Hydrogen internal combustion engine as solution for the decarbonization of heavy-duty and off-highway vehicles

Heitor Souza Chaves
Rafael Antonio Bruno
Felipe Mazuco
MAHLE Metal Leve S.A.

Hannes Marlok
Christian Trabold
Dr. Simon Schneider
MAHLE International GmbH

ABSTRACT

Sustainability and reduction of Greenhouse Gases (GHGs) emissions are strong drivers in every technical and economic discussion in the current world. The transport segment, and specifically the heavy-duty vehicles, are responsible for a significant share of the global CO2 emissions and, therefore, are the focus of many research looking for the most effective solution to reduce this impact. In that sense, hydrogen (H2) internal combustion engines emerge as a promising alternative with a short time-to-market due to simplicity of implementation and performance similar to conventional diesel fueled vehicles.

The use of H2 imposes new challenges to engine components and systems regarding, for example, safe operation, protection against H2 embrittlement, improved blow-by and control of lube oil consumption. Looking at these challenges, MAHLE has developed a hydrogen test center, converted a diesel heavy-duty (HD) engine to H2, and performed a series of evaluations to develop and validate its products in this new application.

This paper focus on the experimental results obtained on MAHLE's test platform and the necessary technical adaptation on engine components and on crankcase ventilation to achieve the highest standards of robustness and safety.

RESUMO

Sustentabilidade e redução de emissões de Gases de Efeito Estufa (GEEs) são fortes direcionadores em todas as discussões técnicas e econômicas no mundo atual. O segmento de transportes, e especificamente os veículos pesados, são responsáveis por uma parcela significativa das emissões globais de CO2 e, por isso, são foco de diversas investigações em busca da solução mais eficaz para redução desse impacto. Nesse contexto, os motores de combustão interna a hidrogênio (H2) surgem como uma alternativa promissora com curto prazo para lançamento devido a simplicidade de implementação e desempenho semelhante aos veículos diesel convencionais.

O uso de H2 impõe novos desafios aos componentes e sistemas do motor relacionados, por exemplo, a operação segura, proteção contra fragilização por H2, redução de blow-by e controle de consumo de óleo lubrificante. Olhando para esses desafios, a MAHLE desenvolveu um centro de testes de hidrogênio, converteu um motor diesel HD para H2 e realizou uma série de avaliações para desenvolver e validar seus produtos nessa nova aplicação.

Este trabalho foca nos resultados experimentais obtidos na plataforma de testes da MAHLE e nas adaptações técnicas necessárias nos componentes do motor e no sistema de ventilação do cárter para garantir os mais altos padrões de robustez e segurança.

INTRODUCTION

During the COP 21 held in Paris, the parties associated to the United Nations Framework Convention on Climate Change (UNFCCC) achieved a landmark agreement aimed at combating climate change, accelerating and reinforcing the necessary actions and investments towards a sustainable, low-carbon future. [1]

Since then, nearly 200 countries have already signed the Paris Agreement, with the shared goal of strengthening the global response to the threat of climate change by "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change". [2]

According to the Intergovernmental Panel on Climate Change (IPCC), achieving the ambitious target of limiting global warming to 1.5°C requires the reduction of global net greenhouse gas emissions to zero by approximately 2050. [3]

In 2021, Brazil released 2.4 billion tons of CO2e into the atmosphere. Alone, the road transportation segment was responsible for the emission of 190 million tons of CO2e, of which 63 million tons was due to passenger cars and 106 million tons was due to heavy commercial vehicles, including trucks and buses. [4]

Addressing the decarbonization of heavy vehicles is essential to decrease the emissions from the transportation segment, however currently there is no clear answer regarding the most efficient and feasible technology route to achieve that goal.

Increasing the efficiency of existing powertrains is an important step in this direction, however, the use of decarbonized energy sources is the ultimate goal targeting climate neutrality in the transport segment. [5]

Different drive cycles and load characteristics require specific solutions for each vehicle concept (Figure 1). Battery electric powertrains are suitable for passenger cars and small/short range commercial vehicles. However, the application in short term of this same technology to heavy trucks and off-highway equipment has disadvantages regarding short range, long charging times and high system weight.

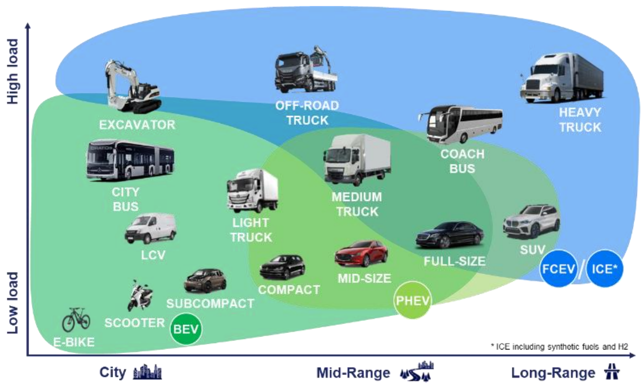

Figure 1: Future application map - Most suitable powertrains for different use cases

Hydrogen appears as an attractive alternative of energy storage for applications in which high energy density and fast refueling is required [6]. It is a carbon-free fuel that can be potentially produced in a climate neutral way using renewable energy sources.

