Coordinated by University of Vaasa VAASAN YLIOPISTO

Co-funded by BUSINESS FINLAND

Flexible Clean Propulsion Technologies

1st Review Meeting

4-5.6.2025 | AALTO UNIVERSITY CAMPUS, OTANIEMI, ESPOO | CONFERENCE SUMMARY

University of Vaasa VAASAN YLIOPISTO · Åbo Akademi · Aalto University · LUT University · VTT · University of Oulu · University of Turku · Tampereen yliopisto Tampere University · Wärtsilä · AGCO Power · Meyer Turku · Proventia · rexroth A Bosch Company · Neste · Lumikko · hycamite · Meriaura

Flexible Clean Propulsion Technologies

Greetings from the event organizers!

The Flexible Clean Propulsion Technologies (Flex-CPT) project marked an important milestone with its 1st Review Meeting, held on 4–5 June 2025 at Aalto University in Espoo, Finland. The event gathered more than 70 participants from industry, academia, and research organisations.

The two-day meeting provided a comprehensive review of the project's technical progress and fostered lively dialogue between research and industry stakeholders. The first day featured plenary presentations from key industrial partners. The plenary session topics included Neste on marine and off-road highlights, Lumikko on challenges in thermal management, and Proventia on the future of exhaust aftertreatment control.

The technical sessions covered rapid prototyping methods in powertrain research and progress in liquid fuel storage, injection and ignition fundamentals, along with dedicated workshops focusing on marine and off-road applications. The second day continued with technical sessions on solutions for gas and dual-fuel engine concepts and developments in emission management, followed by laboratory tours at Aalto University and VTT.

Throughout the event, the consortium's collaborative spirit was evident, as participants exchanged insights across marine and off-road applications, identified synergies, and reinforced Flex-CPT's vision of an economically sustainable, zero-emission future for the transport sector. The laboratory visits at Aalto University and VTT further strengthened this spirit, giving participants an opportunity to connect the discussions with the experimental platforms that underpin the project's research.

In this conference summary, we present abridged overviews of all the contributions, offered in the presenters' own words. This approach not only ensures accuracy but also captures the authentic voice of those advancing the Flex-CPT vision. Our sincere thanks go to all speakers, workshop leaders, and participants whose insights and dedication shaped the meeting into a meaningful and memorable milestone for the project.

Best Regards,

Maciej Mikulski, Merja Kangasjärvi and **Diana Ibraheem**
University of Vaasa

Programme – Day 1, Wednesday 4 June

10:00–10:30	Registration & Coffee
10:30–11:45	**PLENARY SESSION: INDUSTRY PERSPECTIVES** Room AS2 | Moderator: Maciej Mikulski, UVA 1. **Opening & Welcome to the Event** by Maciej Mikulski, UVA 2. **Welcome to the Aalto University** by Ossi Kaario, Aalto 3. **Neste Marine and Off-road Highlights** by Kristian Pettersson, Neste 4. **Challenges in Thermal Management** by Ville Saikkonen, Lumikko 5. **Tier5 delayed or cancelled – what next in exhaust aftertreatment control?** by Arno Amberla, Proventia
11:45–13:00	Lunch
13:00–14:30	**TECHNICAL SESSIONS (PARALLEL TRACKS)**
	Tech 1: Rapid prototyping methods in powertrain research Room AS2 | Moderator: Pasi Peltoniemi, LUT 1. **Automatic model generation for optimization of temperature management systems** by Matti Linjama, TAU. WP5 2. **Passive thermal management of batteries using phase change materials** by Pertti Kauranen, LUT. WP5 3. **Sequential Bayesian optimal design of experiments** by Mikael Kurula, ÅAU. WP1
	Tech 2: Progress in Liquid Fuel storage, injection and ignition fundamentals Room TU2 | Moderator: Anders Brink, ÅAU 1. **Diesels as ignition enhancer for alcohol fuels-combustion research unit results** by Fatimoh Balogun, UVA. WP3 2. **Cryogenic fuel tank modelling** by Anna Pakarinen, ÅAU. WP3 3. **LES study of spray combustion with diesel-methanol fuel blends at different operating temperatures** by Ossi Kaario, Aalto. WP1
14:30–15:00	Coffee Break
15:00–17:00	**WORKSHOPS (PARALLEL TRACKS)**
	Workshop 1: Marine Track | TU5 **Industry Perspectives from Wärtsilä** by Jari Hyvönen **Moderators:** Jari Hyvönen, Wärtsilä Päivi Aakko-Saksa, VTT Mathias Pirttikangas, Meyer Turku Maciej Mikulski, UVA
	Workshop 2: Offroad Track | TU7 **Industry Perspectives from AGCO Power** by Hannu Nenonen **Moderators:** Ossi Kaario, Aalto Teemu Anttinen, AGCO Power Tino Tuominen, VTT Ari Väliheikki, AGCO Power
19:00–21:00	Dinner, Restaurant Fat Lizard

Programme – Day 2, Thursday 5 June

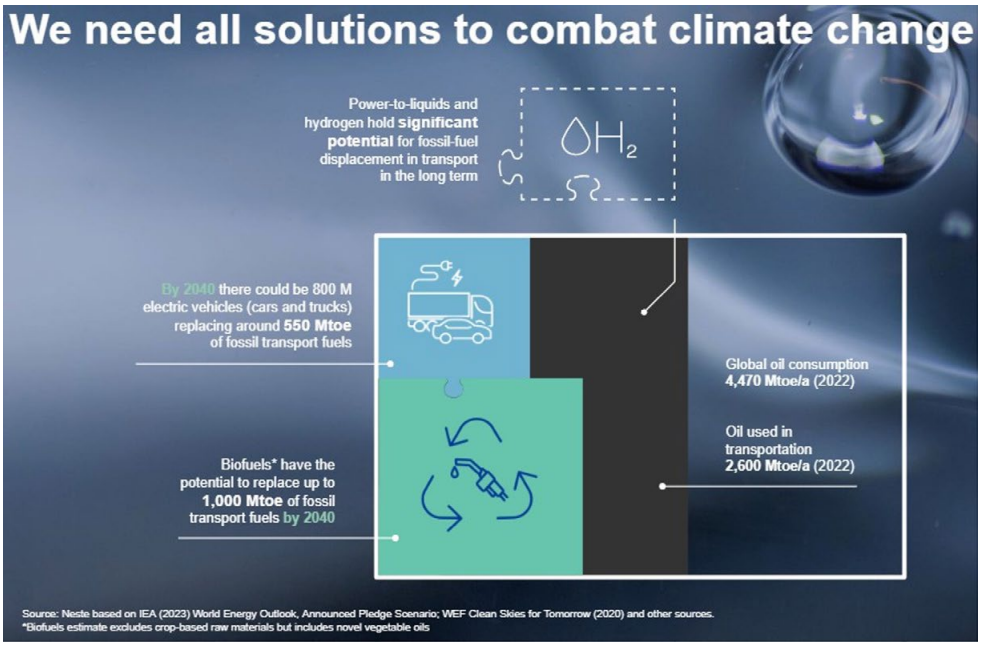
9:00–10:30	**TECHNICAL SESSIONS (PARALLEL TRACKS)**
	Tech 3: Solutions for Gas and Dual Fuel engine concepts Room AS2 | Moderator: Ossi Kaario, Aalto 1. **Results of 'Hydrogen-diesel ignited compression ignition (CI) engine: A dual fuel concept** by Mayanka Jha, Aalto. WP2 2. **Hydrogen spark ignition (SI) engine: Blow-by reference tests** by Tino Tuominen, VTT. WP2 3. **Vibration-Based In-Cylinder Pressure Estimation in Marine Engines: Sensor Placement and Data-Driven Multi-Cylinder Modeling** by Amin Modabberian, Aalto. WP1
	Tech 4: Developments in Emission management Room TU2 | Moderator: Arno Amberla, Proventia 1. **Investigation of urea deposits** by Mika Huuhtanen, UOULU. WP4 2. **State-estimation for SCR aftertreatment control** by Alex Pesu, UTU & ÅAU. WP4 3. **Combined engine and catalytic aftertreatment experiments and simulations** by Teuvo Maunula, UVA & UOULU. WP1
10:30–11:00	Coffee Break
11:00–12:00	**CLOSING SESSION** Room AS2 | Moderator: Maciej Mikulski, UVA 1. **Progress in RCCI technology – simulation/control functions and experiments – overview of corresponding activities** by Jeyoung Kim, UVA 2. **Highlights from the Workshops**
12:00–13:15	Lunch
13:15–15:15	**LABORATORY TOURS (PARALLEL TRACKS)**
	Visit at the Aalto University's labs: • Engine Lab • Renewable Energy Learning Laboratory (Relab) • Chemistry lab
	Visit at the VTT's labs: • Engine and Powertrain laboratory • Hydrogen facilities • Battery laboratory

