Development of a spark ignition engine coupled with an ethanol steam reformer

Frederico Weissinger
Vincent Bigliardi
Eugenio Coelho
Luis Possamai
AVL South America, Powertrain engineering
Pedro Lacava
ITA – Instituto tecnológico da Aeronáutica

Abstract

The Brazilian automotive regime number 13.755, which became known as "Rota 2030", is a remodeling of the extinct incentive program, Inovar Auto. Inovar Auto provided for a significant tax reduction on vehicle final price, allowed only when the company fulfilled a series of obligations related, fundamentally, to investing in R&D, complying with the Vehicle Labeling Program and reaching certain levels of energy efficiency.

Rota 2030 follows a similar strategic line, but the focus is to encourage R&D projects throughout the sector's chain. As a result, the program was expanded to include auto parts and strategic infrastructure for car production, rather than just automakers. And one important topic to be mentioned are the research involving ethanol, which can provide a tax reduction depending on the gap between gasoline (E27) and ethanol (E100) consumption. Currently, the average consumption gap is roughly 30%, and the greater the reduction in this gap, the smaller the tax applied to the vehicle.

Increasing brake thermal efficiency (BTE) of spark ignition (SI) engines currently is a strict requirement for engine manufacturers to meet the future CO2 emission legislation. Several technologies have been investigated and applied to increase the engine efficiency such as cylinder deactivation, variable compression ratio, exhaust gas recirculation (EGR), Miller/Atkinson cycle, water injection, etc. Together with the development of engine technologies, fuel properties play an important role for the potential engine efficiency. Due to the limitation of fossil fuels and the requirement of a sustainable mobility, biofuels using renewable energy sources could play a key role.

Ethanol is a relevant fuel for spark ignition engines because of its high-octane number, high-octane sensitivity, high heat of vaporization and high laminar flame speed. To further boost the efficiency of ethanol engines and reach the very aggressive target in ROTA 2030 to improve the ethanol efficiency, the use of waste heat recovery technologies for driving fuel reforming was considered.

The investigations concerning the possibility to use the reformed-exhaust gas recirculation (R-EGR) concept for higher efficiency of internal combustion engines are presented in this article developed by AVL South America in partnership with AVL Headquarter List (Graz, Austria) and ITA (Instituto Tecnologico da Aeronautica).

Introduction

The need for energy is greatly increased by population growth and technologies in development. In the current scenario, using fossil fuels to supply this demand is insufficient, resulting in pollution, global warming, climate change, and natural disasters. In fact, this increasing in energy demand comes together with more restrict emission legislation, which requires engines coupled with more complex technologies to comply the CO_2 emissions limits.

It is known that about one-third of fuel energy introduced to an ICE is wasted with engine exhaust gases. Even its partial utilization can lead to a significant improvement of the ICE energy efficiency. One of the ways to recover an engine's wasted heat is by using exhaust gases energy to promote fuel endothermic reactions that produce hydrogen-rich reformate. The basic concept involves the use of the engine's exhaust heat to promote on board reforming of ethanol into a mixture of hydrogen and carbon monoxide with some amounts of carbon dioxide, methane, water vapor and some small portion of Aldehydes. The resulted fuel has greater heating value than primary liquid fuel and may be more efficiently burned in the engine in comparison to the original fuel. The efficiency can be improved by utilizing lean burning or a high diluted mixture (due to wide flammability limits of a hydrogen-rich reformate) that leads to reduction of heat transfer energy loses and a possibility of increasing the engine compression ratio (CR).

The strategy of the project is to reduce fuel economy gap between gasoline and ethanol under same engine operating conditions, improving ethanol operation according to INOVAR AUTO (Brazilian automotive regime 12.996 Art. 41-B). Current gap between fuels is of approx. 30%.

The engine hardware used as starting point was the 1.0L TGDI DVVT (Turbo Gasoline Direct Injection / Doble

Variable Valve Timing) which was under development aiming to be best-in-class in friction, thermodynamic and fluid dynamics behavior

The main work will focus on improving combustion, looking at the potential specific benefits coming from the ethanol fuel, in particular at part load where the real-world driving fuel economy is more important in the final customer perspective. Full load performance will be maintained.

There are some keys areas that need to be investigated as lean operation mode which allow pumping loss reduction due to de-throttling and heat transfer losses reduction with lower in-cylinder temperature. Thermal efficiency increases with higher compression ratio, cold phase fuel consumption optimization and fuel characteristics improvements.

And there are challenges to be solved as combustion control and stability extending significantly lean operation limits, higher geometrical compression ratios controlling the effective compression and expansion, emissions control (NOx, soot) and thermal management to improve engine warm-up phase.

The objective is identifying technological contents that enable stable lean operation or diluted mixture operating at part-load, minimizing pumping and heat transfer losses and so improving fuel conversion efficiency, while still managing transition to full load demands.

Development phases

Due to the complexity of the project, it was divided into 5 phases in order to managing all steps as following:

1st Phase:

he first phase was essentially the concept definition. Several 1D simulations are conducted during the first phase, starting with the correlation of engine test bed (ETB) results from a base engine and progressing to the implementation of internal combustion technologies such as the Miller cycle, high compression ratio, and a modeled ethanol steam reformer to simulate the fuel reforming process.

Other important activities performed were combustion tests in a transparent single cylinder engine to simulate the synthetic gas based on the modeled reformatted fuel, CFD simulation and a cylinder head flow bench optimization for better charging motion.

