



Further Evolution of an Ammonia Fuelled Range Extender for Hybrid Vehicles

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With the support of the Tuscany Region (ITALY), a partnership of Research and Industry entities has developed a:

***RANGE EXTENDED HYBRID ELECTRIC VEHICLE EQUIPPED WITH AN
INTERNAL COMBUSTION ENGINE FUELLED WITH AMMONIA AND
HYDROGEN.***



THA AMMONIA-HYDROGEN ENGINE PROJECT

Ammonia can be used as a primary fuel in either spark-ignition (SI) or compression-ignition (CI) engines. However, due to low flame temperature, low laminar burning velocity, high ignition energy and narrow flammability limits, ***it is necessary to couple ammonia with other fuels used as combustion promoters.***

Among them, **HYDROGEN** is the best one, since it's carbon free and displays opposite and complementary combustion characteristics to ammonia.

Moreover, hydrogen can be produced directly from ammonia thanks to appropriate catalytic converters.

WITHIN THE PRESENT PROJECT, AN INNOVATIVE ICE FUELLED WITH AMMONIA AND HYDROGEN HAS BEEN DEVELOPED, WHERE THE NECESSARY AMOUNT OF HYDROGEN FOR CORRECT ENGINE RUNNING IS PRODUCED ON BOARD, THANKS TO A CUSTOM-MADE AMMONIA CATALYTIC REACTOR.

AMMONIA REACTOR FOR HYDROGEN PRODUCTION

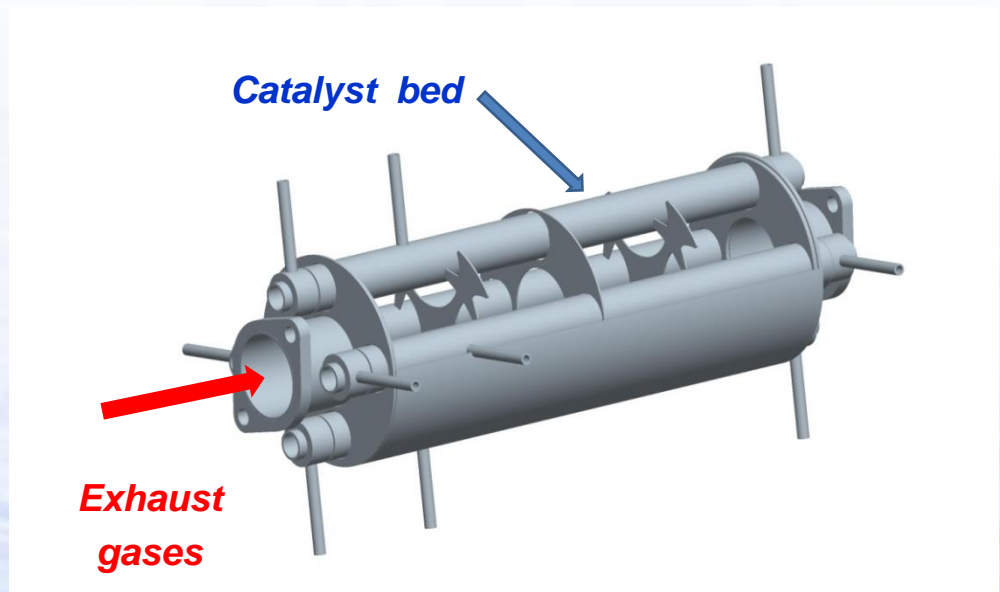
The catalyst (10 wt % RuCs/Al₂O₃) is formed in spheres of 0.6 mm diameter. Based on the catalytic activity data, the catalyst bed has a volume of 0.18 L. The ammonia decomposition reaction is carried out at 500°C.

The catalyst is placed in four beds (chambers), each alimented separately, to reduce the pressure drop (measured with this configuration: ~ 0.46 bar) and to allow the proper heat exchange through the reactor walls.

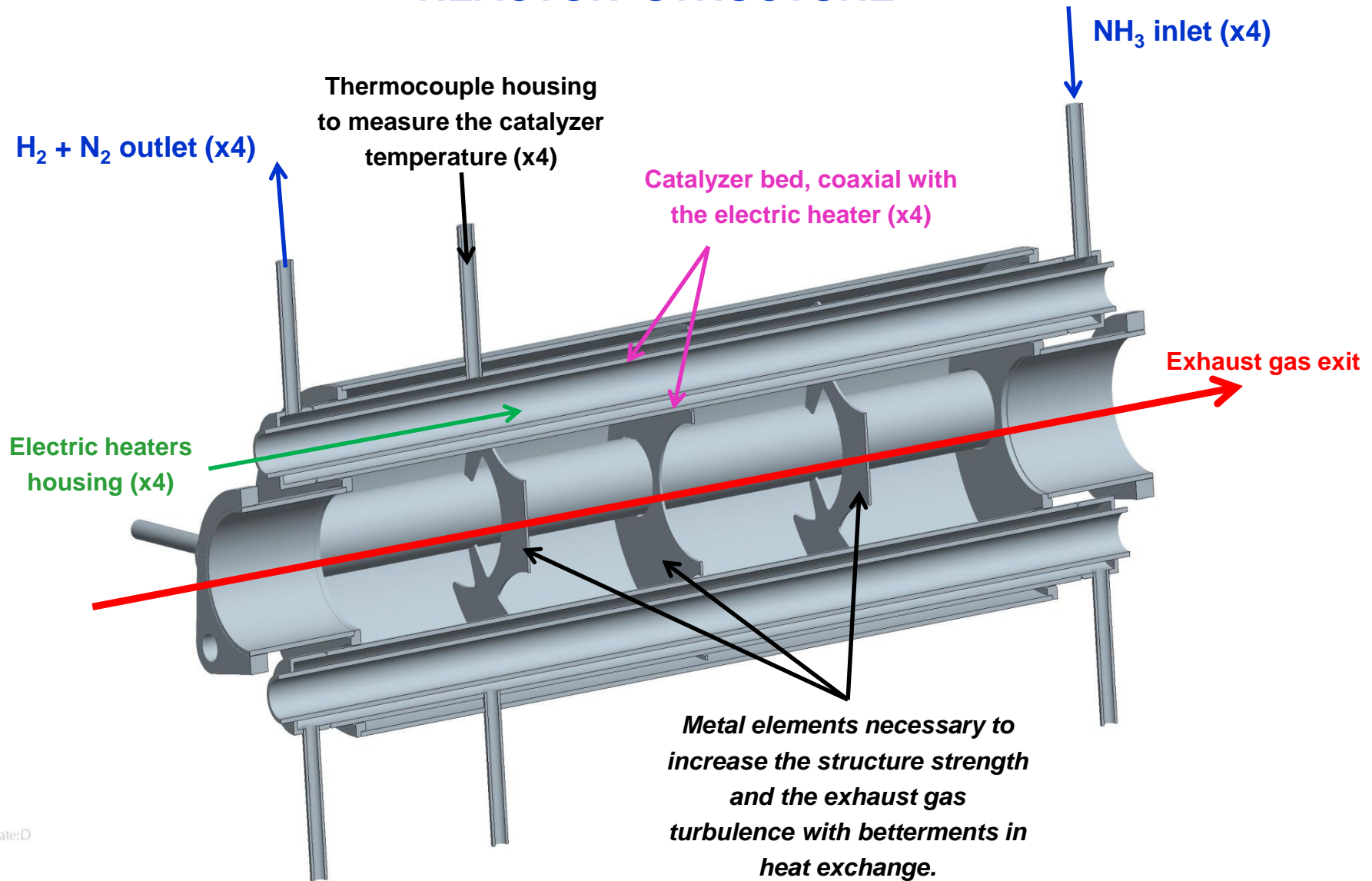
Each catalyst bed has internally an electric heater (opportunely separated from the gas stream) which is able to provide 500 W.