THIS IS NESTE;
Change runs on renewables

Author and Presenter: Kristian Pettersson, *Neste*

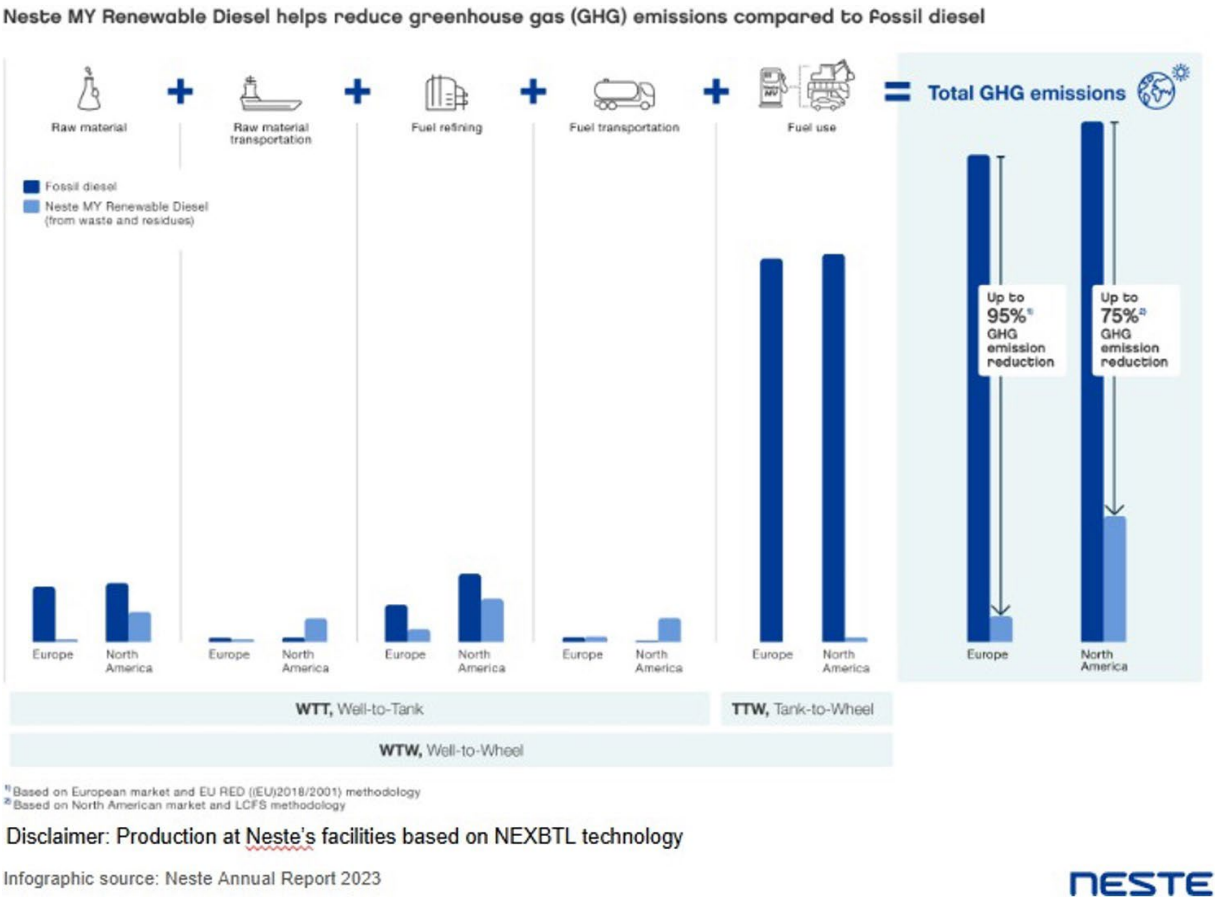
Neste's Business Overview: Neste is a global company with production sites in Finland, the Netherlands, Singapore, and the US, operating in three main business areas: Renewable Products, Marketing & Services, and Oil Products, with a key focus on transforming renewable raw materials into renewable products.

Sustainability Focus: Neste strongly emphasizes sustainability, with goals to achieve a carbon-neutral value chain by 2040, reduce emissions from their production, lower the use phase emission intensity of sold products, help customers reduce their emissions with renewable solutions, achieve a nature-positive value chain, and uphold human rights in their operations and supply chain.



Market Outlook: The presentation addresses global oil consumption and the role of various climate change solutions, noting the significant potential of biofuels, including renewable diesel, to replace fossil fuels, and the expected substantial growth in global demand for renewable diesel due to mandates and regulations like EU RED III and California LCFS.

Neste MY Renewable Diesel: A key product, Neste MY Renewable Diesel, produced from waste, residues, and other renewable raw materials, offers a significant reduction in greenhouse gas emissions compared to fossil diesel and is compatible with all diesel engines. The presentation also covers the development of Neste's NEXBTL technology.



Success Stories: Examples of companies using Neste MY Renewable Diesel, such as Deutsche Bahn and Liebherr, illustrate the real-world application and benefits of renewable diesel in reducing emissions.

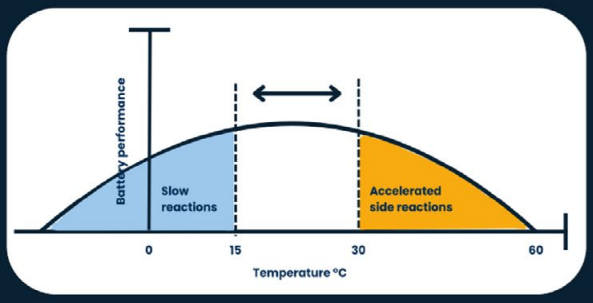
Challenges in Thermal Management

Author and Presenter: Ville Saikkonen, *Lumikko*

Lumikko
THERMAL MANAGEMENT

Key Challenges in Thermal Management for electric and hybrid off-road work machines

1. Natural refrigerants
2. Placement and space constraints
3. Supply Voltages
4. Thermal load management throughout the product's lifecycle
5. Thermal load simulation as a base for the right solution



Impact of Temperature on Battery Performance

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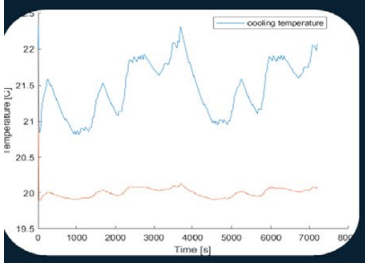
Lumikko
THERMAL MANAGEMENT

Future outlook

2025



Refinement of simulation models throughout the entire product lifecyle

2027

System integration expands

2029

New refrigerants in use, in compliance with the F-gas regulation

Ville Saikkonen, Director, R&D and Technology,
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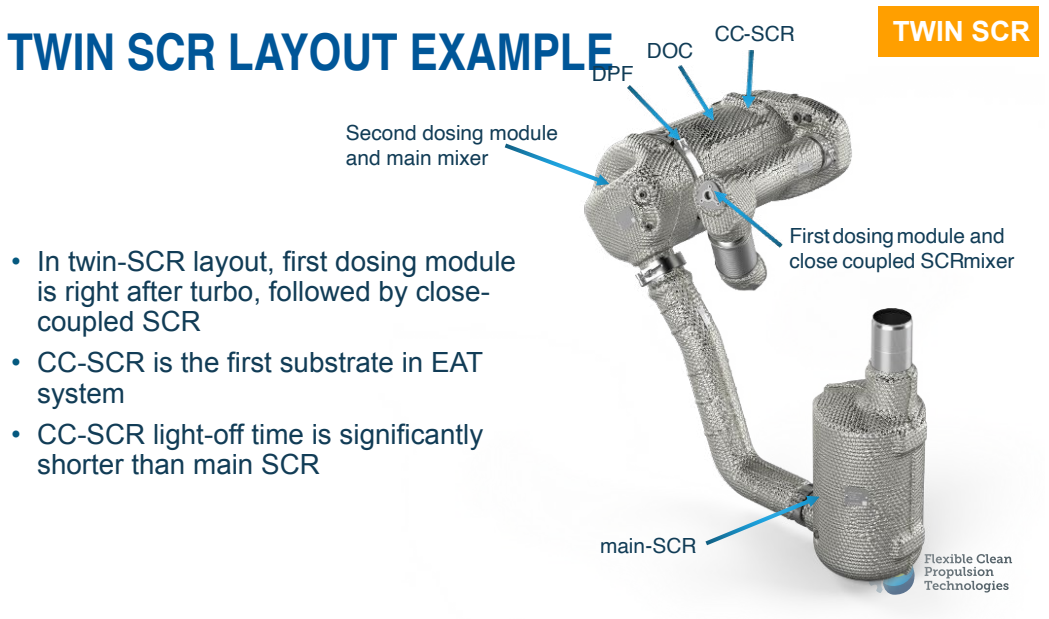
Tier5 delayed or cancelled – what next in exhaust aftertreatment control?

Author and Presenter: Arno Amberla, *Proventia*

The presentation examined the current status and future implications of EU Stage V and CARB Tier 5 emission regulations for non-road mobile machinery (NRMM). Originally scheduled for implementation between 2029 and 2032, CARB Tier 5 aimed to impose ultra-low NOx limits (from 0.4 to 0.04 g/kWh) and drive the adoption of complex aftertreatment technologies such as twin-SCR systems, EGR, and electrically heated exhaust solutions.
With Tier 5 no longer on the regulatory agenda in US, the industry faces a shift toward market-driven approaches and real-world emission strategies. In this context, the Flex-CPT project addresses key technological pathways, including:

- Adoption of alternative low-CO_2 fuels
- Development of hybrid powertrain configurations
- Advanced aftertreatment systems
- Creation of structured roadmaps to meet cost, compliance, and packaging requirements

Proventia's contributions under Flex-CPT include patent-pending aftertreatment innovations, hybrid methanol-diesel engine demonstrations, and in-depth research into urea deposit behavior - supporting robust emissions control solutions regardless of formal regulation. Looking ahead, the possibility of an EU Stage VI standard (~2033) places further emphasis on research-led development and readiness for stricter, real-world emission targets.



Automatic model generation for optimization of temperature management systems

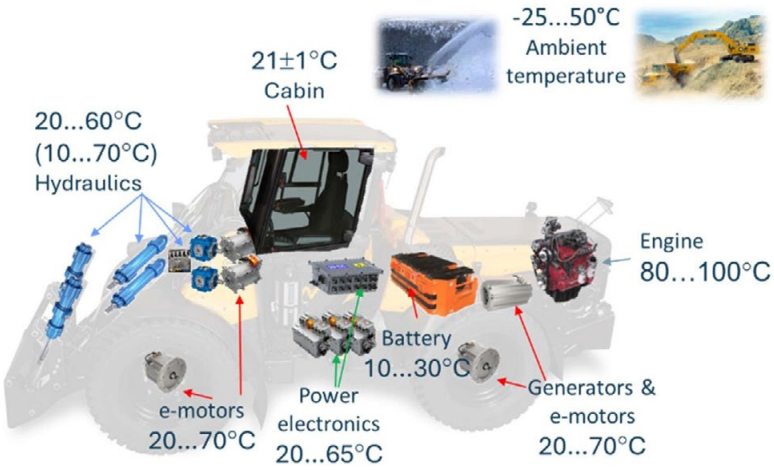
Author and Presenter: Matti Linjama, *Tampere University*
Keywords: Thermal management, Load-cycle data, Control methods, Cooling circuits, Simulation, Interfaces, Feasibility analysis, Component models, Octillion alternatives, Automation, Pressures, Flow rates

Background

The trend in non-road mobile machines (NRMM) is towards hybridization and electrification. This increases the number of different components and requires new methods for temperature management. Electric motors, inverters and power electronics work best at temperatures between 10 and 65 °C. The optimal temperature range for hydraulics is quite the same while accumulators require strict temperature of 10–30 °C and cabin 22°1 °C. Diesel engine temperature is typically 90–100 °C while parts of the aftertreatment system may operate at temperatures exceeding 400 °C. These wide variations at optimal temperatures and cooling powers makes the design, implementation and control of temperature management systems complicated. This presentation addressed these problems and presented possible research approaches.

Challenges

The first challenge is close to infinity ways to implement temperature management system. Typical machine has 20 components related to temperature management, and this results in about 16°1027 different ways to connect components. The second challenge is that a large set of different models must be created, simulated and analyzed automatically. The third challenge is computation time. Modest assumptions result in computation time requirement of 2 ms including model creation, simulation over complete load cycle data and data analysis. The fourth challenge is interfaces between models from different research units.



