HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D10.2**

Interim presentation of overall project results

Revision Final

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

HORIZON 2020

The EU Framework Programme for Research and Innovation

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1 Summary

This Deliverable Report provides an interim presentation of the HERCULES-2 Project results at the milestone of Project Mid-Term i.e. on the completion of month 18. Following a short introduction, the main results of the Project are briefly presented on a per-Work Package basis, followed by a brief description of future work.

2 Introduction

HERCULES-2 is the next phase of the R&D programme HERCULES on large engine technologies, which was initiated in 2004 as a joint vision by the two major European engine manufacturer groups MAN and WARTSILA, which together hold 90% of the world's marine engine market. Three consecutive projects namely HERCULES - A, -B, -C spanned the years 2004-2014 with a combined budget of 80 M EUR and a total of more than 70 partners. More than 500 scientists and engineers worked in 155 subprojects on engine efficiency, fuel consumption, gaseous and particulate emissions and reliability. These three projects produced exceptional results and received worldwide acclaim. Already several research results of HERCULES -A, -B are offered as commercial products in new engines for ships. More than 30 patents are related to these past Projects. The HERCULES programme has shown that commercial competition between research partners does not preclude the sharing of R&D aims and the cooperation, in order to tackle issues of world significance, such as the environment.

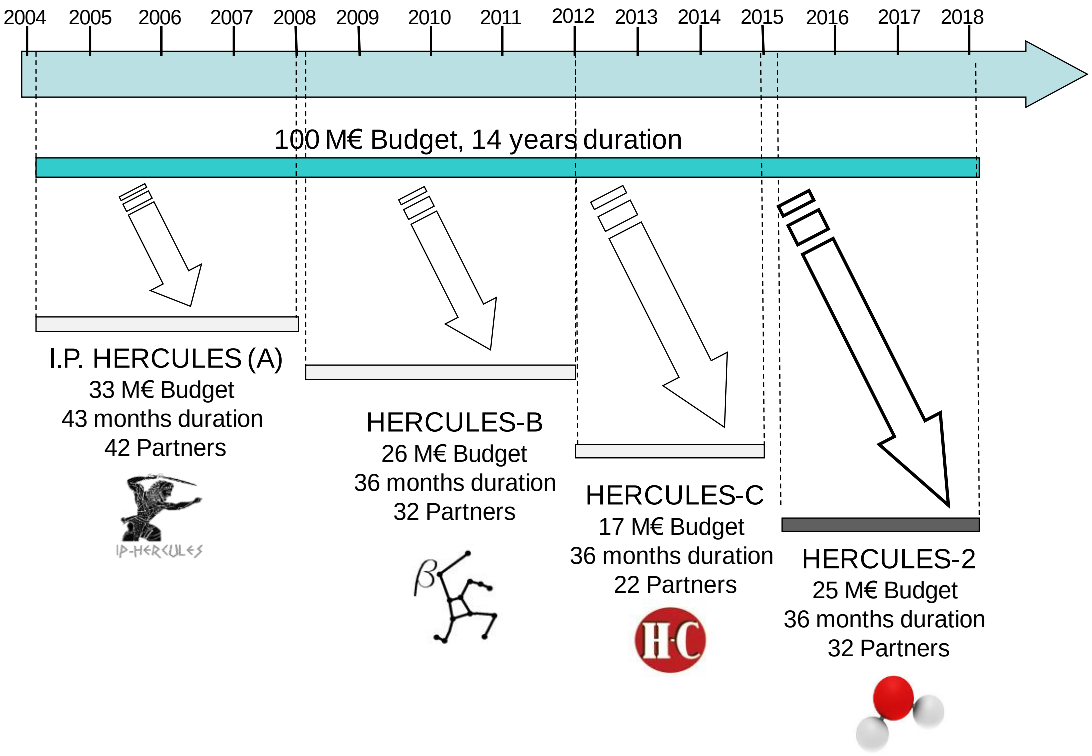


Fig. 1: Lifetime of HERCULES R&D Programme

The first Project HERCULES–A was characterized by wide-spectrum research, with emphasis on emission reduction, considering a multitude of different new technologies. HERCULES-B developed further selected emission abatement technologies, addressing also CO2 and efficiency, whilst HERCULES-C emphasized the integration of groups of technologies, as shown in Fig. 2.

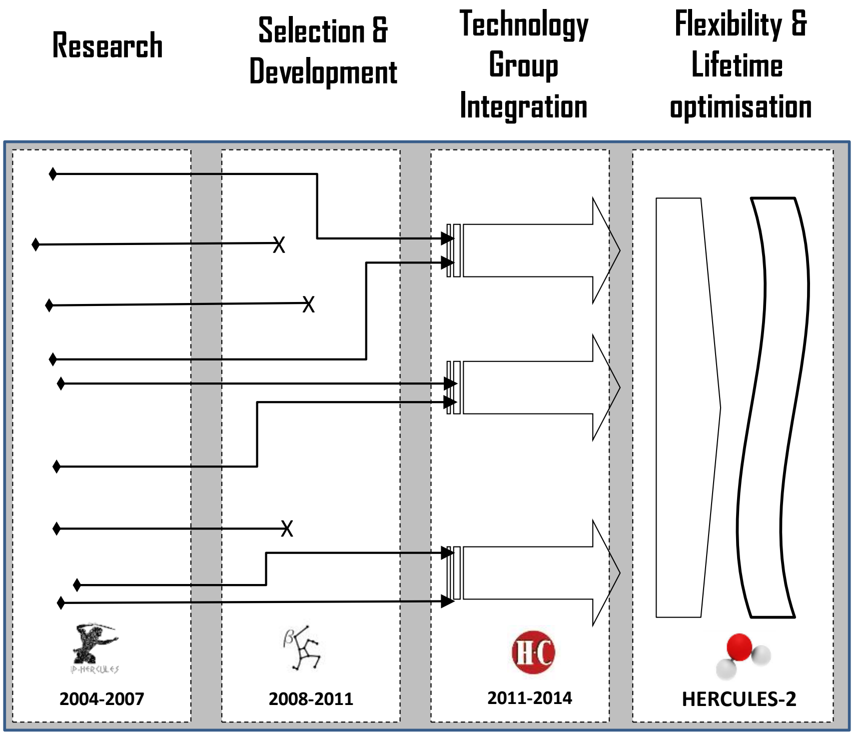


Fig. 2: Evolution of HERCULES R&D Programme

3 Objectives

The project HERCULES-2 is targeting at a fuel flexible large marine engine, optimally adaptive to its operating environment.

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 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.

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

For each R&D Work Package Group, specific Objectives, related Performance Indicators, Target Values and actions How to achieve Targets are provided in Annex 1 of the HERCULES-2 Grant Agreement.

4 Presentation of Project results at Mid-Term

In the following paragraphs, for each Work Package Group the Project results are presented on per Work Package basis. A short description of each Work Package Group is followed by a short description of the results as well as the related presentation.

4.1 WPG I: Fuel flexible engine

The objective of this WPG is to build engines able to switch between fuels, both conventional and alternative and of variable composition and quality, whilst operating in the most cost-effective way and complying with the regulations in all sailing regions. The fuels to be examined are different bio-fuels, DME, methanol, LNG, LPG, as well as HFO and MDO in combination with the former fuels.

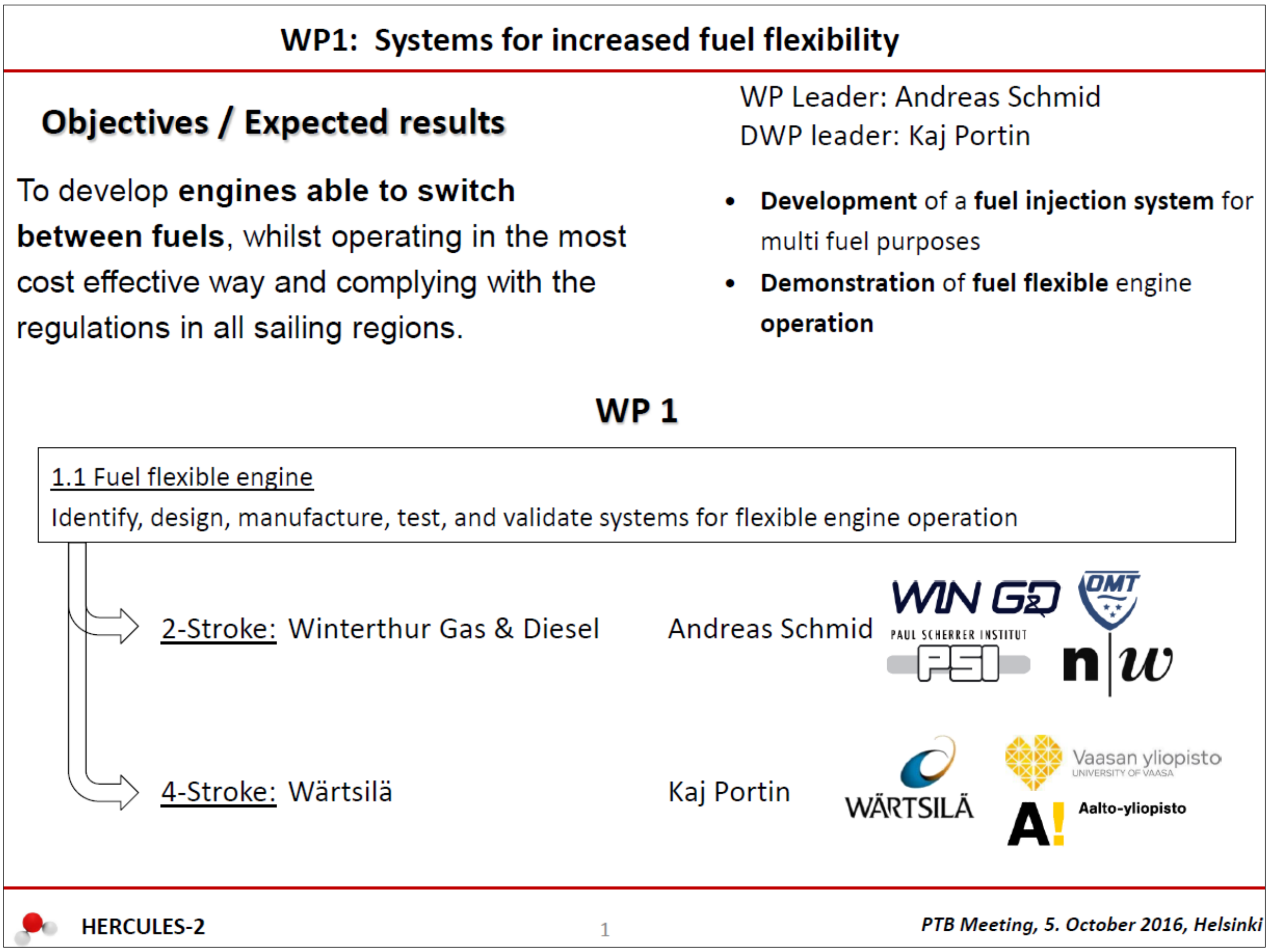
4.1.1 WP1: Systems for increased fuel flexibility

The Work Package 1 objectives are:

- To develop engines able to switch between fuels, whilst operating in the most cost effective way and complying with the regulations in all sailing regions.
- To develop of a fuel injection system for multi fuel purposes
- To demonstrate fuel flexible engine operation

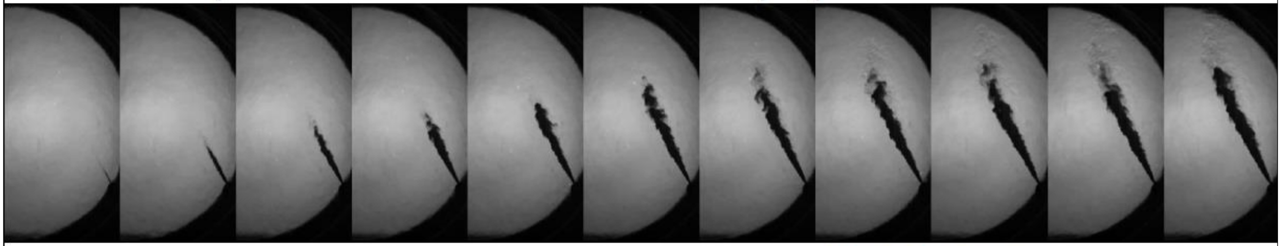
During the first 18 months of the Project, work focused on the development of a fuel flexible engine, as well as a feasibility study for a Rapid Compression Expansion Machine-RCEM. For the design of the fuel flexible injection system, a review on possible fuels for 2-stroke and 4-stroke engines, as well as ignition studies for non-auto-igniting fuels were performed. The Spray Combustion Chamber (SCC), in which the fuel characteristics were to be investigated, was further developed. Furthermore, an advanced droplet evaporation model was used and model results were compared with experimentally obtained values. An investigation on different technologies for gas analyzers and online measurements was also carried out. As far as the RCEM is concerned, a comprehensive assessment of existing RCEMs and their abilities was performed. Simulations in order to assess the performance of an innovative hydraulic system for driving the piston of the RCEM were implemented. Finally, different RCEM configurations that would provide optical accessibility and the application of non-intrusive measurement methods were considered and compared.

