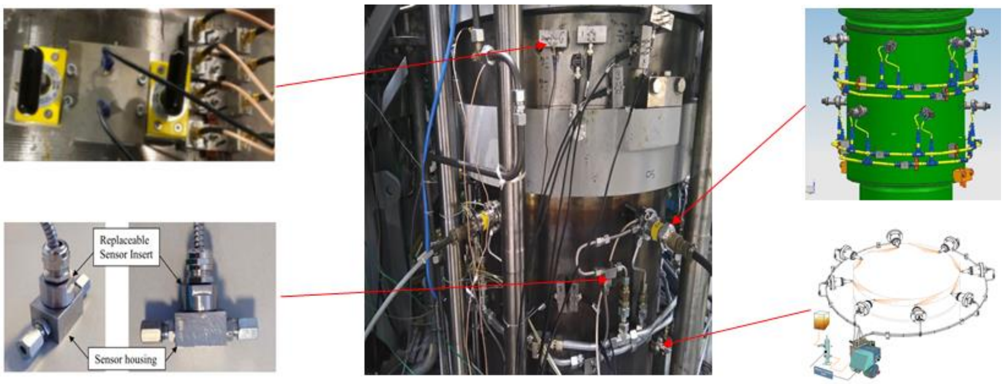


Fig.3.2.6: Arrangement of components of the full scale engine test

The full scale engine test was conducted to compare the standard pulse jet lubricating system performance with the new development simultaneously. Therefore, both systems were installed on the engine, but on different levels of the cylinder liner in order to provide equal testing conditions across the entire engine load range during a testing sequence. Another testing sequence was conducted with changed lubrication system positions to exclude effects related to the lubricating level position.

The real-time lubrication system performance validation is based on the well-established SO2 tracing technology, providing the possibility to quantify lubricant fractions in the exhaust duct. Fig.3.2.7 shows a schematic of the working principle of such a system.

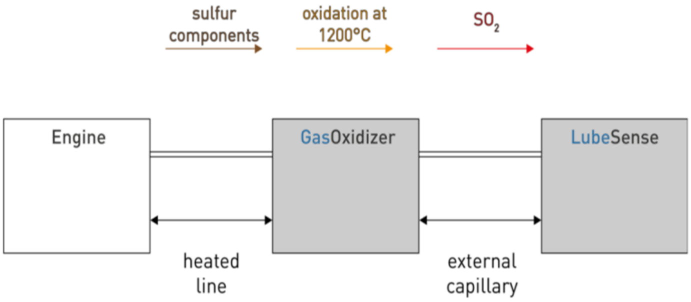


Fig.3.2.7: Schematic of a SO2 tracing technology to quantify lubricant fractions in the exhaust duct

A typical sequence of lubrication system performance evaluation is based on variations of lube oil feed rate settings at different engine load steps, *Fig.3.2.8* shows measurement results of such a feed rate variation test which provides the possibility to calibrate measurement results in real time.

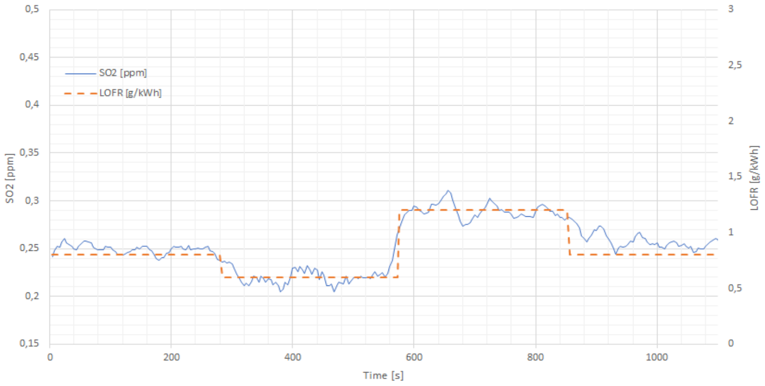


Fig.3.2.8: typical measurement result of a lube oil feed rate variation test

Fig.3.2.9 shows a comparison of SO2 measurement results and related fraction of lubricant in the exhaust duct. Results compare different lube oil feed rate settings at different engine load points. A clear increase of lubricant fractions in the exhaust duct is observed and explained with increased thermal loads of relevant engine components.

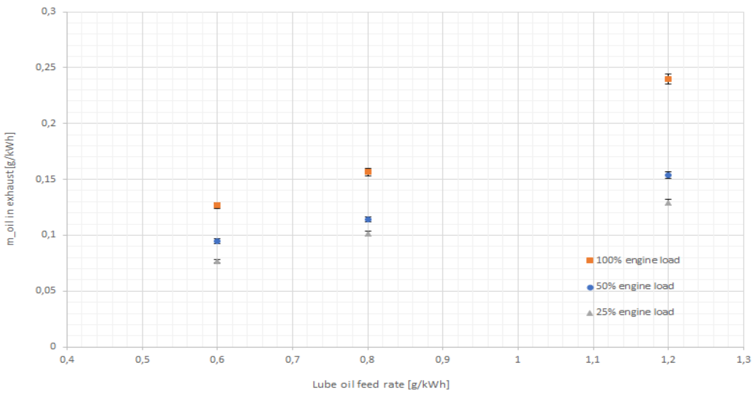


Fig.3.2.9: Comparison between different engine load effects on lubricant fractions in the exhaust gas

Fig.3.2.10 finally compares the already well performing standard pulse jet lubricating system with the new development of a fully flexible and adaptive common rail type of lubrication system.

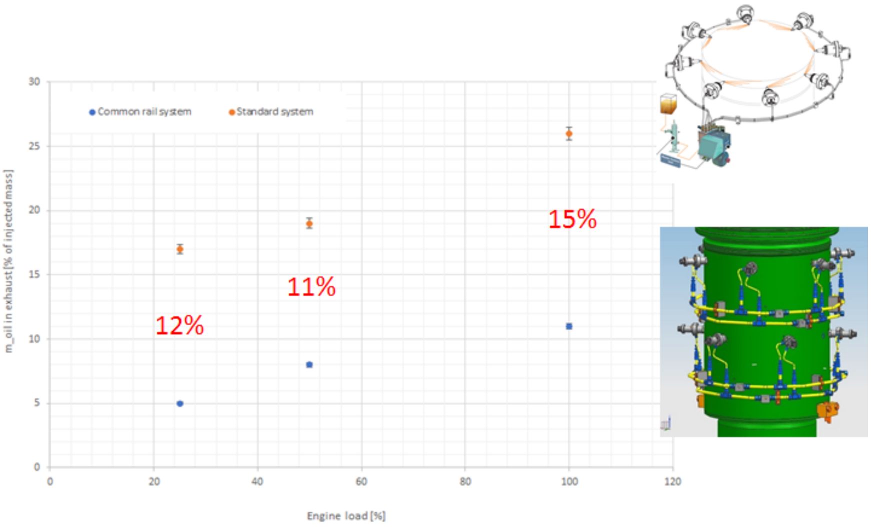


Fig.3.2.10: Comparison between lubrication system performances of tested lubrication systems

The new lubrication strategy clearly demonstrates the potential to considerably reduce lubricant fractions in the exhaust gas and therewith provides a remarkable potential to reduce total lube oil consumption to an extent that clearly exceeds expectations.