Based on this motivation, it was defined some routes for the first phase or definition phase:

- 1 “safe” route that has high confidence of achieving targets
- 2 alternative routes with higher risk
- Simulation phase
    - Prove feasibility of routes by 1D simulation and experience-based analysis
- Layout phase
    - Design parts for at least 2 most promising routes
- Single cylinder phase
    - Test 2 most promising routes on AVL’s optical engine

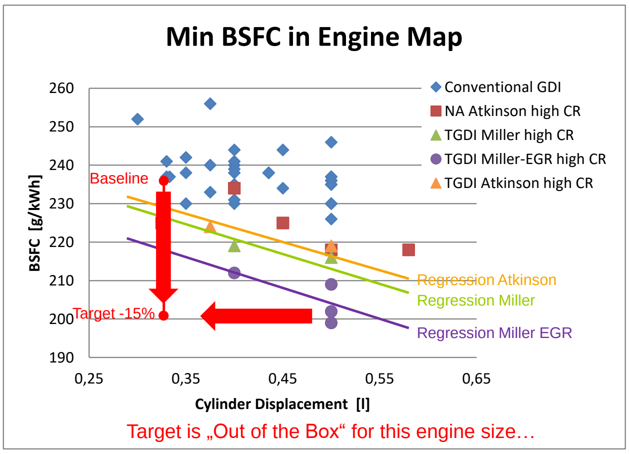

Figure 1 - Perspective of fuel consumption reduction based on ICE technologies overall

1D-simulation

The main objective for 1D simulation was test the maximum standard technologies currently available and define the optimum configuration for the engine optimization. Starting with a correlation, the 1D model passed by some adjustments in order to reproduce the same consumption values of the base engine tested in engine test bed.

The technologies to be simulated were selected based on some criteria as availability, applicability, cost, production intent, experience based and difficulty to implement in the engine and in vehicle. The standard technologies selected were:

1. <u>Compression ratio</u>: It was simulated several compression ratios up to the hardware limit in order to understand the influence in fuel consumption
2. <u>Exhaust Gas Recirculation (EGR)</u>: The external EGR was tested in different configuration to understand, first, the benefits in fuel consumption and second, define a properly layout of EGR
3. <u>Miller Cycle</u>: The Miller Cycle was implemented by the changes in the camshaft. It was proposed different durations and position for intake valve opening. One non-beneficial impact observed was a reduction in the load due to the increase in the pressure drop caused by the reduction in the camshaft duration. This issue was solved using a higher compression ratio
4. <u>Advanced boost</u>: One non-desired effect in implement Miller cycle is the mid and full load impact. It is not possible to reach the load due to reduction in the charge density. In order to reach the mid and full loads, some options of turbochargers were tested
5. <u>Ethanol reformer</u>: The purpose to use the fuel reforming is convert the ethanol into other fuels with higher lower

heating values, including hydrogen. The hydrogen has approximately 120MJ/kg of lower heat value, which means, even a small portion can produce a high energy release in a very fast flame velocity. The benefits to use hydrogen diluted in EGR are since fuel consumption reduction up to heat release reduction.

Conclusion from 1D simulation:

- The strategies for engine efficiency improvement take place in the hardware modification such as camshaft timing and length (Miller cycle implementation), turbo compressor system change, increasing in engine geometric compression ratio, external EGR addition and ethanol reformer system
- Intake camshaft using aggressive Miller camshaft duration presented better results in the reformer model due to the increase in exhaust mass flow, which increases the EGR rate
- When it is used stronger Miller than 160°@1mm, it is not possible to reach the BMEP target due to the high amount of residual gas at 2000rpm/8bar. It is only possible reducing the EGR rate or reducing the turbine mass flow multiplier (reducing the size of the turbine) in order to increase the intake manifold pressure P_IM
- The addition of ethanol reformer in the model presented a reduction in the specific consumption and an increase in the brake efficiency due to the production of hydrogen, which increases the lower heat value and the air-fuel ratio into the cylinder

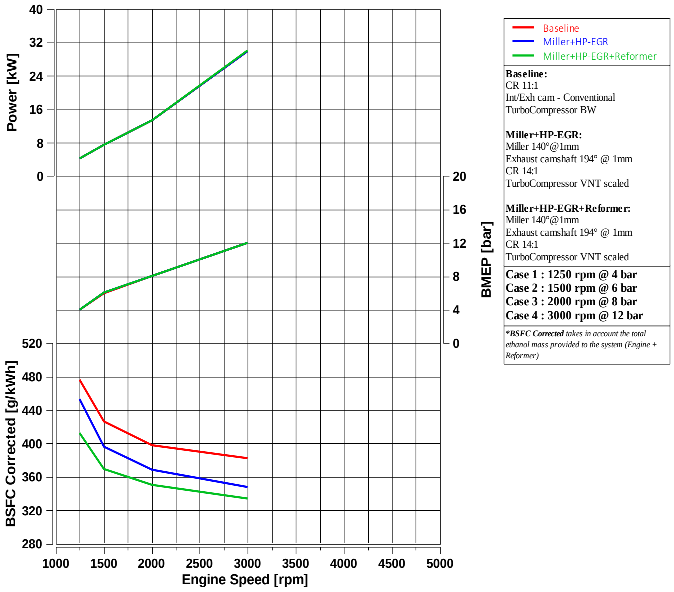

Figure 2 - Comparative between different configuration to the base line

	1250rpm/4bar	1500rpm/6bar	2000rpm/8bar	3000rpm/12bar
High Pressure EGR	-4,96%	-6,89%	-7,47%	-9,09%
Reformer	-13,37%	-13,27%	-11,87%	-12,70%

Table 1 - Results from the 1D simulation comparing different configuration to the baseline

Flow test results – Intake port quality

The development of the flow parameters (flow coefficient and reduced tumble ratio) is shown over the valve lift (normalized by the inner seat diameter), as measured on the stationary flow test bench in AVL Headquarter List (Graz, Austria).

