2025 | 186

Development and application of a flex-fuel single cylinder platform for high-speed engines

Basic research & advanced engineering - new concepts

Francesco Accurso, DUMAREY Automotive Italia S.p.A.

Francesco Concetto Pesce, DUMAREY Automotive Italia S.p.A
Valentina Gorietti, DUMAREY Automotive Italia S.p.A.
Vincenzo De Carlo, DUMAREY Automotive Italia S.p.A.
Luca Marchitto, CNR-STEMS
Pierpaolo Napolitano, CNR-STEMS
Angelo Giardino, Isotta Fraschini Motori S.p.A.

This paper has been presented and published at the 31st CIMAC World Congress 2025 in Zürich, Switzerland. The CIMAC Congress is held every three years, each time in a different member country. The Congress program centres around the presentation of Technical Papers on engine research and development, application engineering on the original equipment side and engine operation and maintenance on the end-user side. The themes of the 2025 event included Digitalization & Connectivity for different applications, System Integration & Hybridization, Electrification & Fuel Cells Development, Emission Reduction Technologies, Conventional and New Fuels, Dual Fuel Engines, Lubricants, Product Development of Gas and Diesel Engines, Components & Tribology, Turbochargers, Controls & Automation, Engine Thermondynamis, Simulation Technologies as well as Basic Research & Advanced Engineering. The copyright of this paper is with CIMAC. For further information please visit https://www.cimac.com.

ABSTRACT

Ambitious greenhouse gas emissions targets imposed by the International Maritime Organization (IMO) necessitate for a rapid transition to low-carbon fuels adoption and the need to develop efficient engines with a reduced carbon footprint. Multiple options are emerging in the marine sector. Above all, natural gas, methanol, and ammonia can reduce emissions compared to diesel engines when produced from renewable energy and controlling the slip of harmful exhaust emissions (CH4, N2O, CH2O).

The efficient operation of engines with low-carbon alternative fuels can only be achieved with tailored combustion systems. In this context, flexible tools such as single-cylinder engines (SCEs) can be used to optimize the mixture preparation and combustion and provide a preliminary calibration of the final multi-cylinder engine. On the other hand, considering the wide variety of fuels and their combustion processes, flexibility and modular platforms are a key factor in reducing costs and time-to-market of new products.

In the last years, Dumarey, in collaboration with Isotta Fraschini Motori and CNR-STEMS, developed a flexible SCE platform, as retrofit from a baseline diesel architecture, for the experimental screening of combustion system designs suitable for both natural gas and methanol, considering a port-fuel injection configuration. In this framework, the target was to maximize commonalities for MeOH and CH4, while customizing only components with specific requirements coming from the fuel. Taking advantage of extensive Dumarey design and simulation capabilities, the combustion concepts and their functional parameters of cylinder head, ignition system, injectors nozzle, camshaft and piston were defined primarily by analysis, producing a limited number of variants for the testing phase.

The SCE was tested in STEMS, where engine facilities were updated to operate safely and with high flexibility with diesel, natural gas and methanol. With limited hardware modifications, SCE is being used to investigate MeOH and CH4, including different intake valve strategies, compression ratio, prechambers and injectors geometry.

In this paper the SCE development process is described, along with main design rules and simulation studies carried out through the project. Moreover, part of the first experimental results on natural gas are presented and compared to simulations, along with a detailed perspective of testing activities on methanol.

1. INTRODUCTION

Maritime mobility is essential for global trade, handling over 80% of commercial transport. However, the vast number of ships in operation leads to significant emissions of pollutants, including CO_2 and other harmful substances. To tackle these environmental challenges, the International Maritime Organization (IMO) has set strict regulations to reduce ship emissions. The IMO aims to achieve net-zero Greenhouse Gases Emissions (GHG) by 2050 with a minimum 70% GHG reduction by 2040 compared to 2008 levels [1]. These ambitious goals require the adoption of alternative fuels and energy sources to replace the commonly used diesel-fueled internal combustion engines. A key step in developing sustainable engines that use alternative fuels is defining the combustion system and the requirements for various components. In this regard, a flexible platform like a Single Cylinder Engine (SCE) can significantly reduce the development time for new engine platforms.

In this perspective, a collaborative partnership program between DUMAREY, Isotta Fraschini Motori, and STEM-CNR was established with two main objectives:

- Development of a flexible SCE platform for testing alternative fuels starting from a conventional diesel architecture.
- Upgrading an existing Multi-Cylinder Engine (MCE) to demonstrate reductions in greenhouse gas and pollutant emissions using low-carbon fuels.

Although Natural Gas, Methanol, Ammonia, and Hydrogen are currently considered viable solutions for marine sector decarbonization, an early down-selection process identified natural gas and methanol as the preferred fuels for this project. The primary reasons for this choice were the retrofitting effort and the maturity of the components, aiming for lower development times and the possibility of having a prototype multi-cylinder engine (MCE) running by early 2025.

To convert diesel engines to natural gas, all major combustion and fuel system components must be updated to support a turbulent flame combustion process. This includes modifications to the engine compression ratio, gas admission system, valve timing, and ignition system, with both passive prechamber (pPC) and active prechamber (aPC) systems being considered. In the case of Methanol (MeOH), the conversion process is in principle less straightforward than for natural gas, as different combustion concepts and specific requirements could be considered. Various alternatives are listed and compared in Table 1. Dual Fuel (DF) concepts ensure a fully diesel backup mode, which is beneficial for customers in case of methanol availability issues. Port Fuel Injection (PFI) architectures require moderate retrofitting efforts compared Direct Injection (DI) systems, where the cylinder head needs to be heavily modified starting from a standard diesel version. Moreover, considering that PFI injection systems are rapidly gaining market acceptance, this solution is particularly attractive for a potential MCE conversion. Dealing with liquid methanol injection, addressing wall wetting phenomena represent a crucial point during the engine design. In PFI systems, methanol film formation on the intake can be mitigated through a careful nozzle design, optimal integration into the intake system, and fine-tuned injection strategies. Considering all these aspects, the PFI-DF engine concept was evaluated as the most advantageous for this project.

Table 1. Comparison of different MeOH engine architectures

	Pros	Cons
PFI Dual Fuel	Limited effort for engine conversion from diesel 100% Diesel backup mode IMO III NOx potential [2]	Performance limited by knocking [2,3] Double fuel system
HP-DI Dual Fuel	High efficiency thanks to diffusive combustion [4] 100% Diesel backup mode	Complexity of cylinder head modification High Pressure Injector and MeOH Fuel lines NOx at IMO III with SCR
PFI Spark Ignition	Limited effort for engine conversion from diesel IMO III NOx potential [5]	No Diesel backup mode Combustion stability at low load
LP-DI Spark Ignition	Higher performance compared to PFI concept IMO III NOx potential	No Diesel backup mode Complexity of cylinder head modification Misfire due to intense MeOH cooling effect and wetting phenomena

The development process of the SCE platform is detailed in the following sections, covering both hardware design for natural gas and methanol, as well as test bench upgrades to safely handle both fuels. Initial results with natural gas are presented, followed by an outlook on upcoming activities and ongoing work for the MCE conversion.

