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PERFORMANCES IMPROVEMENT OF A S.I. CNG BI-FUEL ENGINE BY MEANS OF DOUBLE-FUEL INJECTION

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ABSTRACT

Natural gas represents today a promising alternative to conventional fuels for road vehicles propulsion, since it is characterized by a relatively low cost, better geopolitical distribution than oil, and lower environmental impact. This explains the current spreading of Compressed Natural Gas (CNG) fuelled S.I. engine, above all in the bi-fuel version, i.e. capable to run either with gasoline or with natural gas. This characteristic, on the one hand, permits the vehicle to go even when natural gas is not available, on the other hand requires the engine to be designed to run safely with gasoline, i.e. with compression ratio lower than what natural gas would allow. Moreover the electronic control units are programmed to adopt rich mixture and poor spark advance when running with gasoline at medium-high loads, in order to prevent the engine from dangerous knocking phenomena: this causes an increase in fuel consumption and pollutant emissions. Starting from these considerations, the authors decided to investigate on the benefit attainable by means of a double-fuel injection, i.e. the injection of a certain amount of natural gas during the gasoline operation in order to increase the knocking resistance of the mixture and to run the engine with “overall stoichiometric” mixture even at full load, thus improving both engine efficiency and its environmental impact. To this purpose, the authors carried out an experimental campaign on the engine test bed, equipped with a fully instrumented series production bi-fuel spark ignition engine; the gasoline injection was managed by means of a real-time controlled ECU, while the simultaneous injection of natural gas was performed by means of IGBT transistors properly designed for fuel injection or spark timing control connected to a counter/timing PCI board. The results obtained fuelling the engine with both fuels in stoichiometric proportion with air show, with respect to the pure gasoline operation, considerable increase in fuel economy without remarkable power losses, while, with respect to the pure natural gas operation, only power improvements have been achieved: these advantages may lead the way to the adoption of the double-fuel injection in bi-fuel-engines.

INTRODUCTION

As is known gaseous fuels, such as Liquefied Petroleum Gas (LPG) and Natural Gas (NG), thank to their good mixing capabilities, allow complete and cleaner combustion than normal gasoline, resulting in lower pollutant emissions and particulate matter. Moreover the use of natural gas, mainly constituted by methane, whose molecule has the highest hydrogen/carbon ratio, leads also to lower CO_2 equivalent emissions. Some of the automobile producers already put on the market “bi-fuel” engines, which may be fed either with standard gasoline or with natural gas. These engines, endowed of two separate injection systems, are originally designed for gasoline operation, hence they do not fully exploit the good qualities of methane, such as its high knocking resistance [1], which would allow higher compression ratios. Moreover, when running with gasoline at medium-high loads, the engine is often operated with rich mixture and low spark advance in order to prevent from dangerous knocking phenomena: this produces both high hydrocarbon and carbon monoxide emissions (also due to the low catalyst efficiency caused by the rich mixture) and high fuel consumption. As example Figure 1 reports mixture strength (in terms of lambda values), HC and CO raw emissions acquired on the test bed running at full load a FIAT bi-fuel engine (whose characteristics are reported in Table 1) fuelled with gasoline: as can be seen the strong mixture enrichment operated by the series production ECU causes high HC and CO levels (for a comparison, the dashed lines represent the probable pollutant concentrations which would be measured with stoichiometric mixture). Figure 2 instead reports indicated and effective efficiencies (i.e. evaluated on the base of the IMEP and BMEP respectively) measured at WOT (Wide Open Throttle, i.e. full load) running the bi-fuel engine either with gasoline or with natural gas (best spark timing for both cases); due to the relatively low compression ratio, the engine may be fed with stoichiometric air-natural gas mixtures even at full load without knocking to occur, while, during gasoline operation, in order to prevent knocking, the mixtures adopted are those reported in Figure 1: this is the main cause of the strong difference in the measured efficiencies.