The four catalyst chambers are displaced opportunely in an external room into which the engine exhaust gases flow.

Each catalyst bed is equipped with a thermocouple in order to monitor and control the catalytic process.

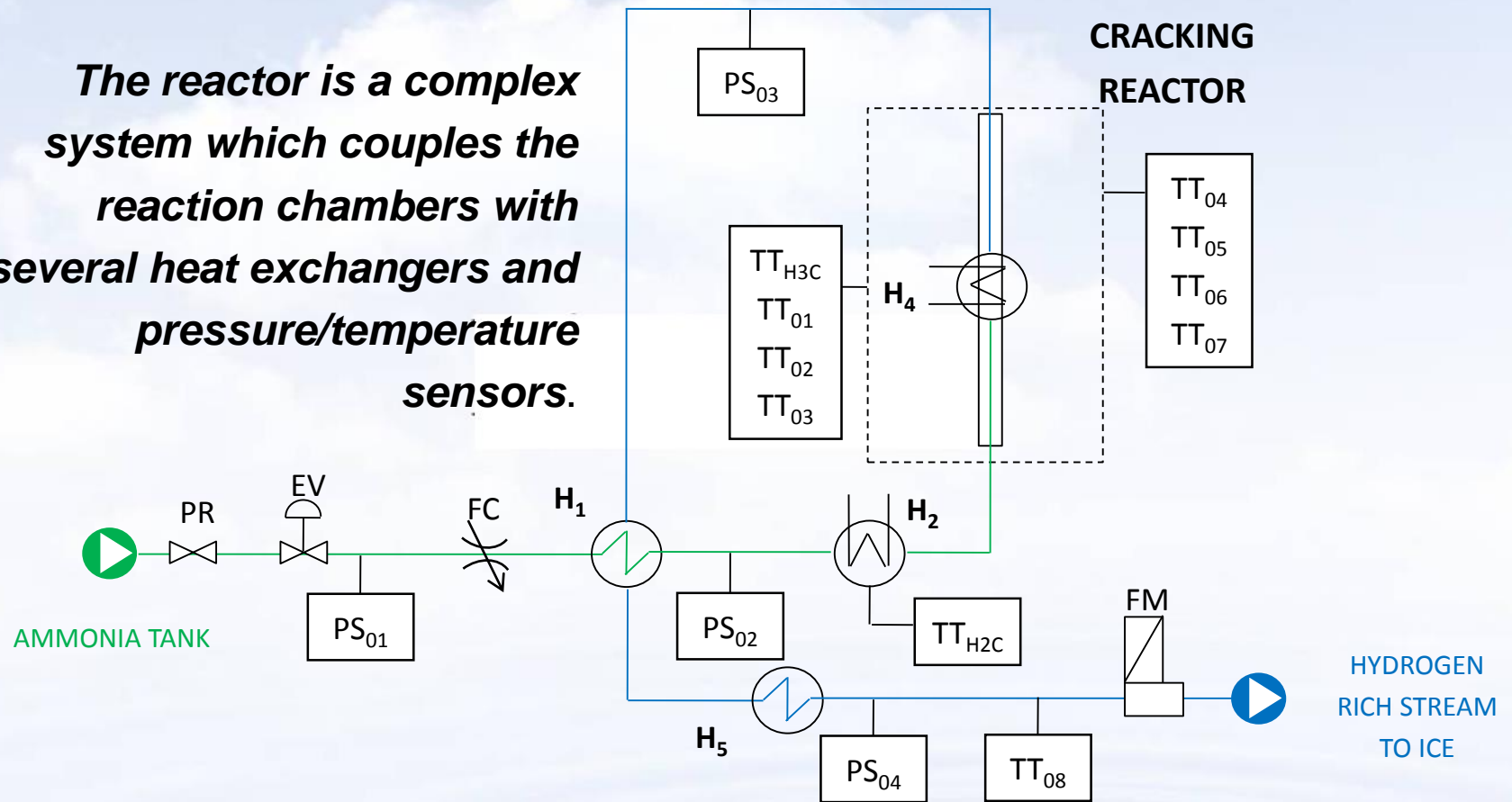


REACTOR STRUCTURE



HYDROGEN PRODUCTION SYSTEM LAY-OUT

The reactor is a complex system which couples the reaction chambers with several heat exchangers and pressure/temperature sensors.