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Input from **WP 6: Model-based Control and Operation Optimization**

Revision Final

Nature of the Deliverable:	Report
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Contributors:	University Bremen TU Vienna Linköping University NTUA Technical University of Denmark KIT
Work Package Leader Responsible:	Dr. Mathias Moser (MAN-ES)

Start date of Project: 01/05/2015 Duration: 42 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020

The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 WP 6 Objectives

WP 6 will deal with the challenges described above. Next to developing technologies further there are the possibility to gain advances for the engine live time behaviour by improving tools, processes and methods in order to reduce operating, maintenance and deployment costs. Non-normative changes in the demands and conditions for the operation of the engine have to be considered. Therefore, in the WP an additional goal is reducing emissions at part load by improving the control and expand the present operating range of emission reduction technologies. In relevant new operating modes NOx emissions are expected to see up to more than 80% reduction.

2 Outline of work performed

2.1 Subproject 6.1: Predictive model-based engine control

The overall objective of this subproject was the development of a classical Proportional-Integral-Derivative (PID) engine speed controller and a Linear Quadratic Regulator (LQR) in order to compare their performances with changing loads. To make this possible, a mathematical model needed to be designed which covered all the subsystems of the engine such as the compressor, turbine, wastegate, etc. and the combustion. A strategy to overcome previous problems was made which turned out to be very successful. The identification of unknown physical parameters was done with the help of WORHP and approved to be very accurate. The data-based modelling of the combustion with the usage of PRIMO lined up to the quality of the other parameter identifications as well.

2.2 Subproject 6.2: Efficiency increase at part load

A predictive thermodynamic and fluid mechanic 1D engine model that is able to perform the electronic cut-out of selected cylinders was developed.

The simulation model predicts a general increase of brake efficiency and a decrease of NO emissions as well as methane slip with cylinder cut-out and fixed relative air/fuel ratio.

The workflow to optimize the engine efficiency was sated up in Noesis Optimus. The aim of the optimization process is to maximize the efficiency by the consideration of defined criteria: the resulting NO emissions must not exceed the emissions originating from a map that represents the IMO Tier III exhaust gas requirements and the knock onset must not be reached. The number of cut-out cylinders and the relative air/fuel ratio is optimized for the load range from 10 % to 50 %. The cylinder cut-out function was developed in MATLAB / Simulink. In order to test the function in the simulation, a *MiL (Model in the Loop)* environment in MATLAB / Simulink was developed. Therefore a FRM (Fast Running Model) of the engine was designed in GT Power. The FRM was integrated in the MiL environment. Engine tests on the testbed has been conducted. Using automatic code generation with Simulink PLC Coder, suitable code from the Simulink model was generated, which has been embedded into the MDT engine control system. Afterwards the cylinder cut-out function was tested on a HiL (Hardware in the Loop) Simulator and on ted bed.

2.3 Subproject 6.3: Development of intelligent algorithms for failure detection and plant analysis

The objective of Work Package 6.3 is to develop intelligent algorithms for failure detection and plant analysis. This is divided into smaller activities, summing up to a whole framework for the efficient and early detection of faults. Since we did not have any data with separable faults, we have used threshold violations as prediction target. First, we have developed a basic framework to predict alarm-threshold violations. We have then confirmed the usefulness of subspaces when detecting unusual engine behaviour by analysing changes. Following this, we have tailored the search for such subspaces to the measurement data used in this project and have designed a change-detection method that takes the stream characteristic of the data into account. Further, we have verified the quality of the compression technique currently in use at MAN-SW and have designed a new technique tailored for the use within our framework. Finally, we have implemented all these algorithms.

2.4 Subproject 6.4: Methods for evaluating engine performance via modelling and simulation

Improvements in the modeling of the cylinder processes have been investigated as well as additional improvements in the compressor efficiency modeling approach. The mean value engine modeling approach was applied to a real EGR engine used by a sailing vessel, to demonstrate the generality of the proposed modelling approach. The complete simulation model consisting of the engine and vessel dynamics model was used for EGR controller investigations. A simulation model of an engine with SCR was also developed for control system investigations. A next generation EGR O2 controller was implemented in production grade software and tested on a vessel operating at sea.

2.5 Subproject 6.5: Continuous combustion control & monitoring of mechanically controlled engines

Task 6.5 focuses on the development of a retrofit solution for mechanical controlled two stroke engine (MC types) aiming at implementing some of the electronic feedback control for performance improvement and emission reduction, that otherwise only exists on fully electronic, hydraulically actuated ME engines. Development and integration of a new electronically controlled pneumatic actuator for the existing mechanical fuel pump injection timing control was utilized in closed-loop performance tuning algorithms.

2.6 Subproject 6.6: Lifetime managed engine software deployment

A concept for lifetime managed engine software deployment has been developed with the aim that a power plant throughout its lifetime is adaptable to changes and future improvements beyond its original design. The electronically controlled two-stroke diesel engines include by design a built-in potential for improvements via software upgrading.

2.7 Subproject 6.7: Lifetime performance improvement by reduction of lubrication rate

The influences from the piston ring curvatures and lubricant injection position have been investigated. Both parameters are important for computing the net oil flow and perform a parameter study. A full-scale study has been conducted where the influence from piston ring curvatures, lubricant injection position, piston ring asymmetry, lubricant injection volume, combustion load and lubricant injection frequency is mapped.

3 Achievements and Final Results

3.1 Subproject 6.1: Predictive model-based engine control

The design and comparison of the PI(D) and LQR showed that both controllers are able to bring the engine speed to its reference value when load is changing. Clearly the LQR performed much better than the PI(D) which has many reasons. On one hand, LQR controls the whole system in order to keep the engine speed constant whereas in PI(D) each controller tries to keep its own reference value. On the other hand, LQR gives an optimal control. Hence, it is expected that it will outperform the PI(D) controller. Nevertheless, it shall be noted that both controllers are dependent on the setting of the weights which makes the comparison difficult.

