Impact of natural gas/hydrogen blends on performance and emission of an SI HD engine

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Abstract

In order to fight global warming and pollution, in the last decades the scientific community is searching for alternative and cleaner energy sources to reduce the environmental impact of the transportation industry. As a matter of fact, multiple fuels have been investigated, such as natural gas, GPL and most recently hydrogen. Among all alternative fuels, hydrogen is one of the most promising to use in internal combustion engines due to its lack of carbon and its combustion properties that can maintain high engine performance [1]. As for heavy-duty engines, hydrogen can be added to Compressed Natural Gas (CNG) to increase combustion efficiency and overall engine performance. Aim of this study is to investigate the impact of natural gas/hydrogen blends on performance and emissions of a spark ignition heavy-duty engine. Experimental tests were conducted on CNG and two natural gas/hydrogen blends, at 15% and 25% of hydrogen in volume, respectively, in stationary conditions, at same MFB50 and at same NOx as the CNG case. Results show that Spark Advance (SA) reduction is always necessary to reach same combustion barycenter of the reference CNG case. In addition, since the use of hydrogen causes an inevitable NOx increase, further SA reduction is necessary to have same NOx emission values as the CNG case, while total hydrocarbons and carbon oxides reduction were observed. Lastly, the first results of an ongoing study aimed at defining an on-board procedure to detect the hydrogen content in CNG/H_2 mixtures feeding the engine, will be presented.

Experimental apparatus and test description

Experimental tests were performed on a 6-cylinder turbocharged Spark Ignition Port Fuel Injection Heavy-Duty gas engine, compliant with EURO III regulation, which properties are shown in Table 1.

Table 1. Main properties of reference engine (left) and tested fuels (right).

Engine type	6-cylinder in line
Displacement	7800 cm^3
Bore x Stroke	115 x 125 mm
Comp. Ratio	11:1
Rated power	200 kW@2100 rpm

	CNG	HCNG15	HCNG25
SAFR Kg/kg	15.8	15.9	16.3
LHV MJ/kg	45.8	46.2	47.8
ρ Kg/Sm^3	0.81	0.72	0.65
H/C --	3.8	4	4.3

An Engine Control Unit (ECU) was used for the control of the main engine parameters as air to fuel ratio and SA angle. A Kistler piezoelectric pressure transducer was installed in one of the engine cylinders for in-cylinder pressure acquisition. Fuel flow rates were detected using a Coriolis mass flow meter. Gaseous emissions were measured by means of an exhaust gas analysis system (from AVL). The characterization of solid particles emissions (described in [2]) is provided by means of a differential mobility spectrometer, the DMS500 (from Cambustion). Lastly, temperature and pressure sensors were installed along the engine apparatus to accurately monitor inlet and exhaust lines [2].

The engine was fueled with CNG and two natural gas/hydrogen blends at 15% and 25% of hydrogen in volume, respectively. Tested fuels' main characteristics are shown in Table 1 (right), including their hydrogen to carbon ratio and density.

The experimental campaign included tests in stationary conditions. Stoichiometric air to fuel ratio was obtained in closed-loop control also for tests on hydrogen blends. Figure 1 shows the stationary conditions analyzed. In order to characterize the blends in steady-state operating conditions, two different approaches were followed: at same combustion barycenter and at same NOx emissions as the reference CNG case. Thanks to the programmable ECU, SA values were properly adjusted according to the specific tests strategy when burning the two hydrogen blends.

