LAMINAR BURNING VELOCITY AND FLAMMABILITY LIMITS IN BIOGAS: A STATE OF THE ART

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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 benefit of preventing its release into the atmosphere, where it results into significant air pollution.

The CH_4 and CO_2 are the main compounds of biogases, 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.

INTRODUCTION

The continuous increasing world consumption of energy and the fast reduction of cheap fossil fuels available, joined with increasing attention to pollutant emissions has 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) and ammonia (NH_3) [2, 3].

Despite its heating value (about $3000 – 6000$ kcal/m^3) is lower compared to natural gas (NG) or liquefied petroleum gas, biogas has a potentiality as 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, 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, one improves the burning characteristics of low heating value fuels. Another approach is

to raise the heating value of biogas through addition of a higher-grade fuel like natural gas, liquefied propane gas [5] and hydrogen [10].

It is of fundamental importance for biogas application in ICEs the detailed determination of some fundamental combustion characteristics such as laminar burning velocity, flammability limits, flame structure, flame temperature and calorific 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 [11].

The laminar burning velocity is one of the most important parameters of a combustible mixture. It is the only flame speed unique to a gas of a fixed composition, initial temperature and pressure, without further specification of hydrodynamic conditions, such as stretch rate, Reynolds number, etc [11, 12]. On a practical level, it affects the fuel burning rate in ICEs and the engine's performance and emissions. On a fundamental level, the burning velocity is an important target for kinetic mechanism development and validation. Accurate determination of laminar burning velocity is extremely important for the development and validation of kinetic mechanisms for gasoline, diesel surrogate fuels and alternative fuels [13].

The flammability limits define the range of concentration of the fuel in a fuel-air mixture at a specified temperature and pressure that allows ignition initiated flame to propagate and sustain. It is mainly affected by the nature of the fuel, direction of the propagation, size and shape of the combustion chamber, temperature and pressure [14].

The object of this paper is to provide an overview of the laminar burning velocity and flammability limits state of the art research for biogas and biogas mixtures with other fuels, with the perspective of application as an ICEs fuel.

LAMINAR BURNING VELOCITY

Laminar burning velocity, also referred to as laminar flame speed, S_L, in this review, is defined as the velocity of the combustion wave normal to itself and relative to the unburnt gas [15]. Idealistically, laminar burning velocity is defined in its one-dimensional configuration and corresponds to the velocity at which the fresh premixed gases make a planar flame steady. This flame is supposed to be one-dimensional, unstretched and adiabatic so that the burned gases achieve equilibrium. The planar burning velocity is considered a fundamental combustion parameter providing a measure of the coupled effects of exothermicity, diffusivity, and reactivity of a combustible mixture [16]. Moreover, it is the volume of combustible mixture, at its own temperature and pressure, consumed in unit time by unit area of flame front. It is independent of flame geometry, burner size and flow rate. The burning velocity is essentially a measure of the overall reaction rate in the flame and is important, both in the stabilization of flames and in determining rates of heat release. One of the main problems in measuring the normal burning velocity is that a plane flame front can be observed only under very special conditions. In nearly all practical cases, the flame front is either curved or is not normal to the direction of velocity of the gas stream. A flame surface propagating in a uniform flow field is

submitted to strain and curvature effects leading to changes in the frontal area. The total flame stretch rate is the combination of stretch rate due to the curvature and stretch rate due to the flow field aerodynamic strain. In flames where the stretch rate is well defined, it is possible to determine the unstretched laminar burning velocity, S_L^0, a useful parameter for comparison with numerically calculated laminar flame speed where no stretch influence is present [17].

LAMINAR BURNING VELOCITY IN BIOGAS

There is in the literature a quite large amount of available measured and calculated laminar burning velocity data for the binary mixture of CH_4 and CO_2 at ambient conditions and some data at ICEs operating conditions. Moreover, the effect of addition of other fuels to the biogas has been reported. These studies show that laminar burning velocity is strongly influenced by the air-fuel-ratio, initial pressure and preheating temperature. The initial thermodynamics conditions and the results of the most relevant works on laminar burning velocity determination in thus mixtures are presented in Tab. 1 and discussed in the following.

A comprehensive work on biogas combustion properties, treatment and utilization technologies, was written by Walsh et al. [18]. Figure 1, adapted for SI units, presents results of S_L^0 numerically determined for content of CO_2 in the range 0 to 60 % as a function of the methane percent in the mixture within the range of mixture flammability. The strong influence of CO_2 on S_L^0 decrease is clearly shown.
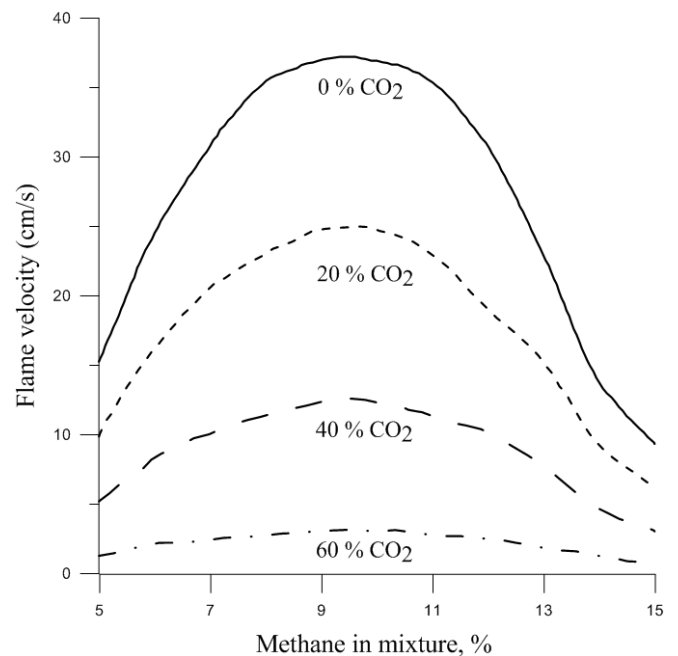

Figure 1 Flame velocity as a function of carbon dioxide concentration, adapted from [18].