Onboard the vehicle, hydrogen can be used in two primary ways, depending on the segment and user profile. It can be employed in a fuel cell to generate electricity and power an electric powertrain, or it can be injected into a hydrogen internal combustion engine (H2 ICE).

Overall, both systems exhibit similar efficiency levels, with the fuel cell holding an advantage at lower loads. However, under high loads, drawbacks related to system efficiency and increased cooling demands become more relevant and the hydrogen combustion engine becomes more suitable. [7]

Both technologies complement each other and create synergy effects not only in the development and manufacturing processes, such as for the tank system, but also in addressing the hydrogen infrastructure, which is currently considered a vulnerable aspect of hydrogen mobility. [7]

MAHLE is working on the development of both technologies and considers them as crucial enablers for achieving climate-neutral mobility, depending on specific applications. For that goal, MAHLE established a new hydrogen test center in its headquarter in Stuttgart (Germany), equipping the company with the capability to provide to its costumers tailored solutions for tomorrow's mobility across all vehicle segments.

This paper focus on recent technology developments for H2 ICEs. For these evaluations, MAHLE has adapted and built a dedicated research heavy duty H2 engine as a baseline for the development activities. Besides new fuel injection and ignition systems, engine components and the crankcase ventilation had to be redesigned.

Figure 2: MAHLE's test facilities for the development of hydrogen internal combustion engines (Stuttgart).

H2 ICE CONFIGURATION AND SETUP

Hydrogen internal combustion engines can be operated with Diesel-like combustion and high-pressure direct injection (HPDI) or with Otto-like spark ignition, using port fuel injection (PFI) or low-pressure direct injection (LPDI).

Hydrogen PFI systems are considered the simpler first series application, due to the advanced development status of injectors and their easier integration into existing cylinder heads [7]. MAHLE has initially adopted this approach, replacing the diesel direct injection (DI) injector with a spark plug, while integrating H2 PFI injectors into a dedicated intake system.

This engine concept also simplifies the necessary H2 storage system, however there are limitations regarding the achievable maximum power output and thermal efficiency. [8]

To maximize thermal efficiency and to achieve power density similar or even higher than conventional diesel engines using H2, it is necessary to adopt high pressure direction injection of fuel. This setup brings challenges to storage tanks, fuel injection system and other engine components, but enables brake thermal efficiency (BTE) of 50% or more. [9]

Spark ignition H2 ICE pose mechanical and thermal loads lower than conventional Diesel engines, which indicate an easier carry over of materials and components from existing applications. On the other hand, the HPDI design is more demanding both on mechanical and thermal loads. [8]

The base engine adapted by MAHLE is a 12.8L HD diesel engine. The modifications include new power-cell unit (PCU), new fuel supply and ignition systems and active crankcase ventilation. Compression ratio was reduced from 17 to 11 do adjust to H2 spark-ignited combustion. The main engine characteristics are displayed in the table below.

Table 1: Main engine parameters before and after adaptation.

Parameter	Base engine	H2 engine
Displacement	12.8L	12.8L
Cylinders	6 inline	6 inline
Compression ratio	17:1	11:1
Peak BMEP	24bar	20bar
Power	375kW	315kW
Fuel injection	DI	PFI

Hydrogen is injected through 6 cylinder-individual injectors that are able to inject the necessary hydrogen amount for full load operation in approx. 60°CA at 1200 rpm / 80 CA at 1800 rpm, enabling complete injection during the intake stroke and thus reducing the risk of backfire.

COMPONENT DESIGN AND CHALLENGES

Despite being a promising carbon neutral alternative, H2 combustion poses new challenges on the engine components. These challenges can be clustered into four topics: combustion anomalies, hydrogen embrittlement, tribology, and corrosion.

In order to achieve high efficiency and power density, hydrogen fueled engines need to work very close to the knocking threshold, therefore the components should be engineered in a way to prevent occurrences that could lead to knocking. In that sense, special attention is dedicated to avoid high surface temperatures, avoid excess of combustion residues in the chamber, or excess of oil particles reaching the chamber, as all of these points could trigger combustion abnormalities.

From a structural perspective, a H2 enriched environment brings special concerns for piston material, once the steel, typical piston material applied to regular high loaded Diesel engines, would present vulnerabilities regarding H2 embrittlement. [10]

Another important point to be considered is the water formation as a combustion product. The excess of water leads to a deteriorated lubrication, impacting the life of ring/liner system, as well as valve/seat system. Corrosion may also be a concern. These effects are even more critical when cooled EGR is applied. Therefore, the material selection for these components should be made taking these aggressive conditions into consideration.

