Experimental Determination of Liquefied Petroleum Gas–Gasoline Mixtures Knock Resistance

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The results of previous experimental researches showed that great advantages can be achieved, both in terms of fuel consumption and pollutant emissions, in bifuel vehicles by means of the double-fuel combustion, i.e., the simultaneous combustion of gasoline and a gaseous fuel, such as liquefied petroleum gas (LPG) or natural gas (NG). The substantial increase in knock resistance pursued by adding LPG to gasoline, which allowed to maintain an overall stoichiometric proportion with air also at full load, is not documented in the scientific literature and induced the authors to perform a proper experimental campaign. The motor octane number (MON) of LPG–gasoline mixtures has been hence determined on a standard cooperative fuel research (CFR) engine, equipped with a double-fuel injection system in order to realize different proportions between the two fuels and electronically control the overall air–fuels mixture. The results of the measurement show a quadratic dependence of the MON of the mixture as function of the LPG concentration evaluated on a mass basis, with higher increase for the lower LPG content. A good linear relation, instead, has been determined on the basis of the evaluated LPG molar fraction. The simultaneous combustion of LPG and gasoline may become a third operative mode of bifuel vehicles, allowing to optimize fuel economy, performances, and pollutant emissions; turbocharged bifuel engines could strongly take advantage of the knock resistance of the fuels mixture thus adopting high compression ratio (CR) both in pure gas and double-fuel mode, hence maximizing performance and reducing engine size. The two correlations determined in this work, hence, can be useful for the design of future bifuel engines running with knock safe simultaneous combustion of LPG and gasoline. [DOI: 10.1115/1.4027831]

Keywords: octane rating, LPG, gasoline, CFR, fuel mixtures, knock resistance, autoignition

Introduction

Gaseous fuels, such as NG or LPG, represent today a concrete alternative to conventional fuels for road vehicles propulsion and stationary engines, since these are characterized by a relatively low cost, better geopolitical distribution than oil, and lower environmental impact. For these reasons in the last 20 years, both LPG and NG have been widely studied with the aim to experience their compatibility and properties as alternative fuels for spark-ignition engines. Bifuel vehicles are nowadays widely spread in the automobile market, thanks to their prerogative of low pollutant emissions and fuel cost saving. These vehicles are equipped with spark-ignition engines endowed with two separate injection systems in order to run either with gasoline or with gaseous fuel, which can be NG or LPG. In medium-high load conditions, the use of gasoline, due to its relatively low knocking resistance (approximately 85 MON), compels the adoption of very rich mixtures (i.e., $0.8 \leq \lambda \leq 0.9$) and low spark advances in order to prevent from dangerous knocking phenomena; this, besides the strong fuel consumption increase, also causes both a significant rise of the amount of carbon monoxide (CO) and hydrocarbon (HC) in the raw exhaust gas, and a strong reduction of the catalytic converter efficiency. The result is a very poor engine efficiency together with very high HC and CO emissions. Gaseous fuels instead, thanks to their higher knocking resistance (92 MON for LPG and 122 MON for NG), allow to run spark-ignition engines with stoichiometric mixture even at full load. These observations induced the authors to experience [1,2] the simultaneous combustion of gasoline and a gaseous fuel, such as LPG or NG, in stoichiometric proportion with air on a series production spark-ignition engine, so as to exploit the good qualities of each fuel to obtain cleaner and more efficient combustions without substantial power loss.