Zhu and coworkers [19] determined the effect of CO_2 on the laminar flame speeds of methane/(Ar, N_2, CO_2)-air mixtures over the stoichiometric range from very lean to very rich, i.e. ϕ from 0.4 to 1.8, by using the counterflow method and numerical

simulation by using a C_1 mechanism and a full C_2 mechanism. The pressure ranges from 0.25 to 2 atm, and the flame temperature ranges from 1,550 to 2,250 K. The effect of adiabatic flame temperature, T_a, has been assessed by substituting N_2 in the air by equal amounts of either Ar or CO_2 such that the O_2 concentration in the (O_2 + inert) mixture is fixed at 21 volume percent. The effect of CO_2 substitution is an adiabatic flame temperature decrease leading to a lower S_L^0 value as shown in Figure 2. The effect of pressure increasing is studied both in terms of S_L^0 and mass burning rates, $\rho_u S_L^0$, both experimentally and numerically. Figure 3 shows that the pressure increase determines an S_L^0 decrease, as expected, and a $\rho_u S_L^0$ increase. Since an overall reaction order $n(\phi)$ can be defined for a given ϕ, such that $\rho_u S_L^0 \sim p^{n/2}$, the increasing trend of $\rho_u S_L^0$ indicates positive values of n.
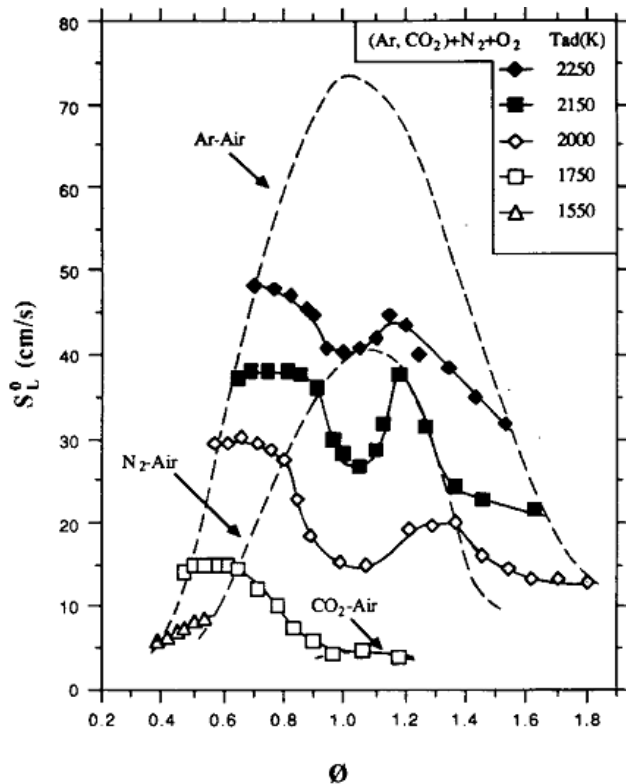

Figure 2 Experimental laminar flame speeds S_L^0 (ϕ) for CH_4/Ar-air, CH_4/N_2-air, and CH_4/CO_2-air mixtures, for constant flame temperatures, T_a, at 1 atm [19].

Ju and coworkers [20] numerically determined S_L of lean mixtures of CH_4 and CO_2 adopting two models, the optically thin model and the heat reabsorption model called OPTM and SNB-GB1D, respectively in Figure 4. The latter shows a better agreement with experimental results as it considers the spectral radiation in the one-dimensional coordinate of heat reabsorption from H_2O and CO_2 that approximately halves the net heat loss thus reducing the lower flammability limit and influencing S_L.

Chen et al. [21] improved the heat reabsorption model by considering spectral radiation in the spherical coordinate for data from spherical flames. They experimentally determined S_L^0

of CH_4-O_2 mixtures diluted with CO_2 and adding He for flame stabilization, CH_4 - {$0.3O_2 + 0.2He + 0.5CO_2$}, in a cylindrical dual-chambered combustion facility for spherical flame studies. The pressure influence was studied in the range 1atm to 5 atm, at 298.3 K. The results were compared with the computational simulation using the improved heat reabsorption model, FSNB CK, providing a better agreement with experimental data than the previous models from [20]. Figure 4 shows that radiation absorption increases the flame speed and extends the flammability limits. Moreover, the authors found that the radiation absorption effect increases with flame size and pressure and that flame geometry has a significant effect on flame radiation.
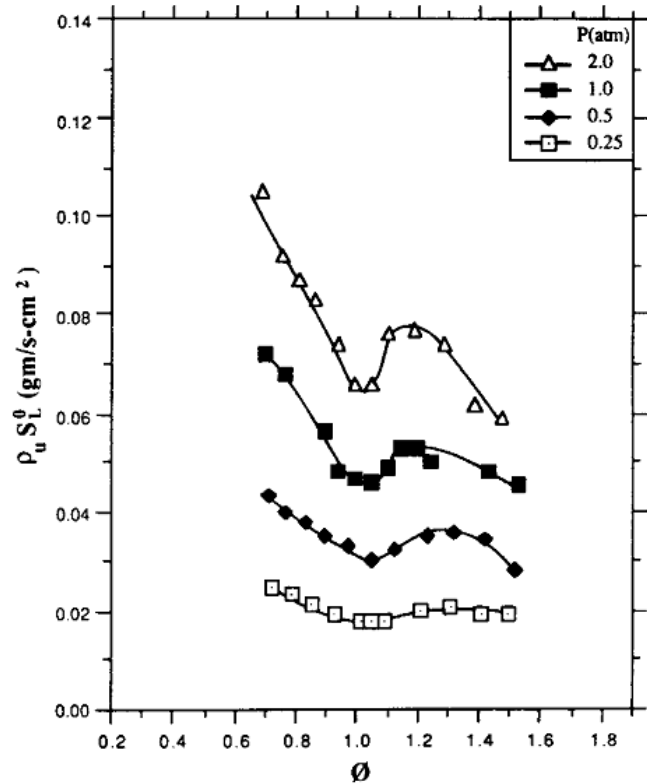

Figure 3 Experimental mass burning rates $\rho_u S_L^0$ (ρ, p), for $T_a = 2,250$ K and pressures between 0.25 and 2 atm [19].

