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Mechanical Development Challenges and Solutions for Alternative Fuels

Mechanics, Materials & Coatings

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ABSTRACT

As global warming has already reached a critical situation and is expected to further increase, it is mandatory to reduce the CO2 emissions from fossil fuels. Especially in transport segments over long distances as well as for power grid stabilization by further increasing alternative electricity generation, the power storage and generation by battery solutions is not sufficient due to the low power density and requires alternatives like liquid or gaseous fuels. To convert the liquid or gaseous stored chemical energy into mechanical or electrical energy, internal combustion engines (ICEs) are still one of the mainstream solutions. This is based on high development and reliability status after decades of using of fossil fuels like diesel or natural gas.

The use of carbon free and carbon neutral alternative fuels results in different mechanical and thermal loads as well as chemical interactions with engine components and lubricants. To still ensure the required reliability of ICEs running on alternative fuels like, for example, hydrogen, ammonia, or methanol, the potential challenges must be identified, considered in engine design and selection of materials and verified and validated to ensure the expected and required reliability.

The paper addresses the identified challenges and risks associated with the operation of alternative fuel engines from a mechanical development perspective. It further explores potential solutions and details the related processes of simulation, development, and verification. Depending on the engine size, the durability test time is typically constrained. To address this limitation, the test program as defined and monitored in the respective DVP, is optimized using AVL’s Load Matrix Methodology.

1 INTRODUCTION

The urgent need to address global warming has made the reduction of CO_2 and other greenhouse gas emission imperative. Despite advancements in alternative energy solutions, long distance transport as well as power grid stabilization required high power and energy storage. Battery solutions are not sufficient due to their limitation in specific storage capacity compared to gaseous or liquid fuels. Internal combustion engines (ICEs) are still promising solutions operating with carbon-neutral fuels based on the high maturity after decades of improvement and development.

Promising fuels for ICEs are currently hydrogen (H_2) with high power density and the ability to be produced by electrolysis, ammonia (NH_3) due its broad availability and the potential to be stored with acceptable effort as well as methanol/ ethanol (CH_3OH/C_2H_5OH).

However, these fuels have properties different to so far used fossil fuels like Diesel, natural gas or heavy fuel oil requiring dedicated attention and adaption of the existing ICE concepts.

This paper focuses on the request and challenges from a mechanical view and do not address any detailed combustion and fuel supply topics.

2 CHALLENGES OF CARBON-NEUTRAL FUELS

2.1 Challenges by Fuel Properties

The physical and chemical properties of alternative fuels differ significantly from conventional fuels such as diesel or natural gas. These differences directly affect engine reliability and operation and demand targeted adaptions in engine design and materials as well as calibration and operation.

2.1.1 Hydrogen – H_2

Hydrogens' unique properties present both opportunities and challenges:

- **Low Ignition Energy:** Although hydrogen has a high auto ignition temperature of nearly 600°C, it has a lower ignition energy compared to conventional fuels, making it highly susceptible to pre-ignition. This necessitates precise control of air-fuel mixtures, ignition timing and the avoidance of ignition sources.

- **High Flame Speed:** The fast-burning nature of hydrogen improves engine efficiency but increases the likelihood of knocking, requiring careful calibration

- **Diffusivity & Permeability:** Hydrogen's ability to diffuse through gaps and fractures and to permeate through materials can lead to challenges such as leakages, particularly in high-pressure systems. This property further increases the effort for storage and tank systems. However, hydrogen embrittlement, despite often mentioned as potential issue, is not considered as relevant failure mechanism in hydrogen combustion engines.

- **Impact on Lubrication:** Hydrogen is not chemically reacting with the typical hydrocarbon-based lube oils, but the higher water content in exhaust and blowby gases increases the potential for water condensation diluting the lube oil. Therefor any consequential effects must be addressed, avoided and the water in oil content monitored.

- **Storage and Handling:** Due to its low power density, hydrogen is typically stored under high pressure or in liquid form, demanding robust and leak-proof fuel systems.

2.1.2 Ammonia – NH_3

Ammonia offers advantages in storage and availability but poses several hurdles:

- **Low Energy Density:** Ammonia has a lower energy density than traditional fuels, requiring larger fuel tanks for equivalent energy storage and increase fuel supply systems.

- **High Ignition Temperature:** Its high ignition temperature necessitates advanced ignition systems, increased compression ratio, supplementation of fuel with better ignitability or the use of pilot fuels to ensure reliable combustion.

- **Corrosion:** It is well known that aqueous solutions of Ammonia are strongly alkaline and highly corrosive to many common metals, including copper, zinc, and their alloys, as well as carbon steel under certain conditions. This raises the question, whether ammonia combustion in an internal combustion engine, causing significant amounts of H_2O a reaction product, could lead to corrosive conditions. Such conditions could for example occur in the blow-by or in the exhaust paths. At the moment there is no clear evidence for failures caused by ammonia corrosion, but potential failure modes and indications for corrosion should be carefully investigated in dyno testing.

- **Impact on Lubrication:** Ammonia can degrade engine oils through chemical reactions that alter oil viscosity and lubricating properties. It can also introduce nitrogen compounds that accelerate oxidative degradation of the oil, requiring shorter oil change intervals and the development of ammonia-resistant oil formulations.

- **Toxicity:** Ammonia's toxicity is a critical safety consideration. Inhalation of even low concentrations can cause respiratory irritation, while higher exposures can be life-threatening. Strict handling protocols, such as leak detection systems and ventilation, are essential. Toxicity also necessitates careful emergency planning to address potential spills or leaks, especially in high-density operational environments. Avoiding release of unburned ammonia to the environment also requires pre-heating of the exhaust after treatment system.

2.1.3 Methanol – CH_3OH

Methanol is a promising liquid fuel with manageable storage requirements but also presents challenges:

- **Lower Energy Content:** Methanol's energy content is about half that of diesel, requiring higher fuel flow rates and adaptations in injection systems.

- **Material Compatibility:** It can degrade certain materials, such as elastomers and plastics, used in conventional fuel systems. Methanol can promote corrosion in metals such as aluminum, copper, zinc, and their alloys. This occurs because methanol absorbs water from the environment, creating an aqueous phase that facilitates galvanic and pitting corrosion. In the presence of oxygen, methanol can oxidize to formic acid and formaldehyde, which further exacerbate corrosion.

- **Miscibility with Water:** Methanol's affinity for water can lead to contamination issues, demanding enhanced fuel filtration and separation systems.

- **Combustion Characteristics:** Methanol's high flame speed improves efficiency but increases thermal loads on engine components, necessitating advanced cooling strategies.

- **Impact on Lubrication:** Methanol can introduce water into the lubrication system through combustion byproducts, promoting emulsion formation and reducing oil film strength. Additives in the oil must be tailored to counteract these effects and maintain viscosity stability.

2.2 Challenges from Combustion

The combustion of carbon-neutral fuels introduces further complexities:

2.2.1 Pre-Ignition

Pre-ignition - uncontrolled combustion before the intended spark is a critical challenge that must be mitigated for reliable engine operation.

- **Causes of Pre-Ignition:** Pre-ignition occurs when the air-fuel mixture ignites prematurely due to hot spots in the combustion chamber, such as glowing oil ash deposits, on the spark plug or hot spots at the core components (piston, liner, fire deck incl. valves). Low autoignition temperatures, as seen with oil droplets in combination with low required ignition energy for hydrogen and methanol, exacerbate the risk.

- **Sources of Pre-Ignition:**

  a. Oil evaporation from cylinder liner surface
  b. Oil mist via piston rings (splash off, reverse blowby)
  c. Oil transport into combustion chamber via intake port from turbocharger, breather system, valve stems
  d. Oil deposits
  e. Ghost sparks
  f. Hot spots on components
  g. Poor air/fuel homogeneity, hot residual gas
  h. High compression temperature

  Lube oil (a-c) also needs an ignition source (f-g) but is acting as indirect source due its lower ignition temperature of ~300°C compared to ~600°C for hydrogen. On the other hand, hydrogen has a significant lower ignition energy than hydrocarbon-based fuels like methane or gasoline that results in a stable chemical chain reaction already after the auto-ignition of small oil droplets. Methanol has here an intermediate position: the self ignition temperature is in between hydrogen and gasoline and similar the required ignition energy.

