

Review

The State of the Art of Laminar Burning Velocities of H₂-Enriched *n*-C₄H₁₀-Air Mixtures

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Abstract: Currently, hydrogen-enriched *n*-butane blends present a real interest due to their potential to reduce emissions and increase the efficiency of combustion processes, as an alternative fuel for internal combustion engines. This paper summarises the recent research on laminar burning velocities of hydrogen-enriched *n*-C₄H₁₀-air mixtures. The laminar burning velocity is a significative parameter that characterises the combustion process of any fuel–air mixture. Accurately measured or computed laminar burning velocities have an important role in the design, testing, and performance of *n*-C₄H₁₀-H₂ fuelled devices. With this perspective, a brief review on the influence of hydrogen amount, initial pressure and temperature, and equivalence ratio on the laminar burning velocity of hydrogen-enriched *n*-C₄H₁₀-air mixtures is presented. Hydrogen has a strong influence on the combustion of butane–air mixtures. It was observed that a parabola with a maximum at a value slightly higher than the stoichiometric ratio describes the variation in the laminar burning velocity of hydrogen-enriched *n*-butane–air mixtures with the equivalence ratio. An increase in initial pressure or hydrogen amount led to an increase in this important combustion parameter, while an increase in initial pressure led to a decrease in laminar burning velocity. Overall, these studies demonstrate that hydrogen addition to *n*-C₄H₁₀-air mixtures can increase the laminar burning velocity and flame temperature and improve flame stability. These findings could be useful for the optimisation of combustion processes, particularly in internal combustion engines and gas turbines. However, the literature shows a paucity of investigations on the laminar burning velocities of hydrogen-enriched *n*-C₄H₁₀-air mixtures at initial temperatures and pressures differing from those in ambient conditions. This suggests that experimental and theoretical investigations of these flames at sub-atmospheric and elevated pressures and temperatures are necessary.



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Keywords: hydrogen; *n*-butane; laminar burning velocity

1. Introduction

Currently, a large part of the energy we use to heat, illuminate, cook, or power our cars is obtained by the combustion of fossil fuels (especially gaseous hydrocarbons). Among these gaseous fuels, frequently used are natural gas (NG), methane, propane, *n*-butane, and LPG (liquefied petroleum gas, a mixture containing mostly propane and *n*-butane). On the other hand, gas turbines used for power generation utilise liquefied natural gas (LNG) that usually includes mostly methane, along with ethane, propane, and *n*-butane.

n-Butane is the smallest alkane that has oxidation characteristics, β -scission, and oxygen addition reactions similar to those of larger paraffins from gasoline [1], and this indicates it as an efficient fuel. Moreover, it has been shown that *n*-butane exhibits pre-ignition reactions and cool flame phenomena [2]. Compared to methane, this fuel has a lower saturation pressure and autoignition temperature; therefore, it can be easily liquefiable, and these properties point toward it being a suitable fuel for micropower systems [3]. Additionally, *n*-C₄H₁₀ is widely used to feed domestic stoves and heaters or automotive engines, either alone or mixed with propane (forming LPG). Furthermore, *n*-butane is

used as an extraction solvent in the fragrance industry and as a basic ingredient for the production of butadiene and ethene, key ingredients of synthetic rubber [4]. *n*-Butane is also used as a solvent in heavy oil recovery processes due to its saturation pressure that is close to the reservoir pressure of many heavy oil reservoirs [5]. A brief summary of the uses of *n*-butane is presented in Figure 1.

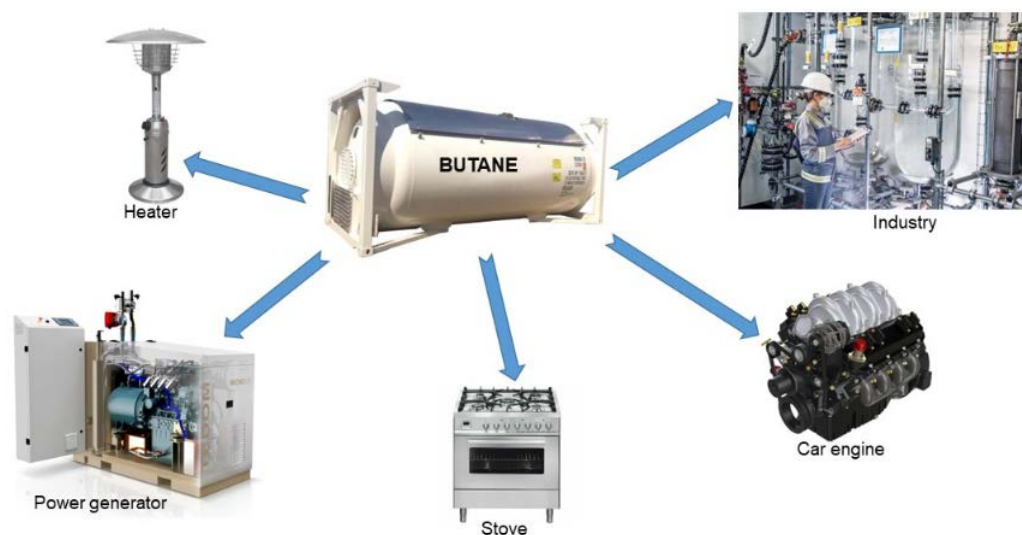


Figure 1. Summary of *n*-butane utilisation.

As can be seen from Figure 1, *n*-butane is widely utilized, especially in combustion processes. Therefore, the study of its combustion properties (including laminar burning velocity) must always be up to date in order to improve combustion devices, such that they use the fuel more efficiently and produce a greater amount of energy and less pollution. On the other hand, sometimes, under certain conditions, unwanted disastrous explosions may occur, due to its high explosive potential. Therefore, new solutions to avoid these accidents are needed. In this sense, experimental and numerical investigations have been conducted on *n*-butane–air flames to determine their global combustion parameters, including ignition delay times [6–8], propagation parameters (peak explosion pressures, explosion times, maximum rates of pressure increase, and deflagration indexes) [9–11], as well as the laminar burning velocities [8,12–30].

Considering that, lately, the fuel crisis is deepening, solutions are being sought regarding the efficient use of existing resources to reduce their consumption and pollutant emissions. Hydrocarbon fuels present low flame stability and low burning speed and their combustion produces pollution that contributes to global warming due to the products released after combustion. Therefore, solutions are being sought to solve these problems.

A method proposed by researchers to attenuate the problems mentioned above is to add a more energetic compound to the combustion flow so that more energy is supplied and less fuel is consumed. In the case of gaseous fuels, hydrogen addition is a promising way to improve the combustion properties. Adding hydrogen to the combustion of a gaseous fuel has multiple advantages such as the following: its burning does not contribute to the production of polluting compounds; a great quantity of energy is released during the course of combustion; the ignition energy is lowered; and the combustion speed is increased. These advantages arise from the combustion characteristics of hydrogen such as large flammability limits, low ignition delay times, and high heat release rate and laminar burning velocity. Therefore, these combustion characteristics indicate it as a superior fuel, comparing with hydrocarbons being, thus, suitable for a smooth combustion in practical applications.

However, some disadvantages exist, i.e., hydrogen is difficult to store and is prone to leakage that can lead to unwanted explosions and even detonations. Thus, numer-

ous experimental and numerical studies have been conducted on gaseous fuel–H₂–air mixtures aiming at their safer use, reducing pollutant emissions, and alleviating global warming [31–35].

A comparison between *n*-butane and hydrogen properties (among them: flammability limits, minimum ignition energy, calorific value, autoignition temperature) taken from the specialized literature [26,36–41] is presented in Table 1. It is easy to see that the fuel properties of *n*-butane present disadvantages in comparison to fuel properties of hydrogen (e.g., low calorific value, narrow combustion limits, slow laminar combustion rate), which often restricts its practical utilisation. However, the combustion performances of *n*-butane could be improved by adding hydrogen.

Table 1. Properties of *n*-butane compared to hydrogen.

Property	<i>n</i> -C ₄ H ₁₀		H ₂	
	Value	Reference	Value	Reference
Molecular weight (kg/kmol)	58.12	Lee et al. [36]	2.02	Qi et al. [39]
Lower heating value (MJ/kg)	45.72	Lee et al. [36]	120	Dinesh et al. [40]
Octane number	92	Lee et al. [36]	>130	Masuk et al. [41]
Flammability limits in air at ambient pressure and temperature (vol%)	1.50–8.50	Chemsafe [37]	4.1–75.6	Masuk et al. [41]
Autoignition temperature (°C)	392	Chemsafe [37]	560	Chemsafe [37]
Minimum ignition energy (MJ)	0.900	Musat et al. [38]	0.018	Masuk et al. [41]
Molar stoichiometric fraction of combustible in mixture with air	3.13	Chemsafe [37]	29.5	Chemsafe [37]
Adiabatic flame temperature at ambient initial conditions and $\varphi = 1$ (K)	2274	Giurcan et al. [26]	2100	Qi et al. [39]
Laminar burning velocity under ambient initial conditions and $\varphi = 1$ (m/s)	0.38	Giurcan et al. [26]	3.51	Dinesh et al. [40]

Over the years, hydrogen addition to gaseous fuel–air mixtures has been used to enhance combustion of some fuels frequently used in the industry, car engines, or households such as natural gas [32,34,42], methane [29], biogas [43,44], and LPG [28,35,45]. Moreover, the combustion characteristics of ammonia with hydrogen addition have been the subject of recent studies. These studies focused on the role of ammonia as a carbon-free fuel for the shipping industry [46] and on developing a chemical reaction mechanism for ammonia combustion in internal combustion engines [47].

Recently, a *n*-C₄H₁₀–H₂–air mixture was considered a prospective fuel for micro-combustors [3]. Giving the importance of using of these mixtures, knowledge of their characteristic explosion parameters is of particular importance so that they can be used and handled safely. In this regard, studies have been undertaken regarding the combustion parameters (including ignition delay times, flammability limits, and laminar burning velocities) of these mixtures using various experimental techniques, computing packages, and initial conditions. For example, Refael and Sher [48] reported the ignition delay times for H₂-enriched *n*-C₄H₁₀–air flames using a detailed reaction scheme of *n*-butane oxidation with hydrogen addition. Their studies revealed that the autoignition process of *n*-C₄H₁₀–H₂–air mixtures has three main stages. In the first stage, the *n*-C₄H₁₀ molecules are attacked by HO₂ radicals, resulting in the formation of H₂O₂ molecules that further decompose into OH radicals. In the second stage, the OH radicals break down the fuel molecules. In the last stage, the CH₂O is transformed into HCO and, thus, exothermic reactions occur. Refael and Sher also mentioned that H₂ enrichment has a delaying consequence on the autoignition process. On the other hand, a study conducted by Jiang et al. [49] on ignition delay times of argon-diluted *n*-butane–hydrogen–oxygen flames showed that addition of hydrogen leads

to a non-linear promoting effect on ignition delay time of this fuel. The authors attributed this phenomenon to the alternation of dominated kinetics from the hydrocarbon to the hydrogen as the hydrogen content is increased.

In another paper, the flammability limits of n -C₄H₁₀-H₂-air mixtures were investigated under various initial pressures ranging from 0.1 to 1.0 atm and room temperature in a closed cylindrical vessel [50]. This study revealed that the flammability limits narrow at initial pressure decreases. Moreover, it was observed that the initial pressure has much greater impact on the upper flammability limits of n -C₄H₁₀-H₂-air mixtures than on the lower flammability limits of these mixtures. The higher the fraction of H₂ in the n -C₄H₁₀-air mixture is, the more significant the impact of the initial pressure on the upper flammability limit. The paper [48] highlighted that the flammability domain of n -C₄H₁₀-H₂-air mixtures widened when the amount of hydrogen added to the mixture was increased.

Adiabatic flame temperatures, a main feature involved in the combustion process that indicates the maximum temperature at equilibrium that a fuel mixture can achieve, were calculated by some researchers using different computing packages [28,50–53]. These studies revealed that the adiabatic flame temperatures of n -C₄H₁₀-H₂-air mixtures increase first with increases in the equivalence ratio (ϕ), reaching a maximum value at about $\phi = 1.1$, and then decrease at higher values of the equivalence ratio. It was also seen that the adiabatic flame temperatures increase monotonically with an increase in the amount of hydrogen added to the mixture.

The laminar burning velocity, another important feature that characterizes the combustion process of H₂-enriched n -C₄H₁₀-air mixtures, was also studied by experimental [27,28,51] and computational [29,54,55] methods. Accurately measured or computed laminar burning velocities have an important role in the design, testing, and performance of n -C₄H₁₀-H₂-fuelled devices. Additionally, the values of laminar burning velocities are essential in validating detailed reaction mechanisms and in developing reduced reaction mechanisms [56–59]. With this perspective, this paper presents a brief review of the laminar burning velocities of n -C₄H₁₀-H₂-air mixtures obtained from experimental studies (using various experimental methods) or from kinetic modelling, under different initial conditions. This paper is helpful not only for combustion specialists, but also for those seeking general information about this important domain. Combustion is used in various applications, from internal combustion engines to household appliances, and understanding its principles is crucial in modern society. Therefore, this paper serves as valuable information for anyone looking to broaden their knowledge in the field of combustion.

Over time, review-type studies have been performed on the laminar burning velocities of H₂-air [60–64], fuel-air [64–67], and fuel-H₂-air mixtures [31,61,67–69]. A brief summary of these review articles is given in Table 2.

Table 2. Summary of representative literature reviews on the laminar burning velocities.

Mixture	Review Title	Year	Reference
H ₂ -air	Recent advances in understanding of flammability characteristics of hydrogen	2013	Sanchez et al. [60]
	A review of laminar burning velocity and flame speed of gases and liquid fuels	2017	Khudhair et al. [61]
	A comprehensive review of measurements and data analysis of laminar burning velocities for various fuel + air mixtures	2018	Konnov et al. [62]
	Premixed flame propagation in hydrogen explosions	2018	Xiao et al. [63]
	A review of laminar flame speeds of hydrogen and syngas measured from propagating spherical flames	2020	Han et al. [64]

Table 2. Cont.

Mixture		Review Title	Year	Reference
Fuel–air	CH ