

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 $\text{MON} > 120$: 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 $\text{CR}=4.5$ 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.

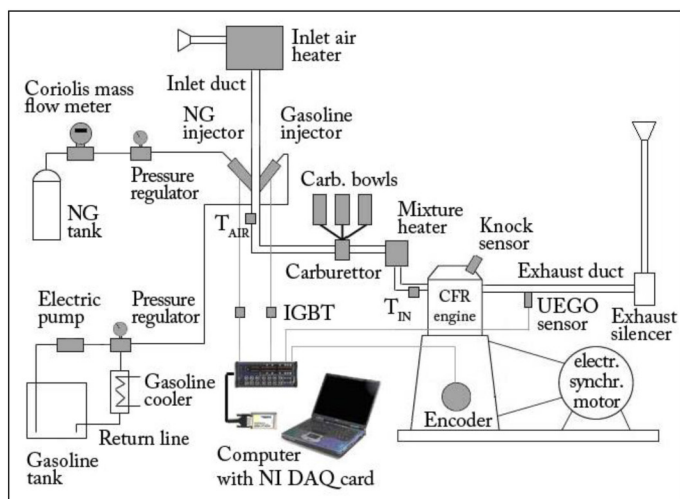


Figure 1. Experimental system layout.

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.

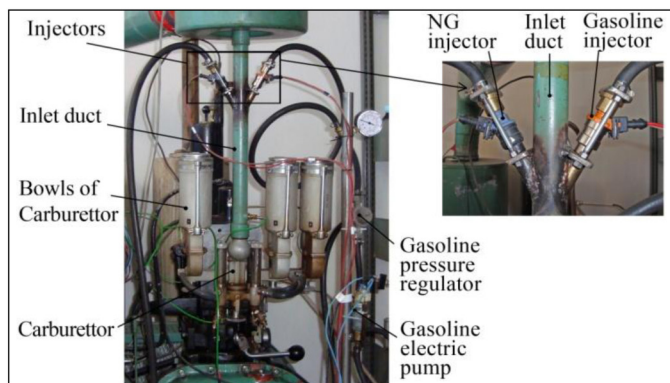


Figure 2. Fuel supply systems: carburettor, NG injector and gasoline injectors.

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. Knock