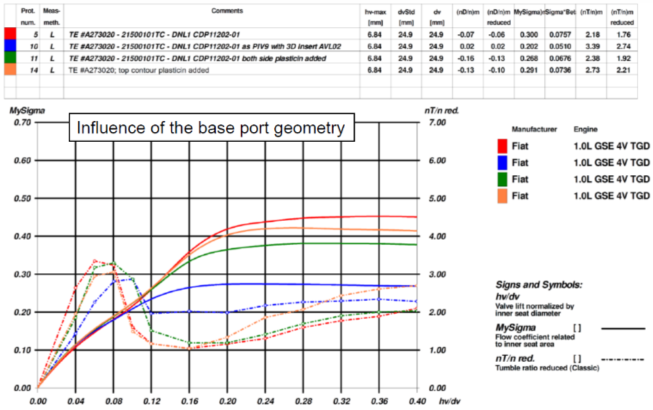

Figure 3 – Cylinder head port quality plot

The flow bench testing conducted by AVL List for several ports inserts is shown in the diagram above. To optimize the tumble ratio, many inserts were investigated and chosen as the best fit for the demand for high EGR rates and low restriction for low pressure drop.

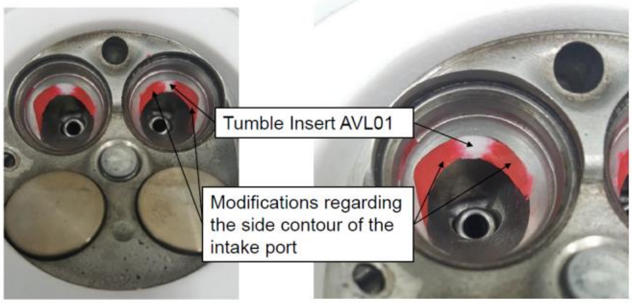

Figure 4 - Inserts implemented by AVL in order to increase the tumble ratio for better charging motion due to the use of high EGR rates

Transparent engine (Single cylinder optical engine)

Future advancements in internal combustion engines will require rigorous adherence to emission laws while also reducing fuel use. To reduce emissions and maximize fuel efficiency, the injector structure and charge flow must be optimized. The modular nature of the spark ignition transparent engine sets it apart. As a result, the test bench can be customized to the needs of the customer in terms of hub and drill hole. The test stand is required for flow and combustion studies and can be supplied with a flow model or a cylinder head. It has a transparent liner and a piston top window that allow for better optical inspection of in-cylinder flow and combustion.

The engine tested has a four-valve overhead cam engine with a nominal 9:1 compression ratio. This optical access will be utilized to analyze cylinder flow and flame behavior, which will then be linked to engine settings in order to improve overall combustion processes and engine power.

The transparent engine testing has the purpose to support the understanding in many topics, including:

- <u>Combustion:</u>
  - Several EGR rates combustion
  - Hydrogen combustion impacts
  - Limits of dilution
- <u>Fuel injection:</u>
  - Injection pattern
  - Injection spray
  - Phase of injection
- <u>Cylinder head:</u>
  - Charge motion
  - Tumble
  - Mixture formation

Physical processes in an internal combustion engine's cylinder are as sophisticated as they are critical to the engine's power and emissions. At the moment, the models used to connect the engine's physical shape to its output are phenomenological.

It is tough to diagnose in-cylinder engine activities since the conditions are both unfriendly to measurement and easy to upset. Because of the small volume involved and the interactive and highly three-dimensional character of the flow, the procedures are delicate. Optical diagnostics are appealing approaches for these reasons, and they are becoming a common way of investigating the minutiae of engine flow and combustion.

Many aspects in our growing understanding of these flows are heavily reliant on the instantaneous or average three-dimensional flow field. Point and plane measurements are insufficient to infer this flow field due to its intrinsic complexity and/or rapid volatility. In order to use optical techniques to assess the complete flow field, optical access across the volume of the cylinder is critical. Furthermore, in order to remain a useful research tool, an engine with such access must retain the properties of genuine engines.

The results measured during the transparent engine testing were used as input in the 1D simulation as a combustion parameter.

The investigated operating points were:

- Catalyst Heating Idle 1200 rpm / 2 bar IMEP
- 2000 rpm Part Load 2.7 bar IMEP
- Evaluation of the combustion system
- Additional points to assess different EGR/H2 rates to check impact on combustion speed/stability
- 1500 rpm / Part Load 6,7bar IMEP
- 2000 rpm / Part Load 8,7bar IMEP
- 2000rpm / Part Load 12,7 bar IMEP
- Investigation on charge of motion, mixture preparation and combustion assessment
- Assessment on the intake valve tumble device with optimized settings
- Increased tumble improves full load stability and combustion speed but needs adaptations in hardware and settings.
- Injection strategy to minimize
- Soot flame formation
- Fuel liner wetting (oil dilution) – big concern for ethanol engines
- Investigation of different piston shapes

Figure 5 - AVL transparent engine picture observed during the tests in AVL headquarter List Graz, Austria.

2nd Phase

Both base engine configuration was studied 1.0L TGDI DVVT (Turbo Gasoline Direct Injection / Doble Variable Valve Timing) and 1.3L TGDI VVL (Turbo Gasoline Direct Injection / Variable Valve Lift) and modifications in design (CAD) were performed. A new compression ratio of 14:1 was selected in order to in future, use this engine as flex-fuel.