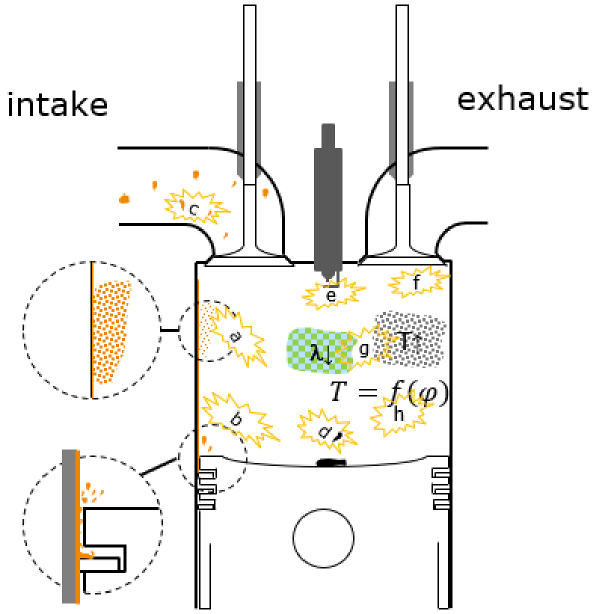

Figure 1: Pre-Ignition Sources

Severity of Pre-Ignition: The severity of pre-ignition depends on the start of the timing of ignition event in relation to the crank angle. The earlier the event the higher is the resulting peak pressure leading to increased load and damage potential on piston, connecting rod and bearings:

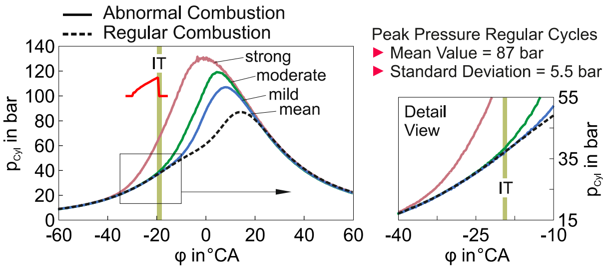

Figure 2: Pressure traces for regular combustion and three oil induced pre-ignitions with different damage potential (IT: ignition timing)

2.2.2 Knocking

Knocking, characterized by uncontrolled pressure waves in the cylinder must be considered in engine calibration, knock control and the layout of the dynamic crank train system.

- **Knocking Mechanism:** Knocking arises when portions of the air-fuel mixture combust spontaneously after the initial flame front has been established. This secondary combustion generates shock waves that resonate within the cylinder, causing mechanical stress and potential damage.
- **Chemical Reactions in Knocking:** Knocking is influenced by end-gas chemistry. In high-pressure and high-temperature conditions, the unburned air-fuel mixture undergoes rapid oxidation. Hydrogen's fast reaction kinetics and low ignition delay times intensify knocking tendencies.

2.2.3 Misfiring

Misfiring occurs when the air-fuel mixture fails to ignite completely or at all, leading to:

- **Causes of Misfiring:** Insufficient mixing of the air-fuel mixture, resulting in local regions with inadequate fuel for combustion, poor ignition energy, especially relevant for high ignition-temperature fuels like ammonia, fouled or overheated spark plugs or also malfunctions in fuel injection or ignition timing systems.
- **Impacts of Misfiring:** Increased emissions by unburnt fuel expelled in the exhaust, lead to elevated hydrocarbon (HC), hydrogen and ammonia slip emissions and result in waste of fuel.
- **Mechanical Stress:** Uneven firing can cause imbalanced forces on the crankshaft, increasing wear on bearings and other components.

2.3 Challenges by Combustion Residuals & Products

2.3.1 Condensation

Non-carbon fuels, particularly hydrogen and ammonia, produce water vapor as a primary combustion up to 20% in exhaust as well as in blowby gases. By this the dew point increases to temperatures up to more than 60°C. Depending on the operating profile, the ambient conditions and the typical lube oil temperatures, especially for medium speed or larger engines, the water steam from the combustion starts to condensate and to mix with the lube oil, forming emulsions that degrade lubrication quality and accelerate wear. In worst case condensed water in the lube oil can separate and freeze leading to blockage of oil suction pipes.

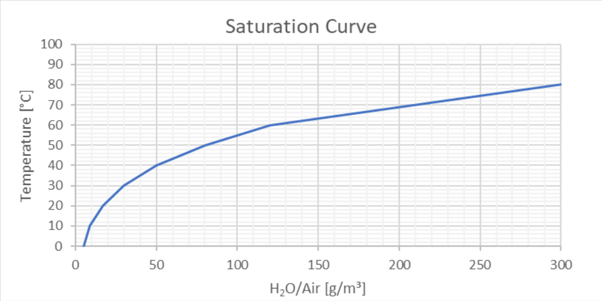

Figure 3: Saturation curve of water in air

One relevant source for condensation is the breather system where blowby gases cool down on its way via the oil separator and the external piping, underrun the dew point and the condensed water flows back to the oil sump via the return of the separator.

2.3.2 Emissions and Aftertreatment

- Hydrogen combustion produces minimal CO_2 but may generate nitrogen oxides (NOx) under high-temperature conditions, necessitating effective aftertreatment systems like selective catalytic reduction (SCR).
- Ammonia combustion can release unburnt ammonia (slip), requiring advanced catalytic converters to minimize emissions. Further any leakage of unburnt combustion gases via the breather system or after engine stop must be avoided by suitable measures.

2.4 Mechanical Challenges

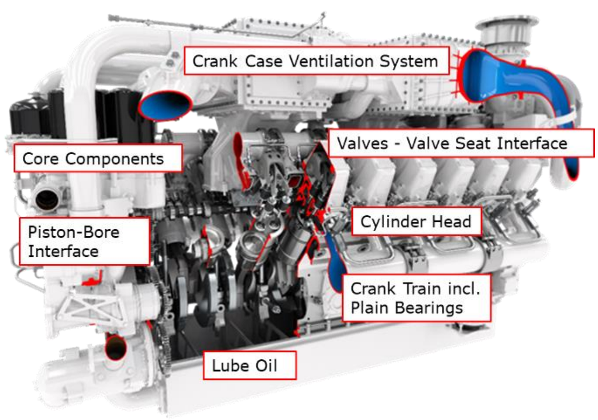

Figure 4: Mechanical influenced Systems/ Interfaces

2.4.1 Core Component Temperature

As previously mentioned, engines operated with alternative fuels are highly sensitive in view of pre-ignition initiation at hot surfaces as well as condensation of fuel or combustion products on cold surfaces. Further the different combustion behavior results in different thermal and mechanical load on the combustion chamber surrounding components.

This requires a higher focus and optimization of the thermal management of cylinder head, liner and piston as well as the valves to avoid hot-spots, cold areas and still ensuring robustness in view of high-cycle as well as thermos-mechanical-fatigue.

2.4.2 Piston-Bore Interface

The piston-bore interface (PBI) is one of the most critical engine systems in view of performance and reliability, especially with alternative fuels. The main topics for this system are optimization of oil transport and blowby volume flow, Wear and corrosion as well as the still relevant friction management.

2.4.2.1 Oil Transport and Blowby

Challenges of Oil Transfer into Combustion Chamber: Alternative fuels like hydrogen and methanol are highly sensitive to pre-ignition indirectly induced to lube oil aerosols, making oil transport through the piston-ring pack and evaporation from the liner wall a critical concern.

Control Strategies for Oil Transport into Combustion chamber: The piston-ring pack must be optimized to minimize oil carryover into the combustion chamber. Advanced oil control rings and improved sealing designs are essential. A further relevant parameter for oil transfer optimization is the cylinder liner: Thermal and mechanical loads can cause cylinder liner deformation, which affects the sealing of the piston-ring pack and increases oil consumption. The honing pattern directly influences oil retention and friction characteristics. Optimized honing can balance oil film formation with minimal oil loss.

Blowby Mechanisms: Blowby gases, a mixture of unburned and burned combustion byproducts, can introduced unburned fuel in the crank case volume and degrade the lube oil quality by these combustion products. The blowby further contains lube oil requiring separation before exit to the ambient or return to the engine inlet.

Mitigation Measures: Improved ring sealing performance incl. dynamic stability can reduce blowby-related issues. Proper bore geometry and honing patterns also play a crucial role in maintaining tight seals.