The addition of LPG to the gasoline–air mixture produced such an increase in knocking resistance that allowed to run a series production bifuel engine in full load condition with overall stoichiometric mixture and better spark advance. As a result [1], remarkable reduction in raw pollutant emissions (as shown in Fig. 1) and strong engine efficiency improvements (+29%) were obtained with marginal power loss (−4%) compared with pure gasoline operation. It is worth to mention that the noticeable
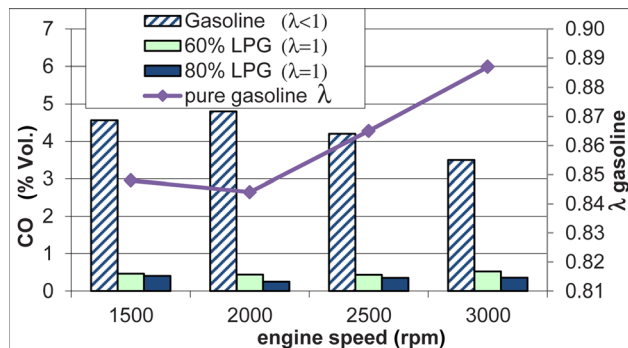
Fig. 1 Raw CO emission measured at WOT for pure gasoline (same λ values of Fig. 1) and double-fuel mode (λ = 1) on a series production S.I. engine [1]

engine efficiency arises both from the overall stoichiometric proportion of air–fuels mixture, and from the thermodynamic cycle improvement due to the better combustion phase allowed by the increased knock resistance. Moreover, it must be also considered that an overall stoichiometric mixture let the catalytic converter reach its best conversion efficiency, thus further lowering pollutant emissions. The combined effect has been evaluated [1] to lead to an overall emissions reduction of about 90% in comparison with pure gasoline operation at wide open throttle (WOT) condition, as also shown in Fig. 2.

These noticeable results may be easily obtained on series production bifuel engines by means of a simple ECU software modification, since both fuels must be injected within the same engine cycle. Obviously, a proper ECU mapping of the injection times and spark advance should be carried out.

The simultaneous combustion of gaseous fuel and gasoline, referred to as double-fuel combustion, can be considered the third operation mode of bifuel engines, which are normally run either with gasoline or with gas, and is quite different from the well-known dual-fuel combustion, in which the autoignition of a small quantity of one of the two fuels (usually diesel fuel) is used to ignite and start the combustion of the second fuel (which may be LPG, NG, etc.). In double-fuel combustion, instead, the ignition is caused by the spark and the two fuels, homogeneously mixed with air, burn simultaneously through the same flame front. The strong knock resistance increase obtained could be further exploited by turbocharged bifuel engines, which could run with high CR both in pure gas and double-fuel mode, thus maximizing performance maintaining low fuel consumption and pollutant emissions; all this obviously could bring to substantial reduction of required engine displacement (downsizing) thus allowing to reduce overall vehicles mass and hence increasing fuel economy. The optimization of such kind of combustion in modern spark-ignition engines
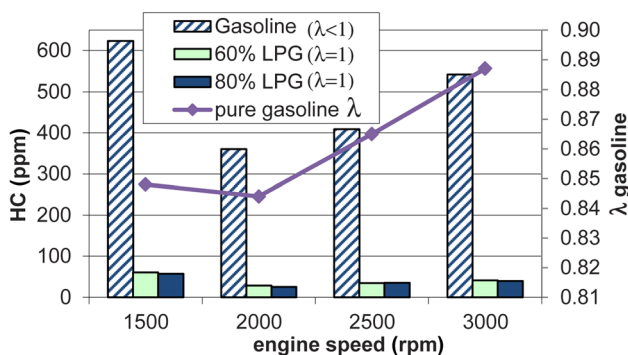
can be carried out both by means of thermodynamic simulations, which should be obviously endowed of proper submodels for the prediction of knock occurrence [3–6], and by experimental tests. In any case, a fundamental information is represented by the knock resistance of the fuels mixture, which should be expressed in terms of octane number or autoignition retard and should take into consideration the mixture composition. As regards the use of LPG in spark-ignition engines, some researchers studied its knock resistance [7,8] and how the gas composition may influence its antiknock properties [9]; the rating of LPG knock resistance has also been widely discussed and several quality standards and rating methods have been produced [10–14]. Various studies also report the use of LPG together with other fuels. LPG–dimethyl ether blend fuel has been investigated in a spark-ignition engine [15] and on homogeneous charge compression ignition engine [16], while the use of LPG on dual-fuel engine is reported in Ref. [17]. Some studies have been carried out in order to employ LPG as a diesel fuel [18], enhancing its ignition quality by means of various cetane number improver, such as normal paraffins.