3rd Phase – Engine test bed (ETB) assessment

The objective of 3rd phase was to execute the prototype engine development on the 1.3L TGDI VVL based on the technical definitions from 1st and 2nd phases

The main target is the BSFC optimization on engine test bench of the reference operating points on E100 fuel which are representative for the FTP-75 and HWFET driving cycle

Packaging definition for ETB

The scope of work was divided in work packages (WP) and the focus of the WP01 was the preliminary prototype design of high pressure EGR system to ethanol reformer configuration and packaging to ETB

In this packaging definition for ETB, it was agreed to deliver the preliminary CAD data of the high pressure EGR individual feeding for reformer application, nevertheless, all the additional investigation as 1D simulation must be performed in order to validate the design assumptions

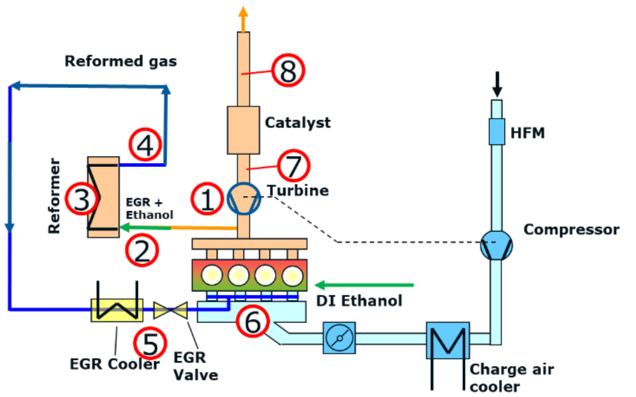

Figure 6 - EGR line and reformer architecture

(1) EGR pickup. Between exhaust manifold and turbine

(2) Ethanol injection in the EGR line

(3) Reformer Brick directly in the EGR line in order to get the highest temperature possible

(4) Reformer out

(5) EGR cooler/EGR valve. Reformed gas

(6) EGR feeding in the intake manifold

(7) Engine out

(8) Post catalyst gas flow → Hot exhaust gas from tailpipe

Standard technologies assessment

During the WP08 was performed the first engine commissioning, the baseline testing, the engine update for standard technologies, the EGR valve characterization and the grid measurement for lowest BSFC with the standard technologies already incorporated

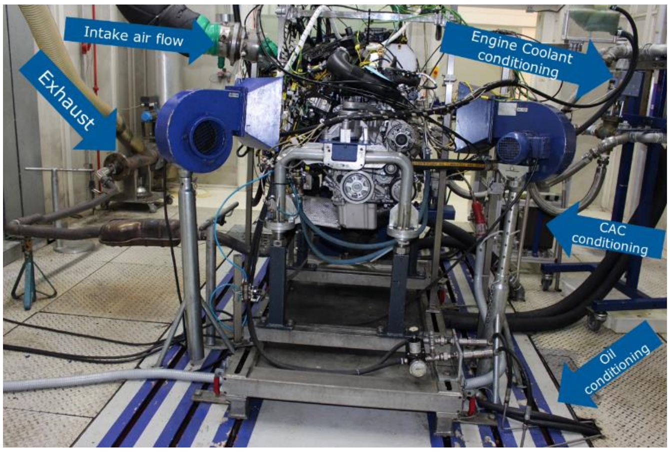

Figure 7 - 1.3L VVL TGDI engine installed in ETB

Baseline measurement

The baseline measurement was tested with the base engine with no technology implemented. For this activity the original engine was installed in the ETB for the measurements as full load curve, full grid measurement (Sweep of engine speed and load).

Standard technologies engine test bed

The standard technologies investigation proposal is to evaluate the main technologies focused on fuel consumption reduction

The engine 1.3L VVL TGDI was updated with the main available technologies as:

- High compression ratio (14:1) → Piston modification
- External cooled EGR → High pressure EGR system
- Advanced boosting → VTG (Variable Geometry Turbine)
- Cylinder head optimization → New intake ports to increase the tumble ratio
- Advanced ignition → High energy spark / Large degrees of thermal pyrolysis of the fuel

The focus on the investigation were the reference operating points in the figure 11 and for each one was performed an EGR sweep starting from 0% of EGR (as reference) up to 30% (or max. as possible / or limited by combustion stability)

For each condition, a optimization in intake valve opening and closing (IVO / IVC) combined with VTG position optimization were performed in order to reach the optimum BSFC

The combustion phasing (MFB_50%) was controlled by spark advance in order to keep constant in 7°atdc (After Top Dead Center) or limited by knock or maximum cylinder pressure

The intake manifold temperature was controlled to keep around 40°C to 45°C

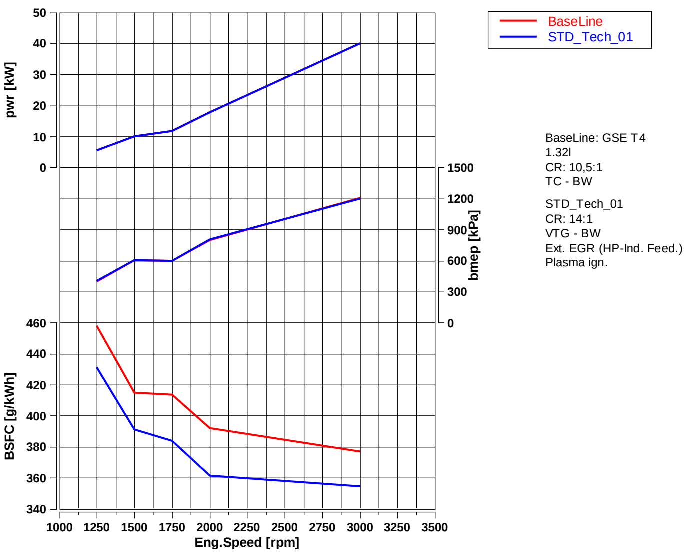

Figure 8 - BSFC measurement comparing baseline engine to standard technologies engine

A reduction in fuel consumption was observed for all operating points due to the addition of new technologies and, of course, the optimization of each one. For example, high CR (14:1), external cooled EGR (Individual Feeding), advanced ignition (for extended degrees of thermal pyrolysis of the fuel), advanced boosting (VTG) and new cylinder head port (for increase the tumble ratio → Better charge motion for high EGR rates).

