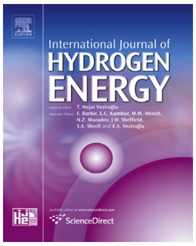
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (2016) 9087–9099

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



Simulation of cycle-to-cycle variations on spark ignition engines fueled with gasoline-hydrogen blends

S.D. Martínez-Boggio [a], P.L. Curto-Risso [a], A. Medina [b,*], A. Calvo Hernández [b]

[a] Instituto de Ingeniería Mecánica y Producción Industrial, Universidad de la República, 11300, Montevideo, Uruguay
[b] Departamento de Física Aplicada, University of Salamanca, 37008, Salamanca, Spain

ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form
14 March 2016
Accepted 20 March 2016
Available online 8 April 2016

Keywords:
Gasoline-hydrogen blends
Spark ignition engine
Cyclic variability
Engine simulations

ABSTRACT

In this work the influence of hydrogen blending of gasoline in a spark ignition engine is surveyed by means of quasi-dimensional simulations. Cycle-to-cycle variations greatly affect the performance of this type of engines, specially under lean conditions. Reduction of cyclic variations eventually would lead to better performance records with reduced consumption and emissions. One option to reduce fluctuations amplitude is by blending gasoline with a component with high flame laminar speed as hydrogen. On the other hand quasi-dimensional simulations have been probed to be a powerful technique to investigate cycle-to-cycle variations in parallel with bench engine experiments. In this work we propose a quasi-dimensional scheme that incorporates flame wrinkling effects associated to hydrogen blending of gasoline. The model is validated by direct comparison with experimental results for indicated mean effective pressure. Long time series of power output are calculated. It is found that for lean mixtures, the amplitude of the oscillations decreases with increasing percentage of hydrogen by volume in the blend up to a minimum value. This optimum hydrogen concentration is characteristic of each fuel-air equivalence ratio. For instance, for a fuel-air ratio of 0.7, minimum variability amplitude is located around 85% hydrogen in the mixture by volume, and for 0.9, the optimum hydrogen concentration is 70%.

Introduction

The research and development of spark ignition engines is nowadays focused to improve performance records and to reduce pollutant emissions. It is also essential to search for substitutive, or at least, supplementary fuels to avoid the problems associated to fossil fuels: shortage, increasing production difficulties, and pollution concerns. One promising alternative that is being extensively studied is hydrogen. It can be used in fuel cells to generate power in electric engines or directly in combustion engines. The first still have high production costs and need specific infrastructures along roads, although achieve a large power output at zero emissions rate.

---

* *Corresponding author*. Tel.: +34 923 294436; fax: +34 923 294584.
E-mail addresses: smartinezb@fing.edu.uy (S.D. Martínez-Boggio), pcurto@fing.edu.uy (P.L. Curto-Risso), amd385@usal.es (A. Medina), anca@usal.es (A.C. Hernández).

http://dx.doi.org/10.1016/j.ijhydene.2016.03.120

The latter provides a more flexible use because standard spark ignition engines do not need extensive changes to work with gasoline-hydrogen blends, allowing governments to develop the required infrastructures.

The use of pure hydrogen to fuel spark ignition engines has important safety shortcomings and also leads to poor power output. The lean operation limit of engines fueled with hydrogen is much lower than that of standard fuels. Moreover, lead to large NO_x emissions due to the high flame temperature of hydrogen. Nevertheless, considered as an additive in gasoline or natural gas blends, hydrogen improves combustion and reduces cycle-to-cycle variability because of its high laminar flame speed. Using hydrogen enriched mixtures has disadvantages as the energy consumption required for its production, the difficulties of its storage, and the modifications needed on standard spark ignition engines. The main positive features and drawbacks of using hydrogen as engine fuel have been summarized by several authors [1–4]. Different techniques have been developed to characterize cyclic variations in engines fueled with gasoline or natural gas/hydrogen blends [5,6]. Also several effects on cyclic variations in those engines have been analyzed: fuel-air ratio, compression ratio, exhaust gas recirculation (EGR), etc. [7–10].