PR: Pressure reducer
FM: Flow meter
EV: Solenoid valve
PS: Pressure sensor
FC: Ammonia injector

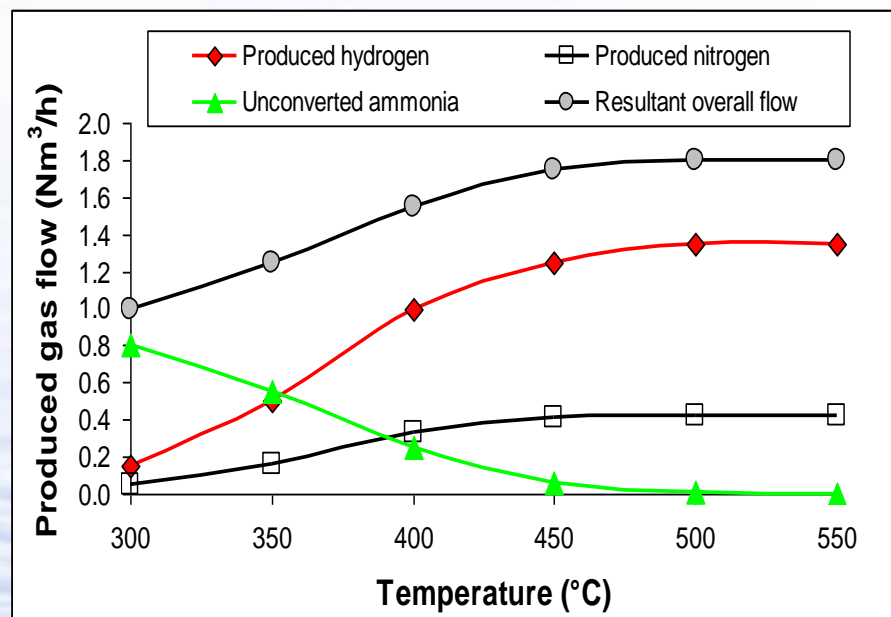
H₁: Ammonia pre-heater for steady-state operation
H₂: Ammonia electric pre-heater for start-up
TT: Temperature sensor
H₄: Reactor electric heater for start-up
H₅: H₂/N₂ mixture cooler

REACTOR PERFORMANCE ON THE TEST BENCH

Before being coupled to the engine, the performance of the catalytic reactor was verified and set by experimental tests.

Taking into consideration the engine needs, verified separately in a dedicated test bench, the ammonia feeding line pressure was set at 2,5 bar, while the hydrogen-nitrogen pressure at the exit was maintained at 0.4 bar.

Ammonia conversion proved to be almost complete even at as low reformer temperature as 450°C, allowing security margin in case of exhaust gas temperature fluctuations.



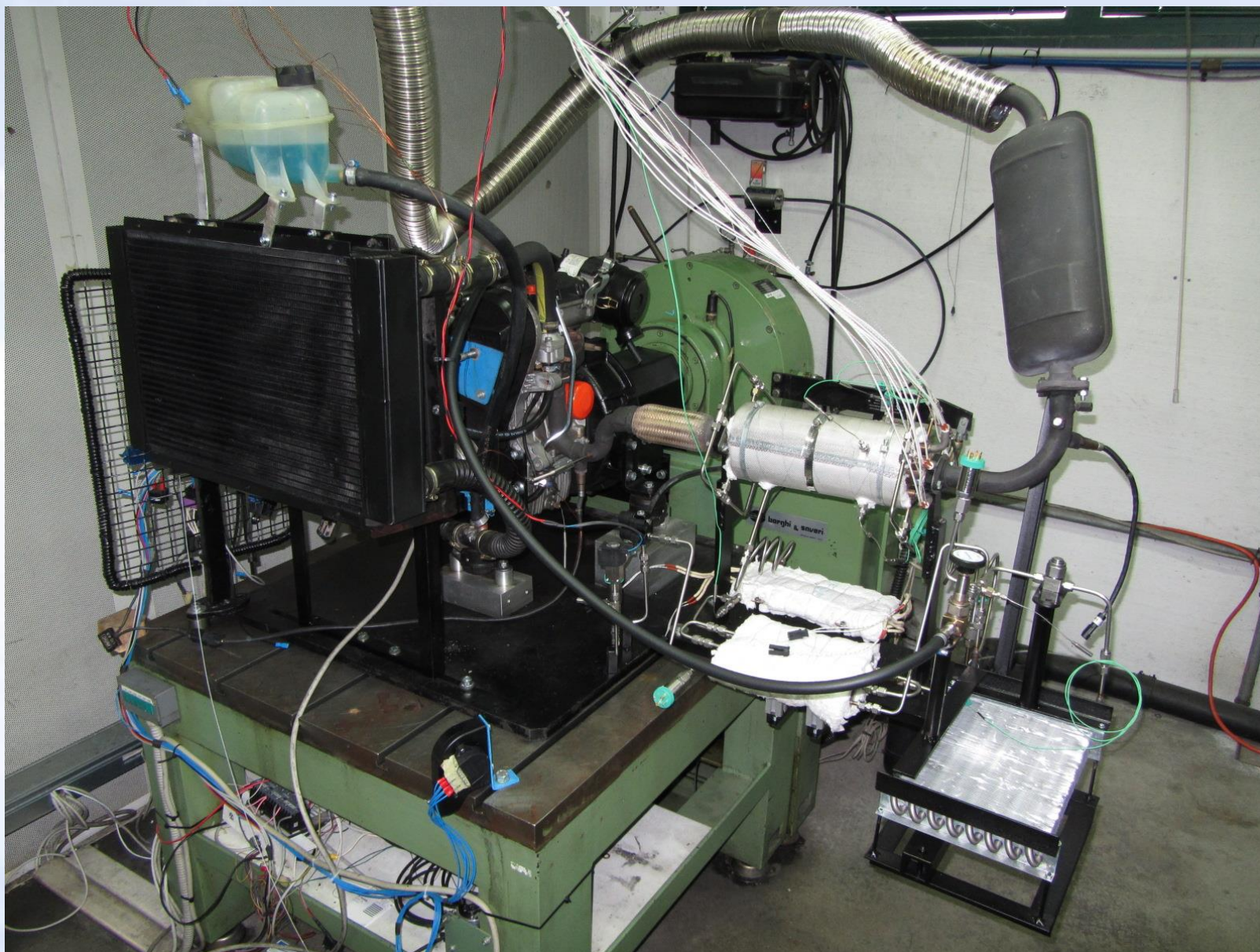
AMMONIA-HYDROGEN FUELLED ENGINE

Taking advantage from previous experimental experiences, an experimental engine, based on a 505 cm³ Lombardini twin-cylinder SI engine, was located on the test bench and coupled with the innovative ammonia catalytic reactor for hydrogen production on board.

