Knock resistance increase through the addition of Natural Gas or LPG to gasoline: an experimental study

Genchi, G., Pipitone, E., Beccari, S., and Piacentino, A.
University of Palermo

DOI:10.4271/2013-24-0100

ABSTRACT

Bi-fuel spark ignition engines, nowadays widely spread, are usually equipped with two independent injection systems, in order run the engine either with gasoline or with gaseous fuel, which can be Natural Gas (NG) or Liquefied Petroleum Gas (LPG). These gases, besides lower cost and environmental impact, are also characterized by a higher knock resistance with respect to gasoline that allows to adopt a stoichiometric proportion with air also at full load. Gasoline, on the other hand, being injected as liquid, maintains higher volumetric efficiency and hence higher power output. As a compromise solution, it could be desired to exploit the advantages of both gasoline and gas (NG or LPG), thus performing a Double-Fuel injection: as already experimented by the authors [1, 2], the addition of gaseous fuel to the gasoline/air mixture increases knocking resistance, allowing to run the engine with both "overall stoichiometric" mixture (thus lowering fuel consumption and emissions) and better spark advance (which increases engine efficiency) even at full load: the results showed high improvements in engine efficiency without noticeable power losses respect to the pure gasoline operation. Since no references have been found in literature on the Octane Number of both NG-gasoline and LPG-gasoline blends, the authors decided to experimentally determine the knock resistance increase due to gaseous fuel addition to normal air-gasoline mixtures. A wide experimental campaign has been carried out in order to evaluate the correlation between the gaseous fuel-gasoline mixture composition and its overall knock resistance measured in terms of Motor Octane Number (MON). To this purpose, a CFR engine was endowed with two independent injection systems in order to realize mixtures with different proportion between gaseous fuels and gasoline and control the overall air-fuel ratio. The experimental results presented in this paper are quite innovative and will be fundamental for future study on the simultaneous combustion of gaseous fuel and gasoline. The experimental results showed that the relationship between the mixture MON and gaseous fuel concentration in the blend is not linear and is quite different between NG-gasoline and LPG-gasoline blends.

INTRODUCTION

Bi-fuel vehicles are nowadays widely spread in the automobile market, thank to their prerogative of low pollutant emissions and fuel cost saving. 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, such as Natural Gas (NG) or Liquefied Petroleum Gas (LPG). In medium-high loads conditions, the use of gasoline, due to its relatively low knocking resistance (approximately 85 MON), compels the adoption of very rich mixtures and low spark advances in order to prevent from dangerous knocking phenomena: this causes high hydrocarbon and carbon monoxide emissions and high fuel consumption. Gaseous fuels instead, thanks to their higher knocking resistance (92 MON for LPG and 122 MON for NG), allow to run the engine with stoichiometric mixture even at full load. These observations induced the authors to experience [1, 2] the simultaneous combustion of gaseous fuels and gasoline in stoichiometric proportion with air on a spark ignition engine, so as to exploit the good qualities of each fuel to obtain cleaner and more efficient combustions. The authors investigated both the use of NG/gasoline [1] and LPG/gasoline blends [2] in order to study the effects of the addition of the two most widely spread gaseous fuels to gasoline in a series production spark ignition engine under different proportion between gas and gasoline. The combustion of gaseous fuel-gasoline mixtures offers various advantages: the addition of natural gas, as well as LPG, to the gasoline, in fact, effectively strongly increases knocking resistance, thus allowing to run the engine with "overall stoichiometric" mixtures also at full load, which in turn gives efficiency increase of about 20% and pollutant emissions (above all HC and CO) decrease in the order of 90%. 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 engine efficiency: in previous works [1, 2] the authors obtained a maximum increase of 26% on engine efficiency, respect to the pure gasoline mode, without noticeable power losses respect to the pure gasoline operation. In exchange for these considerable advantages, the double-fuel strategy 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. These encouraging results lead to consider the double-fuel combustion as a valid alternative to normal gasoline or gaseous fuel (NG or LPG) operation in bi-fuel engines.

