Supercharging the Double-Fueled Spark Ignition Engine: Performance and Efficiency

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Internal combustion engine development focuses mainly on two aspects: fuel economy improvement and pollutant emissions reduction. As a consequence, light duty spark ignition (SI) engines have become smaller, supercharged, and equipped with direct injection and advanced valve train control systems. The use of alternative fuels, such as natural gas (NG) and liquefied petroleum gas (LPG), thanks to their lower cost and environmental impact, widely spread in the automotive market, above all in bifuel vehicles, whose spark ignited engines may run either with gasoline or with gaseous fuel. The authors in previous works experimentally tested the strong engine efficiency increment and pollutant emissions reduction attainable by the simultaneous combustion of gasoline and gaseous fuel (NG or LPG). The increased knock resistance, obtained by the addition of gaseous fuel to gasoline, allowed the engine to run with stoichiometric mixture and best spark timing even at full load. In the present work, the authors extended the research by testing the combustion of gasoline–NG mixtures, in different proportions, in supercharged conditions, with several boost pressure levels, in order to evaluate the benefits in terms of engine performance, efficiency, and pollutant emissions with respect to pure gasoline and pure NG operation. The results indicate that a fuel mixture with a NG mass percentage of 40% allows to maximize engine performance by adopting the highest boost pressure (1.6 bar), while the best efficiency would be obtained with moderate boosting (1.2 bar) and NG content between 40% and 60% in mass. [DOI: 10.1115/1.4036514]

Keywords: supercharging, spark ignition engine, natural gas, fuel mixtures

1 Introduction

The research in the field of internal combustion engines pursuits two main targets: fuel economy improvement and pollutant emissions reduction, with the aim to fulfil the increasingly stringent environmental regulations and reduce harmful pollution in urban area, where, in some cases, will be even forbidden the access to diesel fueled vehicles. These targets induced, in the last decades, the introduction of many innovations in the automotive market. Advanced valve train control systems [1–3], such as variable valve timing and/or actuation, allow to maximize engine volumetric efficiency in a wide range of operative conditions as well as to obtain unthrottled part load operation, thus reducing pumping losses and fuel consumption.

Gasoline direct injection [4] allows to increase power and reduce pollutant emissions, especially in transient or cold-start operation, as well as to perform stratified charge with the aim to further increase fuel economy. Engine downsizing [5], usually coupled with supercharging [6–9], as well as optimal management of continuous variable transmission (CVT) [10,11], allows to increase vehicle fuel economy and torque at low rpm (fun to drive) maintaining adequate power levels. Nowadays, the above mentioned technical solutions are often implemented together to obtain the maximum benefit in engine efficiency and pollutant emissions. Fuel properties and combustion process have a fundamental impact on both the amount and kind of pollutants emitted. Diesel fueled engines mainly suffer for high particulate matter and NO_x emissions, while gasoline fueled spark ignited engines produce primarily carbon monoxide (CO) and unburned hydrocarbons (HC), above all in full load operations. Gaseous fuels, such as NG and LPG, thanks to their higher knock resistance and superior mixing capabilities, allow cleaner and more efficient combustion in SI engines, characterized by lower emissions of CO and HC and almost negligible level of particulate matter. A slight mixture enrichment and spark advance regulation allow to keep also NO_x emissions at acceptable levels. For the same reason, gaseous fuels allow higher compression ratios even in supercharged configuration, resulting in increased engine efficiency and power density. Other attractive features of gaseous fuels are the low cost and uniform geopolitical availability, while their main drawback is related to the relatively low density, which reduces engine volumetric efficiency, and hence power density, of port injected engines. This drawback, however, may be amply counterbalanced by the allowed supercharging levels, or, in some cases, by fuel direct injection [12].

For the above mentioned reasons, gaseous fuels [13–15] as well as liquid fuel mixtures [16] have been deeply studied with the aim to experience their compatibility and properties as alternative fuels for spark ignition engines. Many researchers carried out studies on the use of methane or hydrogen [17], as well as mixtures of gaseous fuels, such as natural gas, with particular attention to efficiency improvement, pollutant emissions, and on the effects of the variation of its chemical composition [18]. Moreover, in recent years, the ethanol–gasoline blends have been extensively studied [16,19,20] and are quite spread in north and south America automotive market.

The authors of the present paper showed in previous works [21,22] that the addition of gaseous fuel (LPG or NG) to gasoline in a naturally aspirated SI engine allows to obtain, with respect to pure gasoline operation, a sharp increase in engine efficiency (+26%) together with a drastic reduction (−90%) of unburned total hydrocarbon (THC) and carbon monoxide (CO) emissions with almost unchanged power output (−4%). Such results were made possible thanks to the higher knock resistance of the gaseous fuel which, added to gasoline, allowed to employ an overall stoichiometric proportion with air and optimal spark advance up to the full load condition, thus minimizing both pollutants and fuel consumption. It was also determined that, in the naturally

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aspirated SI engine, a fuel mixture with a gas mass percentage of about 30% produced the maximum torque, while a mass concentration of 50% allowed to obtain the best engine efficiency.

The addition of gaseous fuel (LPG or NG) to gasoline is particularly easy to implement in bifuel engines, where a double injection system is already available and a simple software modification of the electronic control unit (ECU) is required to inject both gasoline and gaseous fuel within the same engine cycle. The simultaneous combustion of gaseous fuel and gasoline has been named double fuel (DF), being quite different from the well-known dual fuel combustion, in which, instead, the auto-ignition of a small quantity of one of the two fuels (the most reactive) ignites the flame propagation combustion of the second fuel.

As a further development of their previous work, in this paper, the authors aim to evaluate the advantages connected to supercharging the double-fueled SI engine, compared to single fuel operation, by the use of several boost pressure levels.