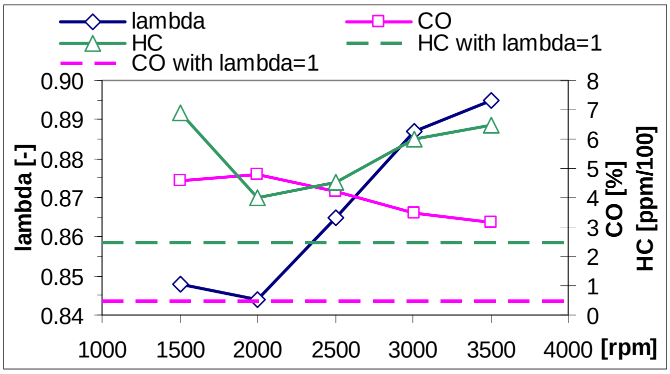

Figure 1 Pollutant raw emissions and mixture strength when running with gasoline at full load

Moreover, in the pure gasoline operation, even fuelling the engine with rich mixtures, the knock safe spark advance may be well below the optimal value and then compromise the efficiency of the thermodynamic cycle: this is confirmed by the measured LPP (Location of Pressure Peak) and MFB50 (location of the 50% of the mass fraction burned), reported in Figure 3, which, for best efficiency, should assume the values of 15° and 8° ATDC respectively [2].

Number of cylinders	4
Displacement [cc]	1242
Bore [mm]	70.80
Stroke [mm]	78.86
Compression ratio ρ	9.8
Rod to crank ratio μ	3.27
Intake valve/cylinder	1
Exhaust valve/cylinder	1
Gasoline Inj. system	Multi Point, Port Injection
CNG Inj. system	

Table 1 Main characteristics of the FIAT bi-fuel spark ignition engine used in the test

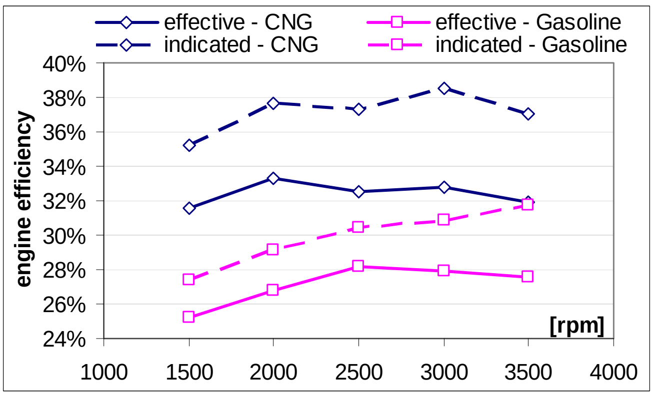

Figure 2 Indicated and effective efficiency for both gasoline (λ reported in Figure 1) and CNG (λ =1) operation at full load

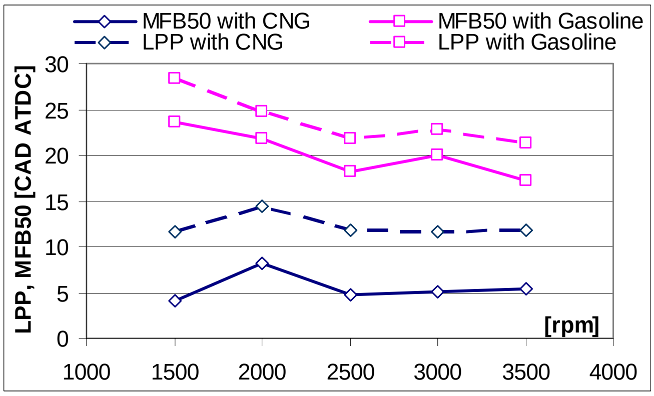

Figure 3 MFB50 and LPP values for both gasoline (λ reported in Figure 1) and CNG (λ =1) operation at full load

