



A HYBRID VEHICLE POWERED BY AMMONIA AND HYDROGEN

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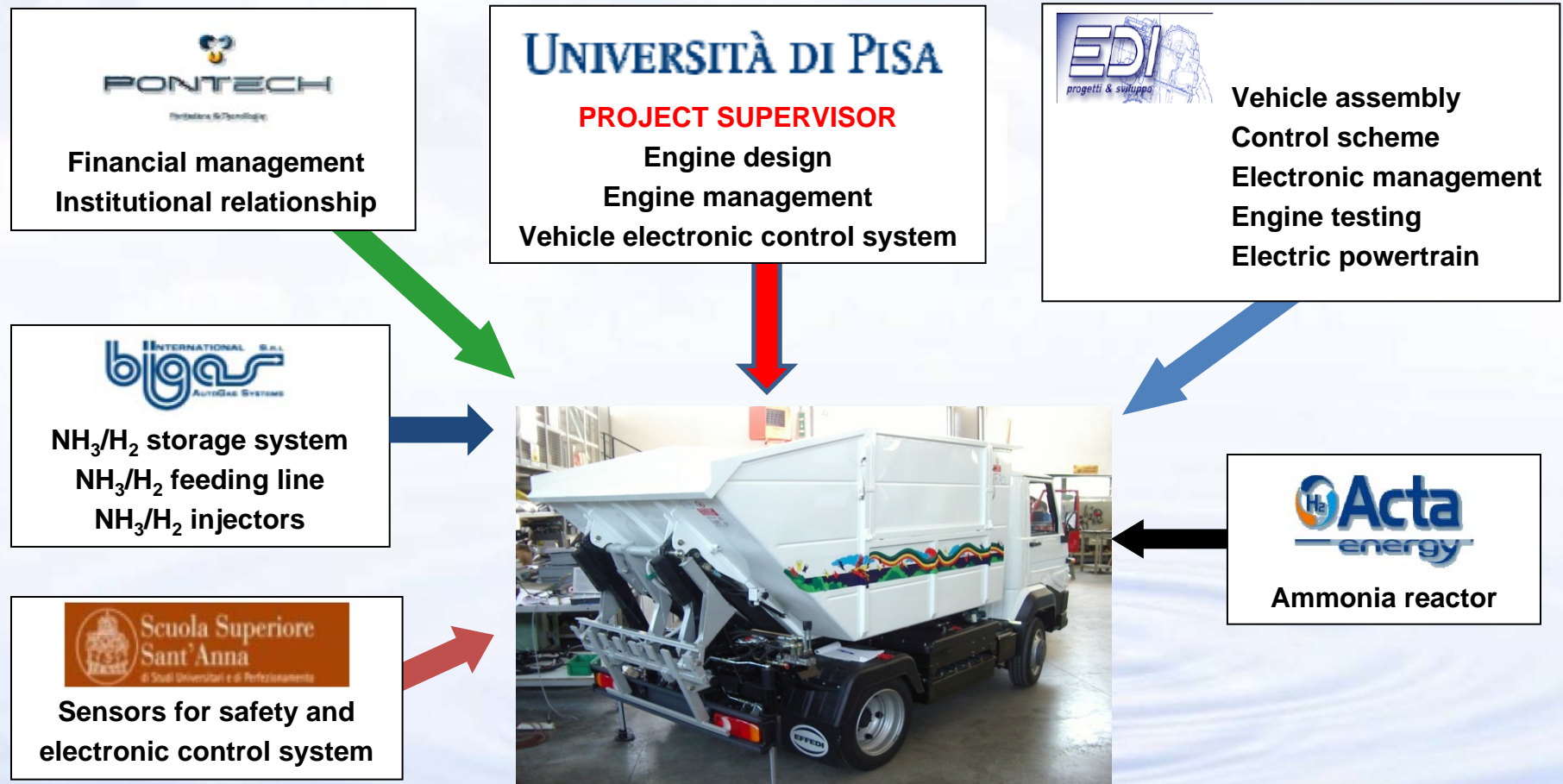
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With the financial support of the Tuscany Region (ITALY), a partnership of Research and Industry entities has developed a RANGE EXTENDED HYBRID ELECTRIC VEHICLE for garbage collection equipped with an IC ENGINE FUELLED WITH A MIXTURE OF LIQUID AMMONIA AND HYDROGEN.



WHY A RANGE EXTENDED VEHICLE ?

Electric vehicles are a promising alternative to conventional vehicles powered by Internal Combustion (IC) engines, offering the opportunity to cut down CO₂, pollutant and noise emissions.

But ***limited battery capacity minimizes the driving range of electric vehicles.***

A POSSIBLE SOLUTION IS REPRESENTED BY A RANGE EXTENDER

Basically, two solutions are available for range extenders :

-Internal Combustion engines

-Fuel cells

At present the most used range extenders are based on IC engines fuelled with gasoline or diesel which have low costs and high reliability but ***high greenhouse gas emissions.***

WHY AN AMMONIA FUELLED ENGINE ?

An alternative solution for range extender is represented by **IC engines fuelled with hydrogen**, which produce carbon-free emissions and are much less expensive than FC, however they still suffer from a very short range.

*An attractive solution is represented by the possibility of **STORING HYDROGEN IN THE FORM OF AMMONIA** that, at environmental temperature, is liquid at roughly 0.9 MPa bar and therefore involves relatively low-cost and light tanks.*

Ammonia can be produced in great quantities from natural gas by Haber-Bosch process, which is highly pollutant. However ammonia **could also be produced by renewable energy**, or recovered from waste water, livestock waste or, for example, geothermal wells.

AMMONIA REPRESENTS AN ALTERNATIVE FUEL TO FEED IC ENGINES AND, IF PRODUCED IN A “GREEN” WAY, IT COULD LEAD TO A REALLY “ZERO EMISSION VEHICLE”.

The use of ammonia to fuel IC engines is not a novelty

Ammonia was used to fuel buses in Belgium during World War II, and a previous (**ITALIAN**) patent of 1938 attests the possibility of using a mixture of hydrogen, ammonia and nitrogen to fuel an internal combustion engine.

However, **the possibility to use ammonia as alternative fuel has been concretely discussed only since mid-1960's.**

Ammonia needs a combustion promoter

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 range, **it is practical to couple ammonia with other fuels used as combustion promoters.**

Among them, **HYDROGEN** displays the lowest ignition energy, the highest combustion velocity and the widest flammability range that allows the engine to operate with very high air-fuel ratios. Therefore a small amount of it, added to air-ammonia mixture, is effective to speed combustion up.