2.4.2.2 Wear and Corrosion

Wear Resistance: Due to the above-mentioned requirement of minimized oil transport into the combustion chamber the wear situation between liner and piston rings, especially the top ring is worsened. Piston rings must endure high mechanical and thermal loads with minimum amount of lube oil at the tribological interface. Enhanced wear-resistant coatings, such as chromium nitride or diamond-like carbon (DLC) or GDC can improve durability.

Corrosion Challenges: Exposure to corrosive byproducts, especially ammonia derivatives, methanol-associated acids or condensed water, requires advanced materials and coatings resistant to chemical degradation. This can be a proper material selection: Use of advanced alloys and composite materials for pistons, rings, and liners. Or the implementation of Coating Technologies: Application of high-durability coatings tailored to specific fuel properties.

2.4.2.3 Friction Management

Opposite to the requirements of reduced oil transfer and blowby volume flow still the friction at the piston-bore-interface must be considered to minimize efficiency losses with the boundary to ensure a robust and wear stable condition.

Friction Challenges: High combustion pressures and temperatures increase mechanical loads on the tribological challenging piston-ring interface, raising friction levels.

Optimized Design: Advanced ring geometries and surface finishes can reduce friction while maintaining effective sealing without running in any seizure risk.

Cylinder Liners

Surface Texturing: Proper surface treatments, such as plateau honing or further band honing, reduce friction and improve oil film stability.

Thermal Considerations: Efficient thermal management helps maintain optimal liner dimensions and minimizes friction-related energy losses.

Structural Optimization: Advanced cylinder head, crank case and liner design in combination with suitable bolt pattern allows minimizing bore-distortion.

Advanced Lubrication

Oil Formulation: Specialized lubricants tailored to alternative fuels can enhance lubrication performance and reduce friction.

Additives: Friction modifiers and anti-wear additives can provide additional protection under extreme operating conditions. Oil degradation by combustion residuals, but also water is compensated avoiding wear or corrosion on engine components.

Conclusion

By focusing on these themes — oil transport and blowby, wear and corrosion, and friction management — engine designers can address the unique challenges posed by alternative fuels. These strategies ensure enhanced performance, reliability, and efficiency for the piston-bore interface.

2.4.3 Crank Case Ventilation System

The crank case ventilation system collects all blowby gases by the sources:

- Piston-Bore Interface
- Turbocharger
- Valve stem seals

and is by this a composition of burned and unburned combustion gases (H_2, N_2, O_2, CO_2, H_2O, HCs, NH_3, etc.) and lube oil aerosols (evaporated lube oil and small oil droplets – HCs). Depending on the relation of its elements this mixture is potentially flammable.

2.4.3.1 Ignition/ Explosion Risk

An ignition requires the presence of an ignitable mixture consisting of fuel and oxygen and an ignition source to activate the chemical chain reaction:

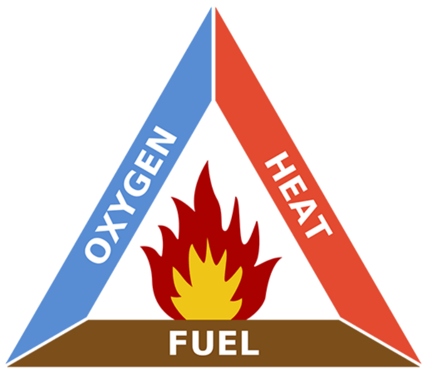

Figure 5: Ignition Triangle

Fuel: Depending on the combustion concept and the fuel admission unburnt fuel can enter the crank case via valve stem seals, turbocharger and the piston-bore interface. This increases the fuel load of the crank case gases by the lube oil aerosols and depending on the type of fuel raises the ignitability.

Oxygen: Especially for lean burn combustion concepts enough oxygen is transferred into the crank case to produce in combination with the previous mentioned fuel an ignitable mixture. Any dilution with external fresh air increases in a first step the ignitability until the fuel ratio drops below the ignition limit.

Ignition Source/ Heat: To start the chemical reaction between fuel and oxygen an ignition source creating locally sufficient heat is required. Here the different properties of fuel and lube oil are interacting and can potentially aggravate the risk as there is for e.g. a low ignition temperature of lube oil compared to hydrogen, but a significant low ignition energy and high flame propagation speed of hydrogen. The ignition sources must be divided in 3 different groups by relevant operating conditions:

1. Normal engine operating conditions
2. Conditions after hot shut down
3. Conditions after engine failure (e.g. piston seizure or bearing seizure

Normal operating conditions: This addresses hot surfaces like the piston cooling gallery as well as any sparks from improper electrical connections or electrostatic discharge as they could appear also from rotating components like active oil separators. This potential ignition sources are rated as relevant to be avoided by suitable design.

Conditions after hot shut down: A potential ignition of crank case gases after hot shut down as it could appear by after heating of turbocharger or also the piston into the gallery must be avoided with either suitable ramp down strategy or measures to ensure safe cool down like aftercooling pump(s).

Situation after engine failure: Engine failures anyway are assumed to be avoided by reliable design, well conducted engine service and maintenance and close monitoring of the engine condition, but in case of the unlikely event of a severe failure like a piston or bearing seizure the ignition of blowby gases cannot be avoided. Such an ignition results in a pressure rise in the crank case and valve cover and demand addressing potential consequential effects.

2.4.3.2 Consequential Effects of Crank Case Ignition

An ignition of the gases in the crank case results in a pressure increase inside the blowby volume although this is not completely closed due to the outlet to the breather system the pressure rise is faster than the release of the gases. Consequently, the surfaces inside the crankcase, valve cover and of the oil pan as well as all shaft sealings see high pressure load of up to 3bar for hydrogen engines.

In worst case this can result in components blasted away (oil pan, valve cover(s), blowby hoses/ oil separator components) leading to either direct injury of humans or fire hazards by oil leaking onto hot surfaces.

2.4.3.3 Summary on Crank Case Ignition Risk

The presence of an ignitable mixture cannot be avoided with acceptable effort. By this the focus must be to avoid potential ignition sources.

Consequences of the worst-case scenario on a severe engine damage must be avoided by suitable pressure release measures like relief valves or burst plates.

2.4.4 Lube Oil

Existing lube oils are challenged by engines operated with non-carbon-based fuels and require improvement to ensure proper reliability and lifetime of the engine.

One important parameter is the handling of condensed water to avoid consequential wear or damage on components. At early phases of the development process, it is important to decide whether hydrophilic of hydrophobic oil is used. Combustion products and also unburned fuel are further potentially chemically reacting with lube oil and demand advanced additive packages to compensate the different amount of oil degradation.

2.4.5 Crank Train incl. Plain Bearings

The crank train incl. the related plain bearings need close attention from two sides: On the one side combustion irregularities can result in increased dynamic load on the overall crank train although the peak cylinder pressure during operation of the discussed fuels is lower in normal condition compared to Diesel combustion. On the other side the combustion products from ammonia combustion or unburned fuel from methanol combustion are known as chemical reacting with typical bearing metals or also known polymer coatings of bearings. This potential risk requires long time observation of lube oil condition, but also the resulting behavior of the bearings itself.

2.4.6 Cylinder Head

The cylinder head from thermal and mechanical loading was already addressed previously within the core components, but additionally the interface between valves and seats requires high attention: Knowing that already, when changing from Diesel to natural gas combustion the tribological behavior of this interface is more sensitive to wear due to missing lubrication from carbon from the fuel. When now changing to hydrogen or ammonia or also when operating with methanol due to its degreasing properties this sensitivity is expected to become even worse and requires more advance tribological alloys and improved contact condition in view of temperature, pressure and impact during closing.

3 EXPERIMENTAL TESTING

AVL is investigating and developing carbon-neutral ICEs over all engine sizes by hardware testing what allows knowledge transfer to speed up development time. Depending on the testing request either full multi-cylinder engines (MCEs) or single-cylinder engines (SCEs) as well as component and system test rigs are used. The AVL own test units are optimized for maximum flexibility in view of used fuel and combustion system.

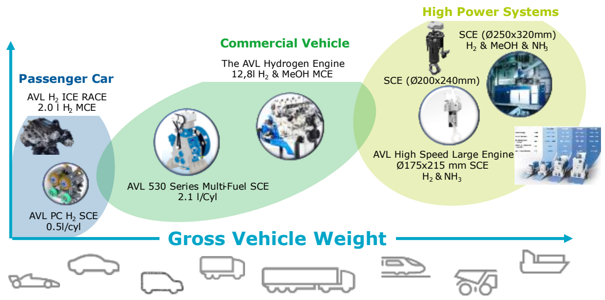

Figure 6: AVL's workhorses for carbon-free fuels across all segments

3.1 Pre-Ignition Detection

Pre-Ignition – a power limiting combustion anomaly on especially hydrogen or methanol engines - defines a start of the combustion before the intended ignition timing due any unliked source like hot spots or sparks. In this case the gravity of the combustion is advanced compared to the demand.