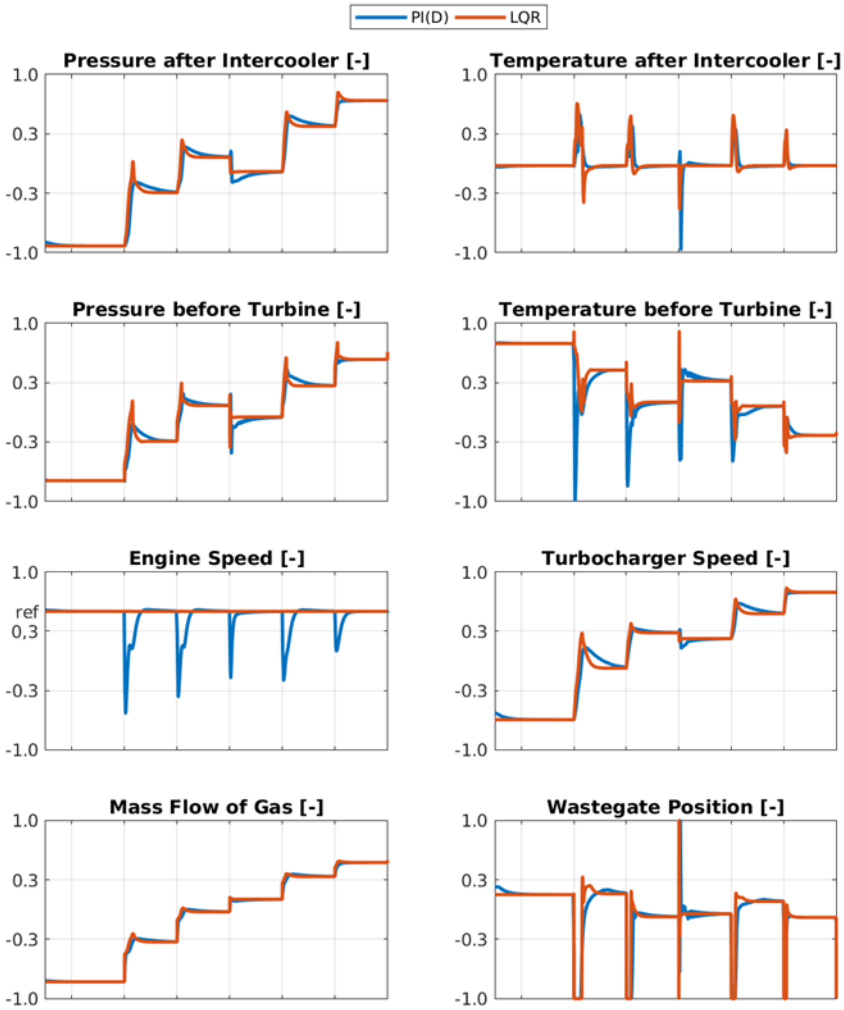

Figure 1: Comparison of PI(D) and LQR control

3.2 *Subproject 6.2: Efficiency increase at part load*

In Figure 2 results of the test bed measurements of the efficiency are depicted. The measurements have been taken at low load and it can be seen that the efficiency increases by switching of more cylinders till an optimum point at approximately 38% increase. If more cylinders are switched off the efficiency starts to go down again because of the too rich combustion in the remaining fired cylinders

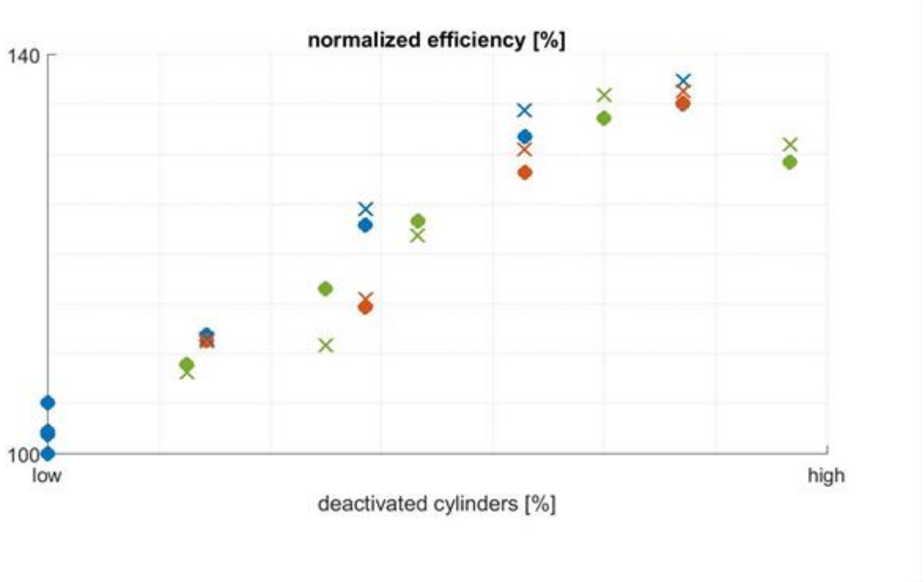

Figure 2: Normalized efficiency (measured on the test bed) for different cylinder cut-out scenarios

In Figure 3 the concentration of unburned hydro carbons (HC) over deactivated cylinders is shown at fixed load and engine speed for various cylinder cut-out scenarios. In this case the HC concentration could be reduced up to 97,5 %.

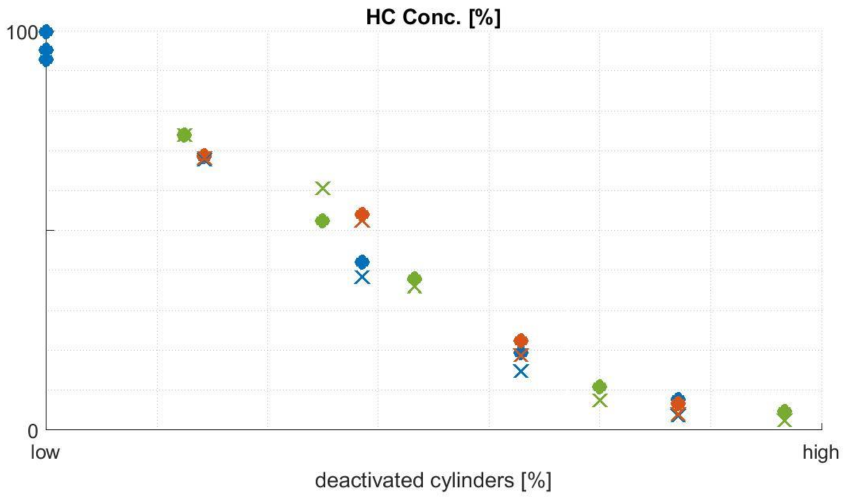

Figure 3: HC concentration (measured on the test bed) for different cylinder cut-out scenarios

3.3 Subproject 6.3: Development of intelligent algorithms for failure detection and plant

Instead of engine faults we have performed our analysis with a different target: alarm states. Such alarms occur when sensor measurements exceed a sensor-specific measurement. However, a real engine fault would most likely not be predictable knowing a single sensor measurement. Thus, we predict the threshold violation with surrogate data, i. e., excluding the sensor which violates the alarm threshold from the data available to the predictor.