In recent years, various researchers have focused their efforts on the study of mixtures of two or more fuels. The ethanol gasoline blends have been extensively studied [3, 4] and are nowadays used in the automotive field. Many researchers carried out studies on gaseous fuels, such as methane or hydrogen [5], and on mixtures of gaseous fuels [6 ÷ 27], with particular attention on efficiency improvement and pollutant emissions [12]. The use of natural gas has also been studied with particular emphasis on the effects of the variation of its chemical composition [12, 13, 27]. In order to measure the knocking resistance of gaseous fuels, the Methane Number (MN) method, developed by Leikar et al. [14, 13, 15, 16, 17], is often used as alternative respect to the ASTM Motor Octane Number method (MON) [22], 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 widespread, showed a good correlation with the MON [13]. The octane scale is not as appropriate for use with very high octane number fuels as it is for lower octane number liquid fuels. In fact the ASTM test method is currently used to rate gasoline but has a rating upper limit of 120.3 MON that is close or lower to the values of several natural gas octane number [12]. However others researchers, including the authors, conducted their works by means of the extrapolation method [13] that allows to extend the octane scale rating capabilities up to approximately 127 MON. This method allows to rate an ordinary natural gas with a methane content lower than 90 percent, that is the scale commonly used among the automotive industry. However, despite many works were carried out on alternative fuels and mixtures of various fuels [3 ÷ 29], the authors did not find any studies on the knock resistance of NG-gasoline or LPG-gasoline blends. This lack of information and of experimental data induced the authors to carry out a specific experimental campaign with the aim to quantify the knock resistance of the two blends as function of the their compositions. The knock resistance was measured in terms of Motor Octane Number by means of a CFR engine meticulously following the reference standard ASTM D2700 test method [22]. To this purpose the CFR used for this experimental campaign was endowed with two independent injection systems in order to realize each desired proportion between gasoline and gaseous fuel and to control the overall air-fuel ratio.

EXPERIMENTAL SETUP

This experimental study has been carried out using a Cooperative Fuel Research (CFR) engine [22] manufactured by Dresser Waukesha, whose characteristics are resumed in Table 1. The CFR engine is a four-stroke two valve stationary single-cylinder spark-ignition engine. The particular engine arrangement 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. This system is operated by a hand crank mechanism and does not affect valve clearances. The combustion chamber is of discoid type and its basic configuration does not change with the compression ratio.

The CFR engine is connected to an electric synchronous motor that keeps a constant engine speed of 900 rpm both in fired and motored condition. The CFR features a capacitive discharge ignition system with a mechanical arrangement that automatically varies spark advance as function of compression ratio: from 26° Before Top Dead Centre (BTDC) with CR=4.5 to 10° BTDC when CR is 16, as prescribed by the ASTM test method D2700.

The CFR is also equipped with two electric heater controlled by two independent PID control systems in order to maintain both inlet air temperature and air/fuel mixture temperature at their reference values. Another electric heater is used to control engine lubricant temperature. The CFR is also endowed with a thermo siphon cooling system to maintain the cylinder jacket coolant temperature at the desired value. All the temperatures were measured using K-type thermocouples.

As regards fuel supplying, the CFR engine features an original carburettor system with three independent bowls. This arrangement allows a fast fuel change while the engine is running, 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 run the engine with gaseous fuel-gasoline mixtures controlling both the proportion between the two fuels and the overall air-fuel ratio.

Table 1. CFR Engine Specifications [22].

