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Laminar burning velocity and flammability limits in biogas: A literature review

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ABSTRACT

A detailed literature review of laminar burning velocity and flammability limits of biogas mixtures combustion is presented. Biogas alone and in mixtures with other fuels is particularly significant because of its capability of application as fuels for internal combustion engines (ICEs). Therefore, a strict determination of the fundamental combustion characteristics required for their application in ICEs is crucial. Producing energy from biogas has the additional advantage of preventing its release into the atmosphere, where it results into significant air pollution.

CH_4 and CO_2 are the main compounds of biogas, such as landfill, agricultural and sewage gas, after the removal of the trace amounts of organic compounds. For the same equivalence ratio, the presence of CO_2 in the fuel feed results in substantial reduction of the laminar flame speed and flammability limits. Several research projects have shown that the decrease in the laminar flame speed of a fuel mixture containing dilution components is caused by the increase in specific heat capacity and the decrease in heat release, flame temperature and thermal diffusivity. The most promising strategies to increase the laminar burning velocity and the flammability limits of biogas are revised and discussed. The thermodynamic conditions under which these properties are determined are analyzed and the work still required for a comprehensive laminar burning velocity and flammability limits determination, at typical ICEs thermodynamic conditions, is addressed. The article provides a brief review of pollutant emissions of ICEs running on biogas and the current and future technological solutions to meet the increasing strict regulation.

Contents

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1. Introduction

The continuous increasing world consumption of energy and the fast reduction of cheap fossil fuels available, joined with considerable attention to pollutant emissions, have driven increasing interest in renewable sources of energy, including biofuels research and applications.

A major challenge for combustion scientists and engine-development engineers is to optimize engine combustion to improve fuel economy, lower pollutant emissions, and provide alternative-fuels capabilities while maintaining outstanding performance, durability, and reliability at an affordable price [1]. The availability of a great number of biofuels in the present context imposes a strict determination of the characteristics required for their application in internal combustion engines (ICEs). Biogas alone and in mixtures with other fuels is particularly significant in this context because of its capability of application as fuels for ICEs, which are the main power source for transport vehicles and also commonly used for powering generators of electrical energy.

Biogas is the product of fermentation of man and animals biological activity waste products when bacteria degrade biological material in the absence of oxygen in a process known as anaerobic digestion. The composition of biogas may vary depending on the feedstock and the fermentation process. The main components are methane (CH_4) and carbon dioxide (CO_2) while minor constituents may be water vapor (H_2O), hydrogen sulfide (H_2S), nitrogen (N_2), hydrogen (H_2), oxygen (O_2), carbon monoxide (CO), siloxanes and ammonia (NH_3) [2,3].

Despite its heating value (about 3000–6000 kcal/m^3) being lower compared to natural gas (NG) or liquefied petroleum gas, biogas is widely used as a fuel. Its total chemical energy is sufficient to sustain the operation of ICEs and to serve as a basis for the production of heat and electricity [4,5]. Nevertheless, studies on CH_4–CO_2 mixtures in spark ignition (SI) engines [6–9] showed that the presence of CO_2 in inlet fuel mixtures not only deteriorated engine efficiency but also increased pollutant emissions of unburned hydrocarbon, while reduced oxides of nitrogen (NO_x) emissions, compared to methane or NG fueling. The presence of CO_2 results in reduced flame temperatures and burning rates, a narrower range of flame stability, and thus lower combustion efficiency [4]. One approach to solving these problems is using specialized power generators that, through thermal energy recuperation of the combustion product gases, increase the temperature in the reaction zone. In doing so, the burning characteristics of low heating value fuels are improved. Another approach is to raise the heating value of biogas through addition of a higher-grade fuel like NG, liquefied propane gas [5] or liquefied petroleum gas [10], and hydrogen [11].

