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Combustion behavior of a spark ignition engine fueled with synthetic gases derived from biogas

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HIGHLIGHTS

- Synthetic gases tested in a SI engine and compared with gasoline, methane and biogas.
- Combustion results at full load, at equivalence ratios 1, 0.85 and 0.7 are obtained.
- H_2 improves combustion, more pressure is obtained and the cyclic variation is reduced.
- CO and CO_2 emissions increment because these gases are part of syngas composition.
- Hydrogen addition increases NO_x emissions.

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ABSTRACT

Combustion results obtained from a spark ignition engine fueled with two synthetic gases obtained from catalytic decomposition of biogas are presented in this paper. These results are compared with those obtained when the engine was fueled with gasoline, methane and with the biogas from which synthetic gases are extracted. Experimental tests were performed under a wide range of speeds and at three equivalence ratios. Results showed that fractions of hydrogen in synthetic gases increased maximum pressures inside cylinder. Moreover, peak pressures were detected closer to top dead center than methane and biogas. Despite the fraction of diluents in the composition of synthetic gases, high speeds and lean conditions resulted in higher indicated efficiencies than those obtained with gasoline. Moreover, combustion speed and heat release rate were strongly influenced by the proportion of diluents and hydrogen in gaseous blends. CO and CO_2 content in the composition of synthetic gases contributed to increase the exhaust concentrations of these pollutants compared with the other fuels, while HC decreased because of the small fraction of methane which remained unburned. Although NO_x emissions were mitigated by diluents, like CO_2 and air excess, high hydrogen fraction in composition of syngas involved elevated NO_x emissions due to the increase in flame temperature that hydrogen produces.

1. Introduction

The gradual reduction of the petroleum reserves and the growing need to reduce pollutant emissions have promoted the search and development of alternative and renewable energy sources which help to reduce the current oil dependency. In the field of ICE, gaseous fuels have become a good alternative to traditional petroleum derived fuels, such as diesel and gasoline. In this way, natural gas has been successfully used for many years as fuel in engines, due mainly to it is abundant in nature and its extraction is inexpensive [1]. The main component of natural gas is methane, with a high octane number and high auto-ignition temperature, which makes it a great fuel substitute of gasoline in SI engines [2]. Biogas, which is composed of methane and carbon dioxide, has also a great interest as fuel in engines, especially in applications involving combined power and heat generation. Biogas can be obtained from biomass by thermochemical processes or by anaerobic digestion, with significant savings with regard to the costs of traditional biofuel production [3]. In addition to natural gas and biogas, hydrogen has become an important fuel for the future because it is free of carbon, which implies a clean combustion with almost zero emissions of CO_2, CO and HC. However, the use of pure hydrogen in ICE has problems, like high NO_x emissions and abnormal combustion. These drawbacks are derived from hydrogen characteristics as high flame speed, high combustion temperature and low ignition energy [4].

In order to avoid these disadvantages, it has been proved that the use of hydrogen combined with other gases, like methane or natural gas, as fuel, is a way to decrease pollutant emissions,

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Nomenclature

A	combustion chamber surface area, m^2
h_c	heat transfer coefficient, J/m^2 s K
Q_{ch}	heat released by combustion, J
Q_{ht}	heat transferred to the combustion chamber, J
p	cylinder pressure, N/m^2
T	mean gas temperature, K
T_W	wall temperature, K
V	cylinder volume, m^3
Greek symbols	
γ	ratio of specific heats
θ	crankshaft angle, degrees
Φ	equivalence ratio
Abbreviations	
ATDC	after top dead center
BTDC	before top dead center
BTE	brake thermal efficiency
CA	crankshaft angle
CDB	catalytic decomposition of biogas
CDM	catalytic decomposition of methane
COV	coefficient of variation, %
DAQ	data acquisition
EGR	exhaust gas recirculation
ECU	electronic control unit
HC	hydrocarbons
ICE	internal combustion engine
IMEP	indicated mean pressure, bar
ITE	indicated thermal efficiency
LHV	lower heating value, kJ/kg
LOL	lean operation limit
MBT	maximum brake torque
MFB	mass fraction burned
SI	spark ignition
TDC	top dead center
°CA	crankshaft angle degrees