	Reduction in BSFC (%)					
	1250rpm/4bar	1500rpm/6bar	1750rpm/6bar	2000rpm/8bar	3000rpm/12bar	Average
Std. Tech01	-5.9%	-5.7%	-7.2%	-7.7%	-5.9%	-6.5%
Std. Tech02	-4.1%	-1.9%	-6.8%	-5.4%	-2.9%	-4.2%
Std. Tech03	-6.0%	-5.6%	-7.0%	-6.9%	-3.8%	-5.9%

Figure 9 - Engine operating points and its fuel consumption reduction per each combination of technology

Baseline	Std. Tech01	Std. Tech02	Std. Tech03
BaseLine: 1.3l VVT	CR: 14:1	CR: 14:1	CR: 14:1
TGDI	VTG	VTG	VTG
CR: 10,5:1	Ext. EGR		Ext. EGR
TC	Advanced ign.	Advanced ign.	
Std. Cyl. Head	Cyl. Head modif.	Cyl. Head modif.	Cyl. Head modif.

Figure 10 - Description of each standard technologies

It was observed the standard technologies 01 an average BSFC reduction in order of 6.5%. Gains are related to the whole technologies implemented in the engine: new cylinder head (High tumble ratio), VTG turbine (Advanced boost control), External EGR (Mixture dilution, low heat rejection, fuel consumption reduction), High compression ratio (high brake efficiency) and advanced ignition (extended pyrolysis)

Standard Technologies 02 presented an average BSFC reduction in order of 4.2%. The gains observed in this investigation are lower than the standard technologies 01 due to the external EGR removal, which is responsible for at least 2.3% of BSFC reduction.

And for the standard technologies 03, the average BSFC reduction presented was 5.9%. The advanced ignition was removed during this investigation and could be observed that in high EGR rates there are higher IMEP covariance, which indicates low combustion stability. Extended pyrolysis provides high energy to the mixture during a longer time, which avoids misfire, even with high EGR content.

Hydrogen test in ETB

Reverend W. Cecil described the first effort at creating a hydrogen engine in 1820. In a paper titled "On the Application of Hydrogen Gas to Produce Moving Power in Machinery," Cecil presented his findings to the Cambridge Philosophical Society. The vacuum concept, in which atmospheric pressure forces a piston back against a vacuum to generate power, was used in the engine. The vacuum is formed by burning a hydrogen-air mixture and then letting it expand and cool. Although the engine worked well, vacuum engines were never practical.

The use of hydrogen as fuel in currently internal combustion engines remains a high challenger, nevertheless, it can use as an additional fuel to support the technologies reach a high diluted mixture with EGR. In this case, the hydrogen is able to avoid the early misfire occurrence due to its chemical properties, which increases the flame speed and heat released, for example.

The hydrogen investigation proposal is to evaluate the combustion behavior by hydrogen addition in a high EGR content dilution.

The focus of the investigation were the reference operating points in the table below (Table 2) and for each one was performed an EGR sweep combined to a H2% sweep starting from 0% of EGR (as reference) up to maximum EGR rate possible or limited by combustion stability.

Operating points	1250rpm	1500rpm	1750rpm	2000rpm	3000rpm
	4bar	6bar	6bar	8bar	12bar
Ext. EGR rate	5%	5%	5%	5%	5%
	10%	10%	10%	10%	10%
	15%	15%	15%	15%	15%
	20%	20%	20%	20%	20%
	25%	25%	25%	25%	25%
	30%	30%	30%	30%	30%

Table 2 - Reference lookup table for hydrogen test with engine speed, load and egr rate

H2
%VOL
0.5%
1.0%
2.0%
3.0%
4.0%
5.0%

Table 3 - Hydrogen volume percentage variation for engine test bed

Some assumptions were taken in order to simplify the test, reduce variables and focus the investigation on the combustion behavior as:

- The IVO selected was 390° (Fixed) in order to add the lowest internal EGR rate as possible
- The combustion phasing (MFB_50%) was controlled by spark advance in order to keep constant in 7,5°(atdc) or limited by knock or maximum cylinder pressure
- The intake manifold temperature was controlled according with the lookup table (Approximately 40°C)

In summary, the observed results are presented below:

Hydrogen addition resulted in combustion stability increasement for all tested speed/load combinations. However, IMEP COV values are higher than the threshold of 3% for 1250rpm-04bar, 1500rpm-06bar and 1750rpm-06bar with EGR rates higher than 20%.

Specific Energy Consumption (BSFC_MJ) presents higher values at high EGR and low H2 rates due to the lowest heat rejection resulting from this combination.

Cylinders #2 and #3 presents higher occurrence of combustion instability with high EGR rates.

EGR rate is limited to 30% at 2000rpm-08bar and 3000rpm-12bar due to hardware limitations.

Peak firing pressure limitation with high boost pressure and knock occurrence with low EGR rates / high H2 contents were observed at 3000rpm-12bar.