As known, supercharged gasoline fueled SI engines are seriously limited by the knock tendency of the fuel, which can be resumed by its octane numbers, obtained by the motor method (MON) or by the research method (RON). To avoid dangerous knocking phenomena, supercharged gasoline fueled SI engines adopt reduced volumetric compression ratio with respect to naturally aspirated versions, and in medium–high load conditions are operated with very rich air–fuel mixtures and poor spark advances, with the aim to cool down the charge and lower the end-gas temperature; the result is a high fuel consumption together with high levels of pollutant emissions, also due to the very low efficiency exhibited by catalytic converter when using rich mixtures. The double-fuel operation mode, instead, due to the higher knock resistance, allows to run the engine with stoichiometric fuel–air mixtures with obvious advantages in terms of engine efficiency and pollutant emissions.

In recent years, the application of double-fuel combustion to turbocharged SI engines has been investigated also by other researchers. Obiols et al. [23,24] tested gasoline–NG fuel mixtures in a 2 l turbocharged SI engine, experiencing torque increments with respect to both gasoline and pure NG operation, with almost the same engine efficiency of pure NG mode.

Momeni Movahed et al. [25] investigated the benefits of gasoline–NG mixtures with respect to pure NG in a turbocharged SI engine, establishing that a fuel mixture with 30% NG mass fraction produced a small reduction of engine efficiency with respect to pure NG mode but a great reduction of both NO_x raw emissions and heat transfer to the engine coolant.

In the mentioned works, however, the boost pressure could not be controlled or modified, being the result of the interaction between the engine and the embedded turbocharging system: this aspect effectively limited the variety of the test conditions explored. It follows that a methodical study which considers the effect of supercharging with several different boost pressure levels on the performances attainable by a spark ignition engine fueled with natural gas–gasoline mixture is not available in the scientific literature: starting from this consideration, the authors carried out a wide set of experimental tests on a commercial SI engine, fueled with gasoline–NG mixtures and supercharged by the use of a Roots compressor powered by an electric brushless motor, thus evaluating performance improvements with respect to pure NG mode and efficiency and exhaust emissions (HC and CO) improvements with respect to pure gasoline operation, for different supercharging levels.

2 Experimental Setup

A fully instrumented test bench equipped with a FIAT bifuel spark ignition engine (whose characteristics are resumed in Table 1) connected to a Schenck W130 eddy current dynamometer has been endowed of an independent supercharging system, composed by a Finder Roots compressor BLW 80-2 powered by a Control Techniques brushless AC servomotor, whose speed was feedback controlled to obtain each desired manifold absolute pressure (MAP); a simple PID controller was employed to maintain the measured MAP value to the desired set point by adapting the compressor speed to each single operative condition of the spark ignition engine. As shown in Fig. 1, where a representation of the test bench layout is reported, an intercooler was employed to maintain the inlet air temperature variation within 10 °C from mean value. The authors took advantage of the original double injection system of the bifuel engine (endowed of four EV6 injectors for gasoline operation and four EV1 injectors for natural gas) to obtain NG–gasoline mixtures of any desired composition by simply acting on the injection times of the two fuels, whose specifications are resumed in Table 2.

Table 1 SI engine specifications

Number of cylinders	4
Displacement (cc)	1242
Bore (mm)	70.80
Stroke (mm)	78.86
Compression ratio	9.8
Rod to crank ratio	3.27
Intake valve/cylinder	1
Exhaust valve/cylinder	1
Gasoline injection system	PFI, Bosch EV6
NG injection system	PFI, Bosch EV1

In the test performed, the composition of the fuels mixture was identified by the natural gas mass fraction (defined as the ratio between the mass of the natural gas and the total mass of fuels injected), which has been varied between 0% (i.e., neat gasoline), 40%, 60%, 80%, and 100% (neat NG), as resumed in Table 3.

As expected, when running with neat gasoline, the engine could not be supercharged, on account of dangerous knocking phenomena: using only gasoline, hence, the manifold absolute pressure was always set to 1.0 bar.

Even the fuel mixture with 20% of NG mass fraction revealed not suitable for the test, since such a low content of NG did not allow supercharging pressure higher than 1.2 bar due to heavy knocking phenomena. The use of mixture with a higher content of natural gas (40% at least) allowed, instead, to supercharge the engine with MAP values up to 1.6 bar.

It must be pointed out that the engine used for the test was not produced and equipped to be supercharged; this put a limit to the supercharging pressure, whose maximum allowable value (1.6 bar) was determined when the in-cylinder peak pressure reached 90 bar

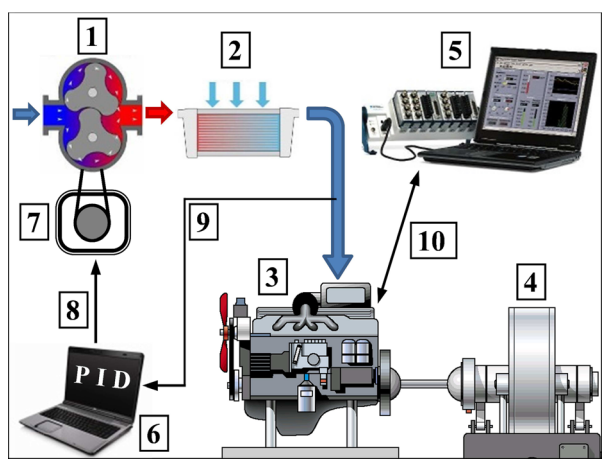

Fig. 1 Test bench layout: (1) Roots supercharger, (2) intercooler, (3) SI engine, (4) eddy current dynamometer, (5) data acquisition and engine control system, (6) feedback PID controller for brushless actuation, (7) brushless AC motor, (8) brushless speed control signal, (9) boost pressure sensor signal, and (10) engine control inputs and sensors output signals

Table 2 Fuels' properties

Gasoline	
Liquid phase density at 15 °C (kg/m^3)	740
Equivalent H/C ratio [26]	1.85
Stoichiometric air/fuel mass ratio	14.7
Lower heating value (MJ/kg) [27]	43.4
Motor octane number	85
Natural gas	
Methane volumetric concentration	85%
Hydrogen/carbon ratio	3.76
Stoichiometric air/fuel mass ratio	16.9
Lower heating value (MJ/kg) [28]	46.67
Measured MON [29,30]	122.1

Table 3 Operative conditions tested

Engine speed (rpm)	From 1500 to 5000 with steps of 500
MAP (bar)	1.0, 1.2, 1.4, 1.6
Inlet temperature (°C)	28 ± 10
NG mass fraction (%)	0, 40, 60, 80, 100
Overall air/fuel ratio	Stoichiometric
Spark advance	Optimal

(averaged over 100 consecutive cycles), as reported in Ref. [8]. Also the engine valve timing posed a problem, since it was optimized for the naturally aspirated operation, with a valve overlap which, in supercharging mode, determined a certain "blow-through" of fresh air–fuel mixture in the exhaust duct. As will be discussed further on, this strongly influenced the THC exhaust emissions.