PISTON DESIGN - Despite the application of steel pistons in newer heavy-duty diesel engines, aluminum pistons are recommended for H2 ICEs. The main driver for this change is the reduction by 50 bar of the peak cylinder pressure in comparison to the diesel version.

The use of aluminum also helps to reduce the surface temperature due to its higher thermal conductivity. Figure 3 shows the simulated piston temperature at full load and 1166rpm. The maximum temperature obtained was 320°C, which is 24°C lower than a comparable steel piston. Another benefit of applying aluminum is the reduced risk of hydrogen embrittlement.

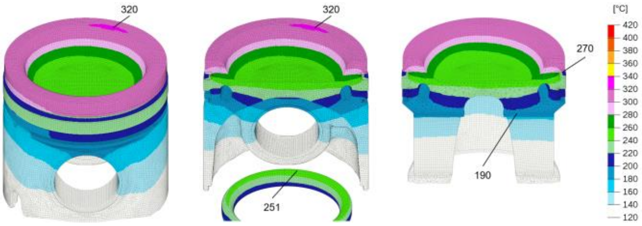

Figure 3: Simulated H2 aluminum piston temperature at 1166 min-1 and full load

Regarding piston dimensions, two main drivers were considered: to maintain similar compression height as the base piston to keep similar crank drive movement; and to have a bigger bowl volume (from 100 cm^3 to 140 cm^3) to comply with the need of lower compression ratio of the H2 spark-ignited combustion.

Numerical simulations were carried out to define the design which met the requirements described while complying with the structural demand. A back-to-back comparison of a state-of-the-art diesel steel piston and the aluminum H2 piston, which resulted from the conducted studies, can be seen in Figure 4. The final design has a compression height 5mm higher than the base piston.

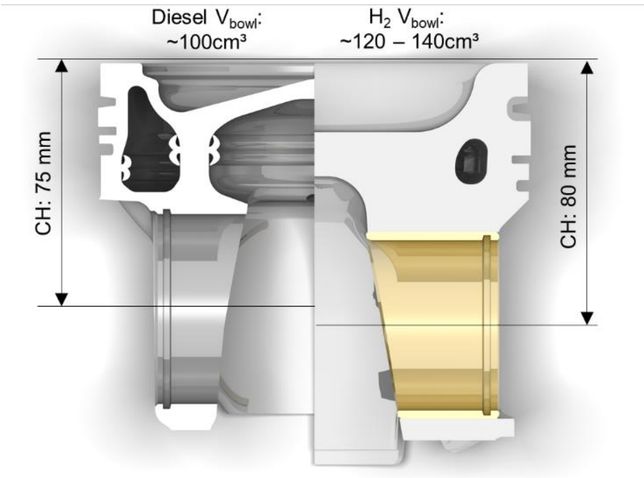

Figure 4: Back-to-back comparison of a diesel steel (left) and the H2 aluminum piston (right).

As seen on the fatigue simulation shown in Figure 5, the flat bowl shape and the increased volume resulted in the lowest high cycle fatigue lifetime to be located in the bowl ground (see purple area) and the lowest low cycle fatigue in the bowl rim area. These results are within MAHLE's guidelines of piston design, showing the conformity of the proposed profile.

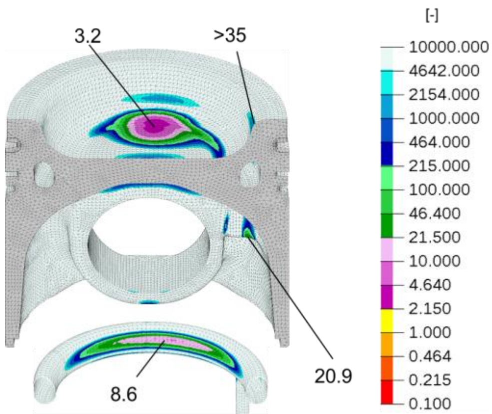

Figure 5: Simulated H2 aluminum piston fatigue lifetime at 1166 min-1 and full load.

The use of aluminum and the position of the cooling gallery were defined to avoid direct sources of hot spots that could create combustion anomalies like preignition and knocking. But other indirect sources should also be considered in the design.

One important point that can induce preignition is the shorter flame quenching distance, which causes the H2 flame to burn into gaps as narrow as 0.5mm. This can promote preignition in the squish area and in the gap volume between piston top land and cylinder wall. Therefore, the final design has a higher squish area, which also reduced the need for a bigger bowl, and a reduced gap between the top land and cylinder wall when compared to the original diesel piston design. These changes are illustrated in Figure 6.