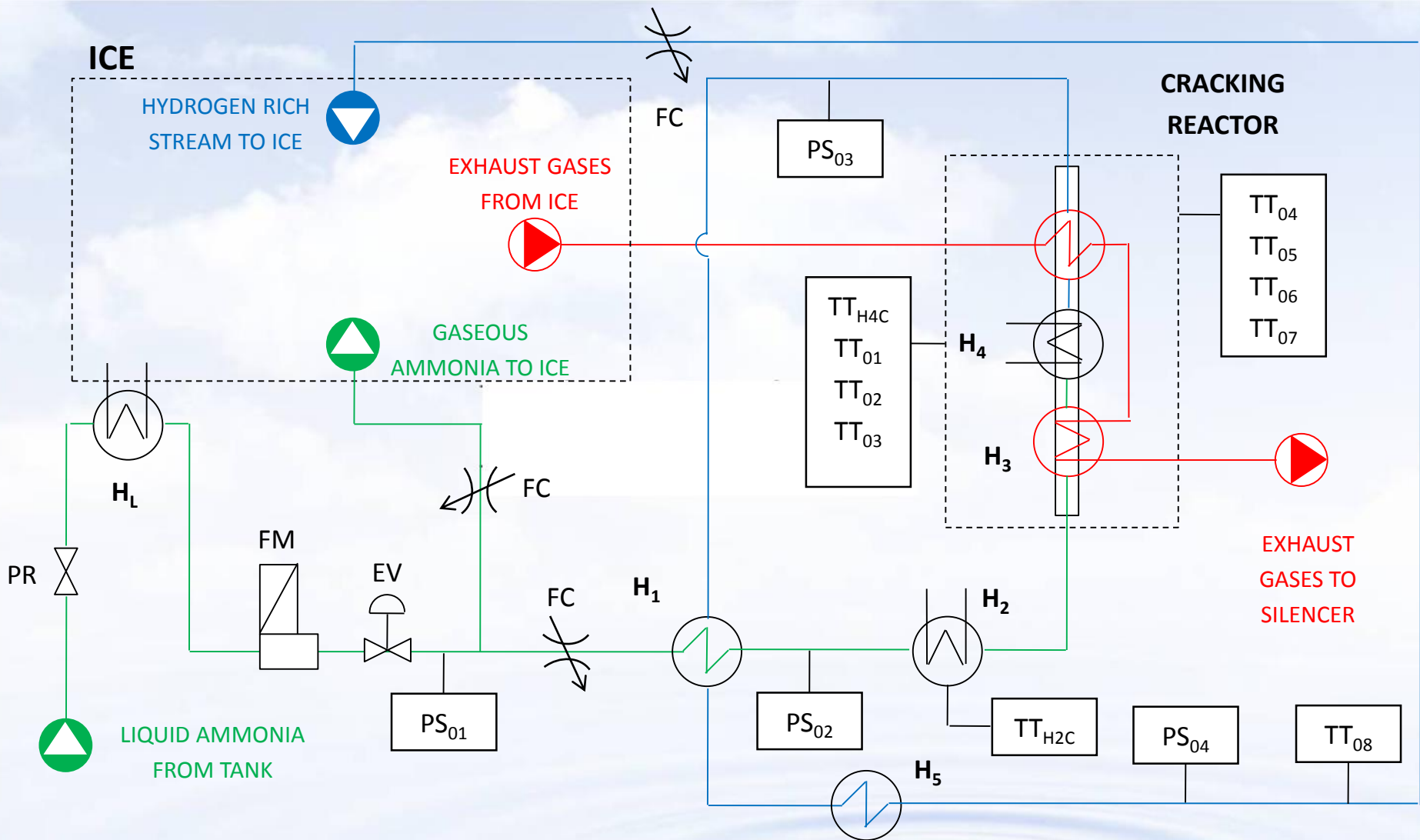
The engine did not undergo any particular mechanical modification compared to the original gasoline version. Only the intake manifold was modified, to inject hydrogen and ammonia in the gaseous phase by electro-injectors added to the original ones for gasoline.



Model	Lombardini <i>LGW 523 MPI</i>
Displacement	505 cm ³
Stroke	62 mm
Bore	72 mm
Compression ratio	10.7:1
Cooling system	water cooled
Valves	2 per cylinder
Max power (gasoline)	21 kW @ 6000 rpm
Max torque (gasoline)	39 Nm @ 2200 rpm
Engine velocity at idle	1100 rpm
Mass	49 kg



