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Fuel consumption and emissions from a vehicle operating with ethanol, gasoline and hydrogen produced on-board

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ABSTRACT

This paper investigates fuel consumption and pollutant emissions from a vehicle operating with gasoline-ethanol blend (E22), hydrous ethanol (E100) and hydrogen produced on-board. The study aims to find out if hydrogen can contribute to reduce fuel consumption and emissions. Hydrogen was produced by a hydrolytic cell adapted to the vehicle, and was mixed to the air charge in the intake pipe. A production automobile powered by a 1.0-L flexible fuel engine was used in the tests. The vehicle was tested on a chassis dynamometer, with the engine operating at idle speed and at 1400 rev/min. The results show that small amounts of hydrogen can provide stable engine operation with lean fuel-air mixture and, thus, reduce fuel consumption without compromising exhaust emission levels. Reductions of up to 11.8% and 13.1% on fuel consumption were obtained for E22 and E100, respectively.

Introduction

Recent automotive engineering development faces the challenge to reduce pollutant emissions and environmental impacts with renewable fuels, such as ethanol. Particularly, there is currently a concern about the emissions of carbon dioxide (CO_2) and other global warming gases, of which fossil fuels are major sources [1,2]. The use of technologies that reduce fuel consumption can also reduce of CO_2 emissions. In this context, the use of hydrogen to improve fuel performance and reduce CO_2 emissions can be qualified as a good alternative, as one of its main benefits is to promote the reduction of carbon compounds in the combustion products [3]. Spark ignition engines can use hydrogen as a supplementary fuel without extensive engine modifications.

The flame speed, antiknock quality and specific energy content of hydrogen are much higher than those of gasoline

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or ethanol [4]. The flame speed of ethanol-air mixtures increases exponentially with increasing hydrogen fractions [5–7]. This results in reduced heat transfer to the combustion chamber walls, increased fuel burning rate, shortened combustion period, decreased exhaust gas temperature and the possibility to operate with higher cylinder pressures. Consequently, the addition of hydrogen to gasoline-air and ethanol-air mixtures produces improved engine thermal efficiency, increased mean effective pressure and reduced fuel consumption [1,8–15]. The use of hydrogen concentrations up to 12% in gasoline-air mixtures reduces the cyclic variation of cylinder pressure, allowing for operation with lean mixtures [10–15]. The decrease of the covariance of the indicated mean effective pressure (IMEP) reveals a reduction of the cylinder pressure cyclic variation [10–12,16]. On the other hand, the high flammability and low density of hydrogen causes difficulties for storage and safety. On-board production of small quantities of hydrogen in a vehicle can reduce those problems [17].

It is commonly agreed that the use of hydrogen as the main fuel or added to gasoline-air and ethanol-air mixtures reduces carbon monoxide (CO) and hydrocarbon (HC) emissions [1,8,13–15,18,19]. The use of hydrogen as a fuel improver reduces acetaldehyde (C_2H_4O) and CO_2 emissions [9,10,12,13]. In contrast, the use of hydrogen generally increases oxides of nitrogen (NO_X) emissions because of increased cylinder gas temperature [1,9,10,13–15].

Nevertheless, under specific operating conditions, the use of hydrogen can achieve reduced NO_X emissions. The use of ethanol-air mixtures with air excess and 3.5% of hydrogen reduces NO_X emissions [1]. With the addition of 2.14% of hydrogen to gasoline-air mixtures and 20% of air excess, the values of NO_X were similar to standard gasoline operation [9]. With the addition of up to 4% of hydrogen–oxygen blend (molar fraction 2:1) to gasoline and air excess ratio higher than 1.32, NO_X emissions were lower than those obtained with gasoline operation [14]. The addition of hydrogen has consistently reduced NO_X emissions from an ethanol-fueled spark ignition engine operating at ultra-lean burn conditions [16]. Using a gaseous fuel from hydrous ethanol reforming containing 60% of hydrogen with 20–60% conversion ratio, reduced NO_X emissions have been achieved [19].

