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Characterization of the combustion process and cycle-to-cycle variations in a spark ignition engine fuelled with natural gas/hydrogen mixtures

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ABSTRACT

A study is presented of the influence of using mixtures of natural gas and hydrogen in different fractions (0, 25, 50, 75, 100%) on the combustion velocity and cycle-to-cycle variations in a spark ignition engine. The experimental facility consists of a single-cylinder spark ignition engine. The engine rotational speeds are 1000, 1750 and 2500 rpm. Fuel/air equivalence ratio was kept constant equal to 0.7 during the experiments. A two-zone thermodynamic combustion diagnosis model, based on solving the mass and energy conservation equations, is used to analyze the experimentally obtained pressure combustion chamber in the engine. The two-zone model considers a spherical flame front centred at the spark plug, and solves the intersection of the flame front with the piston, cylinder head and cylinder wall, in order to provide the values of the flame radius corresponding to the burned mass volume and the surfaces for heat to the piston and walls. An automatic procedure based on genetic algorithms is used to determine the optimum parameters needed for combustion diagnosis: Angular positioning and pressure offset of the pressure register, dynamic compression ratio, and heat transfer coefficients. The paper focuses on using the values of the burning velocity computed from the pressure register and especially on the analysis of the cycle to cycle variation in the natural gas/hydrogen fuelled engine, quantified through the standard deviation and the coefficient of variation of the burning speed. Increasing the hydrogen content in the mixture with natural gas increases its burning velocity. This effect is linear with hydrogen fraction, except for very high values of the fraction, when the effect of hydrogen dominates combustion. Additionally, and of practical importance, increasing the hydrogen fraction reduces the relative dispersion of combustion. This effect of hydrogen addition on reducing combustion variability is evident from 25% hydrogen content.

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Introduction

Due to the increasing interest in energy shortage and environmental protection, much effort has been focused on the use of alternative fuels in internal combustion engines (ICE). Alternative fuels are clean, compared to fuels derived from petroleum. Natural gas (NG) is considered to be a possible alternative fuel due to its properties and higher octane number. NG is a mixture of diverse gases where methane is its major constituent (75–98% of methane; 0.5–13% of ethane; and 0–2.6% of propane [1]). NG combustion causes less emissions than conventional fuels due to the less complex chemical structure of NG and the absence of evaporation phase of the fuel [2]. NG has the capability to completely mix with air eliminating regions with local rich mixture, thus reducing CO emissions. Also, NG produces less CO_2 emissions than gasoline for the same power output, due to its higher hydrogen to carbon ratio [3]. The high octane number of NG (between 120 and 130) represents an elevated anti-knocking potential [4], allowing a spark ignition engine to be operated with a higher compression ratio than by gasoline, so higher thermal efficiency and lower fuel consumption are obtained. Additionally lean mixtures can be stably burned in engines, contributing to a further reduction of CO and HC emissions and an increase in thermal efficiency.

However, NG has a slow burning velocity, compared to other liquid hydrocarbons. Laminar burning velocity is an important property of the combustion process of any fuel/air mixture because fuels with higher burning velocities can improve engine performance [5]. The lower burning velocity in an NG engine requires advancing the spark timing as compared to the gasoline engine, in order to centre the combustion process and optimize indicated efficiency. Additionally the heating value per unit volume of a gaseous fuel–air mixture is smaller than that of a liquid fuel. However, the heating value of the stoichiometric mixture is not so different which is represented by the Engine Fuel Quality (EFQ) defined in Ref. [5].

To increase the burning velocity, it is possible to mix the NG with a fuel with a higher burning velocity, as can be hydrogen [6]. Hydrogen is an attractive fuel due to the variety of methods to produce it [7] and the variety of methods to produce energy from hydrogen (ICE, gas turbines, fuel cells). Some researchers [8,9], have mixed hydrogen with NG or gasoline to increase the burning velocity and then improve the combustion process. The laminar burning velocity of stoichiometric hydrogen-air mixtures is much higher than that of methane (around six or seven times higher at 350 K) [10–13]. Another important thing to consider is that the heating value per unit volume of a NG–hydrogen–air mixture is almost independent of the relative NG/hydrogen ratio [14].

The burning velocity of NG–hydrogen mixtures varying from 0 to 100% have been obtained at different conditions of temperature and pressure. For example, Huang et al. [15] studied the laminar flame characteristics of NG–hydrogen mixtures at normal temperature and pressure, showing that laminar burning velocities increase substantially with the increment of the percentage of hydrogen in the mixture. Also Huang et al. [16,17] studied the combustion characteristics, heat release, engine performance and emissions of a SI engine fuelled with NG–hydrogen mixtures Hu et al. [18] developed an experimental and numerical study of lean mixtures of NG–hydrogen at elevated temperatures and pressures over a wide range of hydrogen percentages in the mixture, showing an increment in the un-stretched laminar burning velocity with the hydrogen fraction and initial temperature. In other works, they studied the combustion characteristics of a SI engine fuelled with NG-Hydrogen and EGR [19,20].

Cycle to cycle variations in spark ignition engines fuelled with NG, hydrogen and mixtures of NG and hydrogen have been extensively studied [21–26], and also in engines fuelled with methanol [27] and ethanol [28] fuels. Sun et al. [25] studied the cyclic variations of an ICE fuelled with hydrogen. They investigated the effect of varying the fuel/air equivalence ratio, the rotational engine speed and the ignition advance angle on the cyclic variations, expressed by the coefficient of variation of the indicated mean effective pressure (COV_{IMEP}). Their results showed a reduction on the cyclic variations with the increment of the fuel/air equivalence ratio, because combustion rate increases with rich mixtures, resulting in a rapid combustion and improving combustion stability. Sen et al. [24] investigated the effect of the exhaust gas recirculation (EGR) on the cycle-to-cycle variations in a NG spark ignition engine, showing that as the percentage of EGR was increased, more persistent low frequency variations tended to develop. Wang et al. [26] studied the effect of hydrogen addition on cycle-by-cycle variations of the natural gas engine. Their results showed that the peak cylinder pressure, the maximum rate of pressure rise and the indicated mean effective pressure increased and their corresponding cycle-by-cycle variations decreased with the increase of hydrogen fraction at lean mixture operation. Huang et al. [21] analyzed the cycle-by-cycle variations in a spark ignition engine fuelled with natural gas–hydrogen blends combined with EGR. Ma et al. [22] conducted a work to investigate the effects of hydrogen addition on the combustion behaviour and cycle-by-cycle variations in a turbocharged lean burn natural gas spark ignition engine. They found that hydrogen addition contributes to reducing the duration of flame development, which has highly positive effects on reducing cycle-by-cycle variations. Reyes et al. [23] characterized mixtures of natural gas and hydrogen in a single-cylinder spark ignition engine by means of a zero dimensional thermodynamic model.

In the work developed by Tinaut et al. [27] different mixtures of NG and hydrogen have been used as fuels to analyze the effect of the addition of hydrogen on the CO and NO emissions, the optimal ignition timing and performance of an ICE.

The experimental study of the combustion process in internal combustion engines through analysis of the combustion chamber pressure is frequently used to accurately know the evolution of the relevant thermodynamic variables, such as temperature, heat release, turbulent combustion speed, etc. These studies are usually focused on the improvement of thermal efficiency and reduction of pollutant emissions. Depending on the aim of the combustion study, different kinds or categories of models can be proposed: zero-dimensional models, two-zone diagnostic models, multi-zone models, etc. [28–30], all of them make a thermodynamic analysis of the pressure inside the cylinder during the combustion process. The outputs of the models are expressed