To identify pre-ignition, cylinder pressure traces must be post processed and evaluated in view of the combustion behavior. Measurement and assessment of the indicated cylinder pressure allows the identification of pre-ignition events and the quantification of the severity of these from the time difference between the pre-ignition event and the desired ignition start. To minimize and to eliminate pre-ignition occurrence the source of these must be identified. The main groups are:

- Direct pre-ignition of the fuel on hot surfaces, due to high compression end temperature, hot residual gases or on glowing lube oil ash residuals
- Direct pre-ignition by ghost sparks or interaction from other cylinders via the intake port
- Indirect pre-ignition after ignition of lube oil aerosols on hot surfaces or due to high compression end temperature

To identify the root cause for the pre-ignitions by localisation the origin a cylinder head was equipped with AVL's optical combustion investigation system Visiolution. 3 groups of optical sensors were installed in one combustion chamber ensuring a view from opposite sides:

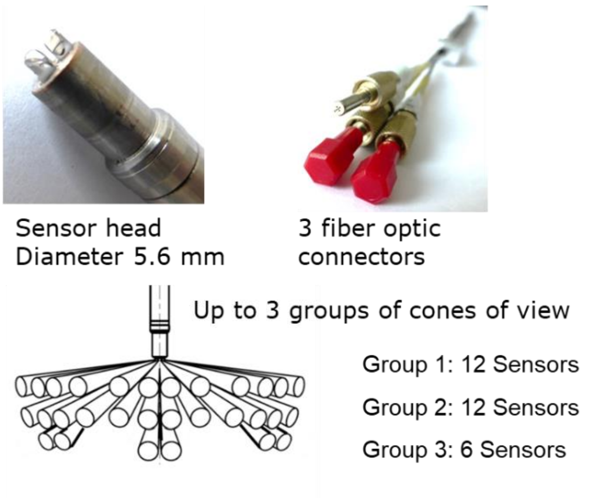

Figure 7: Visiolution sensor

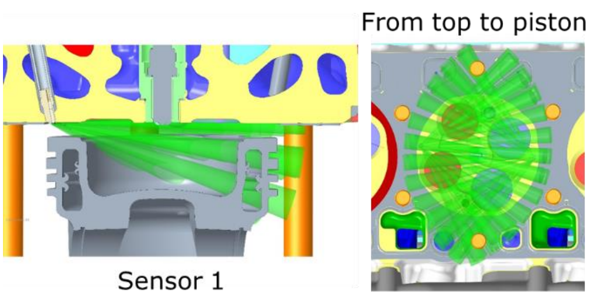

Figure 8: Position of Visiolution sensors

The arrangement of the optical sensors allows by post-processing a localisation of the combustion start by the intersection of the different view angles of the sensors:

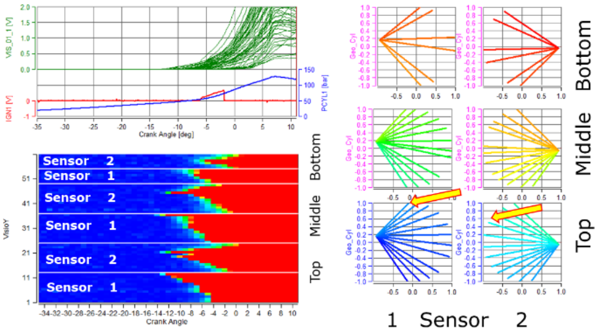

Figure 9: Post processing of Visiolution signals

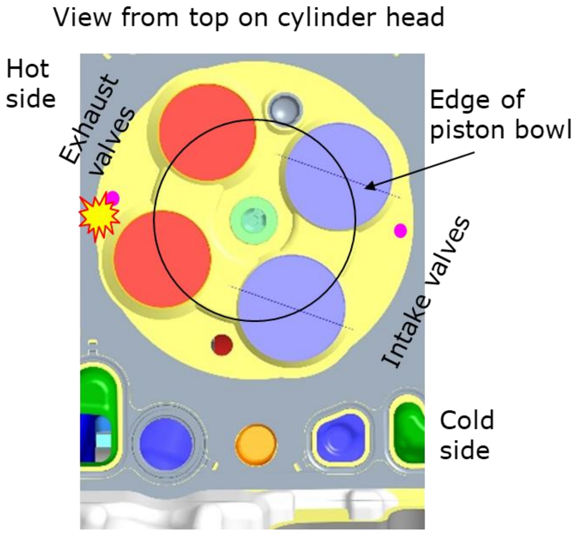

Figure 10: Results of Visiolution measurements: location of pre-ignition origin

The evaluation of the collected data identified more occurrence of pre-ignitions in areas with not the highest surface temperature (exhaust valve, spark plug), but in areas where high amount of lube oil aerosols in combination with sufficient high temperature is present. In this case the outer piston area on the exhaust side was one of the main locations for pre-ignition start.

The conclusion out of these detailed investigations is a dependency on oil aerosol amount, surface temperature and contribution by the pre-ignition sensitivity of the used lube oil.

3.2 Water Accumulation Run

As previously mentioned, is the water concentration in the blowby for operation on hydrogen or ammonia, but also for methanol higher than on Diesel or natural gas. This results in a higher dew point of particularly up to 60°C. Considering further, that medium or low speed engines are generally running at lower lube oil temperatures, high speed engines can be operated in cold environments with longer idling time and the components of the breather system are located outside of the engine, conditions in the breather system and the oil pan can occur allowing water condensation and the accumulation of water in the lube oil.

3.2.1 Water Accumulation Run: Test Cycle

Based on field data AVL developed a so-called water accumulation test cycle focusing on cold, but realistic engine operating conditions to investigate the effect of lube oil dilution due to water condensation inside the engine and drain back to the oil sump.

The cycle consists out of an accumulation phase and a high load phase. The accumulation phase is an alternating test cycle between low speed/ high load operation (high water concentration) and idling (cool down). During this phase gaseous water, coming from the combustion, will be condensed which effects in lube oil dilution. Engine performance parameters and water content in lube oil are continuously monitored until intended or critical quantity is reached. Afterwards the engine is operated for a sufficient time at high load to heat up lube oil and breather system allowing water to evaporate and analysing the effects caused by the water evaporation.

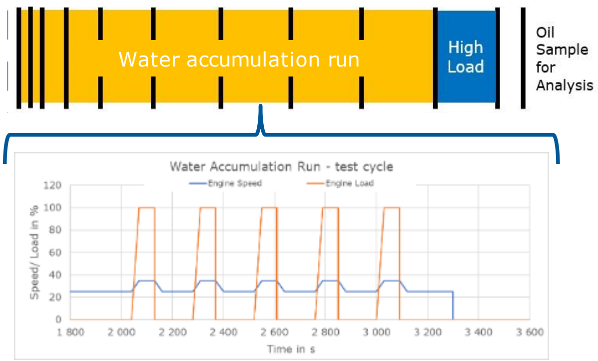

Figure 11: Water accumulation test cycle

3.2.2 Water Accumulation Run: Preparation

With AVL's hydrogen operated workhorse engine online monitoring of lube oil condition in oil pan and valve cover is observable by mounted gauge glasses as shown in figure 12 and 13 during engine operation. For example, discolouration effects, phase separation after engine stop and mixing up of lube oil can be examined.

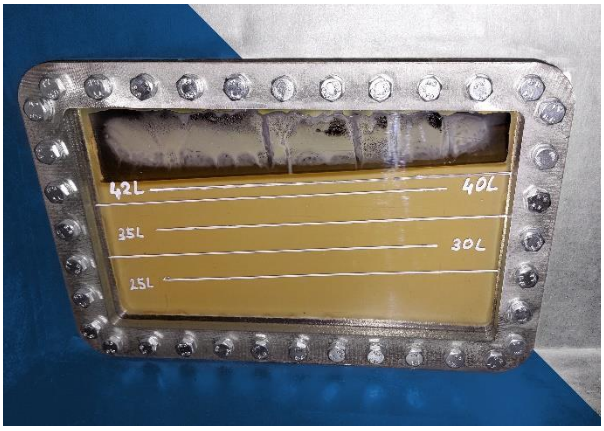

Figure 12: Lube oil condition in oil pan after water accumulation run through gauge glass

Figure 13: Emulsion formation in valve cover through gauge glass

3.2.3 Water Accumulation Run: Test Results

The water accumulation run resulted during the accumulation phase in an increase of 1% of water in oil with a specific oil volume of ~0.1l/kW. For a one-shift operation in cold ambient without high load this results in ~10% accumulated water in oil, what is already a high risk for reliable engine operation.