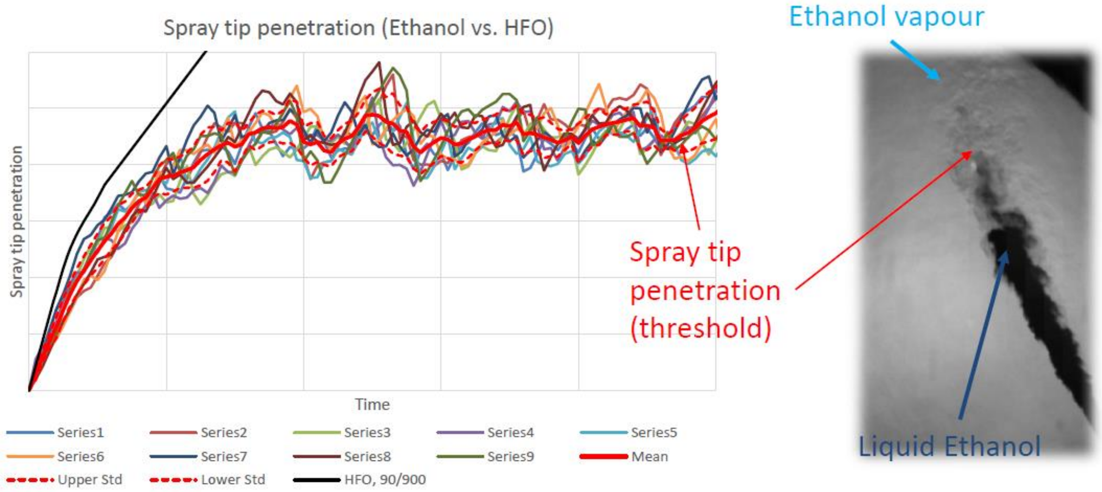
A presentation of the WP1 results follows:



WP1: Sub project 1.1 *Fuel flexible engine (2-stroke)*

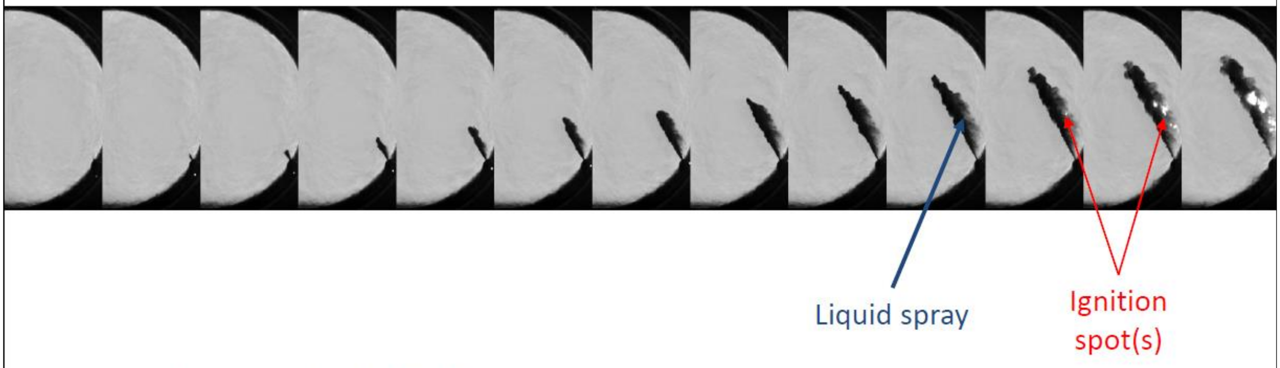
Preliminary results on the SCC: Bio Ethanol spray



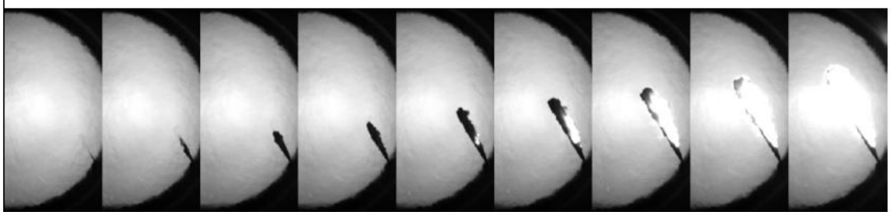


WP1: Sub project 1.1 *Fuel flexible engine (2-stroke)*

Preliminary results on the SCC: Bio fuel spray (reactive conditions)



Comparison to classic fuel



WP1: Sub project 1.1 *Fuel flexible engine (2-stroke)*

SCC - setup

- New cover installed
- Injector adapters installed
- New heating system installed
- New illumination setup (based on Mie scattering)
- Next steps:
  - First measurements with reference injection system (RTX-6)
  - Commissioning Multi fuel injection system
  - Spray tests with alternative fuels
  - Reactive tests with alternative fuels

HERCULES-2 4 *PTB Meeting, 5. October 2016, Helsinki*

WP1: Sub project 1.1 *Fuel flexible engine (4-stroke)*

DWP Leader: Kaj Portin

How

Measurement technology for intermediate combustion products formed inside the combustion chamber will be developed and tested.
The impact of switching between different fuels on possible after-treatment devices and engine components will be part of the investigations.

Partners: Aalto-yliopisto, Vaasan yliopisto UNIVERSITY OF VAASA, WÄRTSILÄ

Expected Results

A fully fuel flexible optical injection and ignition test platform for low-speed Diesel engines will also be produced. A fully optical medium-speed multi-fuel engine will be developed and tested for the first time.

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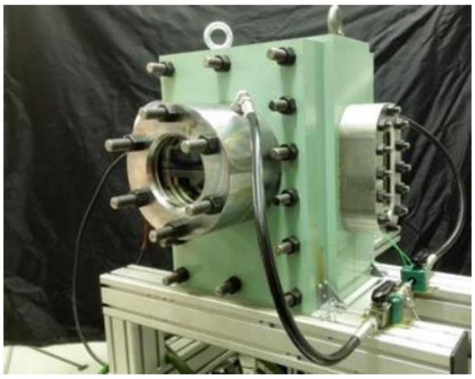
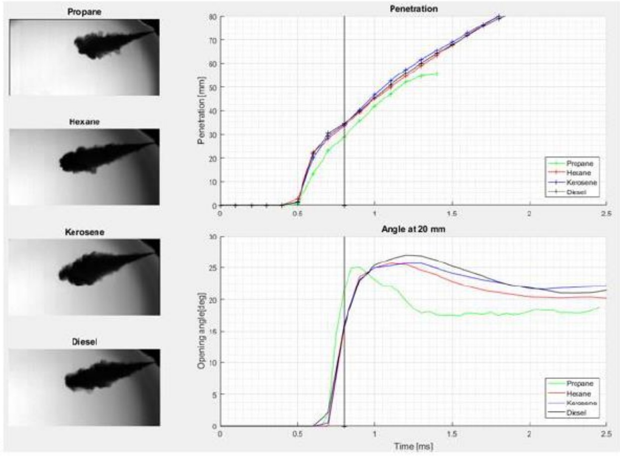
WP1: Sub project 1.1 *Fuel flexible engine (4-stroke)*

Activities Plan Year 2 (Status and progress September 2016)

- Fuel injection measurements in spray chamber with high speed camera
  - → The objective is to determine the opening angle and penetration with different fuels.
    - → Kerosene, Hexane, and Propane. Diesel used as reference fuel
    - → Injection pressures used: 550 bar and 1000 bar
    - → Chamber density: 1,2 kg/m^3, 35 kg/m^3 and 100 kg/m^3





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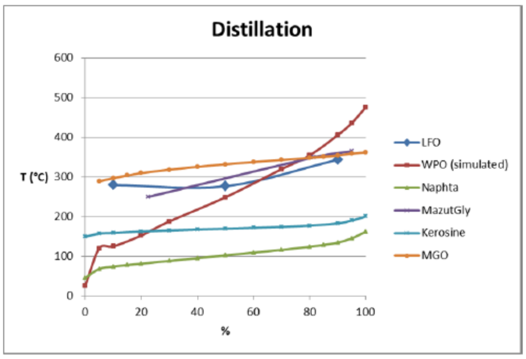
WP1: Sub project 1.1 *Fuel flexible engine (4-stroke)*

Activities Plan Year 2 (Status and progress September 2016)

- Flex fuel pre-study (Identify requirements for flexible injection system)
  - → Investigation started with 5 fuels
- Ignition studies for non-auto-igniting fuels
  - → Background material collected
  - → Selected fuels: Reference fuel LFO, Naphtha, Kerosene, Glycerin+Mazut, MGO, Wood Pyrolysis oil
  - → Studies of fuel properties completed-> WPO fuel was seen unsuitable for engine measurements

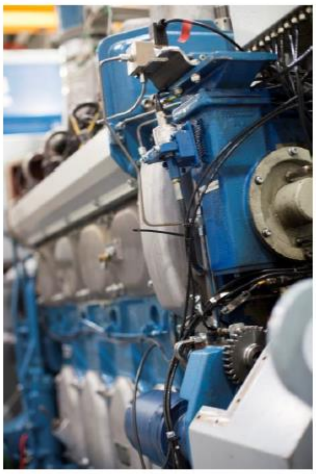


HERCULES-2 7 *PTB Meeting, 5. October 2016, Helsinki*

WP1: Sub project 1.1 *Fuel flexible engine (4-stroke)*

Activities Plan Year 2 (Status and progress September 2016)

- Ignition studies for non-auto-igniting fuels
  - → Engine measurements with high-speed off-road diesel engine planned in October 2016 with as many fuels as possible
  - → Later, also experiments with medium speed marine engine
  - → Simultaneously, fuel safety aspects will be determined and documented
  - → Setup of test platform to be also started in October 2016

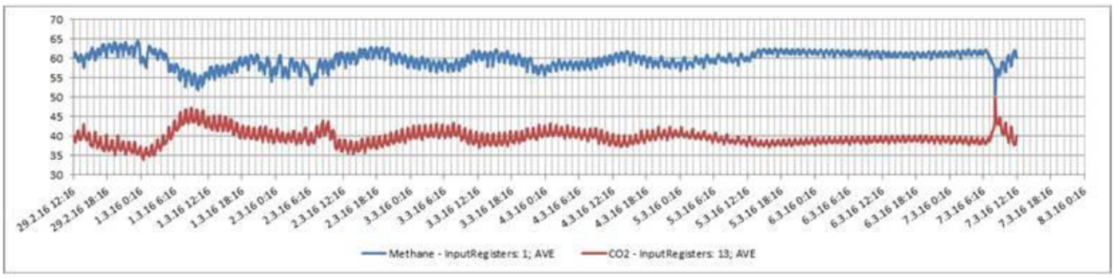


WÄRTSILÄ Vaasan yliopisto UNIVERSITY OF VAASA Aalto-yliopisto

WP1: Sub project 1.1 *Fuel flexible engine (4-stroke)*

Activities Plan Year 2 (Status and progress September 2016)

- The landfill biogas quality fluctuations were monitored
  - → Were analyzed during the gas production process when using collected organic waste. Using an optical gas analyzer, the biogas quality was characterized as the variation of methane, carbon dioxide and contamination components compositions measured online. Below, recorded methane and CO_2 fluctuations are shown against a time period.



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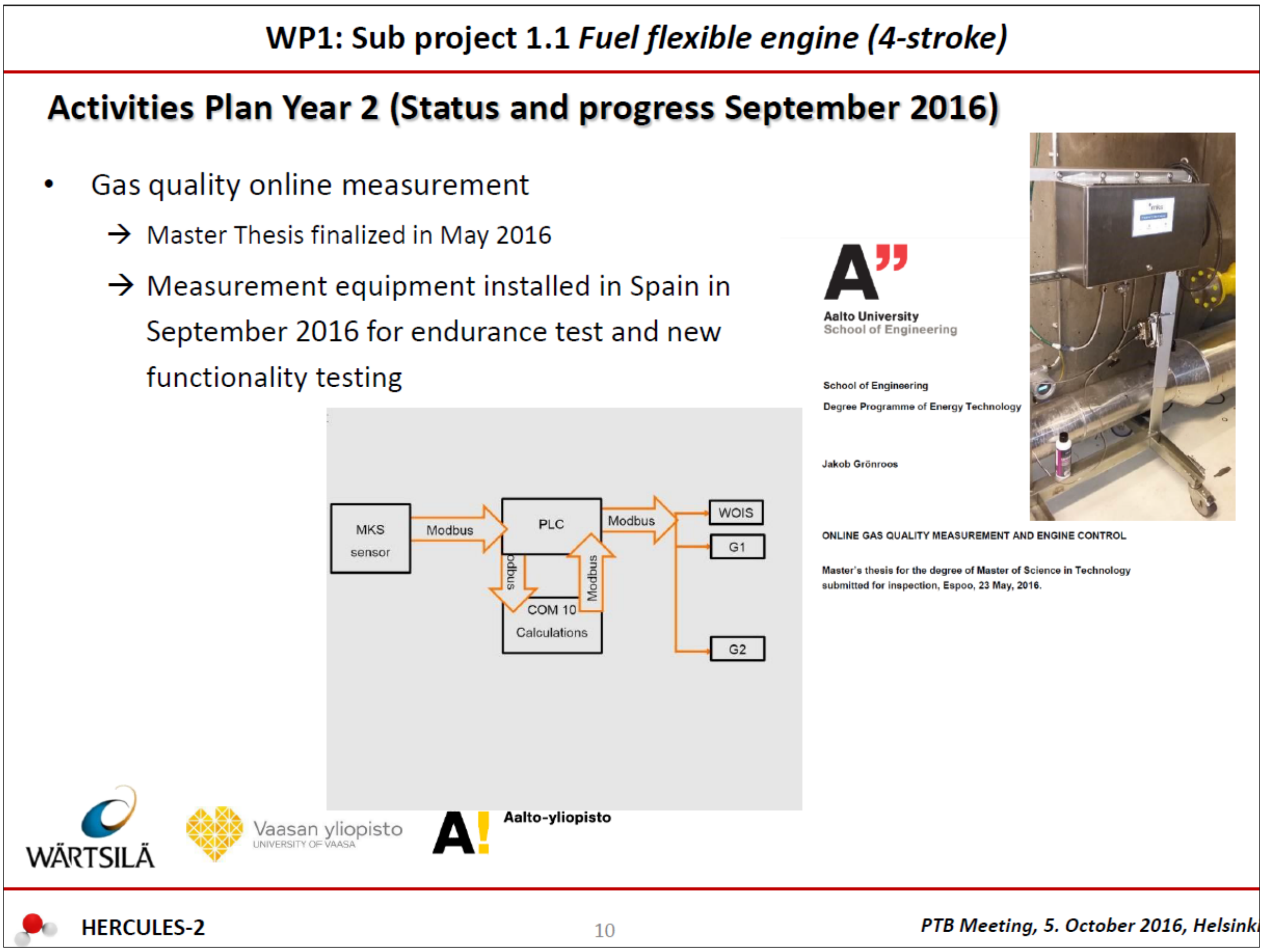


4.1.2 WP2: Multi-fuel combustion

The general objective of Work Package 2 is to develop innovative engine designs and optimized combustion strategies to fulfil future emission standards for both two- and four-stroke engines.