Properties		Ammonia	Hydrogen	Gasoline
Lower heating value	[MJ/kg]	18.8	120	44.5
Flammability limits, gas in air	[vol. %]	15-28	4.7-75	0.6-8
Laminar flame velocity	[m/s]	0.015	3.51	0.58
Auto ignition temperature	[°C]	651	571	230
Absolute minimum ignition energy	[mJ]	8.0	0.018	0.14
Octane number	[RON]	>130	>100	90-98
Density, 25 °C, 1 bar	[g/L]	0.703	0.082	740
Stoichiometric (air/fuel)	[mass]	6.04	34.3	~ 14.5
Energy content, stoichiometric mixt.	[MJ/kg]	2.8	3.3	2.7

THE OPPOSED AND POTENTIALLY COMPLEMENTARY PROPERTIES OF HYDROGEN AND AMMONIA GIVE NEW PERSPECTIVE IN ENGINE COMBUSTION CONTROL

MOREOVER, HYDROGEN CAN BE PRODUCED ON BOARD FROM AMMONIA THANKS TO APPROPRIATE CATALYTIC REACTORS

THE RANGE EXTENDED VEHICLE PROJECT

MAIN DEVELOPMENT LINES

- a) Storage, piping and injection system;*
- b) Ammonia reactor for hydrogen production on-board;*
- c) Ammonia-hydrogen fuelled engine;*
- d) Vehicle assembly and control layout;*
- e) Sensors for safety and electronic control system.*

STORAGE, PIPING AND INJECTION SYSTEM

Management of ammonia is similar to that of LPG, being ammonia liquid, at room temp, at approximately 0.9 MPa.

To keep the costs low, the technology adopted has been derived from the one used for LPG storage, piping and injection system. Obviously many adaptations have been carried out due to the different and very aggressive gas handled.

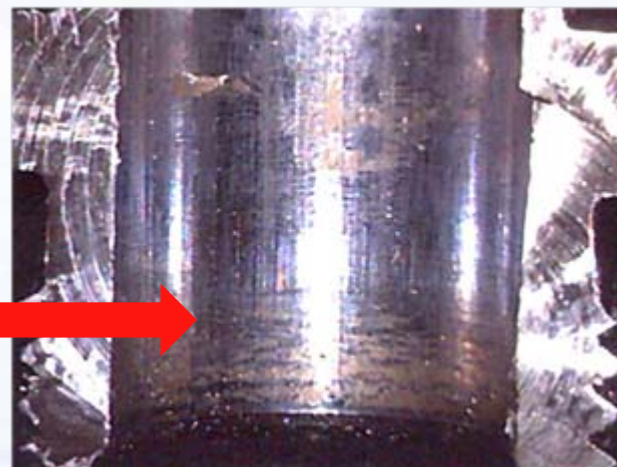
A study of the chemical compatibility of the materials together with various project requirements has been performed and the definition of the technical contents of the feeding system has been set up in order to guarantee requirement of emergency, durability and compatibility with the other systems.

The experimental activity put in evidence that component parts exposed to liquid ammonia were more attacked than the ones exposed to gaseous ammonia.

One of the most attacked metallic part was the electrovalve, where liquid ammonia basically “burned” the component



Concerning the **ammonia injector**, the rubbing of the mobile magnet on its guide led to a partial removal of the original coating ***exposing metal to gaseous ammonia.***



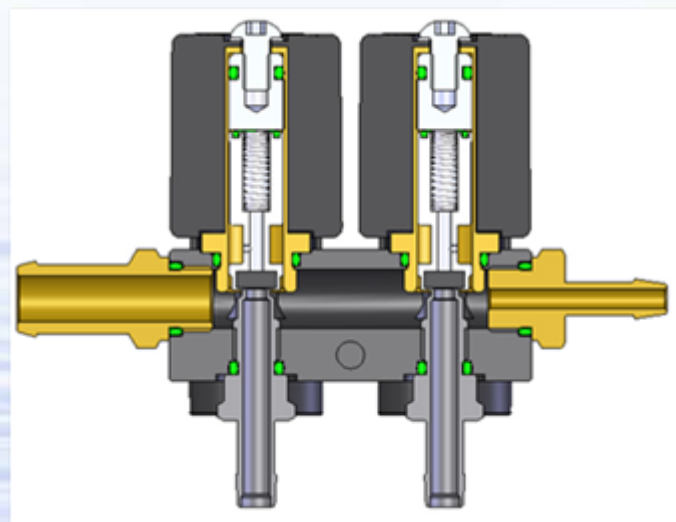
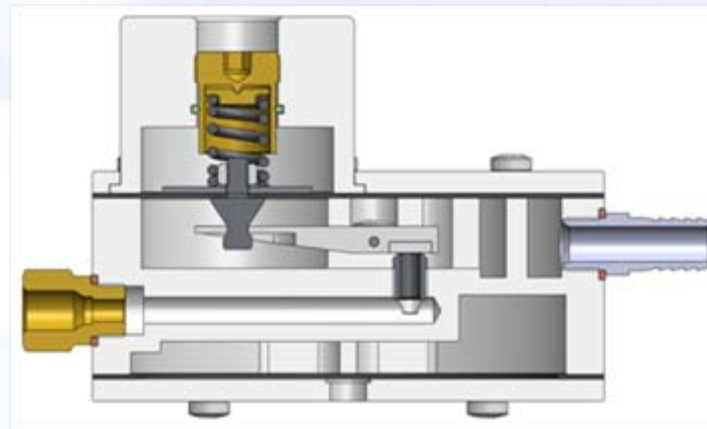
THE USE OF STAINLESS STEEL AND NICKEL COATING HAS GIVEN GOOD RESULTS.

In the adopted version, some components have been re-designed in respect of the original ones for LPG, and in particular:

- ***Expander***
- ***Electrovalve***
- ***Injectors***

For ***the expander***, the principle of operation has been completely changed, passing from the original piston solution to a balance solution.

The injectors were modified in order to improve the flow of the gas and to reduce the exposure of parts in brass to the ammonia.