2. SCE DEVELOPMENT METHODOLOGY

This research project was conducted around Isotta Fraschini engine platform called 12V170 (Figure 1), whose main characteristics are shown in Table 1. A single-cylinder laboratory engine of this platform is available at STEMS-CNR in Naples.

Table 1: Isotta Fraschini Motori 12V170 main technical specifications

Characteristics	**Value**
Bore x Stroke	170 x 185 mm
Swept Volume	4.2 L/Cyl
Engine Configuration	12V
Engine Speed	1500 / 1800 RPM
Max BMEP	25.2 bar @ 1500 RPM
Compression Ratio	13.2
Peak Firing Pressure	160 bar

Figure 1: Isotta Fraschini Motori 12V170 engine

The process of converting the diesel SCE to operate with natural gas and methanol was carried out following the guidelines outlined below:

- Hardware Modifications: The power unit, cylinder head, air system, injection, and ignition components were modified (green component in Figure 2). Cylinder block and rotating assembly, as well as valve system was not impacted.

- Minimizing Component Variants: To reduce the number of component variants for natural gas and methanol, solutions capable of operating with both fuels (e.g., camshaft, piston) were defined.

- Design Methodology: design activities were supported by extensive use of Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), and kinematic analysis.

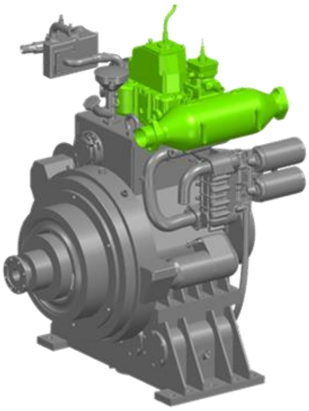


Figure 2: Single-cylinder engine

Overall, the objective was speed-up the development process of the combustion systems, avoid redundancy of components for natural gas and methanol, therefore reducing time and cost of the SCE development. To identify the main hardware changes and possible commonalities between natural gas and methanol components, as first step the main combustion parameters of the two fuels were considered, reported in Table 3.

Table 3: Methane and Methanol combustion properties compared to diesel fuel.

Characteristics	Diesel	Methane	Methanol
Auto Ignition Temp [°C]	205	540	465
RON	low	109	120
Cetane Number	45-55	10	3
LHV [MJ/kg]	42.7	52	20
Flammability Limits [% Vol]	0.6-7.5	4.5-15	3.3 -19
Flame Speed [cm/s]	41.6	43	48
Heat of Vaporization [kJ/kg]	250	510	1100
Stoichiometric Air-Fuel Ratio	14.5	17.2	6.4
Adiabatic Flame Temperature [°C]	2200	1960	1920
Stoichiometric Air per Energy [kg air / MJ]	0.34	0.34	0.31

- Flame Propagation: methane and methanol exhibit similar laminar flame speeds, leading to comparable requirements for in-cylinder turbulence, air motion, and piston top shape, which can be achieved with a common design.

- Knock Resistance: although pure methane features high knock resistance, the composition of natural gas (with methane as the predominant hydrocarbon) can vary significantly, sometimes resulting in a Methane Number (MN) as low as 70 or even lower.

Methanol has lower knock resistance compared to methane, but this is counterbalanced by the strong cooling effect of methanol evaporation, which lowers compression temperatures. This implies similar requirements for the Miller effect and Compression Ratio (CR).

- Valve Timings and Injection System: both fuels are injected into the intake manifold. It is important to control valve overlap to avoid fuel slip into the exhaust and to define fuel valve/injector sizes that can inject the desired fuel amount within a proper angular window [6], optimizing trapping and fuel/air mixing during the intake opening period driven by the desired Miller strategy. Similar design rules were followed for the injection system integration into the manifold and valve timing strategy.

For each subsystem, more details are provided in the following sub-sections.

2.1 Cylinder Head

Starting from a conventional high-swirl cylinder head, a moderate swirl level was targeted as balance between fast combustion with low HC emissions on one side (improved with high swirl) and low heat transfer towards the cylinder wall on the other (better with low swirl). A proper balance was found to be in the range of 0.8 - 1. Intake ports were designed with the aim to introduce a tumble motion, whose dissipation can be used to achieve higher residual turbulence energy at the end of the compression as demonstrated by Figure 3.

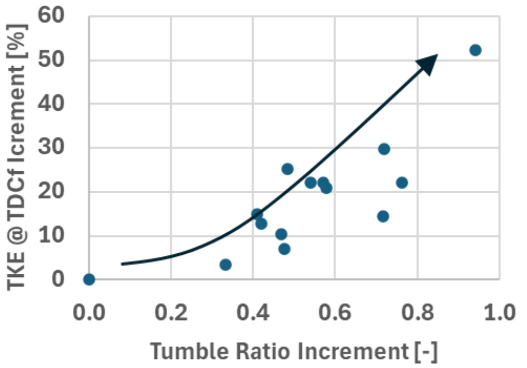


Figure 3: Influence of tumble ratio on TKE production

Figure 4 shows the results of turbulence, swirl and discharge coefficients of the new intake ports. Higher ports permeability was achieved, with similar turbulence levels at TDCf, and swirl ratio reduced to the optimal range.

The water circuit has been optimised considering the geometry of the updated intake ports.

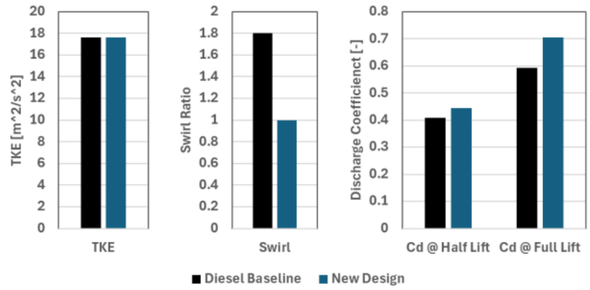


Figure 4: TKE, Swirl and Discharge Coefficients comparison between diesel baseline and new cylinder head

An optimised flow distribution obtained by fine tuning flow passages and shape allowed to increase water velocities in the critical areas of the head, thus obtaining a more uniform temperature distributions and lower risk of thermomechanical fatigue.

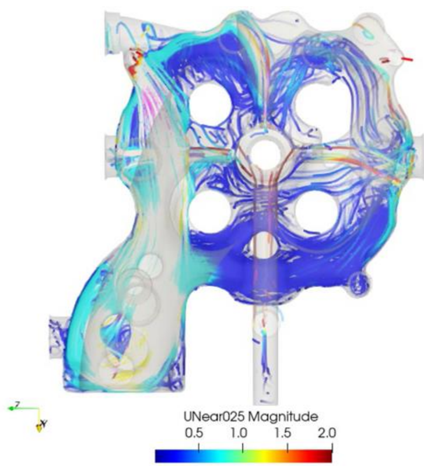


Figure 5: Water jacket updated design

To maintain the same cylinder head design for both natural gas and methanol architectures, a dedicated sleeve for each ignition system was designed. The sleeves share the same outer dimensions, clamping strategy and interfaces with the water circuit, while the inner shape is specifically designed to allow a proper installation of the passive PC, active PC and diesel injector.