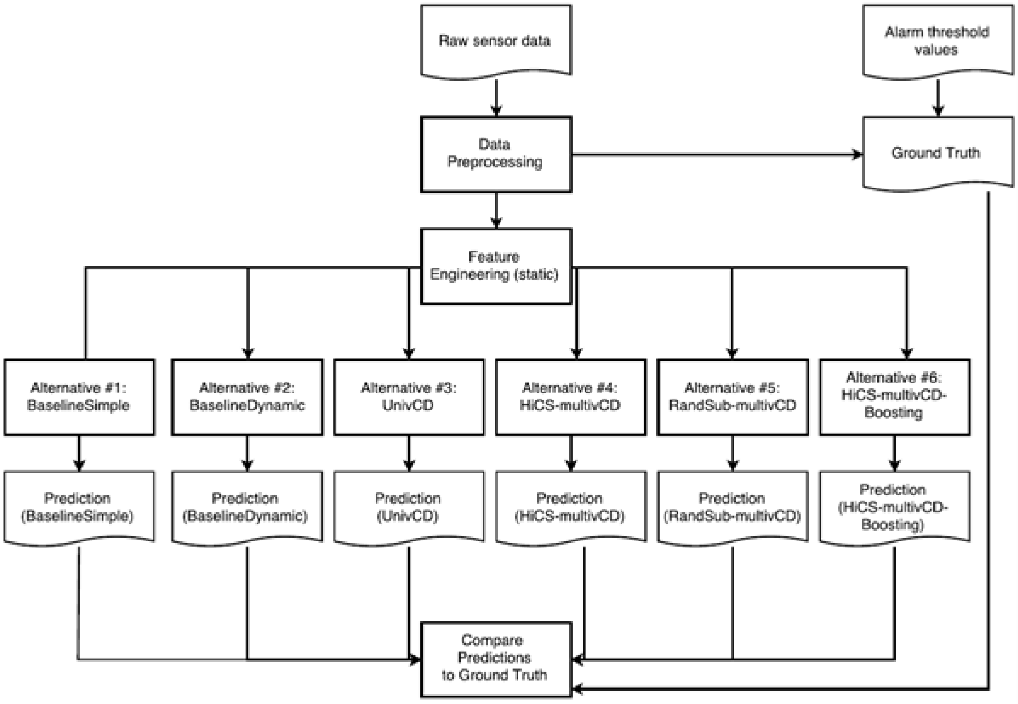

Figure 4: Overall process of framework evaluation

We then developed seven different frameworks for predicting the alarms. The frameworks differ in the subspace search used (which includes not using subspaces), features and actual classifier. We then used multiple metrics to measure how well these frameworks predict the alarms. Figure 4 is a process overview, and Table 1 lists the results. They indicate that the framework HiCS-mCD, using the subspace search method HiCS as well change detection based on hoteling’s T-square statistics is most useful in predicting the alarms.

Framework	***Accuracy***	***Specificity***	***Sensitivity***	***Precision***	***F-score***	***AUC***
BaselineSimple	82.2%	82.4%	21.2%	4.60%	4.20%	0.550
BaselineDynamic	75.4%	75.6%	**30.4%**	6.20%	7.50%	0.548
UnivCD	92.9%	93.2%	23.4%	7.80%	8.90%	0.531
HiCS-mCD	**99.5%**	**99.8%**	23.1%	**36.5%**	**28.2%**	**0.631**
RandSub-mCD	96.0%	96.4%	8.20%	2.30%	3.00%	0.520
HiCS-mCD-Features	77.9%	78.0%	30.5%	9.9%	11.2%	0.537
HiCS-mCD-Ensemble	99.3%	99.6%	14.4%	14.7%	14.6%	0.581

Table 1: Average results for each framework. Best values for a metric are indicated in bold

3.4 Subproject 6.4: Methods for evaluating engine performance via modelling and simulation

A detailed mean value model of a vessel engine with EGR was developed by Linköping University (Figure 5). The model was parameterized with data from engine shop test and from standard operation of the vessel. The model was accurate enough for development and validation of EGR O2 controller concepts. A similar model of an engine with SCR was developed by NTUA. The SCR engine model was also intended for development and validation of control strategies.

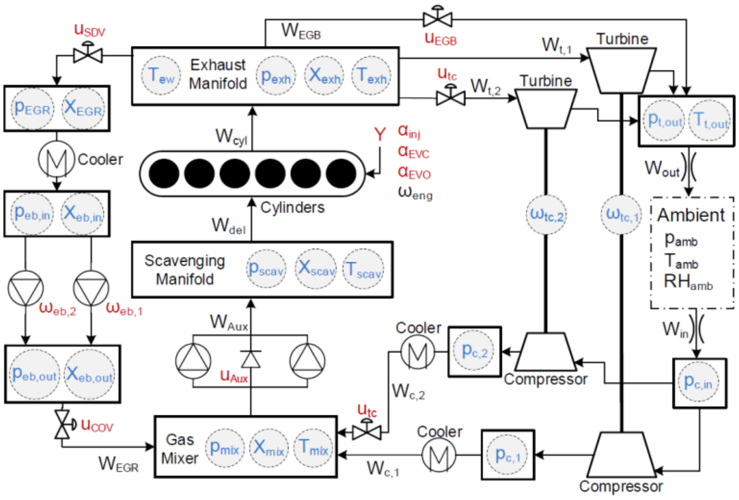

Figure 5: Component overview of the air path part of the EGR mean value model.

A next generation EGR O2 controller (Figure 6) was implemented as part of the Emission Reduction Control System, which controls EGR and SCR on engines from MAN-SE. The control concept was validated by simulation with the mean value engine model from Linköping University.

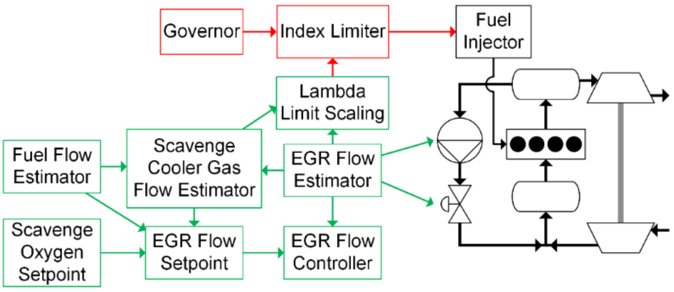

Figure 6: Structure of the new EGR O2 controller that was implemented and tested during the project.

The main reason for implementing the new EGR O2 controller was to solve certain acceleration issues experienced with the first generation EGR O2 controller. These issues involved excessive formation of exhaust smoke during vessel acceleration. The new EGR O2 controller was tested during acceleration of a vessel in service and the acceleration was carried out without excessive smoke generation, so the controller upgrade was very successful (Figure 7).