Approaches and solutions

The possible solutions to the first challenge are the use of AI, rule-based approach and dividing problem into smaller subsystems. None of these are studied yet. Lot of work has been done in the automatic model generation by using Matlab's programming language. The approach seems promising and will continue. The temperature management system of sWille hybrid wheel loader has been used as a benchmark. The numerical performance problem is possibly tackled by code optimizations and the use of high performance computing platforms. The interface problem is discussed with research units, but the approach is still unclear.

Conclusions

The design, implementation and control of the temperature management systems of NMRR is important and challenging problem. Results thus far shows that it is possible to build automatic model generation and analysis tool, which is basic building block for system optimization and control.

Passive thermal management of batteries using phase change materials

Author and Presenter: Pertti Kauranen, *LUT University*
Keywords: Battery Thermal Management System, Phase Change Material, Li-ion Battery, Nickel Cobalt Aluminium

Passive cooling of a Li-ion battery module using phase chang material (PCM) has been evaluated. The battery consisted of 12 cylindrical Li-ion cells (21700 format, nickel cobalt aluminum (NCA) cathode chemistry) connected in 3p4s (3 parallel, 4 series) configuration, Figure 1. The thermal performance of a module with a PCM paraffin with a melting point at 35 °C was compared with a module without the PCM at 1.0, 1.5, 2.0 C-rates.

At 1.5 C (40 min) charging and discharging rate the module without the PCM reach maximum temperatures between 45 and 48 °C. The module with the PCM showed 10 °C lower peak temperatures, and could be cycled at 2.0 C rate (30 min) still maintaining the temperature below 45 °C, Figure 2.

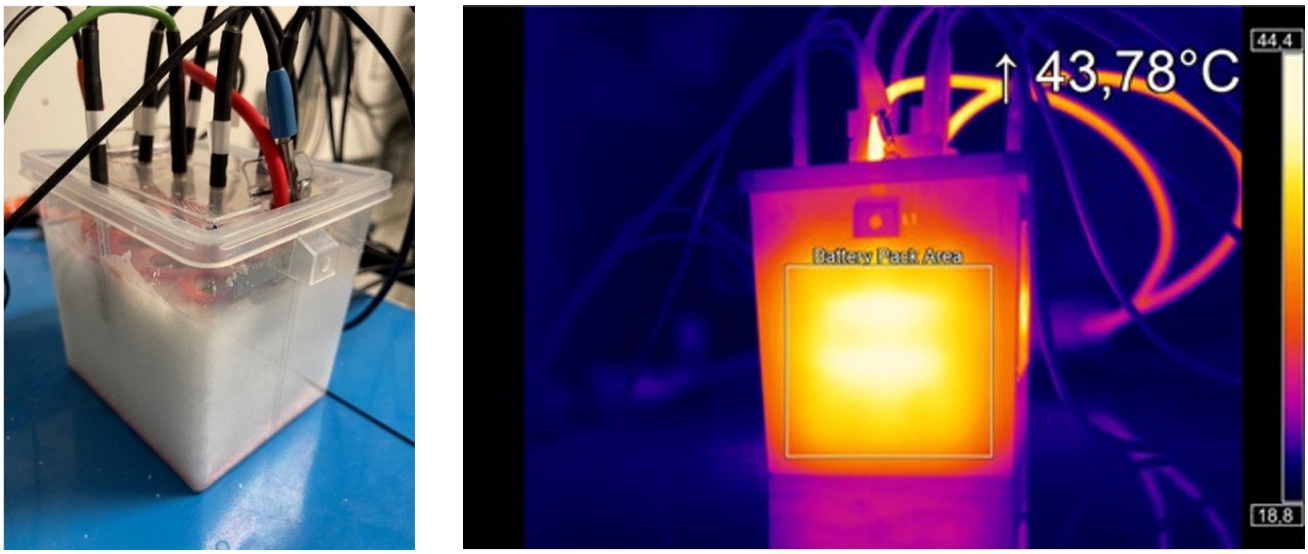


Figure 1. The Battery module filled with the PCM and The temperature of the module at the end of 2.0 C charging.

Progress in Advanced DOE

Authors: Mikael Kurula, Amanda Björkvik and Anders Brink
Presented by: Mikael Kurula, *Åbo Akademi University*
Keywords: Design of experiments, sequential experimental design, Bayesian optimality

Disclaimer: Use of generative AI

A draft for this exenteded abstract was produced by generative AI (Copilot), based on my slides from the talk. I edited and quality checked the draft, leading to the present version.

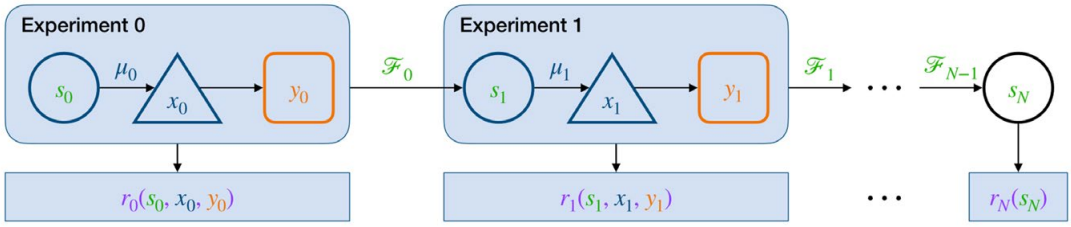
Extended abstract

The talk presents a framework for sequential Bayesian optimal design of experiments (sOED), summarized in Amanda Björkvik's MSc thesis. The goal is to plan a sequence of N experiments to learn an empirical model f:R^D → R of a physical system, where each experiment may have a different cost and the dimensionality D is high while N is small. The challenge lies in maximizing the information gain under these constraints.

A Markov decision process (MDP) is used to model the sequential nature of the experimental design. The policy π = (μ_0, μ_1, ..., μ_{N-1}) determines the experimental settings based on the current state, which encodes prior knowledge and past measurements. The objective is to find an optimal policy π^* that maximizes the expected total utility:

U(π) = E_{y_0, ..., y_{N-1} | π, s_0} [Σ_{k=0}^{N-1} r_k(s_k, x_k, y_k) + r_N(s_N)],

subject to the dynamics x_k = μ_k(s_k) and s_{k+1} = F_k(s_k, x_k, y_k).



The sequential approach allows for adaptive experimentation, where each measurement informs the next decision, akin to closed-loop control. This structure is closely related to reinforcement learning, and solving the resulting optimization problem is computationally demanding. Unlike much of the literature, which focuses on parametric models, this work employs a non-parametric Gaussian process (GP) to model the unknown system. The GP is fully characterized by its mean and covariance functions (m_k, c_k), which together form the belief state s_k of the MDP. The state is updated using GP regression after each measurement, incorporating new data to refine the model. The terminal reward r_N(s_N) is defined via the expected Kullback-Leibler (KL) divergence between the prior and posterior distributions of a Quantity of Interest (QoI), which maps the GP to a finite-dimensional Gaussian. This allows for an analytic expression of information gain, even though GPs themselves lack a density function.

Immediate rewards r_k are used to encode experiment-dependent costs. By augmenting the state with the previous experiment setting, the cost of transitioning between experiments can be penalized, e.g., via a term like -Σ||x_k - x_{k-1}||^p. This introduces memory into the MDP, relaxing the strict Markov property but enabling more realistic modeling of physical experimentation constraints.

Two examples illustrate the framework. The first is an analytically solvable case involving a linear GP model with two experiments. The optimal policy is computed using dynamic programming and known to coincide with with the result of a much simpler batch design, where all experiments are planned in advance without feedback. The second example introduces experiment-dependent costs and uses approximate dynamic programming with simulated trajectories behind the scenes. The results demonstrate how increasing cost penalties shift the optimal experiment locations and reduce the expected utility, highlighting the trade-off between information gain and experimental effort.

A key scientific contribution is the derivation of an explicit formula for the expected KL divergence in the Gaussian setting, starting a systematic investigation of when sOED and batch design are equivalent. A conjecture is proposed:

If all immediate rewards vanish, then sOED is equivalent to batch design.
It is an open question under which additional assumptions this conjecture is true; so far only some particular examples are known. The thesis also raises the question how to represent belief states for non-Gaussian processes and how to efficiently compute near-optimal policies using modern machine learning techniques.
Future work includes implementing the proposed framework in practical applications, exploring scalable algorithms for high-dimensional problems, and comparing the performance of sequential versus batch strategies in real-world scenarios.

Diesels as ignition enhancer for alcohol fuels – combustion research unit results

Authors: Fatimoh Balogun, Huaying Wang-Alho, Michaela Hissa, Katriina Sirviö and Alireza Kakoee
Presented by: Fatimoh Balogun, *University of Vaasa*
Keywords: Methanol, Ethanol, Diesel, Ignition Improver, Combustion Research Unit, Fuel blends, Ignition delay

Introduction

In the marine and off-road sectors, methanol and ethanol are increasingly being explored as alternative fuels for compression-ignition engines (CI) due to their favorable emission characteristics (low-carbon fuels) and renewable origins. Low cetane number, and high latent heat of vaporization can result in cooling of the intake air, which slows down the evaporation of fuel and leads to a longer ignition delay, resulting in need for ignition improvers in CI engines. While these alcohol fuels alone face challenges with ignition stability in CI engines, ignition improvers (II) e.g. diesel blending is a considered option for improving combustion characteristics of the alcohols

Goal & Objective

The objective of the study is to utilize chamber pressure and heat release data from combustion research unit (CRU) to compare combustion characteristics and performance metrics of the liquid fuel samples across three different engine loads using a mixing – controlled diffusion concept. The goal is to investigate diesel blending as ignition improver for alcohol fuels, for use in compression ignition engines (CI), including performance variations due to different fuel injection strategies and fuel blends physico-chemical analysis.

Materials and Methods

The main studied fuels are methanol (MeOH) and ethanol (EtOH). Light fuel oil (LFO), renewable diesel (RD), and Used cooking oil methyl ester (UCOME) were used in the blends as diesel ignition improvers. The blend share were calculated on volume basis. A total of 17 fuel blends were analyzed, classified into 4 categories based on fuel blend types and injection strategies. Fuel blends samples were categorized as 1) ethanol pre-blend (3 samples); 2) methanol pre-blend (3 samples); 3) ethanol + diesel pilot (3 samples), 4) methanol diesel pilot (5 samples); 5) methanol+diesel+1-octanol blends (5 samples). Neat fuels which include methanol, ethanol, LFO, RD, and UCOME were used as reference. Category 1 – 4 have alcohol of 90% and diesel ignition improver of 10%. In category 1 and 2, UCOME is used as a co-solvent for stabilizing the fuel blends. In category 5, the share of diesel varies from 4% to 78%, while the share of methanol from 9% to 83%, 1-octanol is used as co-solvent for stabilizing the fuel blends. Fuel storage stability test performed on the pre-blends showed that all pre-blend samples were stable and clearly homogeneous without phase separation for at least 6 weeks except 2 samples; MeOH90%+LFO3%+UCOME7%, MeOH90%+RD3%+UCOME7%, which were only stable for about 2 hours, after which fuel blend separation is evident. The physico-chemical analyses of these pre-blends were also done as shown in Figure 1. The analyses include kinematic viscosity, density, initial and final boiling points (IBP, FBP), cetane number (CN), and lubricity using high frequency reciprocating rig (HFRR).