2.2 Combustion Systems

The combustion system has been defined through a combined 1D and 3D-CFD analysis. The first step involved a fluid-dynamic optimization of valve timing, targeting higher thermal efficiency, minimizing gas or methanol stagnation in the intake ports, and reducing fuel slip during the valve overlap period. As a result, the overlap period was significantly reduced compared to the original diesel valve strategy, while the Intake Valve Closure (IVC) was advanced compared to the original late IVC. Injection timing and duration were optimized for maximum filling, identifying the correct gas valve size and the appropriate injector size for methanol. In the second step, IVC and Compression Ratio (CR) were further analyzed using GT-SUITE, where a kinetics-based knock model was implemented. To increase robustness to knock when dealing with natural gas, the surrogate selected for the kinetics-based knock model included significant volumes of propane and ethane, resulting in a MN = 70. A constant lambda value of 1.7 with pPC and 2.0 with both aPC and MeOH were considered in this preliminary analysis. These lambda values were tentatively defined as the limit levels for achieving NOx emissions below IMO III standards and ensuring an efficient combustion process. Results are reported in Figure 6, in terms of Brake Thermal Efficiency (BTE), boost pressure, Peak Firing Pressure (PFP) and Knock Induction Time Integral.

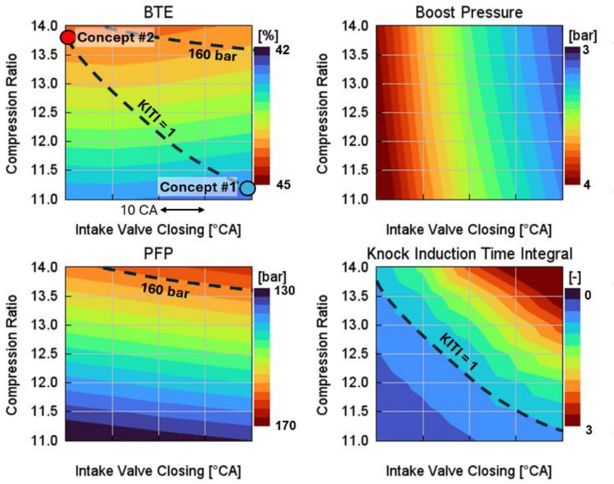


Figure 6. Parametric study of Miller Strategy and Compression Ratio.

Two combustion concepts were identified from this analysis:

1. CR = 11.2 combined with a light Miller strategy: this combination allows to operate with a significant knock margin with reduced boost pressure levels and quite limited maximum pressure levels. Although this concept is not optimized for efficiency, the low boost pressure required, and the low in-cylinder pressure guarantee high power density and excellent transient response when used on a production engine.

2. CR = 13.8 combined with a strong Miller strategy: this combination maintains a similar knock margin while higher efficiency is expected (up to +1.5%) at a cost of higher boost pressure and reduced margin from peak pressure limit.

This optimization was done on natural gas and for the reasons explained above it was verified with methanol. From GT-SUITE analysis, the utilization of high energy share of methanol produces lower temperatures than natural gas operation, therefore a safe knocking margin is expected even running with pilot-ignited methanol with the same combustion system.

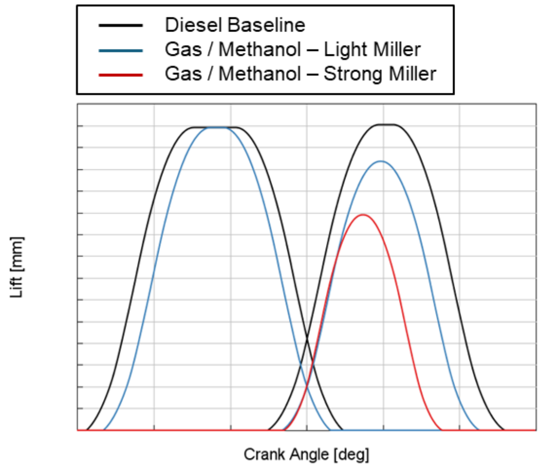


Figure 7. Baseline and updated valve profiles

Two piston designs with different CR were produced. In this perspective, an omega-shape piston design was preferred compared to u-shape since it allows to operate with higher flexibility with both prechamber ignition systems and with pilot fuel when operating with MeOH.

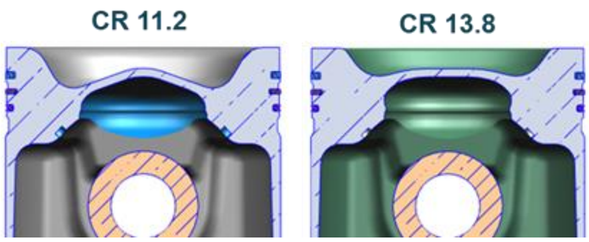


Figure 8. Piston Designs

2.3 Intake Manifold and PFI Fuel System

The intake manifold was designed specifically for gas and methanol. Different alternatives were evaluated with 3D-CFD for both fuels.

2.3.1 Gas Admission System

For natural gas, a suitable gas valve was selected, and a small collecting volume along with a related adduction system to the intake ports was designed and simulated. Several alternatives, as shown in Figure 9, were considered, varying the number of pipes (one or two), diameter, inclination, and type of holes. To evaluate the optimized solution, different indexes were compared, including the mixture uniformity ratio, lambda within the prechamber, and the amount of gas trapped in the crevices.

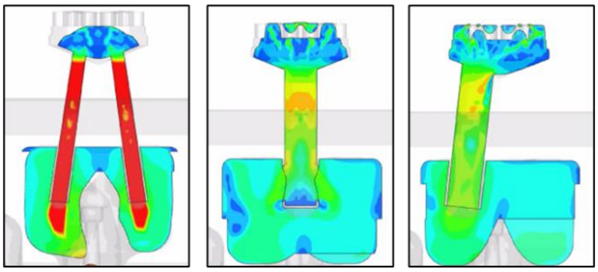


Figure 9: Examples of gas admission systems analyzed with different pipes characteristics.

Results shown in Figure 10 highlight the optimization process undertaken to enhance the design of the gas admission system. Ultimately, a single pipe concept was preferred.

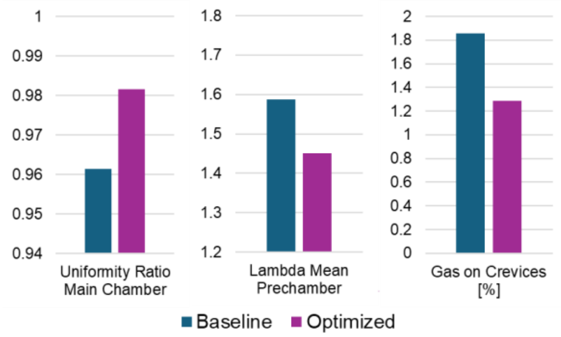


Figure 10: Comparison of Uniformity ratio, PC lambda and gas trapped on crevices for a baseline and the final gas admission concept.