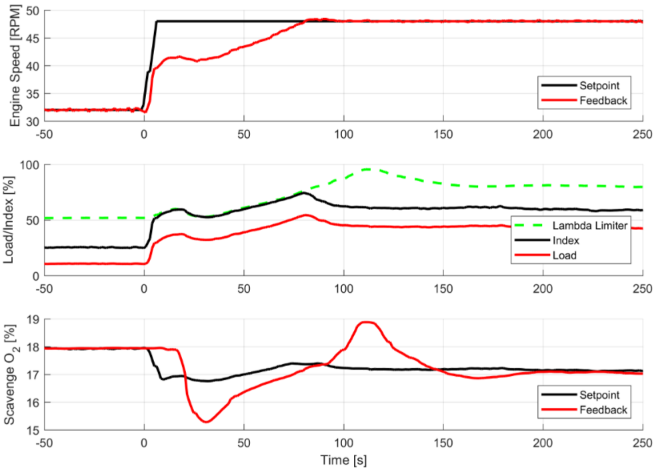

Figure 7: Data from a successful vessel acceleration test with the new EGR O2 controller. The Governor Index and EGR Flow was controlled such that the scavenge receiver oxygen content remained sufficiently high to avoid excessive smoke formation during the acceleration.

3.5 Subproject 6.5: Continuous combustion control & monitoring of mechanically controlled engines

Regarding retrofit of continuous combustion control of mechanically controlled two-stroke engines, it is concluded that the overall concept evaluated is technically feasible. Also, there is an uncovered potential in monitoring the condition of mechanical components. The identified concept contains a suitable control loop architecture. Thus, the actuator integration with the existing online cylinder pressure monitoring system has been performed to an outline level, including acutators and network components, for clarifying the principles of the solution rather than developing a physical implementation in real life. Seen from a technical perspective, the concept is ready to be revisited.

3.6 Subproject 6.6: Lifetime managed engine software deployment

The three objectives, the onsite hardened platform, the description of secure remote connectivity and the IoT collaboration and connectivity model, are steps on the way to lifetime managed software deployment for two-stroke engines, scaling to fleets of vessels without requiring onboard attendance. The objectives are related to the recent developments of the hardened platform for Engine Management Services (EMS) and the Online Engine Concept. A hardened image for EMS has been produced. It follows the principles outlined in the present document. Furthermore, an Online Engine Concept has been described. This serves as a basis for current development of engine software. In this work package it was intended to perform a pilot project with Kongsberg on secure remote access, which however, due to market conditions, was replaced by the ongoing development.

3.7 Subproject 6.7: Lifetime performance improvement by reduction of lubrication rate

A parameter study was performed utilizing the validated numerical model. The relationship between piston ring asymmetries, lubricant consumption and asperity contact friction was investigated. The figure below shows that the smallest asperity contact friction is obtained with large piston ring radii and a lubricant injection position close to TDC (TDC -> l=0).

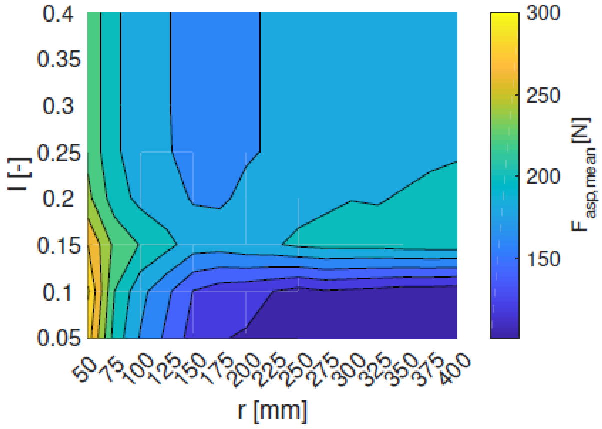

Figure 8: Mean Asperity Contact Friction correlation with Piston Ring Curvature (r) and Lubricant Injection Position (l).

The lubricant consumption and asperity contact friction was established numerically. Both parameters depend on the operating conditions such as lubricant injection position, piston ring curvature and piston ring asymmetry. The figure below shows the volume of lubricant lost (Q_lost) and mean asperity contact friction (F_asp) as function of the piston ring asymmetry (X_h0) for a fixed lubricant injection position and piston ring radius. For this example the smallest lubricant consumption is achieved at approximately X_h0 = 0.65-0.7 and the smallest asperity contact friction at X_h0=0.7-0.73.

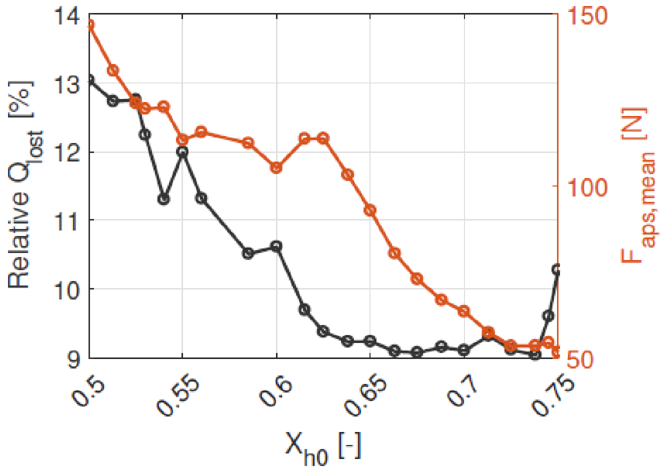

Figure 9: Correlation between piston ring asymmetry (X_h0), lubricant consumption (Q_lost) and asperity contact friction (F_asp,mean).

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Input from **WP7: On-engine aftertreatment systems**

Revision Final

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Contributors:	Wärtsilä Finland
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	University of Vaasa
	PSI
	VTT
	Johnson Matthey
	Dinex Finland
Work Package Leader Responsible:	Jukka Leinonen (Wärtsilä Finland)

Start date of Project: 01/05/2015 Duration: 42 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020
The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 WP 7 Objectives

- Integration of SCR (Selective Catalytic Reduction) with the existing strong Miller cycle 4-stroke diesel engine and combining it with particulate emission (PM) abatement technology would enable to achieve more than 80% NOx emission reduction and 25% reduction in PM. Also a combination of integrated SCR and EGR (Exhaust Gas Recirculation) is to be developed. Feasible solutions of combining the above mentioned technologies having as a target the near zero emission engine are also studied.
- Integrating methane and ethane abatement technology into lean burn 4-stroke gas engines will enable compact solutions to reduce emissions. The objective is a catalytic system working with the engine and optimization of the engine performance. Also the knowledge on deactivation & regeneration strategies for integrated catalyst solutions and methane formation and location in the engine exhaust system should increase. Target is a greenhouse gas emission decrease up to 15% and fuel savings up to 5%.
- Development of key technology for integration of the currently separated SCR aftertreatment into the existing 2-stroke engine structure, which enables widespread installation of SCR systems on all ship types and additionally increase overall NOx removal efficiency above 80%, reduce overall hydrocarbon emissions (HCs) by 50% or more, reduce PM emissions and lead to potential fuel savings of up to 5%.