Methodology

Using Combustion Research Unit (CRU), engine load for pre-blend runs was set at 550 °C, 55 bar (Low-Load), 650 °C, 70 bar (Mid-Load), and 700 °C, 70 bar (High-Load). Engine load for pilot runs was set as Low-Load, and Mid-Load. Key combustion parameters directly derived from CRU experiments includes; Ignition Delay (ID) which is the time at t=0, to t = 0.1bar, Combustion Phasing (CP) which is the time at 50% maxPI, Main Combustion Period (MCP) which is the time at t=10% to 85% maxPI, Maximum Rate of Heat Release (maxROHR), and Maximum Pressure Increase (maxPI)

Current Key Findings and Summary

- In the alcohol-diesel pre-blend cases; Effect of diesel as ignition improver for the alcohol fuels were significant with approximately 30% shortening of ID at low-load and further 30% shortening at high-load.
- Biodiesel UCOME; not only served as a binding agent, it also had relatively best ignition improving effect compared to LFO, and RD in the alcohol-diesel pre-blend cases.
- ID for studied pre-blend alcohol fuels + diesel as ignition improver (≈7 – 11 ms), is not acceptable even at high-load since the minimum ID should be less than 2ms in diesel engines
- In the pilot cases; LFO, RD, and biodiesel UCOME as ignition improver, have similar effect on the alcohol fuel's ID. However, RD as pilot has relatively the best and acceptable ID shortening effect even at low-load.
- For the blends containing MeOH+diesel+1_oct. cases; ignition delay reduces as blend share of diesel increases.
- In the category 4; blend consisting of MeOH9%+RD78%+1_Oct13% has relatively the shortest ignition delay, earliest combustion phasing, shortest main combustion period, high maximum pressure increase and maximum rate of heat release similar to LFO. The next best performance is MeOH17%+RD70%+1_Oct13%, and MeOH28%+RD50%+1_Oct22%. Insights from all fuel pre-blend physico-chemical analysis points out these three samples are currently recommended for engine experiments in T2.2.5, and material compatibility studies in T3.2.1.

For applicability of these samples in a compression ignition engine;

- Alcohol – diesel pilot category have calculated compression ratio (CR) of 17–18, which is ideal for typical CI engines.
- Alcohol – diesel pre-blend category have calculated CR values 37–39, which is significantly high and unacceptable.
- Consequently, use of dual injection system is recommended, otherwise exploration of alternative ignition improver is needed to reduce ignition delay of alcohols pre-blends for adaption in CI engines without much change in engine infrastructure.

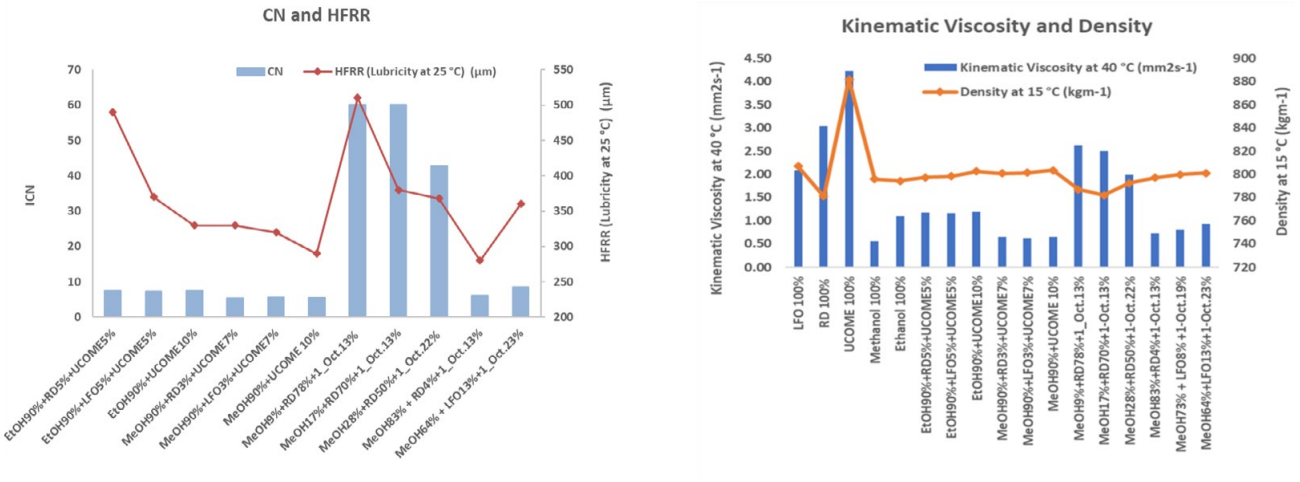


Figure 1. The physico-chemical analysis results of the pre-blend samples. Plots of kinematic viscosity, density, indicated cetane number (CN), and lubricity using value from high frequency reciprocating rig (HFRR).

Cryogenic fuel tank modelling

Author and Presenter: Anna Pakarinen, *Åbo Akademi University*
Keywords: Cryogenic fuels, Cryogenic storage tanks, LNG, Liquid hydrogen (LH2), Tank motion, Heat ingress, Thermal stratification, Boil-off, CFD modelling, Ansys Fluent, Dynamic mesh, Heat transfer

Cryogenic fuels require temperatures below -153 °C to stay in the liquid phase. These include fuels such as LNG and LH2, which in normal conditions exist in gas phase and must be cooled down to extremely low temperatures to liquefy them. In cryogenic storage tanks, LNG and LH2 occur in two phases: the liquid cryogen at the bottom and the vapour phase (or the ullage) on top of the liquid.

Due to the low temperatures that are required to maintain the cryogens in liquid phase, efficient thermal insulation is necessary to prevent heat leaking into the tank from the environment. However, as the temperature difference between the cryogen and the environment is large, there will always be some thermal ingress into the tank. This can cause the liquid at the liquid-vapour interface to start boiling off and other phenomena, such as thermal stratification, to occur in the tank.

Thermal stratification is a result of buoyancy-induced flows in the fluid, as the fluid close to the tank wall is heated and rises to the top while the colder fluid sinks to the bottom, which causes the upper parts of the fluid to have a higher temperature than the lower part. For tanks that are used in moving vehicles, e.g. ships, the motions of the vehicle can cause sloshing and motions in the liquid inside the tank. The moving liquid in its turn can affect the fluid flows and the temperature gradient inside the tank.

The research objective of this work is to create a model to simulate the effect of tank motion on the heat ingress into a cryogenic storage tank, as well as the effect on the thermal gradient and fluid flows in the ullage. Cases with different liquid filling levels, and consequently, different vapour volumes are studied. The different cases are a tank with liquid filling levels of 25%, 50% and 75% of the tank height, and the studied fuels are methane and hydrogen. Figure 1 and 2, respectively, show the temperature gradient and the flow velocities in the ullage of a liquified methane tank with a 50% liquid level.

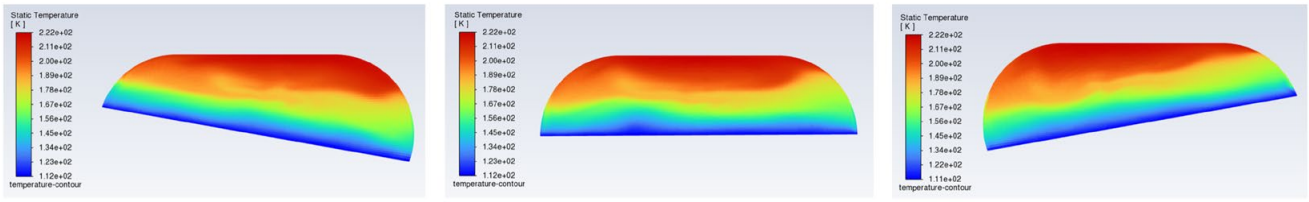


Figure 1. Temperature gradient in the ullage after about 10 s of tank motion.

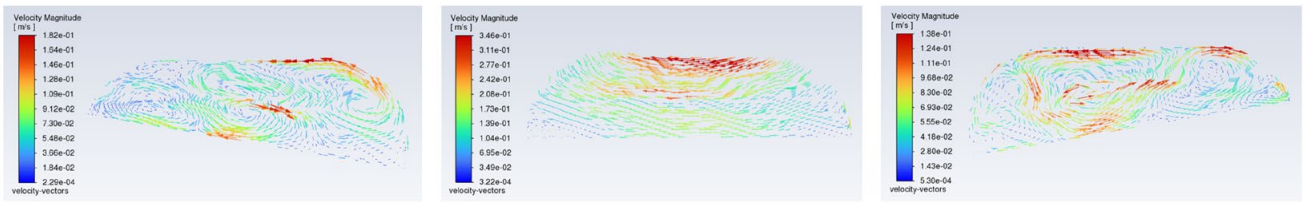
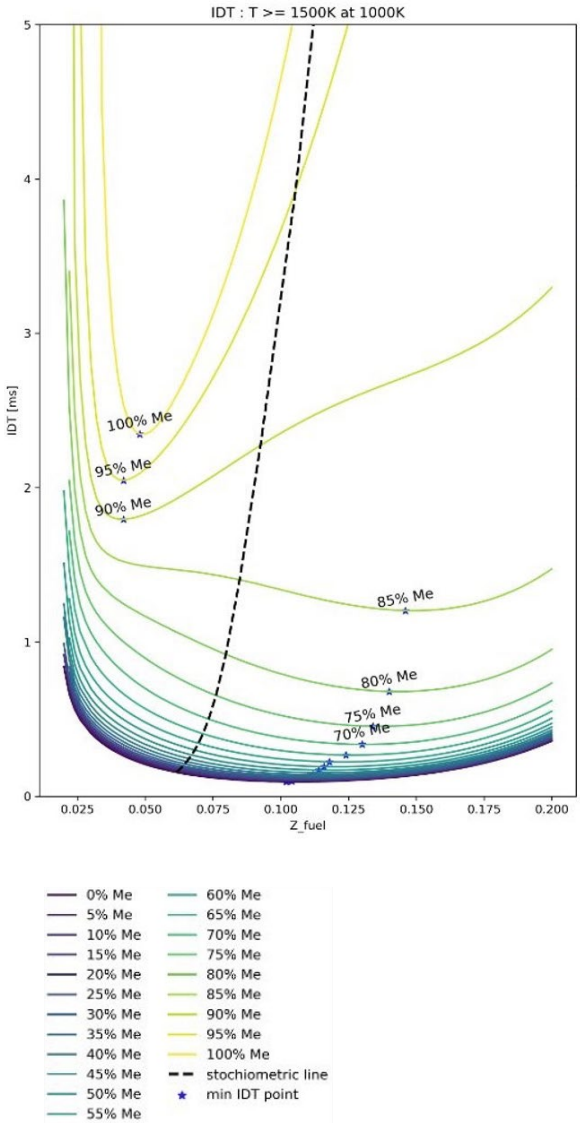


Figure 2. Velocity vectors that show the fluid flow in the ullage after about 10 s of tank motion.