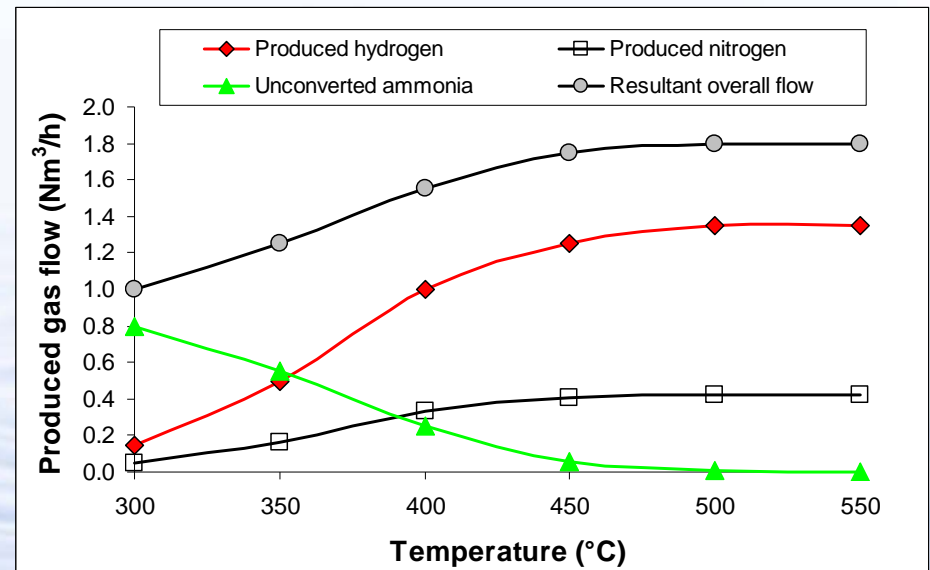
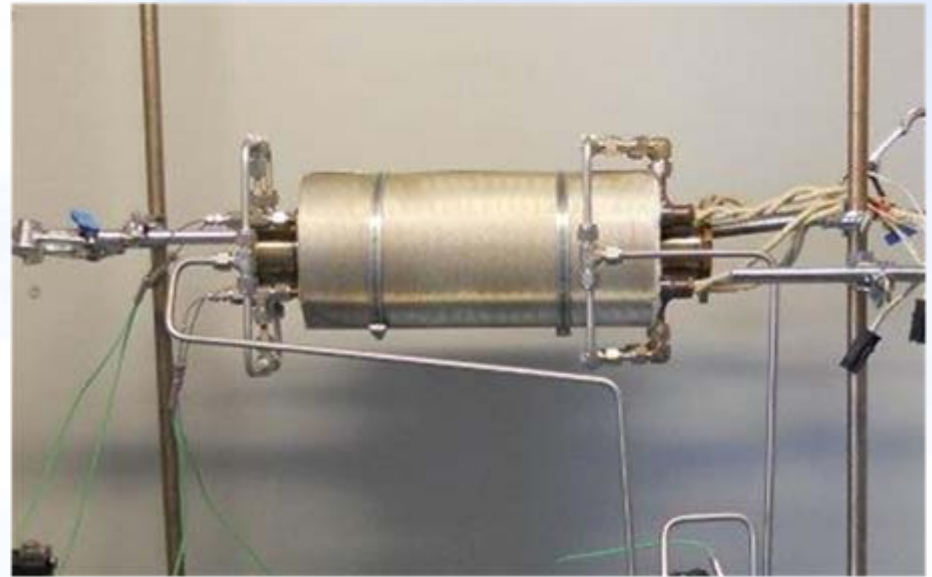


AMMONIA REACTOR FOR HYDROGEN PRODUCTION

*An hydrogen generation system (**catalytic reactor**) was expressly built within the project. The reactor utilizes the thermal energy of the exhaust gases to convert ammonia.*

The performance of the catalytic reactor was separately verified by experimental tests at the designed temperature of 500°C.

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

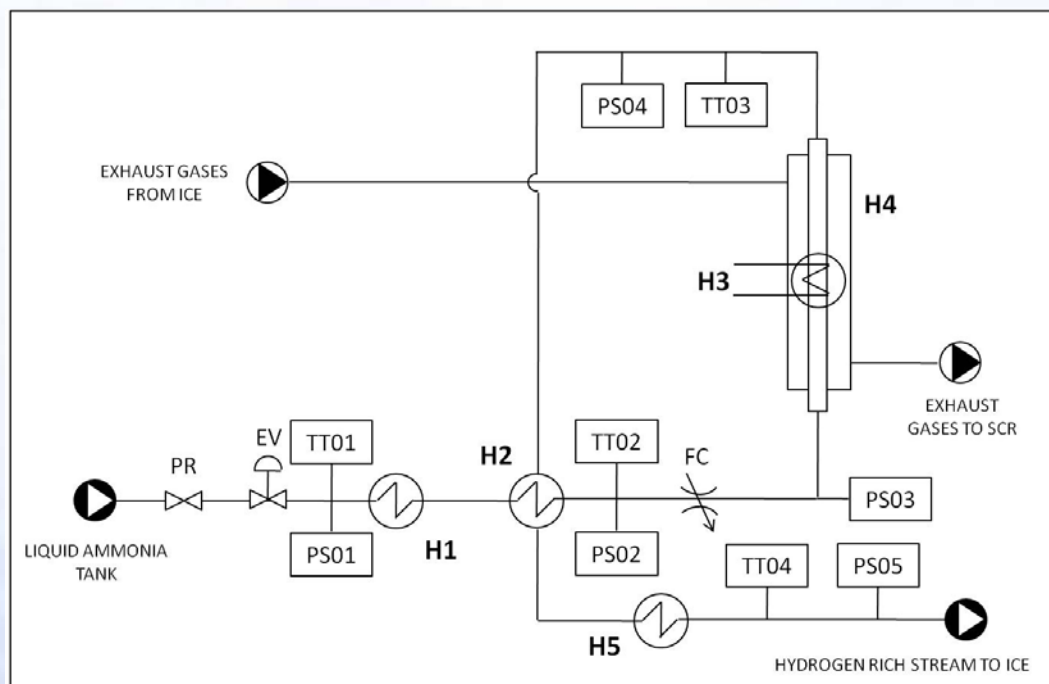


The reactor is a complex system which couples the reaction chambers with several heat exchangers and pressure/temperature sensors.

H1 and H3 are electrical resistances which are necessary to bring the ammonia and the reactor to the proper temperature during the cold start.

The heat exchanger (**H4**) makes use of the exhaust hot gases produced by the ICE.