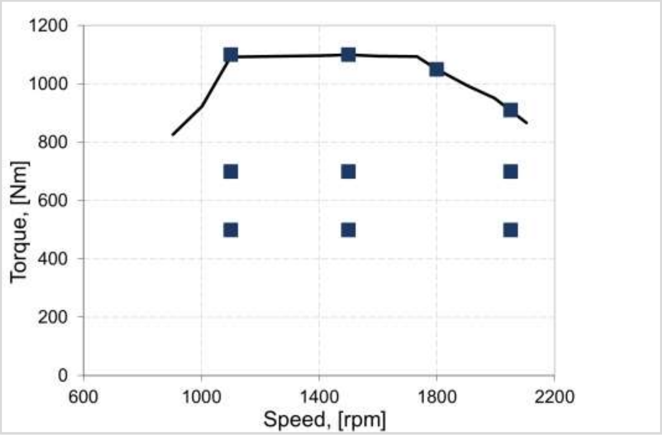

Figure 1. Stationary test conditions.

Results

In the following, results of combustion and emission analyses of HCNG blends will be compared to the reference CNG case. In the initial step of the experimental activity, it was investigated the combustion of the blend at 15% of hydrogen in volume, without changing both injection engine calibration, SA, and general boundary conditions from the CNG case. The main outputs from this first analysis are compared to the CNG case in Figure 2, reporting MFB5%, Pmax and NOx emissions in three test conditions, as example. As foreseeable, results show that switching from the pure CNG case to the HCNG15, the maximum in-cylinder pressure increases and the MFB50% decreases, as shown in Figure 2(a) due to the higher laminar flame speed than natural gas, resulting in faster combustion as well as higher combustion efficiency. As a consequence of faster combustion development and higher peak firing pressure, NOx emission values for the 15% hydrogen blend case are higher because of the higher combustion temperatures, as shown in Figure 2(b).

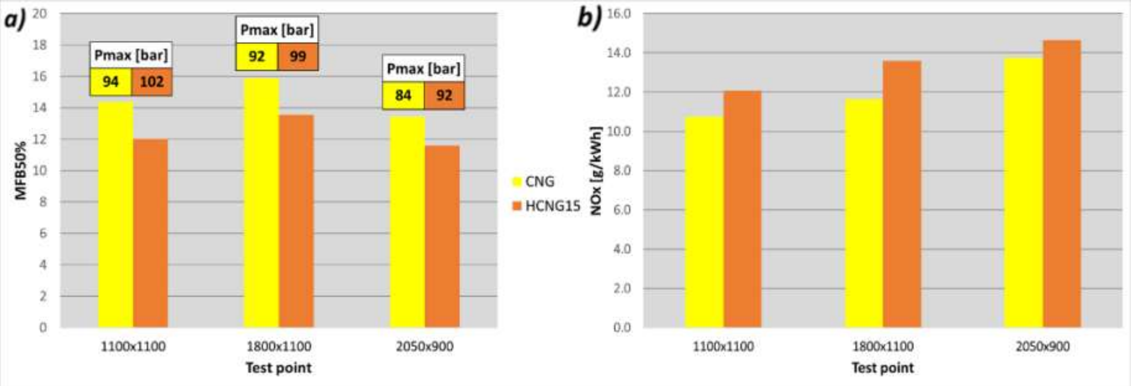

Figure 2. MFB50%, Pmax (a) and NOx emissions (b) for HCNG15. Same reference calibration.

Tests in stationary conditions were then conducted acting on the SA. For an overall and immediate trend analysis of the engine response to hydrogen addition, the testing conditions have been grouped over different engine speeds and the results have been averaged over speed and shown against BMEP values. Figure 3 shows SA and MFB50 results for CNG and the two blends in the two test conditions at same combustions barycenter and at same NOx emissions of the reference case. In particular, Figure 3(b) highlights that the objective of maintaining the same MFB50 as the CNG case has been successfully achieved. Results point out that, since hydrogen has higher laminar flame speed than CNG, SA reduction is always necessary to reach the same MFB50 when burning natural gas/hydrogen blends, as noticeable in Figure 3(a). As for tests at same NOx emissions, it can be seen that further SA reduction was necessary to reach same NOx values, since hydrogen combustion temperatures are generally higher than CNG ones.