As the tank moves, the sidewalls of the tank are wetted by the cold liquid and, consequently cool down. The motion of the liquid surface causes the fluid in the ullage to move around so that the warmer gas layers come into contact with the cold walls, causing the gas to cool down over time (see Figure 1). When the tank leans to one side, the liquid surface forces the gas on that side to move to the opposite side, and as the liquid surface begins turning back towards the centre position, the change in the direction of the flow causes swirling motion in the fluid, which is visible in the images in the left and right side of Figure 2. The flows in the ullage are driven by the movements of the liquid surface and depend on the amplitude and frequency with which the liquid surface turns, meaning that for higher frequencies faster flows and mixing is expected in the gas.

LES study of spray combustion with diesel-methanol fuel blends at different operating temperatures

Authors: Bishal Shrestha, Shervin Karimkashi and Ossi Kaario
Presented by: Ossi Kaario, *Aalto University*
Keywords: Ignition Delay Time (IDT), Spray combustion, LES (Large-Eddy Simulation), OpenFOAM, Cantera, CFD, Emissions, Renewable fuels, Combustion modelling



The objectives of the study are:

1. To understand the combustion of blended diesel-methanol spray.

2. To find the optimum diesel-methanol blend ratio at different operating temperatures for combustion.

3. To calculate the emissions (NOx, soot precursors, CO2) resulting from the blended fuel.

A 0-D study was conducted using cantera for blended n-dodecane and methanol. The x-axis shows the mixture fraction of fuel (Z), and the y-axis shows the ignition delay time (IDT) in ms. The different lines are the IDT vs Z curves for different methanol percentages. The dashed line is the stoichiometric line. The right side of the dashed line shows a rich mix whereas the left to the dashed line shows a lean mix. This shows that methanol is most reactive (determined by the lowest value of IDT or by * in the figure) on the lean side, and n-dodecane combusts on the rich side. Preliminary 3-D LES study with coarse mesh (125 μm) shows that, at lower concentrations of methanol, ignition occurs on the rich side, whereas for high concentrations of methanol, ignition occurs on the lean side. In addition, IDT and NOx emissions were also calculated. It is shown in Table 1 and Figure 3.

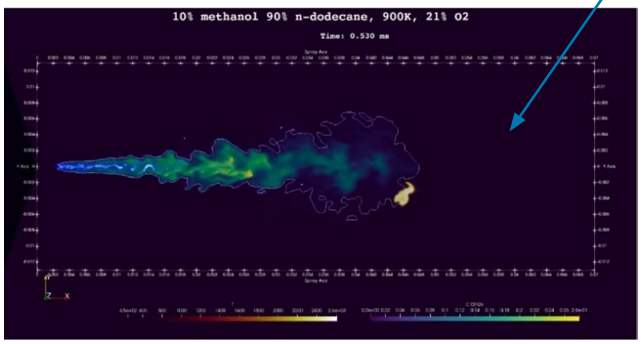


Figure 1. Figure showing IDT vs Z plots for different ratios of methanol and n-dodecane at 1000K ambient.

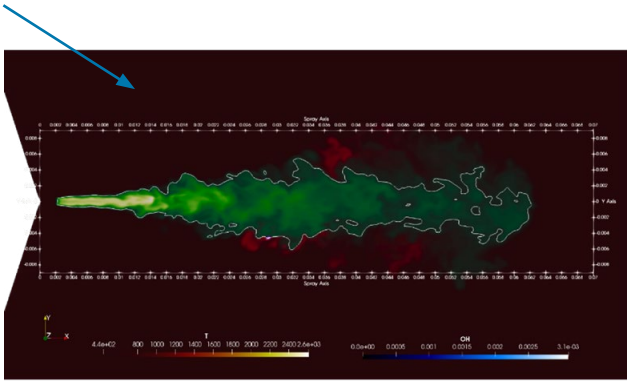


Figure 2. Figure showing the location of ignition for 10% methanol and 90% n-dodecane (left) and 70% methanol and 30% n-dodecane(right). The white contour shows the stoichiometric line.

Methanol	Diesel	Ambient Temperature [K]	Minimum IDT [ms]	Flame Temperature [K]	IDT 3D Coarse [ms]
10%	90%	900	0.23	2500	0.4825
20%	80%	950	0.16	2372	0.57
30%	70%	1000	0.122	2212	0.68
70%	30%	1100	0.198	1950	0.85

Table 1. Table showing the different percentages of methanol and diesel (w/w) and their corresponding IDT and flame temperature.

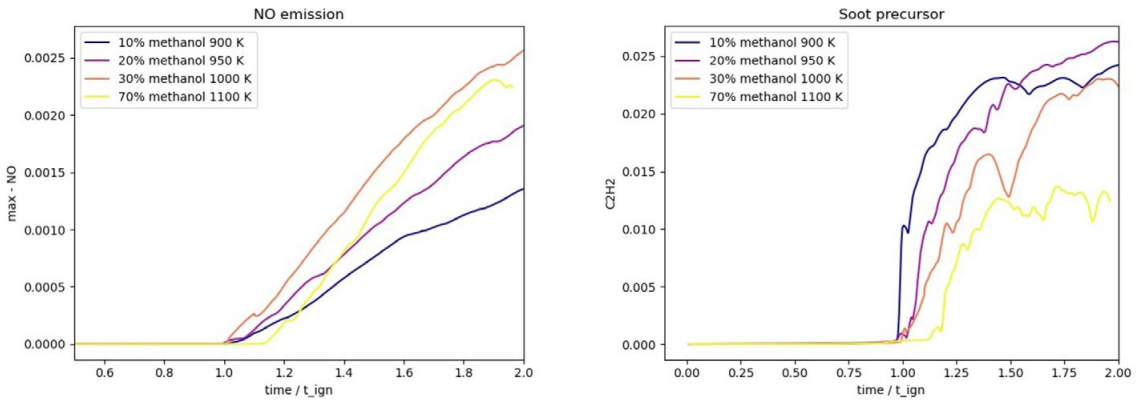


Figure 3. Figure showing the NOx emission (left) and soot precursor emissions(right) from the cases.

Figure 3 shows the limits of the amount of methanol for a given ambient temperature. The limit is set in such a way that, IDT of the spray is less than 1 ms. Till now, the study concludes the following:

1. Methanol is most reactive when the mixture is lean, and n-dodecane is most reactive when the mixture is rich.
2. Methanol does not combust well at low ambient temperatures.

Results of Hydrogen-diesel ignited compression ignition (CI) engine: A dual fuel concept

Authors: Mayanka Jha, Ari Ainsalo, Joakim Kapp, Qiang Cheng, Olli Ranta, Otto Blomstedt and Ossi Kaario
Presented by: Mayanka Jha, *Aalto University*
Keywords: Diesel ignited dual fuel engine, hydrogen combustion, port fuel injection, combustion analysis, emissions, natural luminescence, OH* chemiluminescence

The presentation focussed on describing the latest diesel ignited hydrogen combustion experiments in the research engines of Aalto University. With the motivation to study the effect of hydrogen enrichment in a compression ignition engine the investigation was conducted in both full metal research engine as well as the optical engine. With such an approach it was possible to understand the in-cylinder behaviour and emission trends quantitatively (focus of full metal engine tests), as well as conduct qualitative analysis about hydrogen enrichment by utilising visual information (focus of optical engine tests).

Following a systematic approach, the experiments were first conducted in the full metal engine where the engine speeds were varied as 1000 RPM, 1500 RPM and 2000 RPM owing to the flexibility offered by the engine while keeping the total energy and air mass flow rate per cycle constant. Additionally, at each of the RPMs the hydrogen energy share was varied between 0-50 %, while fixing the CA50 values at 10, 8 and 6 CA degrees. In summary, at each RPM the hydrogen energy share was varied and at each of the hydrogen energy the three CA50 values were fixed sequentially. This way it was possible to isolate factors such as RPM, hydrogen energy share as well as combustion phasing to derive conclusions about the effect of hydrogen enrichment in terms of both combustion analysis and emission trends. Following the completion of experiments and analysis on the full metal engine, the next phase involved test campaigns using an optical engine where natural luminescence and OH* chemiluminescence measurements were taken simultaneously. Due to the sensitivity of the optical components, experiments were conducted at an engine speed of 1000 RPM to ensure safe operation while keeping the total energy constant. In the initial test series, CA50 was not fixed; instead, the hydrogen energy ratio was varied between 0–40 % to investigate the effects of hydrogen enrichment. In a subsequent test series, with the hydrogen energy ratio fixed at 30%, the start of injection (SOI) was systematically varied from 8 to 12 Degrees BTDC.

From the full metal engine results it was noted that at any particular RPM with an increase in hydrogen energy share the in-cylinder pressure and heat release rate (HRR) values kept on increasing. Furthermore, at any constant hydrogen energy share, the heat release rate increased with an increase in RPM and at least the HRR peak corresponding to the combustion phase dominated by premixed hydrogen appeared to increase with an early CA50 value. Due to the constant total energy condition the indicated thermal efficiencies (ITE) and indicated mean effective pressures (IMEP) across all engine speeds, hydrogen energy ratio and CA50 values remained nearly constant. Regarding emission trends the engine results suggested that increasing the hydrogen energy share at a given engine speed led to higher Nitric Oxide (NO_x) while the CO_2 emissions and soot emissions decreased. With increased engine speed both NO_x and CO_2 emissions declined, whereas the soot emissions increased significantly. With respect to the influence of CA50 earlier CA50 was associated with elevated NO_x emission, whereas the CO_2 emissions remained relatively unaffected. Notably, at high engine speeds and operating points with lower hydrogen contribution, the soot emissions tended to increase with later CA50 values. Figure 1 presents the carbon dioxide and nitric oxide emission trends at the lowest engine speed used in the tests.