Elia and coworkers [22] experimentally determined the laminar burning velocity of mixtures of CH_4 with up to 15 % diluents (86 % N_2 and 14 % CO_2) in air simulating those conditions found during idle in internal combustion engines employing the exhaust gas recirculation (EGR) techniques to reduce the flame temperature, a major factor in the NO_x creation. Laminar burning velocity is determined from pressure measurements in a constant volume combustion chamber in a range of pressures from 0.75 to 70 atm, unburned gas temperatures from 298 to 550 K, fuel air equivalence ratio from 0.8 to 1.2. Figures 5 and 6 show the influence of initial pressure and temperature on laminar burning velocity, comparing their results with previous data [23]. Burning velocity is shown decreasing as diluents concentration increases due to the lower flame temperature.
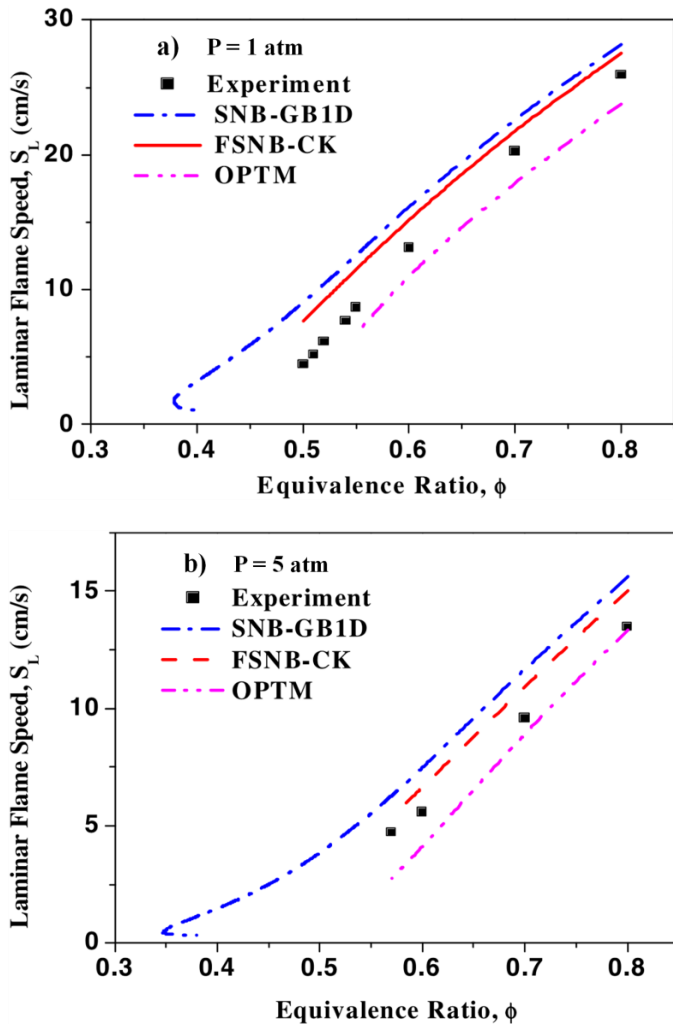
Figure 4 Measured and predicted laminar flame speeds of CH_4 - $\{0.3O_2 + 0.2He + 0.5CO_2\}$ flame as a function of equivalence ratio at 1 atm (a) and 5 atm (b) [21].
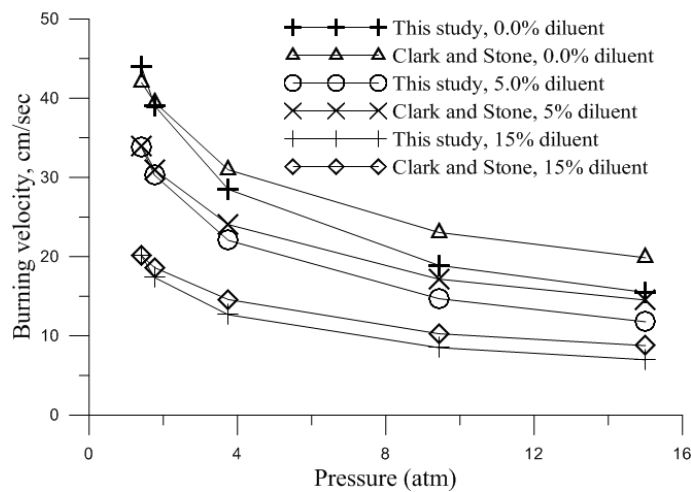

Figure 5 Comparison of laminar burning velocity of CH_4-air-diluent mixtures as a function of pressure at 350 K and $\phi = 1.0$, adapted from [22].
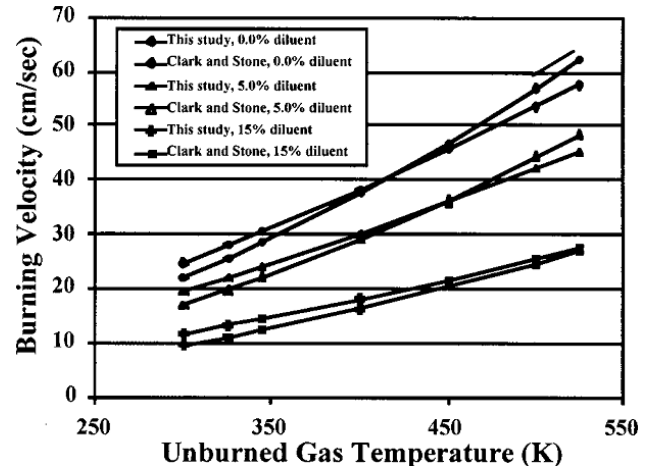

Figure 6 Comparison of S_L^0 of CH_4-air-diluent as a function of unburned gas temperature at 3.5 atm and $\phi = 1.0$ [22].

A comprehensive research on S_L^0, flammability limits and other fundamental combustion parameters of landfill gas (LFG) has been realized by Qin and coworkers [4]. A stagnation flow burner was used for the experimental work while two codes considering or not the heat reabsorption have been integrated with the Chemkin II using the GRI 2.11 mechanism for the description of the kinetics in the numerical study. The experiments have been conducted at atmospheric pressure and unburned gas temperature of 300 K along the stagnation streamline of the stagnation flow while the simulations were computed by employing the code that does not consider reabsorption. Figure 7 shows the comparison between experimental and simulations results with a reasonable agreement in general. A three-dimensional plot of simulated S_L^0 as a function of X_{CO2} and ϕ is shown in Fig 8. As X_{CO2} increases, the flames become weaker and the ability to operate fuel-lean diminishes.
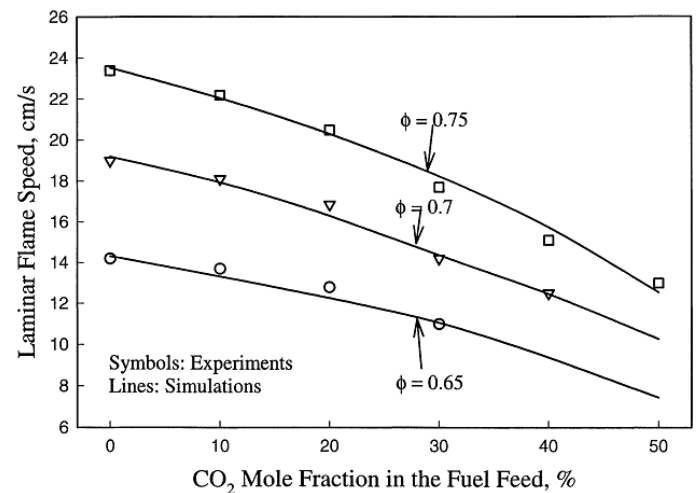

Figure 7 Experimentally and numerically determined laminar flame speeds as functions of CO_2 mole fraction in the fuel feed and equivalence ratio, ϕ [4].
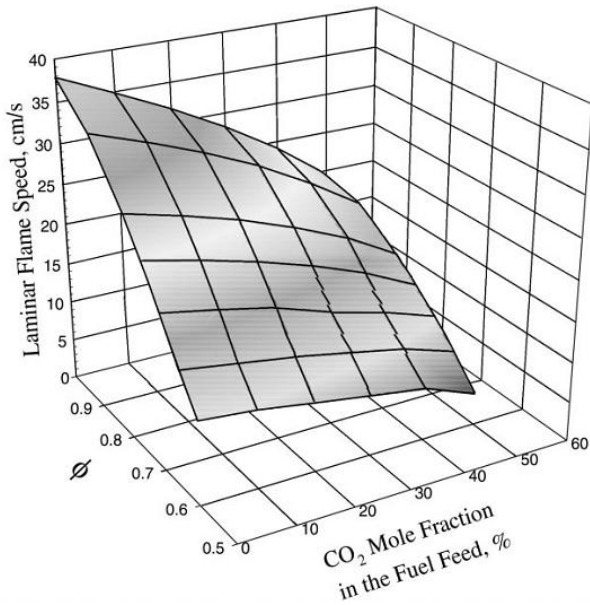
Figure 8 Variation of the numerically determined laminar flame speeds with CO_2 mole fraction in the fuel feed and equivalence ratio, ϕ, in a 3D view [4].

The effects of CO_2 addition on premixed flame structure and laminar burning velocity of CH_4/O_2 mixtures diluted by nitrogen have been examined by Le Cong and Daugat [24]. Species concentrations were measured in a jet-stirred reactor and simulated using PREMIX and a mechanism consisted of 128 species and 924 reversible reactions, for a wide range of equivalence ratios and temperatures, at pressure from 1 atm to 10 atm. It was observed that CO_2 inhibits the oxidation of H_2 and CH_4, reacting with H radicals in the reaction $CO_2 + H = CO + OH$. This chain-carrying reaction competes for H atoms consumption with the chain-branching reactions $H + O_2 = OH + H$ and $H + HO_2 = OH + OH$. Laminar burning velocities of such mixtures have been experimentally determined by [25] as shown in Figure 9 using a perforated plate burner for mixtures of $CH_4 + O_2 + CO_2$ with % dilution ratios $R = O_2 / (O_2 + CO_2)$ of 29, 31.55 and 35 with plate temperature of 368 K.

Anggono and coworkers [26] studied laminar burning velocity and flammability limits of a 66.4% methane, 30.6% carbon dioxide and 3% nitrogen biogas at ambient pressure and temperature. The laminar burning velocity have been found to be 7.43 cm/s for lean ($\phi = 0.6$), 20.86 cm/s for lean ($\phi = 0.8$), 26.38 m/s for stoichiometric ($\phi = 1.0$) and 18.64 m/s for rich ($\phi = 1.2$) biogas-air mixtures.

Lee and coworkers [5] experimentally and numerically studied the laminar burning velocity of LFG fuel and mixtures of LFG with liquefied propane gas (LPG) and natural gas. The objective was the determination of proper blends for achieving higher heating values, Wobbe Index and adiabatic flame temperature that allows interchangeability of this blends with NG. In terms of higher heating value, Figure 10, the mixture 10A (70% LFG and 30% LPG) fits the values of NG while in terms of Wobbe Index it is the 13A mixture (50% LFG and 50% LPG) that fits the NG value. They found that both

mixtures may be used as interchangeable gas of liquefied NG (LNG) without any modification of domestic combustion appliances [27]. In a following work [28] they studied two kinds of mixed fuels (MF(WI)) and MF(HV)) produced to have a Wobbe Index (WI) and a heating value (HV) nearly equivalent to those of LNG, respectively. All those mixtures, Figure 11, present laminar burning velocity sufficiently high for applications in any combustion system and are substantially higher than that of CH_4 at lean fuel conditions.

Cardona and Amell [29] studied the effect of adding C_3H_8 and H_2 to CH_4 (66%) / CO_2 (34%) biogas combustion at normal air and at slight oxygen enrichment air to solve the problem of
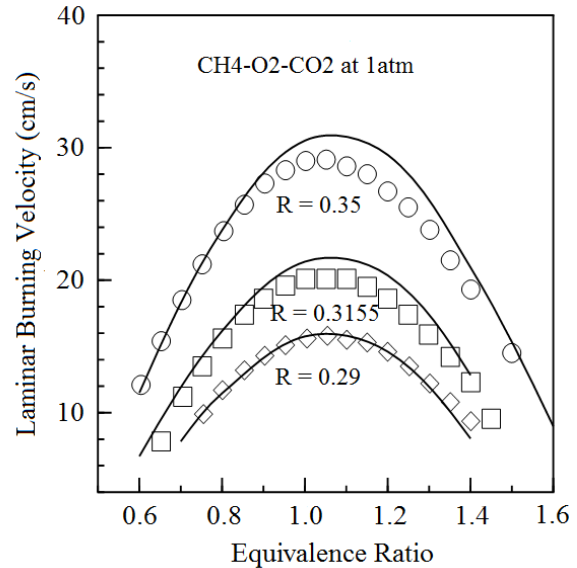