Manufacturer	Dresser Waukesha
Model	F1/F2 Octane
Compression ratio	4.5 ÷ 16
Bore	82.6 [mm]
Stroke	114.3 [mm]
Connecting rod length	254.0 [mm]
Displacement	611.2 [cm³]
Speed (for MON test method)	900 [rpm]
Inlet valve opens	10° ATDC
Inlet valve closes	34° ABDC

Exhaust valve opens	40° BBDC
Exhaust valve closes	15° ATDC
Spark advance (variable with CR)	29° ÷ 10° BTDC
Motor Octane Number Rating Range	40 ÷ 120.3

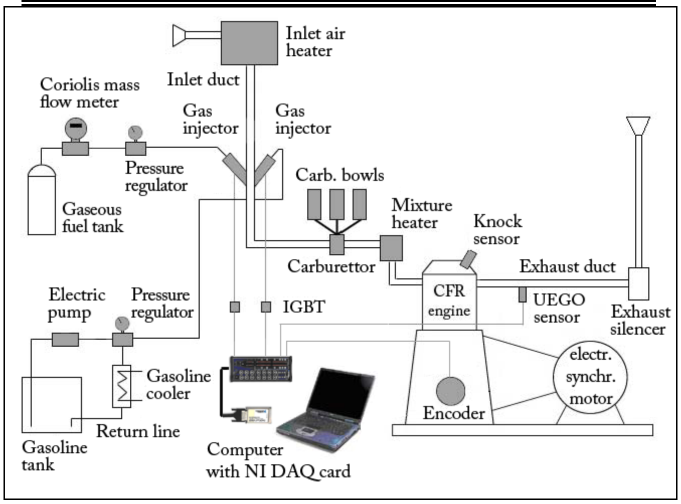

Figure 1 - Experimental system layout.

Two port fuel injectors were placed on the CFR intake duct before the carburettor (Figure 1): this arrangement was chosen in order to preserve the original air inlet path without varying any part dimension. The gaseous fuel used in the test, stocked in proper tank, passed through a Bronkhorst mini CORI-FLOW® Coriolis effect mass flow meter and through a pressure regulator, used to maintain the injector feed pressure of 3 bar, thus reaching a plenum placed before the gas injector in order to reduce upstream gas pressure oscillation due to pulsed injection.

The gasoline injection system was composed by an electric fuel pump and an automatic pressure regulator to maintain a constant injection pressure of 4 bar. A fuel cooler, placed on the return line, ensured a proper gasoline temperature. Gasoline mass flow was deduced on the base of the injection time by means of the injector flow chart, previously experimentally determined on the same fuel supply system using the mentioned high precision Coriolis type flow meter. Both gaseous fuel and gasoline injectors were operated through two IGBT transistors activated by digital pulses generated by means of a National Instruments DAQCard 6062E. A personal computer was used to manage the injection systems and perform data acquisition, both programmed in LabVIEW environment. In order to realize the desired overall air-fuel ratio, the gaseous fuel injection system was controlled in closed-loop using as feedback the output signal of a Universal Exhaust Gas Oxygen (UEGO) sensor placed in the exhaust duct. The gasoline injection was instead operated in open-loop in order to reach the desired proportion with the gaseous fuel. The ambient pressure, a very important parameter for the fuel octane rating, has been measured by means of a barometric pressure sensor Druck PMP 1400 and its value has been 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 (3.56 ÷ 7.12 g of water per kg of dry air) imposed by the ASTM standard method.

All the relevant quantities were sampled using as trigger and scan clock the outputs of a 360 pulses per revolution incremental optical encoder connected to the engine crankshaft.

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 (Figure 1), a knock meter for knock signal conditioning and an analogical display showing the knock intensity. As required by the reference standard ASTM D2700 [22], the knock meter has been properly calibrated before each test.

TEST METHODS AND EXPERIMENTAL RESULTS

The aim of the present work was to evaluate the correlation between the overall knock resistance and the composition of the two blends: NG-gasoline and LPG-gasoline. These mixtures were experimentally tested according to the ASTM D2700 test method [22], whose operating conditions are reported in Table 2, under different proportions between gaseous and liquid fuel.

Table 2. Motor octane number rating conditions [22].