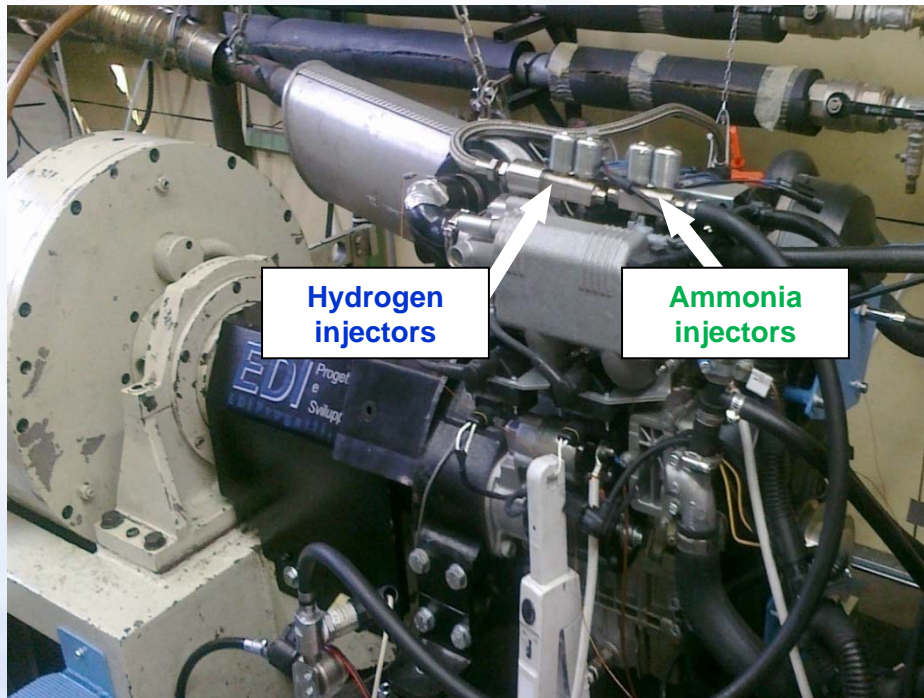
The hot gas mixture produced by the reactor is then flown into **H2** and consequently in a last heat exchanger (**H5**), which brings the gas temperature to values below 80°C. This last unit (finned tube type) cools down the gas mixture by exchanging heat with ambient air.



AMMONIA-HYDROGEN FUELLED ENGINE

Taking advantage from a previous experimental experience, during which an innovative (*PATENTED*) hydrogen direct-injection system was developed, an experimental engine, based on a 505 cm³ Lombardini twin-cylinder SI engine, was realized and located on test bench maintaining the original (gasoline) mechanical configuration.

The only mechanical modification of the engine involved the intake manifold, where hydrogen and ammonia are injected 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

Preliminary tests were performed to verify the possibility to operate the engine with a mixture of air, ammonia and hydrogen and to determine proper injection timings and feeding-line pressures of hydrogen and ammonia.

Ignition advance was set for MBT and for each experimental condition 100 cycles were recorded and analysed.

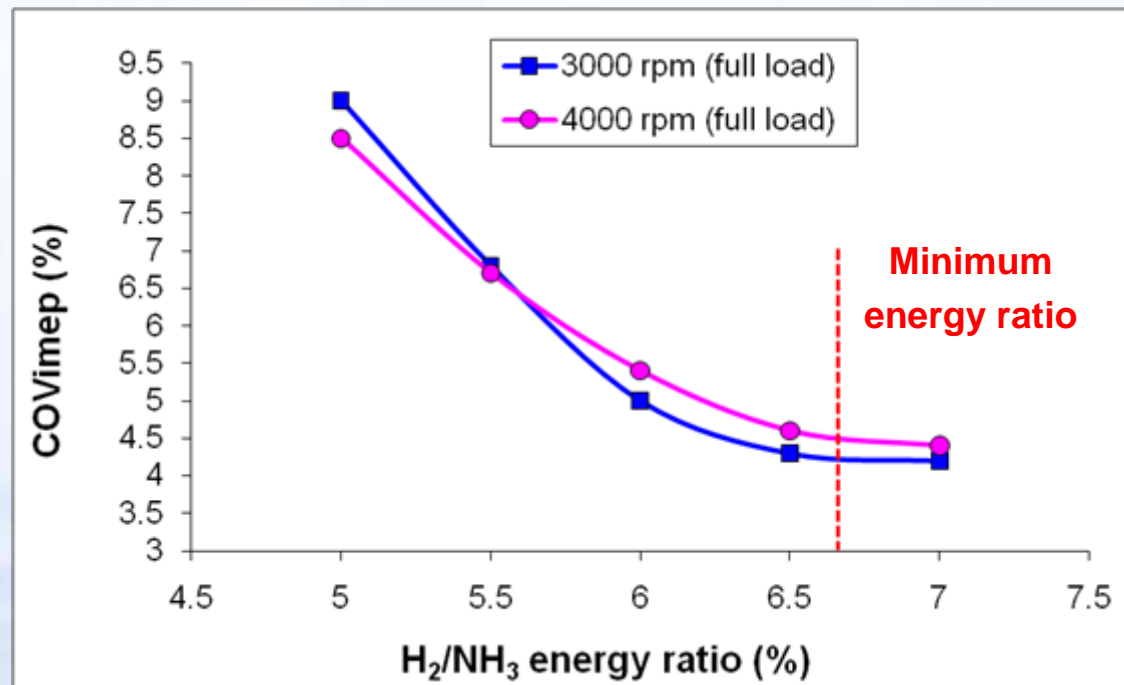
Injection timing NH ₃	TDC at the end of the exhaust stroke
Injection timing H ₂	TDC at the end of the exhaust stroke
NH ₃ feeding line relative pressure	2.4 bar
H ₂ feeding line relative pressure	0.4 bar (maximum reactor pressure output ~ 0.5 bar)

The following experimental activity was focused on determining the minimum hydrogen-to-ammonia energy ratio that keeps the engine cyclic variation at an acceptable level, that is $COV_{imep} < 10\%$.