In spite of the *a priori* good expectation of hydrogen as additive to gasoline engines in order to decrease cycle-to-cycle variability there are not many studies on this subject. Most studies are experimental. D'Andrea et al. [11] calculated the coefficient of variation (COV) of the indicated mean effective pressure (IMEP) and the mass fraction burned for 100 individual cycles for a 20 HP four-stroke engine. Hydrogen was added to gasoline up to 66% by volume (3.7% by mass). It was found a decrease of cycle-to-cycle variation for lean operation (fuel-air equivalence ratio below 0.85). Close to stoichiometric conditions little difference in engine performance was seen. Correlations between the decrease in 10–50% burn duration when adding hydrogen and the COV of IMEP were presented. An special mention deserves the extensive work by C. Ji and co-workers [12–17]. This group calculated the COV of IMEP for 300 cycles for a 1.6 l four-stroke commercial engine at idle (around 790 rpm) and hydrogen volume fraction in the total intake gas of 6.52% [12]. An appreciable decrease of the COV of IMEP when plotted in terms of the hydrogen energy fraction was observed. Whereas a minimum of HC and CO emissions was found for a hydrogen energy fraction around 12%, NO_x emissions decreased monotonically with increasing hydrogen energy fraction. In a subsequent work [13], for a similar engine and identical number of cycles, the COV of IMEP was obtained as a function of the excess air ratio, λ, between 1.0 and 1.7. The progressive addition of hydrogen on gasoline prevented a rapid increase of the COV of IMEP when going to lean mixtures. The influence of spark timing was analyzed in Ref. [14], also for 300 consecutive cycles. For some particular combinations of the hydrogen fraction in the mixture and the excess air ratio, a minimum for the COV of IMEP was found in terms of the spark timing. The COV of the maximum pressure was obtained by the same group [15], for several excess air ratios and hydrogen concentrations. Recently, the engine performance at wide open throttle condition was analyzed and the COV of IMEP measured [16,17].

As reported and summarized by Verheslt et al. [3,18] several thermodynamic models (zero- and multi-dimensional) have been proposed and validated for simulating combustion, engine performance parameters, and emissions in hydrogen-gasoline fueled engines from the 1970s up to now. But, in general, they do not deep in the effect of hydrogen addition on cycle-to-cycle variations. Also different Computational Fluid Dynamics (CFD) schemes were proposed [3,19,20]. But, as it happens in experimental calculations, to obtain long time series and statistically significant results is not easy. Usually, just a few hundred of cycles are analyzed, and so to obtain long time correlations on the evolution of variables such as IMEP, heat release or power output is still an open field.

During the last years a quasi-dimensional simulation model capable to simulate the cyclic variability observed in real engines has been developed by our research group. It incorporates the evolution of the flame front radius and two control volumes, for unburned and burned gases, during combustion. The evolution of the masses is calculated from an eddy-burning model. A set of differential equations for masses are coupled with the thermodynamic ones. The model takes into account valves overlapping, heat transfer from the cylinder to the coolant, the effects of residual gases from previous cycles, and specific turbulent flow models and turbulent combustion in the chamber. Its accuracy to reproduce the main engine records as well as variability effects was stated for engines fueled with pure gasoline [21–23] and also for gasoline-ethanol blends [24,25].

Comparing the model we have developed against other computational schemes, its strength relies on its relatively easy implementation and reduced computational cost. This enables to check the influence of a wide variety of parameters and so to perform optimization studies. With respect to cyclic variability studies, in addition to its capability for reproducing experimental phenomenology, allows to obtain long time series and so statistically representative data and long time correlations. This is not easily done by means of experimental measures or CFD simulations. We shall see in this work that this point is essential in order to get reliable information on cycle-to-cycle variability.

In this work we model gasoline-hydrogen engine fueling by considering the peculiarities of combustion for such blends. Several hydrogen concentrations and fuel-air equivalence ratios will be analyzed. Model numerical predictions will be compared with the experimental measures with validation purposes. After validation cyclic variability of power output time series will be analyzed in detail. It will be shown that long time series (of about 1000 cycles) are required to obtain statistically representative results. Amplitude of cyclic oscillations decreases with increasing concentration of hydrogen in the mixture. Moreover, for each fuel-air equivalence ratio of the mixture there is a particular concentration of hydrogen in the blend leading to minimum amplitude fluctuations of the power output.

Simulation model

The simulation model we have developed along the last times [26,27] relies on the first principle of thermodynamics for open systems. The model has been described in detail in several publications [28], so hereafter we only present a brief summary.