Visual inspection of the optical engine test results revealed that increasing the hydrogen energy ratio led to a reduction in natural luminescence intensity, accompanied by an increase in OH* chemiluminescence intensity—indicative of characteristic hydrogen flame behaviour. Interestingly, ignition delay was observed to increase with higher hydrogen content. This counter intuitive trend can be preliminarily attributed to the relatively low in-cylinder temperatures, resulting from the low compression ratio and skip-firing operation in the optical engine. Additionally, the tendency of hydrogen to displace intake air may have reduced the available air for diesel ignition, further contributing to the prolonged ignition delay. However, these are some initial speculations and more tests needs to be performed to confirm these. From the second test campaign where the start of injection was varied for 30 % hydrogen case, it was observed that the ignition became later with later injection (as suggested by both natural luminescence and OH* chemiluminescence results). Figure 2 presents the natural luminescence results for the operating points where the hydrogen energy share was varied.

In conclusion, a key limitation identified in replacing diesel with hydrogen was the increased NO_x emis- sions, particularly at low engine speeds. Consequently, as discussed in the meeting, future test runs will be conducted using the full metal cylinder engine at 1000 RPM, with varying lambda values to identify optimal conditions that minimize NO_x emissions without compromising engine efficiency or increasing other emissions.

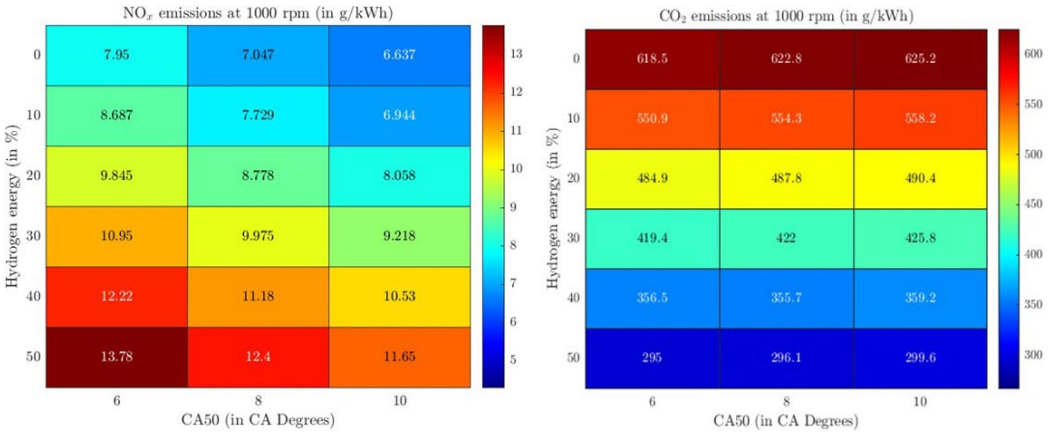


Figure 1. NO_x and CO_2 emission trends at an engine speed of 1000 RPM.

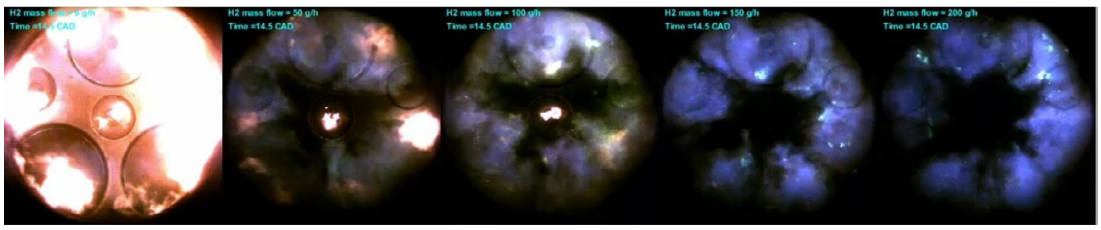


Figure 2. Natural luminescence results at varying hydrogen energy ratio when the engine was running at a constant speed of 1000 RPM.

Hydrogen spark ignition (SI) engine: Blow-by reference tests

Authors: Tino Tuominen, Mårten Westerholm and Rasmus Pettinen
Presented by: Tino Tuominen, *VTT*
Keywords: hydrogen combustion, blow-by gas

During the previous Clean Propulsion Technologies project, it was discovered that the hydrogen concentration in the blow-by gases might possess a risk of explosion in the engine crank case due to low (4%) lower explosion limit of hydrogen. Hence, the work conducted within task 2.1.2 aims to address these concerns by recognizing the main mechanisms and factors affecting the hydrogen concentration in the blow-by gases and providing information of the level of hydrogen concentration in the crank case over the whole engine operation range. This abstract summarizes the results from the first experimental tests performed at VTT research facilities.

Experimental tests were performed with a 4-cylinder NRMM engine manufactured by AGCO Power. The engine is the same unit as used in the earlier CPT project and it is based on the latest CORE50 engine platform with specific modifications to facilitate H2 combustion. This engine has a H2 direct injection fuel injection system, hence fuel injection timing can be used as a calibration parameter. To mitigate the risk of forming an explosive mixture in the crank case, nitrogen was fed into the crank case to dilute the mixture.

The tests were performed in two steps: steady-state points covering the whole engine operation range were run first followed by a parameter study in selected operation points. The first step gives us an understanding of the overall level of H2 blow-by in relation to engine speed and torque. Then, the parameter study highlights the impact of different parameters on H2 blow-by. Parameters selected for the parameter study were lambda, ignition advance angle and start of injection. In Table 1 below is seen the selected engine operation points with parameter setting range for the parameter study.

Speed [rpm]	Load [Nm]	Lambda [-]	Change in SOI [CAD]	IGN [CAD]
1100	150	2 – 2.6	0 – 190	Lambda dependent
1100	350	2 – 2.6	0 - 55	Lambda dependent
1500	200	1.9 - 2.6	0 - 190	Lambda dependent
1500	400	2.1 - 2.7	0 - 190	Lambda dependent

Table 1. Operation points with parameter settings

The result analysis included a correlation analysis for the whole data set including all measured data points in both steps. With correlation analysis, the main factors impacting the engine total blow-by and H2 blow-by could be recognized. Based on the analysis, the most significant impact on engine total blow-by flow is with intake manifold pressure (correlation of 0.97). For H2 blow-by flow, the intake manifold pressure did not correlate that well (0.66) and the highest correlation was shown for engine torque (0.78).

Looking at the H2 blow-by flow over the engine operation range in Figure 1, it is seen that the hydrogen blow-by flow increases with load. This is naturally caused by increased overall engine blow-by flow with increasing load. The hydrogen concentration, however, does not behave similarly and it seems that for most engine speeds the concentration seems to be lower at full load compared to low load operation points. The results shown in all of graphs are relative values, but it can be said that the lower explosion limit is exceeded in the crank case and some type of dilution is needed with this hardware to lower the concentration.

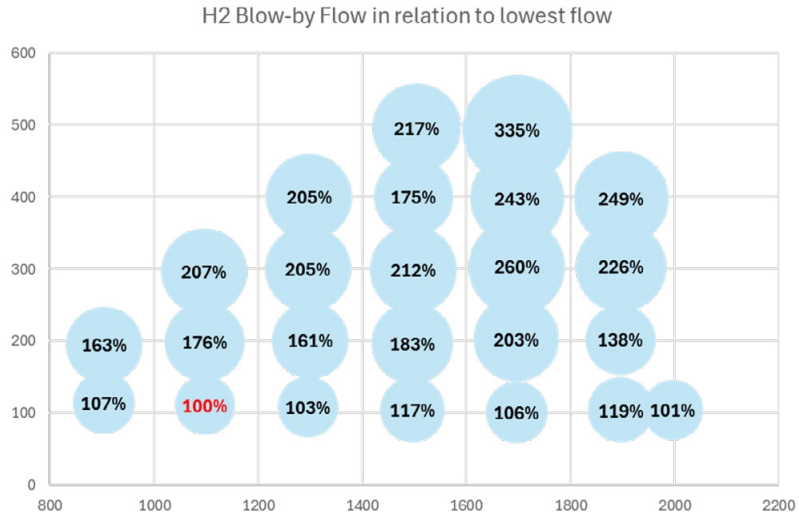


Figure 1. H2 Blow-by Flow over the engine speed/torque range

When investigating the impacts of different parameters, it was noticed that the impact of ignition advance angle cannot be explicitly determined. This is due to several overlapping mechanisms since changing ignition angle it alters, for example, BTE and intake manifold pressure. Lambda has a visible trend for H2 concentration since increasing lambda clearly reduces the H2 concentration in the blow-by gases. This can be seen in Figure 2. Similarly, start of injection has a clear impact on the H2 blow-by flow as earlier injection increases the H2 blow-by flow for all load points, Figure 3.

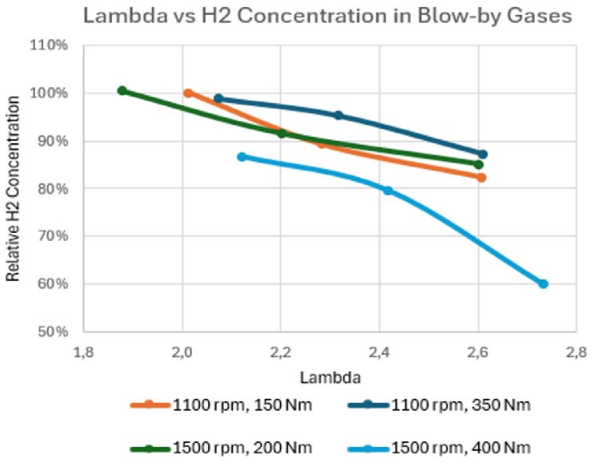


Figure 2. Impact of lambda on H2 concentration in blow-by gases

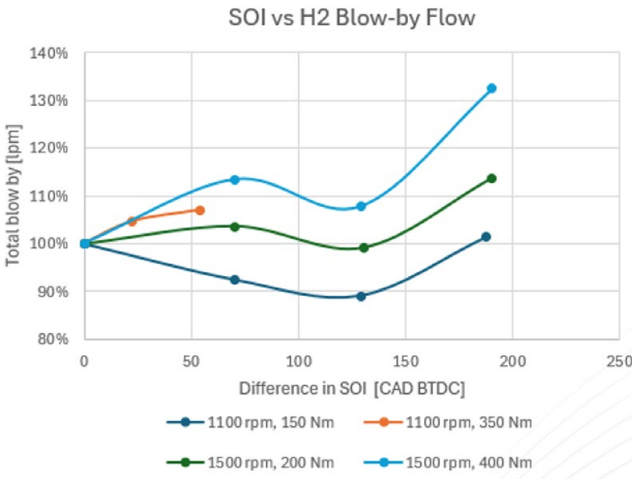


Figure 3. Impact of start of injection on H2 blow-by flow

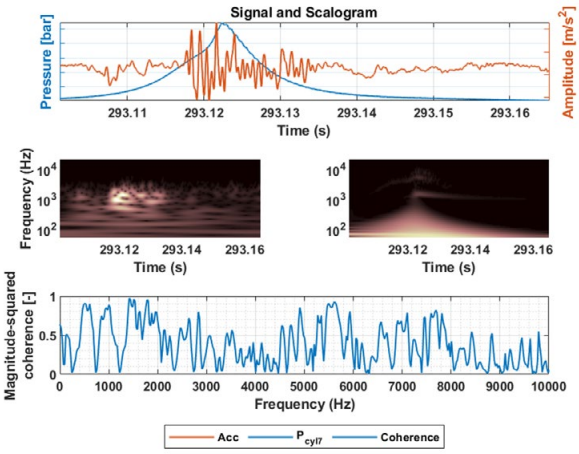
Vibration-Based In-Cylinder Pressure Estimation in Marine Engines: Sensor Placement and Data-Driven Multi-Cylinder Modelling