Starting from these observations, the authors decided to develop an innovative research concerning the simultaneous combustion of natural gas and gasoline in a spark ignition engine (here called "double-fuel" combustion); to this purpose, an experimental investigation was carried out fuelling the engine with gasoline-natural gas mixtures in stoichiometric proportion with comburent air, so as to exploit the good qualities of both fuels to obtain cleaner and more efficient combustions: the addition of natural gas to the gasoline-air mixture in fact raises knocking resistance, allowing thus to run the engine with both "overall stoichiometric" mixture and more efficient spark advance even at full load, with a strong increase in fuel economy. As example, Figure 4 shows the knock limited spark advances (i.e. the minimum between the MBT values and the knocking values) registered at full load for different CNG mass fractions (i.e. the ratio between the injected natural gas mass and the total fuel mass): as shown, increasing the amount of CNG added to the gasoline, boosts the engine knocking resistance (pure gasoline operation is represented for CNG mass fraction=0%).

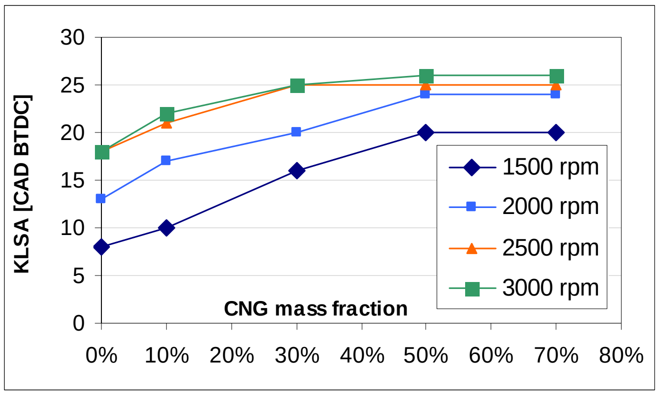

Figure 4 Knock Limited Spark Advance measured at WOT both for pure gasoline (CNG=0%, λ reported in Figure 1) and double-fuel combustion (overall λ =1)

Naturally, besides efficiency improvements, the stoichiometric combustion has the great advantage to minimize pollutant emissions with respect to the rich mixture combustion which normally takes place in a gasoline fuelled spark ignition engine at high load: this prerogative contributes to take into consideration the double-fuel combustion as a valid alternative to pure gasoline operation in bi-fuel engines.

MAIN SECTION

The aim of the present paper was to experimentally assess the advantages attainable by the simultaneous combustion of gasoline and natural gas, under different proportion between the two fuels and maintaining an overall stoichiometric air-fuel ratio. An experimental campaign hence was carried out at the engine test bed of the Department employing a four cylinders 8V 1242cc bi-fuel spark ignition engine from FIAT connected to a Schenck eddy current dynamometer W130; the engine was fed with gasoline-natural gas mixtures with different values of CNG mass fraction. A Walbro-TDD ECU connected to a personal computer was used to control in real time gasoline injection and spark timing, while the amount of natural gas injected was controlled operating the gas injectors through IGBT transistors activated by digital pulses sent using a National Instruments PCI-6602 Counter/Timer board programmed and controlled under LabVIEW. The gasoline mass flow was measured using a Endress+Hauser Coriolis effect PROMASS 80A, while the natural gas mass flow was deduced on the base of the real injection time using the injector flow chart, previously determined employing the Coriolis effect mass flow meter. In order to maintain the overall stoichiometric mixture with air, an ECM AFRecorder 2400 connected to a UEGO sensor placed in the exhaust duct was used. The in-cylinder pressure was measured using an AVL GU13X piezoelectric pressure sensor (installed by means of its ZC32 spark plug adaptor). A fundamental aspect in indicating analysis is the precise determination of the TDC position [3]: as is known, in fact, a 1 degree error (which can be introduced setting the TDC at the peak pressure position of a motored pressure cycle) can cause up to a 10% error in the IMEP estimation. In the experimental campaign carried out the TDC position was determined by means of the Kistler capacitive sensor 2629B, whose precision is of 0.1 Crank Angle Degrees (CAD). All the quantities were sampled by means of a high speed National Instruments DAQ Board PCI-6133 using as trigger and scan clock the pulses generated by a 360ppr incremental encoder connected to the engine crankshaft. As resumed in Table 2, the double-fuel combustion was tested under different conditions of engine speed, load (expressed by means of the Manifold Absolute Pressure, MAP) and CNG mass fraction. For each operative condition tested, the spark advance was chosen as the minimum between the MBT value and the knock onset spark advance. Knock occurrence was monitored by means of a piezoelectric accelerometer fastened on the engine block and connected to an oscilloscope.