In view of the possible benefits of the use of hydrogen in engines, as reported in the literature, this work investigates the effects of the addition of small concentrations of hydrogen to a flexible fuel engine. The engine operated with hydrous ethanol (8% of water by volume), here called E100, and a blend of 22% gasoline and 78% anhydrous ethanol, here called E22. Raw emissions of CO_2, CO, total HC and NO_X, cyclic cylinder pressure variation, and fuel consumption were evaluated at stoichiometric condition and with lean air/fuel mixtures. Hydrogen was here produced by an on-board water electrolysis system. This is a different approach from that used by Refs. [11–16], where compressed gaseous hydrogen has been supplied to the engine, and that presented by Refs. [19], where hydrogen was produced by steam reform of hydrous ethanol. While, in those studies, large amounts of hydrogen has been used as a partial or total replacement of gasoline or ethanol, in the present work small amounts of hydrogen are used as combustion improver.

Experiments

Experiments were carried out in a production compact automobile equipped with a flexible fuel, four-stroke, four-cylinder, 1.0-L, sixteen-valve spark-ignition engine. Table 1 shows the engine specifications at the test conditions. The vehicle was tested on a double-roll, eddy current chassis dynamometer of 75 kW rated power, at warmed-up condition and constant engine speed. E100 (Research Octane Number – RON – 106) and E22 (RON 97) were used as main fuels. The test cell was kept at reference conditions, around 25 °C and 0.92 bar.

For cylinder pressure measurement the engine was equipped with four spark plugs instrumented with piezoelectric pressure transducers, of reading range from 0 bar to 200 bar and maximum uncertainty of 1.5%. Pressure data acquisition was done by a dedicated system, AVL Indicom model. K-type thermocouples of reading range from 0 °C to 1000 °C and uncertainty of ±2 °C were used for monitoring the coolant, lubricant and exhaust gas temperatures. A linear oxygen sensor was used determine the air/fuel mixture equivalence ratio (λ), with reading range from $\lambda = 0.50$ to $\lambda = 2.50$ and uncertainty of $\lambda = 0.01$. The oxygen sensor operates pre-heated at 800 °C and can perform measurements at exhaust gas temperatures from −7 °C to 900 °C, with a response time from 0.08 s to 0.15 s. The oxygen sensor was installed in the exit of the exhaust manifold.

The fuel injection and ignition timing system was controlled by an electronic module for engine development, which allowed for optimization of mixture equivalence ratio and ignition timing. Air/fuel mixture equivalence ratio was set to $\lambda = 1$ (stoichiometric), $\lambda = 1.07$ and $\lambda = 1.14$ (lean mixtures) using open loop conditions. The maximum air/fuel mixture equivalence ratio of 1.14 was set because, with leaner mixtures, the engine presented some misfires. For leaner mixtures the engine presented high cyclic variability, making it

Table 1 – Engine specifications.

Parameter	Value
Bore × stroke (mm)	70.00 × 64.90
Displaced volume (cm^3)	999.06
Compression ratio	12.15:1
Maximum torque @ 3850 rev/min (N.m)	97.12 (ethanol)/93.20 (gasoline)
Maximum power @ 6250 rev/min (kW)	55.20 (ethanol)/53.70 (gasoline)
Output torque @ 1400 rev/min (N.m)	31.38 (ethanol)/30.40 (gasoline)
Output power @ 1400 rev/min (kW)	4.60 (ethanol)/4.46 (gasoline)
Manometric intake pressure @ 1400 rev/min (mbar)	605–610
Throttle valve position @ 1400 rev/min (degree)	11.9
Volumetric efficiency @ 1400 rev/min (%)	45
Idle speed (rev/min)	840
Manometric intake pressure @ 840 rev/min (mbar)	370–375
Throttle valve position @ 840 rev/min (degree)	3.8
Volumetric efficiency @ 840 rev/min (%)	23