Engine speed	900 [RPM]
Inlet air temperature	38 ± 2.8 [°C]
Air/fuel mixture temperature	149 ± 1 [°C]
Engine coolant temperature	100 ± 1.5 [°C]
Lubricant temperature	68 ± 8 [°C]
Engine load condition	full load
Compression ratio (CR)	regulated to obtain standard knock intensity

Overall air/fuel ratio	regulated to obtain the maximum knocking intensity
Spark advance	10÷29 [CAD BTDC], depending on compression ratio

The octane rating values are strictly dependent on the CFR engine features and therefore some preliminary tests were conducted in order to validate the octane rating capabilities 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 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 rating the octane number of both NG and LPG used for the test, whose composition is shown in Table 3 and Table 4. As a result, for NG a 122.1 MON was measured, which is very similar to the 122.6 MON obtained by means of the empirical formula of Kubesh et. al. [13], based on the natural gas composition and widely used by others researchers [15, 17]. The octane rating of the LPG sample gave a result of 92.7 MON, which is very similar to the 93.0 MON achieved with same LPG composition by other researchers [20, 21]. It is worth to mention that a difference of 0.3÷0.5 MON is quite admissible since lower than the CFR MON reproducibility standard deviation, which varies from 0.4 to 0.7 MON on a range of 90÷120 MON, as reported on the standard reference ASTM D2700 [22]. Moreover, at the beginning of the experimental campaign, the overall engine compliance was instead established in accordance with the standard "Fit-for-Use" procedure using Toluene Standardisation Fuels, whose known accepted reference values are prescribed by reference ASTM D2700 [22].

As is known, the standard octane test procedure requires the use of some Primary Reference Fuels (PRF) obtained mixing isooctane and n-heptane in predetermined volumetric proportion [22]. The knock rating of the tested fuel is determined by a comparison of its knocking tendency 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. The PRF blends were prepared on a gravimetric basis using a high precision balance. The isooctane and n-heptane used in the experimental campaign were analytical grade quality with a minimum purity of 99.75%. In the test performed, the PRF were always used with the original carburettor system, which, thanks to its three independent fuel bowls, allowed rapid change of fuel without stopping the engine. The gaseous fuel-gasoline mixtures instead were realized by injecting the proper amount of both fuels (gaseous and liquid) in the intake duct using the added injection systems (Figure 1), thus pursuing a very accurate control on the overall air-fuel ratio and on the proportion between the two fuels.

As prescribed by the standard method, each fuel used was rated at the air-to-fuel ratio that produces the maximum knock intensity (KI): for each of the fuel tested hence, this operative condition was achieved by means of a sweep procedure in which all the other parameters were kept constant. For each NG-gasoline blend, as well as LPG-gasoline mixture tested, the MON value presented in this paper was obtained as mean value over three successive measurements which satisfied certain stability and repeatability conditions exposed in the standard procedure [22], such as a maximum difference of 0.3 MON between two consecutive knock ratings. For octane rating of sample fuel with a knock resistance greater than 100 MON, the standard procedure involves the use of reference blends consisting of iso-octane with specified quantities of tetraethyl lead (TEL). Figure 2 shows the relationship between MON and the TEL quantity to add to 400 ml of iso-octane: 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 iso-octane which results in an upper rating limit of 120.3 MON for a CFR engine. However, by means of the extrapolation method [13], it is possible to extend the octane scale up to 127 MON, that is sufficient to rate a natural gas with a methane concentration up to 90 percent (vol.).

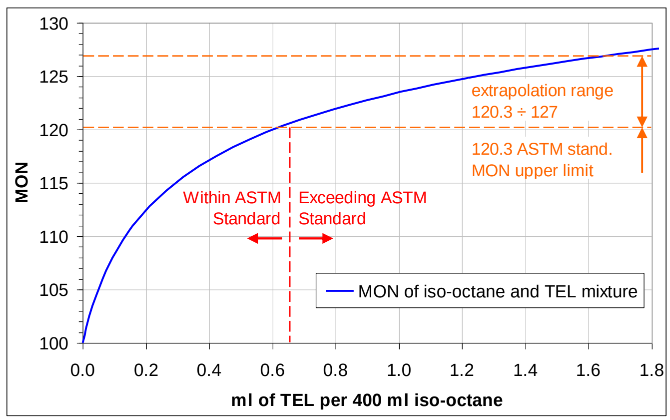

Figure 2 - Relationship between MON and TEL addition to 400 ml of iso-octane [13, 22].