Engine speed [rpm]	1500, 2000, 2500, 3000
Manifold Pressure [kPa]	100 (i.e. WOT), 90 and 80
CNG mass fraction [%]	10, 20, 30, 50 and 70
Overall A/F ratio	Stoichiometric
Spark Advance	knock limited or best torque

Table 2 Operative conditions tested

All the quantities measured or determined in the double-fuel mode were compared to those obtained for the pure gasoline and the pure natural gas mode in the same operative conditions of load and speed. Table 3 reports the mean composition and properties of the natural gas used in the test.

Methane – CH_4	88.539
Ethane – C_2H_6	6.519
Propane – C_3H_8	1.298
Carbon dioxide – CO_2	0.925
Nitrogen – N_2	2.176
Other	0.543
Density [kg/m^3]	0.7675
Lower Heat Value [MJ/m^3]	35.795

Table 3 Composition [% VOL] and properties of the Natural Gas used in the test

EXPERIMENTAL RESULTS

As example of the result obtained for a single operative condition, Figure 5 shows the indicated and effective efficiencies measured in double-fuel combustion at 2000 rpm and WOT. For a comparison, the effective efficiencies measured in the same operative condition of speed and load for the gasoline (red dashed line) and natural gas (blue dashed line) operation are reported; in this operative condition the double-fuel combustion permitted efficiency increments, with respect to the gasoline operation, in the order of 27% (i.e. 7 percentage points) for the effective and 29% (about 8 percentage points) for the indicated: these strong efficiency improvements have been obtained simply by means of the parallel actuation of both the gasoline and the natural gas injectors. It must be also pointed out, as for example shown by Figure 5, that no relevant efficiency losses were measured with respect to the pure CNG operation in all the operative conditions tested. As concerns engine performances, if on the one hand the addition of CNG to normal gasoline raises the knock resistance allowing to run with stoichiometric comburent air and better spark advance, on the other hand, being a gaseous fuel, it decreases the engine volumetric efficiency and hence its power output: this effect increases with increasing the CNG mass fraction, and, depending on the operative condition, may be counterbalanced by the improved thermodynamic efficiency due to the better combustion phasing. Figure 6 as example reports the results obtained at 2000 rpm and WOT in terms of both IMEP and BMEP. As shown the double-fuel operation maintained peak performances near to those measured with pure gasoline, causing the heavier power losses, as expected, for the higher CNG mass fraction.

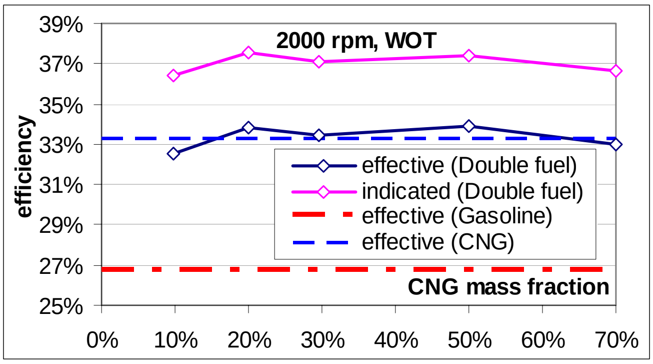

Figure 5 Indicated and effective efficiency for Double-fuel (overall λ=1), gasoline (λ=0.84) and CNG (λ=1) operation