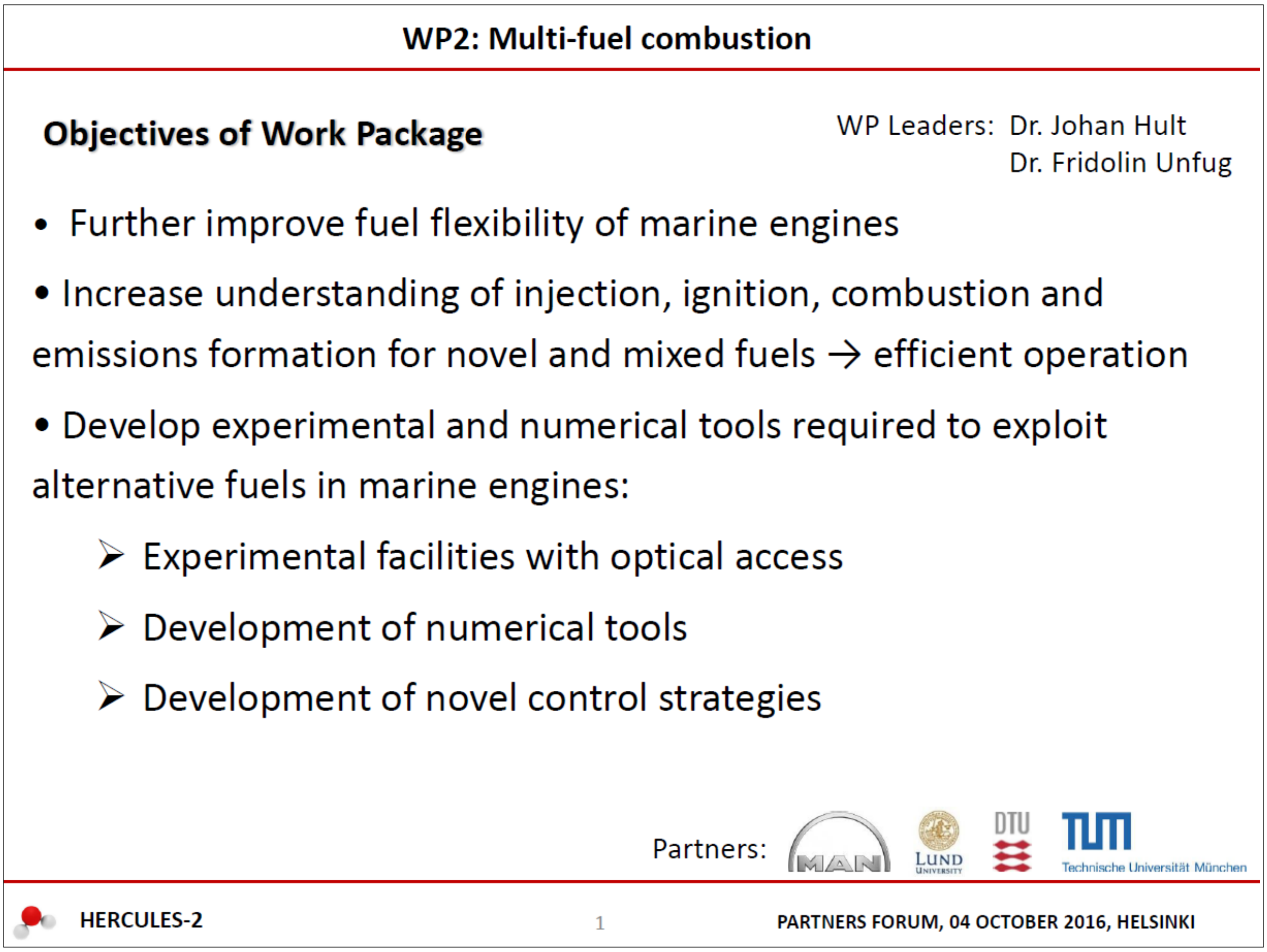
More specific objectives are:

- Further improve fuel flexibility of marine engines
- Increase understanding of injection, ignition, combustion and emissions formation for novel and mixed fuels → efficient operation
- Develop experimental and numerical tools required to exploit alternative fuels in marine engines:
  - ➢ Experimental facilities with optical access
  - ➢ Development of numerical tools
  - ➢ Development of novel control strategies

The following achievements can be reported at Mid-Term:

Work carried out focused on the development of experimental and numerical tools required to exploit new alternative fuels. To begin with, an overall system design specification was conducted for a fuel flexible test facility. Moreover, optical techniques for studying fuel injection, ignition and flame propagation were developed. This included the development of a Schlieren imaging setup as well as the design of a new spray chamber. Lubrication strategies tailor made for the specific fuel were also investigated. Moreover, the capability for modelling ignition and combustion of novel fuels in marine engines was also studied. In this framework chemical kinetic models were developed and experiments were carried out in order to obtain data for model calibration and validation. Furthermore, a new optical measurement technique is being developed, for investigating the three-dimensional in-cylinder mixture of a fully optical accessible fired medium-speed single-cylinder engine. Components for the optical lateral access were designed and manufactured. A measurement technique to investigate the in-cylinder fuel distribution was also derived, based on a wide literature study and pre-tests. In addition, the differences in engine operation with DMA and HFO were investigated. Finally, numerical and CFD simulations were carried out in order to investigate low-temperature NOx formation in combustion chamber and exhaust tract.

A short presentation of the above mentioned results follows:

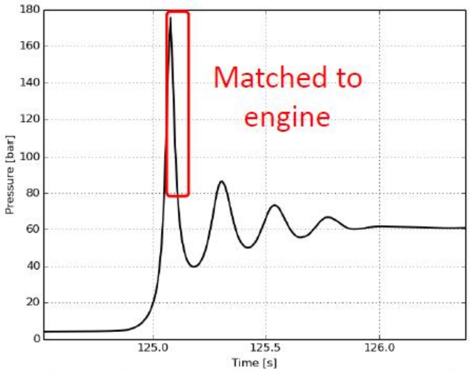


WP2: Multi-fuel combustion

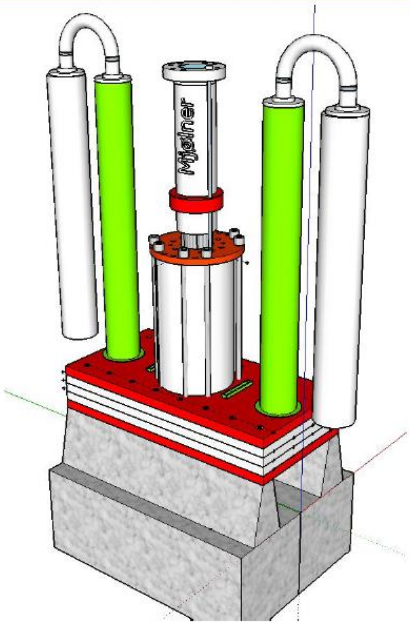
Progress update and results

2.1 Fuel-flexible test facility

- Concept evaluation → finished
- Design specifications → finished
- Building specifications → finished
- Detailed design work, purchasing & construction → reduced pace



Simulated compression/expansion cycle



Proposed design for fuel-flexible test facility

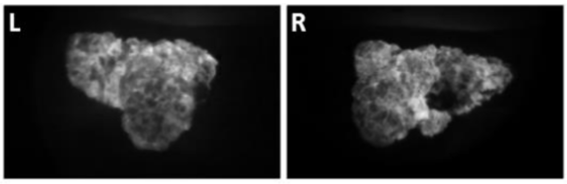
- Hydraulic drive
- Ø 500 mm
- Optical access
- Expansion
- P_{max}~200 bar

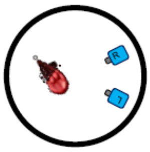
WP2: Multi-fuel combustion

Progress update and results

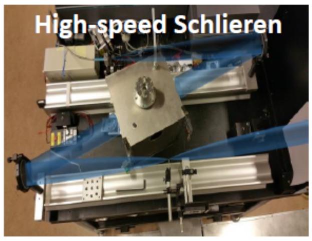
2.2 Injection and ignition characterization

- Ethane operation (2×HS) → finished
- Flame volume mapping NG (3×H) → Oct-Nov
- High-speed Schlieren imaging → prepared
- Seeding of lubrication oil → ongoing
- Improved engine optical access → ongoing





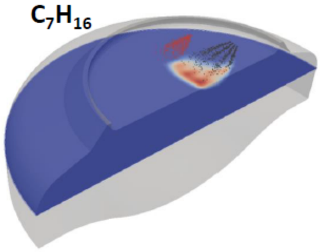
Ethane dual-camera test



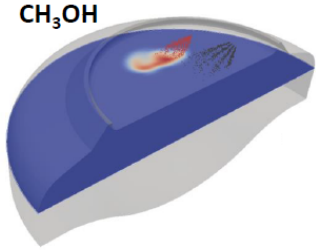
2.3 Numerical studies of fuel and ignition

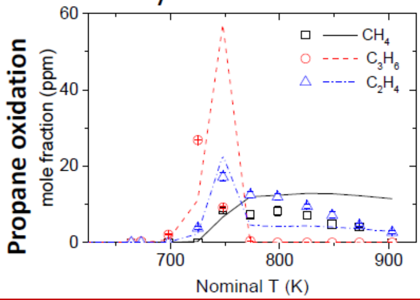
- Improved kinetic model for NG → finished
- Propane oxidation experiments → finished
- Model extended to propane → finished
- Tabulated chemistry for CFD → tested

C_7H_{16}



CH_3OH



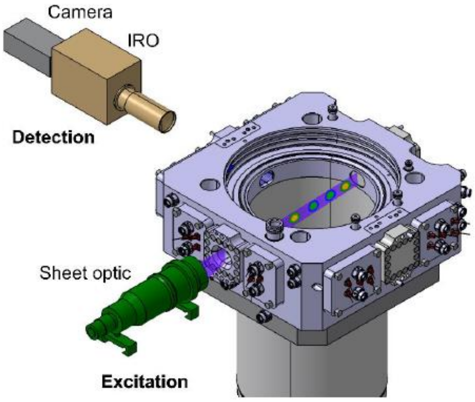


WP2: Multi-fuel combustion

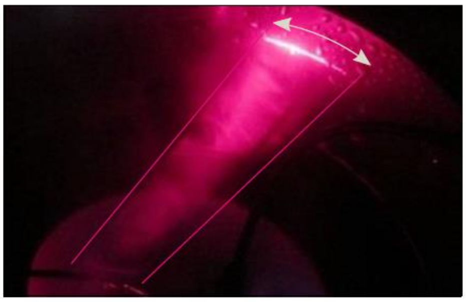
Progress update and results

2.4 In-cylinder mixture formation

- Lateral optical access design → finished
- Testing rig assembly → ongoing
- Design further optical access → ongoing
- Validation measurement technique → ongoing
- 3D CFD mixture formation → started



Design for measuring mixture distribution



Light-sheet test

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WP2: Multi-fuel combustion

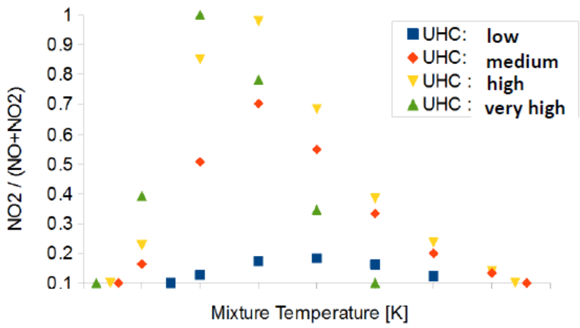
Progress update and results

2.5 Fuel-specific engine-control strategies

- First basic engine tests → finished 10/2015
- Single cylinder tests using advanced injection timings → 50% finished
- Preparation of spray chamber measurements for investigation of different fuels → finished
- Preparation of CFD model → finished

2.6 Low temperature NO_X formation

- Conversion of NO to NO2
- First calculations show promising results
- Thermodynamic conditions understood
- Modeling in CFD --> ongoing



Sensitivity Analysis of NO2 Formation Regarding Mixture Temperature and Unburned Fuel

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WP2: Multi-fuel combustion

Future work (2.1-2.3)

- Fuel-flexible test facility: design at reduced pace
- Optical engine tests: - *multi-camera flame mapping*
  - *high-speed Schlieren/shadowgraph*
  - *LPG*
- Design compact fuel-jet visualization units
- Lubrication oil seeding for imaging
- CFD: implementation of chemical mechanisms
- Detailed chemical kinetic model extended to butane (LPG)
- Experimental validation for butane
- Reduced mechanisms for ignition scenarios

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WP2: Multi-fuel combustion

Future work (2.4-2.6)

- Build up and test of 1^{st} optic release of the optical engine
- Design and Procurement of 2^{nd} optic release of the optical engine
- 1^{st} test of optical measurement techniques at the optical engine
- Further improvement of optical measurement techniques
- Single cylinder engine tests with different fuels
- Spray Chamber measurements for investigation of fuels with different viscosity
- Validation of NO/NO_2 model with single cylinder engine data

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4.2 WPG II: New Materials (Applications in engines)

The objective of this WPG is to examine the possibilities of using novel intermetallic and cast iron materials in important engine components, such as cylinder head and turbocharger turbine casing. These new materials should enable the development of components that can withstand higher temperature and mechanical loads, hence increasing efficiency and lower emissions by providing more freedom to optimize combustion. Additionally, the WPG work will contribute to a wider operational window for marine engines, enabling also a wider range of vessel speeds. Moreover, the high wear resistance of the intermetallic materials should ensure a longer lifetime and durability of these components.

4.2.1 WP3: Intermetallics and advanced materials for marine engines

The specific objectives of the Work Package 3 are

- To examine possibilities of using novel materials in engines to facilitate the development of components that enable higher engine loads, hereby increasing efficiency and lower emissions, as well as to ensure proper lifetime performance and durability.
- To examine novel materials of turbine casing in respect of material and design in order to meet requirements needed for higher exhaust gas temperatures.

In this context, during the first 18 months of the Project, novel materials for use in turbine casing and other engine applications were evaluated and tested. To begin with, five intermetallic materials were selected and tests were carried out in order to acquire their properties. Moreover, processing routes, namely, casting, thermal spraying, hot isostatic pressing and welding, have been identified and optimized. A bearing test rig was also assembled, in order to investigate bearing materials Multi-metal bearing tests have commenced. As far as novel materials for turbine casing are concerned, two groups of materials were initially identified and then a detailed survey and analysis was performed. Material specialized tests were carried out in order to obtain material properties that could not be found in literature. Furthermore, a TMF (thermo-mechanical fatigue) and creep assessment, of a reference design of a turbine inlet casing, using preliminary material properties was performed. Finally, a parameterized geometric model of the casing was developed in order to enable automatic optimization.

A short presentation of the above mentioned results follows:

WP3: Intermetallics and advanced materials for marine engines

WP Leader: Monika Damani
WP Deputy: Sebastiaan Bleuanus

Objectives

Subproject 3.1: ***Novel materials for engine applications***

Examine possibilities of using novel materials in engines to facilitate the development of components that enable higher engine loads, hereby increasing efficiency and lower emissions. Ensure proper lifetime performance and durability.

Subproject 3.2: ***Novel materials for tubine casing***

Material of turbine casing is reviewed in respect of material and design in order to meet requirements needed for higher exhaust gas temperatures.

Expected outcome

Subproject 3.1: Suitable new materials can be identified for at least two components for higher load operations and longer life time.

Subproject 3.2: Performance is improved through material / design optimization.

Partners: Max-Planck-Institut für Eisenforschung GmbH, ABB, Deloro Wear Solutions, WÄRTSILÄ, WIN GD Winterthur Gas & Diesel

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WP3: Intermetallics and advanced materials for marine engines

Structure: Partners, roles

Max Planck Institut für Eisenforschung Düsseldorf:
Materials selection & optimization; materials investigation and testing activities

Deloro Koblenz:
Materials selection and optimization of processing and joining technologies. Manufacturing of sample materials

ABB Baden:
Evaluation, prototyping and test of new material and test of new materials for advanced turbine case.