2.3.2 Methanol Injection System

A similar process was applied to the design of the intake manifold for the methanol architecture. Different variants of the MeOH injector nozzle were studied using 3D-CFD analysis, along with various integrations with the intake runner. The main objectives of this development process were to enhance the evaporation of methanol and its mixing with air, while reducing wall wetting. Controlling the film formation in the intake runner and ports was the biggest challenge in this optimization process, as it is a complex phenomenon that cannot be fully captured in a single cycle and requires multiple cycles to achieve convergence. To address this, a multi-cycle simulation methodology was developed and used in this project. An example is shown in Figure 11: the blue parcels represent the wall film of methanol produced during previous cycles, while the colored parcels (parcels with velocity > 0) correspond to the methanol injected in the current engine cycle.

Using this methodology, a flexible manifold concept was designed, where the injector is oriented towards the intake ports, and the distance between the nozzle and the cylinder head can be adjusted by installing an adapter of the desired length between the manifold and the cylinder head.

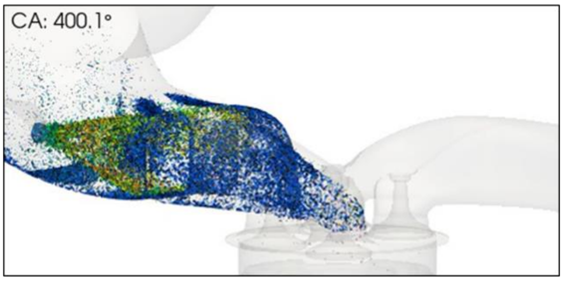


Figure 11: Simulation of methanol injection for two consecutive engine cycles.

With shorter distance between nozzle and cylinder, a reduced MeOH wall film was observed. Moreover, since methanol reaches the intake ports and valves that are at higher temperatures than the intake runner, wall film reaches a convergence in fewer cycle.

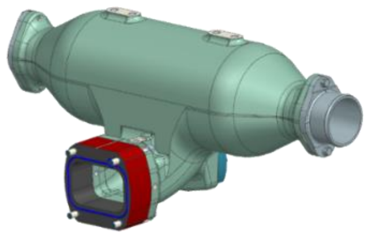


Figure 12: Design of intake manifold adapted for methanol operation.

By increasing the distance and adjusting the injection timing, better mixing is achieved due to the improved interaction with the air. However, this comes at the cost of increased wall film extension and formation time. Figure 13 shows the results for two different installations after four consecutive engine cycles.

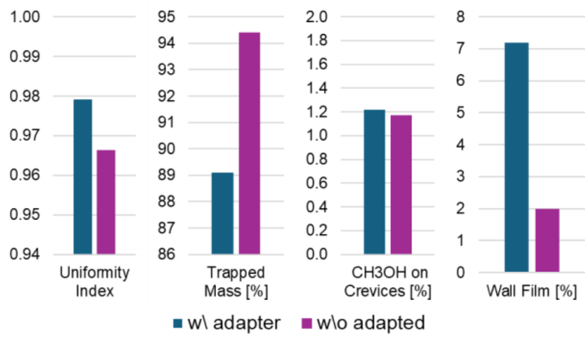


Figure 13: Comparison of uniformity ratio, trapped mass, methanol on crevices and methanol on intake wall film for the two concepts.

2.4 3D-CFD Combustion Analysis

A detailed 3D-CFD combustion analysis was finally conducted on the different combustion systems as verification and possible fine-tuning of the components identified in the previous development steps.

2.4.1 Model development

The first step was the development of a baseline 3D-CFD model for diesel combustion, which was validated with engine data. As shown in Figure 14, there is a good agreement between experimental and simulation results. This validation ensures that the overall methodology accurately captures the pumping loop and heat transfer, both for diesel and when simulating gas and methanol combustion.

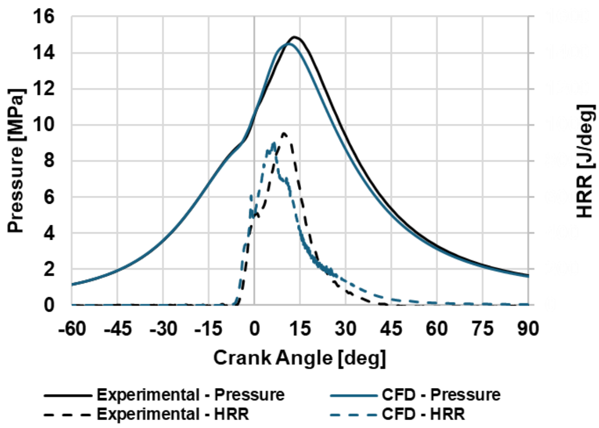


Figure 14: Comparison between experimental and simulated pressure and HRR for diesel engine.

Subsequently, the CFD model was updated to handle the combustion of the alternative fuels [7].

The simulation of the combustion process for natural gas and methanol is managed using models based on the Well-Stirred Reactor (WSR) approach. This method allows for the simulation of combustion by considering chemical kinetics models. Since these models account for the chemical reactions that characterize the oxidation process of the fuels, it is possible to achieve a high-fidelity combustion simulation without the need to calibrate the models with experimental data, which were not available in the design phase. Extensive work was undertaken to select the most appropriate reaction mechanism, including ignition delay and laminar flame speed calculations, and comparison with available experimental data from the literature [8].

2.4.2 Simulation Results

The updated CFD model was used to verify the combustion chamber design produced for gas and methanol SCE architectures. Results, reported in Figure 15, are aligned with the preliminary screening done with GT-SUITE. For the gas combustion systems, both concepts (different combinations of CR and Miller) can operate at knock-free for IMEP up to 23 bar and combustion phasing of 10-12 deg aTDC. The concept with the higher compression ratio is limited by the maximum in-cylinder pressure, while the concept with the lower compression ratio shows quite large margin and it is mainly limited by knocking.