Despite many works have been produced on alternative fuels and mixtures of various fuels [15–19], no studies or literature references have been found on the knock resistance of 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 LPG–gasoline mixture as function of the LPG concentration.

Experimental Setup

The knock resistance of the LPG–gasoline mixtures has been measured in terms of MON by means of a CFR engine [9,20] manufactured by Dresser Waukesha (see Table 1 for main engine specifications); the CFR engine is a four-stroke two-valve stationary single-cylinder spark-ignition engine endowed with a particular arrangement that allows to accurately vary the 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 discoid type and its basic configuration does not change with the CR (Fig. 3).

MON measurements have been carried out meticulously following the reference standard test method ASTM D2700 [20] which was originally developed to test liquid fuels but, as experienced by others researchers [21–23], can be also properly used for gaseous fuels. To this purpose, the CFR used for this experimental campaign was endowed with two independent injection systems (see Figs. 4 and 5) in order to realize each desired gasoline–LPG mixture and to accurately control the overall air–fuel ratio.

The CFR engine is connected to an electric synchronous motor that maintains a constant speed of 900 rpm both in fired and motored condition and features a capacitive discharge ignition system with a mechanical arrangement that allows to vary the spark advance as function of CR. From 26 deg before top dead centre (BTDC) with CR = 4.5–10 deg BTDC when CR is 16, as prescribed by the ASTM test method D2700 [20].

The CFR engine used in the test was equipped with two electric heaters connected to two independent PID controllers Omega CN4116 in order to maintain both inlet air temperature and air/fuel mixture temperature at their reference values (see Table 2),

Fig. 2 HC emissions after catalytic converter at WOT for both pure gasoline mode (λ values reported on the right axis) and double-fuel mode (λ = 1) on a series production S.I. engine [1]

Table 1 CFR engine specifications [20]

Manufacturer	Dresser Waukesha
Model	F1/F2 Octane
CR	4.5–16
Bore	82.6 (mm)
Stroke	114.3 (mm)
Connecting rod length	254.0 (mm)
Displacement	611.2 (cm^3)
MON measurement range	40–120.3
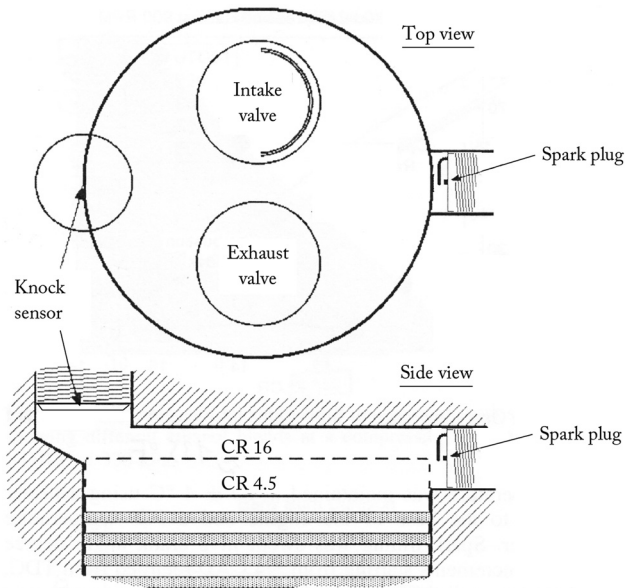
Fig. 3 CFR engine combustion chamber: the knock sensor is placed on the opposite side to the spark plug
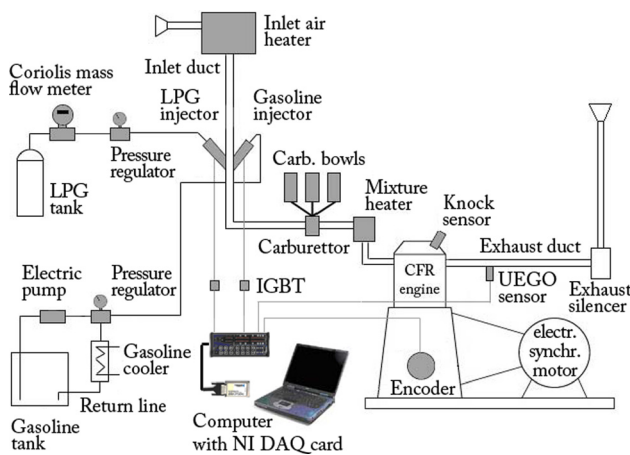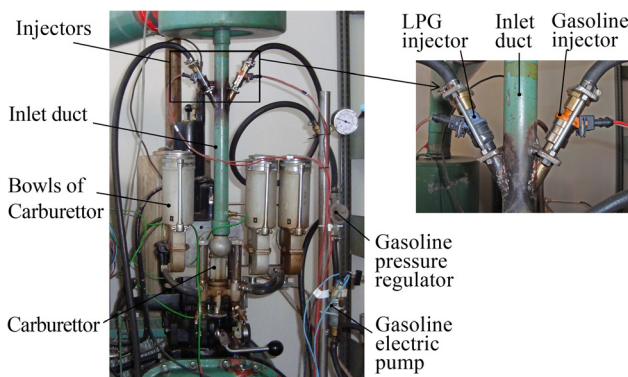
Table 2 Standard MON rating conditions [20]