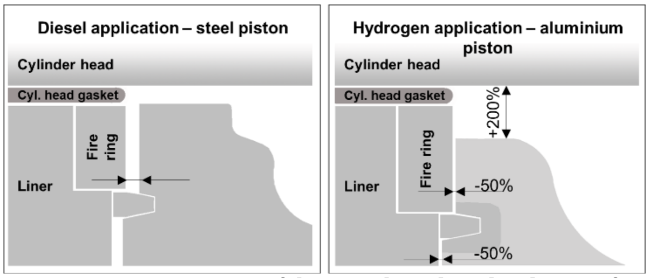

Figure 6: Comparison of the squish and top land area of a diesel steel and H2 aluminum piston at top dead center (not drawn to scale)

PISTON RINGS DESIGN - The conventional compromise of a ring pack in a regular engine is to keep both lube oil consumption (LOC) and blow-by under control whereas offering the lowest friction loss.

For H2 engines this compromise is kept, but with a reinforced importance for LOC and blow-by control. There are some reasons for that: the amount of lube oil reaching the chamber may trigger abnormal combustion events, which can be harmful for the system and for the components. Another important point is that part of the lube oil reaching the chamber will be burned, resulting in minimal emissions of HC, CO and CO2, which may jeopardize the compliance of H2 ICEs as a carbon neutral technology.

There is also a safety reason regarding blow-by control to prevent flammable hydrogen-air mixtures being accumulated inside the crankcase. The challenge is to reduce blow-by level around 50% (at maximum engine torque condition) as compared to conventional diesel engines, to reduce the power requirements for active crankcase ventilation.

MAHLE's first approach was an optimized diesel-like ring pack, that means applying same typical design applied for Diesel engines, but fine-tuned in certain design features.

The general design of the rings is shown in the Figure 7.

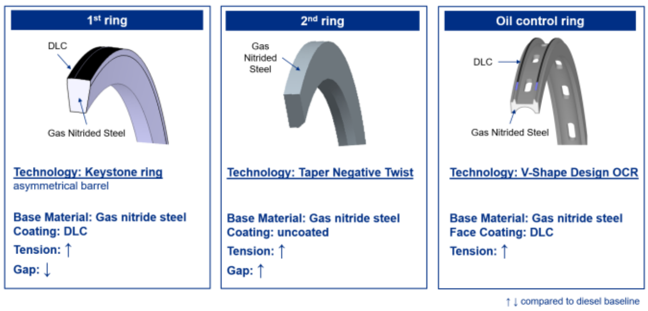

Figure 7: Diesel-like ring pack for a H2 engine.

As the 1st ring groove and ring are exposed to the combustion process and particularly threatened by combustion anomalies, therefore the main focus is set on robustness. For this reason, a GNS (Gas Nitride Steel) material is applied, in combination with DLC (diamond-like carbon) coating on the running face, which is the state-of-the-art for tribological resistance, providing excellent scuffing and wear resistance even with the use of low viscosity oils and gaseous fuels.

The 1st ring tangential load was slightly increased and ring gap was reduced in order to match with lower thermal expansion ratios typical for H2 combustion. Moreover, gap tuning was important to reach improved blow-by control. In the same way, piston groove tilt design had to be adjusted given the different thermal boundary conditions. Piston groove chamfer was also reduced to minimize gas flow.

2nd ring layout is also very similar to a conventional design applied to Diesel engines. Tangential load was also slightly increased and groove tilt angle was adjusted according to thermal conditions. The axial clearance of the 2nd ring groove was almost doubled, and the piston 2nd land clearance was reduced. As the 2nd ring environment is not that aggressive (temperature, pressure), a non-coated GNS was applied.

For the Oil Control Ring (OCR), MAHLE's V-shape design was selected to reduce the ring-liner contact area. Therefore, a high contact pressure can be achieved with low ring tensions, hence reducing the oil control ring induced friction while minimizing oil consumption. DLC coating is applied to the running face in order to keep wear level under control even with reduced viscosity oils.

The tuning of gaps and clearances was made with support of MAHLE's ring dynamic design simulation tool. Figure 8 shows the gas flow around the ring belt regions (indicated on the sketch). By adjusting the gap values, general driver is to minimize the gas flow behind top ring and through top ring gap (paths 1→2→3 and 1→3, respectively) and maximize the gas downflow behind 2nd ring (path 3→4→5). This measure acts reducing the blow-by and, at the same time, reducing the reverse flow (upwards) that could carry oil particles to the combustion chamber.