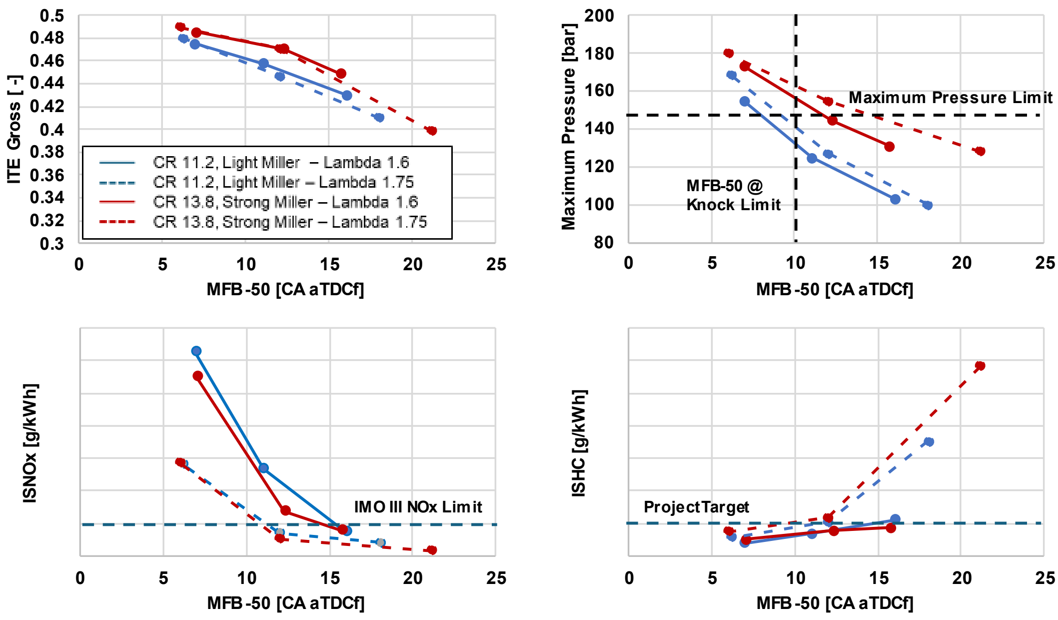


Figure 15: Performance comparison between CR 11.2 and CR 13.8 combustion concepts operating with natural gas evaluated by 3D-CFD analysis.

Lambda is confirmed as the main parameter to control emissions. For both systems, a lambda of about 1.75 is considered a good balance to keep NOx levels lower than IMO III without excessively increasing unburned gas emissions.

The developed model was also used to study different passive prechamber geometries provided by the supplier. A remarkable sensitivity between PC parameters and emissions was found during this analysis. From Figure 16 it is possible to figure out the impact of pPC internal volume and holes angle on the NOx-HC trade-off at high load. pPC configuration with higher volumes (and constant holes area) showed an advantage on HC emissions, while the variation of the jet angle showed a limited sensitivity. In general, pPC internal design can be optimized to speed up the flame propagation toward the squish region, thus providing benefits on wall quenching and HC emissions. Based on this virtual assessment, a down-selection of the most promising pPC configuration to be tested was performed.

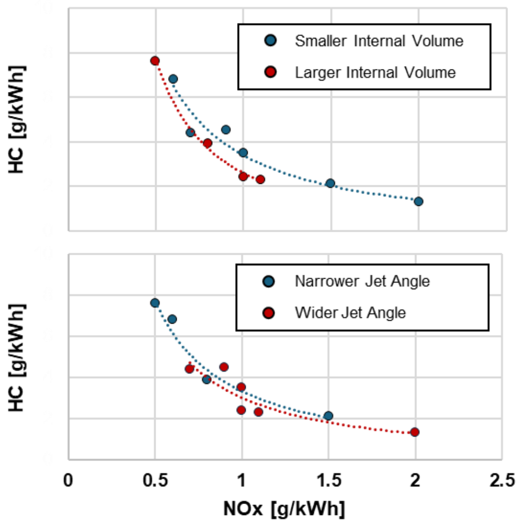


Figure 16: Sensitivity analysis to prechamber internal volume and jet angle simulated by analysis (variation of calibration parameters included in the trade-off).

The developed model was employed to study combustion process also with active prechamber systems and to evaluate the effect of different geometrical parameters. Results with aPC demonstrate the possibility to run with higher dilution rate while maintaining rapid combustion process. As it is possible to observe from Figure 17, combustion duration below 30 deg are obtained with aPC system operating at lambda up to 2.3, while lean operation with pPC needs to be limited to lambda = 1.8 to achieve a similar combustion duration.

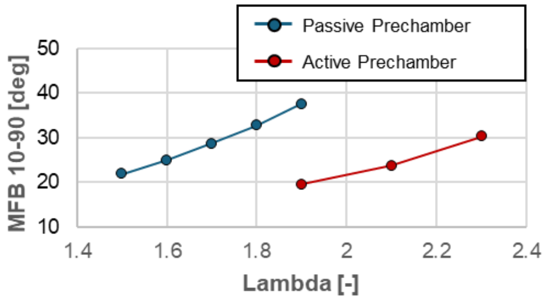


Figure 17: Comparison between pPC and aPC combustion duration (MFB 10-90) evaluated by CFD analysis

CFD combustion analysis were performed for DF methanol combustion. Based on the CFD results, the extreme cooling effect of methanol produced compression temperatures much lower than those obtained with natural gas. Although this was beneficial from a knocking and efficiency perspective, the analysis pointed out a very long ignition delay of the pilot fuel, particularly when working with >95% MeOH energy ratio, which leads to very small pilot quantities that can overdilute in the combustion chamber. For the time being, the Light Miller strategy combined with the baseline diesel piston and the CR 13.8 piston provided best combustion and emissions results. Further investigations are currently ongoing, and both 3D-CFD and GT-SUITE model refinements are planned after the experimental campaign.

As an example, Figure 18 shows the flame propagation process from a few degrees after the pilot autoignition up to almost the end of combustion.

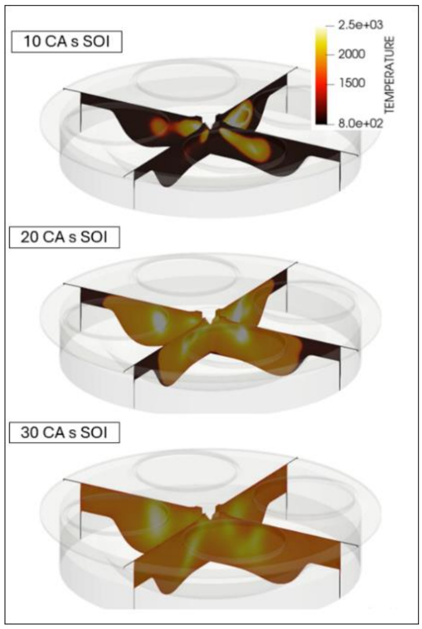


Figure 18: CFD analysis of MeOH combustion concept.

2.4.3 Hardware definition and performance assessment

As conclusions of the SCE development activity, a summary table of the main components designed to test natural gas and methanol is provided in Table 4.

Table 4. Components produced for testing gas and methanol combustion systems

	Natural Gas	MeOH Dual Fuel
Cylinder Head	Common	
Cam Profile	Common – 2 Variants (Light and Strong Miller)	
Piston	Common – 2 Variants (different compression ratio)	
Injection System	Gas Valve	Low Pressure Injector (2 nozzle variants)
Ignition System	Passive and Active PC	Diesel Pilot
Intake Manifold	Gas Specific	MeOH Specific

A final assessment by analysis of the different combustion concepts is proposed in Figure 19.