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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	Regulated to obtain standard KI
Overall air/fuel ratio	Regulated to obtain the maximum knocking intensity
Spark advance	10–29 (crank angle degree BTDC) depending on CR
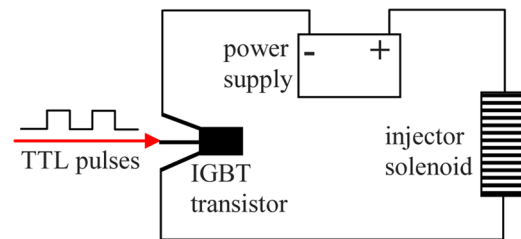
Fig. 6 Scheme of the injection system

while the original thermosiphon cooling system maintained the cylinder jacket coolant temperature at the prescribed value of $100 \pm 1.5\,°C$. All the temperatures were measured using type K thermocouples.

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 (some more details are given further on in the Test Conditions and Methods section) without stopping the engine, as required during an octane rating test, but does not allow the use of gaseous fuels. As already mentioned, hence, two Bosch EV1 port fuel injectors were placed on the engine intake duct before the carburettor (Figs. 4 and 5). This arrangement was chosen to preserve the original air inlet path without varying any part dimension. As illustrated in Fig. 4, in the experimental setup used for the test, the gaseous fuel stored in a reservoir tank passes through a Bronkhorst mini CORI-FLOW® Coriolis effect mass flow meter (with 0–2 kg/h range of measurement and accuracy of $\pm 0.2\%$ of reading value) and hence 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.

As shown in Fig. 4, the gasoline injection system was also composed of an electric fuel pump, an automatic pressure regulator used to maintain a constant injection pressure of 4 bar, and a fuel cooler placed on the return line to ensure a proper gasoline temperature. 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 that this procedure allowed to control gasoline mass flow with the accuracy of 1% of the desired value.

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. Figure 6 schematically represents the electrical circuit employed for the excitation of each fuel injector, mainly composed by the power supply device, the injector solenoid and an insulated gate bipolar transistor (IGBT), which acts as a "digital switch," thus opening or closing the electrical circuit on the basis

Fig. 4 Experimental system layout

Fig. 5 Fuel supply systems: carburettor, LPG injector, and gasoline injector

of the voltage level at its input (0 and 5 V, respectively). A National Instruments DAQCard 6062E programmed under LabVIEW has been used to generate the necessary transistor to transistor logic pulses for the IGBT, whose high level (5 V) duration is exactly the injection time. The modulation of this high level width allowed hence the precise control of the amount of each of the two fuels injected.