Figure 9 The laminar burning velocities of CH_4-O_2 in presence of CO_2 ($R = O_2/(O_2+CO_2)$). The data (symbols) are compared to the modeling (lines) adapted from [24].
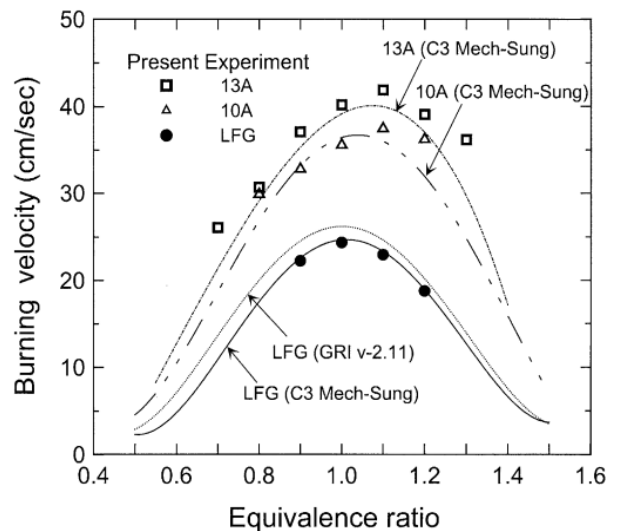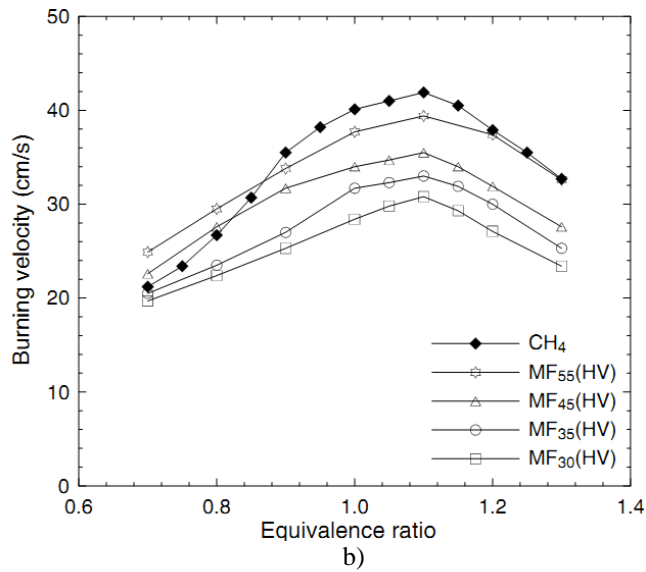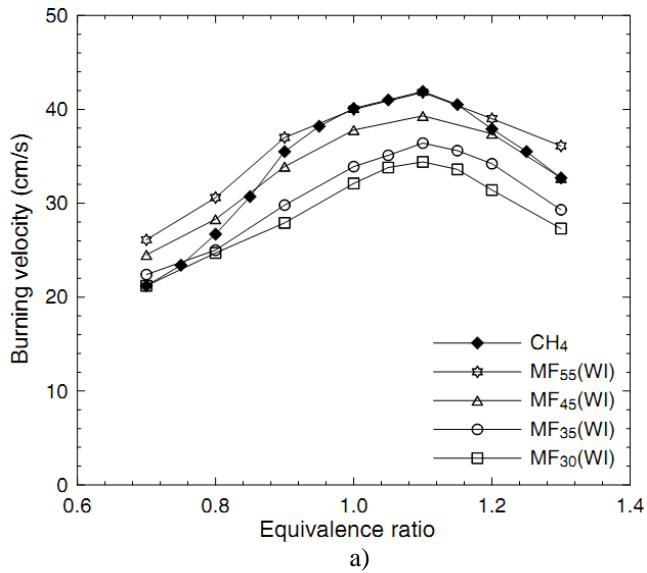

Figure 10 Comparison of predicted and measured burning velocities according to equivalence ratio for LFG and LFG-mixed fuel with LPG, [5].

Table 1. Laminar burning velocity data in the literature for biogas alone and in mixture with other fuels

Author	Composition (% vol)	Pi (atm)	Ti (K)	ϕ	Technique	S_L^0 (cm/s)
[18]	$CH_4/CO_2(0-60)$ - air	1	Ambient	/	Numerical	Figure 1
[19]	$CH_4/(Ar, N_2, CO_2)$-air	0.25-2	/	0.4-1.8	Num: C_1-C_2 Mech. Exp: Counterflow	Figs. 2, 3
[20]	$CH_4 - \{0.21O_2+(0.79-\gamma)N_2+\gamma CO_2\}$	1	300	< 0.8	Num: Chemkin code	Figure 4
[22]	$CH_4/(0-15)$ $(86N_2 +14CO_2)$ - air	0.75-70	298-550	0.8-1.2	Exp: Spherical bomb	Figs 5, 6
[4]	$CH_4/CO_2(0-60)$ - air	1-4	300	0.5-2	Num:1D Premix code	Figs 8,
[4]	$CH_4/CO_2(0-60)$ - air	1	300	< 1	Exp: Stagnation flow	Figs 7
[5][27][28]	LFG + NG LFG + LPG	1	300	0.5 -1.5	Num:C3 Mech Sung Exp: Nozzle burner	Figs 10, 11
[21]	$CH_4/\{0.3O_2 + 0.2He + 0.5CO_2\}$	1-5	298.3	0.4-0.8	Num: PSR Exp: Spherical bomb	Figure 4
[24]	CH_4 based fuels - $O_2/N_2/CO_2$	1	323, 338, 368	0.6-1.5	Exp: Jet stirred reactor	Fig 9
[26]	$66.4CH_4/30.6CO_2/3N_2$ - air	1	Ambient	0.5-1.3	Exp: Spherical bomb	7.3 -26.4
[29]	$66CH_4/34CO_2$ $50(66CH_4/34CO_2)/40C_3H_8/10H_2$ −air	0.828	298.3	0.5-1.6	Num: GriMech 3.0, C1-C3 Exp: contoured slot burner	Figs 12, 13

biogas's low flexibility as a fuel for use in commonly used burners due to its low burning velocity. The results are shown in Figures 12 and 13.

