

Octane Rating of Natural Gas-Gasoline Mixtures on CFR Engine

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ABSTRACT

In the last years new and stricter pollutant emission regulations together with raised cost of conventional fuels resulted in an increased use of gaseous fuels, such as Natural Gas (NG) or Liquefied Petroleum Gas (LPG), for passenger vehicles. Bi-fuel engines represent a transition phase product, allowing to run either with gasoline or with gas, and for this reason are equipped with two separate injection systems. When operating at high loads with gasoline, however, these engines require rich mixtures and retarded combustions in order to prevent from dangerous knocking phenomena: this causes high hydrocarbon (HC) and carbon monoxide (CO) emissions together with high fuel consumption. With the aim to exploit the high knock resistance of NG maintaining the good performances of gasoline, the authors experienced, in a previous work [1], the simultaneous combustion of NG-gasoline mixtures on a series production Spark Ignition (SI) engine, obtaining, with respect to pure gasoline operation, strong reduction in pollutant emissions, noticeable efficiency increase and no significant power losses. In order to ascertain the knock resistance increase due to the addition of natural gas to gasoline, and given the total absence of such information in the scientific literature, the authors decided to carry out a dedicated experimental campaign: a standard Cooperative Fuel Research (CFR) engine, properly upgraded to inject both fuels in the intake duct, has been employed to determine the Motor Octane Number (MON) of several fuel mixtures following the ASTM Standard D2700. The results showed a non-linear relation between mixture knock resistance and natural gas concentration, correctly interpolated by a polynomial law. The correlation found can be usefully implemented in knock onset prediction sub-models for thermodynamic engine simulation, or used in future works involving the simultaneous combustion of natural gas and gasoline in a SI engine.

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INTRODUCTION

Gaseous fuels, such as natural gas and LPG, due to their lower cost and environmental impact, represent today a concrete alternative to conventional fuels for road vehicles propulsion and stationary engines. For these reasons in the last 20 years both NG and LPG 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 in spark ignition engines [2], and on the use of mixtures of gaseous fuels, such as natural gas [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21], with particular attention to efficiency improvement, pollutant emissions [9] and on the effects of the variation of its chemical composition [9, 11, 21]. Moreover, in recent years, various researchers focused their efforts on the study of mixtures of two or more fuels, such as LPG-DME blend [23]; ethanol-gasoline blends have been extensively studied [24, 25] and are nowadays used in the automotive field.

As a result of all these efforts, nowadays bi-fuel vehicles are spreading in the automobile market. These vehicles are equipped with spark ignition engines endowed of two separate

injection systems in order to run either with gasoline or with gaseous fuel. In medium-high loads conditions, the use of gasoline, due to its relatively low knocking resistance, which is approximately 85 Motor Octane Number (MON, [16]), compels the adoption of very rich mixtures and retarded combustion in order to avoid dangerous knocking phenomena: this causes strong hydrocarbon and carbon monoxide emissions together with poor engine efficiency. Gaseous fuels instead, thanks to their higher knocking resistance (approximately 92 MON for LPG and 122 MON for natural gas), allow to run the engine with stoichiometric mixture even at full load, thus minimizing pollutant emissions and improving fuel consumption.

These observations induced the authors to experience in a previous work [1] the simultaneous combustion of homogeneous mixtures of NG and gasoline in stoichiometric proportion with air (with different NG/gasoline proportions) on a series production spark ignition engine, so as to exploit the good qualities of both fuels to obtain cleaner and more efficient combustions.

The addition of natural gas to gasoline, due to the high knocking resistance increase obtained, allowed to run the engine with overall stoichiometric mixtures even at full load and to improve the thermodynamic cycle by advancing the combustion phase. As a result, with respect to the pure gasoline mode, efficiency increments of about 26% were obtained, together with HC and CO reduction in the order of 90%, without noticeable power losses (-4%). In exchange for these considerable advantages, the simultaneous combustion of natural gas and gasoline does not entail any added complexity: it can be easily implemented by means of a simple ECU software update, since no hardware modifications are required, being the two injection systems already available on a bi-fuel engine. This third combustion mode, called by the authors Double Fuel combustion (quite different from the well-known Dual Fuel, in which the auto-ignition of a small quantity of one of the two fuels acts as igniter to start the flame propagation combustion of the second fuel), represents hence a valid alternative to normal gasoline or gaseous fuel operation in bi-fuel engines.

An adequate calibration of ECU spark timing and injection times maps for Double-Fuel operation can be carried out by means of engine cycle thermodynamics simulations, employing knock onset prediction sub-models for knock safe combustion phasing; these sub-models require proper information on the knock resistance of the natural gas-gasoline mixture adopted [26, 27, 28, 30]. Despite the massive presence in the scientific literature of papers on alternative fuels and mixtures of various fuels [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25], the authors did not find any studies on the octane rating of NG-gasoline mixtures. This total absence of studies or experimental data induced the authors to carry out a specific experimental campaign with the aim to quantify the knock resistance of a NG-gasoline mixture as function of the NG mass fraction (i.e. the ratio between the NG mass and the total amount of fuel injected).

Dealing with the octane rating of gaseous fuels, the Methane Number (MN) method, developed by Leikar et al. [11, 12, 13, 14, 15], is often used as alternative respect to the ASTM Motor Octane Number method, which is not suited for the rating of very high knock resistance fuels, i.e. for $MON > 120$: below this threshold, the Methane Number, nowadays fairly spread, showed a good correlation with the MON [11]. The octane scale of the ASTM test method, currently used to rate gasoline, is instead widely spread, even if not appropriate for the use with very high or very low knock resistant fuels. Its rating upper limit of 120.3 MON, lower than the octane number of several natural gas [9], induced many researchers to adopt the extrapolation method [11] which allows to extend the octane scale rating capabilities up to approximately 127 MON: this roughly corresponds to a natural gas with a methane content lower than 90%.

EXPERIMENTAL SETUP

In the experimental campaign carried out, the knock resistance was measured in terms of Motor Octane Number by means of a Cooperative Fuel Research (CFR) engine [16] manufactured by Dresser Waukesha, meticulously following the reference standard ASTM D2700 [16] and employing the extrapolation method, as already experienced by others researchers [11, 12]. The CFR is a four-stroke two valve stationary single-cylinder spark-ignition engine (see [Table 1](#) for main engine specifications) with a particular arrangement that allows to vary quickly and accurately the Compression Ratio (CR) from 4.5 to 16 by moving the engine head (fixed to the cylinder sleeve) with respect to the piston. The combustion chamber is of disc-shaped type and its basic configuration does not change with the compression ratio.

The engine is connected to an electric synchronous motor that maintains a constant rotational speed both in fired and motored condition. The CFR features a capacitive discharge ignition system with a mechanical arrangement that allows to vary the spark advance as function of compression ratio [16]: from 29° Before Top Dead Centre (BTDC) with CR=4.5 to 10° BTDC when CR is 16.

Table 1. CFR Engine Specifications [16].

| | |
|-----------------------|--------------------------|
| Manufacturer | Dresser Waukesha |
| Model | F1/F2 Octane |
| Compression ratio | from 4.5 to 16 |
| Bore | 82.6 [mm] |
| Stroke | 114.3 [mm] |
| Connecting rod length | 254.0 [mm] |
| Displacement | 611.2 [cm ³] |

The CFR is equipped with two electric heaters which have been connected to two independent PID control systems Omega CN4116 in order to maintain both air temperature T_{AIR} and inlet air/fuel mixture temperature T_{IN} at their reference values (see [Figure 1](#)). The CFR is also endowed with a thermo siphon cooling system to maintain the cylinder jacket coolant temperature at the prescribed value of $100 \pm 1.5^\circ\text{C}$. All the temperatures were measured using type K thermocouples, placed ([Figure 1](#)) as prescribed by the ASTM D2700 [16].

As regards fuel supplying, a standard CFR engine features an original carburettor system with three independent bowls. This arrangement usually allows a fast alternation between the tested fuel and the two reference fuels without stopping the engine, as required during an octane rating test, but does not allow the use of gaseous fuels. The authors hence endowed the CFR engine with two independent injection systems in order to realize the desired NG-gasoline mixtures and to control both the proportion between the two fuels and the overall air-fuel ratio. Two port fuel injectors were placed on the CFR intake duct before the carburettor ([Figure 1](#) and [Figure 2](#)): this arrangement was chosen to preserve the original air inlet

path without varying any part dimension. As illustrated in the experimental setup of [Figure 1](#), the gaseous fuel stored in a reservoir tank passed through a Bronkhorst mini CORI-FLOW® Coriolis effect mass flow meter (with a range of measurement of 0.1-2.0 kg/h and the accuracy of $\pm 0.2\%$ of the read value) and hence through a pressure regulator, used to maintain the injector feed pressure of 3 bar. The gas, then, reached a plenum placed before the injector in order to reduce upstream pressure oscillation due to pulsed injection, which has been performed by means of a Bosch port injector.

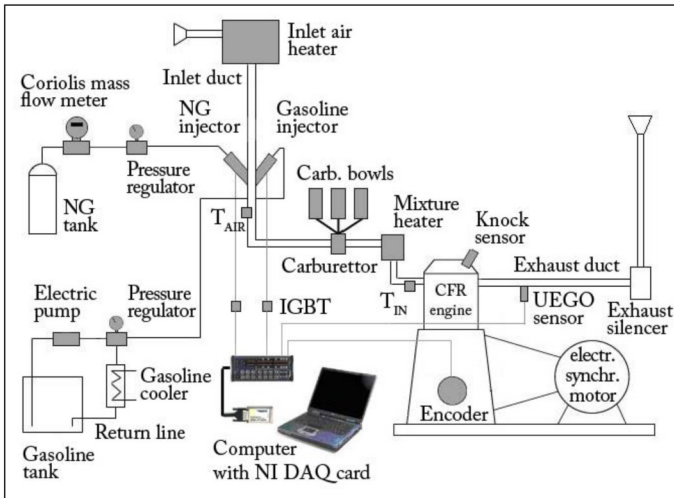


Figure 1. Experimental system layout.

As also shown in [Figure 1](#), the gasoline injection system was composed by an electric fuel pump, an automatic pressure regulator used to maintain a constant injection pressure of 4 bar, a fuel cooler placed on the return line to ensure a proper gasoline temperature, and a Bosch port injector. During the test, the gasoline mass flow was deduced on the basis of the imposed injection time by means of a proper injector flow chart previously experimentally determined on the same fuel supply system by a gravimetric method using a high precision balance: several validation tests proved a gasoline mass flow control accuracy better than 1% of the desired value by the use of the injector flow chart.

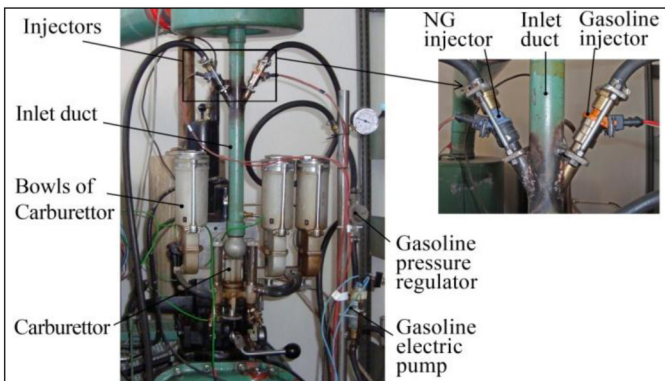


Figure 2. Fuel supply systems: carburettor, NG injector and gasoline injectors.

A personal computer was used to manage the two injection systems and perform data acquisition, by means of an expressly designed software developed by the authors in LabVIEW environment.