The injection times of the two fuels were modulated following two different strategies. LPG injection was controlled in closed-loop using the output signal of an universal exhaust gas oxygen (UEGO) sensor placed in the exhaust duct, while gasoline injection was operated in open-loop, pursuing the predetermined 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 actual H/C ratio of the fuels mixture, which has been calculated on the basis of the measured fuel mass flow rates.

Both ambient pressure and intake air humidity are very important parameters to be considered for a correct fuel octane rating [20]. For this reason, they have been measured by the use of proper sensors and acquired, together with all the other relevant quantities (exhaust gas oxygen concentration, LPG mass flow, inlet air and air–fuel mixture temperatures), by means of the mentioned National Instruments DAQCard 6062E using as trigger and scan clock the pulses generated by a 360 pulses per revolution 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 (KI) was measured by means of the original CFR system, constituted by a knock sensor placed on the combustion chamber (Fig. 3), a knock meter for knock signal conditioning and an analogue display showing the KI. As required by the reference standard ASTM D2700 [20], the knock meter has been properly calibrated before each test.

Test Conditions and Methods

The operative conditions prescribed by the reference standard test method ASTM D2700 are represented in Table 2. 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 [20]. The knock rating of the tested fuel is determined by a comparison of its knocking tendency with that of two 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 the high precision balance already mentioned. The isooctane and n-heptane used in the experimental campaign were of 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, allows a rapid change of fuel without stopping the engine. The LPG–gasoline mixtures instead, as already mentioned, were obtained injecting the proper amount of both fuels in the intake duct using the added injection systems (Figs. 4 and 5), thus realizing 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 KI. For each of the fuel tested, this operative condition was achieved by means of a sweep procedure in which all the other parameters were kept constant. It was observed that pure gasoline, pure LPG, and LPG–gasoline mixtures produces their maximum KI in almost stoichiometric proportion with air, while PRF blends gave maximum KI with slightly lean air–fuel ratios.

For each LPG–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 [20], such as a maximum difference of 0.3 MON between two consecutive knock ratings.

The entire experimental campaign was carried out using a single sample of pump grade gasoline (Table 3) and a single commercial LPG 50 l tank reserve.

As known, LPG is a mixture of various fuels and its composition may differ according to the producer and the period of production. The main components of commercial LPG mixture are propane, butane, propylene, and others in lower quantities [9]. These components feature different knocking resistance and, as consequence, the MON of the mixture is strongly depending on its composition. For this reason, in order to refer the experimental results to a known LPG mixture, the composition of the gaseous phase of the LPG used in the test was determined and is reported in Table 4.

Since the octane rating values strictly depend on the CFR engine features, some preliminary tests were conducted in order to validate the octane rating capabilities of the CFR engine endowed with the double injection systems. For 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 LPG injection system was instead carried out comparing the measured MON of the LPG used for the test (i.e., 92.7) with the MON evaluated using the empirical formula reported in UNI EN 589:2009 [14], which allows to evaluate the mixture MON as the weighted sum of each component volume concentration multiplied by a proper MON volumetric factor (Table 4). As a result, a difference of only 0.1 MON was detected, which is quite admissible since lower than the CFR MON reproducibility standard deviation, which varies from 0.4 to 0.5 MON on a range of 90–100 MON (see ASTM D2700 [20]). Moreover, at the beginning of the experimental campaign, the overall engine compliance was established in accordance with the standard "fit-for-use" procedure using toluene standardization fuels, whose known accepted reference values are prescribed by reference ASTM D2700.