Nowadays worldwide biogas applications range from cooking, heating, lighting to transportation and power generation. Less developed countries use small residential-scale and farm-scale biogas plants for cooking, heating and lighting, whereas more developed countries use large biogas plants for heat and power generation and for biogas upgrading to bio-methane fed into the natural gas grid or compressed and used as a vehicle fuel.

In Europe, for example, roughly 50% of the total biogas produced in 2014 was used to generate electricity and the other 50% for heat production [12]. When electricity is generated from biogas, normally heat is produced which can be utilized, thus increasing the economics of the plant. Combined heat and power generators (CHP) normally run on three types of stationary engines: compression ignition (CI) engines, SI stoichiometric engines, and SI lean-burn pre-chamber engines [13]. The electrical efficiency of these engines ranges between 35% and 40% and are suitable for energy production of up to 2 MW each unit [14]. Depending on the plant size and the desired electrical efficiency, gas turbines, micro gas turbines, steam turbines, high and low-temperature fuel cells, or a combination of a high-temperature fuel cell with a gas turbine are available alternatives [14]. However, most of these alternatives have been limited to experimental stages due to high initial costs [15]. When the gas delivery can be uneven, the lean-burn dual-fuel CI stationary engines are usually chosen for installation [16]. These engines are employed by fumigating the intake air with biogas and injecting a small amount of diesel as pilot fuel. However, in the absence of biogas it can run on diesel alone. When the gas supply is stable, lean-burn pre-chamber SI gas engines are the most suitable type of engine for larger stationary applications (>1 MW) and are gaining interest for automotive application [16]. They are more efficient than stoichiometric engines and can achieve low emissions without exhaust after-treatment.

From an economic point of view, the use of biogas, directly in conventional SI engines, is strictly linked with the time between overhaul (TBO) and the engine life. The minor constituents present in biogas, especially H_2S, NH_3 and siloxanes may be detrimental for the engine, thus reducing TBO and the engine life. During combustion, H_2S reacting with H_2O forms acids that lead to rapid oil degradation and engine corrosion wear. Similarly NH_3 reacts with H_2O forming acids that corrode aluminum and copper parts. Moreover, siloxanes are responsible for high wear rates in bearings or liners and silicate deposits in manifolds and engine combustion chamber [13,15]. Removing these minor constituents from biogas increases its production costs. The engine tolerance against impurities and its TBO and life time can be increased by making some structural modifications. Between them, using bearings made of more resistant to corrosion materials, keep the lubricating oil temperature high enough to prevent water condensation, using steel instead of aluminum pistons and using cutting rings insert to prevent deposit formation on cylinder walls [15].

According to [15], biogas fueled reciprocating engines are a quite mature technology but despite the large number of CHP running on ICEs, the number of published paper is not large. Theoretical and experimental work is needed to understand the exact combustion mechanism considering real biogas composition and to develop dynamic models for biogas engine control.

In this view, it is of fundamental importance for biogas application in ICEs the detailed determination of some fundamental combustion characteristics such as laminar burning velocity (LBV), flammability limits, flame temperature, ignition temperature, flame stability, Methane Number (MN) and heating value of both pure biogas and biogas mixtures with other fuels. Their values depend mainly on the fuel type, the mixture strength, the temperature and the pressure [17]. Moreover, important engine operational parameters that should be considered are the ignition delay time and the compression ratio of the engine. The LBV and flammability limits of biogas will be widely reviewed in this article, whereas the other parameters will be only defined and references for more details suggested. The object of this paper is to provide an overview of the LBV and flammability limits state of the art research for biogas and biogas mixtures with other fuels, with the perspective of application as ICEs fuels.

2. Fundamental parameters

The laminar burning velocity is one of the most important parameters of a combustible mixture. It is the only flame speed unique for a gas of a fixed composition, initial temperature and pressure, without further specification of hydrodynamic conditions, such as stretch rate, Reynolds number, etc. [17,18]. On a practical level, it affects the fuel burning rate in ICEs and the engine's performance and emissions. On a fundamental level, the