The electrical circuit employed for the excitation of each fuel injector, was mainly composed by a power supply device connected to a common IGBT transistor for automotive ignition/injection purpose. A National Instruments DAQCard 6062E programmed under LabVIEW has been used to generate the injection digital pulses: the modulation of the injection time (i.e. the high level duration) allowed to perform a very accurate control of the amount of both fuels injected.

The injection times of the two fuels were modulated following two different strategies: NG injection was controlled in closed-loop using the output signal of an Universal Exhaust Gas Oxygen (UEGO) sensor placed in the exhaust duct ([Figure 1](#)), so as to maintain each desired overall air-fuel ratio; gasoline injection instead was operated in open-loop, controlling the amount of gasoline so as to obtain each desired proportion between the two fuels.

Moreover, the output of the UEGO sensor has been corrected by means of proper coefficients in order to take into account the variation of the mixture H/C ratio with the NG fraction: for each fuel blend tested, the H/C ratio has been calculated on the basis of the measured fuel mass flow rates. During the steady conditions of the tests performed, the variation on the NG mass flow due to the closed loop control was always very small and did not produce any relevant change ($< 0.1\%$) with respect to the predetermined NG mass fraction.

The ambient pressure, a very important parameter for the fuel octane rating, has been measured by means of a barometric pressure sensor and its value used for the correction of compression ratio values, as prescribed by the ASTM standard method. Also intake air humidity is a critical parameter for the fuel octane rating because of its strong influence on knocking phenomena: as the amount of water vapour in the intake air increases, knock intensity decreases. For this reason, a relative humidity sensor (Measurement Specialties HTM2530LFL) together with an air temperature sensor were used to measure the amount of water vapour in the inlet air, thus checking the respect of the limits imposed by the ASTM standard method (between 3.56 and 7.12 g of water per kg of dry air). All the relevant quantities (intake duct pressure, air humidity, exhaust gas oxygen concentration, NG mass flow, inlet air and air-fuel mixture temperatures) were acquired by means of the mentioned National Instruments DAQCard 6062E using as trigger the output signal of an incremental optical encoder connected to the engine crankshaft. The same trigger has been employed to synchronize the two injections digital pulses with the piston movement.

During each octane rating test, the knock intensity was measured by means of the original CFR system, constituted by a knock sensor placed on the combustion chamber, a knock

meter for knock signal conditioning and an analogical display showing the knock intensity. As required by the reference standard ASTM D2700 [16], the knock meter has been properly calibrated before each test.

TEST METHODS

The operative conditions prescribed by the reference standard test method ASTM D2700 are represented in Table 3. As known, the standard fuel octane rating procedure requires the use of some Primary Reference Fuels (PRF) obtained mixing isooctane and n-heptane in predetermined volumetric proportion [16]. The knock rating of the tested fuel is determined by a comparison of its knocking intensity with that of two Primary Reference Fuels (PRF), whose octane number is known by definition on the basis of their composition: the octane number of the tested fuel is then obtained by means of an interpolation procedure.

Table 2. Motor octane number rating conditions [16].

| | |
|---------------------------------|--|
| Engine speed | 900 [RPM] |
| Inlet air temperature T_{AIR} | 38 ± 2.8 [°C] |
| Air/fuel mixture temp. T_{IN} | 149 ± 1 [°C] |
| Engine coolant temp. T_{ENG} | 100 ± 1.5 [°C] |
| Lubricant temperature T_{OIL} | 68 ± 8 [°C] |
| Engine load condition | full load |
| Compression ratio (CR) | regulated for standard knock intensity |
| Overall air/fuel ratio | regulated for the maximum knocking intensity |
| Spark advance | 29 -10 [CAD BTDC], depending on CR |

In the test performed, each PRF was employed using the original carburettor system, which, thanks to its three independent bowls, allows rapid change of fuel without stopping the engine. The NG-gasoline mixtures instead, as already mentioned, were obtained injecting the proper amount of both fuels in the intake duct using the added injection systems (Figure 1 and Figure 2), thus realising a very accurate control on the overall air-fuel ratio and on the proportion between the two fuels.

For each MON measurement, the air-to-fuel ratio (λ) was regulated to obtain the maximum knock intensity (KI), as prescribed by the standard method [16]: this operative condition was achieved by means of a λ sweep procedure in which all the other parameters were kept constant (CR and spark advance). Each CFR engine is endowed of a particular automatic mechanical system which, according to the standard MON method, allows to linearly decrease the spark timing when the engine compression ratio increases.

For each NG-gasoline mixture tested, the MON value presented in this paper was obtained as mean value over three successive measurements which satisfied the stability and repeatability conditions exposed in the standard procedure: in particular, a maximum difference of 0.3 MON between two consecutive knock ratings is tolerated for a valid MON measurement. This procedure, which reveals time consuming and requires the use of a consistent amount of fuels and PRF, ensures the required measurement precision, whose reproducibility standard deviation varies between 0.3 and 0.7 MON in a wide range of octane numbers (between 80 and 120), as reported in the ASTM standard [16].

The entire experimental campaign was carried out using a single sample of pump grade gasoline (Table 3) and a single sample of commercial natural gas, whose composition, provided by the supplier, is reported in Table 4.

Table 3. Properties of gasoline used in the tests.

| | |
|-------------------------------|-----------------------|
| Liquid phase density at 15 °C | 730 kg/m ³ |
| Equivalent H/C ratio [29] | 1.85 |
| Molar mass (assumed) [25, 33] | 110 g/mole |
| Stoichiometric ratio | 14.7 |
| Lower heating value [32] | 43.4 MJ/kg |
| Motor Octane Number | 84.1 |

Table 4. Composition and properties of the NG used.