Table 4 Composition and properties of the LPG used in the tests

Components (gaseous phase)	% vol.	MON vol. factor [14]	Molar mass (g/mol)
Propane—C_3H_8	75	95.6	44
Propylene—C_3H_6	25	83.1	42
N-butane—C_4H_{10}	0.0	88.9	58
Isobutane—C_4H_{10}	0.0	97.1	58
Butylene—C_4H_8	0.0	75.7	58
Physical properties and knock resistance			
Liquid phase density at 15 °C			510 kg/m^3
Gaseous phase density at 15 °C, 1 bar			1.82 kg/m^3
H/C ratio			2.50
Molar mass			43.5 g/mol
Stoichiometric air–fuel ratio			15.5
Lower heating value			46.2 MJ/kg
MON, calculated [14]			92.6
MON, measured [20]			92.7

Table 3 Properties of gasoline used in the tests

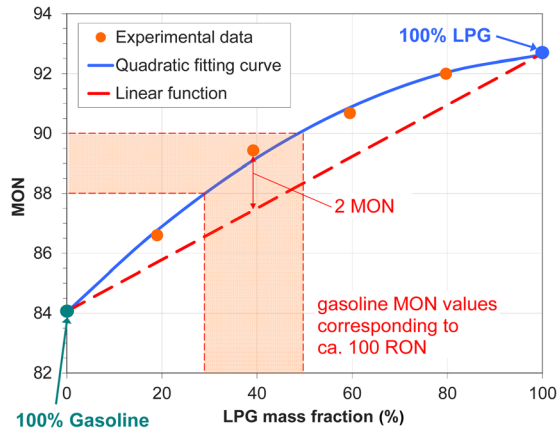|	
Liquid phase density at 15 °C	730 kg/m^3
Equivalent H/C ratio [24]	1.85
Molar mass (assumed)	110 g/mol
Stoichiometric ratio	14.7
Lower heating value [25]	43.4 MJ/kg
MON [20]	84.1

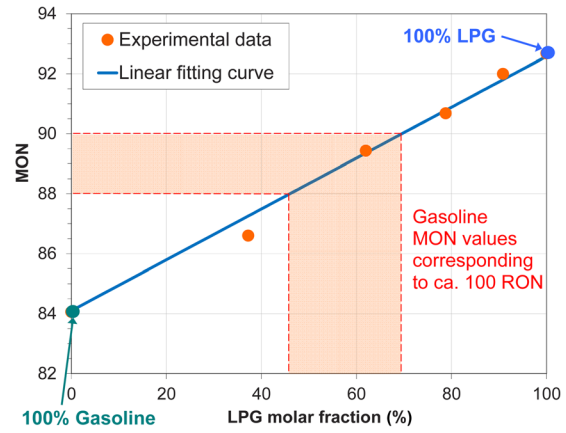**Fig. 7 Measured MON as function of the LPG mass fraction**

Fig. 8 Measured MON as function of the LPG molar fraction

Experimental Results and Discussion

The MON measurements performed on the LPG–gasoline mixtures confirmed that the addition of LPG to gasoline effectively raises the resistance to autoignition; as a result, Fig. 7 reports the MON of each LPG–gasoline mixture tested as function of the LPG mass fraction (i.e., the ratio between the injected LPG mass and the mass of the total amount of fuel injected), which varies from 0%, i.e., pure gasoline, to 100%, which instead refers to the sole LPG. As can be noted, the relationship between MON and LPG mass fraction is not linear. The knock resistance increase is more pronounced when LPG mass concentration is lower.

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

$$x_{LPG} = \frac{m_{LPG}}{m_{LPG} + m_{Gasoline}} \cdot 100 \tag{1}$$

Applying an ordinary least squares (OLS) regression to the experimental data allowed to determine the second-order polynomial fitting curve shown in Fig. 7 whose equation is

$$MON = 84.04 + \frac{15.72}{10^2} \cdot x_{LPG} - \frac{71.31}{10^5} \cdot x_{LPG}^2 \tag{2}$$

This permits to evaluate the MON as function of LPG mass fraction with a maximum error of 0.3 MON.