Further the engine showed during the succeeding high load operation phases severe combustion anomalies not allowing an immediate full load operation and requiring a stepwise heat up.

Potentially the evaporating water in the oil when increasing the temperature caused additional oil transport of atomized oil droplets into the combustion chamber. This theory needs further investigation or requires measures to avoid the accumulation of such high amount of water in oil and its consequential effects.

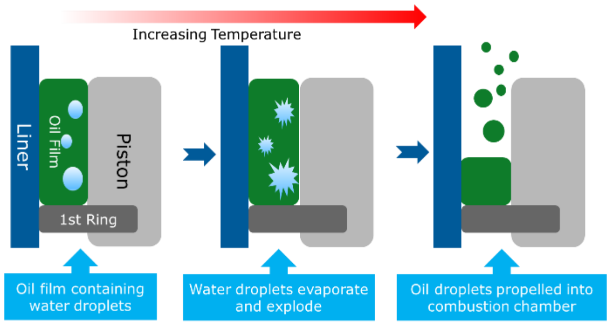

Figure 14: Transfer of atomized Lube Oil into Combustion Chamber by Water Evaporation

3.3 Compressor Fouling Test

To investigate the influence of oil aerosols returned before the compressor inlet dedicated engine test were conducted with closed crank case ventilation system. Operation of the engine with single stage turbocharger and a state-of-the-art disk plate oil separators in the breather system with an oil content in blowby after separator of ~20mg/m³ showed already after a few hundred hours operation time a drop of engine power and efficiency of up to 5%. As root cause for this drop of power fouling of the compressor and the volute by deposit formation from the oil aerosols was identified:

Figure 15: Volute and impeller of compressor after fouling test with closed breather system

Based on this fouling effect it is mandatory to consider this degradation in case of closed breather system with return before compressor: for high performance chargers with high outlet temperature oil separators with high efficiency and a resulting oil content in blowby after separator well below 10mg/m³ are mandatory as well as the consideration of this effect during verification and validation with proper testing.

4 SOLUTIONS

4.1 Pre-Ignition

Pre-ignitions are the most dominant factor limiting the maximum achievable power output of hydrogen- or methanol-based spark ignited ICEs.

This challenge necessitates careful consideration and the implementation of appropriate measures to ensure safe engine operation within the pre-ignition limit. Both direct pre-ignition and indirect pre-ignition caused by the ignition of oil droplets must be effectively addressed. Especially these indirect pre-ignitions are often ignored in early development stages and play a very important role. The latter can be mitigated through several strategies:

- Avoiding hot surfaces or localized hot spots in the cylinder charge that exceed the self-ignition temperature of the fuel or the used lube oil
- Reducing and minimizing the presence of oil aerosols in the combustion chamber
- Optimizing the lubricant formulation to reduce its propensity for pre-ignition

4.1.1 Pre-Ignition Investigation based on Combustion Simulation

The mitigation of pre-ignition and combustion anomalies in hydrogen and methanol-fueled internal combustion engines (ICEs) is a critical challenge for engine development. In advance of mitigating indirect pre-ignitions by lube oil aerosols in the combustion chamber all potential direct pre-ignition sources must be mitigated. This study employs the CFD code AVL FIRE M, an advanced simulation tool, to investigate the occurrence and severity of pre-ignition in hydrogen-based combustion. The simulations utilize the General Gas Phase Reactions (GGPR) model with revised H_2/O_2 reaction mechanisms to predict the impact of thermal boundary conditions, mixture composition, and component surface temperatures on auto-ignition events.

The results highlight that pre-ignition can be triggered by localized “hot spots” on engine components, such as spark plugs and exhaust valve heads, when ignitable hydrogen-air mixtures (4%–77% H_2 volume fraction) remain in contact with these surfaces long enough to reach the auto-ignition temperature. Furthermore, auto-ignition within the core mixture is observed when excessive compression ratios or high residual gas temperatures are present. These findings confirm that thermal boundary conditions play a crucial role in pre-ignition risks, requiring precise control of surface temperatures to ensure reliable combustion operation.

However, the CFD model in AVL FIRE M does not account for pre-ignition caused by oil droplet combustion or random ignition sources such as foreign particles. Instead, the study focuses on thermally induced pre-ignition mechanisms, assuming a uniform piston bowl temperature for consistency. This work underscores the necessity for enhanced cooling strategies, optimized component design, and improved combustion control to minimize pre-ignition risks in hydrogen ICEs. Future developments will enhance AVL FIRE M’s predictive capabilities by incorporating additional combustion influences such as oil droplet ignition dynamics and advanced heat transfer effects.

Through its highly detailed chemistry modeling and robust CFD framework, AVL FIRE M proves to be an indispensable tool for developing next-generation hydrogen and methanol-fueled engines, ensuring optimized performance and reliability.

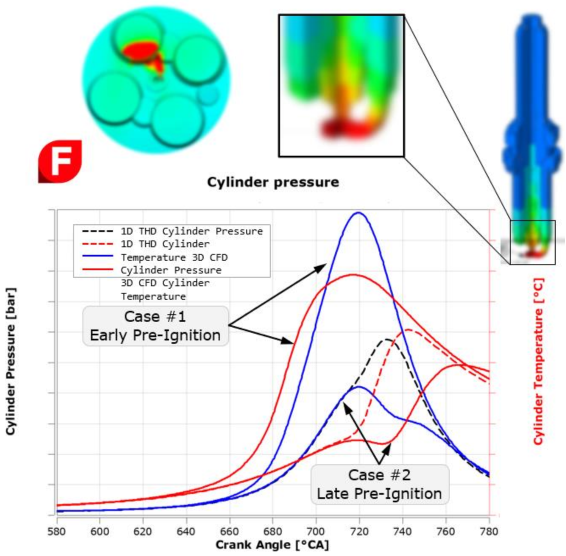

Figure 16: Pre-Ignition Simulation by AVL FIRE

4.1.2 Optimization of Surface and Component Temperature

As previously mentioned, for combustion concepts sensitive to pre-ignition, it is crucial not only to consider component lifetime limitations related to temperature (both High Cycle Fatigue (HCF) and Thermo-Mechanical Fatigue (TMF)) but also to achieve lower surface temperature targets. This helps prevent both the evaporation of lubricant oil and the ignition of oil droplets.

The combustion chamber can be divided in three key areas:

- Cylinder head fire deck, including valves, pre-chamber and spark plug
- Cylinder liner
- Piston top land and ring zone

4.1.2.1 Cylinder Head Temperature Optimization by Top-Down Cooling

The contrary challenges of the strength versus cooling of cylinder head and piston unit need to be solved. Where the gas loads from the combustion require high structural stiffness with thick fire deck design, the request for lowering the temperatures demands coolant flow as close as possible to the combustion chamber.

To solve this, AVL combines its unique top-down cooling concept to allow temperature control at the fire deck also to dedicated hot spot areas to avoid pre-ignition issues and allow maximization of lifetime e.g. for the spark plug. This is even possible in combination with reduced volume flow allowing for friction reduction and improving response time in transient conditions. The concept allows a significant increase of heat input to the fire deck setting new limits for future combustion concepts, independent of diesel, gas or other alternative fuels operation.

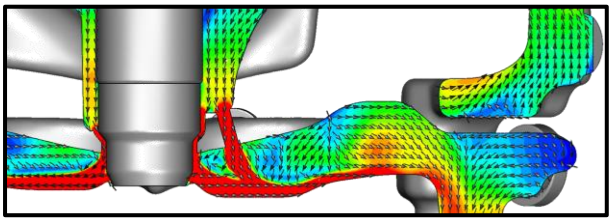

Figure 17: Cylinder head cooling water flow velocities CFD

4.1.2.2 Liner Surface Temperature Optimization by Top-Down & Split Cooling

The cylinder liner design must balance multiple requirements: it must provide sufficient structural stiffness to withstand gas forces during combustion without any relevant deformation from clamping loads, maintain high enough temperatures to minimize engine friction and prevent condensation on the liner wall, while simultaneously ensuring temperatures remain low enough to prevent robustness issues between the piston rings and liner, as well as pre-ignition events.