Wärtsilä Finland & Wärtsilä Netherlands:
WFI: Boundary conditions, material and processing selection; material testing activities incl. rig or engine validation; WNL: Work package deputy and coordination of research activities at partners

Winterthur Gas & Diesel Ltd.:
Boundary conditions, material and processing selection; material testing activities incl. rig or engine validation; Project lead and co-ordination of research activities at partners

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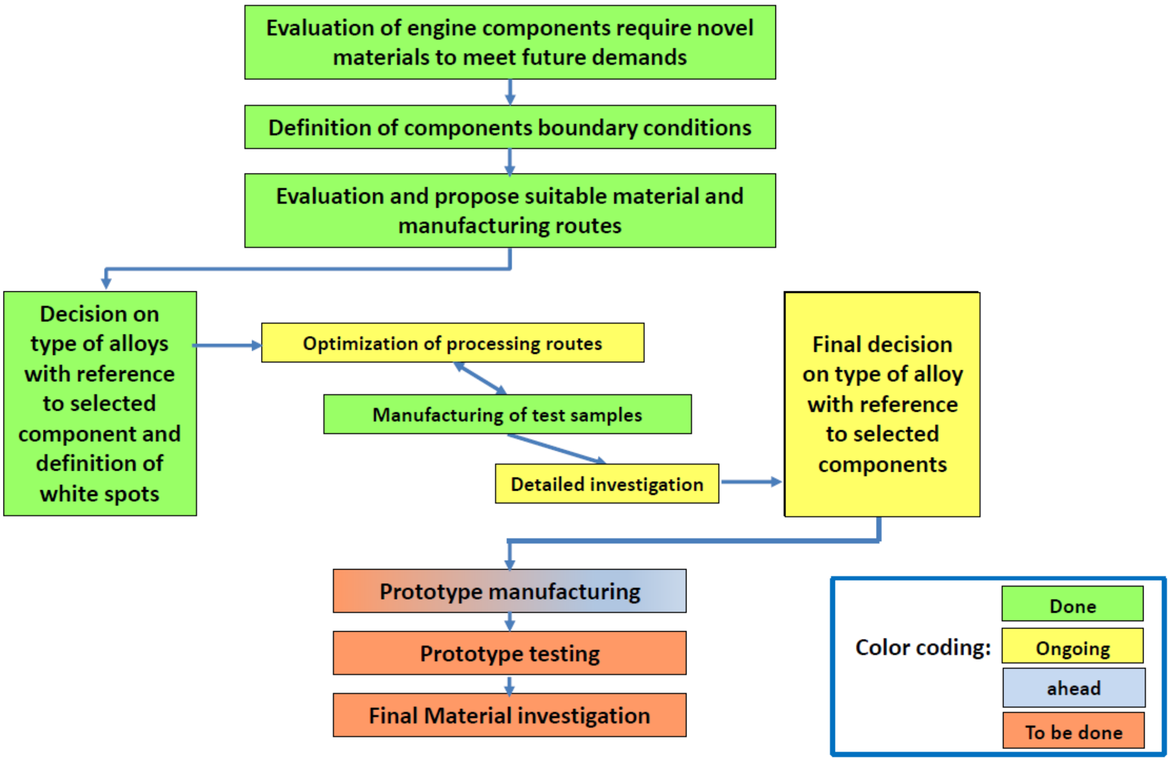
WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.1: Novel materials for engine application



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WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.1: Novel materials for engine application

First results from materials characterisation:

Different manufacturing routes have been chosen and test samples were made / materials characterisation done

Status of different testing:

DONE

- Microstructure from different manufacturing routes & materials
- Mechanical properties (mostly done)

Pending...

- Corrosion testing (cold & hot corrosion) partially done, evaluation still pending
- Thermal shock testing - pending (laser for test rig under repair)
- Tribo testing – samples ready / testing pending

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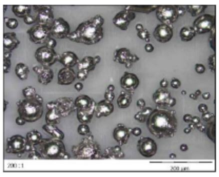
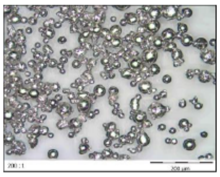
WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.1: Novel materials for engine application

Optimising processing routes:

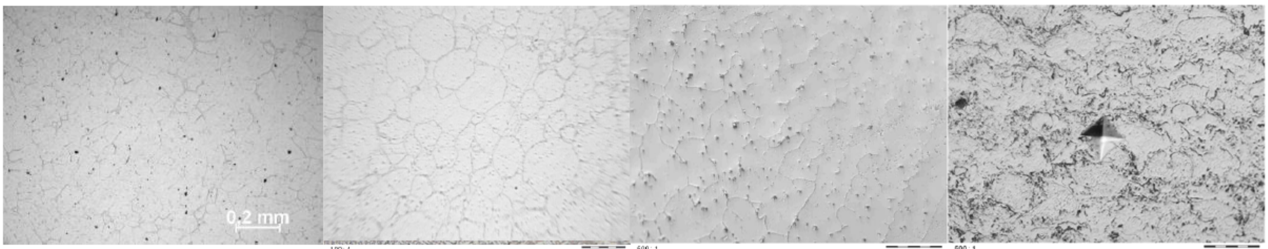
Powder was made in order to facilitate processing methods like welding, thermal spraying or hot isostatic pressing.





- ❑ Powder morphology not optimal
- ❑ Fracture with small partical size needed to be sieved out
- ❑ Dense samples achieved from all processing routes

Microstructures resulting from different manufacturing routes:



As-Cast sample | HIP (from powder) | Welding (from powder) | Thermal spray (from powder)

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WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.1: Novel materials for engine application

Optimizing manufacturing routes: Castings made of Mat 1 with different parameters

Mould preheated and oven switched off

Mould preheated and controlled cooling

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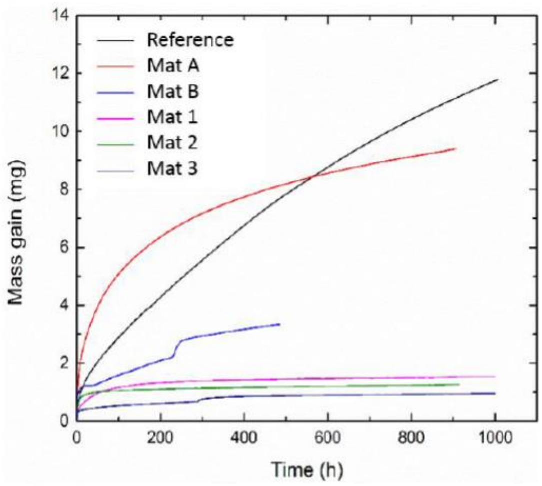
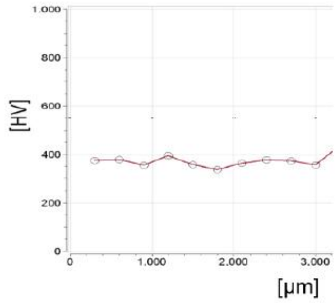
WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.1: Novel materials for engine application

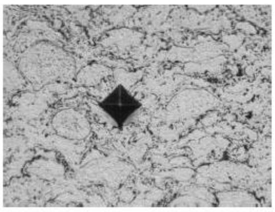
Selected results from materials characterisation done:



Corrosion behaviour (in oxidizing atmosphere)



Hardness profile of thermal spray layer (Mat 2)

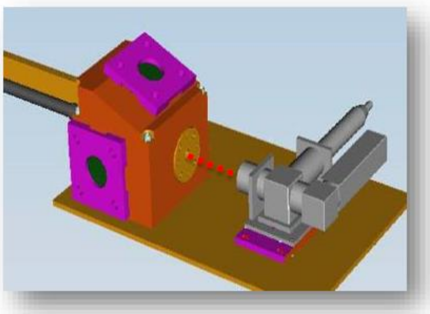


WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.1: Novel materials for engine application

Planned next activities:

- ❑ Evaluation of samples from corrosion test
- ❑ Thermal cycling
- ❑ Tribo testing & sample evaluation



Thermal cycling test rig

Tribo tester: CPT

Milestone 2: Decision on type of alloy/part combination due in December 2016
- most likely 1-2 months delayed due to delay in material characterisation

WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.1: Novel materials for engine application

Achievements, advanced bearing materials:

The following activities below have been completed so far:

- Finalized assembly of rig
- Oil feeding concept selected for durability comparison tests
- Completed oil system and calibration of instrumentation
- Multi-metal bearings first tests on rig started

Planned next activities:

- Baseline bearing rig testing: different sizes, rpm levels, oil temperatures
- Multi-metal bearing rig testing: different sizes, rpm levels, oil temperatures
- Comparison of durability of bronze bearings and multi-metal bearings

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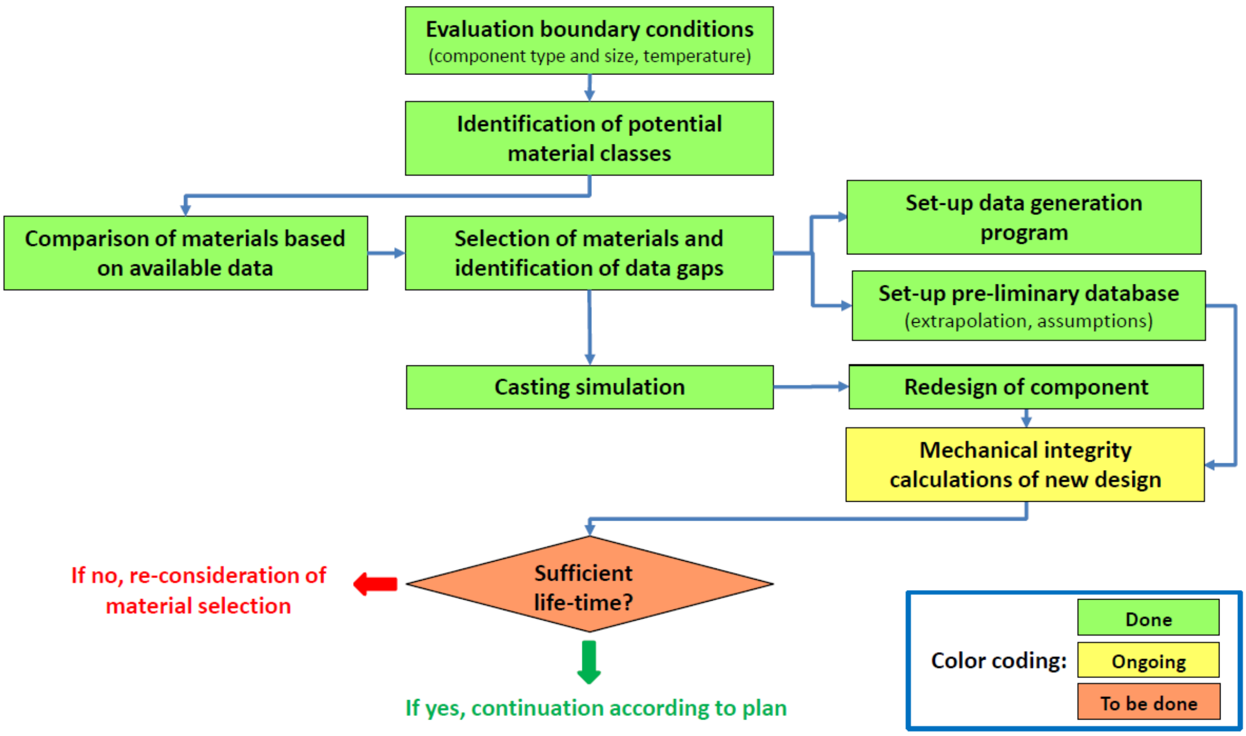
WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.2: Novel materials for turbine casing



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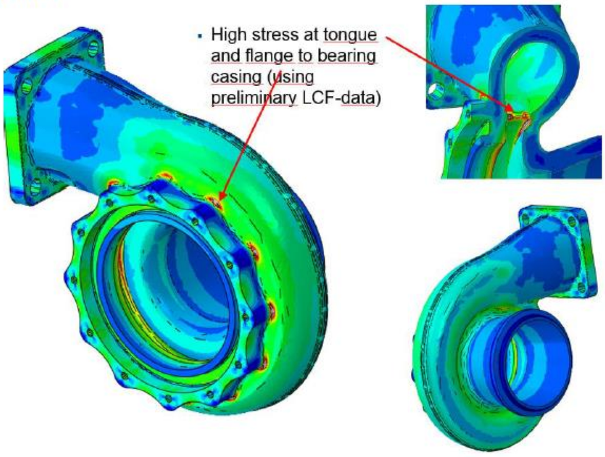
WP3: Intermetallics and advanced materials for marine engines

Status of Sub-project 3.2: Novel materials for turbine casing

Work already done:

- Decision on casting type, requirements are defined
- Decision on manufacturing method
- Material classes identified
- Review of availability of required material data
- Preliminary material database setup
- Casting simulation
- Parametrisation of CAD-model
- Defintion of load profile
- Elimination of stress hot-spots



Next planned activities:

- Completion of experimental material characterisation
- Production of prototype casings
- Qualification tests

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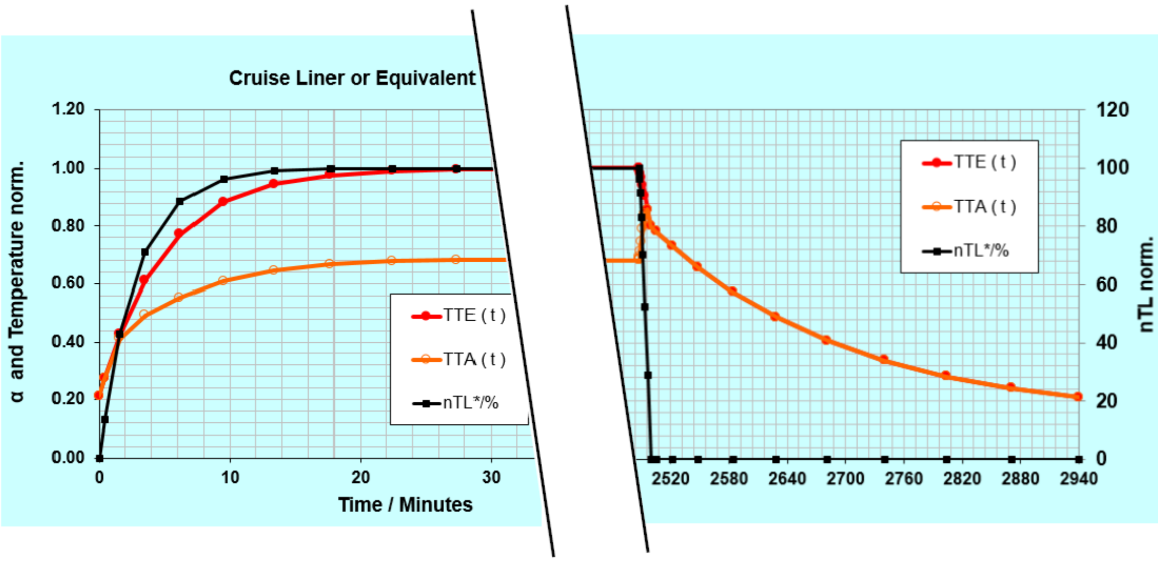
Load Profile for life-time assessment (cruise ship or equivalent application)

Maximal gas temperature at turbine inlet: TTE = 800°C

The profile consists of a start up, full load for 40 hours and a shut down.