A good linear regression is instead obtained if LPG concentration is expressed in terms of molar fraction, as shown in Fig. 8. For this purpose, the gasoline molar mass has been assumed to be 110 g/mol [19,26], even if values ranging from 103 to 114 g/mol are reported in literature [27,28]. Gasoline is in effect a complex mixture of HC compounds [27,29] 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.

If 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 Tables 3 and 4), then the percentage LPG molar fraction is

$$y_{LPG} = \frac{N_{LPG}}{N_{LPG} + N_{Gasoline}} \cdot 100 \tag{3}$$

and the MON mixture can be expressed by the OLS regression line shown in Fig. 8 whose equation is

$$MON = 83.80 + \frac{8.852}{100} \cdot y_{LPG} \tag{4}$$

Its maximum estimation error with respect to experimental data revealed to be 0.5 MON, which, as mentioned above, is also the allowed measurement deviation according to ASTM Standard D2700 [20].

The regression curves obtained however refer to the commercial LPG employed in the test which is characterized by a knock resistance of 92.7 MON and represents a mean situation among the different LPG compositions that can be encountered all over the world [9]; this however puts some limits to the validity of Eqs. (2) and (4), which cannot be safely extended to the case of LPG with substantially different MON. However, if the linear regression between mixture MON and LPG molar fraction remains valid, the knock resistance of gasoline-LPG can be still evaluated by a simple linear interpolation between the two fuel's MON

$$MON = MON_G + \frac{MON_{LPG} - MON_G}{100} \cdot y_{LPG} \tag{5}$$

where MON_G and MON_{LPG} represent the MON of gasoline and LPG, respectively.

Comparing the results of this simple linear interpolation to the experimental data revealed a maximum MON estimation error of 0.7, which is comparable with the maximum error of 0.5 MON encountered by the use of Eq. (5).

Such a simple linear interpolation could also be performed on the basis of LPG mass fraction, but the comparison with the experimental data would give a (conservative) estimation error of 2 MON, as reported in Fig. 7.

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 LPG; 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 compositions of gasoline (mainly composed by C_4 to C_{12} HCs [27,29]) and LPG (which instead contains C_3 to C_4), the radicals involved in the chain-branching reactions of gasoline components are quite different from the radicals produced by the reactions of LPG components, which are characterized by lower reaction rate and longer lives [30,31]. This explains the higher knock resistance of LPG with respect to gasoline. A possible explanation of the knocking resistance increase obtained by adding LPG to gasoline may hence be given by supposing that the LPG intermediate products interact with gasoline radicals slowing down their reactions and hence extending the autoignition time. This let the flame front to continue its propagation in the
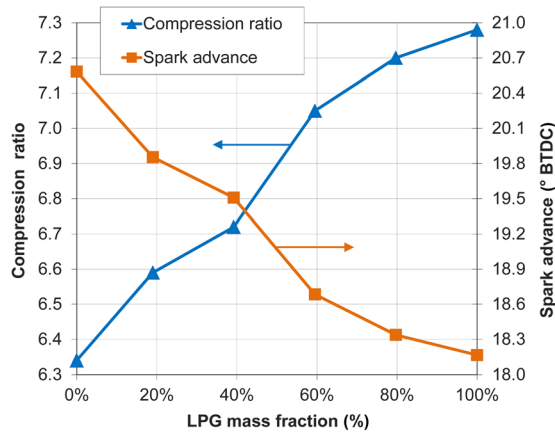
Fig. 9 Engine CR and spark advance adopted in the tests

combustion chamber thus reducing the end-gas[2] mass and, consequently, the energy released by its autoignition. This explains the experimentally observed reduction of KI caused by the addition of LPG to gasoline, with unchanged engine operative conditions.