The entire experimental campaign was carried out using unique samples of commercial gasoline, natural gas and LPG. In fact, as known, both LPG and NG are mixtures of various gases and their composition may differ according to the producer, to the period of production and to the geographic location. The main components of commercial NG are methane, ethane, propane, others heavier hydrocarbons and inert gases, such as CO_2 and N_2, in lower quantities. Commercial LPG is instead usually constituted by propane, butane, propylene and others in lower quantities.

All these components feature different knocking resistance and, as consequence, both LPG [19] and NG [13] MON are heavily dependent on mixture composition. Methane has the very high knock resistance of 140 MON [13], while heavier hydrocarbons, such as propane and ethane (characterized by lower MON) tend to lower NG knock resistance.

Carbon dioxide increases the knocking resistance of the mixture [13, 27] since acts as a fuel diluent and has a high specific heat. As observed by Brecq et al. [27], CO_2 has a higher anti-knock effect than N_2. Table 3 and Table 4 report the composition of the natural gas and of the LPG samples used in the tests.

Table 3. Composition and properties of the natural gas used

Components	% vol.
Methane - CH_4	85.79
Ethane - C_2H_6	7.86
Propane - C_3H_8	1.61
N-butane - C_4H_{10}	0.19
Iso-butane - C_4H_{10}	0.28
Butylene - C_4H_8	0.05
Iso-penthane - C_5H_{12}	0.06
N-penthane - C_5H_{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
Calculated MON [13, 17]	122.6
Measured MON [13, 22]	122.1
Calculated Methane Number [13, 17]	80.0
Lower heating value [MJ/kg]	46.0
Stoichiometric Air/fuel mass ratio	16.9

Table 4. Composition and properties of LPG used

Components (gaseous phase)	% vol.	MON volumetric factor [18]
Propane - C_3H_8	75	95.6
Propylene - C_3H_6	25	83.1
N-butane - C_4H_{10}	0.0	88.9
Iso-butane - C_4H_{10}	0.0	97.1
Butylene - C_4H_8	0.0	75.7
Properties		
Calculated MON [18, 19]		92.6
Measured MON [18, 22]		92.7
Lower heating value [MJ/Nm³]		91.8
Stoichiometric Air/fuel mass ratio		15.5
Pressure at 15 °C [bar]		7.66

The tests performed confirmed that the addition of NG or LPG to gasoline significantly raises the resistance to autoignition. As reported in Figure 3, the MON of each gaseous fuel-gasoline mixture tested is represented as function of the gaseous fuel mass fraction (i.e. the ratio between the gaseous fuel mass and the total amount of fuel injected, x_{NG} for NG and x_{LPG} for LPG) which varies from 0% for pure gasoline, to 100%, which instead refers to pure NG or pure LPG. The upper (blue) curve refers to the NG-gasoline mixtures while the lower (orange) curve to the LPG-gasoline blends.

As can be observed, for both the gaseous fuels used, the relationship between MON and gas mass fraction is not linear and it is quite different between the two type of mixtures. Due to the higher knock resistance of natural gas (122 MON) with respect to LPG (92.6 MON), the same gas mass fraction produces in the NG-gasoline mixtures a higher knock resistance than in the LPG-gasoline blends. Moreover, the difference between the two gas on enhancing the overall MON raises as the gaseous fuel mass fraction increases.