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4.2.2 WP4: New materials for higher engine efficiency

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. Specific objectives for the new materials and design for cylinder heads are the improvement of thermomechanical cycle resistance of factor 2 under increased temperature of 50 K, as well as the decreased weight of cylinder head of 20%.

For the new materials for the turbocharger turbine casing, the objective is the improvement of thermomechanical cycle resistance under increased temperature of 70 K under corrosion environment.

In this context, during the first 18 months of the Project material tests were performed to investigate appropriate materials that will be used to increase the fatigue resistance of cylinder heads and turbocharger inlet casing. In Subproject 4.1, plates and sleeves were produced at the foundry using five different materials. The final material for further investigation was chosen based on the thermal shock resistance parameter. In Subproject 4.2 a material that is expected to have 25% higher corrosion resistance compared to current turbine casing materials has been selected, based on experience gained about corrosion and fatigue. Due to a delayed delivery of the test specimens, material tests have been initiated but the test program was not yet completed. Results from these tests are used for the calibration and validation of a material model. Existing modelling tools have been reviewed and development of new ones has begun.

A short presentation of the achieved results follows:

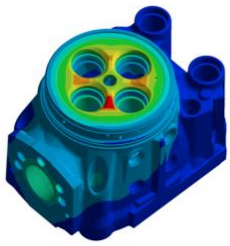
WP4: New Materials for Higher Engine Efficiency

Objectives of Work Package

WP Leader: Dr. Rayk Thumser, MDT -AUG
Deputy: Santiago Uhlenbrock , MDT-AUG

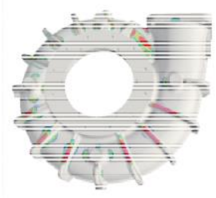
WP 4.1 New materials and design for cylinder heads

- Improvement of thermomechanical cycle resistance of factor 2 under increased temperature of 50 K
- decreased weight of cylinder head of 20%



WP 4.2 New materials for the turbocharger turbine casing

- Typical Load Cycles for Ferry Applications
- Improvement of thermomechanical cycle resistance under increased temperature of 70 K under corrosion environment



Partners: Fraunhofer IWM, Hochschule Offenburg University of Applied Sciences, Fraunhofer ICT, BAM Bundesanstalt für Materialforschung und -prüfung, MAN

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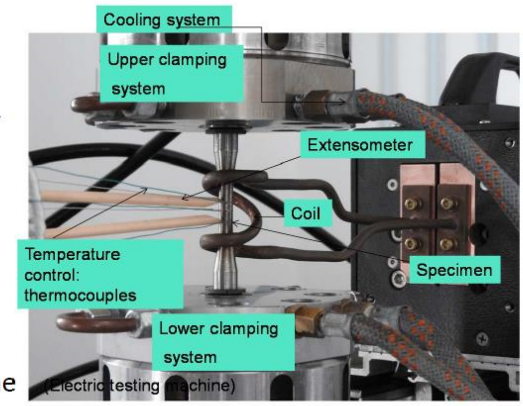
WP4: New Materials for Higher Engine Efficiency

Main results achieved during 1st year WP4.1

- 2 of 8 pre experimental material tests have been finished
- Fatigue tests and incremental step test for a preliminary study
- Typical influence of the temperature on the sequence of elasticity modulus



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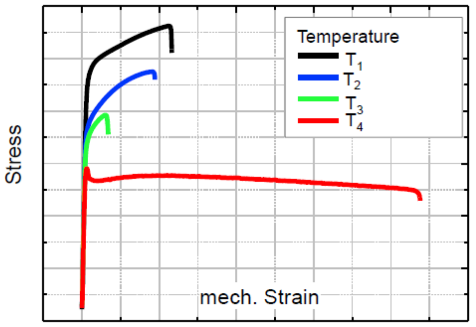
WP4: New Materials for Higher Engine Efficiency

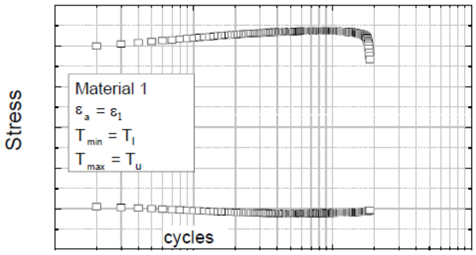
Main results achieved during 1st year
WP4.1

- Hot tensile test for first rating of materials

Hot tensile test and OP-TMF Test of material 1



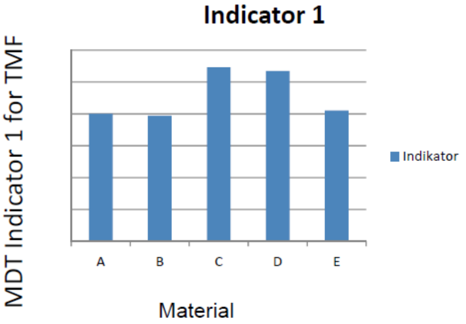
- Out-of-Phase TMF operations for preliminary estimation of thermomechanical fatigue



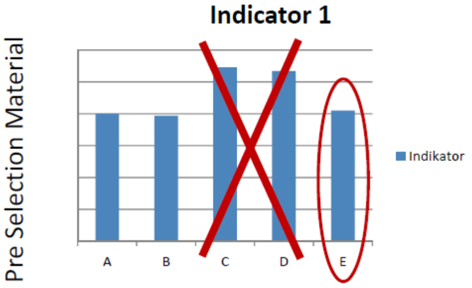
WP4: New Materials for Higher Engine Efficiency

Main results achieved during 1st year
WP4.2

- Evaluating the pre tests
- Selection of the material by a predefined indicator



- Material C,D is not suitable due to
  → Material costs too high
  → Processing costs relative high
  Material E is the choosen one

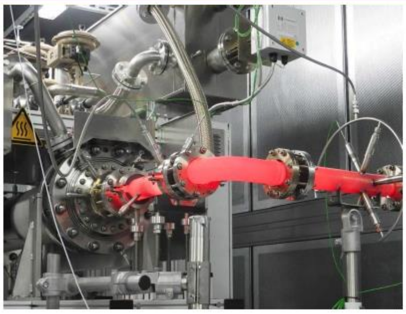


WP4: New Materials for Higher Engine Efficiency

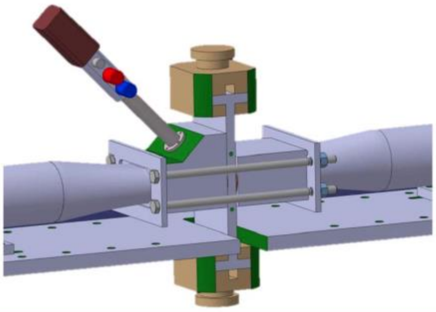
Main results achieved during 1st year

WP4.1

- Planning of test rig is still ongoing
- CFD Analysis is conducted for pre defining the specimen for test operation
- Based on FEM and CFD analysis suitable hardware must used for testing
- Design for the test bed is in discussion (exemplary showing in the right)



Hot Gas Test Rig



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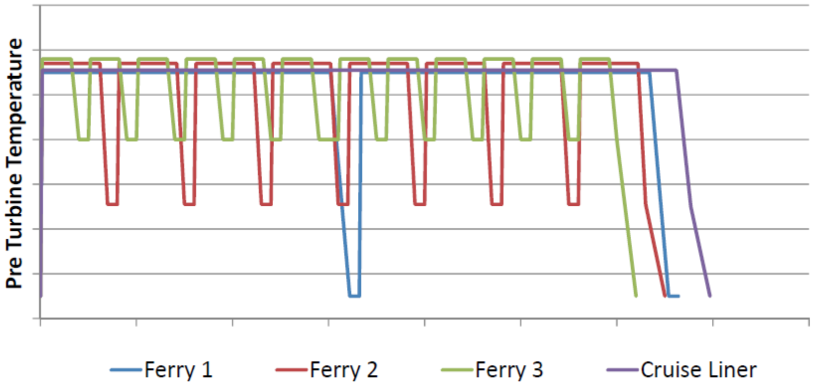
WP4: New Materials for Higher Engine Efficiency

Introductuion WP4.2

- Ferry applications are very cyclic marine applications. Thermo-mechanic fatigue damage is dominant compared to creep damage.
- Cruise liner applications are stationary applications with large dwell times at elevated temperature. Creep damage is dominant compared to thermo-mechanic fatigue damage.



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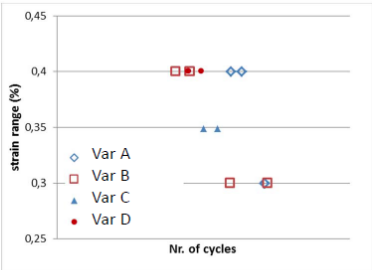
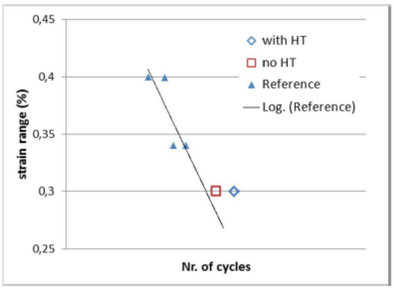
WP4: New Materials for Higher Engine Efficiency

Main results achieved during 1st year
WP4.2

- three different casting batches produced
- manufacturing problems solved (bent shape)
- Test Running @ BAM



LCF Results



TMF Results

WP4: New Materials for Higher Engine Efficiency

Future Work

WP4.1
- Final Material investigation for TMF
- First test at fatigue test rig for superimposed thermal and mechanical loading

WP 4.2
- Finalisation of low cycle fatigue, thermomechanical fatigue and creep tests
- Derive of a constitutive equation for the creep behaviour and the load limits of the material
- Validation of the material model

4.3 WPG III: Adaptive Powerplant for Lifetime Performance

The objective of this WPG is to develop systems, methods and processes allowing for a continuous optimized performance of the powerplant, throughout its lifetime, with reduced operating and maintenance costs. The work aims at expanding the present operating range of emission reduction technologies to new operating modes. Development of novel advanced (adaptive) lubrication injection systems, as well as early detection of creeping failure modes through advanced diagnostics, will lead to reduction in operating cost and harmful pollutants. Model-based control will also lead to improved dynamic performance. An efficiency gain in transient conditions throughout the lifetime of the engine with optimal adaptive control parameters and operation points is also expected.

4.3.1 WP5: Lifetime Performance Control

The general objective of WP5 is to secure optimized performance of the power plant throughout its lifetime. The WP aims at developing technology demonstrators retaining an engine's as-new performance, using optimized engine control. To this end, current state of the art and knowledge of engine controls are applied to iteratively develop, simulate and test prototypes to reach technology demonstrator levels TRL 6. Establishing such concepts for two-stroke engines requires further development of the tribosystem, in particular of advanced (adaptive) lubrication monitoring systems, based on dedicated sensor technologies, as well as of a fully flexible lube oil injection system, involving also the generation of profound knowledge with regards to the development of a sophisticated tribosystem performance simulation tools.

Work performed in Work Package 5 targets on retaining engine's as-new performance, using optimized engine control and parameterization methods, as well as on developing control methods for hybrid engine propulsion systems. In this framework, different control strategies of knock margin were implemented and verified. Moreover, a lambda controller was designed and experimentally tested in a hybrid diesel-electric powertrain. A load estimation study using cylinder pressure traces was also carried out in order to check the reliability of this method, so that it can be used for estimation of engine load during transient operation. As far as the engine control parameterization in concerned, a practically oriented Design of Experiments-DoE algorithm method, for the engine static maps design and optimization was developed. A model-based offline optimization approach was also studied. Furthermore, work included the development and simulation of an adaptive, fully-flexible lubrication system. In this direction, a 1-D simulation model has been developed in order to investigate the injection behavior of the lubricating system. A test cell for the lubricating system was developed as well. Finally, an advanced real-time tribosystem performance monitoring system is being investigated; various measurements related to the lubricating systems were performed during the reporting period.

More details can be seen in the presentation that follows:

WP5: Lifetime Performance Control

Objectives

- Develop methods, systems and processes allowing a continuous optimized performance of the power plant throughout its lifetime

WP Leader: Jonatan Rösgren
WP Deputy: Matthias Stark

How

- Optimized control methods
- Adaptive lubrication system

Partners:

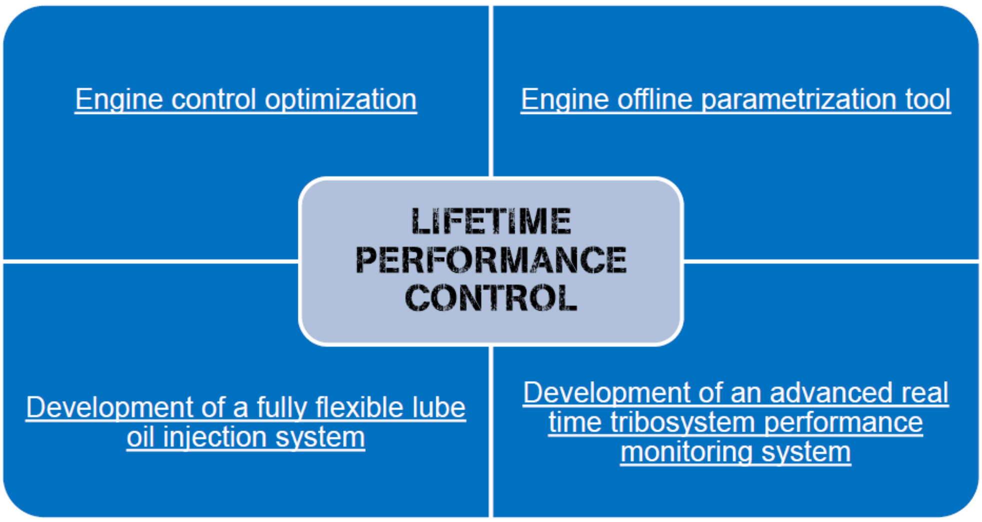
Expected Results

- Technology demonstrators at TRL 6
- Max 5% divergence of any performance parameter from "as-new" state
- Advanved lubrication control system
- Optimized lube oil feed rates
- 10% lube oil consumption reduction

WP5: Lifetime Performance Control

Structure

Building blocks for lifetime performance



WP5: Lifetime Performance Control

Structure: Subprojects, Activities: 5.1, 5.2

Sub-project 5.1: Engine control optimization
- Optimized control study, algorithm development, simulation, testing

Sub-project 5.2: Offline engine control parametrization tool
- Parametrization study, concept, prototype tool development, prototyping, testing

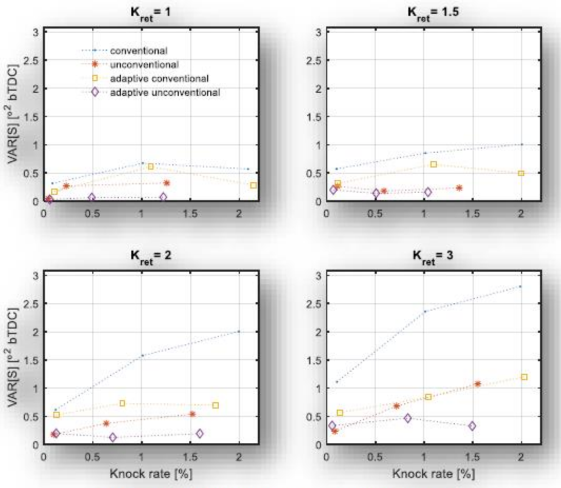
WÄRTSILÄ
ETH
Vaasan yliopisto
Aalto-yliopisto

WP5: Lifetime Performance Control

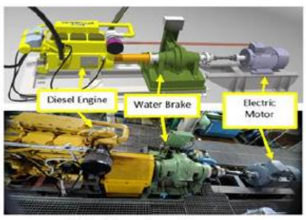
Progress (5.1, 5.2)

5.1 Engine control optimization
- Hercules C: stochastic knock margin identification, adaptive controllers development
- Hercules 2: knock & optimal control control strategies and methods including measurement chain accuracy

Progress:
- Adaptive knock control strategies – strategy development and testing ongoing
- Measurement chain accuracy study
- Engine laboratory setup (Vaasa)
- Hybrid engine control – lambda regulation development



Spark timing variance. Comparison of the adaptive strategies.