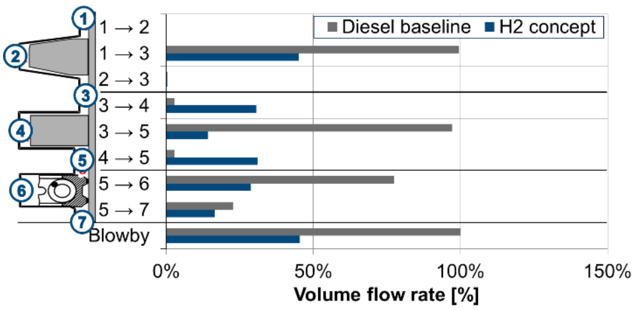

Figure 8: Relative gas flows per piston ring and total blowby at 1166 min-1 full load

Given the cleaner combustion environment when using H2, a second approach for ring pack is currently under investigation. Differently from the first one, the idea is to propose a gasoline-like ring pack (Figure 9). As consequence, the 1st ring could be a rectangular cross section instead of a keystone, as the carbon build-up formation level will be way lower than Diesel engines.

2nd ring design could also follow a typical gasoline design (napier or stepped) in order to offer a better oil scrapping and prevent the oil entering the groove.

The clean combustion of H2 brings a great opportunity for OCR design. It enables the application of a 3-piece OCR, typically applied to gasoline engines, but not to regular diesel engines due to high carbon/soot level, which impacts on component durability. The application of this design to H2 ICEs is very favorable because it offers better LOC performance in idle, motoring, part loads and transient conditions. This is the best OCR design option for cases where a negative intake pressure occurs (due to throttle effect).

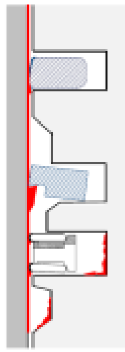

Figure 9: Gasoline-like ring pack

VALVES SET COMPONENTS DESIGN - The valve set also have to be adapted due to new tribological challenges that come from the absence of liquid fuel and its lubricating effects. The starting point of the material selection for the H2 ICE was the already known solutions for compressed natural gas (CNG) applications.

H2 combustion usually imposes lower temperatures on the valve set components compared to CNG combustion, therefore the temperature resistance requirement for the materials is less critical. However, the use of EGR (exhaust gas recirculation) brings some concerns regarding corrosion due to the water steam which composes the exhaust gas.

Water steam combined with the low temperatures of the cooled EGR gases can create condensates on the surface of the components, which increases the risk of corrosive attacks.

Figure 10 summarizes the main challenges of each component of the valve set. In general, valves and valve seats have to withstand a corrosive environment and the materials should be able to work in an unlubricated dry condition.

Besides that, the intake valves are susceptible to hydrogen embrittlement due to the cyclic load profile combined with the exposition to unburned H2, which has to be considered for the material selection.

Specially for the exhaust position, sodium-filled hollow valves are an option to reduce the surface temperature, therefore mitigating knocking risk.

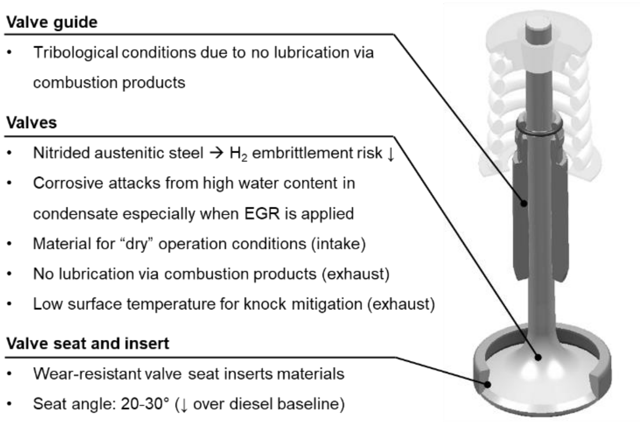

Figure 10. Challenges and requirements of a hydrogen dedicated valve set.

The chromium and nickel alloys usually applied in conventional diesel engines are not ideal for H2 ICEs due to the lower thermal requirement and the high cost of these materials. Austenitic materials are preferred for this new application over martensitic ones since they are less susceptible to hydrogen embrittlement.

The high wear resistance needed due to the dry condition of the gaseous fuel impacts the choice of the material for the valve seat and valve guide. Nitriding treatment over austenitic steel is one of the preferred solutions to give the required wear resistance to the valve seat and valve guide.

SCAVENGED CRANKCASE VENTILATION

As already mentioned, another challenge in using hydrogen in internal combustion engines is the potential accumulation of H2 in the crankcase. Due to the low ignition energy of the fuel, there is a risk of explosion of the crankcase gases if the concentration of H2 surpasses 3.5%.

Blowby gases are a mixture of air (O2), unburned hydrogen and exhaust. To better understand blow-by flow, composition, and the impact of PCU design, several simulations were performed at MAHLE.