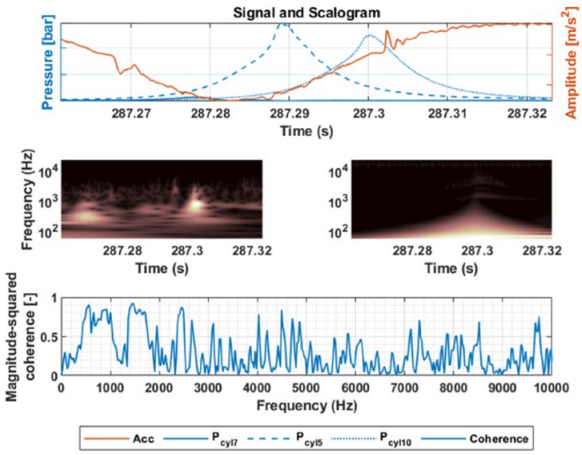
Author and Presenter: Amin Modabberian, *Aalto University*
Keywords: In-cylinder pressure estimation, vibration analysis, marine engines, sensor placement, data-driven modelling, coherence analysis, MISO model, ANN (Artificial Neural Network), combustion frequency

Vibration-based in-cylinder pressure estimation of internal combustion engine (ICEs) has been an area of interest among research communities in recent years. Vibration sensors, such as accelerometers or microphones, offer a cost-effective, nonintrusive measurement approach. In contrast, pressure sensors are continuously affected by the harsh conditions of the cylinder, leading to their deterioration over time. The ability of accelerometers to capture key combustion events makes them a cost-effective alternative compared to pressure sensors.

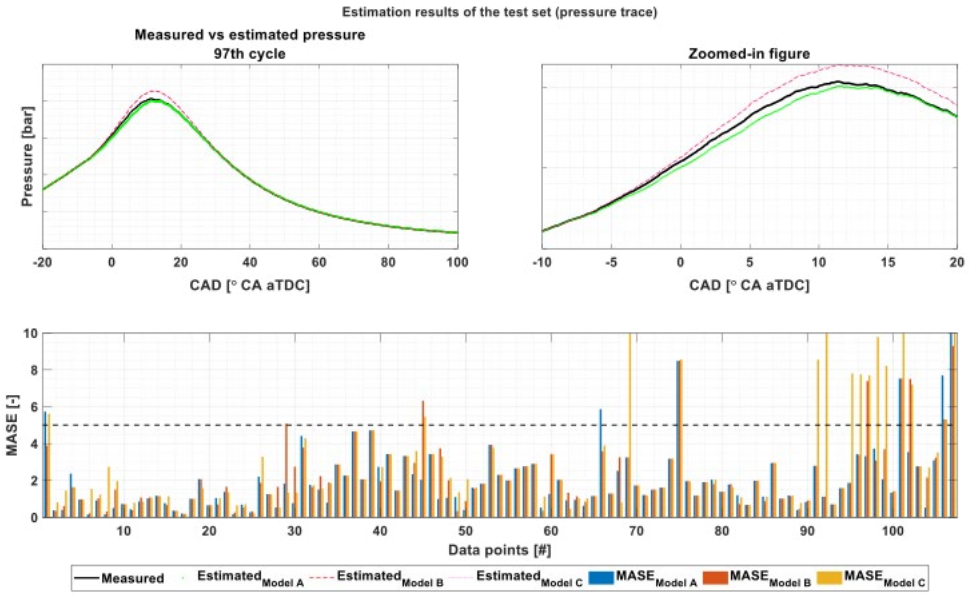
In this work, vibration-based pressure estimation was investigated in a multi-cylinder marine engine. The main objective was to explore the correlation between pressure of all cylinders and vibration measurements taken from different locations.

All vibration sensors were installed on various parts of cylinder number 7, namely the cylinder head, connecting rod, piston skirt, and counterweight. Fast Fourier transform (FFT) analysis indicates that combustion events occur within the frequency range below 1 kHz. Time-frequency –domain correlation analysis confirms these findings: the highest correlations between pressure and vibration were observed around 1kHz. In addition, accelerometers located on cylinder head, piston skirt, and connecting rod showed stronger correlations with pressure than those on the counterweight. Correlations between the pressure of other cylinders and vibration were also analyzed. The results revealed that some correlation exists at specific cycles and frequencies, often with a delay. However, the correlation was not sufficiently strong to support reliable model training.





Model input selection was based on these findings. Three different models, each with a different input but the same output, were trained and regularized. The inputs were measurements from vibration sensors mounted on the cylinder head, connecting rod, and piston skirt, respectively. The target output was the pressure of cylinder number 7.
The overall accuracy of pressure trace estimation was similar across the models. The model using data from the sensor on the cylinder head yielded the highest accuracy. Additionally, model performance was evaluated based on indicated mean effective pressure (IMEP), maximum pressure, and the location of maximum pressure. Comparable levels of accuracy were achieved in these metrics as well.



The preliminary results indicate that vibration-based pressure estimation is feasible. Furthermore, suggest a degree of correlation between vibration and the pressures of neighboring cylinders, offering potential flexibility in sensor placement. Future work will focus on a more detailed investigation of the correlation between vibration and pressure in the frequency-crank angle domain, enabling a more sophisticated analysis of cycle-wise correlations.

State-estimation for SCR aftertreatment control

Authors: Alex Pesu and Jari Böling
Presented by: Alex Pesu, *Åbo Akademi University*
Keywords: State estimation, SCR, Aftertreatment, Kalman filter

In this presentation, an SCR state estimator was introduced. It is based on a simplified mathematical SCR model to enable real-time estimation of both NOx and ammonia concentrations at the catalyst outlet. A state-of-the-art validation model is utilized to ensure that the derived SCR model was accurate enough when compared to a system used by the industry. Some kinetic reaction parameters of the SCR model had to be fine-tuned to reach a satisfactory compromise for both NOx and ammonia output concentrations. The main state estimation algorithm that is used is the Kalman filter which builds the basis of the SCR estimator. A traditional Kalman filter cannot handle nonlinear systems, such as our SCR model, and thus a modified version called the Constant Gain Extended Kalman Filter (CGEKF) was developed. The motivation for using the “constant gain” approach lies in the fact that a large-scale marine combustion engine operates mostly at constant loads, and thus the SCR dynamics are often bound inside a set operating window. Thus, the need to constantly update the Kalman gains (the terms that corrects the initial prediction of the mathematical model), specifically for this application, is deemed an unnecessary modeling complexity with minimal advantage in estimation accuracy.
The CGEKF estimator performed as expected and improved the result compared to the simplified SCR model in both NOx and ammonia responses. In addition, several variations of the baseline estimator have been configured and evaluated. A more realistic modeling approach disabled the ammonia measurement from the baseline case, because ammonia measurements are rarely available onboard real applications. The performance of the ammonia estimate decreased as expected, but the slip estimate could be maintained to a satisfactory degree due to the dynamics of the underlying prediction model and the remaining NOx measurement.

To improve the steady-state error of the initial estimator formulation, a proportional integral estimator (PIKF) was investigated. The performance increase with the added integral effect was immediately evident, but it should be noted that the estimator can easily be rendered unstable if too much of this effect is added.
Finally, the estimator matrices were modified so that cross-sensitive conditions generated by ammonia slip could be considered. The initial results show promise that if the NOx sensor cross-sensitivity can be modeled accurately enough the estimator is able to converge towards the desired direction. In the future, it is planned to apply the gained knowledge from this research to power plants with various green fuels, ammonia being the most interesting for the industry partner.

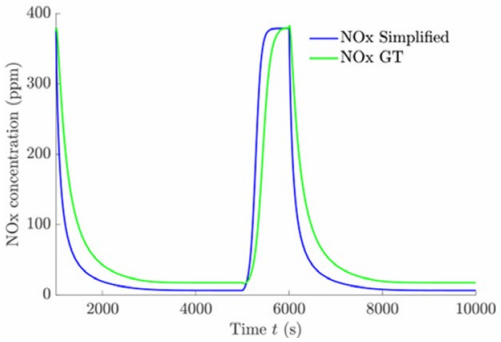


Figure 1. Simplified SCR model VS GT validation model

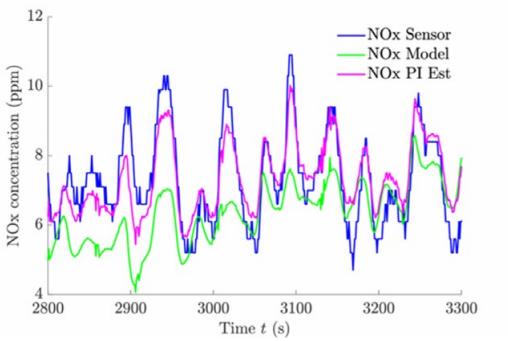


Figure 2. Proportional integral Kalman filter estimator VS simplified model VS NOx sensor signal.

Combined engine and catalytic aftertreatment experiments and simulations

Authors: Teuvo Maunula, Jan Nemec and Alireza Kakoee
Presented by: Teuvo Maunula, *University of Vaasa & University of Oulu*
Keywords: Catalysts, Experiments, Simulations, Nitrogen oxides, Marine, SCR

Engine and catalytic aftertreatment system (ATS) simulations are efficiently combined with conventional experiments in research and development. Many design variables and ideas are often first investigated with modelling and simulations tools based on physical-chemical and small-scale experimental data. Input data for ATS simulations are received from engine experiments or simulations (Fig. 1).