For each fuel mixture and MAP level, the engine speed was varied from 1500 to 5000 rpm with steps of 500 rpm: hence, as resumed in Table 3, a total of 136 operative conditions were investigated by the authors. The aim of this large set of experimental data is to provide an extensive knowledge of the improvements attainable by supercharging a small displacement SI engine fueled by NG–gasoline mixtures.

A Walbro-TDD ECU connected to a personal computer was used to control both spark timing and gasoline injection. Natural gas injection, instead, was controlled through a National Instruments PCI6602 Counter/Timer board (programed in LABVIEW) connected to proper insulated gate bipolar transistor (IGBT) transistors. As mentioned before, this layout allowed to pursue two fundamental tasks: realize any desired proportion between the two fuels and control the overall air–fuel ratio, thanks to the real-time mass flow measurement of both air and fuels; to the purpose, two Coriolis effect mass flow meters (Endress + Hauser PROMASS and Bronkhorst mini CORI-FLOW) were employed to measure each fuel mass flow, while a vortex flow meter Endress + Hauser Prowirl was used to measure the air flow introduced in the engine. For each of the two pure fuels, the stoichiometric air/fuel ratio (A/F) was determined in naturally aspirated operation using an ECM AFRecorder 2400 connected to a universal exhaust gas oxygen (UEGO) sensor placed in the exhaust duct.

The overall A/F was maintained to the stoichiometric value both in the double-fuel test and in the neat natural gas test, in order to maximize engine efficiency with minimal environmental impact. When running with pure gasoline, instead, A/F was maintained to the original values prescribed by the engine manufacturer to avoid dangerous knocking phenomena: Fig. 2 shows the relative air/fuel ratio (λ) used in pure gasoline operation.

A Motorscan 8020 analyzer was employed to measure both carbon monoxide (CO) and unburned total hydrocarbon (THC) in the exhaust gas.

The in-cylinder pressure was measured using a flush mounted AVL GU13X piezoelectric pressure sensor. For each operative condition tested, 100 consecutive pressure cycles were sampled and employed to evaluate the mean values of both indicated mean

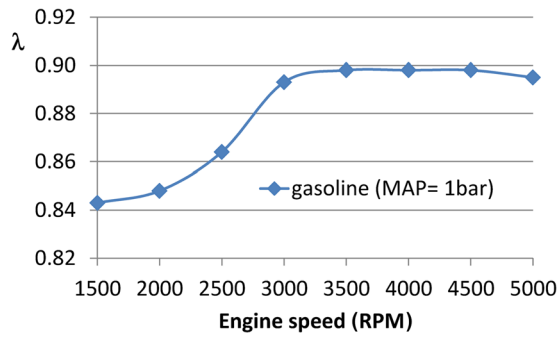

Fig. 2 Relative air/fuel ratio λ adopted for pure gasoline operation

effective pressure (IMEP) and indicated thermal efficiency (ITE). As known, a fundamental aspect in indicating analysis is the correct[1] determination of the top dead center (TDC) position [32], which can be accomplished by the use of proper instruments or by thermodynamic methods [32]: in this work, the authors carefully fulfilled this task by means of a Kistler capacitive sensor 2629B, whose precision is 0.1 CAD.

All the sensors' output signals were sampled by means of a high-speed National Instruments PCI-6133 DAQ Board using as trigger and scan clock the pulses generated by a 360 ppr incremental encoder connected to the engine crankshaft.

For each operative condition tested, the optimal spark advance, i.e., the minimum allowed value for best efficiency, was adopted by setting the location of in-cylinder pressure peak (LPP) as near as possible to 15 crank angle degrees (CAD) after top dead center (ATDC) without causing knocking phenomena: this procedure, well known in SI engine calibration and control, allows to quickly determine the optimal combustion phase in spark ignition engines, apart from the particular fuel employed, the engine wear, the different ambient conditions, etc. [31,33]. Knock occurrence was monitored by means of a Brüel & Kjær Cubic DeltaTron piezoelectric accelerometer fastened on the engine block, whose output signal was observed on a 100 MHz Agilent oscilloscope.

Being the supercharging system adopted in the test independent from the spark ignition engine, its power consumption did not affect directly the engine power output; this made the measured brake mean effective pressure (BMEP) and brake thermal efficiency (BTE) not representative of the real engine performance and efficiency.

The power consumption of the supercharging system was not employed anyway to obtain the effective power produced by the engine due to the following considerations:

(1) The compressor speed of rotation was varied by the PID controller to obtain constant MAP values, apart from engine speed and fuel mixture, thus causing a continuous change of the compressor-engine "speed-ratio" resulting in compressor efficiencies far from best values and out of line with conventional mechanical supercharging devices.
(2) The measurable electric power consumption of the supercharging system included the efficiency of the brushless AC servomotor, whose contribution could not be separated.

Consequently, the engine performance and efficiency have been expressed in terms of the indicated parameters IMEP and ITE, respectively, both evaluated, as mentioned before, on the basis of the mean pressure cycle measured for each operative condition tested.

[1]A TDC reference error of just 1 deg, which can be easily introduced by setting the TDC position at the peak pressure position of a motored pressure cycle, can cause up to a 10% error in the IMEP estimation [31].