| Components | % vol. |
|---|--------|
| Methane - CH ₄ | 85.79 |
| Ethane - C ₂ H ₆ | 7.86 |
| Propane - C ₃ H ₈ | 1.61 |
| N-butane - C ₄ H ₁₀ | 0.19 |
| Isobutane - C ₄ H ₁₀ | 0.28 |
| Butylene - C ₄ H ₈ | 0.05 |
| Isopentane - C ₅ H ₁₂ | 0.06 |
| N-pentane - C ₅ H ₁₂ | 0.06 |
| Carbon dioxide - CO ₂ | 1.04 |
| Nitrogen - N ₂ | 2.96 |
| Helium - He | 0.09 |
| Properties | |
| Reactive Hydrogen/Carbon Ratio | 3.76 |
| Molar mass [g/mole] | 18.47 |
| Stoichiometric air/fuel mass ratio | 16.9 |
| Lower heating value [MJ/kg] | 46.0 |
| Measured MON [11, 16] | 122.1 |
| Calculated MON [11, 15] | 122.6 |
| Calculated Methane Number [11, 15] | 80.0 |

As known, natural gas is a mixture of various gases and its composition may differ according to the geographic location and the period of extraction. The main components of commercial NG are methane, ethane, propane, others heavier hydrocarbons and inert gases, such as CO₂ and N₂, in lower

quantities. These components (except the inert gases) feature different knocking resistance and, as consequence, natural gas MON is strongly depending on its composition: methane has a very high knock resistance with 140 MON [11], while heavier hydrocarbons, such as propane and ethane (characterized by lower MON) tend to reduce NG knock resistance. Carbon dioxide increases the knocking resistance of the mixture [11, 21] since acts as a fuel diluent and has a high specific heat. In particular, as observed by Brecq et al. [21], CO₂ has a higher anti-knock effect than N₂.

The reactive H/C ratio of the NG used in the tests (Table 4) has been evaluated on the basis of the molar fraction of each component, while, as regards gasoline, the reference value of 1.85 has been assumed on the basis of literature reference [29]. Hence, as already mentioned, the reactive H/C ratio for each NG-gasoline mixture tested has been evaluated on a mass basis, computing the total hydrogen mass flow and the total carbon mass flow by means of each fuel mass flow rate.

Since the octane rating of fuels strictly depends on the CFR engine features, some preliminary tests were conducted in order to validate the reliability of the CFR engine endowed with the double injection systems. To this purpose, a gasoline sample was rated using alternatively both the original carburettor system and the added port injection system: as a result, the same MON value of 84.1 was obtained by both fuel supplying systems. The validation of the gaseous fuel injection system was instead carried out by comparing the measured octane number of the NG used for the test, whose composition and properties are shown in Table 4, with the octane number evaluated by means of the empirical correlation obtained by Kubesh et al. [11], reported in equation (4): this correlation, derived from the experimentally measured knock resistances of twelve different natural gas mixtures, is today widely recognized as reference [13] and is part of the international UNI standard [15]. As a result of the validation test, the octane rating of the natural gas used in the test yielded 122.1 MON, which is very similar to the 122.6 MON evaluated by means of the correlation of Kubesh et al. [11]: the resulting difference of 0.5 MON is quite admissible, considering that the CFR MON reproducibility standard deviation, as already mentioned, varies from 0.4 to 0.7 MON [16].

Moreover, the overall engine compliance has been verified, in accordance with the standard “fit-for-use” procedure, rating Toluene Standardisation Fuel (TSF) blends, whose accepted reference values are reported in ASTM D2700 [16]. Since the CFR compliance is a critical feature in octane rating tests, this procedure has been repeated during the experimental campaign for different octane rating levels, as prescribed by the ASTM, giving always satisfying results.

As known, according to the standard ASTM procedure, the octane rating of fuel with knock resistance higher than 100 MON requires the use of reference blends consisting of isooctane with specified quantities of tetraethyl lead (TEL).

Figure 3 shows the relationship between MON and the TEL quantity to add to 400 ml of isooctane: as can be observed, the effect of TEL addition on MON is not linear. The ASTM standard sets a maximum of 0.634 ml of TEL per 400 ml of isooctane which results in an upper rating limit of 120.3 MON for a CFR engine. The rating of the pure NG sample (122.1 MON) hence required the use of the already mentioned extrapolation method [11], which allows to extend the octane scale up to 127 MON, as shown on Figure 3.

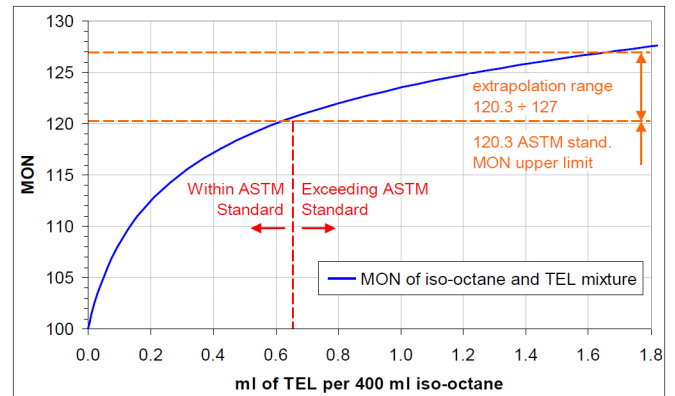


Figure 3. MON as function of TEL addition to 400 ml of isooctane, for standard [16] and extrapolation method [11].

EXPERIMENTAL RESULTS AND DISCUSSION

The tests performed confirmed that the addition of NG to gasoline significantly raises the resistance to auto-ignition, as reported in Figure 4: here the MON of each NG-gasoline mixture tested is represented as function of the NG mass fraction (x_{NG}), which varies from 0%, i.e. pure gasoline, to 100%, which instead refers to the sole NG. As can be noted the relationship between MON and NG mass fraction is not linear: the knock resistance increment of the mixture, in effect, is more pronounced for the higher NG concentrations.

Given m_{NG} and $m_{gasoline}$ the injected mass of both fuels within the same engine cycle, the percentage NG mass fraction x_{LPG} can be expressed as:

$$x_{LPG} = \frac{m_{LPG}}{m_{LPG} + m_{Gasoline}} \cdot 100 \quad (1)$$

Applying an Ordinary Least Squares (OLS) regression to the experimental data allowed to determine the third order polynomial fitting curve shown in Figure 4, whose equation is:

$$MON = 84.1 + \frac{22.57}{100} \cdot x_{NG} + \frac{33.09}{10^5} \cdot x_{NG}^2 + \frac{11.74}{10^6} \cdot x_{NG}^3 \quad (2)$$

This correlation can be implemented in sub-models used for knock onset prediction [22, 27, 30] for a correct estimation, by means of more or less complex thermodynamic simulations, of

knock safe combustion phase when the simultaneous combustion of NG and gasoline is considered. It is worth to mention that this correlation however refers to a commercial available NG with 122.1 MON, which represents a mean situation among various NG compositions that can be encountered all over the world, as shown in [9, 10, 11].

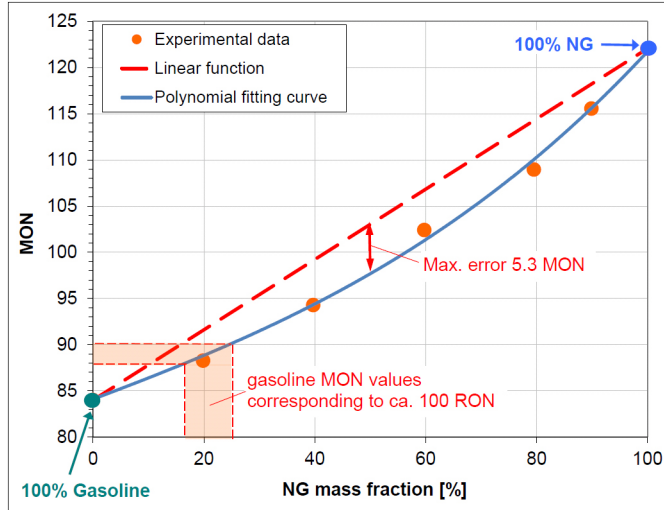


Figure 4. Measured MON of NG-gasoline blends as function of the NG mass fraction.

The relationship between MON and natural gas content may be also expressed in terms of percentage molar fraction y_{NG} :

$$y_{NG} = \frac{N_{NG}}{N_{NG} + N_{Gasoline}} \cdot 100 \quad (3)$$

where N_{LPG} and $N_{gasoline}$ represent the mole number of the two fuels, evaluated as ratio between each fuel mass injected and its molecular weight (see Table 3 and Table 4). To this purpose, the gasoline molar mass has been assumed to be 110 g/mole [25, 33], even if values ranging from 103 to 114 g/mole are reported in literature [34, 35]. Gasoline is in effect a complex mixture of hydrocarbon compounds [34, 36] and its specific composition may vary depending on the source of petroleum and refinery method and include a number of additives, such as antiknock agents and antioxidants: hence the adoption of a reference value for gasoline molecular weight may introduce a sort of uncertainty.

As a results, Figure 5 shows the MON of each natural gas-gasoline mixture tested as function of the natural gas molar fraction: as clear, the non-linearity of the relation appears even more pronounced than the relation of Figure 4: quite a different result was determined by the same authors for the LPG-gasoline mixtures [37], which revealed a good linear regression between mixture MON and LPG molar fraction.

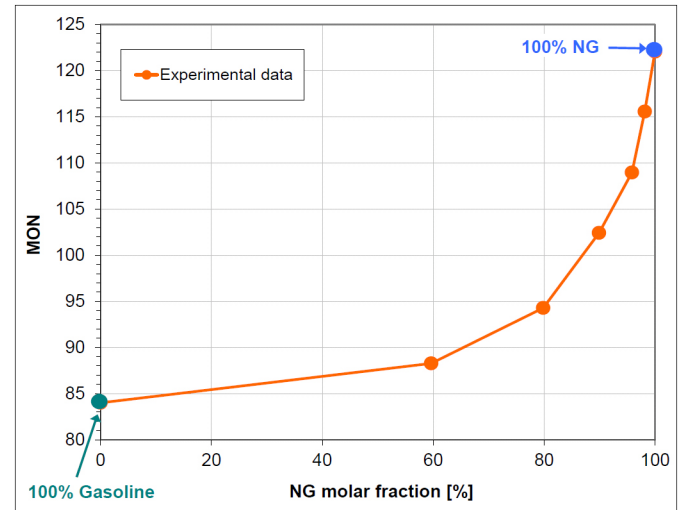


Figure 5. Measured MON of NG-gasoline blends as function of the NG molar fraction.

Anyway, on the basis of the results obtained it can be stated that, as regards knock resistance, the gasoline-air mixture strongly benefits from the addition of NG; the experimentally observed knock resistance increase could be explained taking into consideration an interaction between the intermediate products of the pre-ignition reactions of both fuels. During flame front propagation, in effect, each fuel in the unburned mixture is characterized by a certain number of pre-ignition reactions which are essentially governed by the radicals produced by each single components of the fuel. Due to the very different composition of gasoline (mainly composed by C_4 to C_{12} hydrocarbons [34, 36]) and NG (which instead mainly contains methane, Table 4), the radicals involved in the chain-branching reactions of gasoline components are quite different from the radicals produced by the reactions of NG components, which are characterized by lower reaction rate and longer lives [38]: this explain the higher knock resistance of NG with respect to gasoline.

A possible explanation of the knocking resistance increase obtained by adding natural gas to gasoline may hence be given by supposing that the NG intermediate products interact with gasoline radicals slowing down their reactions and hence extending the auto-ignition time. This let the flame front to continue its propagation in the combustion chamber thus reducing the end-gas¹ mass and, consequently, the energy released by its auto-ignition. This explains the experimentally observed reduction of knock intensity caused by the addition of NG to gasoline, with unchanged engine operative conditions.

It is worth to mention that in a standard octane rating test the CFR engine compression ratio must be regulated in order to reach the standard knock intensity, which corresponds to the 50% on the provided analogue gauge [16]. As a consequence of the increased fuels mixture knock resistance, the CFR engine compression ratio has been gradually incremented with growing NG concentration in order to perform standard MON

1. The air-fuel mixture portion most distant from ignition point, which undergoes auto-ignition if not promptly reached by the flame front.

measurement, as reported in Figure 6. The same figure also shows the respective spark advance values, imposed by the original CFR mechanical control system.

