Development of a spark ignition engine coupled with an ethanol steam reformer (P-11H)

F. Weissinger, L. Possamai

[1] *AVL South America, Rua Antonio Utrilla 315 Cidade Industrial Satelite de SP, 07230-650 Guarulhos Brazil*

(1) Pres. author: frederico.weissinger@avl.com (1) Corresp. author: luis.possamai@avl.com

Keywords: Ethanol, Internal combustion engine, hydrogen, reformer

1. 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. As consequence more restrict global emissions legislation are being implemented in several markets requiring further complex developments on the engine design to attend the CO2 emissions limits.

Align with emissions legislations, several countries are adopting incentive programs to drive further automotive industry development with focus on the Greenhouse gases emissions reduction. With the same target Brazillian government has released the program ROTA 2030, as an evolution of INOVAR AUTO program (Brazilian automotive regime 12.996 Art. 41-B).

Aiming to support on this program was verified that currently in Brazil around 61% of the passenger cars sold in the market are equipped with flex fuel engine and even the gasoline fuel has 27% of ethanol in its composition, although the efficiency gap between ethanol and gasoline is around 30%, where any reduction on this gap would reflect directly in the air quality and envirolment quality. Then the strategy of this project is to reduce fuel economy gap between gasoline and ethanol under same engine operating conditions, improving ethanol operation according to INOVAR AUTO.

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 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.

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.

2. Experimental

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

2.1 1st phase

The 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

2.2 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.

2.3 3rd phase

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.

2.4 4th phase

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

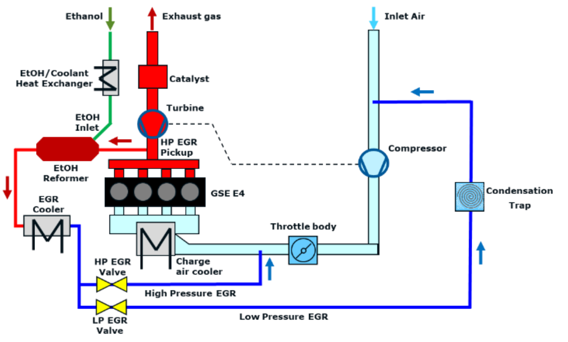

Figure 1 - Structure of the reformer unit in the engine configuration

During this phase, some important points were observed:

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

2.5 5th phase

In this phase, it was performed the 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.

3. Results

The important result from this study is mainly focused on the 4th and 5th phase. The 4th phase, as mentioned previously, in correct some path on the internal combustion engine and the tests of the ethanol reformer coupled on the ICE.

During the tests in the engine test bench, could be observed that, the BSFC benefit was measured 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

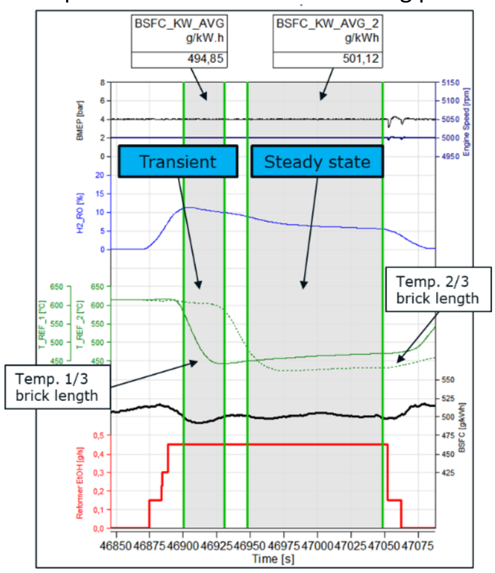

Figure 2 - Measurement over time in transient condition for 5000rpm and 4 bar of BMEP

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.

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

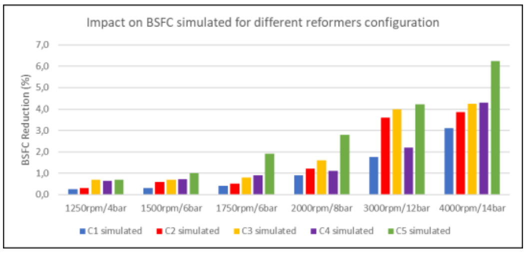

Figure 3 - Results of simulation between different types of reformers. Y-axis is referred to the reduction in BSFC

4. Conclusions

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 and in flex-fuel engines usually the modification reflects in fuel saving for both fuels.

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 reach a 9% to 12% range of reduction in fuel consumption running on 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 Hydrocarbons
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