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PR: Pressure reducer

H_L : Ammonia vaporizer

FM: Ammonia flow meter

EV: Solenoid valve

PS: Pressure sensor

FC: Ammonia – Hydrogen injectors

H_1 : Ammonia pre-heater for steady state operation

H_2 : Ammonia electric pre-heater for start-up

TT: Temperature sensor

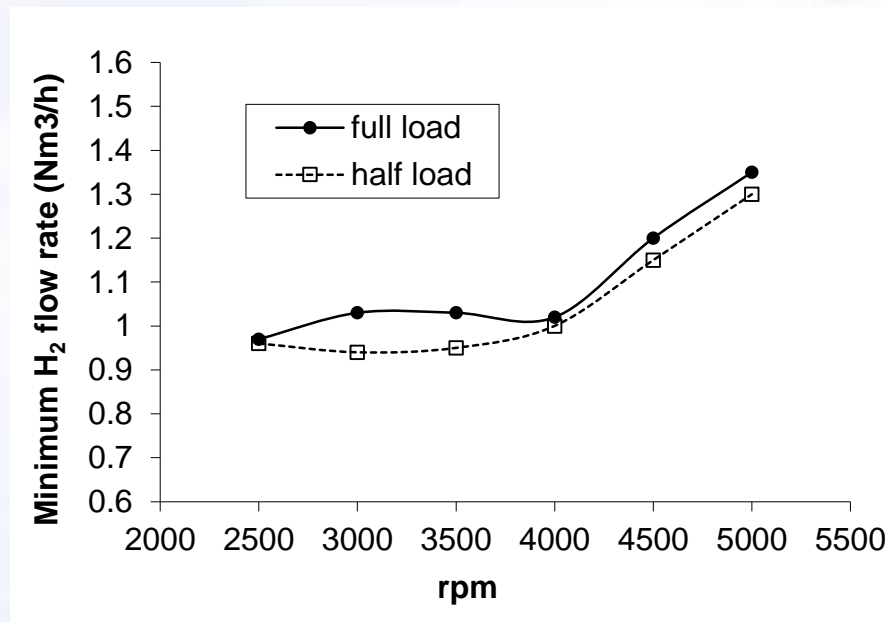
H_3 : Ammonia exhaust gas heater

H_4 : Reactor electric heater for start-up

H_5 : H₂/N₂ mixture cooler

In the previous experimental campaign the possibility to operate the engine with a mixture of air, ammonia and hydrogen was verified.

During that campaign the engine was fed with ammonia and hydrogen coming from tanks and the experimental activity was focused on determining, at different engine speeds and loads, the ***minimum amount of hydrogen to keep the engine cyclic variation at an acceptable level*** ($COV_{imep} < 10\%$).



THE RESULTS SHOWN HEREAFTER ARE RELATED TO THE ENGINE COUPLED WITH THE CATALYTIC REACTOR ON THE TEST BENCH

REACTOR CONTROL LOGIC

Coupling the reactor with the engine requires a specific control strategy.

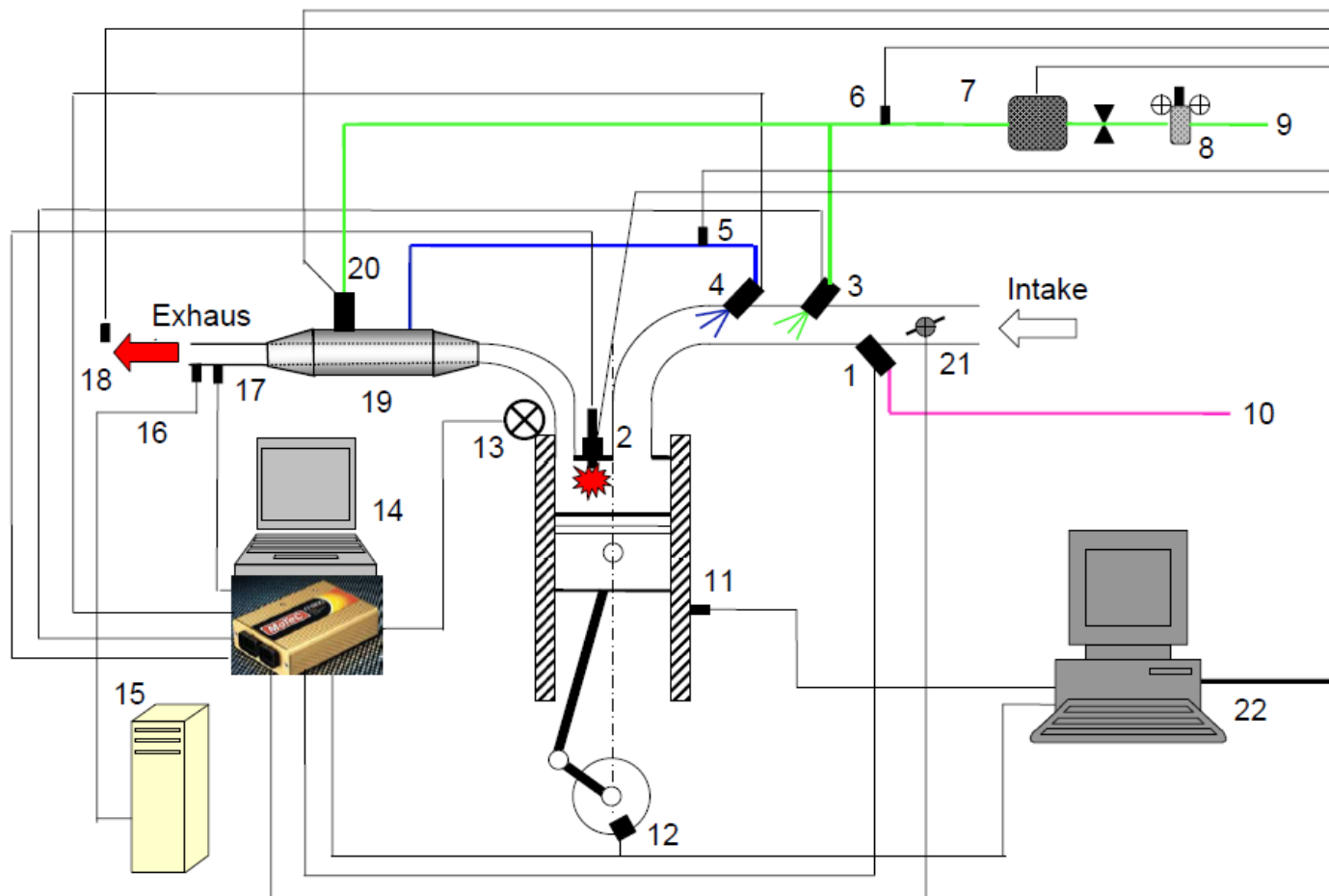
On the one hand the engine needs a minimum amount of hydrogen that changes varying speed and load while, on the other hand, reactor operation is eased if it works at steady state.

In the present case (range extended vehicle) the control strategy is eased since the engine drives an electric generator to recharge the batteries and does not operate on a wide range of rpm and loads.

Accordingly, it was decided to operate the reactor at steady state, always keeping constant the inlet (ammonia) and exit (hydrogen) flow rates and pressures.

As a matter of fact, the engine is fed with all the hydrogen produced by the reactor ($\sim 1.35 \text{ Nm}^3/\text{h}$), which is more than the minimum required ($\sim 1 \text{ Nm}^3/\text{h}$), with benefits for the combustion process.

To manage this strategy, a pressure sensor is located in the hydrogen feeding line and its signal is processed by the ECU, which varies the hydrogen injector opening time in order to keep the feeding line pressure at 0.4 bar.