obtaining good results of efficiency and performance [5–8]. The use of hydrogen in these blends implies the increase of the burning speed of the mixture and thus, the combustion is faster [9]. The temperature of combustion rises as the hydrogen fraction increases, so higher NO_x emissions are produced [6,10]. The extension of the flammability limits of the mixture entails an increase in the LOL, so the engine can operate in leaner conditions [9]. Leaner mixtures reduce NO_x and CO_2 emissions [6,7,10]. Hydrogen presence also mitigates cycle by cycle variations, which are significant, at lean conditions in SI engines [11,12].

However, the BTE may be reduced and the decrease of power density is emphasized [6,7]. NO_x emissions and knock events can be mitigated by engine modifications, like EGR or water injection, while good values of BTE are maintained [13–17]. Retarding the ignition timing with regard to the MBT timing also contributes to reduce NO_x because of the decrease of the burned gases temperature [4].

The interest of using hydrogen as component of gaseous fuel blends in engines has opened a wide field about syngas extraction by methods such as biomass gasification [18]. These blends usually contain CO, H_2 and an important percentage of inert gases, which reduces the heating value of the blends and hinders a good combustion in ICE. Synthetic gases have been used in diesel engines operating in dual fuel mode, obtaining a reduction of NO_x, HC and smoke emissions, despite the decrease in efficiency, especially at partial loads [19–21]. A reduction in CO, HC emissions has also been obtained by the use of syngas in SI engines [22,23]. However, an increase of NO_x emissions was detected, although they can be reduced by the modification of the spark timing, which also contributes to avoid knocking and backfires caused by the H2 presence [24,25]. The concern about the use of synthetic gases has caused that, in addition to experimental tests, some advanced theoretical models had been developed in order to simulate the behavior of these gases used as fuel in ICE [26–28].

Hydrogen–methane blends can be obtained by catalytic decomposition of raw gases, like natural gas or biogas, producing also high added value graphite-like materials [29,30]. Catalytic decomposition of methane/natural gas can result in hydrogen–methane blends with a variable percentage of hydrogen from 0% to 50%. Tests performed on an SI engine for use in vehicles fueled with blends similar to those obtained by CDM resulted in an increase in BTE and a decrease in emissions (excepting NO_x) as the equivalence ratio decreases in the blends with highest hydrogen content [31].

Catalytic decomposition applied to biogas extracted from biomass allows obtaining synthetic gases with a lower proportion of inert gases (CO_2), while hydrogen and CO are generated in this process. The resulting syngas has similar heating values than the original biogas. While biogas has low heating value owing to the high fraction of CO_2, in synthetic gases, part of this CO_2 has been replaced by hydrogen and CO. However, because of low energetic density of hydrogen, heating value of synthetic gases remains low. The main advantages of synthetic gases over raw biogas are the possibility of using lean conditions and the improvement in combustion that hydrogen produces, obtaining good results of efficiency and low pollutant emissions [32]. Moreover, despite the presence of a fraction of CO_2 penalizes the heating value of the blend, and consequently the power generated, it contributes to control NO_x emissions, because the diluent decreases the temperature of combustion [33–35].

It has been demonstrated that the use of catalysts is a feasible way to obtain quality gas blends, which can be used in ICE to improve performance and reduce emissions [36]. In this paper, combustion characteristics of two synthetic gases obtained from CDB are examined and compared with the biogas from which they are derived, with gasoline as reference fuel, and with methane, which is the natural gas main component, under the same test conditions.

2. Experimental setup and procedures

The experimental tests were performed on a spark ignition Lombardini engine whose specifications are detailed in Table 1. Fig. 1 shows a scheme of the bench where the tests were carried

Table 1
Original engine specifications.

Engine	Lombardini LGW 523 MPI spark ignition engine
Number of cylinders	2 in line
Bore × Stroke	72 × 62 mm
Compression ratio	10.7:1
Valves per cylinder	2
Fuel delivery system	Electronic indirect fuel injection