The experimental data of the NG-gasoline mixtures can be interpolated by means of the following quadratic function:

$$MON = 84.14 + 17.04 \cdot 10^{-2} \cdot (x_{NG}) + 20.19 \cdot 10^{-4} \cdot (x_{NG})^2 \quad (1)$$

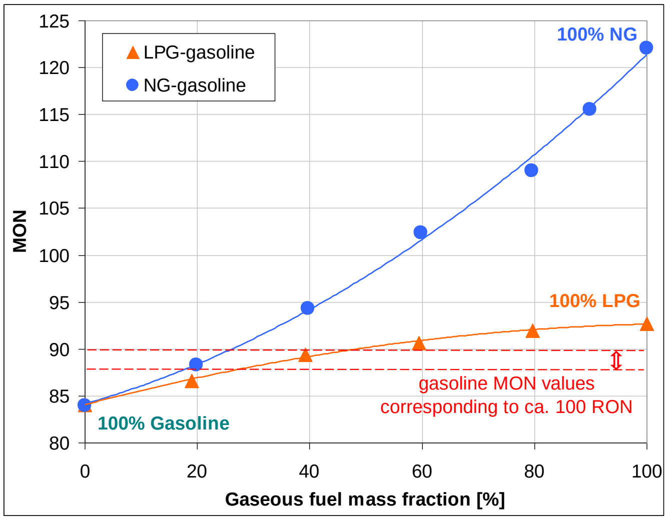

Figure 3 - Measured MON of NG-gasoline mixtures and LPG-gasoline blends as function of the mass fraction of the respective gaseous fuels.

Referring to the upper blue curve of Figure 3, as the NG mass fraction increases from 0% to 20%, the MON of the NG-gasoline mixture increases from 84.1 to 88.3, which results in a significant knocking resistance improvement. In fact, starting from a common gasoline, the same results can be achieved by means of particular additives or increasing the quantity of oxygenates components, usually present in gasoline composition.

Using a natural gas mass fraction from 20% to 25%, allows to reach an overall MON between 88 and 90, which corresponds to the high knock resistance of commercial gasoline type with

100 RON (Research Octane Number), such as "Super Plus" quality gasoline. The iso-octane knock resistance (i.e. MON 100) has been reached with natural gas mass fraction between 50% and 60%.

For NG mass fraction higher than 60%, the MON increase is more pronounced. The last 20% of NG mass fraction produced a great knock resistance improvement, i.e. from 109 to 122.1 MON, quite different from that produced by the first 20% (Figure 3).

As regards the LPG-gasoline mixture, the experimental results can be interpolated by means of the following quadratic function:

$$MON = 84.07 + 15.56 \cdot 10^{-2} \cdot (x_{LPG}) - 69.73 \cdot 10^{-5} \cdot (x_{LPG})^2 \quad (2)$$

The lower orange curve of Figure 3 shows that the LPG-gasoline mixture reaches a MON of 88.1 with an LPG addition of 30%. An overall MON between 88 and 90 (corresponding to the high knock resistance of commercial gasoline type with 100 RON) can be achieved with LPG mass fraction from 30% to 50%.

Unlike for the NG-gasoline mixtures, for LPG mass fraction higher than 60%, the MON increase is less pronounced. The last 20% of LPG mass fraction produced a small knock resistance improvement, i.e. from MON 92 to 92.7, quite different from the first 20% of LPG mass fraction, which instead produced a strong MON increment from 84.1 to 86.7.

CONCLUSIONS

The authors of the present paper experienced in previous works [1, 2] the simultaneous combustion of NG-gasoline mixtures, as well as LPG-gasoline blends, on a spark ignition engine. The strong increase in knocking resistance due to the addition of gaseous fuel (especially using NG) to the gasoline/air mixture allowed to run the engine at full load with both "overall stoichiometric" mixture, thus lowering fuel consumption and emissions, and to adopt better spark advance, thus further increasing engine efficiency. These improvements were obtained without noticeable power losses respect to the pure gasoline operation. Given the absence in literature of reports dealing with the knock resistance increase obtainable by NG, as well as LPG, addition to air-gasoline mixtures, the authors decided to quantify through a proper experimental campaigns the knock resistance of both NG-gasoline mixture and LPG-gasoline mixture as function of the gaseous fuel concentration.