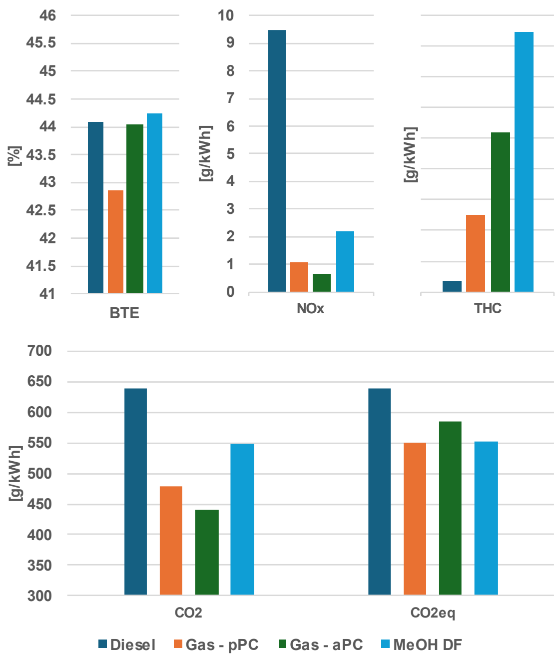


Figure 19: Comparison between diesel, gas (pPC and aPC) and DF methanol performance

From an efficiency standpoint, the passive pPC system exhibits a small gap compared to the other system, mainly due to lower dilution, worse thermodynamic efficiency, and higher heat transfer. In terms of NOx emissions, all the alternative fuel concepts have the potential to reach IMO III levels. Lambda is the key parameter for gas combustion, while the DF methanol system can achieve IMO III NOx levels when operating with a minimum pilot fuel quantity. Regarding Total Hydrocarbons (THC) emissions (CH4 for gas systems and CH3OH for the DF system), there is a strong correlation with lambda, which affects quenching phenomena, and the oxidation of molecules trapped in crevices. Concerning CO2 emissions, the favorable hydrogen-to-carbon ratio of methane combined with the efficiency of the concept represents the optimal solution, with about a 20% reduction compared to diesel. However, when considering an equivalent CO2 calculation, the Global Warming Potential of unburned methane can partially offset this benefit.

3. TEST BENCH CONVERSION AND SETUP

The test bench setup at CNR-STEMS in Naples, originally designed for diesel engines testing, was highly modified to manage spark ignited combustion of natural gas and methanol-diesel dual fuel combustion.

Starting from the first fuel, a schematic layout of natural gas line is reported in Figure 20: natural gas is stored compressed at 200 bar, and pressure is kept at 40 bar. The line connecting the gas from the cylinders storage to engine room is made of AISI 316L stainless steel, cold-drawn and DN=15, with the following safety systems: overpressure valve, ATEX dual-threshold pressure switch, ATEX thermostat for methane use, contact manometer for nitrogen; gas leakage sensors are installed along the entire line. At the engine room entrance, two lines branch out: one high-pressure line (40 bar) and one low-pressure line (16 bar). The first is used for the active pre-chamber system, while the second for the main gas injection into the intake manifold.

Safety systems have been provided to prevent overpressures in case of first-stage regulator failure:

- Pressure switches to stop gas supply if preset values are exceeded.
- Safety valve to release overpressure if the set value is exceeded, with an intervention pressure lower than the system’s test pressure.
- Temperature control of the first stage to prevent adiabatic undercooling of components.

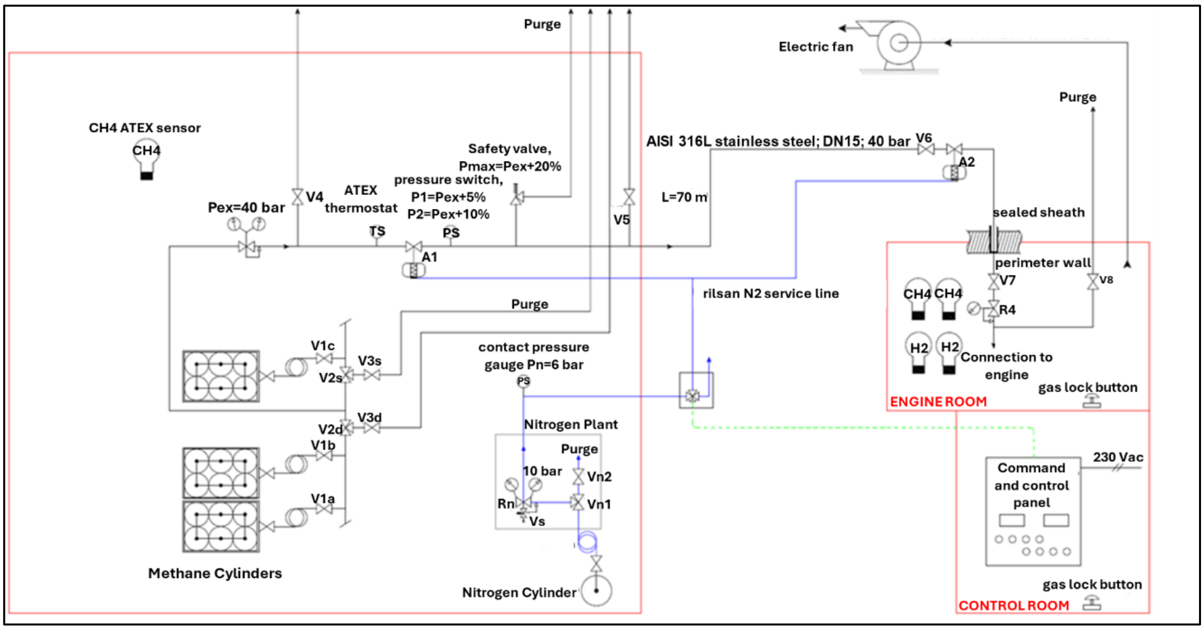


Figure 20: Natural Gas fuel system layout

The methanol supply line system was specifically designed for this project, with a strong emphasis on safety due to the specific properties of methanol:

- Flammability: Methanol has a broad vapor flammability range, which poses a significant fire hazard in the test bench environment.
- Toxicity: Methanol is highly toxic, and concentrations above 200 ppm must be strictly avoided to ensure safety.
- Corrosion: As a polar conductive solvent, methanol can cause severe galvanic corrosion, potentially damaging storage tanks and pipelines. This necessitates careful material selection.
- Hygroscopic Nature: the ability to absorb humidity from the air can increase the overall corrosion rate and reduce the purity and performance of the stored methanol.

The methanol supply system was designed with these considerations in mind. The most critical countermeasures implemented to ensure safe operation are detailed in Table 5, while a schematic layout of the methanol line is reported in Figure 21.

The methanol is stored outdoor, immediately out of the testing room. To reduce the plant size, instead of containment water vessel, double-wall tanks is installed and the cavity between the walls is filled with nitrogen. In this way, the methanol leakages are prevented by means of methanol and oxygen sensors. Nitrogen pressure in the sleeve is controlled by means of contact pressure gauges.