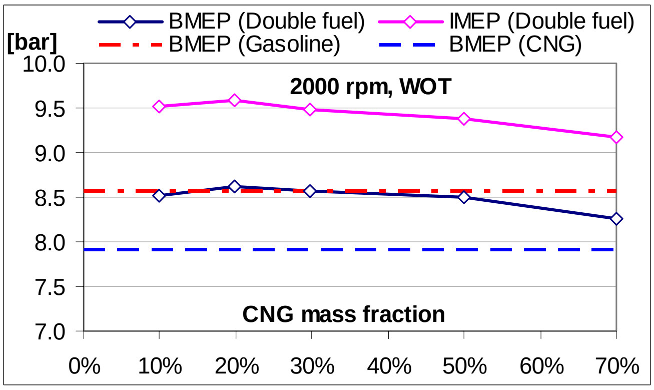

Figure 6 IMEP and BMEP for Double-fuel (overall λ=1), gasoline (λ=0.84) and CNG (λ=1) operation

It is worth to mention that a considerable power improvement has been obtained with respect to the pure CNG operation, even for the higher CNG concentration: the use of gasoline in place of part of the natural gas allowed in fact to raise the volumetric efficiency of the engine without compromising the thermodynamic cycle efficiency. Table 4 reports the increments, with respect to the pure gasoline mode, measured for IMEP, BMEP and engine efficiency at WOT and overall stoichiometric mixtures for all the engine speeds and CNG mass fractions tested. As shown, efficiency improvement moves between a maximum value of +26.9% and a minimum of +10.7%; moreover, it lowers with increasing engine speed, i.e. when the turbulence level in the combustion chamber is high enough to allow more advanced knock-safe combustions even with pure gasoline: Figure 3 in fact shows how the LPP progressively decreases toward the optimal value of 15° ATDC for the gasoline operation, that is how the combustion can be advanced increasing the engine speed. For these higher engine speed, hence, the advantage of the CNG addition to gasoline is above all related to the lower fuel consumption achieved with overall stoichiometric air-fuel mixture, rather then to a better thermodynamic cycle.

Engine speed [rpm]	CNG mass fraction	IMEP increment	BMEP increment	effective efficiency increment
1500	8%	-2.7%	-1.1%	17.5%
1500	19%	-2.2%	0.3%	21.0%
1500	30%	-0.9%	2.1%	24.0%
1500	51%	-0.9%	1.1%	26.9%
1500	70%	-3.4%	-1.4%	26.3%
2000	10%	-1.2%	-0.6%	21.6%
2000	20%	-0.5%	0.6%	26.3%
2000	30%	-1.6%	-0.1%	25.0%
2000	50%	-2.8%	-0.9%	26.6%
2000	70%	-4.8%	-3.6%	23.3%
2500	10%	-1.4%	-4.1%	13.3%
2500	19%	-1.6%	-2.7%	18.5%
2500	29%	-2.6%	-2.7%	18.0%
2500	50%	-4.4%	-4.0%	19.2%
2500	70%	-7.1%	-7.5%	16.8%
3000	10%	0.7%	-3.2%	10.7%
3000	21%	-1.7%	-0.9%	14.6%
3000	30%	-2.1%	-1.5%	14.5%
3000	50%	-4.6%	-2.7%	16.8%
3000	70%	-5.5%	-6.3%	14.6%

Table 4 Increments obtained with double-fuel combustion at WOT and overall λ=1

In order to assess the existence of an optimal value of the CNG mass fraction, Figure 7 and Figure 8 reports, for each of the engine speed tested, the effective efficiencies and the normalized power curves respectively for the different speeds investigated.