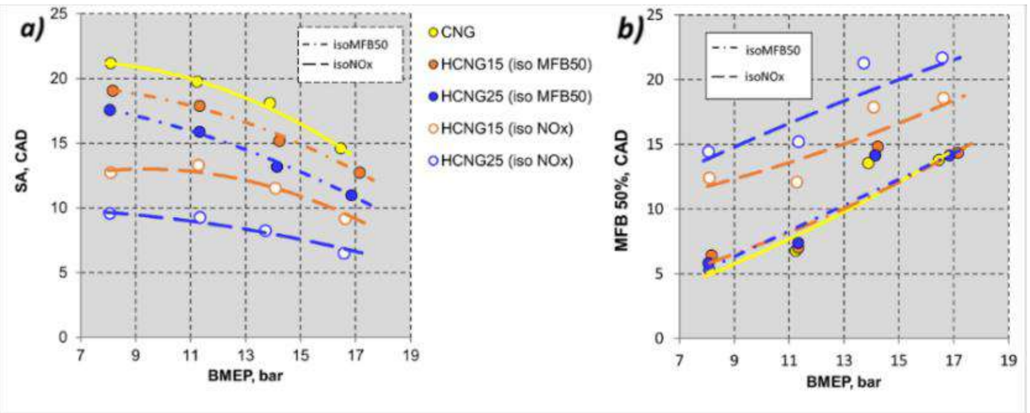

Figure 3. SA (a) and MFB50 (b) results for all fuels and test conditions.

The analysis of combustion evolution is reported in Figure 4 in terms of in-cylinder pressure, SA signals, as well as rate of heat release (ROHR), considering a single test point at medium engine speed and load, at same MFB50 as the CNG case, as example. The SA signal results confirm that SA reduction is necessary for Natural gas/hydrogen blends to have the same combustion barycenter as CNG. On the other hand, in-cylinder pressures and heat release curves show no significant changes from the CNG base case. Figure (a) also reports the values of maximum in-cylinder pressure and exhaust temperature, in all the test cases, highlighting results coherent with what above commented.

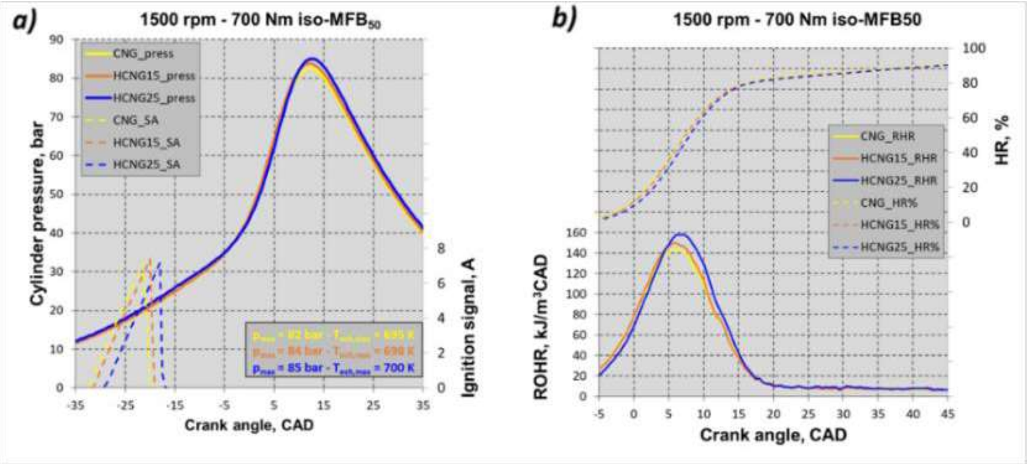

Figure 4. SA (a), and MFB50 (b) results for all fuels and test conditions.

Figure 5(a) reports carbon dioxide emissions at the engine exhaust. As noticeable, for both test conditions and for the two blends, CO_2 values are reduced, the more hydrogen is added to CNG. One of the downsides of hydrogen fueling, as known, is its high nitrogen oxides production due to higher combustion temperatures than other the reference fuel, as revealed in Figure 5(b).