3 Results and Discussion

This section presents the results of the experimental tests, divided into three subcategories: indicated mean effective pressure, efficiency, and pollutant emissions.

Being the aim of this work the evaluation of the effect of supercharging on the performance attainable by double-fuel combustion, also in comparison to single fuel operation, the results here presented are collected into diagrams, one for each fuels mixture tested, reporting the progress of the performance parameter (e.g., IMEP) as a function of engine speed, with one data series for each different boosting pressure (MAP) employed.

It is worth to remember that the double-fuel combustion has advantages with respect to both single fuel operation [21]: when compared to pure gasoline operation, as already mentioned, the advantage relies on the possibility to run the engine with overall stoichiometric mixture even at full load, thus strongly improving both engine efficiency (+26%) and pollutant behavior (−90%); when compared to gaseous fuel operation, instead, the advantage relies on the increased power output, due to the better volumetric efficiency obtained by substituting part of the gas with gasoline. According to these considerations, in the diagrams reporting the measured IMEP, the increment with respect to pure NG operation is also shown, with the aim to allow a direct evaluation of the advantage mentioned before. As regards the efficiency results, instead, the increment is calculated with respect to pure gasoline operation, with the aim to immediately highlight the benefit connected to the use of DF combustion in place of only gasoline, which could be hence considered for new supercharged low-emissions engines.

3.1 Indicated Mean Effective Pressure. To take account of the intake temperature variations occurred during the test, the measured IMEP values were corrected according to the usual procedure followed on engine test benches:

$$\mathrm{IMEP} = \mathrm{IMEP}_m \cdot \sqrt{\frac{T_m}{T_r}}$$

where the subscript m denotes the measured values, while T_r represents the reference temperature, assumed as the mean value recorded during the test (28 °C, as reported in Table 3).

As a result, the corrected IMEP values obtained by alternatively using the two pure fuels are reported in Fig. 3 (gasoline is obviously present with only 1 bar MAP). As expected, for the same MAP, the engine exhibits an higher IMEP when fueled with gasoline, thanks to the better volumetric efficiency.

In the same diagram, the dispersion of the experimental data is also reported in terms of standard deviation bars. The amplitude of each bar, hence, represents the standard deviation evaluated over the 100 consecutive values measured for each operative condition tested. It is worth to point out that the measured data dispersion is related only to normal combustion instability and not to measurement errors, since the pressure measurement chain has been periodically checked during the test. As can be observed in Fig. 3, in the pure fuels test, no evident variation of the data dispersion was encountered with varying MAP levels.

As regards the double-fuel operation, Figs. 4–6 report, for each fuels mixture tested, the corrected IMEP values, together with the IMEP increment evaluated with respect to pure NG operation for the same MAP level. The standard deviation bars are also shown for each operative condition tested.

As can be noted, the double-fuel combustion benefits from supercharging similarly to the neat NG operation, being the performance increments obtained with higher MAP, comparable with the increments recorded with pure NG of Fig. 3.

It can also be observed that, among the different fuel mixtures tested, the 40% NG mixture gave rise to the higher IMEP increments with respect to pure NG (Fig. 4), with an average increment of 6% and peaks above 10%. With mixture containing a higher concentration of NG, the IMEP increment revealed lower, as attested by the diagrams in Figs. 5 and 6.

More in detail, Fig. 5 shows that the IMEP variations with respect to pure NG mode are almost positive from 1500 to 3500 rpm, with a marked decay for higher engine speed, while the 80% NG mixture showed a limited mean IMEP increment (around 1%) due to the decreased volumetric efficiency caused by the high NG content in the mixture. Hence, double-fuel supercharging has a marked advantage over pure NG supercharging if the NG concentration remains between 40% and 60%. A very similar result was obtained in previous experimental tests [21] carried out on a

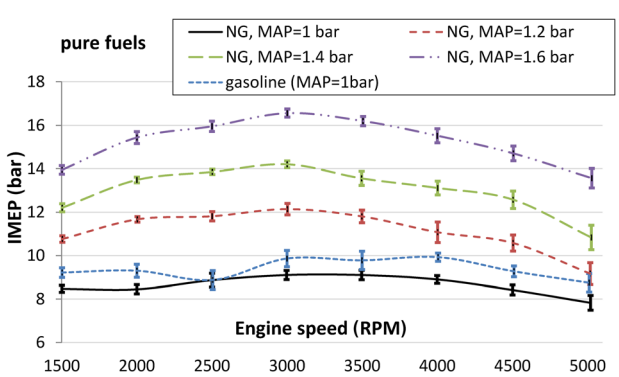

Fig. 3 IMEP results for both pure NG and pure gasoline (st. dev. bars are also reported)

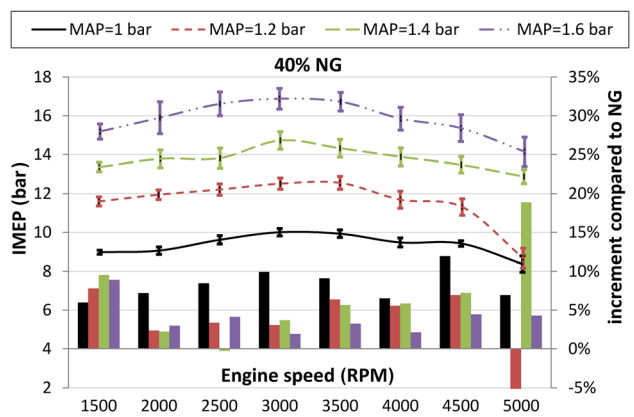

Fig. 4 IMEP, and its increment with respect to pure NG mode, for the 40% NG fuel mixture (st. dev. bars are also reported)