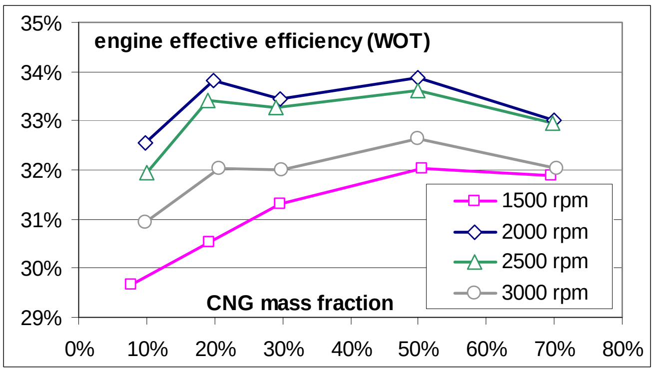

Figure 7 Effective efficiency measured in double fuel-mode at WOT and λ=1

It can be observed that, as concerns engine efficiency, the maximum is reached for a 50% natural gas mass fraction, apart from the engine speed: this means that, with this CNG concentration in the fuel mixture, the knock resistance becomes so strong to allow to place the combustion with the best phase (i.e. LPP=15° ATDC) thus obtaining, besides the stoichiometric mixture advantage, also the maximum benefit in terms of thermodynamic cycle. However, as reported in Table 4, considerable efficiency improvements with respect to the gasoline operation can be obtained even for the minimum CNG addition (10% mass fraction). As regards the power output, Figure 8 shows that the maximum can be found for CNG mass fractions between 20% and 30%.

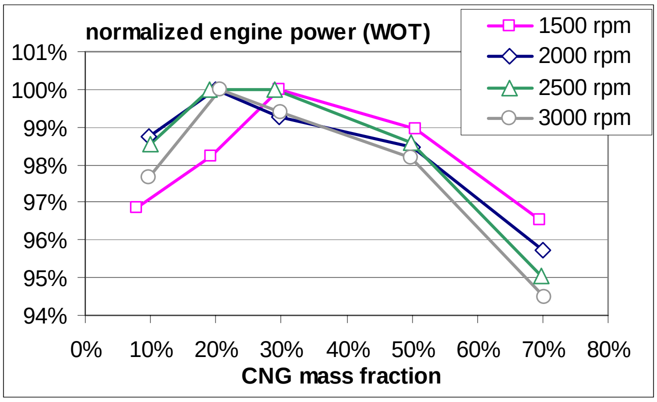

Figure 8 Normalized engine power measured in double-fuel mode at WOT and λ=1

To sum up, as regards the full load conditions, the double fuel mode proved to be advantageous with respect to both pure gasoline, in terms of engine efficiency, and pure natural gas, in terms of engine power, thus becoming a valid alternative combustion mode for bi-fuel engines. Focusing on the two mentioned CNG mass fraction of 50% and 30%, the graphs reported in Figure 9 and Figure 10 resume the IMEP, BMEP and efficiency increments measured with respect to the pure gasoline mode at WOT for all the tested engine speed (the broken line represents the pure gasoline engine efficiency). As also reported in Table 4, for a 50% natural gas fraction (maximum efficiency, Figure 9), the power loss never exceeds the 4%, which is lower than the usual 13% power loss connected to the use of CNG in place of gasoline in spark ignition engine. For a 30% CNG mass fraction (Figure 10) the efficiency increases are slightly inferior, as well as the power losses. The benefit gained by the double-fuel combustion at full load can however be considered as the highest, since in this condition knocking danger is higher and gasoline fuelled engines run with rich mixtures; decreasing the engine load, knocking becomes less dangerous and probable, and air-fuel mixture can return to be stoichiometric: these factors tend to reduce the benefit derived from the simultaneous combustion of gasoline and natural gas, as on the other hand is shown by graphs in Figure 11 and Figure 12, which report the efficiency increments measured with a 50% CNG mass fraction and manifold pressure of 90 and 80 kPa respectively. In these part load conditions, missing the benefit related to the mixture strength, which is stoichiometric also for pure gasoline operation, the only advantage in the addition of CNG to the gasoline relies in the possibility to advance combustion: as shown in Figure 12, at the part load condition of 80 kPa in the manifold, the maximum effective efficiency increment is lower than 6%.