Due to the varying heat input along the liner surface from top to bottom, different cooling strategies are required. To address this, AVL developed a top-down cooling system as already implemented in the 175 mm high-speed large engine (HSLE), featuring separate water jackets for the upper and lower regions of the liner. This design enables higher heat transfer coefficients (HTC) in the upper region, where heat input is highest and more cooling is required, while allowing for lower coolant flow velocities in the lower region to achieve a more homogeneous overall temperature distribution. The optimization was conducted by FEA simulation in combination with combustion and coolant side CFD simulation.

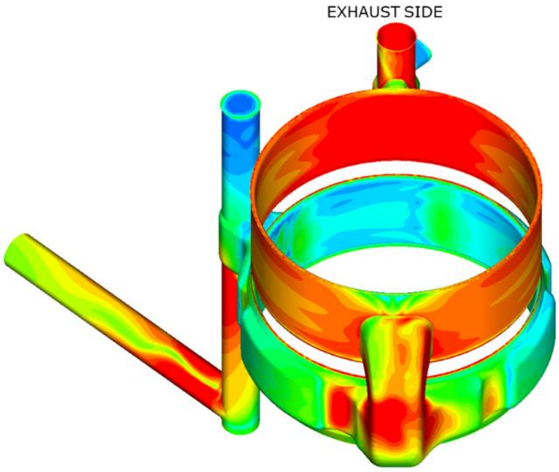

Figure 18: HTC distribution on liner water jacket of AVL's HSLE

Except of a minor spot on the anti-polishing ring the cylinder liner wall temperature could be optimized into a homogeneous distribution well below a potential risk to ignite lube oil droplets also at outstanding high BMEP levels:

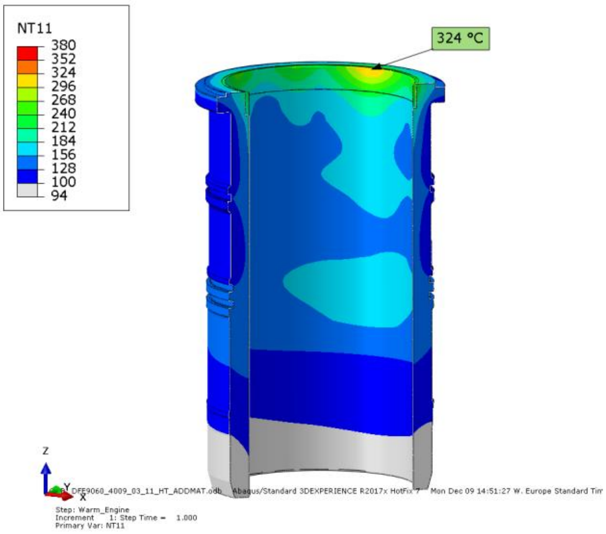

Figure 19: Resulting cylinder wall temperature @ 33bar BMEP

4.1.2.3 Piston Surface Temperature Optimization by CFD/FEA Simulation

The piston itself is from the thermal condition one of the most challenging components: The heat input surface towards the combustion chamber is large, there is no continuous high heat flow towards the liner due to the minimized contact surface for friction reduction and the cooling via the lube oil is complex due to the movement of the piston itself.

The piston cooling gallery itself is constrained by the space for the piston ring zone located close to the combustion chamber to minimize crevice volumes, and this results especially in the outer top land area to lower heat transfer to the cooling oil and higher temperature. To improve and to optimize the heat transfer in the piston cooling gallery AVL is simulating the cooling condition by moving mesh CFD simulation to be able to optimize the cooling gallery design as well as the optimum in piston cooling jet oil flow:

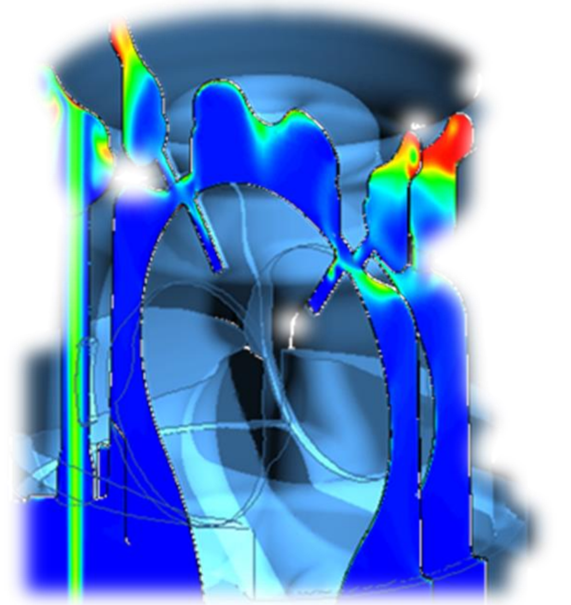

Figure 20: CFD simulation of piston cooling condition

The resulting HTC and temperature conditions in combination with the heat input from the combustion side CDF simulation are used as input for the FEA allowing design optimization until the surface temperatures are well below ignition limit of lube oil.

For detailed verification pistons are equipped with thermocouples at relevant locations allowing confirmation of simulation results for various operating conditions (engine speed, BMEP, piston cooling oil flow and temperature, etc.).

4.1.3 Minimization of Oil Transport into Combustion Chamber

An improper specified ring pack can deliver relevant amount of oil into the combustion chamber leading to pre-ignition and irregular combustion. Especially the mechanism of throw-off from the top ring describes an unliked behavior. Virtually testing the ring pack and validating the ring pack against a benchmark or optimizing the shape and design in terms of ring dynamics and lube oil consumption (oil accumulation above the ring and throw off is a valuable contribution in the efficient development of the piston bore interface. In combination with the optimization of crevice volume at the top land new engines benefit from piston and piston ring pack simulation using AVL Excite Power unit and Excite Piston & Rings.

Even better control of piston secondary motion can improve the oil transport to the combustion chamber.

4.1.4 Development of Lube Oils with less Pre-Ignition Tendency

The transport of lubrication oil into the combustion chamber can be minimized, as described in the previous chapter, but cannot be entirely prevented. In addition to avoiding surface temperatures that exceed the ignition threshold of the lubricating oil, the oil composition itself must be optimized to reduce its susceptibility to early ignition.

The external dosing method developed by TU Graz - ITNA enables the quantification of the pre-ignition sensitivity of lube oils as well as the influence of various base oils and additive packages under real world in-cylinder boundary conditions. This method involves injecting a precisely controlled amount of lubricating oil as an aerosol into the intake port over a defined time period, while operating the engine at a stable load point.

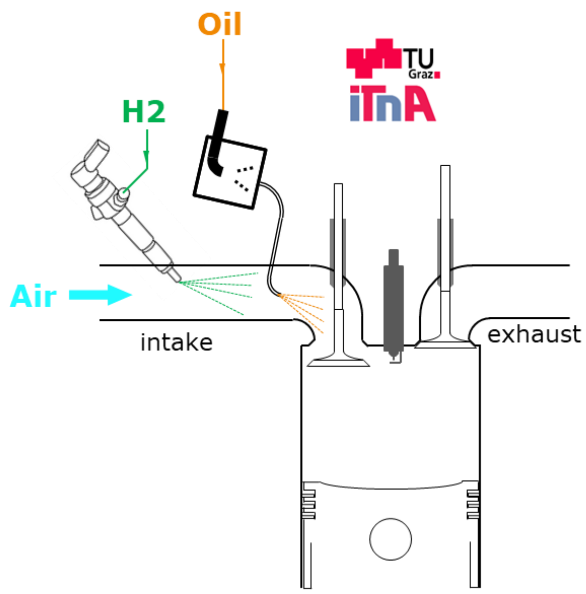

Figure 21: Oil dosing method develop by TUG ITNA

The selected load condition is sufficiently high to be representative but remains well below the engine's inherent pre-ignition threshold. To ensure repeatability and eliminate external influences, the engine is operated at this stable load point with adequate pre- and post-conditioning phases. Further, the other cylinders where no oil is, doses are monitored by cylinder pressure measurement to prove PI free operation.