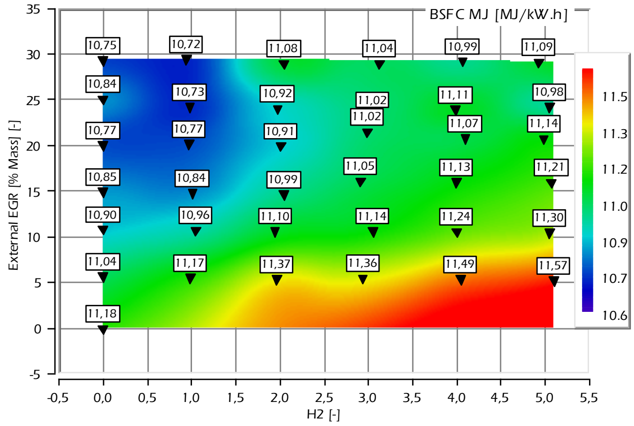

Figure 11 - Specific energy consumption @1250 rpm and 4bar (load)

BSFC MJ and ISFCH are calculated considering H2 + E100, decreases with EGR application as consequence of lower heat rejection. However, H2 application leaded to a reduction of conversion efficiency as average combustion temperature increases, as shown by NOx behavior in the picture below.

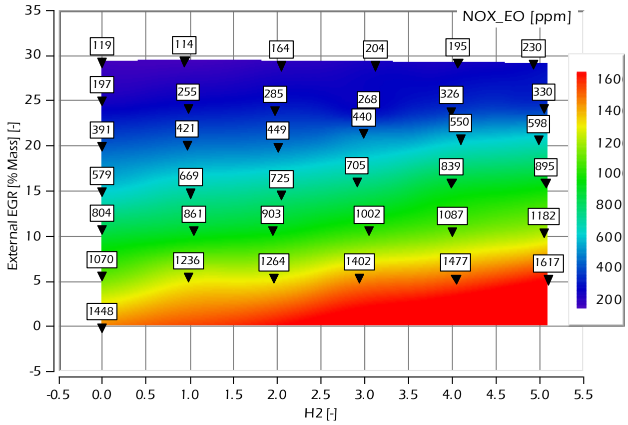

Figure 12 - Measurement of NOx in the engine out (EO) @1250 rpm and 4bar (load)

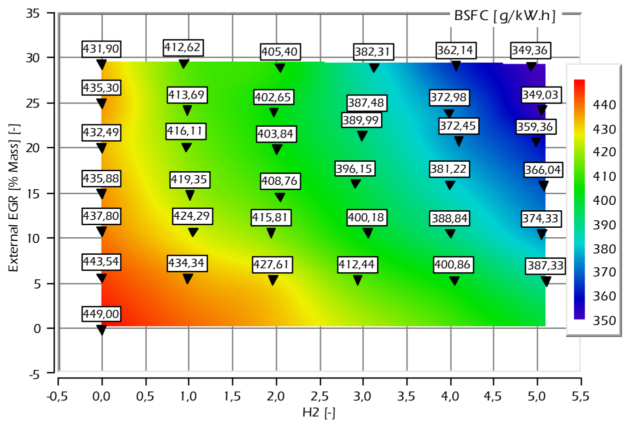

Figure 13 - BSFC measurement @1250 rpm and 4bar (load)

BSFC is calculated considering ethanol consumption as unique fuel source, and shows expected decrement as function of EGR and H2 addition:

- EGR reduces overall heat rejection to combustion chamber surfaces
- H2 application reduces ethanol consumption for the same BMEP

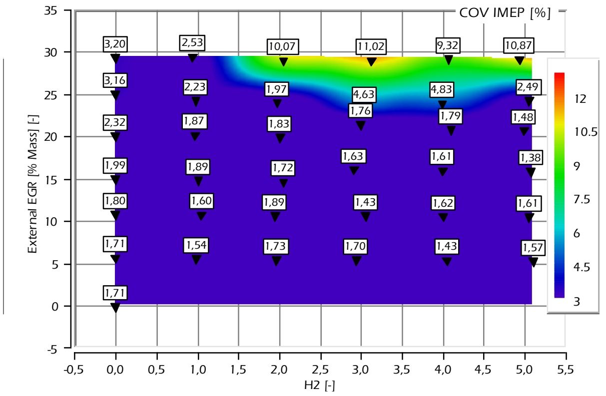

Figure 14 - Covariance of IMEP (Indicated Mean Effective Pressure)

Unexpected increment of IMEP COV with high H2 contents has been observed due to EGR/H2 dynamic distribution characteristics.

In order to summarize the hydrogen testing, we can say that the decarbonization of the global economy is one of the most pressing issues today. The key to overcoming this problem is to continue to expand renewable energy sources, as well as the concept of sector coupling, which entails integrating renewables into developed industry, energy, and mobility infrastructures via green hydrogen. Using reforming process, we produce "green" hydrogen from renewable energy, as ethanol, making a significant contribution to the global energy shift.

The addition of hydrogen provides excellent results as expected in high EGR rates. The benefits to use hydrogen diluted in EGR presents an overall fuel consumption reduction which only EGR cannot provide, even in the balance of dual fuel (Ethanol and Hydrogen). The benefits in combustion observed in the 1st phase, where it was tested the transparent engine, could be observed in the combustion results in the hydrogen test as an increase in flame speed, extension of the EGR dilution limits and an excellent reduction of fuel consumption.

4th phase

In the 4th phase, it was applied some correction in the EGR path and tested the reformer in the engine test bed.