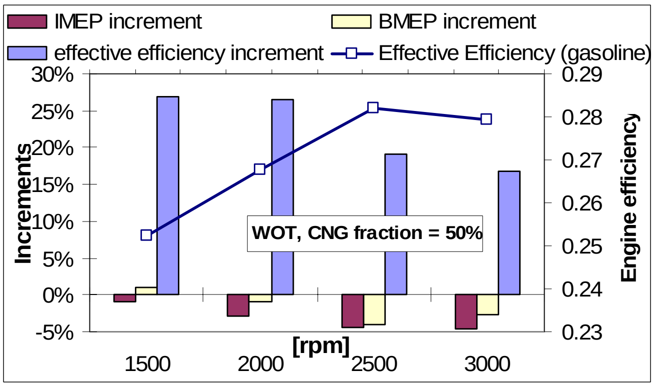

Figure 9 Improvements obtained at WOT and λ=1 with CNG mass fraction=50%

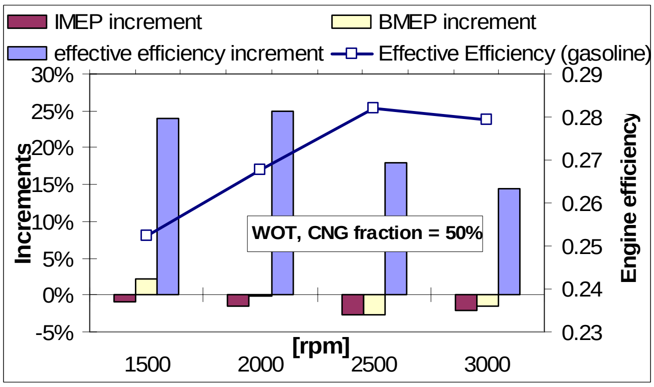

Figure 10 Improvements obtained at WOT and λ=1 with CNG mass fraction=30%

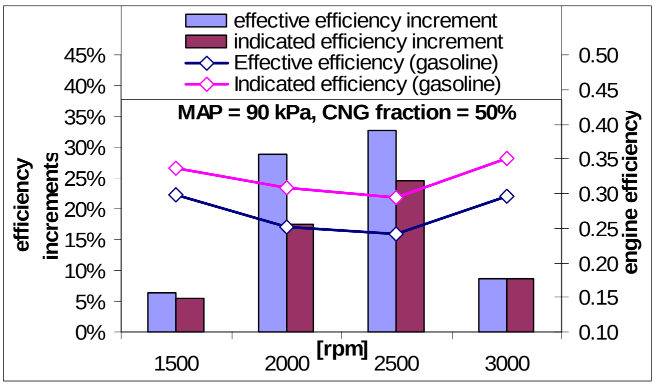

Figure 11 Efficiency improvements obtained with respect to gasoline (MAP=90 kPa, λ=1, CNG mass fraction=50%)

CONCLUSION

In this paper the authors present the results of an innovative research developed on the simultaneous combustion of natural gas and gasoline in a spark ignition engine; although there is no evidence of a similar work in the scientific literature, the combustion of natural gas-gasoline mixtures offers different advantages: in fact, the addition of natural gas to the gasoline effectively increases the knocking resistance of the engine, allowing thus to fed it with “overall stoichiometric” mixtures also in full load, which in turn allows to lower both fuel consumption and pollutant emissions (above all HC and CO). Moreover, the increased resistance to knock also allows to improve the thermodynamic cycle by advancing the combustion up to its best phase, which in turn implies a further improvement in terms of both IMEP and BMEP.