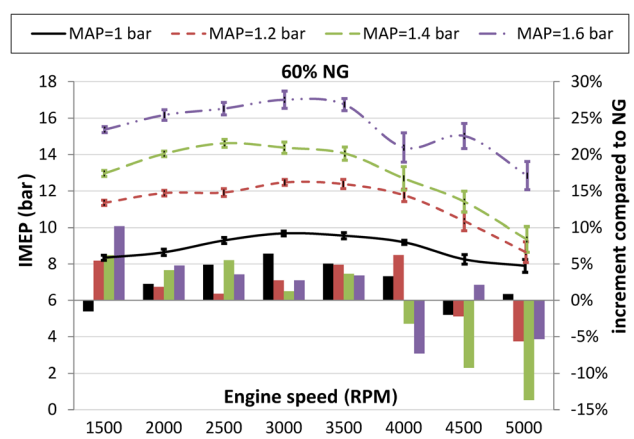

Fig. 5 IMEP, and its increment with respect to pure NG mode, for the 60% NG fuel mixture (st. dev. bars are also reported)

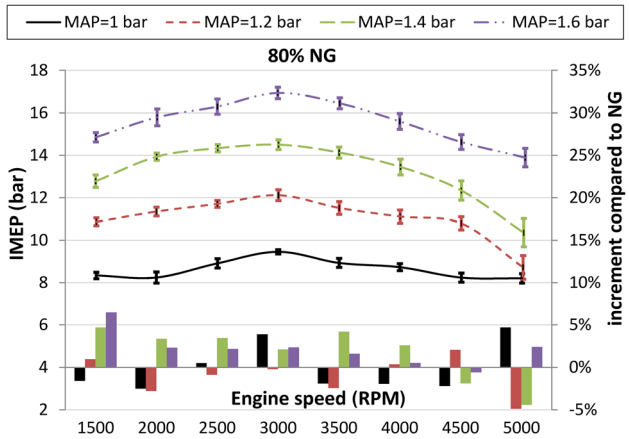

Fig. 6 IMEP, and its increment with respect to pure NG mode, for the 80% NG fuel mixture (st. dev. bars are also reported)

naturally aspirated engine, where the 30% NG mixture was found to produce the higher brake power increment with respect to pure NG operation.

For the higher NG concentration, however, even if with a negative variation with respect to pure NG operation, supercharging always produced clear IMEP improvement with respect to naturally aspirated mode.

As regards the combustion stability in the double-fuel test, Figs. 4–6 clearly show a marked effect of the boost pressures on the IMEP standard deviation. This has been explained with the progressive combustion phase retard which was necessary to avoid knocking phenomena when increasing MAP level, as will be discussed in the next paragraph.

3.2 Engine Efficiency. Figure 7 reports the indicated thermal efficiency measured with both pure fuels (gasoline is present with only 1 bar MAP) as a function of engine speed; the efficiency increments with respect to pure gasoline operation are also reported, as already discussed above. The standard deviation bars are also shown for each operative condition tested.

The efficiency measured with gasoline ranged from 0.28 to 0.33 due to the rich air–fuel mixture (reported in Fig. 2) employed to avoid dangerous knocking; the use of NG for the same MAP, instead, thanks to the stoichiometric proportion with air, revealed an almost constant efficiency of 0.35 up to 4000 rpm, followed by a decrease which was encountered also with higher MAP levels: this behavior can be explained considering that methane is characterized by a lower flame propagation speed with respect to gasoline, which further reduces when pressure increases [34]. At higher engine speed, hence, due to the faster expansion stroke, the combustion of methane did not arrive at completion, resulting hence in an efficiency loss. Considering all the MAP tested in Fig. 7, the use of pure NG brought to a 13% average efficiency increment compared to pure gasoline, with peaks up to 30% at 2500 rpm (as reported by the bar chart of Fig. 7), where the tested engine is characterized by a poor gasoline–air mixture formation.

The results concerning the double-fuel operation are represented in the diagrams reported from Figs. 8–10. In particular, Fig. 8 shows the indicated thermal efficiency measured with the 40% NG mixture: the average increment, compared to pure gasoline, revealed of 11%.

The experimental data show, this time, a noticeable effect of supercharging pressure on engine efficiency, since the curves are not grouped together: this may be explained considering that supercharging produces in-cylinder pressure and temperature increase, which, using fuel mixtures with high gasoline content, forces to reduce the spark advance, with respect to the optimal values, to avoid knocking, thus lowering the engine efficiency. As already mentioned, the LPP is a commonly used combustion phase indicator for spark ignition engines [33], whose value is around 15 CAD ATDC when the combustion phase is optimal [31]. Figure 11 reports the LPP measured in the test with 40% NG mixture, and with pure gasoline for comparison purpose. As can be noted, LPP remains next to the optimal value only for 1 bar

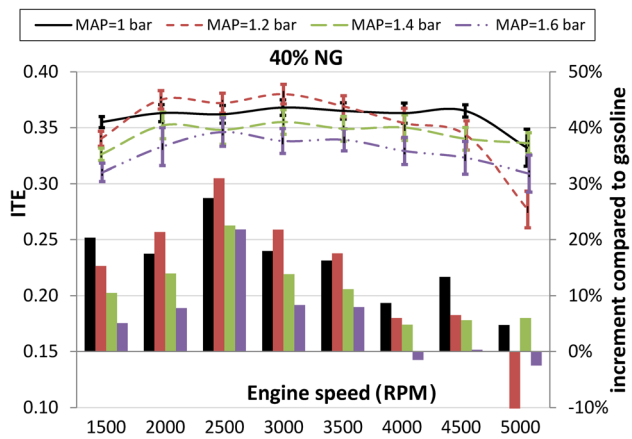

Fig. 8 Indicated thermal efficiency, and its increment compared to gasoline, measured with the 40% NG fuel mixture (st. dev. bars are also reported)

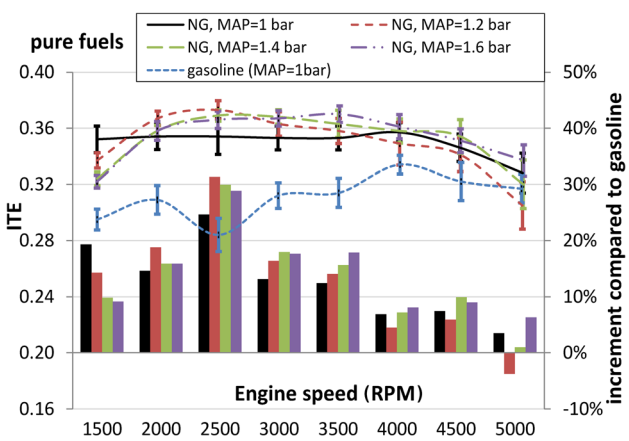

Fig. 7 Indicated thermal efficiency measured with both pure fuels, and its increment with respect to gasoline (st. dev. bars are also reported)