Hybrid engine setup

WP5: Lifetime Performance Control

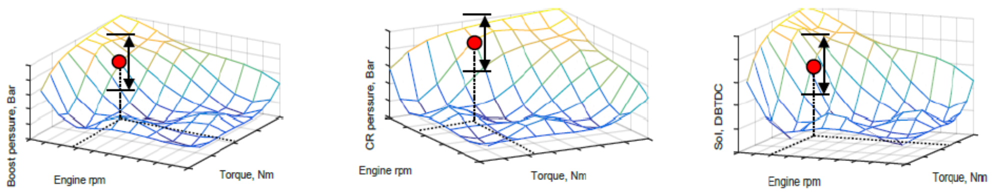
Progress (5.1, 5.2)

5.2 Offline engine control parametrization tool

- Hercules C: focusing on adaptive controllers (PID)
- Hercules 2: focus on reference maps.
- Reference maps big affect on engine characteristics

Progress:

- Rapid prototyping systems introduction ongoing (Aalto & Wärtsilä)
- Design of Experiments (DoE) algorithm development & simulation ongoing
- Screening experiments with **2^3** factorial design: construction of linear regression model
- Engine testing to be initiated in October 2016.



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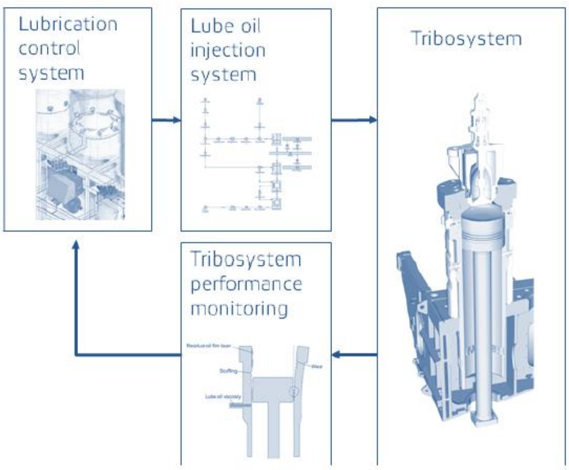
WP5: Lifetime Performance Control

Structure: Subprojects, Activities

DWP Leader: Matthias Stark

Sub-project 5.3:
Development and simulation of an adaptive lubrication system

Sub-project 5.4:
Development of an advanced real time tribosystem performance monitoring system



WIN GD Winterthur Gas & Diesel

UNIVERSITÀ DEL SALENTO

The University Of Sheffield.

HERCULES-2 6 *Partners forum, 5 Oct 2016, Helsinki*

WP5: Lifetime Performance Control

Objectives / Expected Results

Tribosystem monitoring technology development
Identification and development of suitable sensor technologies including prototype testing and initial validation

Flexible lubrication system development
Development and validation of substantially modified lubrication system components

Adaptive lubrication system development

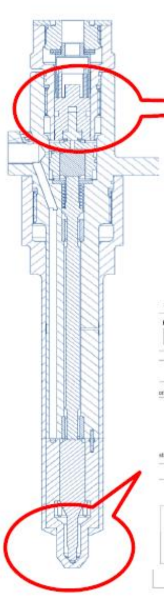
Tribo performance simulation tool developmet
Development of a simulation model to predict tribosystem performance

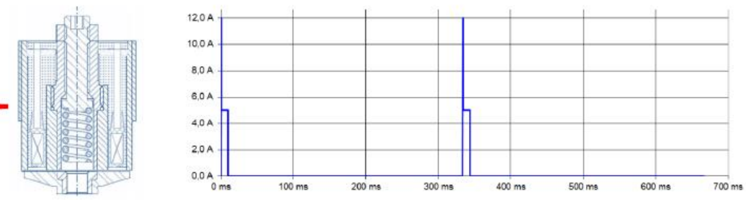
Testing and validation
Initial validation and demonstration of the lubrication system on specialized test rigs and a full scale engine test

Partners: WIN GD Winterthur Gas & Diesel, UNIVERSITÀ DEL SALENTO, The University Of Sheffield.

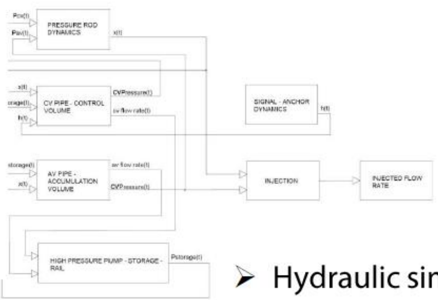
WP5: Lifetime Performance Control

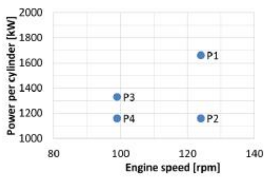
Sub-project 5.3: Development and simulation of a fully flexible lubrication system

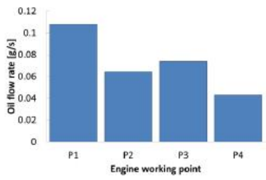




➢ Prototype development of the new lube oil injector







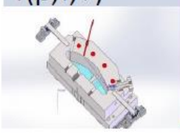
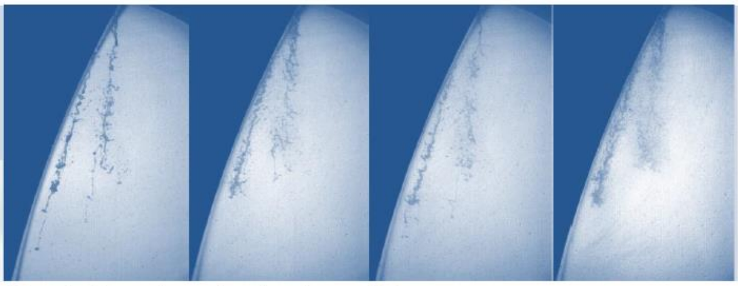
➢ Hydraulic simulation optimization results

WIN GD Winterthur Gas & Diesel, UNIVERSITÀ DEL SALENTO

WP5: Lifetime Performance Control

Sub-project 5.3: Development and validation of a fully flexible lubrication system

Experimental setup

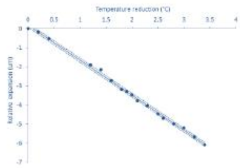
Engine Load Load [%]	25	50	75	100
Lube Oil Spray Pattern f(p,T,ν) 				

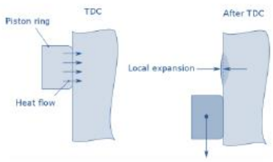
Simulation of engine load conditions

Software and hardware modifications → Pulse jet lubrication system testing

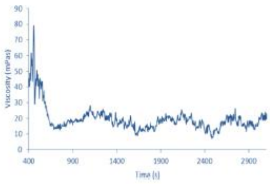
WP5: Lifetime Performance Control

Sub-project 5.4: Development of an advanced real time tribosystem performance monitoring system





In-line scuffing indicator prototype testing



In-line viscosity indicator prototype testing

4.3.2 WP6: Model-based control and operation optimization

The objective of WP6 is to develop systems, methods and processes allowing for improved engine lifetime performance with reduced operating, maintenance and deployment costs. Non-normative changes in the demands and conditions for the operation of - and emissions from - the engine are to be taking into account. Included in the objective is the aim of expanding 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. Development of a novel lubrication injection system will lead to reduction in operating cost and particle emissions.

Through development of condition monitoring and diagnostics for optimized lifetime performance, maintenance and operating cost—through fuel savings—are estimated to be reduced by 15 to 20 and 2 percent respectively compared to current engine systems. This leads further to reduction of harmful pollutants—hydrocarbons, carbon monoxide, particulate matter and oxides of nitrogen—via early detection of creeping failure modes. Novel algorithms based on Model-based control will lead to enhanced dynamic performance and part load efficiency without deteriorating the control-stability at constant load.

The results that were achieved during the first 18 months of the Project are presented in the presentation overleaf and are briefly summarized next.

In Work Package 6 the majority of the work included model development and simulations. To begin with, a mathematical engine model, which will be used to setup a model based controller, was developed and validated. Moreover, in order to investigate engine behavior during cylinder cut-out a thermodynamic engine model was developed and calibrated using recorded measurement data. Following the investigation, a FRM (Fast Running Model) was designed to be the base on which the control software will be developed. Work was also done in the field of fault detection, where data driven approaches were investigated. Novel frameworks were proposed and validated to both identify and predict faulty states at early stages. Furthermore, the expansion of the operating range of Tier III technologies was investigated. An SCR model capable of simulating the temperature variations inside an SCR system was developed and will be coupled to a detailed thermodynamic model of an engine fitted with an SCR. In addition, a compressor model capable of low load operation was developed and was integrated in a complete EGR engine model. An oscillation damping controller for low load SCR operation was also developed and validated. Work was also performed on the development and integration of a new electronically controlled pneumatic actuator for the existing mechanically controlled conventional engines. Also, regarding lifetime engine performance, a remote deployment process platform is being investigated which scales to fleets of vessels without requiring on board attendance and allows for collaboration between multiple partners. Finally, regarding lifetime performance by reduction of lubrication rate, a test rig capable of delivering cylinder oil was assembled and tested.

WP6: Model-based Control and Operation Optimization

Objectives / Expected Results

WP Leader: Dr. M. Moser, T. Moeller

Cut operating, maintenance and deployment costs

- Develop systems, methods an processes for improved engine lifetime performance

Reduction of emission & increased efficiency at part load

- Cylinder cut-out
- NOx: expanding operation range emission reduction technologies
- Particle: novel lubrication injection system

Enhance dynamic performance

- Model-based control

Partners:

University of Bremen
Vienna University of Technology
Karlsruher Institute of Technology
Linköping University
Aventics GmbH
Technical University of Denmark
National Technical University of Athens

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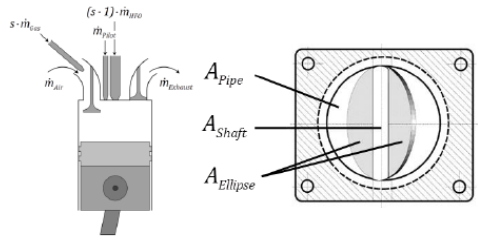
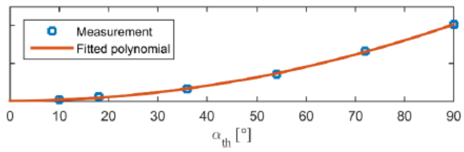
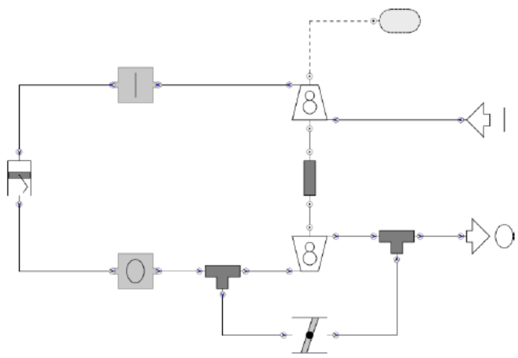
WP6: Model-based Control and Operation Optimization

Engine control and optimization

- Development of physical-based models for Model-based engine control
- More engine parts and features (e.g. Jet Assist) were included in the model
- Rework of models for WG and TC towards more model stability
- Dynamics for temperature & pressure in receivers
- Dynamics for TC speed
- Interpolation along turbocharger-maps
- Development in C++ and validation in Modelica and Matlab/Simulink
- Test bed measurements for identification of parameters ware performed







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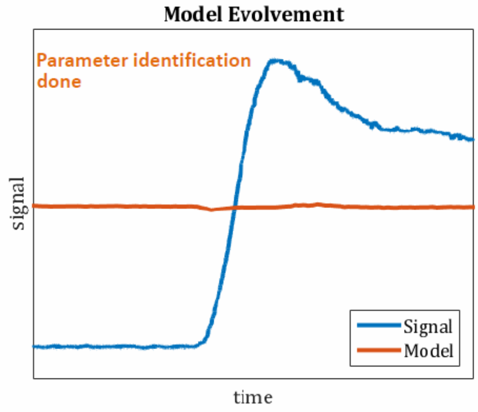
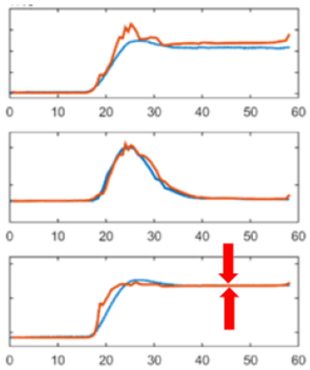
WP6: Model-based Control and Operation Optimization

Engine control and optimization

- Parameter identification to identify not covered effects (like friction, real gas behavior, ...) has been done
- Model has ~100 free coefficients
- Numerical problems could be solved by implementing a new solver for the differential equations
- Parameter identification in terms of minimize differences between measurements and simulation
- Parameter identification successful for gas- and liquid fuel mode at certain data sets
- To achieve good model accuracy parameter identification for more/all datasets ongoing