Figure 11 Burning velocities of CH_4 and MF(WI)s having equivalent Wobble Index a), and MF(HV)s having equivalent heating value b), versus equivalence ratio, [28].
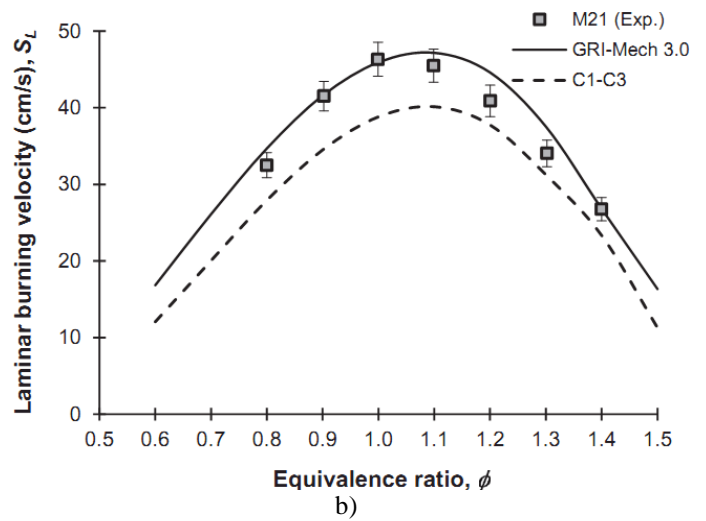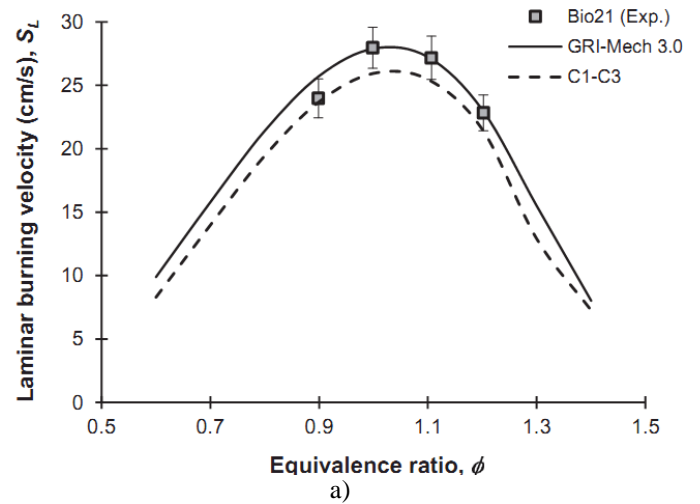
Figure 12 a) Laminar burning velocity of pure biogas, Bio21, and b) laminar burning velocity of mixture of biogas with C_3H_8 and H_2, M21, at 0.828 atm and 295 K in standard air [29].

These results, along with the High Wobbe Index suggests that natural gas can be replaced by the biogas/propane/hydrogen mixture (33% CH_4- 17% CO_2 - 40% C_3H_8 - 10% H_2). The High Wobbe Index is an index proportional to the thermal power of the system that permits interchangeability of fuels without changes in the combustion system geometry, injectors or gas supply conditions.
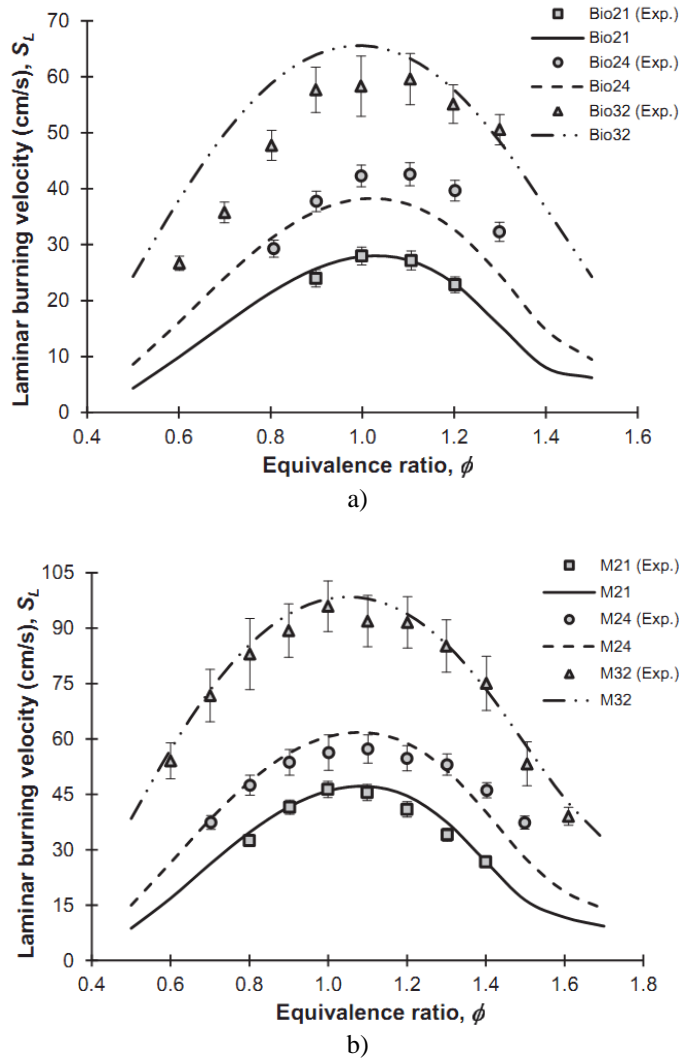

a)

b)

Figure 13 Laminar burning velocity of pure biogas a) and of the biogas/propane/hydrogen mixture b) with oxygen-enriched air at 0.828 atm and 295 K [29].

Methane is actually used as a fuel for automotive applications in SI engines either under stoichiometric or lean-burn conditions of the air-fuel mixture. The lean limits of methane is approximately $\phi = 0.6$ [30, 31]. Therefore, the region of greater interest for this work is that going from lean to stoichiometric conditions. i.e. $\phi = 0.6$ to $\phi = 1$. The literature revision of laminar burning velocity of biogas shows that pure biogas with a content of CO_2 of 50% has a maximum S_L^0 slower than 10 cm/s and that it is possible to experimentally determine the burning velocity only for few equivalence ratios.

The addition of CO_2 to the combustion of methane leads to a decrease in the burning velocity and a reduction of the adiabatic flame temperature. This behaviour is explained as CO_2 absorbs energy from the reaction due to its high specific heat and emits radiation to the surrounding due to its high emissivity. This phenomenon significantly affects the stability of the flame, leaving the biogas as a low flexibility fuel for its use in SI engines and conventional burners [29].