The knock resistance was measured by means of a standard CFR engine [7, 22] in terms of Motor Octane Number (MON), which is the scale commonly used among the automotive industry. In order to test the simultaneous combustion of gaseous fuel and gasoline for different composition of the blend, the CFR engine was endowed with two independent injection systems, thus allowing to perfectly control the amount of gas and gasoline injected at each cycle. A personal computer was used to manage both fuels injection systems and the data acquisition by means of a specific software, developed in LabVIEW.

In the experimental campaigns, various blends were tested for each of the gaseous fuel considered, going from a 0% of gaseous fuel mass fraction (i.e. the ratio between the gaseous fuel mass and the total amount of fuel injected) when running with pure gasoline, to the 100% gaseous fuel mass fraction, i.e. pure NG or pure LPG.

The results obtained confirmed that the addition of both NG and LPG to gasoline significantly increase the engine knock resistance. Obviously, having natural gas a higher knock resistance than LPG, the addition of NG to gasoline produced stronger MON increments than those obtained adding LPG. The difference between the two gas in enhancing knock resistance increases with the mass concentration of the gaseous fuel.

The experimental results also showed that the relationship between mixture MON and gaseous fuel mass fraction is not linear and is quite different between NG and LPG. The experimental data of each gaseous fuel can be interpolated by means of a quadratic function.

As a result, the knock resistance of commercial gasoline type with 100 RON, such as "Super Plus" quality gasoline, can be obtained by adding to gasoline a 40% in mass of LPG or a 25% in mass of natural gas. The latter also allowed to reach the knock resistance of pure iso-octane (i.e. 100 MON, by definition) with a mixture mass concentration of 55%. Starting from a standard commercial gasoline, the same MON increments may be pursued by means of particular additives or increasing the quantity of oxygenates components. The simultaneous combustion of gasoline and gaseous fuel (NG or LPG) in a internal combustion engine may have further development, including some industrial application, such as the use of the double fuel strategy on series production spark ignition engine. The experimental results presented in this paper hence give an important contribution for a more detailed comprehension of the significant effects of gaseous fuel addition in enhancing the knock resistance of a normal air-gasoline mixture.

REFERENCES

1. E. Pipitone, S. Beccari, "Performance improvement of a S.I. CNG bi-fuel engine by means of double-fuel injection", SAE technical paper 2009-24-0058, DOI: 10.4271/2009-24-0058.

2. E. Pipitone, S. Beccari, "Performance and emission improvement of a S.I. engine fuelled by LPG/gasoline mixtures", SAE technical paper 2010-01-0615, DOI: 10.4271/2010-01-0615.

3. Christopher P. Cooney, Yeliana, Jeremy J. Worm, Jeffrey D. Naber, “Combustion Characterization in an Internal Combustion Engine with Ethanol-Gasoline Blended Fuels Varying Compression Ratios and Ignition Timing, Energy & Fuels Volume 23 May 2009.

4. J.E. Anderson, D.M. DiCicco, J.M. Ginder, U. Kramer, T.G. Leone, H.E. Raney-Pablo, T.J. Wallington, “High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States”, Fuel 97 (2012) 585-594, Elsevier.

5. Ghazi A. Karim, “Hydrogen as a spark ignition engine fuel”, International Journal of Hydrogen Energy 28 (2003) 569-577, Pergamon, Elsevier.

6. G. A. Karim, I. Wierzba and Y. Al-Alousi, “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.

7. S.O. Bade Shrestha, G.A. Karim, “Hydrogen as an additive to methane for spark ignition engine applications”, International Journal of Hydrogen Energy 24 (1999) 577-586, Pergamon, Elsevier.

8. Bauer CG, Forest TW. Effect of hydrogen addition on the performance of methane-fueled vehicles. Part I: Effect on S.I. engine performance. Int J Hydrogen Energy 2001;26:55-70.

9. Hailin Li, Ghazi A. Karim, “Exhaust emissions from an SI engine operating on gaseous fuel mixtures containing hydrogen”, International Journal of Hydrogen Energy 30 (2005) 1491-1499, Elsevier.