The diagram shown in Figure 11 presents the cumulative blowby flow along the crank angle. The blow-by simulation shows that the maximum rate occurs between 20-25°CA after top dead center fired (aTDCF). Thermodynamic analysis also shows that the combustion ends at 25-30 °CA aTDCF. Thus, it can be deduced that approximately 2/3 of the blowby volume consists of a mixture of air and unburned hydrogen.

This result shows that, without external scavenging, unburned H2 would accumulate in the crankcase and pose an explosion risk once the concentration exceeds the lower explosion limit of 3.5%.

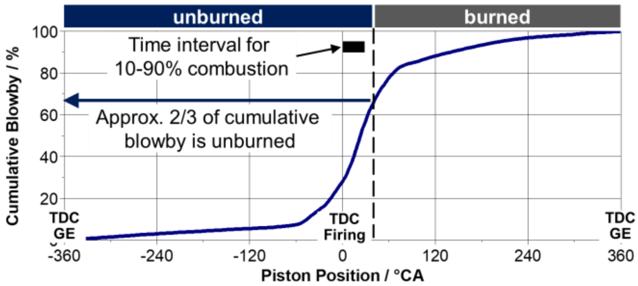

Figure 11: H2 ICE blowby composition.

To dilute the hydrogen concentration in the crankcase, an active ventilation system called High-Pressure-Impactor (HPI) was developed by MAHLE and was used on the test engine (Figure 12).

MAHLE HPI is an electrically driven compressor coupled to a pressure-controlled impactor that allows for high efficiency separation of oil particles and also offers controllability of the flow rate within wide operating limits.

Figure 12: MAHLE HPI.

In order to refresh the crankcase and dilute the H2 concentration, a scavenging line through which fresh ambient air is drawn was also added. The schematic of the system is shown in Figure 13.

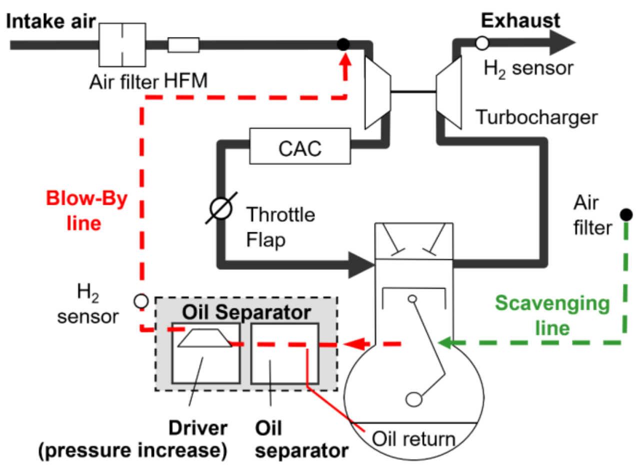

Figure 13: MAHLE HP system layout.

On the next session, experimental results will be presented showing the effectiveness of the system in keeping the H2 concentration in the crankcase bellow the risk threshold of 3.5%.

EXPERIMENTAL RESULTS

In order to study the hydrogen combustion process and assess the performance of MAHLE components, an extensive test plan was created and executed at the H2 test center in Stuttgart. This comprehensive plan includes engine commissioning, thermodynamic investigations, performance tests, and evaluations of blow-by.

A base engine calibration was created and optimized with focus on the ESC (European Stationary Cycle) operating points by adjusting parameters such as ignition angle, start of injection (SOI) timing, throttle valve position and EGR rate.

Taking advantage of the high reactiveness of H2 and flammability, engine operation is possible at very lean mixtures. As can be seen on the next diagram (Figure 14), it was possible to achieve stable operation with lambda>2 at up to 15bar BMEP over all speed ranges.

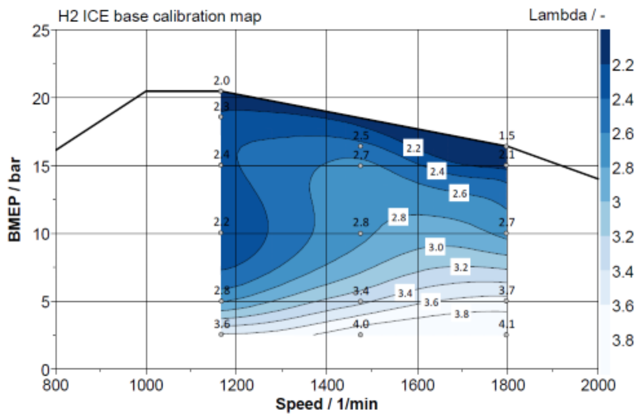

Figure 14: Lambda map for H2 calibration.

With this lean burn concept, in-cylinder temperature and NOx formation can be minimized. The next diagram (Figure 15) shows that engine-out NOx emissions are lower than 1g/kWh on the majority of the engine map. Compared to conventional diesel engines, the results achieved with the PFI H2 ICE are lower by a factor of more than 10.

