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Laminar burning velocity and interchangeability analysis of biogas/C_3H_8/H_2 with normal and oxygen-enriched air

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ABSTRACT

Numerical and experimental measurements of the laminar burning velocities of biogas (66% CH_4 – 34% CO_2) and a biogas/propane/hydrogen mixture (50% biogas – 40% C_3H_8 – 10% H_2) were made with normal and oxygen-enriched air while varying the air/fuel ratio. GRI-Mech 3.0 and C_1–C_3 reaction mechanisms were used to perform numerical simulations. Schlieren images of laminar premixed flames were used to determine laminar burning velocities at 25 °C and 849 mbar. The mixture's laminar burning velocity was found to be higher to that of pure biogas due to the addition of propane and hydrogen. An increase in the laminar burning velocities of both fuels is reported by enriching air with oxygen, a phenomenon that is explained by the increased reactivity of the mixture. Additionally, an analysis of interchangeability based on both the Wobbe Index and the laminar burning velocity between methane and a biogas/propane/hydrogen mixture is presented in order to consider this mixture as a substitute for natural gas. It was found that the variations of these properties between the fuels did not exceed 10%, enabling interchangeability.

1. Introduction

The high production of gaseous pollutants such as NOx, CO, CO_2 and HC is due to the use of fossil fuels, which still constitute the primary sources of global energy [1]. Both the growing concern about the amount of these gases emitted into the environment and the predictions of the exhaustion of petroleum-derived fuels have motivated the inclusion of alternative fuels, such as syngas (produced from biomass gasification), biodiesel (produced from plants) and biogas (generated from organic waste), to the energy basket. In recent decades, the use of these fuels has taken a leading role due to a change in global consciousness, as evidenced by scientific advances that have been focused on three aspects, as established by Chen et al. [2]: (1) replacing fossil fuels with renewable fuels, (2) the development of more efficient technologies and (3) the combination of fossil and renewable fuels.

Unprepared for total replacement, the latter option is most attractive because it requires no major changes in transport infrastructure, distribution and storage, does not demand significant changes in combustion equipment and provides a fast reduction in greenhouse gas emissions. However, there is a high level of complexity required for this alternative to be efficient because these types of renewable fuels have low energy density and heating values, very low burning velocities, high ignition energy and narrow flammability limits; these features affect its combustibility when compared to conventional fossil fuels.

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Among alternative fuels, biogas has certain advantages with respect to its production because it is generated from the anaerobic digestion of biomass and organic waste, such as manure, garden waste and sewage, among others. It can be used for heating, lighting, transportation, power generation and as a complementary fuel for large turbines [2,3]. The composition of biogas, though it varies depending on the production process, is approximately two-thirds methane, and the rest is carbon dioxide with some traces of other gases, as shown in Table 1.

As a fuel, biogas has a low heating value, low burning velocity and narrower flame-stability limits, mainly due to the high amount of inerts present in the fuel. The auto-ignition temperature is high, so it is resistant to self-ignition [3]. Due to these characteristics, biogas presents certain problems related to instability when used in conventional combustion systems, which hinders their integration with traditional methods of converting chemical energy to thermal energy [4].

There are two alternatives for improving the combustion properties of biogas: mixing it with other fuels with better features [5] or increasing the amount of oxygen in the mixture. Addressing both alternatives, this study raises the possibility of studying the combustion of biogas and a biogas/propane/hydrogen mixture, with both normal air and air enriched with pure oxygen. A mixture with natural gas is not considered because, although it solves the problems of instability, the calorific value remains low.

The chemical kinetics and laminar burning velocities of propane, hydrogen and methane (the main constituent of biogas) have been widely discussed separately [6–9], but the study of their specific mixture has rarely been considered. For this reason, studies should be performed to predict the behavior of the combustion of this mixture in order to establish new properties to be used for equipment design that uses this mixture as fuel. One of the most important properties is the laminar burning velocity (S_L), which characterizes all air/fuel mixtures and is defined as the speed with which the unburnt gases move through the flame front [10,11]. This parameter, which is characteristic of each fuel mixture, contains essential information regarding reactivity and diffusivity, and it is also used in the analysis of combustion phenomena, such as stability, premixed flame structure, kinetic mechanism validation, turbulent burning velocity, fuel interchangeability and burner design [12,13].

The idea of mixing these fuels is not new; hydrogen [8,11,14–19] and propane [19,20] have been mixed with methane to improve its combustion properties. However, the combustion properties of the biogas/propane/hydrogen mixture have been reported in few publications. Chen et al. [2] studied a hydrogen-enriched biogas diffusion flame subjected to a slight oxygen enrichment, and Lee et al. [21] determined the burning velocities of biogas and a biogas/propane mixture, varying the amount of propane in the mixture and the air-fuel ratio. Other publications by the same authors focused on the study of the flame stability of biogas and two landfill gas/propane mixtures in laminar premixed and turbulent non-premixed combustion [13]; the authors were also focused on the interchangeability between some biogas/propane mixtures with natural gas for domestic appliances [22]. The compositions of the mixtures were such that the calorific value and the Wobbe index were the same as those of natural gas. Tang et al. [6] and Park et al. [19] determined the burning velocity and other combustion properties of the hydrogen/propane mixture at different air/fuel ratios and hydrogen fractions, and Milton and Keck [8], determined the laminar burning velocity of the stoichiometric mixture of hydrogen with some hydrocarbons, including propane, at different pressures and temperatures.

In the field of reciprocating thermal machines, biogas has enjoyed some popularity as a fuel for internal combustion engines. Some authors [1,3,23,24] have considered the addition of hydrogen to biogas in different proportions in order to study their performance in spark ignition engines, showing benefits in terms of efficiency and reduction of greenhouse gases.

To improve the combustion properties of methane, the addition of oxygen to the fuel mix has also been considered [25]. This addition increases the reactivity of the mixture and therefore increases the laminar burning velocity.

The objective of this study is to numerically and experimentally determine the laminar burning velocity of biogas and a biogas/propane/hydrogen mixture with both normal and oxygen-enriched air at different air/fuel ratios.

Table 1 – Composition of biogas.

Methane	55–65%
Carbon dioxide	35–45%
Hydrogen sulfide	0–1 ppm
Nitrogen	0–3 ppm
Hydrogen sulfide	0–1 ppm
Oxygen	0–2 ppm
Ammonia	0–1 ppm

2. Experimental methodology

2.1. Gas composition

The chemical composition of the mixture has been defined such that its High Wobbe Index (HWI) is equal to that of methane ($HWI_{CH4} = 8.14$ kW h/m$^3_{st}$) as it is of interest to use this mixture as a substitute for natural gas in burners for both residential and industrial use and for internal combustion engines. Table 2 presents the composition of the studied gases and the oxygen enrichment level.

2.2. Experimental setup

The experiments were performed in a contoured slot burner, and S_L values were determined through the angle method using Schlieren images of the flame front. The flames were generated in three contoured slot burners with different outlet geometries. The selection of the burner depends on the estimated burning velocity of the mixture, considering that the slot output speed is directly related to S_L. The internal geometry of these burners can maintain laminar flows for all air/fuel ratios studied while reducing the effects of flame stretch