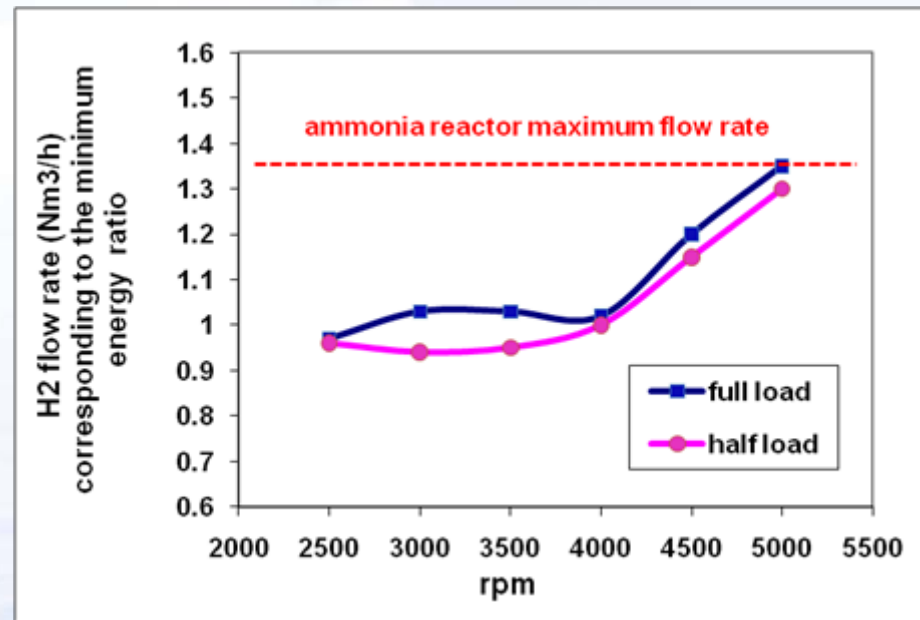
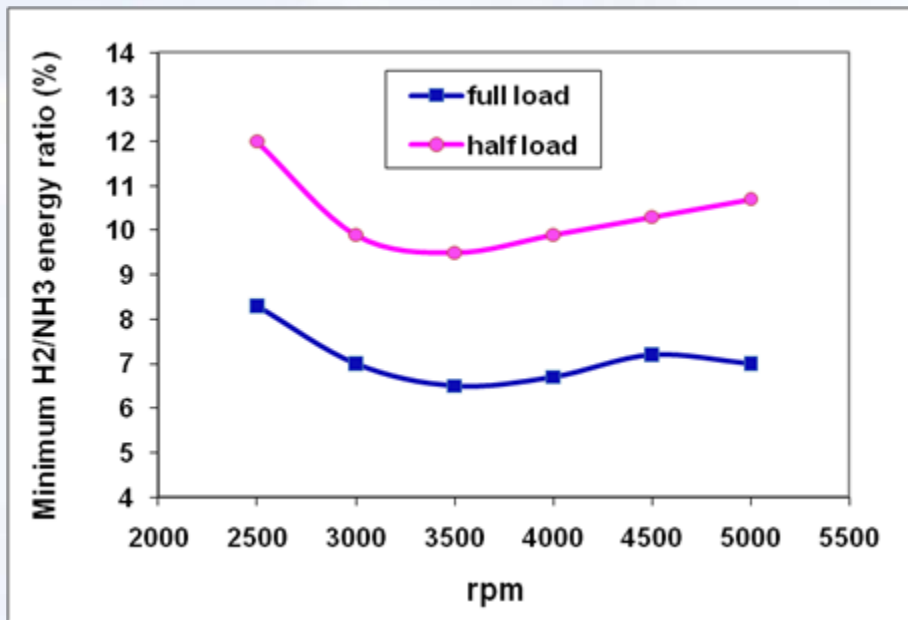
The experimentation, carried on running the engine with an overall equivalence ratio slightly lean, put in evidence some important aspects:

- Engine COV_{imep} rapidly increases as soon as hydrogen-to-ammonia energy ratio falls below a certain value.

Conservatively, the hydrogen-to-ammonia energy ratio below which engine COV_{imep} hastily increases is regarded as the “**MINIMUM**” energy ratio.



The minimum energy ratio depends mainly on load and less on engine speed, while the corresponding H_2 flow rate doesn't change significantly.



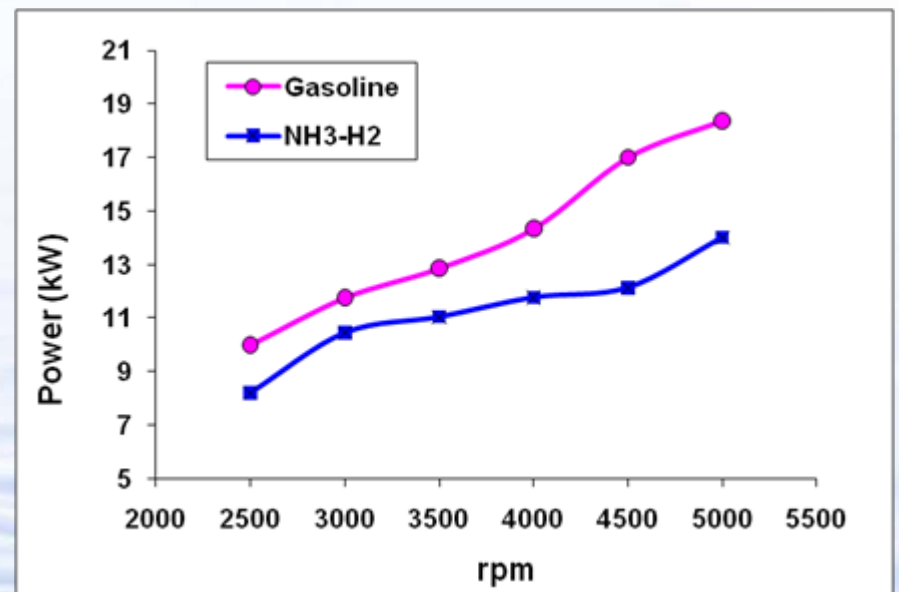
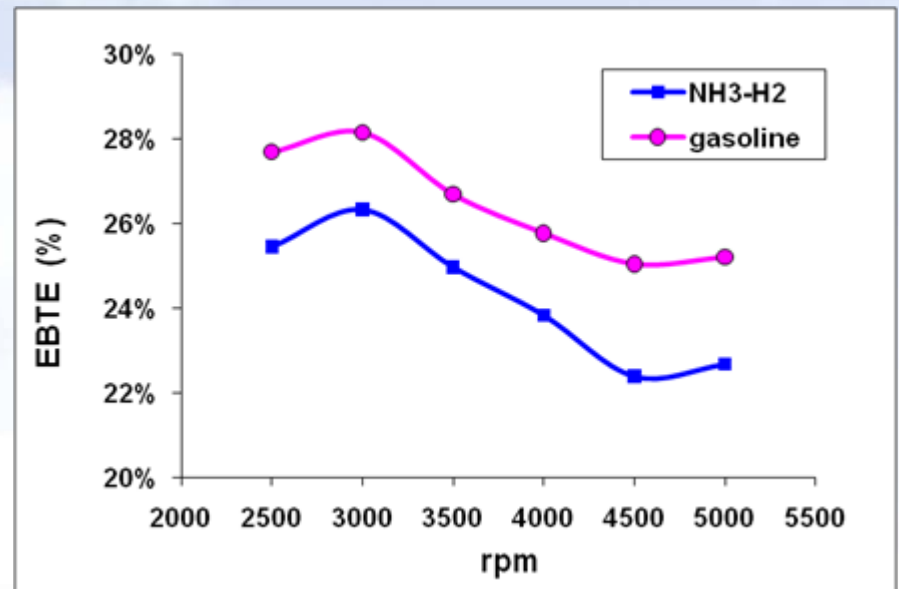
The H_2 flow rate is compatible with the ammonia reactor output.

- With the practical minimum hydrogen-to-ammonia energy ratios, the best spark advance is 10° to 15° larger than with gasoline.