Pre-ignition events are recorded and analyzed based on their timing. In addition to counting the number of pre-ignition events, their severity is also assessed: The earlier a pre-ignition event occurs, the greater the damage potential, as it leads higher peak cylinder pressures.

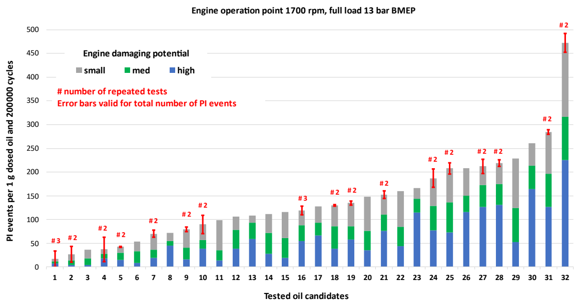

Figure 22: Extract from AVL's pre-ignition benchmark for various lube oils

Based on this it is possible to select already in advance promising lube oil types, but it must be considered that the pre-ignition tendency of the lube oil is not the only relevant parameter initiating pre-ignitions. Depending on the ignition source (e.g. hot spot on piston top) it can be possible that the occurrence and amount of pre-ignition is independent from the lubrication oil. For that reason additional tests are required investigating the pre-ignition limitations in real engine operation with various oil types.

4.1.5 Active Cooling of Cylinder Charge by Water Injection

Pre-ignition and knocking are major challenges in high-efficiency hydrogen and methanol-fueled internal combustion engines. One effective method to mitigate these issues is active cooling of the cylinder charge through water injection. By introducing a controlled amount of water into the intake air or directly into the combustion chamber, the charge temperature is reduced, lowering the risk of auto-ignition and improving combustion stability.

Water injection primarily works by utilizing the latent heat of vaporization, absorbing thermal energy from the air-fuel mixture and delaying ignition timing. This effect is particularly beneficial in hydrogen engines, where the low ignition energy and high flame speed increase susceptibility to pre-ignition and knock. Similarly, in methanol applications, where combustion is characterized by rapid heat release, water injection helps to moderate pressure rise rates, reducing excessive mechanical and thermal loads on engine components.

There are two primary water injection strategies: Port Water Injection (PWI), where water is introduced upstream of the intake valves to achieve charge cooling and mixture homogenization, and Direct Water Injection (DWI), where water is injected directly into the combustion chamber to cool specific regions such as exhaust valves, spark plugs, and piston surfaces. The selection of the appropriate injection method depends on engine architecture and knock suppression requirements.

CFD simulations and experimental testing show that optimized water injection reduces peak in-cylinder temperatures, preventing early auto-ignition and allowing for higher compression ratios and advanced ignition timing without knocking. By this higher power output is achievable with same engine configuration. Figure 23 shows an increase of power density by 20% when operating the engine with water injection.

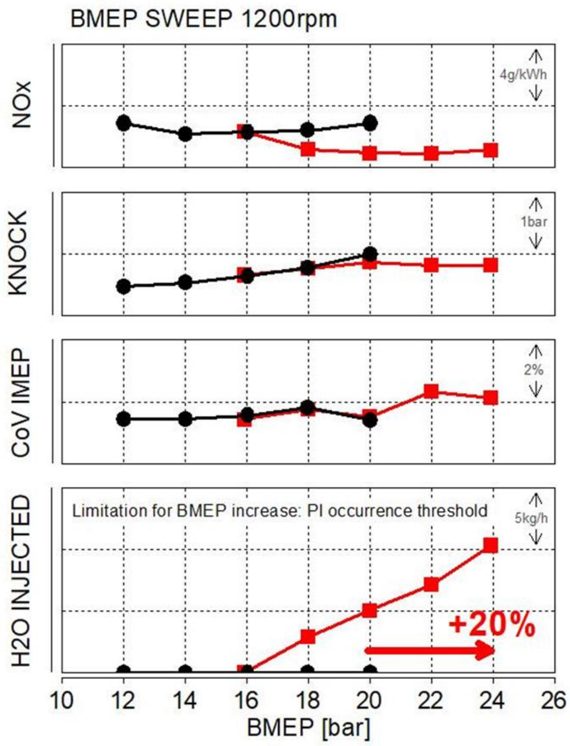

Figure 23: BMEP increasing potential by water injection for H_2 ICEs

However, excessive water injection can lead to overcooling, misfires, incomplete combustion, and condensation of water from the blowby into the lube oil, requiring precise metering and control. Additional considerations include water quality, as impurities may cause corrosion or deposit formation, and system complexity, as water injection requires dedicated injectors, pumps, and control systems to function reliable.

Water injection presents a viable solution for improving combustion stability, efficiency, and durability in hydrogen and methanol ICEs. Further research will focus on optimizing injection parameters and refining control strategies to enhance its effectiveness in real-world applications.

4.2 Valve Guide and Seat Wear

The contact between the valve stem and the guide typically experiences poor lubrication, particularly in engines operating with non-carbon based fuels, where the lubricating properties of carbon are absent. As a result, the tribological interfaces of the valve require even greater attention compared to fossil-fueled engines.

In a first approach it is mandatory to address the contact interfaces valve to valve seat but also the guiding of the valve stem in view of homogeneous contact pressure distribution and minimized deformations under assembly and thermal load from operation.

AVL solves these challenges employing new concepts for valve pattern and cylinder head bolt arrangement, allowing for a new load transfer path which offers an optimized load distribution with minimized deflection.

The motion of the valve is a balance of the guiding in the head, gas force, seat impact and valve actuation. As the motion is not fully constrained and guided, a review of the dynamic trajectory supports deeper system understanding especially with evolution of the valve seat wear or valve guide wear on the hardware. This wear can either stabilize or lead to undesired disbalance in the system leading to malfunction.

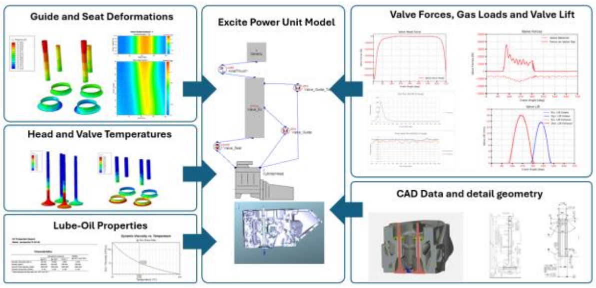

Figure 24: Boundary conditions for multibody dynamics simulations on valve guide and valve seat

Multi-Body dynamics simulation using Excite Powerunit can be used to reproduce the behavior, modelling the contacts in seat and guide in elasto-hydrodynamic formulation. Considering the stiffness, local deformations, elasticity, local temperatures and material properties (figure 24) allows to calibrate the model to an existing state of observation. Based on which mitigation actions can be derived and virtually tested, wear and damage hypothesis can be proven right or wrong and wear prognosis over lifetime becomes virtually feasible.

The advantage of such a virtual wear model is the interaction of the wear progression on the guidance and seat interaction and hence the dynamics of the valve. With accumulated abrasion of material, the contact is changing and consequently the valve is experiencing different balance of force continuously changing the dynamics

4.3 Condensation

As described previously it is mandatory based on the higher water concentration in the blowby gases to avoid condensation and by this water accumulation in the lube oil. This can be approached from two sides: avoiding from the beginning any condensation in the breather system and any drain of water into the oil sump or ensuring a safe separation/ evaporation of already collected water in the oil sump.

4.3.1 Crank Case Gas Dilution

One effective method to prevent water condensation in the blowby gases is dilution with fresh air. By introducing fresh air, the concentration of water vapor is reduced, which in turn lowers the dew point. However, it is crucial to ensure that the incoming fresh air does not excessively cool the blowby gases, as this would counteract the intended effect of shifting the dew point.

The most efficient approach is to introduce filtered fresh air at a location opposite to the blowby outlet, allowing the air to be heated as it passes through the engine. Alternatively, routing the fresh air through pathways near the exhaust system can help preheat the incoming air, further minimizing condensation risks.