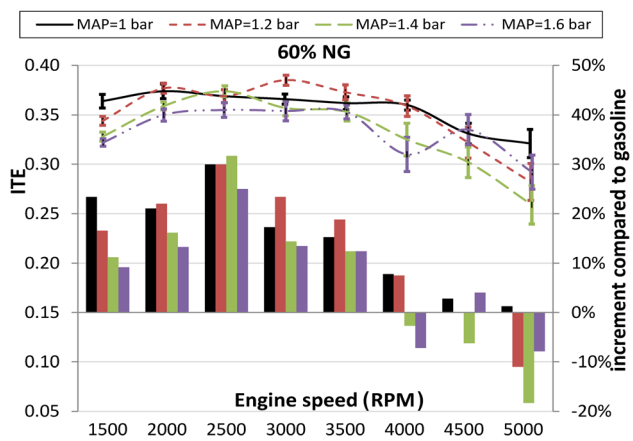

Fig. 9 Indicated thermal efficiency, and its variations with respect to pure gasoline, measured for 60% NG (st. dev. bars are also reported)

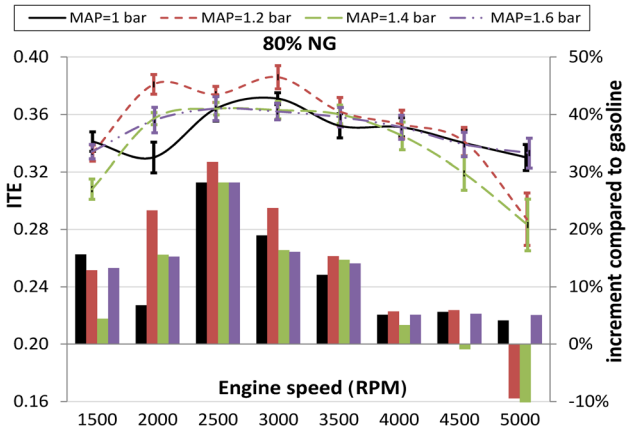

Fig. 10 Indicated thermal efficiency, and its variations with respect to pure gasoline, measured for 80% NG (st. dev. bars are also reported)

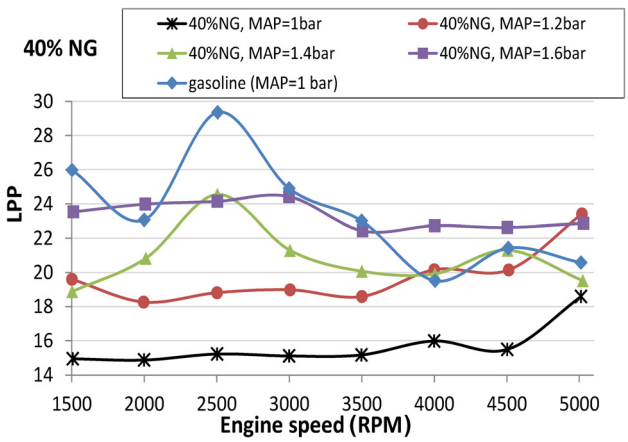

Fig. 11 Comparison between LPP measured with 40% NG mixture and with pure gasoline

MAP, while higher MAP levels required higher LPP (i.e., retarded combustion phase) to avoid knocking, thus reducing thermodynamic efficiency. This explains the efficiency decrement recorded with MAP increasing from 1.2 to 1.6 bar, shown in Fig. 8.

Figure 9 shows the efficiency measured using the 60% NG fuel mixture, together with the increments obtained with respect to pure gasoline operation, whose average values resulted 11%. The efficiency decrease connected to the higher boost pressure appears to be reduced, thanks to the lower gasoline content of the fuel mixture, whose subsequent higher knock resistance allowed better combustion phases.

About the same conclusion can be drawn for the test carried out with the 80% NG fuel mixture, resumed in Fig. 10: the average increment with respect to pure gasoline resulted 12%, while the effect of increasing MAP appears negligible.

It is worth to mention that with 1 bar MAP some double-fuel mixtures exhibited higher efficiency values also with respect to pure NG (see Fig. 12): in particular, the 40% and the 60% NG mixture outperforms the pure NG efficiency, probably thanks to a combustion speed increase promoted by the gasoline in the fuel mixture, confirming the results obtained in previous test [21] carried out on the naturally aspirated engine, which revealed that maximum engine efficiency can be obtained with 50% NG fuel mixture. When supercharging, however, the already mentioned effect of in-cylinder temperature increments on the combustion phase counterbalanced this positive effect.

It can be resumed, hence, that all the double-fuel mixtures gave results similar to the pure NG test, with almost equal average

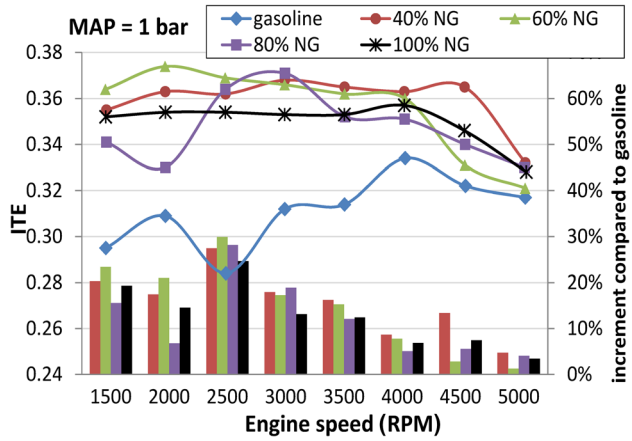

Fig. 12 Indicated thermal efficiency measured for the two pure fuels with 1 bar MAP

increments of the indicated thermal efficiency with respect to pure gasoline operation (11% and 12%), thanks to the overall stoichiometric air/fuel ratio and to the better combustion phase; the higher increments were recorded with the lower supercharging pressure (1.2 bar).