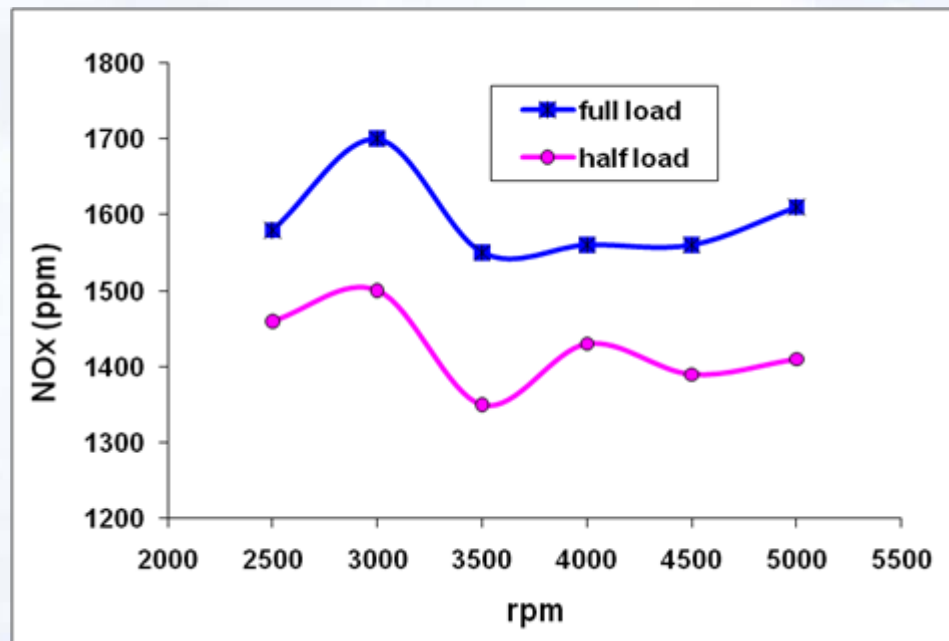
This is tied to the *low flame speed that prolongs ammonia combustion*.

The “extended” ammonia combustion leads to higher heat loss through cylinder walls and less residual expansion than with gasoline, with consequent *less engine brake thermal efficiency (EBTE) and power*.

This last is *also due to mixture poor volumetric heating value*, because of the high specific volume of ammonia and hydrogen.



NO_x is the only meaningful pollutant found in the exhaust emissions (unburned hydrocarbons from lubricant are negligible and the presence of ammonia in the exhaust gas was not measured quantitatively but only checked with a threshold sensor [alarm set at 100 ppm], the same adopted on the range extended vehicle).



However, NO_x emission is not a problem since the use of a SCR is eased by the presence of ammonia onboard.

ENGINE BEHAVIOUR AT COLD START

Hydrogen-to-ammonia energy ratio must be considerably increased to guarantee correct engine cold start.

Cold start feeding conditions must be kept for few seconds after starting, with the engine at idle (1800 rpm, quite high idle speed in respect of around 1100 rpm with gasoline). Then hydrogen-to-ammonia ratio is progressively reduced and engine speed increased to reach the required operating conditions.

H₂ flow rate	2.6 Nm³/h
H₂ feeding line relative pressure	0.4 bar
NH₃ flow rate	0.54 Nm³/h
NH₃ feeding line relative pressure	2.1 bar
H₂/NH₃ ratio (by energy)	360 %

At cold start a hydrogen flow rate higher than that provided by the catalytic reformer is needed. Therefore a suitable amount of hydrogen must be stored in a tank that will be recharged during engine normal running.

VEHICLE ASSEMBLY AND CONTROL SCHEME

The vehicle chosen for the hybridization is a small truck (capacity = 3.5 tons) conceived for garbage collection.

The original Diesel model was modified taking advantage of its flexible chassis that can be adapted to the transformation to hybrid.



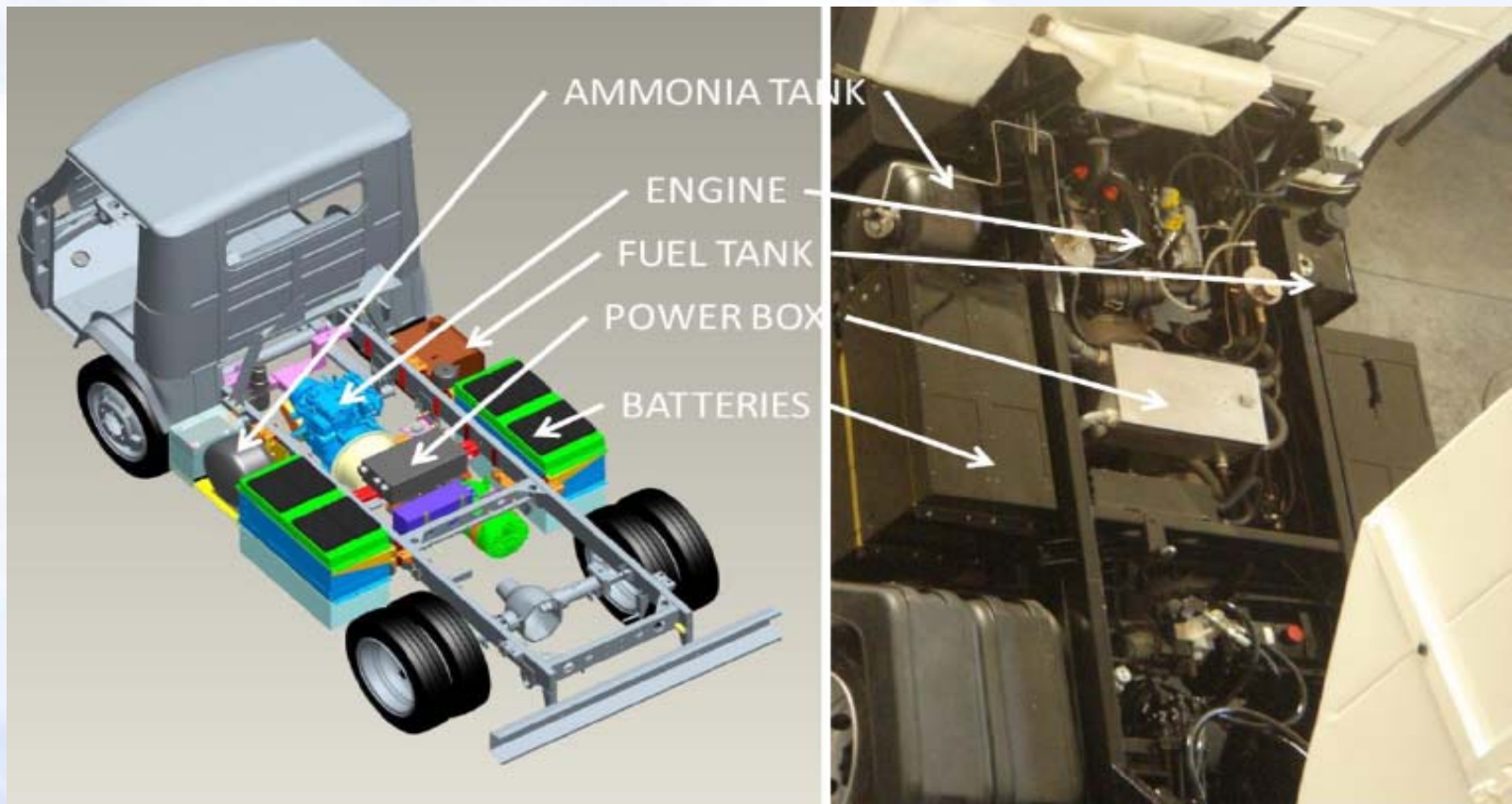
These kinds of vehicle are often used in Italian historical city centres where noise and pollution problems are very important issues. A hybrid vehicle can be used in city centre the in electrical mode (sometimes garbage collection takes place during the night), and the engine can run, in range extender mode, during transfers.