The increase of pressure determines a non linear decrease of S_L^0 and an increase of the mass burning rates. The increase of mass burning rates is due to mixture density increase while the non linear decrease of S_L^0 can be explained with the shift of importance of some two-body reactions to three-body chain-terminating reactions as pressure increases [32]. Numerical studies have proved that considering models with radiation absorption the calculated flame speed increases and the flammability limits extend and that this enhancement effect increases with pressure.

The influence of both initial temperature and adiabatic flame temperature on S_L^0 is revised. The burning velocity increases almost linearly with unburned fuel initial temperature while increases not linearly with T_a. The increase of S_L^0 with T_0 is mainly due to preheating effects. Even a small increase of T_a due to preheating, leads to strong increase of S_L^0. At high temperatures dissociation reactions, that introduce free radicals into the flame, are favoured. These free radicals act as chain carriers to promote the reaction and hence the propagation speed of the flame [33]. Therefore the increasing of unburned gases initial temperature is an effective method to increase S_L^0 of biogas mixtures.

The oxyfuel combustion is a very effective way to increase S_L^0 of biogas. The use of oxygen instead of air represents a reduction in the inert in the fuel and its consequent ability to absorb heat during the reaction, resulting in a higher flame temperature according to [29].

Finally a promising and economically feasible way for increasing biogas burning velocity, thus allowing its use in conventional NG burners and SI engines, is the mix of fuels with higher laminar burning velocity such as H_2, NG and LPG.

FLAMMMABILITY LIMITS IN BIOGAS

The flammability limit is defined as the range of fuel concentrations, normally in percentage volume, at a specified temperature and pressure, in which the fuel in air can be ignited and support the flame propagation [34]. It is mainly affected by the nature of the fuel, direction of the propagation, size and shape of the combustion chamber, temperature and pressure. A lower flammability limit (LFL) describes the minimum fraction of fuel concentration in air below which there is not enough fuel to cause the flame propagation since the temperature cannot reach a level that sustains the combustion process. An upper flammability limit (UFL) describes the maximum fraction of fuel concentration in air above which there is an insufficient oxygen source for the reaction to cause flame propagation. Therefore, the flame will only propagate if the equivalence ratio of the particular fuel is within its flammability limit [34].
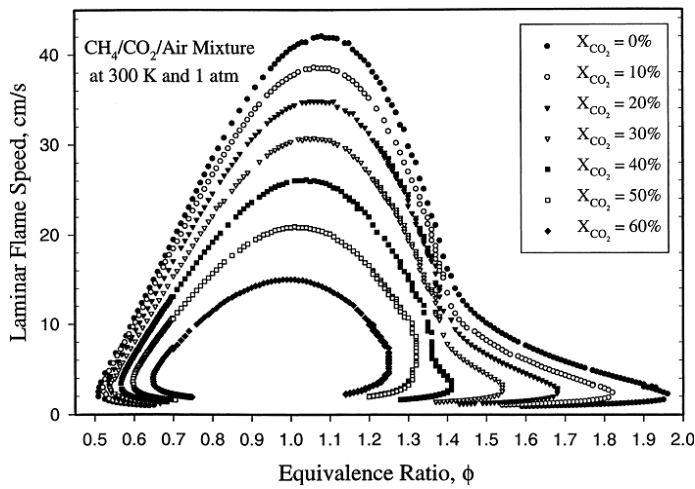
Figure 14 Numerically determined flammability limits of CH_4/CO_2/air mixtures as functions of the CO_2 mole fraction in the fuel feed, [4].

Figure 15 Numerically determined flammability limits of CH_4/CO_2/air mixtures for $X_{CO2} = 0$ % as functions of pressure, [4].

Ju and coworkers [20] in a numerically study of premixed gas flames in mixtures of CH_4, O_2, N_2 and CO_2 found that while considering heat reabsorption mechanisms can increase burning velocities and extend flammability limits considerably, fundamental limits, independent of the system dimensions, exist due to net heat loss intrinsic of the nature of gas radiation.

Qin and coworkers [4] realized detailed biogas flammability limits simulation study using a modified Premix code and determining the turning points in the equivalence ratio domain. The turning points in Figure 14 and 15 indicate the concentration limits beyond which propagation is not possible, and their existence is caused by the presence of thermal radiation. The simulations were conducted for different values of X_{CO2}, T = 300 K and pressures between 1-4 atm. Increasing X_{CO2}, the flammable range noticeably decreases and the value of S_L^0 is reduced for the same ϕ. Increasing pressure for $X_{CO2} =$ const, both the lean and rich flammability limits increase, resulting thus to a shift of the flammable range towards higher ϕ values.

In the experimental work of [26], realized in a spherical bomb burning a fixed biogas composition in air, at ambient pressure and temperature the measured LFL and UFL are $\phi =$ 0.6 and $\phi = 1.2$, respectively. The flammability region is a bit narrower but in reasonable agreement with the simulation results of [4].
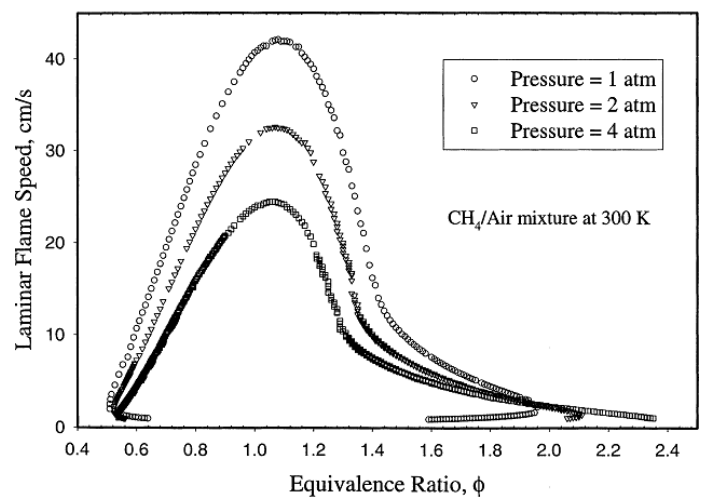
The influence of water vapor on flammability limits in a biogas air mixture has been studied by few researchers. Numerically calculated flammability limits for both dry biogas and 50 mg/L of water vapor in the mixture, for CH_4 content varying from 40 % to 100 %, are presented in Figure 16 [18]. More recently [35] experimentally measured the flammability limits of a 50-50% CH_4-CO_2 synthesized dry and water saturated biogas mixtures at atmospheric pressure in a spherical bomb. The effect of temperature, varying in a range between 20ºC to 70ºC, over flammability limits is shown in Figure 17. The experimentally measured LFL and UFL, for dry gas at 20ºC, gives values of 5.2 % and 11.4 % methane content in air, i.e, 10.4 % and 22.8 % biogas content in air. The experimentally LFL value is in good approximation with the numerical value found by [18] while the UFL differs from more than 10% from the numerical value of [18] which did not consider water saturated biogas. Considering the water saturated biogas, the temperature increase has a double and contradictory influence on flammability limits. Flammability limits widens with increasing temperature by reduction of LFL and by increase of UFL. On the other hand, rising temperature leads to increasing water vapor concentration which is inert gas thus shortens LFL and UFL of fuel-air mixture by reducing the burning velocity.