It is worth to mention that in a standard octane rating test, the CFR engine CR is regulated to reach always the same standard KI, indicated by the provided analogue gauge [20]. As a consequence of the increased fuels mixture knock resistance, the CFR engine CR has been gradually incremented with growing LPG concentration in order to perform standard MON measurement, as reported in Fig. 9. The correlations (2) and (4) allow to estimate that for LPG mass fraction going from 0% to 30% (which correspond to a LPG molar fraction going from 0% to 45%), the mixture MON increased from 84.1 to 88.1, 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 LPG mass fraction between 30% and 50% (hence molar fraction between 45% and 70%), the LPG–gasoline mixture achieved an overall MON between 88 and 90, which corresponds to the high knock resistance of the best commercial gasoline type with 100 research octane number (RON)[3], such as "super plus" quality gasoline.

The MON correlations of Eqs. (2) and (4) can be usefully implemented in submodels for knock onset prediction [3–6] when a correct estimation of knock safe combustion phases is required for thermodynamic simulations involving the simultaneous combustion of LPG and gasoline.

Conclusions

The results of a previous work [1] showed the advantage connected to the knock resistance increase obtained by adding LPG to normal gasoline–air mixture in a spark-ignition engine; in the present work, the authors intended to quantify the knock resistance of LPG–gasoline blends, for different proportions between the two fuels; given the absence of any literature report dealing with this particular theme, the authors carried out a proper experimental campaign, measuring the MON of several LPG–gasoline mixtures on a CFR engine following the reference standard ASTM D2700 [20]; for this purpose, the CFR engine has been equipped with a double injection systems in order to precisely meter the amount of each fuel, thus realizing different mixture compositions and controlling the overall air–fuel ratio. A proper and up-to-date instrumentation was employed to manage both fuels injections and digital data acquisition.

Various blends were tested, with LPG mass fraction ranging from 0%, i.e., pure gasoline, to 100%, which corresponds to the sole LPG; the overall results showed a quadratic dependence of mixture MON toward LPG mass fraction, while quite a linear correlation has been found toward the LPG molar concentration. As pointed out by the authors, this linear trend also allows to overcome the validity limit due to the particular LPG used in the test, whose MON is however a mean value of the various LPG available in the world [9]. Both the regression curves allow to predict the knock resistance of LPG–gasoline blends whichever is the proportion between the two fuels and can be implemented in knock onset prediction submodels, usually employed in thermodynamic simulations, for the knock safe optimization of the LPG–gasoline simultaneous combustion in spark-ignition engines. As also pointed out, the knock resistance increase obtained could be well exploited by turbocharged bifuel engines, which could run with high CR both in pure gas and double-fuel mode, thus maximizing performance (and reducing engine size) maintaining low fuel consumption, and pollutant emissions.

As future developments, the authors intend to repeat the octane rating of the LPG–gasoline mixtures in terms of RON, which could not be determined yet because of the different engine speed it requires; moreover, on the basis of the knowledge acquired, the authors also aim to study and develop knock onset prediction models for the combustion of both LPG–gasoline and NG–gasoline mixtures.

Nomenclature

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
CO = carbon monoxide
CR = compression ratio
DME = dimethyl ether
HC = hydrocarbon
IGBT = insulated gate bipolar transistor
KI = knock intensity
LPG = liquefied petroleum gas
$m_{gasoline}$ = gasoline injected mass per engine cycle
m_{LPG} = LPG injected mass per engine cycle
MN = methane number
MON = motor octane number
MON_G = gasoline motor octane number
MON_{LPG} = LPG motor octane number
$N_{gasoline}$ = mole number of gasoline
N_{LPG} = mole number of LPG
NG = natural gas
PID = proportional integral derivative
PRF = primary reference fuel
RON = research octane number
TTL = transistor to transistor logic
UEGO = universal exhaust gas oxygen
x_{LPG} = percentage mass fraction of LPG
y_{LPG} = percentage molar fraction
λ = relative A/F = ratio between actual A/F and stoichiometric A/F

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[2]The air–fuel mixture portion most distant from ignition point, which undergoes auto-ignition if not promptly reached by the flame front.
[3]The research octane number [32] 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 [11]. For this reason, the RON of a fuel is usually higher than its MON.

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