1) Original gasoline injector; 2) Spark plug with integrated cylinder pressure sensor; 3) Ammonia injector; 4) Hydrogen injector; 5) Hydrogen feeding line pressure sensor; 6) Ammonia feeding line pressure sensor; 7) Ammonia thermal flow meter; 8) Ammonia feeding line pressure regulator; 9) Ammonia line from the tank; 10) Gasoline feeding line; 11) Water and oil temperature sensors; 12) Optical encoder; 13) Magnetic sensor for injection and ignition timings; 14) ECU for injection and ignition control; 15) Chemiluminescence NO_x analyzer; 16) Exhaust gas probe, 17) Exhaust gas oxygen sensor (UEGO); 18) Ammonia threshold sensor; 19) Catalytic reactor; 20) Ammonia injector to regulate the flow into the reactor; 21) Motorized throttle valve; 22) Data acquisition and processing system.

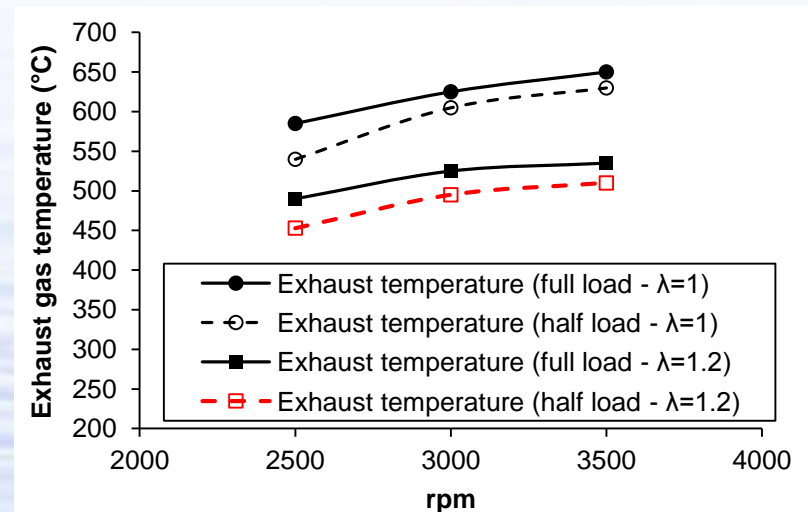
ENGINE PERFORMANCE

The second experimental campaign was limited to the operating conditions of the engine and the reactor on the range extended vehicle, which means from 2500 to 3500 rpm and from 50 % to 100 % of maximum load.

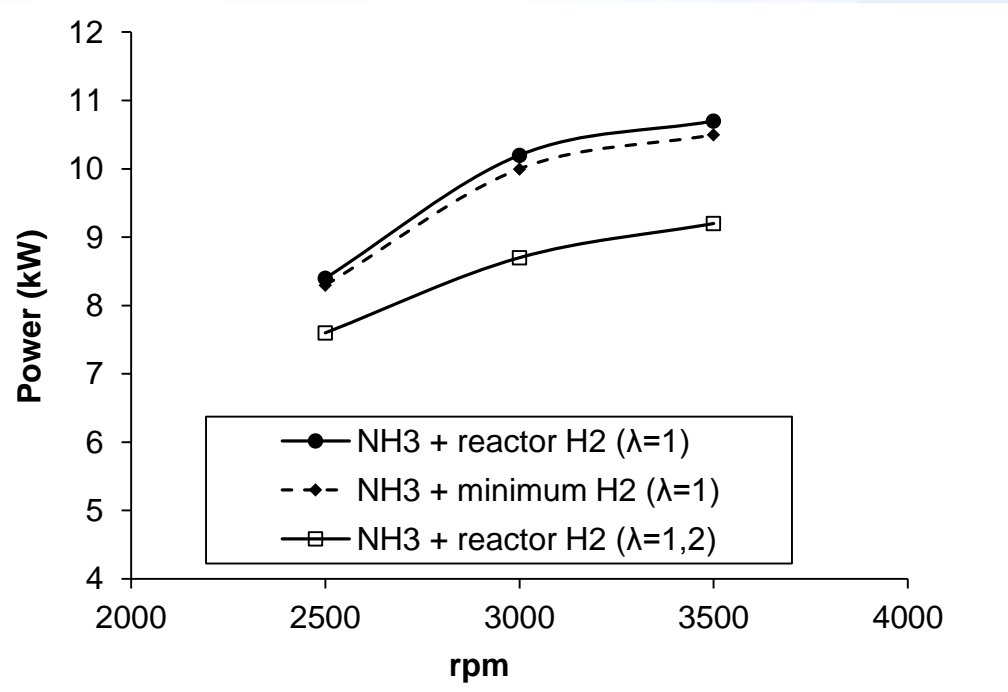
In agreement with the aforementioned conditions, hydrogen flow rate was kept constant at $\sim 1.35 \text{ Nm}^3/\text{h}$ (therefore the amount of hydrogen injected per cycle changed with engine speed) and engine power was regulated only varying the amount of ammonia injected. Ignition timing was set at MBT.

Two global air/fuel relative ratios (λ) were tested: 1 and 1.2. The last value was chosen to be wholly sure of unburned ammonia absence at the exhaust of the engine placed on the hybrid vehicle, since a stoichiometric mixture might not guarantee complete ammonia burning in every engine operating condition, e.g. during transients.