Table 5. Main safety guidelines adopted for MeOH supply system design

Issue	Countermeasure
Broad Vapor Flammability	• Continuous monitoring with detection sensors • ATEX-certified sensors and electrical devices
Corrosion and hygroscopicity	• Use of stainless steel for every system component in contact with methanol • No contact with air humidity (nitrogen adopted)
Toxicity	• Extensive use of detection sensors Forced air ventilation
Methanol Leakages	• Double-wall pipes and double wall pipes • Continuous feeding of tanks with nitrogen (redundant N2 supply lines)

Such a kind of pressure gauge is equipped with a switch contact: these establish, or interrupt circuits based on the pointer position of the indicating measuring instrument. If the reading deviates significantly from a threshold value, they activate an alarm. The sleeve between the tank walls is provided with vent pipes, confined within a fenced area with inert gas flow and continuous monitoring of emitted methanol concentration, along with oxygen sensors to verify inertization. A seal-less, magnetically coupled rotary sliding vane pump provides methanol to engine circuit at a differential pressure up to 13 bar. The return circuit to the tank via a three-way valve and arranged outside the engine room for safety purpose.

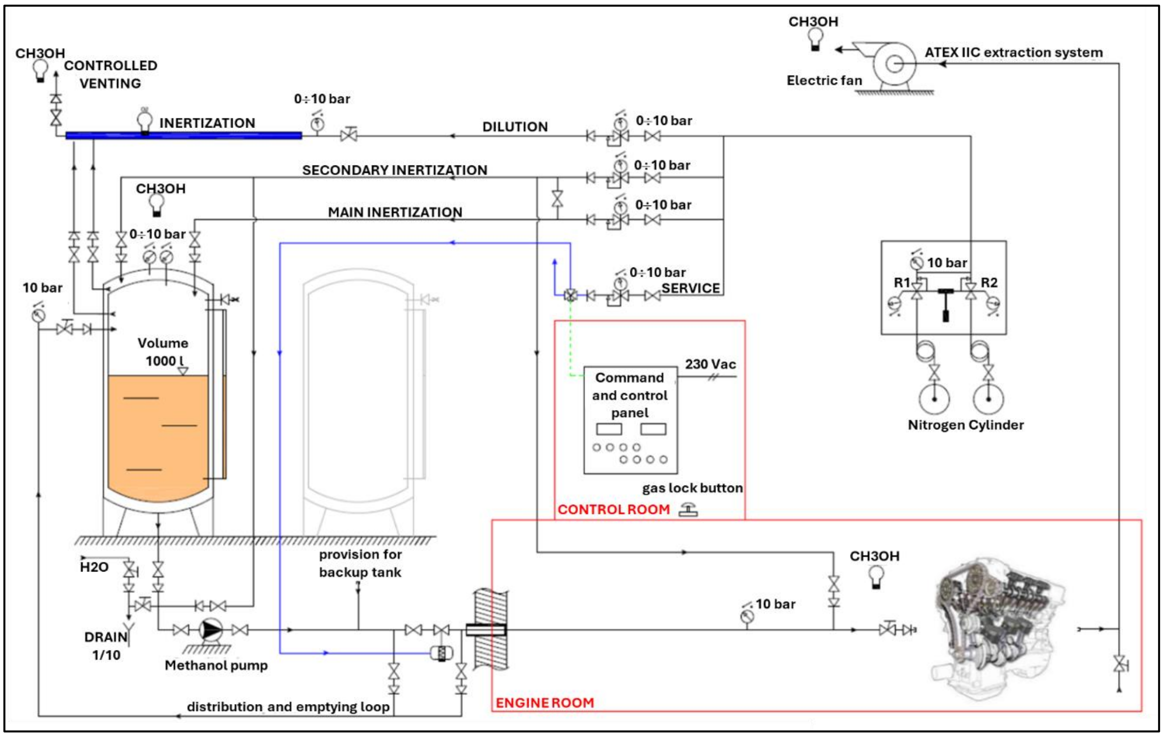


Figure 21: MeOH fuel system layout

The connection piping between the tanks and the engine is made of drawn stainless steel, TIG (Tungsten Inert Gas) welded. Tubes inside the engine room are double-wall with nitrogen pressure-tight counter-tube and control pressure switch. A methanol sensor at the connection to the engine prevents leakages. A sensor system is placed in the engine room and close to control valves. In the event of a pre-alarm from any sensor, the system automatically shuts off the methanol supply outside the test room and activates the extractors to increase air circulation. If an alarm is triggered by any sensor, in addition to halting the methanol flow, the system automatically depressurizes the pressurized tank by venting the nitrogen in the headspace.

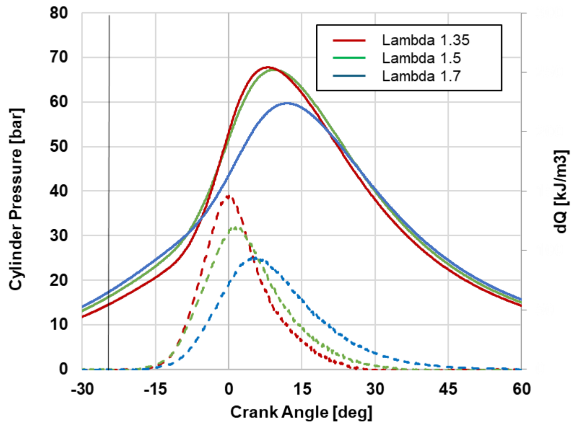
Most of the plant safety systems rely on the presence of nitrogen inerting the sleeve interspace and the counter-tubes, as a dilution fluid for methanol emission through vents and as a service fluid for pneumatic actuators.

Boost pressure is provided by an external volumetric air compressor; air mass flow was monitored by a fan anemometer coupled with an actuator system for the boost regulation. For both gas and methanol configurations, the engine is operated with controlled intake and exhaust pressure: intake pressure is controlled in order to operate with a specified lambda level, while exhaust backpressure is controlled to replicate engine relevant conditions with a turbocharging system. The SCE is equipped with in-cylinder pressure piezoelectric transducer to perform combustion analysis and to control knock and misfire phenomena, as well as thermocouples installed in the cylinder head to monitor metal temperatures. Pollutant emissions (NOx, HC, CO, CO2, smoke) and oxygen in the exhaust are measured with standard gas analyzer systems. An additional FTIR system is employed to evaluate specific molecules like CH4, CH3OH, CH2O.

4. PRELIMINARY RESULTS – PPC GAS COMBUSTION SYSTEM

In this section the first test results with natural gas operating with a passive PC ignition system are presented and discussed. As first concept, low CR and light Miller strategy has been tested. As it is possible to see from Figure 22, a fast and efficient combustion process is obtained with the developed combustion system. CoV IMEP below 1.5% is obtained in a broad range of lambda and combustion phasing. Indicated efficiency of the engine exceeded 45%, slightly higher than values predicted by simulations.