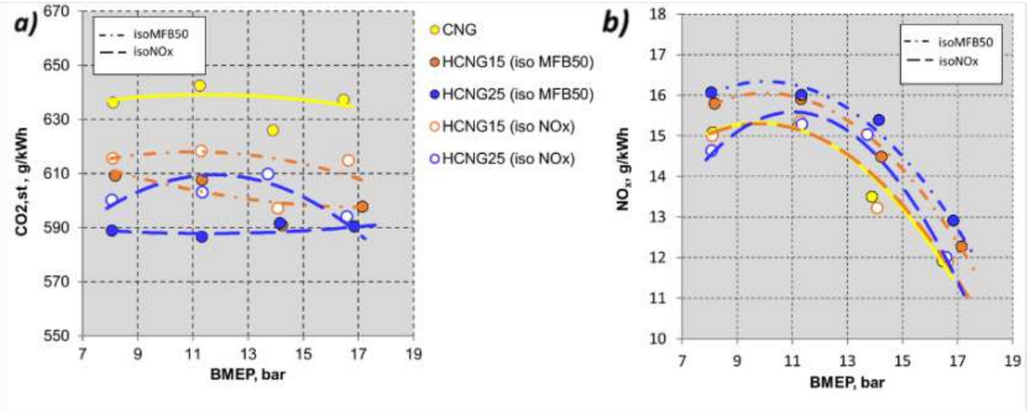

Figure 5. CO_2 (a) and NOx (b) emissions for all the fuels and test conditions.

Hydrogen blending detection methodologies

The interest in the potentiality provided by the use of HCNG blends in internal combustion engines, has driven the authors to the study of methodologies for the detection of the percentage of hydrogen content (hydrogen blending detection) in HCNG fuels. The on-board detection of the exact composition of the fuel can offer the possibility of the combustion optimization by means of engine control parameters adaptation with intuitive benefits also in terms of engine durability.

An initial study was conducted, starting from previous research developed in [3] on diesel/biodiesel blends and by means of calculations based on laboratory measurements. In the present work, two different bending detection methodologies were implemented called Method A and Method B. Assuming constant torque conditions between reference and blends cases, the first method links the hydrogen ratio to the variation of fuel mass flow rates and Lower Heating Value of the blend. Based on the assumption of stoichiometric lambda (λ) conditions for both pure CNG and blends, the second method links the hydrogen ratio to the variation of air and fuel mass flow rates and stoichiometric air-to-fuel ratio, as can be seen in equation (1) and (2) and detailed in [3].

$$BR_{mass} = 100\,\frac{\left({Qfuel_{HCNG}}/{Qfuel_{CNG}}\right)^{-1}}{\left({LHV_{CNG}}/{LHV_{HCNG}}\right)^{-1}} \tag{1}$$

$$BR_{mass} = 100\,\frac{\left(\dfrac{\left({Q_{air\ actual,HCNG}}/{Q_{fuel\ actual,HCNG}}\right)}{\lambda_{comb}\cdot A/F_{st,\,CNG}}\right)^{-1}}{\left({A/F_{st,H2}}/{A/F_{st,\,CNG}}\right)^{-1}} \tag{2}$$

First results from the two procedures, applied on the natural gas/hydrogen blends of Table 1, are shown in Figures 6 and 7, together with target values and error bars from an error propagation analysis. Results highlight that the two methodologies are efficient even if not very precise. Indeed, for the blend at 15% hydrogen in volume, both strategies show promising results, as the BR distributions and their mean values are close to the target. Meanwhile, for the blend at 25% hydrogen content, Method A gives unprecise outcomes, as the distribution and mean BR value are far from the target, while Method B gives a positive outcome as for the 15% hydrogen blend.