10. 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.

11. S. Orhan Akansu, Nafiz Kahraman, Bilge Çeper, “Experimental study on a spark ignition engine fuelled by methane–hydrogen mixtures”, International Journal of Hydrogen Energy 32 (2007) 4279-4284, Elsevier.

12. Hien Ly, “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.

13. 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.

14. 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.

15. A. A. Attar, G. A. Karim; Dennis N. Assanis, “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.

16. Martin Malenshek, Daniel B. Olsen, “Methane number testing of alternative gaseous fuels”, Fuel 88 (2009) 650-656, Elsevier.

17. UNI EN ISO 15403-1:2008 Natural Gas - Natural Gas For Use As A Compressed Fuel For Vehicles - Part 1: Designation Of The Quality.

18. UNI EN 589:2009 Combustibili per autotrazione - GPL - Requisiti e metodi di prova.

19. Department of Environment and Heritage, Commonwealth of Australia, “Setting National Fuel Quality Standards, Paper 5, Proposed Standards for Liquefied Petroleum Gas”, CCP Instant Printing, 2001, ISBN 0 642 54772 6.

20. Kai J. Morganti, Tien Mun Foonga, Michael J. Breara, Gabriel da Silvab, Yi Yanga, Frederick L. Dryerc, “The Research and Motor octane numbers of Liquefied Petroleum Gas (LPG)”, Fuel, available online 18 February 2013 at: http://www.sciencedirect.com/science/article/pii/S0016236113000811#

21. Boldt K. Motor (LP) knock test method development. SAE Technical Paper 670055. http://dx.doi.org/10.4271/670055

22. Standard Test Method for Motor Octane Number of Spark-Ignition Engine Fuel, ASTM International D2700.

23. Anton Perdih, Franc Perdih, “Chemical Interpretation of Octane Number”, Acta Chim. Slov. 2006, 53, 306-315.

24. E. Pipitone, S. Beccari, “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, DOI: 10.1115/ICEF2009-14057.

25. C. Rahmouni, G. Brecq, M. Tazerout, O. Le Corre, “Knock rating of gaseous fuels in a single cylinder spark ignition engine”, Fuel 83 (2004) 327-336, Elsevier.

26. Aparna Arunachalam, Daniel B. Olsen, “Experimental evaluation of knock characteristics of producer gas”, Biomass and Bioenergy 37 (2012) 169-176, Elsevier.

27. Guillaume Brecq, Jérôme Bellettre, Mohand Tazerout, Thomas Muller, “Knock prevention of CHP engines by addition of N_2 and CO_2 to the natural gas fuel”, Applied Thermal Engineering, Volume 23, Issue 11, August 2003, Pages 1359–1371, Elsevier.

28. J. B. Heywood, “Internal Combustion Engines Fundamentals”, McGraw-Hill automotive technology series, 1988, ISBN 0-07-100499-8.

29. R. Stone, J. K. Ball, “Automotive engineering fundamentals”, SAE International, 2004.

CONTACT INFORMATION

Ing. Giuseppe Genchi,
giuseppe.genchi@unipa.it
tel. ++39 091 23897261
fax. ++39 091 23860672
Dipartimento di Ingegneria Chimica Gestionale Informatica Meccanica,
Università degli Studi di Palermo,
Viale delle Scienze, Edificio 8, 90128 Palermo, Italy.

ACKNOWLEDGMENTS

The authors would like to express their acknowledgments to Mr. Beniamino Drago for his invaluable technical support.

DEFINITIONS/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
CR	Compression Ratio
KI	Knock Index
LPG	Liquefied Petroleum Gas
MON	Motor Octane Number
PRF	Primary Reference Fuel
RON	Research Octane Number
UEGO	Universal Exhaust Gas Oxygen
$\mathbf{x_{LPG}}$	LPG mass fraction on LPG-gasoline mixture
$\mathbf{x_{NG}}$	NG mass fraction on NG-gasoline mixture