ETB assessment

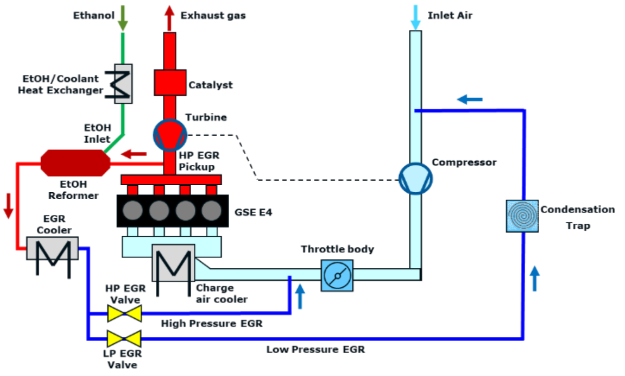

Figure 15 - Structure of the reformer unit in the engine configuration

1. **EtOH Reformer:** The first element in the complex hybrid EGR path is the reformer unit - located right next to EGR pickup, hence, retaining most of the available heat power from EGR stream
2. **EGR Cooler:** Hot reformed EGR gas must be cooled down to temperatures within EGR valve safe levels. Moreover, cooled EGR enhances compressor efficiency (in Low Pressure EGR) and reduces knock for both EGR layouts
3. **High Pressure EGR:** Provides the benefit of elevated pressure ratio in N/A operation are due to controlled intake manifold pressure at ~90% of atmospheric pressure. Therefore, high EGR rates are supported, and the added pressure drop from the reformer unit has no impact on BSFC benefit
4. **Low Pressure EGR:** Provides the benefit of maximized pressure ratio in turbocompressor operation area due to the low atmospheric pressure at compressor inlet compared to intake manifold boost pressure levels. However, a liquid condensation trap must be considered to avoid compressor wheel damage from droplets collision

The BSFC benefit was observed in the operation point 3000rpm/6 bar, which provide adequate conditions to the reforming process.

it is presented the additional reformer evaluation focused on the determination of its characteristics. The operating point selected was 5000rpm, which shows optimal environment condition for testing due to high temperature and reduced back flow.

The following strategy was applied to characterize reformer's behavior:

1. Baseline BSFC measurement

2. Steady state reforming measurement → The measurement starts only when all parameters are already stabilized
3. Transient state reforming measurement → Use the maximum temperature available for reforming process

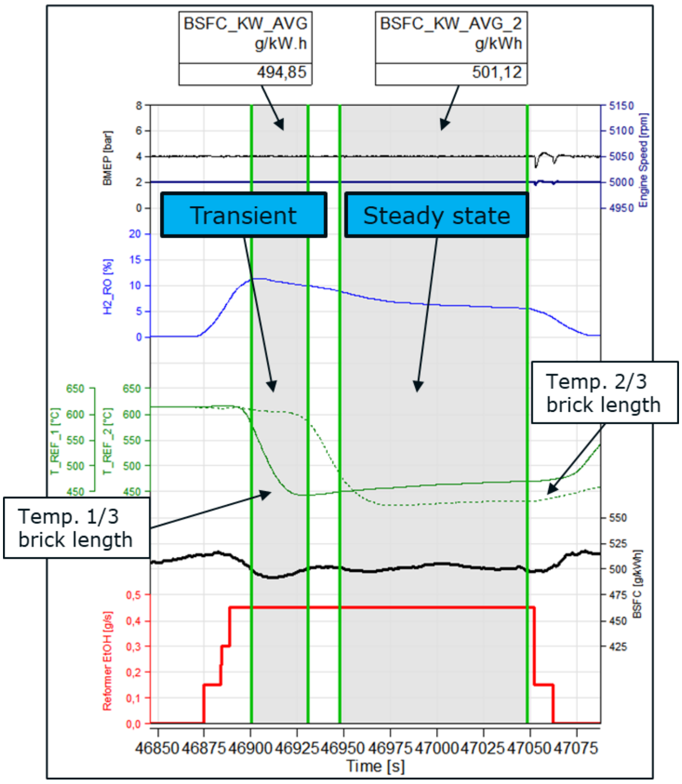

Figure 16 - Measurement over time in transient condition for 5000rpm and 4 bar of BMEP

Exhaust gas pulsation is one driver for reduction in overall BSFC benefit. Specific combinations of engine speed and load create high amplitude pulses in exhaust stream.

When normal (EGR only, no reforming) ICE operation results in unstable combustion, a higher BSFC advantage can be gained. In this specific condition, the products of the reforming process, particularly H2, boost combustion stability and result in a larger BSFC benefit (relative to LHV gain only).

The concept of Ethanol Reforming as waste heat recovery device has been proven as a potential technology to enhance global ICE efficiency, therefore reducing fuel consumption.

5th phase: Simulation of different concepts of ethanol reformer

The process of reforming is not simple and requires a specific condition to provide any benefit in fuel consumption.

In this sense and using the experience aggregate during the previous phases, which some devices of ethanol reformer were tested, it can be concluded that there is more than one possibility to deliver fuel consumption reduction using the wasted heat from the internal combustion engine. For many months, it was discussed with some companies to define the optimum device capable to improve the lower heat value of the ethanol converting it into hydrogen.

The efficiency of the reformers proposed were simulated in 0D and 1D and the configuration of each propose are presented below:

- C1 – Catalyst brick only: Simple brick coated with ethanol steam reformer technology
- C2 – Catalyst brick coupled with an ethanol vaporizer
- C3 – Catalyst brick coupled with an electric heater (e-cat)
- C4 – Heat exchanger: Single stage reformer recovering the heat after the TWC catalyst to improve the reformer process
- C5 – 2 stages heat exchanger: 1st stage reforming the ethanol using the heat in the EGR gas and 2nd stage recovering heat from the TWC catalyst installed in the opposite face of the reformer

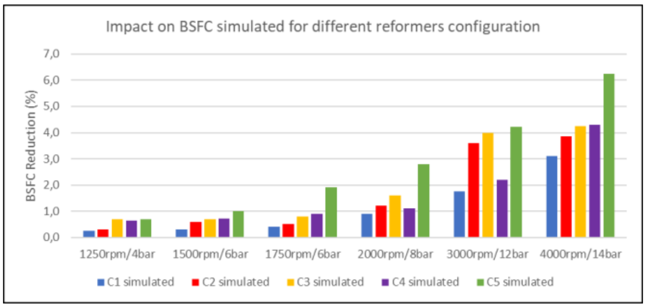

Figure 5 - Results of simulation between different types of reformers. Y-axis is referred to the reduction in BSFC

Conclusion

The growing demand for fuel consumption reduction and more efficient engines requires more complex powertrains. Several discussions are turning around electrification, nevertheless, due to the high cost of production, complexity, customer acceptance and non-sufficiently energy mix, the internal combustion engine will remain for some year.