Since hydrogen itself is carbon free, HC and CO emissions of the H2 ICE are virtually zero. Considering also the much lower NOx emissions, the after-treatment systems (ATS) of vehicles can be greatly simplified to achieve Euro 6 and post-Euro 6 emission targets.

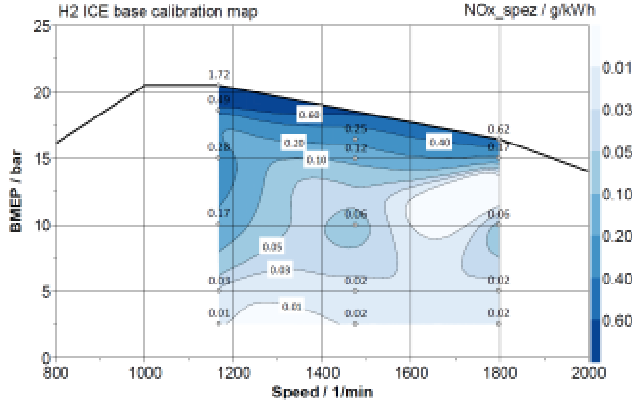

Figure 15: NOx map for H2 calibration.

The full load curve of MAHLE's PFI H2 ICE can also be seen on the two previous diagrams (Figures 14 and 15). It was possible to achieve a maximum BMEP of 20.5 bar at 1166 rpm. This represents more than 80% of the original diesel engine BMEP. It was also possible to reach brake thermal efficiency (BTE) of more than 44% for a significant portion of the engine map.

Regarding scavenging and H2 concentration on the crankcase, the diagram displayed in Figure 16 shows the initial results obtained operating the HPI at full power to guarantee maximum safety.

In this plot, the values of the map in blue show the crankcase volumetric flow at the output of the HPI system, in this case the combination of blowby and scavenging air. Hydrogen concentration (%v) in the crankcase is shown by the green isolines.

As expected, there is a trend of increasing crankcase flow towards higher loads and speeds, since blowby also increases. It can also be noticed that H2 concentration was kept well below the 3.5% threshold. In fact, the maximum H2 concentration at 15bar BMEP was 2.3% and more recent measurements at full load show results in the range of 3.0% at 20.5bar BMEP.

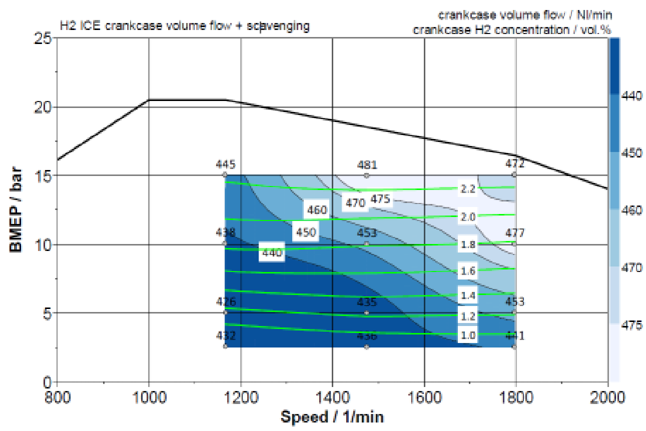

Figure 16: Crankcase flow including scavenging with HPI at maximum power and H2 concentration (%v).

For a series application, the HPI speed can be adjusted depending on the engine operation point. The ultimate objective would be to keep the H2 concentration below 3.5% while minimizing the electric power requirement for the HPI and saving fuel.

FURTHER INVESTIGATIONS AND DI SETUP

Despite being a simpler setup, the spark ignited PFI configuration presents limitations to increase power output and BTE due to abnormal combustion occurrences like knocking and backfire, for example.

Looking at these limitations, MAHLE has already adapted its H2 ICE to enable DI combustion. The cylinder head now contains an insert with central injector and the sparkplug was dislocated 15mm at a slight angle (Figure 17).

With this configuration, the H2 ICE research engine can be operated on two modes of combustion by changing the injection timing:

- Injection during the intake stroke, so called “PFI Mode”.
- Injection during the compression stroke, so called “DI Mode”.

The PFI mode has as an advantageous longer time for mixture preparation. The DI mode, on the other hand, enables higher volumetric efficiency, as the fuel is injected into the cylinder after intake valve closing. This enables higher air-fuel ratios with benefits for raw NOX emissions.

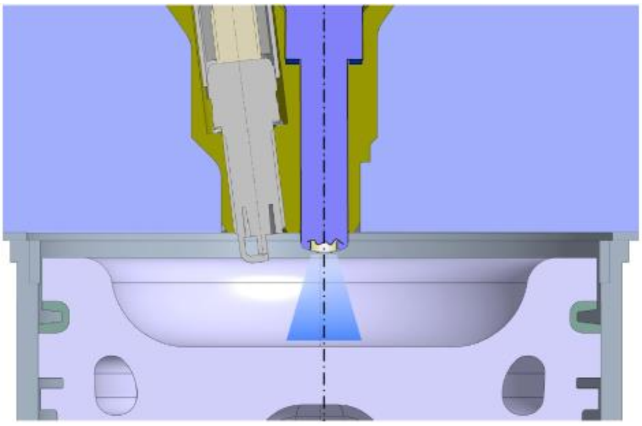

Figure 17: New configuration for DI/PFI.