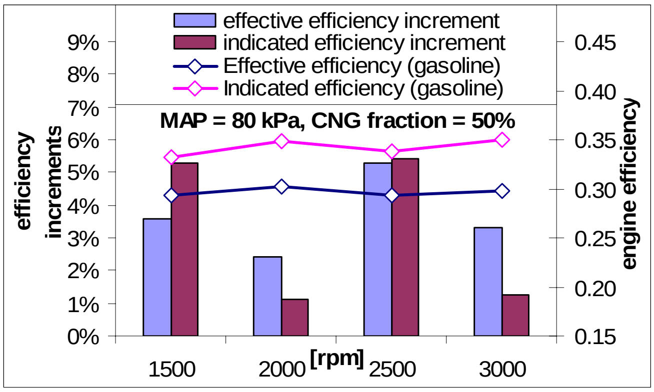

Figure 12 Efficiency improvements obtained with respect to gasoline (MAP=80 kPa, λ=1, CNG mass fraction=50%)

An extensive experimental campaign was carried out on the engine test bed equipped with a bi-fuel spark ignition engine, under different operative conditions of speed and load and employing natural gas-gasoline mixtures in many different proportion. The performance obtained by means of the double-fuel combustion, in terms of engine efficiency and power output, are here presented and compared to those achieved running the engine on pure gasoline. The results of this comparison show engine efficiency increments from 10% to 27% at full load and “overall stoichiometric” mixture, depending on the CNG concentration: the best results were observed for a CNG mass fraction (i.e. the ratio between the injected natural gas mass and the total fuel mass) of 50%. It is worth to mention that no relevant efficiency losses were measured with respect to the pure CNG operation in all the operative conditions tested. As regards the engine power, the increment with respect to the pure gasoline mode depends on two contrasting factors: in fact, if on one hand the addition of natural gas to gasoline raises the fuel knocking resistance, thus allowing to advance the combustion to a better phase and obtain a higher IMEP, on the other hand, being a gaseous fuel, it lowers the volumetric efficiency of the engine, thus causing a power loss. The results of the experimental tests showed that the two factors compensate each other, making the power increment to remain around zero: for the best efficiency condition, i.e. 50% CNG mass fraction, the maximum power loss with respect to the pure gasoline mode was found to be 4%, which is lower than the usual 13% power loss connected to the use of CNG in place of gasoline in spark ignition engine. The data collected also show that in the double-fuel mode, the engine reached its maximum power with a 30% natural gas addition. These encouraging results lead to consider the double-fuel combustion as a valid alternative to normal gasoline or CNG operation in bi-fuel engines.

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REFERENCES

1. J. B. Heywood, “Internal Combustion Engines Fundamentals”, McGraw-Hill automotive technology series, 1988, ISBN 0-07-100499-8
2. E. Pipitone, A. Beccari, “A Study on the Use of Combustion Phase Indicators for MBT Spark Timing on a Bi-Fuel Engine”, SAE Technical Paper 2007-24-0051
3. Pipitone E., Beccari A., “Determination of TDC in internal combustion engines by a newly developed thermodynamic approach. Part 2: assessment of the method and robustness test”, currently under review process, www.pipitone.dima.unipa.it/pubblicazioni.htm
4. A. Das, H. C. Watson, "Development of a natural gas spark ignition engine for optimum performance", Proc Instn Mech Engrs, Vol 211, Part D, 1997

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

A/F: Air to Fuel Ratio

ATDC: After Top Dead Centre

BMEP: Brake Mean Effective Pressure

BTDC: Before Top Dead Centre

CAD: Crank Angle Degree

CNG: Compressed Natural gas

CO: Carbon Monoxide

ECU: Electronic Control Unit
HC: Hydrocarbon
IMEP: Indicated Mean Effective Pressure
Lambda $= \lambda$ = Air Excess Index = $(A/F)/(A/F)_{stoichiometric}$
LPG: Liquefied Petroleum Gas
LPP: Location of Pressure Peak
MAP: Manifold Absolute Pressure
MBT: Maximum Brake Torque
MFB: Mass Fraction Burned
MFB50: Location of 50% of Mass Fraction Burnt
NG: Natural gas
TDC: Top Dead Centre
UEGO: Universal Exhaust Gas Oxygen
WOT: Wide open throttle (full load)