2 Outline of work performed

Performed work at Work Package 7 consisted five subprojects:

- 7.1 Combined on-engine aftertreatment solutions for 4-stroke diesel engines
- 7.2 SCR reduction agent injection solutions
- 7.3 Integration of methane and ethane abatement technology with gas engines
- 7.4 Emission measurement systems for integrated after treatment technologies
- 7.5 Experimental assessment of newly developed vibration resistant SCR catalyst in field & Concept about catalyst aging from in-field monitoring and laboratory experiments

University of Vaasa concentrated literature reviews about SCR integration with engine and particulate abatement with particulate filters. University of Vaasa made experimental study about Methane slip abatement by hydrogen.

VTT made research and testing of NH3 sensors and PN measurement system in laboratory and ship campaigns. VTT did also some PM measurements with help of Wärtsilä Finland.

Wärtsilä Finland build test platform for particulate reduction research with real exhaust gas and performed testing at Vaasa laboratory. Reduction agent injection in SCR and development of control strategies performed by Wärtsilä Finland.

Wärtsilä Spain performed feasibility and demonstration of integrated methane and ethane abatement with gas engine at engine laboratory with support from Wärtsilä Finland.

PSI performed feasibility and demonstration of NOx and particulate reduction with tests on test engine and made laboratory testing of catalyst activity and investigating SCR reaction kinetics under elevated pressure.

WinGD defined an end of life vibration test cycle by measurements from engines and test new catalyst concepts in the field.

Johnson Matthey / Dinex Finland studied development of a vibration resistant SCR catalyst for the use in a pre-TC SCR application integrated in the engine.

3 Achievements and Final Results

PSI, All the work finalized due to plan. Comprehensive measurement campaign performed with detailed data analysis (performance information, in-cylinder pressure analysis, emission measurements) and potential of the combined application of EGR and WFE on the simultaneous abatement of NOx and soot has been successfully investigated (Figure 1).

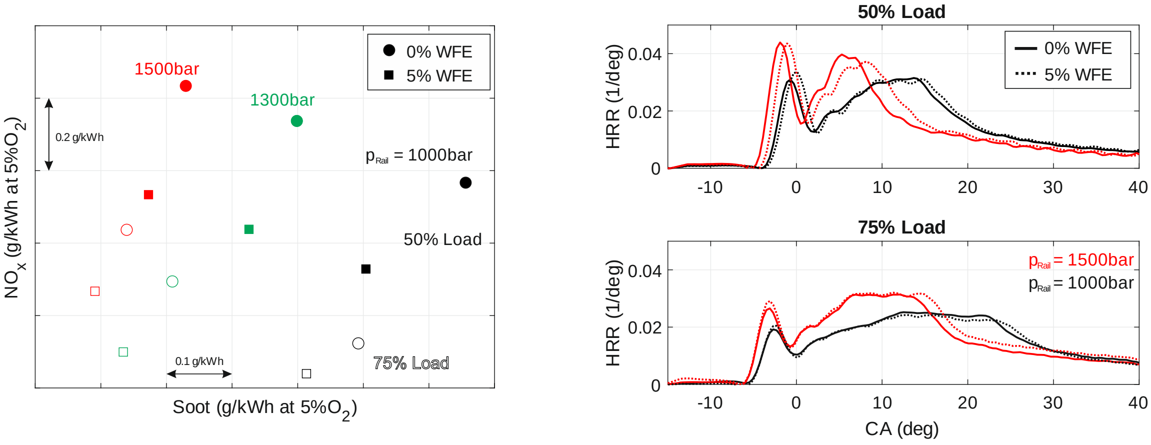

Figure 1: 50/75% Load, 22% EGR, SOI 10/11°CA bTDC

WFI, All Deliverables submitted due to plan and other activities were finalized within schedule. Test platform for particulate reduction research with real engine exhaust has been built and testing was done (Figure 2). Results have shown test setup feasible and the potential for the particulate reduction. Work on improved SCR reagent injection systems has also done, as has support for the measurements conducted at Wärtsilä Spain in the subproject: “Integration of methane and ethane abatement technology with gas engines”.

Figure 2: ESP + Cyclone container and inlet pipe during installation

WSP, Feasibility and demonstration of integrated methane and ethane abatement with gas engine testing was ended due to plan (Figure 3).

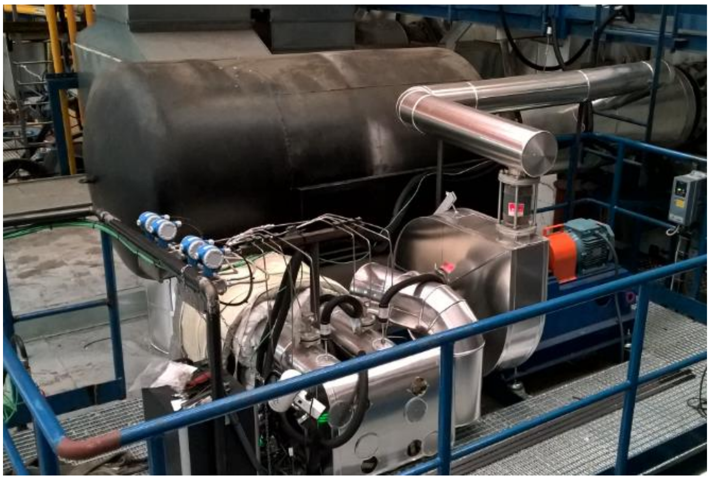

Figure 3: Small scale test bench at the roof of engine test cell

University of Vaasa, All Deliverables submitted due to plan. Literature review regarding SCR engine integration and particulate abatement and Feasibility and demonstration of methane catalyst element regeneration method study and experimental study has completed due to plan. Feasibility study about catalyst rig testing showed that technically suitable engine can be found and that the VEBIC laboratory in Vaasa would be cost efficient possible location for the rig. The experimental study about Methane slip abatement by hydrogen addition was completed at two different temperatures (Figure 4).