This prototype is a plug-in series hybrid , so the engine runs for battery charging only.

80 lithium batteries series connected store roughly 24 kWh at 264 V, while the **useful power is about 19 kW**.

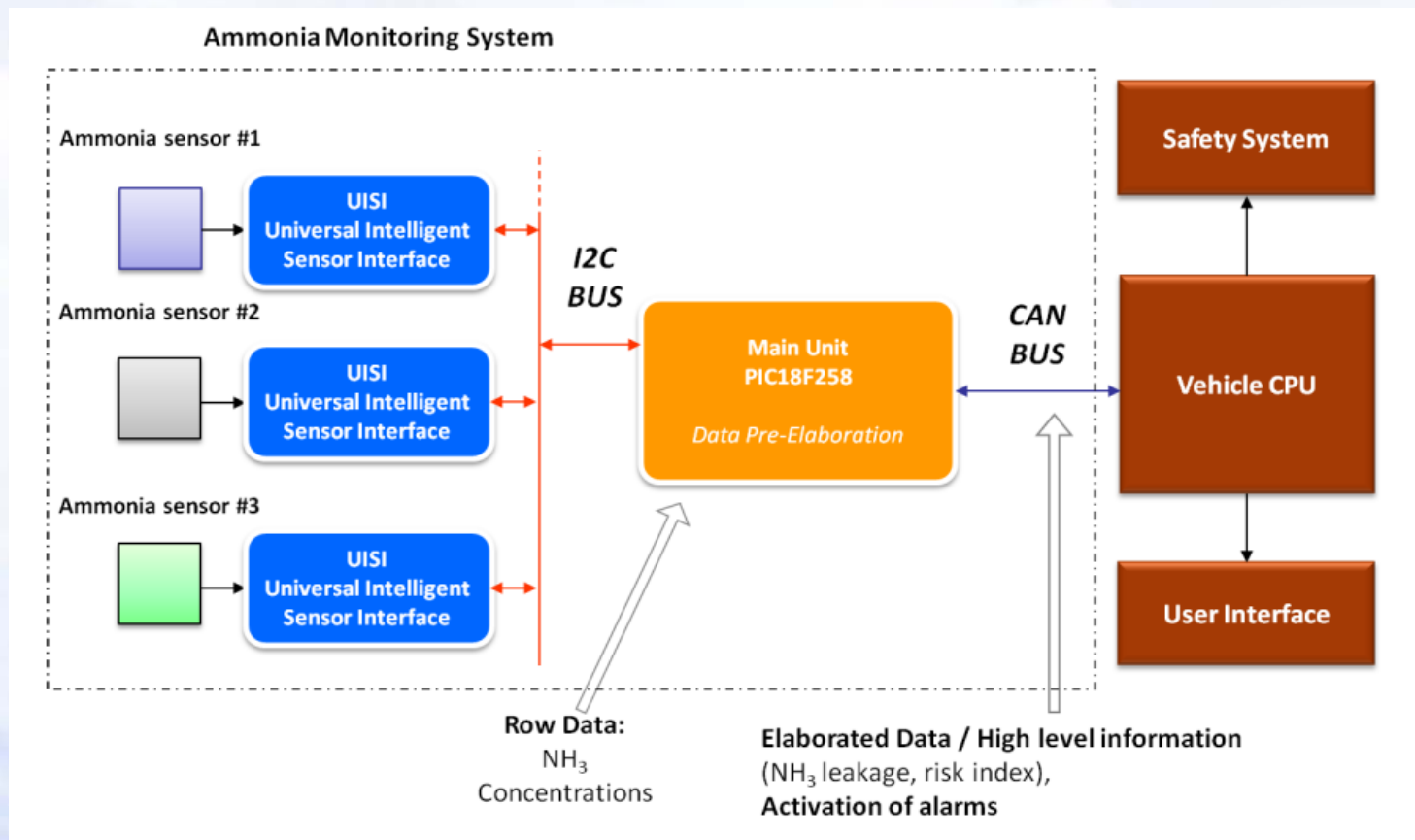
The **electric motor** is connected directly to the inverter by power connection .

The **generator** is of the three-phase synchronous type, dragged by the engine and powering only the bridge rectifier .



SENSORS FOR SAFETY AND ELECTRONIC CONTROL SYSTEM

Because of the toxicity of gaseous ammonia, a suitable monitoring system has been integrated into the vehicle. It is based on a modular architecture that allows the integration of several different sensors (including the ones for ammonia), in a scalable and *plug-and-play* way, as well as data pre-elaboration.



Three sensors are located in different places of the vehicle.

The most sensitive one, assembled within the electronic control box, is placed inside the cockpit of the vehicles for the safety of the driver.

The second sensor is placed near the ammonia tank and catalytic reactor, to monitor possible leakages, and the last one is near the exhaust pipe to detect unburned ammonia.

The system alarms were settled on a threshold of 20 ppm of ammonia for inside the vehicle and of 100 ppm for outside.



CONCLUSIONS 1/2

- A partnership of Research and Industry entities has developed a fully working range extended hybrid electric vehicle equipped with an IC engine fuelled with liquid ammonia and hydrogen.
- All the different technical aspects have been faced, i.e. the design of a new supply and injection system for ammonia and hydrogen, the ammonia reactor for hydrogen production; the IC engine, the electric and electronic components, the selection of sensors for safety and electronic control system.
- The first campaign of engine tests has given encouraging results, considering that an optimization phase has to come. The experimental results confirm that ammonia can represent an alternative carbon free fuel for IC engines, but also the need to speed combustion up by adding a small amount of hydrogen to air-ammonia mixture, with ratios that mainly depend on load and less on engine speed.
- NO_x is the only meaningful pollutant found in the exhaust emissions. In this first phase of experimentation only a threshold sensor for ammonia was adopted.