Figures 7–10 also report the data dispersion of the measured efficiencies by the use of the standard deviation bars, whose amplitude represents the standard deviation evaluated over the 100 efficiency values measured for each operative condition tested. Even if the different scales on IMEP and ITE diagrams may result to be deceptive, the accurate analysis of ITE standard deviation revealed a very close correlation with the standard deviations of the measured IMEP: this is rather clear, considering that ITE data dispersion derives almost entirely from combustion instability, given the high accuracy of the fuel mass flow meters employed, which always produced measurement deviation not higher than the 0.5% of the mean value.

3.3 Engine Pollutant Emissions. As mentioned above, one of the main advantages of double-fuel combustion is the strong pollutant emissions reduction with respect to pure gasoline operation, due to the use of stoichiometric air even at full load: besides a drastic reduction of both HC and CO raw emissions, this also maximizes the conversion efficiency of the three-way catalyst, thus leading to an overall 90% emissions reduction. The test carried out by the authors shows that this advantage persists when the engine is supercharged, as, for example, confirmed by Fig. 13: here, the CO raw emissions measured with the 60% NG mixture

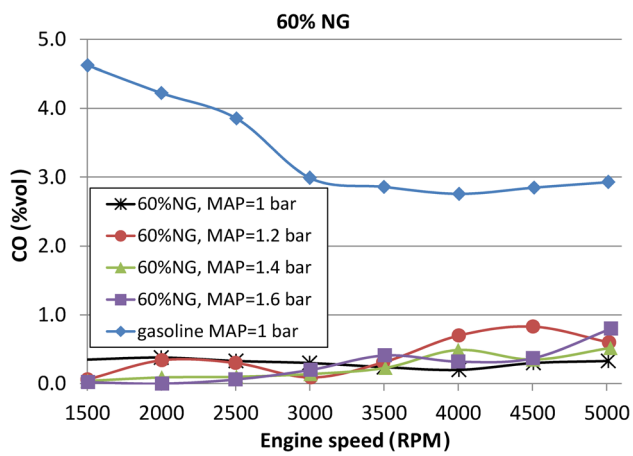

Fig. 13 CO raw emissions measured with both 60% NG mixture and pure gasoline

and with pure gasoline are represented as a function of engine speed.

As clear, regardless of the MAP value, the raw CO emissions in double-fuel mode remain below 1 vol %, while in gasoline operation the recorded values ranged from 3 to 4.5 vol % (as a result of the rich mixture, see Fig. 2). For comparison purpose, the raw CO emissions measured with pure NG operation are shown in Fig. 14.

Both in Figs. 13 and 14, a slight CO concentration increase with engine speed can be observed: this is a further confirmation of the slower burning velocity of methane which, at high engine speed and boost pressure, does not arrive to complete the combustion thus leaving some unreacted carbon monoxide.

It is worth to remind that the raw emissions measured with both double-fuel combustion and with neat NG should be further reduced thanks to the high conversion efficiency (≈80%) that common three-way catalyst has when (A/F) is stoichiometric; the very rich air/fuel mixture used for pure gasoline operation, instead, causes strong catalyst conversion efficiency reduction, thus leaving almost unchanged the pollutant concentration in the exhaust gas.

Figure 15 reports the raw total hydrocarbon (THC) emissions measured with both 80% NG mixture and pure gasoline.

As shown, the raw THC emissions measured in double-fuel mode with 1 bar MAP revealed always lower compared to pure gasoline operation, while, for manifold pressure over 1 bar, substantially higher levels of THC have been measured in the exhaust gas with respect to pure gasoline operation; this strange behavior, however, is not related to a bad performance of the double-fuel operation, but rather to the improper valve timing of the engine, which was originally designed for naturally aspiration and not for supercharging; the original valve overlap, in effect, allowed the blow-through of fresh air–fuel mixture in the exhaust duct when the manifold pressure was higher than the exhaust backpressure; the high level of THC measured at low rpm is then the result of the fuel–air mixture blow-through, whose amount obviously depends on the pressure difference between intake and exhaust, and hence, on the MAP level. At higher rpm, due to the shorter time available, the bypass flow is reduced, together with its effect in terms of THC emissions.