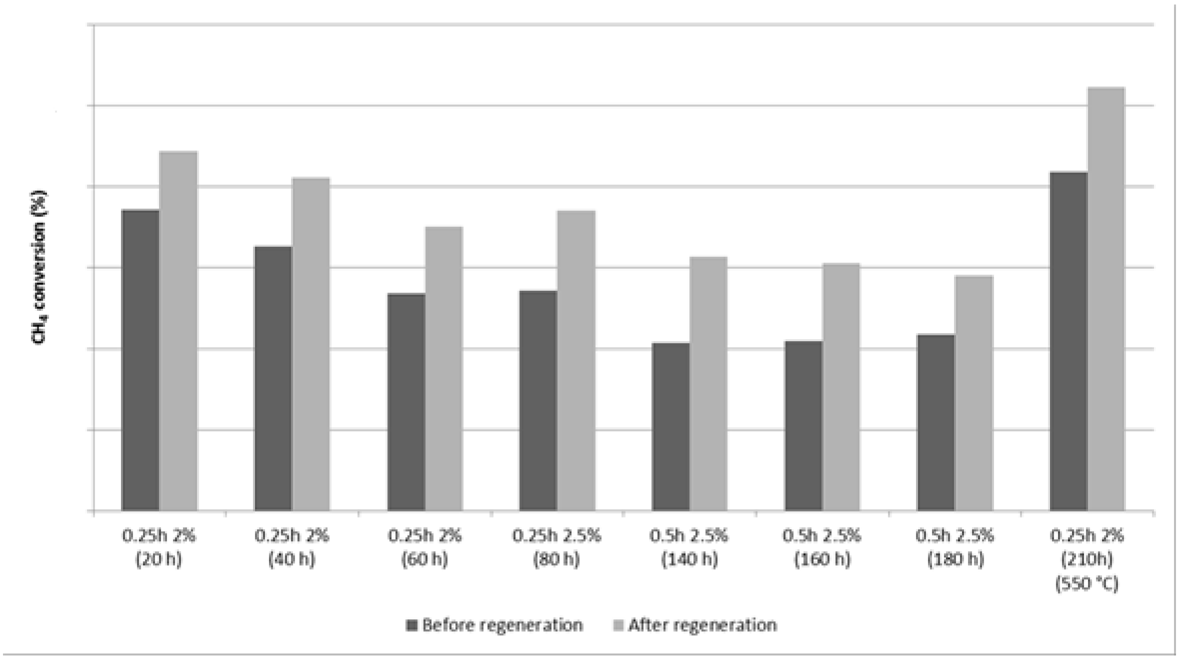

Figure 4: Average CH4 conversions during the experiment at 500 °C and at 550 °C.

VTT, All Deliverables submitted due to plan. A commercial NH3 sensor designed for automotive applications using high quality diesel fuel was tested in laboratory and in ship campaigns. The sensor´s response was compared to results obtained by FTIR and LDS methods (Figure 5). With Sulphur free (S< 10 ppm) diesel the methods gave equal results. However, the on-board tests clearly demonstrated the difficulties of NH3 measurements with extractive sampling from exhaust gas in the presence of SO2. The long-term campaigns showed that NH3 sensor has potential for monitoring of NH3 in harsh conditions if precautions are taken for protecting the sensor against particle matter.

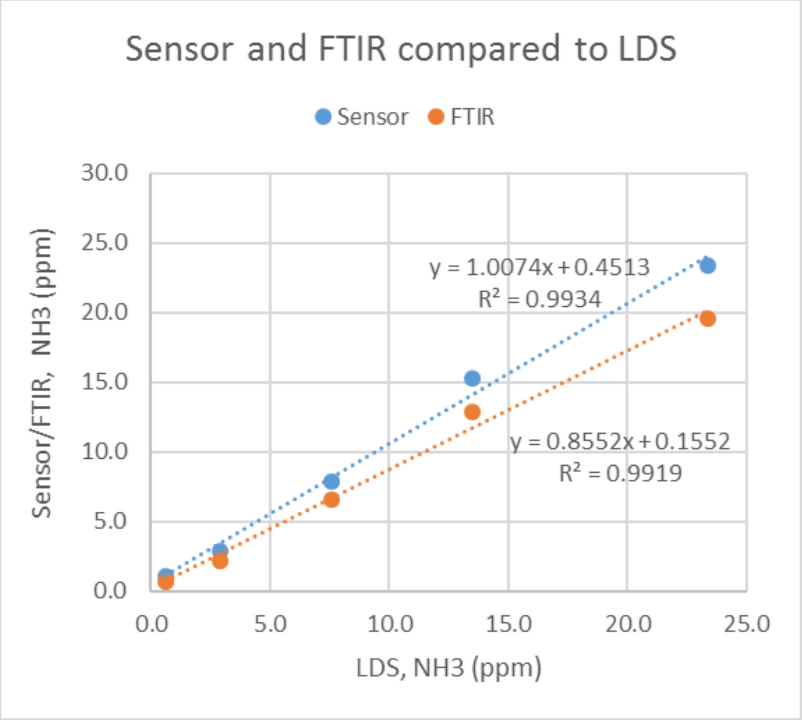

Figure 5: Comparison of NH3 measurement methods

WinGD, Johnson Matthey and Dinex Finland researched re-design of standard element frame for ceramic catalyst and re-design of substrate of metallic catalyst in order to improve the vibration resistance of their standard catalyst technology. Several concepts were tested on hot shaker test bench according test cycle based on field measurements supported by WinGD. The most promising concepts as test sample in field test on a vessel were prepared and condition analysis was made after field tests (Figure 6). There were no significant findings in terms of mechanical damage and wash coat loss. Both partners enabled their catalyst to cope with the requirements of an integrated pre-turbo SCR-system.

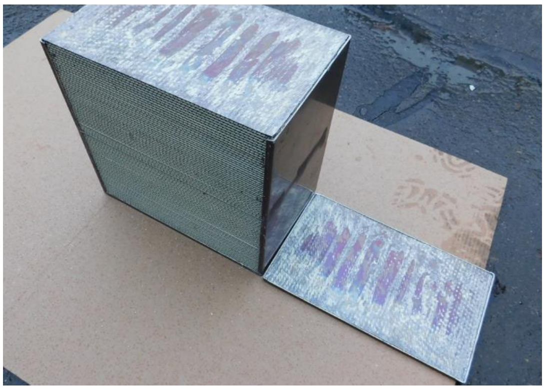

Figure 6: Condition analysis after hot shaker test

WinGD and PSI made investigation of SCR reaction kinetics under elevated pressure for catalyst characterisation under real operation condition. In addition, laboratory experiments about SCR reliability, focussing on temperature management when operating on high sulphur fuels, were conducted. A fully extruded ceramic catalyst was installed in an SCR-system on a vessel (Figure7) in order to gain knowledge about catalyst activity due to operation. The Post Mortem Analysis of catalyst after 900hours field testing revealed higher DeNOx-activity compared to the fresh one, presumably due to vanadium uptake from the flue gas. The elemental analysis of the samples regarding poisons causing catalyst de-activation did not reveal any significant uptake of catalyst poisons.