CONCLUSIONS 2/2

- The amount of hydrogen necessary for correct engine running is produced on board thanks to a catalytic reactor expressly designed and built within the project.
- The catalytic reactor has shown some structural problems. A new re-designed reactor is under construction.
- Concerning the engine, no meaningful mechanical inconvenience occurred during the engine experimental activity. Nevertheless, long-time reliability of the injection system for ammonia and for hydrogen, as well as for the entire engine, has to be verified.



THANK YOU FOR YOUR ATTENTION

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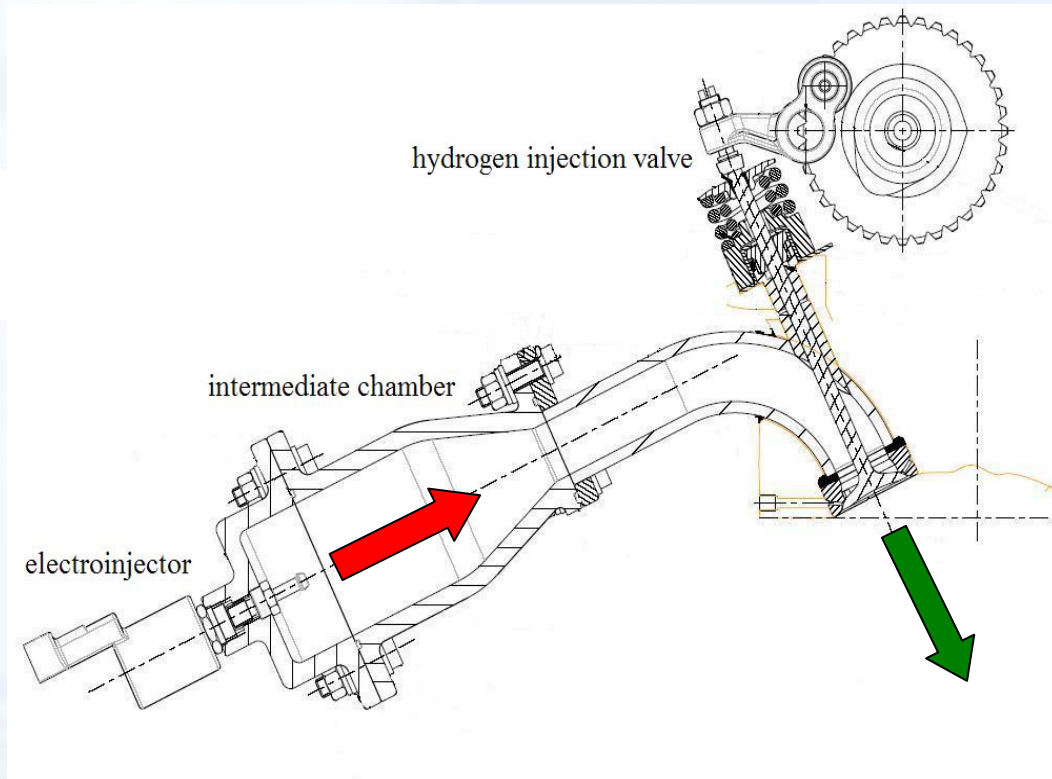
In a previous research an innovative (*and PATENTED*) hydrogen direct injection system was developed.

The hydrogen injection was realised in two steps:

1) an electroinjector (a conventional one for LPG applications) feeds an intermediate small chamber;

2) next, hydrogen is injected into the cylinder by means of a mechanically-actuated valve.

The electro-injector controls the amount of hydrogen while the high-flow mechanically-actuated valve times hydrogen injection into the cylinder.

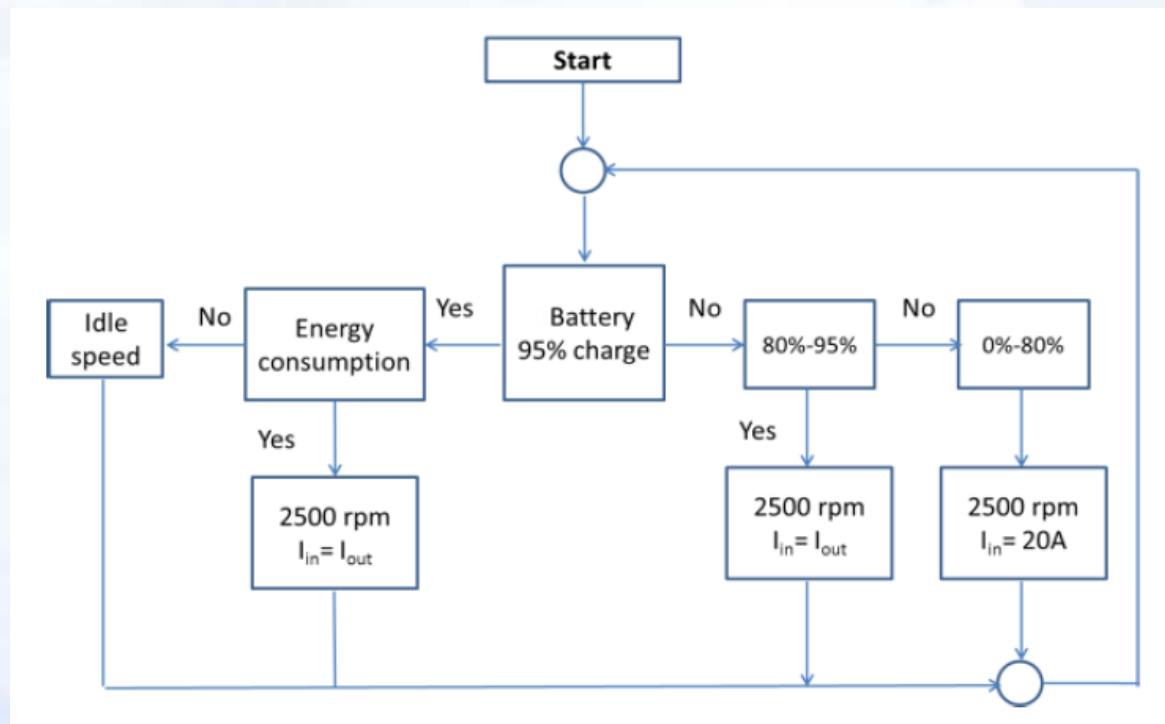


Hydrogen feeding line pressure = 12 bars

Intermediate chamber max pressure = 6 bars

Engine logic of control in hybrid mode

If batteries charge is 95% and there is no energy consumption, engine runs at idle because batteries can be considered full (they never reach 100% charge) otherwise engine runs in order to level energy consumption. The same happens when charge is between 80% and 95%. When charge is between 0% and 80% engine runs full load in order to recharge batteries.



**Current is proportional to charge level taking into account the voltage of each battery.
Charging rate is calibrated on the maximum voltage battery in order to avoid damages.**