However, the more restricted emissions legislation will require more efficient internal combustion engines. There are several ways to reduce fuel consumption in an internal combustion engine. However, in a flex-fuel engine, any modification reflects in fuel saving for both fuels.

The technology called ethanol reformer is dedicated only for this specific fuel and when coupled in an internal combustion engine, it can reformate only the ethanol due to the characteristics of the coating.

It was proved that using reformed-exhaust gas recirculation (R-EGR) and recovering the wasted heat available in the exhaust gas to improve the reforming process, it is possible to reduce the fuel consumption. Of course, in order to provide the values of fuel consumption benefits is required some tests and some methodologies to produce the heat exchanger.

The improvement in fuel consumption observed using standard technology in a base engine during the research given in this study, is on average 6,5%, however, at a sweet spot, the advantage can reach 8,5% of fuel consumption reduction. If the conditions for wasted heat recovery are met, the benefit of standard technologies combined with the ethanol heat exchanger reformer can give a 9% to 12% of reduction in fuel consumption in ethanol (FTP & HW combined cycles).

Acronyms

Acronyms	**Meaning**
EGR	Exhaust Gas Recirculation
FTP-75	Federal Test Procedure - Number 75
ICE	Internal Combustion engine
LHV	Lower Heat Value
CR	Compression Ratio
HEX	Heat Exchanger
s	Second
THC	Total Hydrocarbon
BSFC	Break Specific Fuel Consumption
R-EGR	reformed-exhaust gas recirculation
TGDI	Turbo Gasoline Direct Injection
DVVT	Doble Variable Valve Timing
VVL	Variable Valve Lift
CTB	Component Test Bed
ETB	Engine Test Bed
BMEP	Break Mean Effective Pressure
IMEP	Indicated Mean Effective Pressure
HWFET	Highway fuel economy test procedure
VTG	Variable Turbine Geometry
MFB	Mass Fraction Burned
ATDC	After Top Dead Center
ETOH	Ethanol
H2	Hydrogen
MJ	Mega Joules
IVO	Intake Valve Opening
IVC	Intake Valve Closing
HER	Heat Exchanger Reactor
CFD	Computer Fluid Dynamics
NA	Naturally Aspirated
TC	Turbocompressor
TWC	Three Way Catalyst

References

[1] CHEOLWOONG PARK, YOUNG CHOI, CHANGGI KIM, SEUNGMOOK OH, GIHUN LIM, YASUO MORIYOSHI (2008). PERFORMANCE AND EXHAUST EMISSION CHARACTERISTICS OF A SPARK IGNITION ENGINE USING ETHANOL AND ETHANOL-REFORMED GAS.

[2] TSOLAKIS, A. MEGARITIS, AND M. L. WYSZYNSKI (2003). APPLICATION OF EXHAUST GAS FUEL REFORMING IN COMPRESSION IGNITION ENGINES FUELED BY DIESEL AND BIODIESEL FUEL MIXTURES

[3] K. VASUDEVA, N. MITRA, P. UMASANKAR AND S. C. DHINGRA (1996). STEAM REFORMING OF ETHANOL FOR HYDROGEN PRODUCTION: THERMODYNAMIC ANALYSIS

[4] PERRY LEUNG, ATHANASIOS; TSOLAKIS, JOSÉ M. HERREROS; MIROSLAW L. WYSZYNSKI (2018). USING CATALYTIC HEAT RECOVERY TO IMPROVE EFFICIENCY OF GASOLINE SPARK IGNITION ENGINES

[5] BERNAY CIFUENTES, MANUEL F. VALERO, JUAN A. CONESA AND MARTHA COBO (2015). HYDROGEN PRODUCTION BY STEAM REFORMING OF ETHANOL ON RH-PT CATALYSTS: INFLUENCE OF CEO2, ZRO2, AND LA2O3 AS SUPPORTS

[6] V. KALYANA CHAKRAVARTHY, C. STUART DAW, JOSH A. PIHL AND JAMES C. CONKLIN (2010). STUDY OF THE THEORETICAL POTENTIAL OF THERMOCHEMICAL EXHAUST HEAT RECUPERATION FOR INTERNAL COMBUSTION ENGINES

[7] ATSUSHI SHIMADA, YUZO SHIRAKAWA, AND TAKAO ISHIKAWA (2016). IMPROVED THERMAL EFFICIENCY USING HYDROUS ETHANOL REFORMING IN ADVANCED SPARK-IGNITION ENGINES

[8] M. BOGARRAA, J.M. HERREROSA, A. TSOLAKISA, A.P.E. YORKB, P.J. MILLINGTONB, F.J. MARTOSC (2017). IMPACT OF EXHAUST GAS FUEL REFORMING AND EXHAUST GAS RECIRCULATION ON PARTICULATE MATTER MORPHOLOGY IN GASOLINE DIRECT INJECTION ENGINE