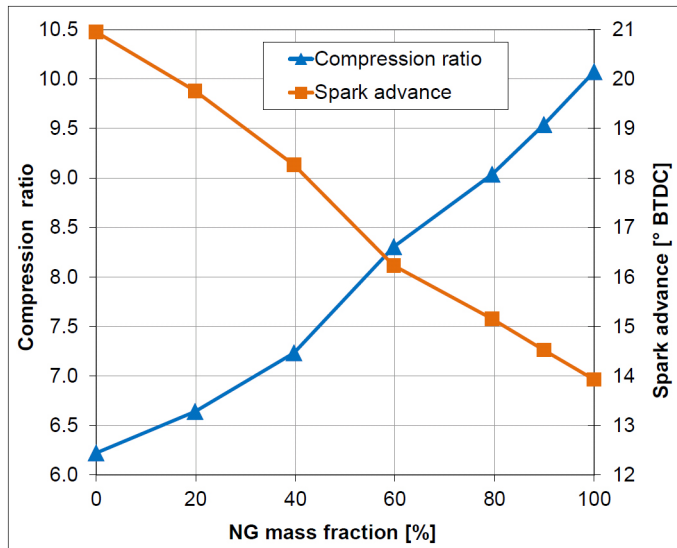


Figure 6. Compression ratios and spark advances adopted in the tests.

On the basis of the polynomial correlation of equation (2), it can be evaluated that, for NG mass fraction going from 0% to 20%, the mixture MON increases from 84.1 to 88.3, which is a significant increment: starting from a pump grade gasoline, the same results can be achieved only by means of particular additives or increasing the quantity of oxygenates components. For NG mass fraction between 20% and 25%, the NG-gasoline mixture reaches an overall MON between 88 and 90, which corresponds to the high knock resistance of commercial gasoline type with 100 RON² (Research Octane Number), such as “Super Plus” quality gasoline. The pure isooctane knock resistance (i.e. MON 100) can be reached with NG mass fraction between 50% and 60%. For NG mass fraction higher than 60%, the MON increase is more pronounced and with a 100% NG sample it was measured a knock resistance of 122.1 MON. Figure 4 also reports a straight line connecting the MON measured for the two pure fuels: as shown, the real MON of each NG-gasoline mixture is always lower than the MON evaluated by the simple straight line. More in details, the difference between the straight line MON and the real mixture MON reaches the maximum value of 5.3: these is a remarkable difference, since, for an ordinary spark ignition engine, a fuel knock resistance variation of 4 MON implies the transition from knock free to heavy knock operation. Therefore the use of the straight line approximation of Figure 4 is not appropriate because implies a not safe prediction of the knock resistance properties of the NG-gasoline mixtures.

As is known, the auto-ignition temperature of a gaseous fuel, which is strictly connected to the knock resistance, is also related to its molecular weight [31], and hence to the H/C ratio:

2. The Research Octane Number [17] is another ASTM knock rating method that prescribes the use of a CFR engine under different and less heavy test conditions respect to MON method [16]. For this reason the RON of a fuel is usually higher than its MON.

methane, to which corresponds a H/C ratio of 4, has the highest auto-ignition temperature, while, as the number of carbon atoms increases in the molecule, the auto-ignition temperature decreases. The relationship between molecular weight (or H/C ratio) and auto-ignition temperature, however, fades away when the carbons atom increase over 5: as is known, for heavier hydrocarbons, such as liquid fuels, the molecular structure plays an important role in determining the auto-ignition temperature. On the basis of this concept, the cited reference [11] (which gave origin to the international UNI standard [15]) allows to evaluate the MON of natural gas based mixtures as function of the reactive H/C ratio by means of the following equation:

$$MON = -406.14 + 508.04 \cdot \frac{H}{C} - 173.55 \cdot \left(\frac{H}{C}\right)^2 + 20.17 \cdot \left(\frac{H}{C}\right)^3 \quad (4)$$

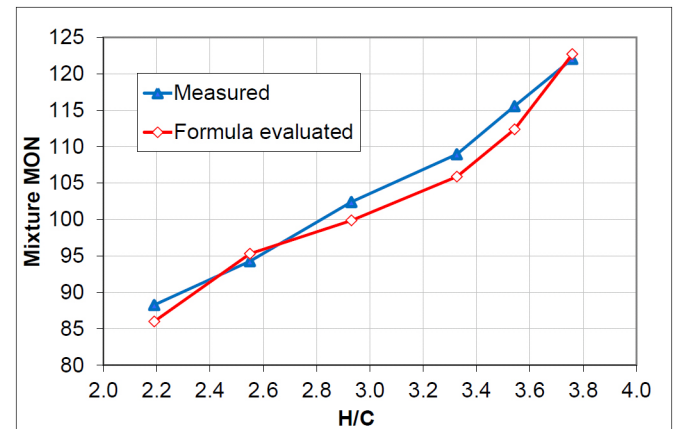


Figure 7. Measured MON compared to the MON evaluated according to equation (4) [11, 15].

The diagram in Figure 7 shows the measured MON values together with the MON evaluated by the use of equation (4). Being the formula recommended for H/C ratio higher than 2.5, the pure gasoline value (whose H/C can be assumed to be 1.85, as shown in [29]) has been excluded from the comparison. As can be observed in Figure 7, equation (4) well approximates the experimental measurements carried out in this paper, with a maximum conservative difference of about 3 MON: considering that the MON measurement accuracy declared by its authors is ± 2 MON [11], it can be deduced that the validity of equation (4) can be roughly extended to the case of gasoline-natural gas mixtures; this is of particular interest if a natural gas with composition different from Table 4 is taken into account, since the reactive H/C ratio of the NG-gasoline mixture could be however determined and used to compute a conservative value of the mixture MON.