As a matter of fact, ***$\lambda=1.2$ represents the upper limit of air/fuel ratio to obtain, at the lowest rpm and load, the necessary exhaust gas temperature ($\sim 450 \text{ }^\circ\text{C}$) for correct reactor operation.***

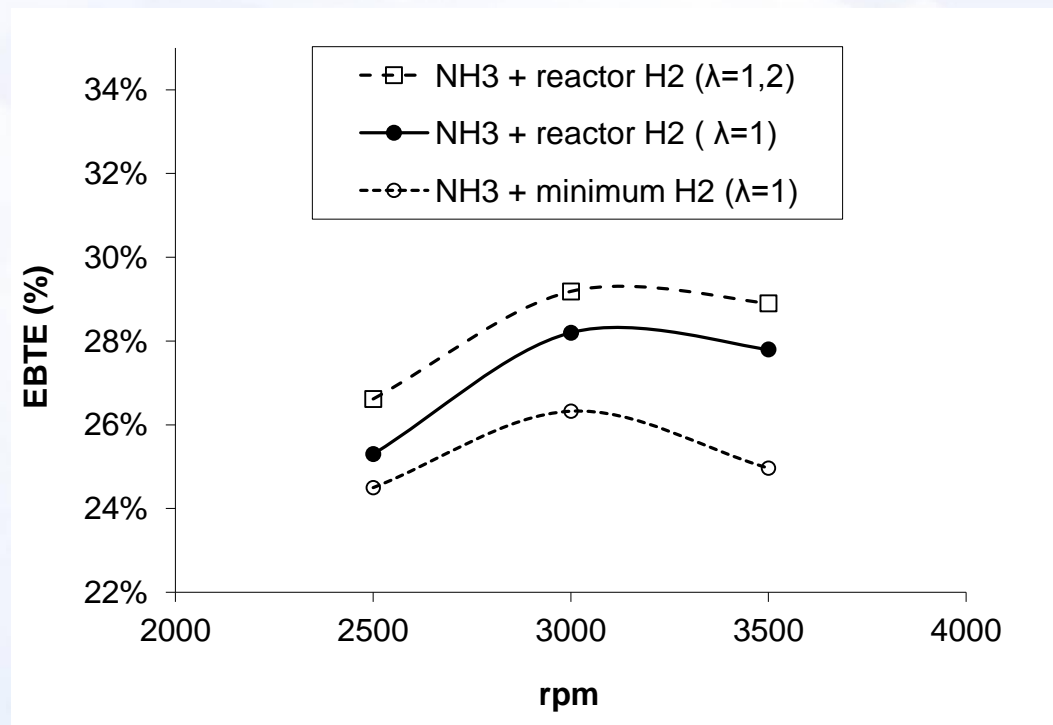


Results obtained using the hydrogen from the reactor are compared with those obtained during the previous experimental activity using the minimum amounts of hydrogen for correct engine running.

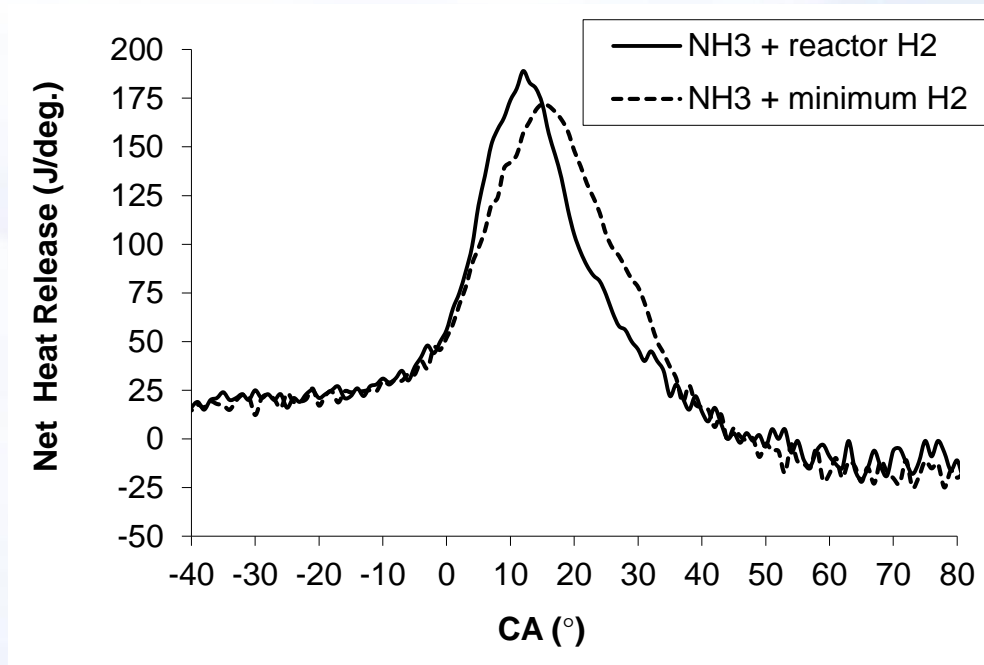


Results are quite similar, with ***a slight increase in engine power in the case of reactor hydrogen***, especially at high rpm. This is due to the increase in the amount of hydrogen injected which leads to higher combustion velocity and hence to a smaller combustion angle that improves engine efficiency and power (lower *heat loss through cylinder walls* and higher residual expansion).

As expected, **engine brake thermal efficiency (EBTE)** at full load increases increasing the amount of hydrogen injected (faster combustion) and using the lean mixture (lower combustion temperature with consequent less heat loss from the cylinder walls).