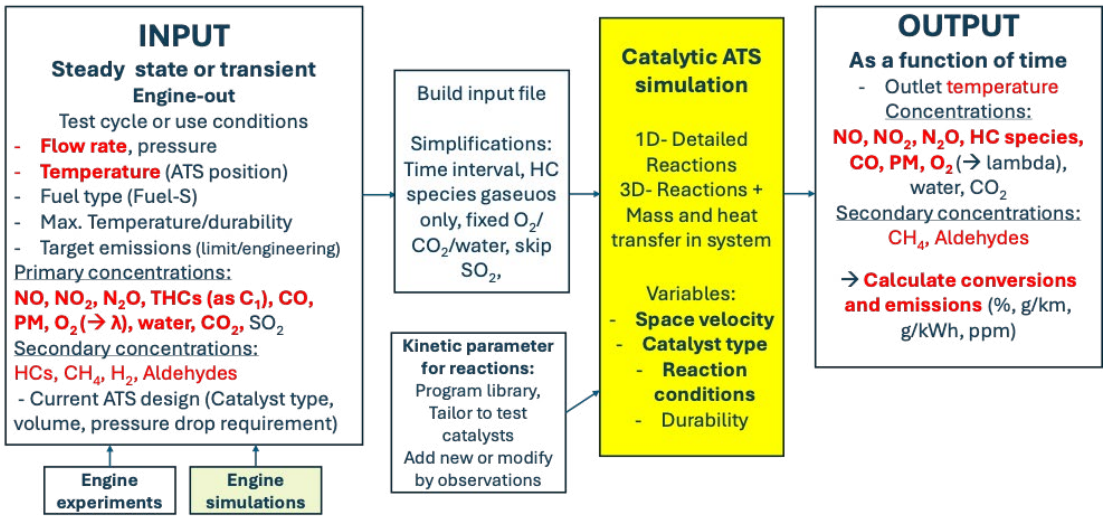


Figure 1. Input and output variables in catalytic ATS simulations.

Catalytic ATSs for marine applications were simulated with GT Power simulation program (Gamma Technologies). Extruded vanadium-SCR (Selective Catalytic Reduction) catalysts with low cell densities have been traditionally applied to reach marine NOx emission limits (latest Tier III) (Fig. 2). Kinetic parameters for SCR reactions were fine tuned in by typical diesel exhaust gases.

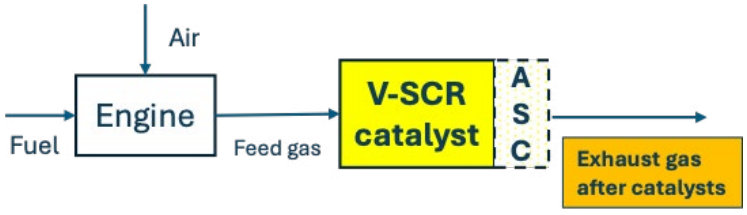


Figure 2. SCR and ASC systems in simulations.

The meaning of pore diffusion was investigated to explain better mechanistically SCR reactions rates in thick catalyst walls. When pore diffusion was included in reaction studies in simulations, the match to experimental results was improved and realistic limitations were seen in NOx and ammonia conversions. Pore diffusion limitations are related to macropores in catalyst layer. Therefore, the pore sizes in the range 0.1 – 1.0 µm in modelling explained best to diffusion limitations (Fig. 3).

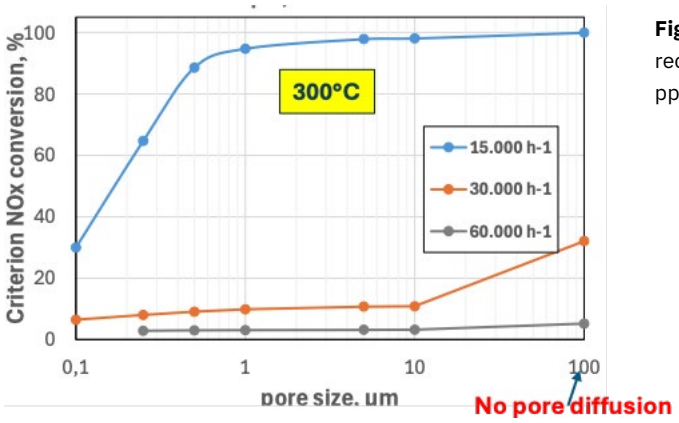


Figure 3. The effect of pore size for the SCR rection by NOx criterion conversion (when 10 ppm NH3 in NH_3/NO_x sweep test).

The ammonia slip catalyst (ASC) is an option to cut ammonia but also CO, hydrocarbons and oxygenates (aldehydes, alcohols) from exhaust gases. A model based on two-layer ASC included in GT Power library was calibrated to match better to existing experimental data. Similar modelling approaches will be next applied to other exhaust gases from varying fuels (ammonia, methanol, hydrogen, methane).

Progress in RCCI technology – simulation/ control functions and experiments – overview of corresponding activities

Authors: Amir Soleimani, Michaela Hissa and Jeyoung Kim
Presented by: Amir Soleimani, *University of Vaasa*
Keywords: RCCI, dual-fuel engine, variable-valve actuation, simulation-guided testing, adaptive control, hydrogen blending

Reactively Controlled Compression Ignition (RCCI) is a promising low-emission, high-efficiency combustion concept that plays a central role in Work Package 1 (WP1) of the Flex-CPT project. WP1 aims to develop and validate flexible dual-fuel combustion strategies that are robust, scalable, and ready for next-generation fuels such as hydrogen blends. The experimental effort at the University of Vaasa forms the backbone of this development, providing a critical test platform to validate control strategies, assess simulation predictions, and de-risk future engine concepts.
Figure 1 depicts the upgraded Wärtsilä 4L20 research engine. Cylinder 4 operates in RCCI mode (NG + pilot diesel) while cylinders 1–3 remain conventional diesel (CDC), enabling direct benchmarking. CPT-era upgrades (new cylinder head, re-entrant piston bowl, electro-hydraulic valve actuation, dual-fuel injector) have been complemented in Flex-CPT by a SOGAV gas-admission valve, rerouted exhaust manifold, gas-valve unit, dedicated pilot-fuel circuit and emissions hardware (Gasmet FTIR, fast NOx, fast THC). Alongside these hardware upgrades, we are developing a three-layer control approach. The goal is to keep combustion stable by adjusting CA50 and IMEP in real time, enable flexible fuelling through coordinated control of injection and valve timing, and ensure safety by limiting peak pressure and pressure-rise rate.

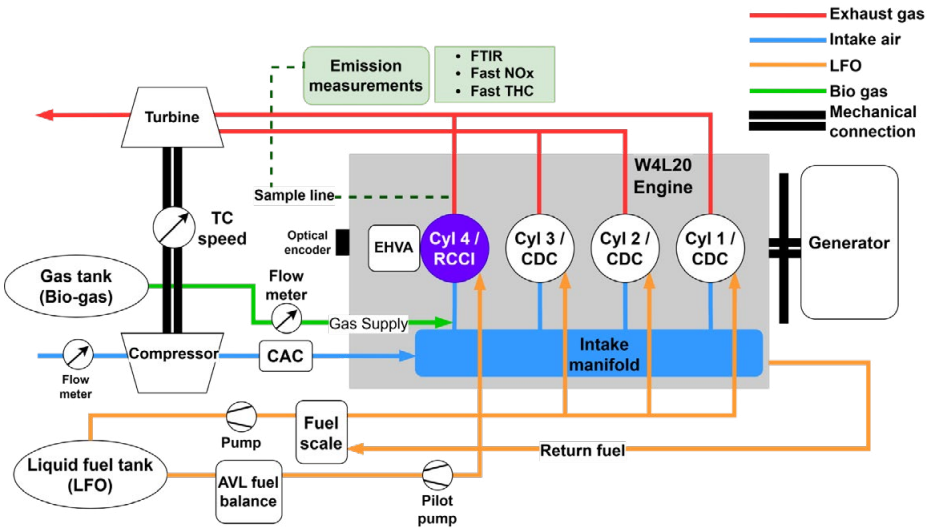


Figure 1. Layout of the upgraded W4L20 engine: Cylinder 4 runs RCCI, cylinders 1–3 stay diesel.

Initial experiments focused on validating simulation-predicted VVA strategies for load extension. Results confirmed that early intake valve closing (EIVC) is effective at high loads by reducing peak pressure rise, while negative valve overlap (NVO) enables low-load extension by improving combustion efficiency and reducing methane slip. The observed trends matched earlier GT-Power simulations, confirming the effectiveness of model-guided test planning.

To accelerate testing cycles, a custom MATLAB-based post-processing toolbox has been implemented. The system automatically processes crank-angle-resolved data and emissions, flags outliers, and generates KPI summaries with minimal user input. This post-processing pipeline supports a closed-loop workflow where experiment and simulation actively feed into one another, as illustrated in Figure 2.

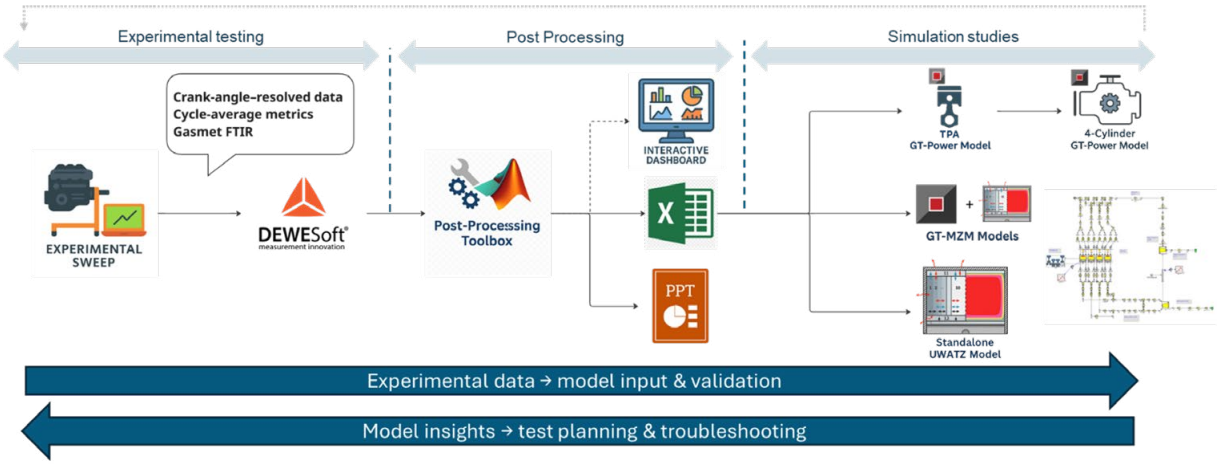


Figure 2. Closed-loop workflow: test data pass through an automated toolbox to update models; updated models then define the next sweep.

Looking ahead, the experimental platform is now fully ready to begin NG–Diesel RCCI optimisation studies and hydrogen co-combustion testing. The roadmap includes small-scale H_2/NG blends (up to 25%) by Q4 2025, followed by large-scale blends (up to 80%) before the end of 2026.

Flexible Clean Propulsion Technologies

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