CONCLUSIONS

In the wake of the results of a previous work [1] dealing with the simultaneous combustion of NG and gasoline on a spark ignition engine, the authors aimed to determine the knock resistance of NG-gasoline mixture. The total lack of such

information in the scientific literature induced the authors to carry out a proper experimental campaign, using a standard CFR engine expressly modified to perform the injection of both fuels. Various blends have been tested, from 0% NG mass fraction, which corresponds to pure gasoline, to 100% NG mass fraction, which instead refers to the sole NG, evaluating the knock resistance of each mixture in terms of Motor Octane Number (MON) according to the standard method ASTM D2700 [16]. The results of the tests not only confirmed that the addition of NG to gasoline considerably raises the knock resistance, but also pointed out a noticeable non-linearity between the effect obtained and the NG concentration in the mixture, expressed in terms of both mass fraction and molar fraction. The relationship between the MON mixture and the NG mass fraction has been expressed by means of a polynomial law in [equation \(2\)](#), which can be usefully employed in knock onset prediction models for the simulation of knock safe spark ignition engine cycle. Even if the polynomial law determined is rigorously valid only for the NG tested (characterized by a MON of 122.1), it must be pointed out that the composition of the NG used represents a mean situation among the different NG mixtures present all over the world [11]; hence the result obtained can be still considered a valid reference, above all if the total absence of similar works in literature is considered. The authors also pointed out that the linear variation of the mixture MON as function of the NG mass fraction cannot be considered a valid alternative: the use of a simple straight line connecting the MON of the two pure fuels would cause, in effect, remarkable errors (up to 5 MON) on the estimation of the mixture knock resistance, and this could lead the engine to run in dangerous heavy knock conditions. A comparison has also been made between the MON measurement and the MON evaluated by means the common formula [11, 15] employed to calculate the knock resistance of natural gas mixtures on the basis of the reactive H/C ratio: as a result, the formula proved to remain valid also for the NG-gasoline mixture, showing conservative errors lower than 3 MON. The authors consider this another relevant results of their work, since the extension of the validity of [equation \(4\)](#) to the gasoline-natural gas mixtures is proved on the basis of experimental results. Moreover, this finding allows to overcome the validity issue related to the composition of the NG employed in the tests, since the evaluation by means of the reactive H/C ratio can be performed anyway.

REFERENCES

- Pipitone, E. and Beccari, S., "Performances Improvement of a S. I. CNG Bi-Fuel Engine by Means of Double-Fuel Injection," SAE Technical Paper 2009-24-0058, 2009, doi:10.4271/2009-24-0058.
- Karim Ghazi A., "Hydrogen as a spark ignition engine fuel", International Journal of Hydrogen Energy 28 (2003) 569-577, Pergamon, Elsevier.
- Karim G. A., Wierzbka I. and Al-Alousi Y., "Methane- hydrogen mixtures as fuels", ht. J. Hydrogen Energy Vol. 21, No. 7, pp. 625-631. 1996, Copyright @ 1996 International Association for Hydrogen Energy, Elsevier Science Ltd, 0360-3199(95)001344.
- Shrestha S.O. Bade, Karim G.A., "Hydrogen as an additive to methane for spark ignition engine applications", International Journal of Hydrogen Energy 24 (1999) 577-586, Pergamon, Elsevier.
- Bauer CG, Forest TW. Effect of hydrogen addition on the performance of methane-fuelled vehicles. Part I: Effect on S.I. engine performance. Int. Journal of Hydrogen Energy 2001;26:55-70.
- Hailin Li, Karim Ghazi A., "Exhaust emissions from an SI engine operating on gaseous fuel mixtures containing hydrogen", International Journal of Hydrogen Energy 30 (2005) 1491-1499, Elsevier.
- Sierens R, Rosseel E. Variable composition hydrogen/natural gas mixtures for increased engine efficiency and decreased emissions. J Eng Gas Turbines Power 2000;122:135-40.
- Akansu S. Orhan, Kahraman Nafiz, Çeper Bilge, "Experimental study on a spark ignition engine fuelled by methane-hydrogen mixtures", International Journal of Hydrogen Energy 32 (2007) 4279-4284, Elsevier.
- Ly Hien, "Effects of Natural Gas Composition Variations on the Operation, Performance and Exhaust Emissions of Natural Gas - Powered Vehicles", NGV 2002 Conference Paper - Effects of Gas Composition - Aug 2002.
- Min Byung Hyouk, Chung Jin Taek, Kim Ho Young, Park Simsoo, "Effects of Gas Composition on the Performance and Hydrocarbon Emissions for CNG Engines", KSME International Journal, February 2002, Volume 16, Issue 2, pp 219-226.
- Kubesh, J., King, S., and Liss, W., "Effect of Gas Composition on Octane Number of Natural Gas Fuels," SAE Technical Paper 922359, 1992, doi:10.4271/922359.
- Leikar M, Christoph K, Rankl M, Cartellieri E, Pfeifer U., "Evaluation of anti knocking property of gaseous fuels by means of methane number and its practical application to gas engines", ASME-72-DGP-4; 1972.
- Attar A. A., Karim G. A.; Assanis Dennis N., "Knock rating of gaseous fuels", Journal of engineering for gas turbines and power Y. 2003, vol. 125, American Society of Mechanical Engineers, ISSN: 0742-4795 CODEN: JETPEZ.
- Malenshek Martin, Olsen Daniel B., "Methane number testing of alternative gaseous fuels", Fuel 88 (2009) 650-656, Elsevier.
- UNI EN ISO 15403-1:2008 Natural Gas - Natural Gas For Use As A Compressed Fuel For Vehicles - Part 1: Designation Of The Quality.
- Standard Test Method for Motor Octane Number of Spark-Ignition Engine Fuel, ASTM International D2700.
- Standard Test Method for Research Octane Number of Spark-Ignition Engine Fuel, ASTM International D2699.
- Perdih Anton, Perdih Franc, "Chemical Interpretation of Octane Number", Acta Chim. Slov. 2006, 53, 306-315.
- Rahmouni C., Brecq G., Tazerout M., Le Corre O., "Knock rating of gaseous fuels in a single cylinder spark ignition engine", Fuel 83 (2004) 327-336, Elsevier.
- Arunachalam Aparna, Olsen Daniel B., "Experimental evaluation of knock characteristics of producer gas", Biomass and Bioenergy 37 (2012) 169-176, Elsevier.
- Brecq Guillaume, Bellettre Jérôme, Tazerout Mohand, Muller Thomas, "Knock prevention of CHP engines by addition of N2 and CO2 to the natural gas fuel", Applied Thermal Engineering, Volume 23, Issue 11, August 2003, Pages 1359-1371, Elsevier.
- Heywood J. B., "Internal Combustion Engines Fundamentals", McGraw-Hill automotive technology series, 1988, ISBN 0-07-100499-8.
- Lee, S., Oh, S., and Choi, Y. (2009). Performance and emission characteristics of an SI engine operated with DME blended LPG fuel. Fuel, vol.88, pp.1009-1015.
- Cooney Christopher P., Yeliana, Worm Jeremy J., Naber Jeffrey D., "Combustion Characterization in an Internal Combustion Engine with Ethanol-Gasoline Blended Fuels Varying Compression Ratios and Ignition Timing, Energy & Fuels Volume 23 May 2009.
- Anderson J.E., DiCicco D.M., Ginder J.M., Kramer U., Leone T.G., Raney-Pablo H.E., Wallington T.J., "High octane number ethanol-gasoline blends: Quantifying the potential benefits in the United States", Fuel 97 (2012), Elsevier. <http://dx.doi.org/10.1016/j.fuel.2012.03.017>
- Linvingood, J.C, Wu, P.C. "Correlation of autoignition phenomenon in internal combustion engines and rapid compression machines", Symposium (International) on Combustion, Volume 5, Issue 1, 1955, Pages 347-356