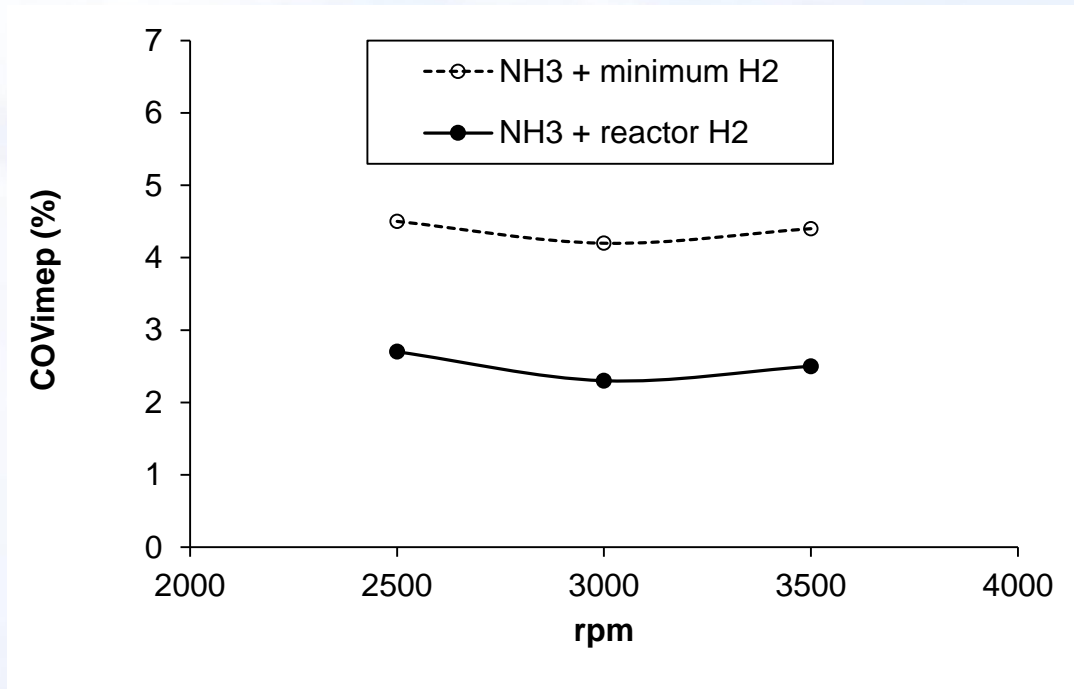


The increase of combustion velocity due to the larger hydrogen flow rate produced by the reactor is confirmed by the **heat release rate ($dQ/d\theta$)** at full load, $\lambda=1$, 3000 rpm, (ignition timing is kept constant).



The heat release rate curve with ammonia plus the reactor hydrogen is sharper and its peak is in advance with respect to the one obtained using the minimum hydrogen..

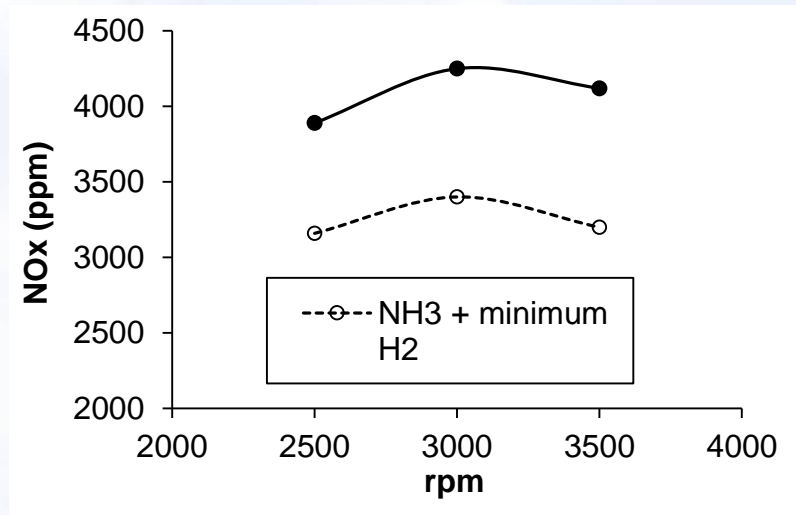
The figure compares at different rpm, the *coefficient of variation of the indicated mean effective pressure (COV_{imep})* obtained using ammonia plus the minimum hydrogen and plus the reactor hydrogen, at full load and $\lambda=1$.



The larger amount of hydrogen coming from the reactor leads to betterments in engine cyclic variability.

NO_x is the only meaningful pollutant in the exhaust emissions (unburned hydrocarbons from lubricant are negligible).

The presence of ammonia in the exhaust gasses was not measured quantitatively but only checked by a threshold sensor [alarm set at 100 ppm], the same adopted on the range extended vehicle.



The graph shows that the larger hydrogen flow rate coming from the reactor leads to an increase in NO_x emission due to combustion velocity increase with consequent higher pressure and temperature peaks.

However, NO_x emission is not a problem, since, in the case of stoichiometric mixture, NO_x can be abated by a reducing catalyst and, in the case of lean mixture, the use of a SCR is eased by the presence of ammonia onboard..

ENGINE BEHAVIOUR AT COLD START

The aforementioned feeding strategy must be changed for engine cold start.

The hydrogen flow rate produced by the reactor, determined in the previous research activity, is not enough for correct engine running at cold start, so additional hydrogen must be supplied.

At present, as a provisional solution, the additional hydrogen is provided by a small tank of compressed hydrogen.

H ₂ flow rate	2.6 Nm ³ /h
H ₂ feeding line relative pressure	0.4 bar
NH ₃ flow rate	0.54 Nm ³ /h
NH ₃ feeding line relative pressure	2.5 bar
H ₂ /NH ₃ ratio (by energy)	360 %

Other solutions are under study, such as a dedicated hydrogen storing system that is recharged during the normal engine operation, as well as systems to reduce the needed amount of hydrogen, e.g. an increased engine compression ratios, or unconventional ignition systems.

SUMMARY AND CONCLUSIONS 1/2

- ***A research activity was carried on by the University of Pisa and other industrial partners of the Tuscany region, proving the feasibility of fuelling a SI ICE with ammonia and hydrogen obtained by ammonia catalytic conversion.***
- A Lombardini 505 cm³ twin-cylinder SI engine, implemented with injection systems for ammonia and for hydrogen, was employed for the experimentation, together with a ***catalytic reactor (designed and built within the project)***, where the energy for ammonia conversion is provided by the exhaust gases of engine.
- The engine experimental activity confirmed the reactor performance, previously verified on a dedicated test bench. ***The hydrogen flow rate supplied by the reactor is larger than the minimum amount necessary for correct engine running, with benefits for fuel economy and engine cyclic variability.***
- ***NO_x emissions are penalized by the larger hydrogen amount since it leads to higher combustion temperatures.*** However, NO_x emissions are not a problem since technologies for their abatement are currently available.

SUMMARY AND CONCLUSIONS 2/2

- ***Ammonia slip at the exhaust was monitored by a threshold sensor***, set at 100 ppm, which did not give any alarm during the experimentation, proving suitable ammonia combustion.
- ***The amount of hydrogen produced by the reactor is not enough for engine cold start.*** To solve this problem, avoiding the use of other fuels except ammonia, some solutions are under study, such as a hydrogen storing system to be recharged during the normal engine operation, as well as systems aimed at reducing the necessary amount of hydrogen, for example an increased engine compression ratio, or an unconventional ignition system.
- ***No meaningful mechanical inconvenience occurred during the described experimental activity***, except structural failures of the reactor that were solved improving the reactor design. Nevertheless, long-time reliability of the injection systems for ammonia and for hydrogen, as well as of the reactor and of the whole engine has to be verified.



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