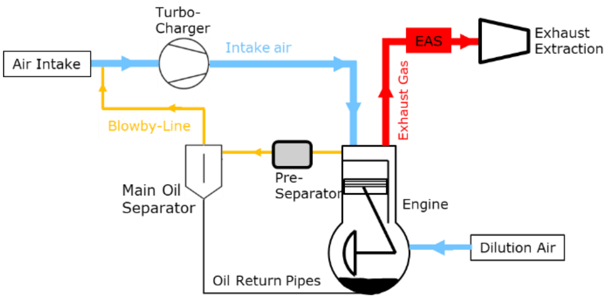

Figure 25: Closed crankcase ventilation configuration with fresh air dilution

4.3.2 Thermal Management

Another key strategy to mitigate water condensation in internal combustion engines is optimizing the thermal management to minimize the time interval in which condensation can occur. by proper thermal management. The first step is to minimize the thermal mass avoiding unnecessary large lube oil but also coolant volumes in the engine. In the next level it is important to ensure also heat transfer from coolant to oil via the lube oil cooler, because the coolant is via the combustion chamber walls typically heated faster than the oil. If due to operating profile or boundary conditions the time to heat up the lubrication system is still too long avoiding water entering the lube oil, additional auxiliary heating devices must be integrated in the system maintaining the oil temperature at levels well above 70-80°C. At this sump oil temperature there are already sufficient surfaces like in the piston cooling gallery where the water is evaporating from the lube and not condensation again.

Not to forget is here the path of the blowby from engine outlet to the return connection in the intake path: If this path is too long or exposed to cold environment either insulation or heating devices must be applied to prevent re-circulation of the evaporated water from the oil.

4.3.3 Water Separation

If the previous described measures avoiding water enrichment of the lube oil by condensation are not sufficient avoiding too high water in oil content, measures must be implemented for water separation. There two main paths possible:

1. Gravity-based separation of the water from the lube oil using the higher density of water compared to lube with e.g. cyclone or centrifugal separators. This method is highly efficient for hydrophobic lube oil but is less effective for lube oils with hydrophilic properties that tend to form emulsions.

2. The other path to separate water from the lube oil is by evaporation of the water at temperatures above boiling point of water (100°C) but below the boiling point of the lube oil. The evaporated water can either be collected or returned to the engine air intake system for disposal.

4.4 Closed Breather System

Due to the described aspects a breather system in open configuration is not appropriate and must be designed in closed configuration. Two potential layouts can be used for alternative fueled engines to avoid release of crank gases without any treatment into the engine room or the environment.

4.4.1 Blowby Return before Compressor Inlet

Unburned fuel or lube oil aerosols transported by the blowby gases will be burned in the combustion process with benefit for engine efficiency.

Due to the lower pressure at the blowby return point between air filter and compressor inlet a negative pressure level in the crank case can be generated over nearly the whole engine map preventing leakages at shaft seals.

The main disadvantage of a closed breather system is the risk of efficiency loss due compressor coking and fouling of intake air system especially at high performance turbochargers. A further negative aspect could be oil collection in charge air cooler which can be avoided by using of highly efficient oil separator systems.

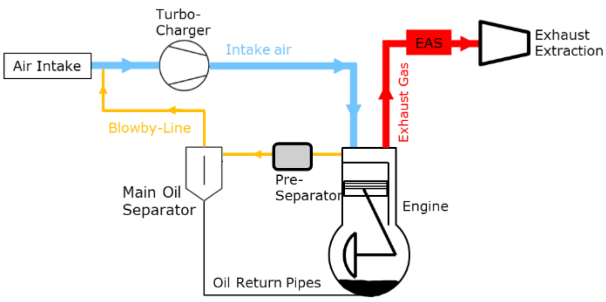

Figure 26: Closed crankcase ventilation configuration in intake path

4.4.2 Blowby Return after Turbine Outlet

Alternative to the blowby return before the compressor inlet, it is also possible to pass the blowby gases to the exhaust gas path before the EAS system. The advantage of such a design is the elimination of deposit formation on compressor stage and intake air path.

On the other side this setup requires an additional pump to transfer the blowby to the exhaust with higher pressure level and especially for fuels with low ignition energy request like hydrogen or methanol a pump can act as ignition source.

A potential remaining risk for plugging of aftertreatment components cannot be completely avoided and should be considered.

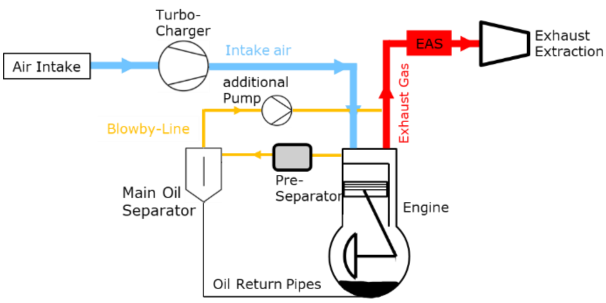

Figure 27: Closed crankcase ventilation configuration in exhaust path

5 CONCLUSIONS

The transition to carbon-neutral fuels presents both opportunities and challenges for internal combustion engines (ICEs). While hydrogen, ammonia, and methanol offer viable alternatives to fossil fuels, their unique combustion characteristics demand targeted adaptations in engine design, materials, and operational strategies. AVL has developed engineering solutions that address these challenges and enable the successful integration of alternative fuels into ICE applications. Key findings and solutions include:

- **Pre-Ignition Control:** Pre-ignition remains the primary limitation of power output in hydrogen- and methanol-fueled ICEs. Our advanced strategies, including optimized surface temperature management, minimization of oil transport, and advanced measures like water injection, effectively mitigate the pre-ignition risk.
- **Thermal Management:** To ensure durability and efficiency, AVL applies innovative cooling concepts such as top-down cooling for cylinder heads and split cooling for liners, providing precise thermal control and preventing component degradation.
- **Lubrication Optimization:** The impact of alternative fuels on lubricants requires tailored oil formulations that resist water contamination, emulsification, and corrosion. AVL's expertise in tribology and material selection as well as hardware testing supported development ensures reliable long-term engine operation.
- **Water Condensation Management:** Alternative fuels such as hydrogen and ammonia generate higher water content in combustion and blowby gases, increasing the risk of condensation and oil dilution. AVL addresses this with optimized breather system designs, selection of advanced oil formulations with improved water separation properties, and targeted thermal management strategies to minimize condensation and ensure reliable operation.
- **Advanced Simulation and Testing:** By combining advanced simulation tools CFD, FEA, and experimental validation, AVL accelerates development cycles and ensures robust performance in real-world operating conditions.

As an engineering service provider, we offer comprehensive expertise in optimizing ICEs for alternative fuels, ensuring high efficiency, reliability, and compliance with future emissions regulations. With our deep understanding of combustion processes, thermal management, water handling, and materials science, we develop tailored solutions that empower our partners to successfully transition to sustainable propulsion technologies.

Our continuous innovation and rigorous testing enable us to support customers in overcoming these challenges, ensuring that internal combustion engines remain a highly viable and efficient power source for high-performance and long-distance applications in the decarbonized future.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

BMEP Brake mean effective pressure

DWE Direct water injection

EAS Exhaust aftertreatment system

ICE Internal combustion engine

ITNA Institute of thermodynamics and sustainable propulsion systems

GDC Goetze Diamond Coating

HCF High cycle fatigue

HSLE High Speed Large Engine

HTC Heat transfer coefficient

PBI Piston-bore interface

PWI Port water injection

PI Pre-ignition

SI Spark ignited

TMF Thermo-mechanical fatigue

TU University of Technology

7 REFERENCES AND BIBLIOGRAPHY

[1] Gschiel, Wilfling and Schneider, 2024: Development of a method to investigate the influence of engine oil and its additives on combustion anomalies in hydrogen engines. *Automotive and Engine Technology 9, No. 1*

[2] De Feo et al, 2024: The Role of Lubricant Formulation in Controlling Pre-Ignition Phenomena in a H_2 ICE. *45th International Vienna Motor Symposium*

[3] Winklhofer, E., Jocham, B., Philipp, H., Kapus, P. et al., 2023: "Hydrogen ICE Combustion Challenges," SAE Technical Paper 2023-24-0077, doi:10.4271/2023-24-0077

[4] Estebanez, Gareth et al, 2023: Greenhouse Gas Emissions Reduction on High-Speed Large Engines, Paper 652, 30th CIMAC Congress, Busan 2023

[5] Murakami S., Kirsten M., Segura Carrasco M. and Kammerdiener Th. 2023. Evaluation of the CO2 reduction potential when considering diesel, natural gas and hydrogen operation in a 175 mm bore engine, MTZ industrial, May 2023.

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