27. Douaud, A. and Eyzat, P., "Four-Octane-Number Method for Predicting the Anti-Knock Behavior of Fuels and Engines," SAE Technical Paper 780080, 1978, doi:10.4271/780080.
28. Moses Eduard, Yarin Alexander L., Bar-Yoseph Pinhas, "On Knocking Prediction in Spark Ignition Engines", Combustion and Flame, vol. 101, pag. 239-261, 1995
29. Myers Mark E. Jr., Stollstelmer Janis and Wims Andrew M., "Determination of Hydrocarbon-Type Distribution and Hydrogen/Carbon Ratio of Gasolines by Nuclear Magnetic Resonance Spectrometry" in ANALYTICAL CHEMISTRY, Vol. 47, N°. 12, October 1975.
30. Pipitone E., Beccari S., "Calibration of a Knock Prediction Model for the Combustion of Gasoline-Natural Gas Mixtures", Paper no. ICEF2009-14057 pp. 191-197, ISBN: 978-0-7918-4363-5.
31. Coward, H.F. and Jones, G.W., "Limits of Flammability of Gases and Vapours", US Dept. of the Interior, Bureau of Mines Bulletin 503 (1952).
32. Boundy Bob, Diegel Susan W., Wright Lynn, Davis Stacy C., "BIOMASS ENERGY DATA BOOK: EDITION 4", U.S. Department Of Energy, 2011, ORNL/TM-2011/446, <http://cta.ornl.gov/bedb>
33. Anderson J. E., Kramer U., Mueller S. A., and Wallington T. J., "Octane Numbers of Ethanol-and Methanol-Gasoline Blends Estimated from Molar Concentrations", Energy Fuels, Volume 24, Issue 12, 2010, pag. 6576-6585, DOI:10.1021/ef101125c.
34. American Petroleum Institute (API), Alcohols and Ethers, Publication No. 4261, 2nd Ed., Washington DC, July 1988
35. Lanje Ashish S., Deshmukh M. J., "Performance and emission characteristics of SI engine using LPG-Ethanol: A Review", International Journal of Emerging Technology and Advanced Engineering, ISSN 2250-2459, Volume 2, Issue 10, October 2012.
36. Nikolaou N., Papadopoulos C.E., Gaglias I.A., Pitarakis K.G., "A new non-linear calculation method of isomerisation gasoline research octane number based on gas chromatographic data", Fuel, Volume 83, Issues 4-5, March 2004, Pages 517-523, <http://dx.doi.org/10.1016/j.fuel.2003.09.011>
37. Pipitone E., Genchi G., "Experimental Determination of LPG-gasoline Mixtures Knock Resistance", Journal of Engineering for Gas Turbines and Power, ASME. DOI:10.1115/1.4027831.
38. Kukkadapu Goutham, Kumar Kamal, Sung Chih-Jen, Mehl Marco, Pitz William J.. Experimental and surrogate modeling study of gasoline ignition in a rapid compression machine. Combustion and Flame, Volume 159, Issue 10, October 2012, Pages 3066-3078, <http://dx.doi.org/10.1016/j.combustflame.2012.05.008>

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SYMBOLS AND ABBREVIATIONS

A/F - Air to Fuel Ratio

ASTM - American Society for Testing and Materials

BTDC - Before Top Dead Centre

CAD - Crank Angle Degree

CFR - Cooperative Fuel Research

CNG - Compressed Natural Gas

CR - Compression Ratio

H/C - Hydrogen to carbon ratio

IGBT - Insulated Gate Bipolar Transistor

KI - Knock Index

LPG - Liquefied Petroleum Gas

MN - Methane Number

MON - Motor Octane Number

NG - Natural Gas

ON - Octane Number

PRF - Primary Reference Fuel

RON - Research Octane Number

TEL - Tetraethyl Lead

TSF - Toluene Standardization Fuel

UEGO - Universal Exhaust Gas Oxygen

x_{NG} - NG mass fraction [%]

y_{NG} - NG molar fraction [%]