Table 2. Biogas flammability limits

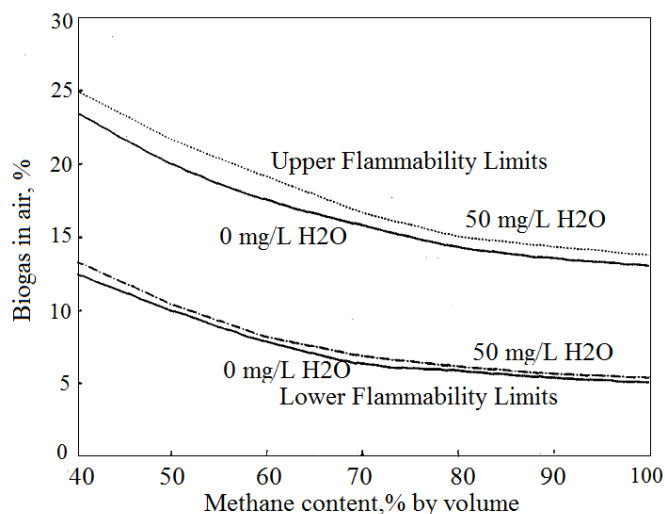| Author	Composition (% vol)	Pi (atm)	Ti (K)	ϕ	Technique	LFL	UFL
[18]	CH_4/CO_2(0-60) - air	1	amb	/	Numerical	Fig 16	Fig 16
[20]	CH_4 - {0.21O_2+(0.79-γ)N_2+γCO_2}	1	300	< 0.8	Chemkin code	$\phi = 0.442$ @(γ=30)	/
[4]	CH_4/CO_2(0-60) - air	1-4	300	0.5-2	1D Premix code	Figs 14, 15	Figs 14, 15
[35]	50 CH_4/ 50 CO_2 - air	1	293-343	1	Spherical bomb	Figure 17	Figure 17
[26]	66.4 CH_4/ 30.6 CO_2/ 3 N_2 - air	1	amb	0.5-1.3	Spherical bomb	$\phi = 0.6$	$\phi = 1.2$

Figure 16 Flammability limits as a function of CO_2 content and water vapor concentration, adapted from [18].

The simulation results form [21] shows that because of radiation absorption by CO_2, the radiation heat loss in the burned zone becomes much smaller. As the equivalence ratio decreases, it is seen from Figure 4 that radiation absorption plays an increasing role in increasing the flame speed and extending the flammability limit.
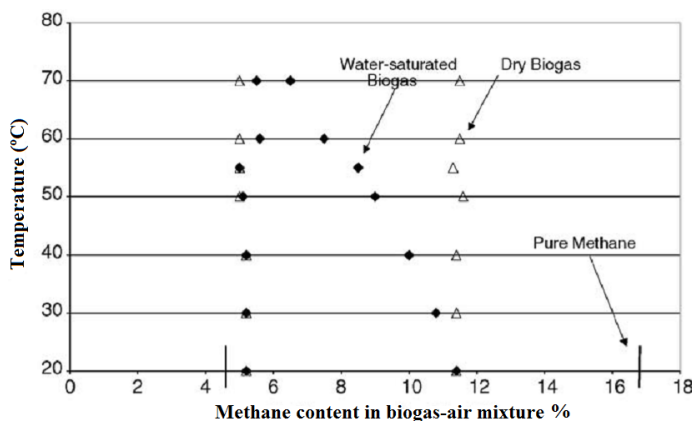

Figure 17 Influence of temperature and humidity on the flammability limit of the biogas (50 vol. % CH_4 and 50 vol. % CO_2) at atmospheric pressure, adapted from [35].

From the bibliographic revision we can conclude that biogas has narrower flammability limits than methane or NG. A larger content of CO_2 in the mixture results in narrower flammability limits. Nevertheless, the radiation absorption by CO_2 improves the lean limit for biogas [36], thus extending the operational conditions for lean burn engines. On the other hand, the presence of water vapor in biogas combustion leads to an increase of the lean flammability limit.

CONCLUSIONS AND PERSPECTIVES

The available literature laminar burning velocity and flammability limits of biogas combustion has been revised. The following conclusions were drawn from this study:

1. The presence of CO_2 to the combustion of biogas leads to a decrease in the burning velocity and a reduction of the adiabatic flame temperature. This phenomenon significantly affects the stability of the flame, leaving the biogas as a low flexibility fuel for its use in SI engines and conventional burners.
2. The increase of pressure determines a non linear decrease of S_L^0 and an increase of the mass burning rates.
3. The burning velocity increases almost linearly with unburned fuel initial temperature while increases not linearly with T_a.
4. The oxyfuel combustion is an expensive but very effective way to increase S_L^0 of biogas.
5. The biogas mix with higher laminar burning velocity fuels such as H_2, NG and LPG is a reliable and economically feasible way for increasing biogas S_L^0, thus allowing its use in conventional NG burners and SI engines.
6. Biogas has narrower flammability limits than methane or NG. Nevertheless, the radiation absorption by CO_2 improves the lean limit for biogas, thus extending the operational conditions for lean burn engines.
7. The presence of water vapor in biogas combustion leads to an increase of the lean flammability limit.

Despite the quite large literature on fundamental combustion properties of pure biogas and mixture with other fuels, experimentally determined laminar burning velocity and flammability limits at operational conditions of pressure and temperature encountered in SI engines are scarce. Therefore, detailed and rigorous experimental studies of laminar burning velocity and flammability limits in these conditions would be very useful for simulation verification and for a deeper understanding of biogas combustion at SI operational conditions.

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