SCE testing activities are currently in progress, and many combustion systems are being characterized experimentally. During the testing phases for natural gas, the main aim is to identify the optimal pre-chamber configuration that produces the best results in terms of combustion stability and emissions within the defined targets. For methanol, the goal of the tests is to exploit the flexibility of the designed engine to maximize the energy share of methanol and achieve the best results in terms of emissions and CO2 reduction compared to diesel.



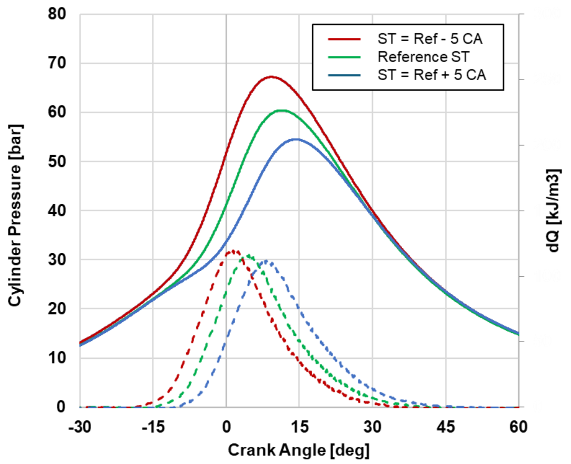


Figure 22: Cycle-average cylinder pressure and heat release rate on 10 bar IMEP operating with natural gas. Lambda variation in the top picture, spark timing variation in the bottom picture.

5. OUTLOOK AND NEXT ACTIVITIES

Considering the satisfactory results shown in the previous section and the significant potential for GHG emissions reduction, natural gas was selected as the fuel for the MCE conversion, adopting the pPC combustion system. Leveraging the experience gained on the SCE and supported by the testing results, the MCE upgrade for natural gas was nearly finalized by Q4 2024, with the first firing planned for Q2 2025. The conversion of the MCE included a substantial update of the combustion system to replicate the concept developed for the SCE, modifications of the charging system to operate in the correct lambda region, including a new turbocharger system, and a revised energy management system developed by DUMAREY to control gas combustion specifically for each cylinder.

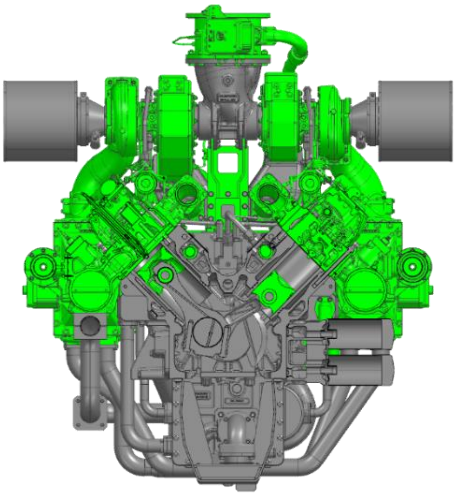


Figure 23: Cross section of the V1712 Isotta Fraschini Motori. Gas-specific updated components highlighted in green.

6. CONCLUSIONS

Driven by the need to reduce anthropogenic GHG, the use of alternative fuels has become a priority in the marine sector, and consequently there is a strong focus on adapting existing engines or developing of new solutions to work with alternative more sustainable fuels.

In this context, the partnership between DUMAREY, CNR-STEMS, and Isotta Fraschini Motori enabled the rapid development of a flexible SCE engine and all the test bench facility to experimentally characterize natural gas and methanol combustion for the V1712 Isotta Fraschini high-speed engine.

Thanks to advanced simulation tools, it was possible to define the design and the requirements of the main engine components. First tests with natural gas highlighted satisfactory results with passive PC ignition system and poses the basis for an MCE conversion to natural gas.

Ongoing testing activities on SCE aim to experimentally evaluate pros and cons of different combustion concepts defined by analysis.

7. DEFINITIONS, ACRONYMS, ABBREVIATIONS

aPC: active Prechamber

BMEP: Brake Mean Effective Pressure

BTE: Brake Thermal Efficiency

CFD: Computational Fluid Dynamics

CR: Compression Ratio

DF: Dual Fuel

DI: Direct Injection

FEA: Finite Element Analysis

GHG: Greenhouse Gases

HC: Unburned Hydrocarbons

HP: High Pressure

HRR: Heat Release Rate

IMEP: Indicated Mean Effective Pressure

IMO: International Maritime Organization

IVC: Intake Valve Closure

LHV: Lower Heating Value

LP: Low Pressure

MCE: Multi-Cylinder Engine

MFB-50: Crank Angle at 50% Fuel Burned

MFB-1090: Crank Angle Interval between 10% and 90% Fuel Burned

MN: Methane Number

NOx: Nitrogen Oxides

PFI: Port Fuel Injection

PFP: Peak Firing Pressure

pPC: passive Prechamber

SCE: Single Cylinder Engine

SOI: Start of Injection

TDC: Top Dead Center

TKE: Turbulence Kinetic Energy

8. ACKNOWLEDGMENTS

The Authors acknowledge the support of Large Bore Project funded by Italian Minister of Enterprises & Made in Italy (FCS programme).

The authors would like to thank all the colleagues within DUMAREY Automotive Italia S.p.A., CNR-STEMS and Isotta Fraschini Motori S.p.A for the valuable contribution to the research activity presented in this paper. Special recognition is extended to L. Buzzi, A. Grosso, M. Luci, P. Pagliaro, G. Gallo, A. Zingariello, F. Numidi, V. Rescina, L. Casale, G. Falanga and E. Baietto for their significant contribution.

9. REFERENCES AND BIBLIOGRAPHY

[1] 2023 IMO Strategy on Reduction of GHG Emissions from Ships (https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx)

[2] Auer M., Kunkel C., et al. MAN Energy Solutions – Four-stroke engine solutions for low-carbon and carbon-free fuels. 30th CIMAC World Congress, Busan, Korea, 2023

[3] Coulier, J., Verhelst, S. (2016). Using alcohol fuels in dual fuel operation of compression ignition engines: a review. 28th CIMAC World Congress, Helsinki, Finland, 2016.

[4] Repo J., Axelsson M, et al. Methanol combustion concept alternatives for new build and retrofit of 4-stroke medium speed engines. 30th CIMAC World Congress, Busan, Korea, 2023

[5] Güdden, A., Pischinger, S., Geiger, J., Heuser, B., & Müther, M. (2021). An experimental study on methanol as a fuel in large bore high speed engine applications–Port fuel injected spark ignited combustion. Fuel, 303, 121292.

[6] Park H., Lee YS, et al. Methane emission reduction technologies for medium-speed dual fuel engines. 30th CIMAC World Congress, Busan, Korea, 2023

[7] Luci, M. Virtual Design of Low-Carbon Fuels Combustion Systems for a Large Bore Marine Engine. CONVERGE Applications Workshop: Solutions for Low-Carbon Transportation. Turin, Italy. 2024.

[8] Zanatta M., Piano A., Millo F., Accurso F., et al. Numerical investigation of the combustion process on prechamber systems for high-speed large bore gas engines. CO2 Reduction for Transportation Systems Conference. Turin, Italy. 2024.