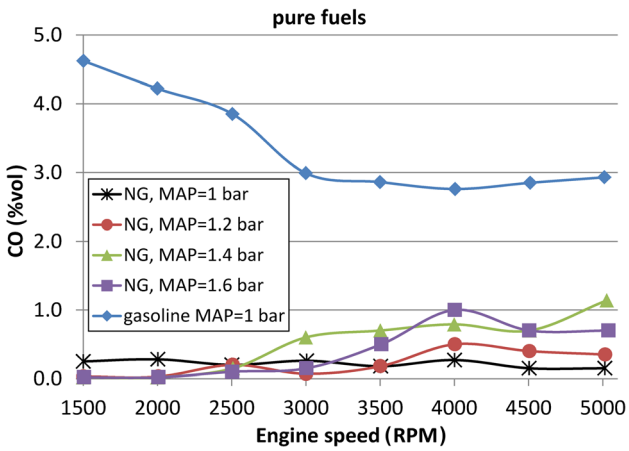

Fig. 14 CO raw emissions measured with both pure fuels

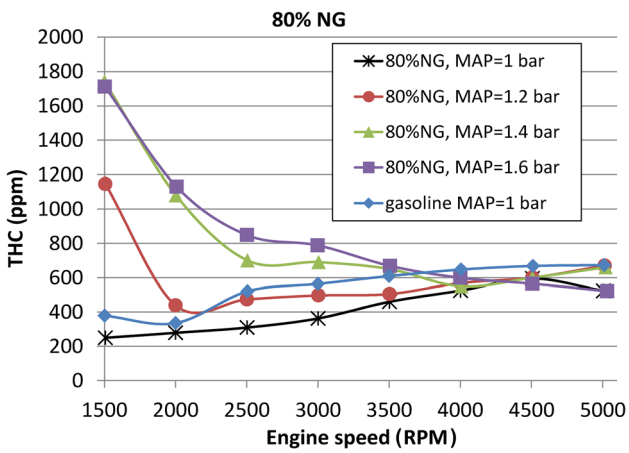

Fig. 15 THC raw emissions measured with both 80% NG mixture and pure gasoline

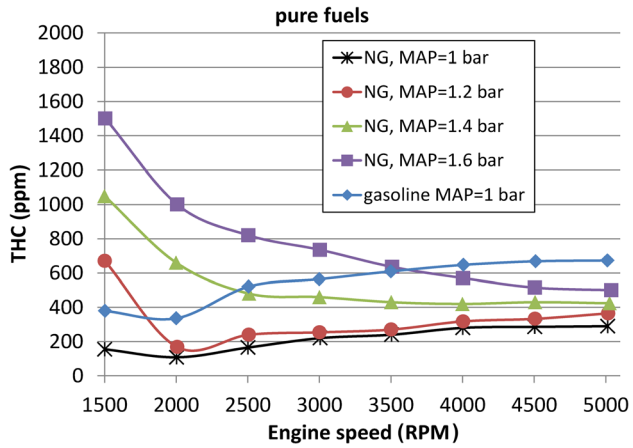

Fig. 16 THC raw emissions measured with both pure fuels

In confirmation of this, Fig. 16 shows the raw THC emissions measured with both pure NG (stoichiometric) and pure gasoline (rich mixture): as clear, the blow-through effect is present for MAP higher than 1 bar and for engine speed lower than 3500 rpm.

4 Conclusion

This paper presents the results of a wide series of experimental test carried out on a properly equipped engine test bed, endowed of a series production passenger car bifuel SI engine.

The aim of this study was to evaluate the effect of supercharging on the performance, the efficiency, and the exhaust emissions of the engine fueled with mixtures of gasoline and natural gas (NG), in different proportions between the two fuels, making the necessary comparison with the results obtained using alternatively the two pure fuels. Supercharging was performed by the use of an independent properly designed system, endowed of a Roots compressor whose rotational speed was feedback controlled to obtain each desired boost pressure. When fueled with gasoline, the engine could not be supercharged, due to the occurrence of dangerous knocking phenomena.

As regards engine performance, the use of gasoline–NG mixtures (also called double-fuel combustion) exhibited higher indicated mean effective pressure (IMEP) values with comparison to pure NG operation, for the same boost pressure levels. The maximum IMEP increments with respect to pure NG were recorded using the 40% NG mixture, which gave an average IMEP increment of 6% among the several different operative conditions tested. This result was obtained thanks to the increased engine volumetric efficiency associated to the use of gasoline in the fuel mixture.

As regards engine efficiency, the supercharged double-fuel combustion was characterized by substantial increments (11% and 12%) compared to pure gasoline mode, due to the overall stoichiometric air/fuel ratio allowed by the knock resistance increase produced by the addition of NG to gasoline. The higher efficiency increments were obtained with lower MAP levels (i.e., 1 and 1.2 bar).

Due to the stoichiometric proportions with air, the supercharged double-fuel combustion also exhibited lower CO emissions (below 1 vol %) compared to naturally aspirated gasoline operation, whose CO emissions range from 3 to 4.5 vol %.

As concern the THC emissions, instead, the improper engine valve timing (designed for naturally aspiration) caused the blow-through of fresh air–fuel mixture in the exhaust duct when the manifold pressure was higher than the exhaust backpressure, resulting in high THC emission levels for each supercharging pressure, a part from the NG concentration in the fuel mixture. In the high-speed region, where this phenomenon is mitigated, the THC emissions exhibited by gasoline–NG mixtures revealed lower than the emissions recorded with pure gasoline.

Resuming, it can be stated that the engine fueled with gasoline–NG mixtures exploits the benefits of both gasoline (higher combustion speed and volumetric efficiency) and natural gas (higher knock resistance and lower pollutant emissions) also when supercharged with boost pressure up to 1.6 bar. The higher power density can be obtained with higher gasoline content in the fuel mixture and high boost pressures, while, when asking for best engine efficiency, lower boost pressure and gasoline content should be set. A proper engine ECU calibration could hence allow to shift between different driving behaviors, allowing the desired performance through the injection of the correct amount of both fuels and through the use of proper boost pressure. The several advantages pointed out by the combined use of gasoline and natural gas could hence allow to increase efficiency and power density of bifuel engines, contributing to the engine downsizing and pollutant emissions reductions.

The authors of this work aim to evaluate the actual impact of supercharged double-fuel combustion on THC (with properly modified engine valve timing) and NO_x emissions. Experimental study and simulation model of the double-fuel combustion heat release rate will follow.

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Nomenclature

ATDC = after top dead center
A/F = air/fuel ratio
$(A/F)_{ST}$ = stoichiometric air/fuel ratio
BMEP = brake mean effective pressure
BTDC = before top dead center
BTE = brake thermal efficiency
CAD = crank angle degrees
CO = carbon monoxide
DAQ = data acquisition
DF = double fuel
ECU = electronic control unit
HC = hydrocarbon
IGBT = insulated gate bipolar transistor
IMEP = indicated mean effective pressure
ITE = indicated thermal efficiency
$IMEP_m$ = measured IMEP
LPP = location of pressure peak
MAP = manifold absolute pressure
MON = motor octane number
NO_x = nitrogen oxide
ppr = pulse per revolution
PID = proportional integral derivative
RON = research octane number
SI = spark ignition
T_m = measured inlet temperature
T_r = reference inlet temperature
THC = total hydrocarbon
UEGO = universal exhaust gas oxygen
λ = relative $A/F = (A/F)/(A/F)_{ST}$

[2]www.amaru.it

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