This flexible setup has already been run at MAHLE’s headquarter in Stuttgart and allows for better understanding of the advantages/disadvantages of each one and also the specific impacts on its products.

Besides the basic investigations about H2 combustion and the functionality of its products, MAHLE is currently also performing longer evaluations (>150h) to access the durability of the components and the impact of H2 on material after extended periods of time under high pressure and high temperature.

SUMARRY AND CONCLUSIONS

In a society in which reducing GHG emissions is a major concern in all economy segments, any solution for decarbonization should be considered and evaluated considering the particularities of each specific application.

Not only in Brazil, but also worldwide, the commercial vehicles segment is a significant contributor to CO2 emissions and have to be addressed. The application of battery electric powertrains in these vehicles presents limitations due to short range, long charging times and high system weight.

Hydrogen with its high energy density and short refueling times appears as a great carbon free energy carrier for sustainable heavy-duty and off-highway vehicles. It can be used in a fuel cell or burned in internal combustion engines.

MAHLE believes that both technologies can be complementary and can create synergy effects not only in the development and manufacturing processes, such as for the tank system, but also in addressing the hydrogen infrastructure.

To fully understand the challenges and benefits of H2 ICEs, MAHLE successfully adapted a conventional diesel internal combustion engine for a heavy-duty application to run on hydrogen. The engine was commissioned and operated within MAHLE’s own hydrogen test center in Stuttgart.

Looking at the specific requirements of this application, pistons, piston rings and valve set were redesigned in order to deliver safe operation, protection against H2 embrittlement, improved blow-by and control of lube oil consumption

Besides that, an active scavenging ventilation system, called MAHLE High Pressure Impact (HPI), was introduced to keep the concentration of H2 in the crankcase below 3.5% and mitigate explosion risk.

With the tests carried out, MAHLE achieved stable and robust full engine operation with PFI, 80% performance of the original diesel engine (power and torque) and brake thermal efficiency as high as 44% in big portion of the operation map.

A baseline calibration shows the potential of the hydrogen combustion in terms of very low engine-out NOx emissions. Compared to a series diesel calibration, the hydrogen engine emits more than 10 times less NOx in most of the map area and full load curve.

MAHLE HPI also presented very good performance keeping the H2 concentration well below the 3.5% threshold, while still keeping room for optimization and reduction of power requirement to save fuel.

Furthermore, MAHLE has already operated the engine with H2 direct injection in a thermodynamic investigation and to understand the specific impacts of this setup on the engine component. Besides that, the next evolution of PCU components is being tested with the aim to further reduce LOC and blow-by, and the durability of the engine components is being analyzed through tests with longer duration.

REFERENCES

[1] UNECE. “Summary of the Paris Agreement”. Available at: https://unece.org/fileadmin/DAM/stats/documents/ece/ces/2016/mtg/Session_1_Bigger_picture_of_COP21.pdf

[2] United Nations. “Paris agreement”, 2015. Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[3] EU Parliament. “Carbon dioxide removal - Nature-based and technological solutions”, 2021. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689336/EPRS_BRI(2021)689336_EN.pdf

[4] SEEG. “Panorama das Emissões de GEE no Brasil em 2021”, 2021. Available at: https://plataforma.seeg.eco.br/sectors/energia

[5] Rieger, D., Mayer, F., Weller, F., Schneider, S., Stiehl, R. “Experimental investigation of a hydrogen powered heavy-duty truck engine”. 9th International engine congress, Baden Baden, 2022.

[6] Schneider S., Trabold, C., Friedrich, T., Mayer, F., Weller, F., Stiehl, R. “H2 ICE DI multicylinder engine tests for thermodynamics and component development”, 2022.

[7] Marlok, H., Trabold, C., Puck, A., “Engine component development for H2 combustion engines”, 2022.

[8] Ferrarese, A., Kumoto, E., Marquard, R.; “Resistant Cast Iron for a 50% Efficient Hydrogen Engine”, 2022.

[9] Kufferath, A., Naber, D., Cornetti, G., Grzeszik, R., Kueger, M., Gaballo, M. “Development of combustion process and operating strategy for a low-emission hydrogen engine”. 31st Aachen Colloquium Sustainable Mobility 2022.

[10] Lynch, S. “Hydrogen embrittlement phenomena and mechanisms”. Corrosion Reviews, 2012.