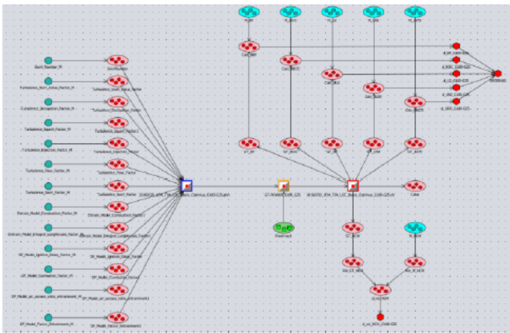


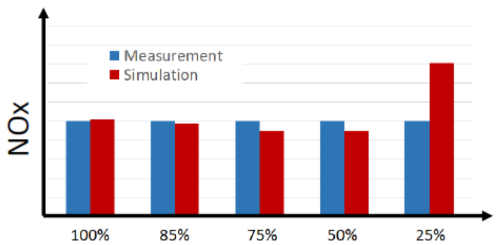
Learned on **three** datasets

WP6: Model-based Control and Operation Optimization

Engine control and optimization

- First step was modeling of Single-Cylinder model for TPA and adjustment of combustion model
- Calibration of the combustion model (which was developed during Hercules C) with the help of optimization tool
  - Optimization of 11 Input variables
  - *Differential Evolution Algorithm* for middle term optimization (~500 iterations)
  - *Covariance Matrix Adaptation - Evolution Strategy* for long term optimization (>1500 iterations)
- Good overall agreement of simulation and measurement from G100 down to G50
- Further investigations of G25 slated

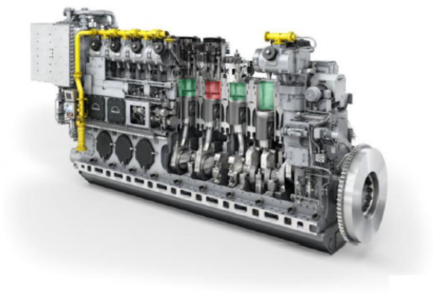


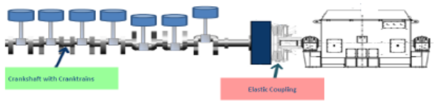


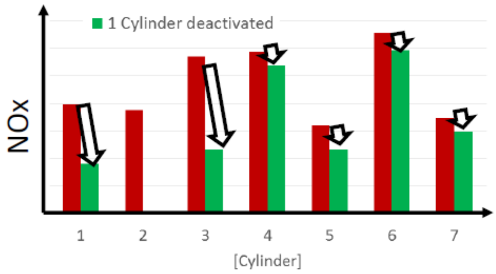
WP6: Model-based Control and Operation Optimization

Engine control and optimization

- Low load operation with cylinder cut out was investigated
- 350 different cut out sequences are calculated and analyzed in terms of torsional vibrations and resonances
- Investigation concerning restrictions of engine operation area for different cut out scenarios in terms of combustion behavior
- Calculation of the effects on emissions and fuel oil consumption due cylinder deactivation (global and cycle average) shoed promising results
- First control strategies derived
- FRM model was already successful coupled with Simulink in order to develop the control for the engine test run







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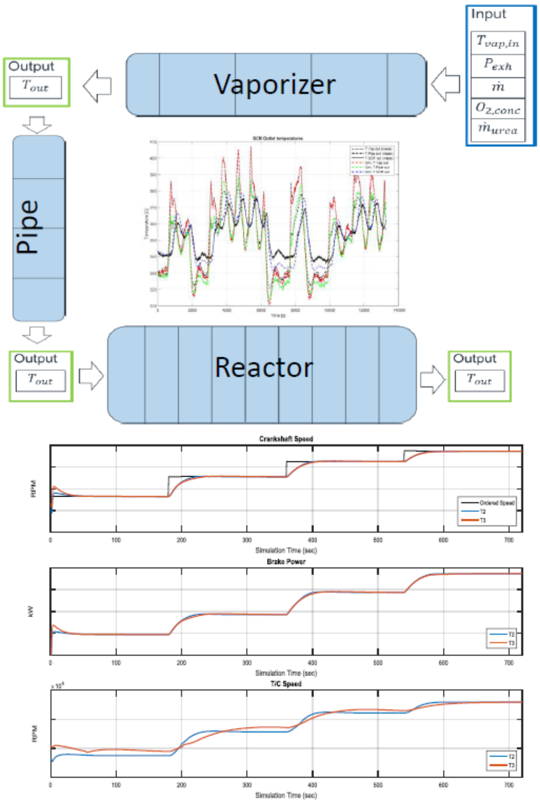
WP6: Model-based Control and Operation Optimization

Engine control and optimization

- Full SCR model developed and validated on test data from 2013 – 2014. Each SCR subsystem modelled and validated individually
- Mass flow simulation with influence from valve positions
- Developed in order to simulate observed thermal oscillations at low load
- Implementation of the SCR model in the engine model
- Steady state simulations performed for Tier 2 and Tier 3 engine configurations
- Initial transient simulations performed
  - ➢ A real loading profile used from an engine of the same type
  - ➢ Engine response during transient simulations examined



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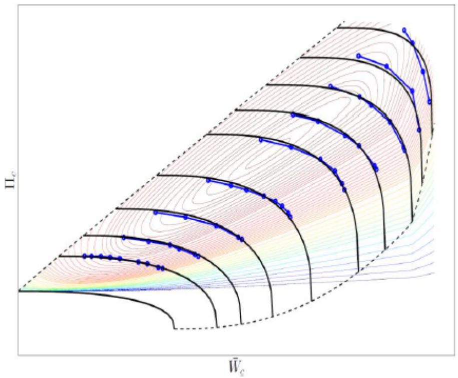
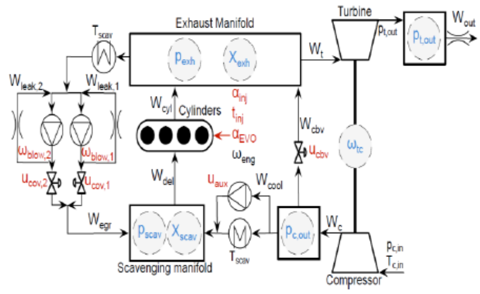
WP6: Model-based Control and Operation Optimization

Engine control and optimization

- EGR model was designed to simulate low load operation
- Low load operation → investigation of vessel load profiles (e.g. approaching the harbor)
- The model is capable to extrapolate efficiency and mass flow for compressor speeds below the lowest measured speed line
- Complete compressor model parameterized with the manufacturer compressor performance map and is capable to operate at very low speeds
- The EGR engine model also includes a model for the auxiliary blower
- Paper* published with information about the parameterization and the model equations
- Developement of the control will be done on the model and testd on the vessel



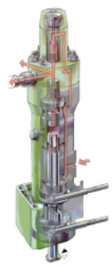


*) Llamas X, Eriksson L. A Model of a Marine Two-Stroke Diesel Engine with EGR for Low Load Simulation. 9th EUROSIM Congress on Modelling and Simulation. Oulu, Finland. 2016

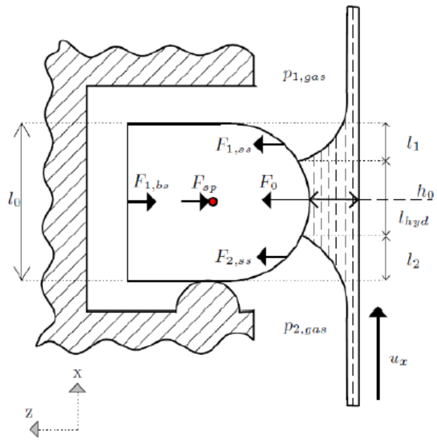
WP6: Model-based Control and Operation Optimization

Engine control and optimization

- Development of an retrofit solution for continuous engine performance optimization for mechanical controlled engines
- Electronically controlled actuator for fuel injection
- Prototype sample designed, produced and available
- Validation of porotype actuator on test rig



- Theoretical investigation of the hydrodynamic lubrication of the top compression piston ring was performed
- Modelling of hydrodynamic lubrication and free surface flow
- Inaccuracies of the existing model tracked down and solved



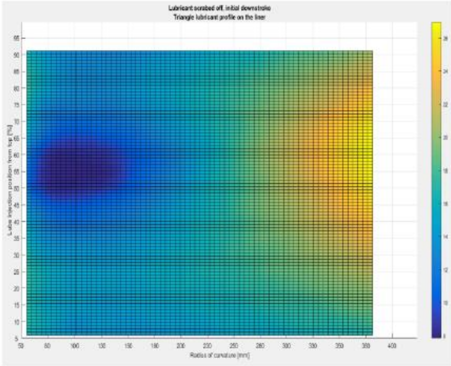
WP6: Model-based Control and Operation Optimization

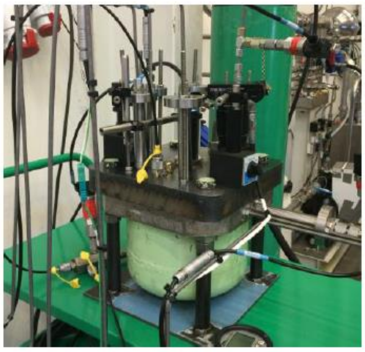
Engine control and optimization

- Experimental testing and validation of lube oil injection model
- Modelling of the axial and circumferential oil flow in front of the piston ring
- Different initial lubricant profiles are being investigated

- Model will be improved by implement multi-ring mass flow balance into system
- Parametric investigation of parameters affecting the oil transport (up-down / circumferential)
- Experimental investigation of oil usage in piston ring pack will be performed

Lubricant scrubbed off in the initial down stroke





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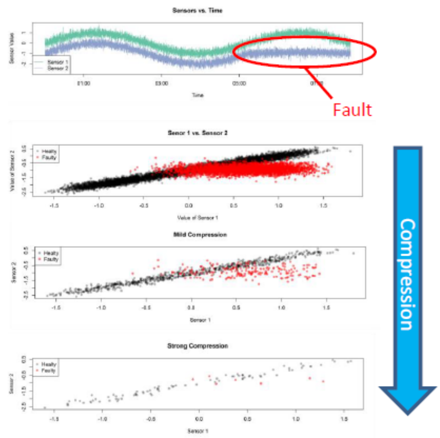
WP6: Model-based Control and Operation Optimization

Remote monitoring & software distribution

- Different frameworks has ben validated (BaselineSimple/Dynamic, univCD, HiCS-mCD, RandSub-mCD, HiCS-mCD-Features, HiCS-mCD-Ensemble)
- Investigation of compression of measurement data in terms of sub space search quality was carried out
- Compression heavily reduces the quality
  - ➢ Making the search for subspaces difficult
  - ➢ Reducing the subspace effects dramatically
- Work on uncompressed data to investigate patterns and subspaces will be performed
- Investigations of alternative compression methods in terms of subspace search quality slated



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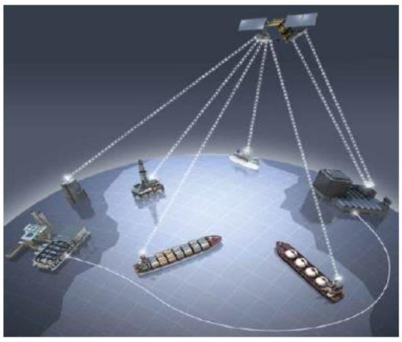
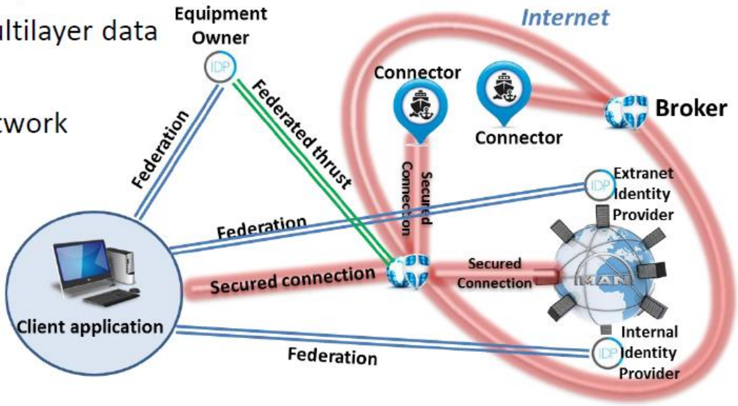
WP6: Model-based Control and Operation Optimization

Remote monitoring & software distribution



- Development of hardened secure onboard control system platform, designed for remote updating.
- Access management to applications and devices based on user access policy via federated thrust for collaboration between multiple partners
- Multifactor authentication and multilayer data encryption
- Zero-thrust, micro-segmented network as general IoT solution

- Prototype implementation done in laboratory
- Roll out of full system in progress



4.4 WPG IV: Near-Zero Emissions Engine

The objective of this WPG is to achieve substantial reductions in NOx, Particulate Matter (PM) and Greenhouse gases (GHG) emission towards the "Near-Zero" emissions engine.

4.4.1 WP7: On-engine aftertreatment systems

The Work Package 7 objectives are

• 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 achieve more than 80% NOx emission reduction and 25% reduction in PM. A combination of integrated SCR and EGR (Exhaust Gas Recirculation) is to be developed. Feasible solutions of combining the above technologies targeting the near zero emission engine are also studied.

• Integrating methane/ethane abatement technology into lean burn 4-stroke gas engines will enable compact solutions to reduce methane slip. 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/ethane 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 after treatment into 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%.

During the first 18 months of the Project, the following major results were achieved:

Literature review, simulations as well as experiments on the different emission reduction technologies have been conducted. To begin with, a demonstration experiment of particulate matter abatement technology, i.e. a combination of a cylindrical electrostatic precipitator and a cyclonic separator, was carried out. Moreover, ways to improve SCR reduction agent injection were also examined. The performance and regeneration of a methane catalyst element were investigated using a small-size gas engine and in parallel potential oxidation catalysts for methane and ethane reduction were evaluated. Furthermore, simultaneous abatement of NOX and soot was investigated by employing a semi-short route EGR configuration on a test engine. As far as particulate number (PN) measurements are concerned, the applicability of a PN measuring device was tested in field conditions. In addition, vibration measurements were performed, on engines operating in the field, using mobile vibration monitoring sensors in order to derive a test cycle for the evaluation of catalyst samples from catalyst suppliers. Finally, SCR catalyst deactivation and reactivation of deactivated catalyst was investigated during the reporting period. A brief presentation of the above mentioned results is presented next.

WP7: On-engine aftertreatment systems

Objectives

WP Leader: Jukka Leinonen

- 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 methane and ethane slip. 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%.

Partners: WÄRTSILÄ VTT Vaasan yliopisto University of Vaasa Paul Scherrer Institut PSI

HERCULES-2 1 PTB MEETING, 5 OCT 2016, HELSINKI

WP7: On-engine aftertreatment systems

Subprojects

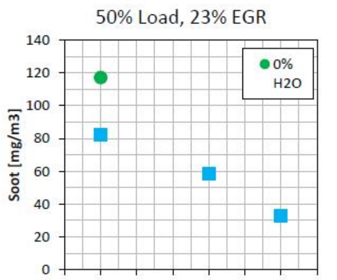
- 7.1 Combined on-engine aftertreatment solutions for 4-stroke diesel engines
- 7.2 SCR reduction agent injection solutions
- 7.3 Integration of methane and ethane abatement technology with gas engines
- 7.4 Emission measurement systems for integrated after treatment technologies

HERCULES-2 2 PTB MEETING, 5 OCT 2016, HELSINKI

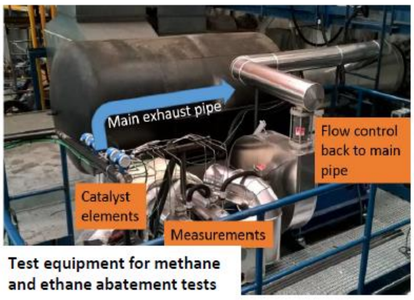
WP7: On-engine aftertreatment systems

Progress update

- PSI, Feasibility and demonstration of NOx and particulate reduction with pre-tests on test engine was completed and analysis & evaluation of obtained data is started. Work will continue due to plan.
- WFI, Activities are ongoing within schedule. PM measurement tests are ongoing and first results are under analysis.
- WSP, Feasibility and demonstration of integrated methane and ethane abatement with gas engine testing continues as planned.
- UV, First deliverable D7.1 regarding literature reviews ready and approved in schedule. Work will continue due to plan.
- VTT, NH3 sensors testing was started due to plan and first results are under analysis. PM emission testing plans was updated and testing will be completed at the end of the second year of the project.