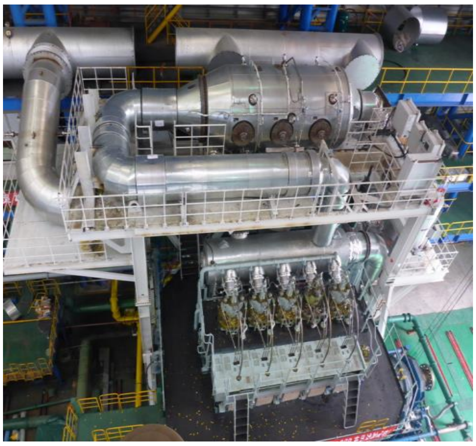

Figure 7: SCR-installation on WinGD field test vessel

HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.4**

Overall review of Project Results

Input for **WP8: Integrated SCR and combined SCR and filter**

Revision Final

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Contributors:

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Work Package Leader Responsible: Lone Schmidt (MAN Energy Solutions SE)

Start date of Project: 01/05/2015 Duration: 42 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020
The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 WP 8 Objectives

1.1 Engine Integrated SCR (2 stroke)

- Investigation of High Pressure SCR process; injection, mixing, decomposition and flow distribution with the aim of making the SCR components compact while still maintaining the same high performance as best available technology today
- Designing of engine integrated High Pressure SCR with system with unaffected engine footprint and only slightly affected gallery arrangement around the engine
- Testing of compact High Pressure SCR component performance on 4T50ME-X test engine

1.2 Combined DPF and SCR (4 stroke)

- 80% PM reduction with after-treatment system (based on IMO Tier II engine out emissions)
- 80 % NO_X reduction with after-treatment system to reach IMO Tier III limits
- Reduce the necessary installation space for after-treatment system SCR on DPF within IMO Tier III (SCR only) system
- Adaption and integration of the after-treatment system (SCR on DPF) on a marine Diesel engine

2 Outline of work performed

2.1 Engine integrated SCR (2 stroke)

HP SCR process has been investigated by CFD simulations and in pilot scale testbeds before scale-up. A full scale engine integrated HP SCR system has been designed, installed and successfully tested on the 4T50ME-X R&D engine. Furthermore, a measurement device for traverse NH_3 measurements was developed and tested on the engine as well.

A Pilot scale reactor with pulsating flow has been developed in order to study SCR flow conditions in reactor inlet. Test results have been used for characterisation and optimization of flow conditions and validation of numerical models.

2.2 Combined DPF and SCR (4 stroke):

Based on the SDPF benchmark in laboratory scale, a full scale EAT system has been installed on a four-stroke marine Diesel engine (12V175D R&D). The EAT system comprises SCR coated DPF (SDPF) and a sulphur resistant DOC, which provides the required NO_2 for the passive soot regeneration.

Investigation of the urea injection, mixing and decomposition processes have been carried out under the influence of temperature and pressure in a hot gas test rig. A prototype of an ammonia generator, as a compact device for urea decomposition has been developed and tested as well.

3 Achievements and Final Results

3.1 Engine Integrated SCR (2 stroke)

An engine integrated high pressure SCR system has been designed, installed and successfully tested on the R&D 2-stroke diesel engine in Copenhagen. The result is a compact high pressure SCR system fully integrated with the engine, see Figure 1

Figure 1 Integrated SCR receiver installed on a 4-cylinder 2-stroke R&D engine

A significant reduction in size occupied by SCR has been obtained. The footprint is reduced with more than 90% compare to traditional high pressure SCR. The test results verified the engine integrated HP SCR concept by fulfilment of IMO Tier III NO_X limits. Furthermore a measurement device for traverse NH_3 measurements was developed and tested successfully on the engine. For the gas probe device new methods of using purge air for sealing, cooling and cleaning were developed.

Flow phenomena in a simplified SCR reactor setup has been investigated for optimization of inlet reactor flow conditions, see Figure 2.

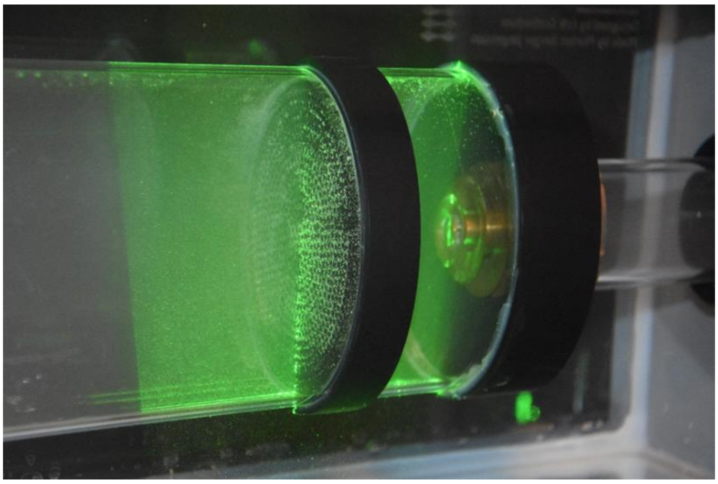

Figure 2 Experimental setup for investigation of pulsation phenomena

The test results were used for successful comparison of numerical and experimental concentration and velocity profiles at different development stages of flow turbulence.

3.2 Combined DPF and SCR (4 stroke)

A benchmark of SCR coated DPF in laboratory scale has been carried out based on measurements in a synthetic gas test bed as well as BET and SEM/EDX investigations. A full-scale EAT system comprising an SDPF and a sulphur resistant DOC has been investigated to validate the results of the benchmark. The EAT system has been applied to the 12V175D R&D marine distillate engine, see Figure 3

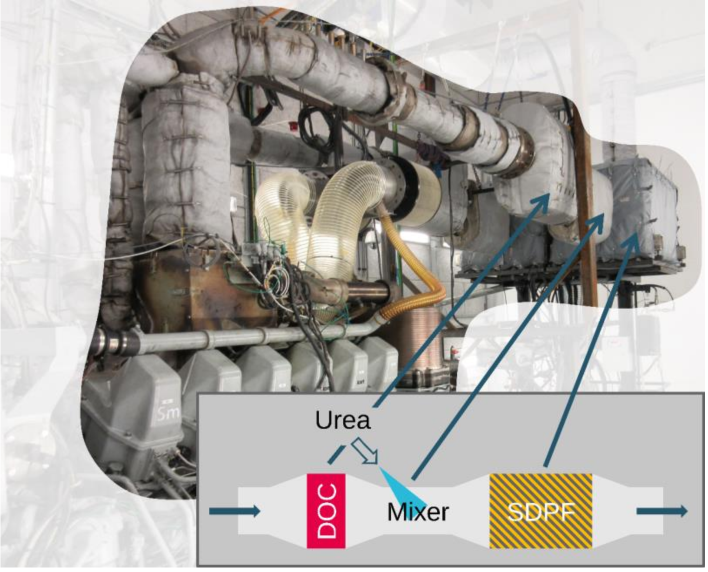

Figure 3 EAT system comprising DOC, mixer and SDPF installed on a 12-cylinder 4-stroke R&D test engine

The test results showed that the compact SDPF system fulfills the 80 % PM and NO_X reduction based on IMO Tier II engine out emissions.

Urea decomposition and mixing has been investigated in a hot gas test rig, see Figure 4.

Figure 4 Hot exhaust gas flow rig for investigation of urea injection, evaporation and mixing

In detail, the urea decomposition has been investigated at different temperature and pressure conditions and the influence of mixing elements has been characterized. Furthermore, a calibration method for the application of PDA at the hot gas test rig has been developed. The PDA measurements have been used for reliable droplet spectra of urea sprays as validation data for numerical simulations.