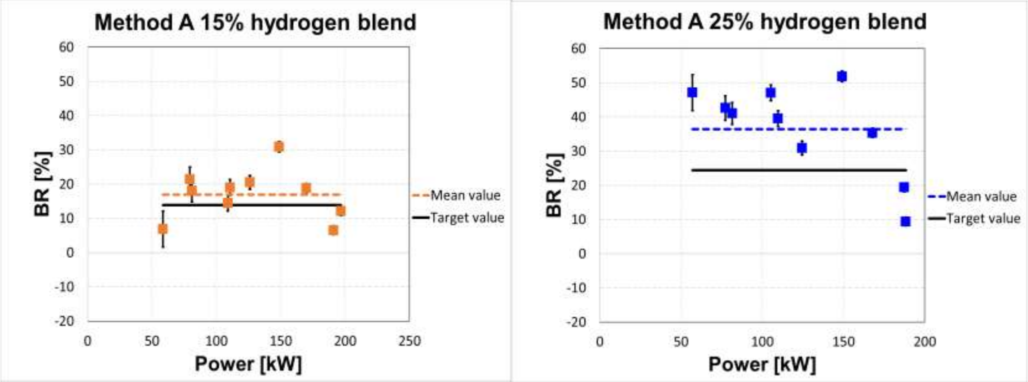

Figure 6. Hydrogen BR values for tested HCNG blends (Method A).

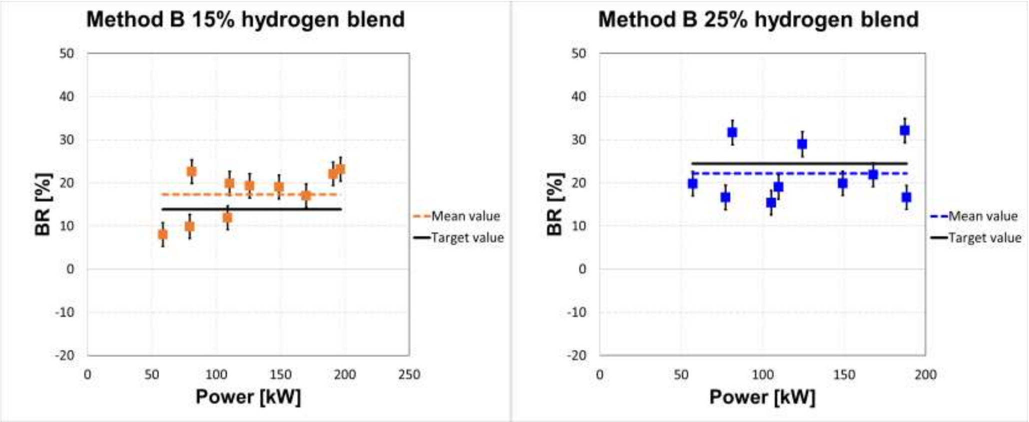

Figure 7. Hydrogen BR values for tested HCNG blends (Method B).

Further activities are ongoing to investigate the above described aspects, by means of a larger experimental dataset.

Conclusions

The present work describes an experimental study conducted on a Heavy-Duty engine fueled with natural gas/hydrogen blends. The main aim was to evaluate combustion and emission effects when adding hydrogen to natural gas. Experimental tests were performed in two different test conditions: at same combustion barycenter and at same NOx emissions as CNG fueling case. In particular, the engine was operated acting on SA and the focus was on parameters as SA itself, in-cylinder pressure and Heat Release curves, as well as emissions such as CO2 and THC. Results show that SA reduction was always necessary to meet the target test conditions. Furthermore, initial analyses on hydrogen blending detection were performed, showing promising results for both methods that, notwithstanding not very precise, can successfully sense the hydrogen content variation in the blends. Future developments can foresee blending detection analysis based on larger dataset and on-board implementations to achieve engine calibration techniques at variable Blending Ratio.

References

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