Preliminary results from EGR tests



Test equipment for methane and ethane abatement tests

Test equipment installation for PM measurement tests

NH_3 sensor installed in stack

WP7: On-engine aftertreatment systems

Deliverables and Plan for future work

- Literature review regarding SCR engine integration and particulate abatement.
- Emission measurement systems for SO3, NH3 and PM emissions to support integrated after-treatment technologies
- Experimental assessment of integration of methane and ethane abatement technology into gas engine structure
- Experimental assessment of SCR reduction agent injection systems with sensors for feedback control

Vaasan yliopisto UNIVERSITY OF VAASA

VTT

WÄRTSILÄ

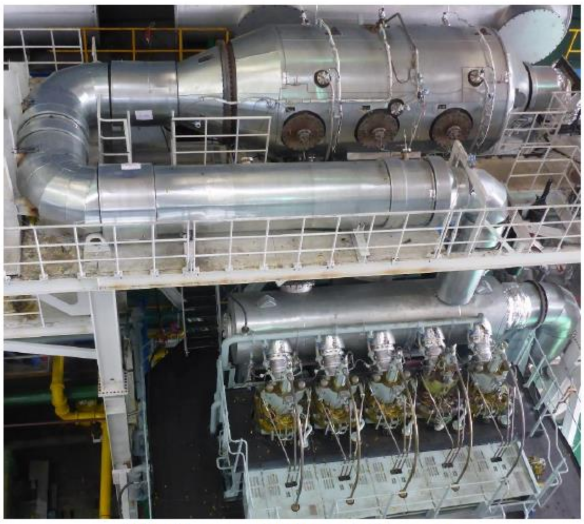
WÄRTSILÄ

WP7: On-engine aftertreatment systems

Objectives of Work Package

WP deputy: Daniel Peitz

Development of key technology for integration of the currently separated SCR aftertreatment into 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%.



WinGD pre-turbocharger SCR system

Subproject

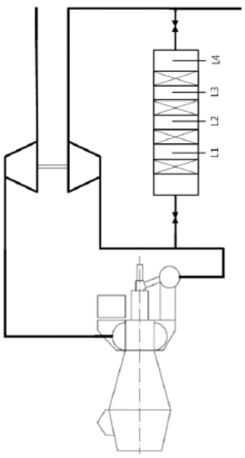
7.5 Robust catalysts for pre-turbo SCR

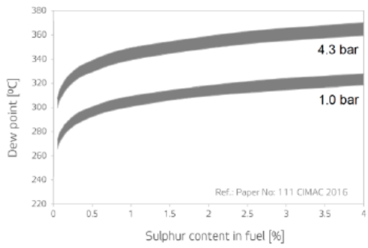
Partners: WIN GD Winterthur Gas & Diesel, DINEX ECOCAT Fresh Ideas - Cleaner Future, JM Johnson Matthey, PAUL SCHERRER INSTITUT PSI

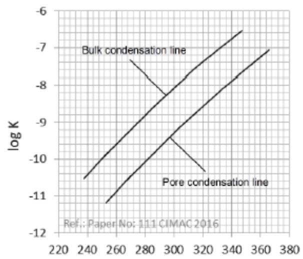
WP7: On-engine aftertreatment systems

Results for WinGD/PSI

- Vibration test cycle specification for SCR components in future 2-stroke marine diesel engine SCR applications
- SCR catalyst durability against ammonium bisulphate (ABS) deactivation from high sulphur fuels investigated
- Safe operating temperatures for SCR defined from slip stream SCR tests



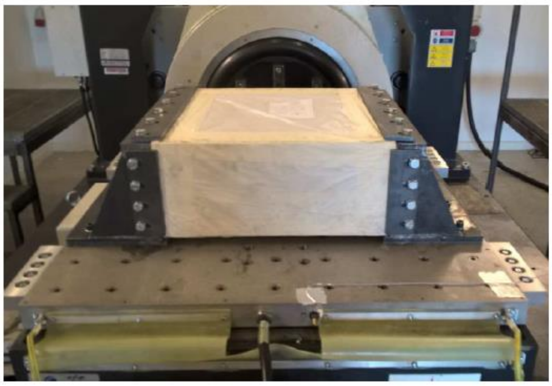




$$K = \frac{p_{NH_3(g)} \times p_{H_2O \cdot SO_3(g)}}{a_{(NH_3 \cdot H_2SO_4)(cd.)}}$$

WP7: On-engine aftertreatment systems

Results for Dinex Ecocat



- Catalyst support designs were tested on vibration test bench
- Designed catalyst support prototypes withstand vibration requirements
- Washcoat adhesion will be further investigated and improved

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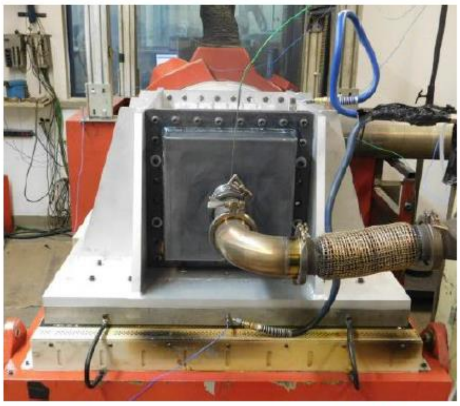
WP7: On-engine aftertreatment systems

Results for Johnson Matthey



- Vibration resistant catalyst supports were designed and manufactured
- Hot gas vibration test bench testing started, but delayed due to test bench downtime and sample holder malfunction
- Sample holder to be reworked and test bench back in operation in October

HERCULES-2 8 PTB MEETING, 5 OCT 2016, HELSINKI

WP7: On-engine aftertreatment systems

Deliverables and Plan for future work

- Further investigate Washcoat adhesion and produce prototypes for field testing.
- Re-weld hot gas vibration test bench, finish vibration tests and produce prototypes for field testing.
- Laboratory testing of catalyst performance and catalyst deactivation assessment.
- Vibration testing of prototype SCR catalysts on engines operating in the field.

DINEX ECOCAT Fresh Ideas - Cleaner Future

Johnson Matthey

PAUL SCHERRER INSTITUT PSI

WIN GD Winterthur Gas & Diesel

4.4.2 WP8: Integrated SCR and Combined SCR & Filter

The objectives of the Work Package 8 for the engine integrated SCR for 2-stroke engines are:

- 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 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

The objectives of the Work Package 8 for the combined DPF and SCR for 4-stroke engines are:

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

The main results achieved during the first half of the HERCULES-2 Project are summarized below: Work related to the engine integrated SCR, included the design of a control setup for dynamic operation. This control setup was tested in full scale shop test, giving high NOx conversion rates and minimum ammonia slip. Moreover, a mini SCR test bed was designed and built including the design of a high pressure evaporator as well as the selection of a reactant dosing system. In parallel, extensive CFD simulations were carried out during the design of the test bed components. Furthermore, a mechanism to perform local transversal measurements in an exhaust gas stream before and after the catalyst was designed and built. In addition, an experimental setup to investigate turbulent mixing of gases, in order to validate CFD models, has been built and tested. Work concerning combined SCR and DPF focused on studying urea decomposition via model development and experiments. An existent hot gas test rig was enhanced to match the requirements for urea decomposition investigations. Urea decomposition was investigated for various pressure and temperature combinations. Different mixer configurations were investigated through numerical simulations and a CFD urea injection model was calibrated and optimized using experimentally obtained measurements. As far as SCR coated DPF's are concerned, a synthetic gas test bed including particle generation and characterization has been designed and is under construction. This test bed is required to investigate simultaneously the SCR and CRT (Continuous Regeneration Trap) performance of SCR coated DPFs.

A short presentation of the above described results follows:

WP8: Engine Integrated SCR and combined DPF and SCR

Objectives

Engine Integrated SCR

- 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

Combined DPF and SCR

- 80% PM reduction with after-treatment system (based on IMO Tier II engine out emissions)
- 80 % NOx 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

WP8: Engine Integrated SCR and combined DPF and SCR

Partners

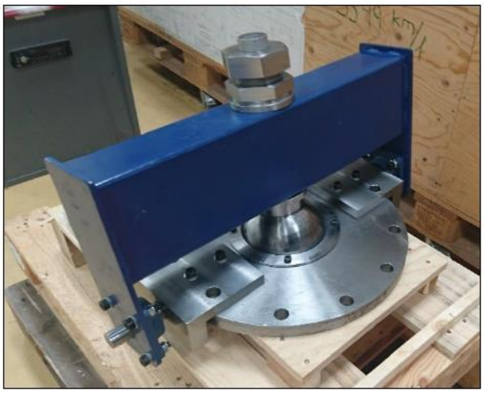
- LUH: Leibniz University Hannover (Hannover)
- DTU: Technical University of Denmark (Copenhagen)
- MDT: MAN Diesel & Turbo

Roles

- LUH: Test rig for investigation of urea injection and decomposition
- DTU: Investigations of SCR mixing and flow distribution.
  Development of mechanism for NH_3 measurements.
- MDT-CPH: Compact mixer, Integrated SCR design and NH_3-slip investigation.
- MDT-Aug: Catalyst coating and filter test bed. Selection & design of SCR on DPF prototype. Modelling of urea injection and decomposition.

WP8.1: Engine Integrated SCR for diesel engines

Measurement equipment for mixing and flow distribution

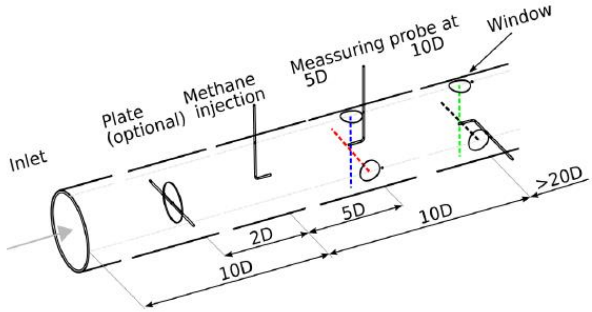


Progress update

- Traverse mechanism is ready for testing
- Flow experiments done with/without mixer plate, CFD calculation.

Future tasks

- Test on 4T50ME-X engine
- Flow expansion experiments and compare with CFD



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WP8.1: Engine Integrated SCR for diesel engines

NH_3-slip investigation, compact SCR mixer, Integrated SCR design

Progress update

- NH_3 slip measurements performed. Control strategy updated and implemented
- Urea Injection study on-going
- Mini SCR commissioned, first test performed
- Integrated SCR design specified

Future tasks

- Urea mixing/evaporator study (mini SCR)
- Design integrated SCR for 4T50ME-X

Mini SCR

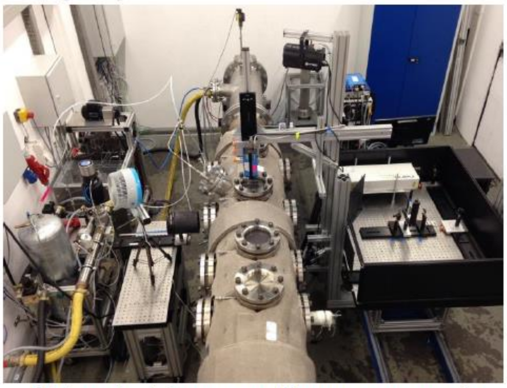
HERCULES-2 4 Partners Meeting, 5th October 2016, Helsinki

WP8.2: Combined SCR and DPF

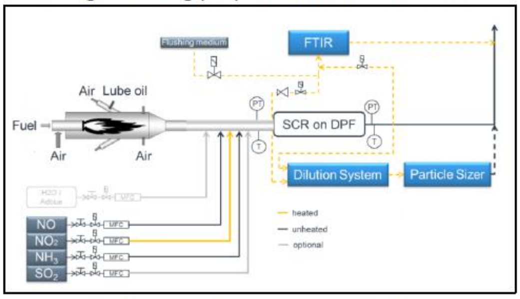
Main results achieved during 1st period of the project

- Set-up of hot gas test rig completed and successfully tested (M44)
- Parameter study for validation of urea decomposition for different pressure and temperature conditions completed (M45)

- Design and procurement of synthetic gas test bed including particulate matter generation and characterisation
- Specification and procurement SCR coated Diesel particulate filters
- Investigation of SCR coated DPF samples by a pre-defined characterization test program



Hot gas test rig prepared for measurements

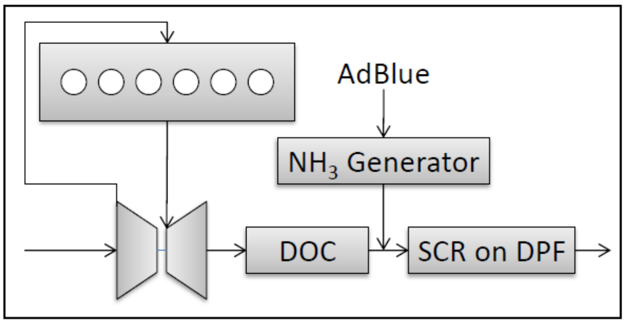


Synthetic gas test bed for filter testing

WP8.2: Combined SCR and DPF

Future Work

- Studying influence of mixing elements on urea decomposition
- Design and study of alternative and improved set-ups
- Build-up of synthetic gas test bed
- Ongoing characterisation and investigation of SCR on DPF samples
- Particulate measurement data base
- Pre-tests of EAT system components on engine test bed



High speed engine with SCR on DPF after-treatment system

5 Conclusions

The HERCULES-2 project has now completed 50% of its duration with excellent progress and cooperation between the partners.

During the first 18 months of the HERCULES-2 Project all Work Packages have exhibited substantial progress. Concept studies have been finalised in most Work Packages, test rigs have been designed and setup, measurement methods have been developed and evaluated, software models have been developed and validated, prototype components have been produced and tested.

The overall vision of the HERCULES programme is for sustainable and safe energy production from marine power plants. The technological themes of the HERCULES initiative, since its inception in 2002, are “higher efficiency”, “reduced emissions” and “increased reliability” for marine engines.

The aim is for marine engines able to produce cost-effectively the required power throughout their lifecycle, with responsible use of the natural resources and respect for the environment.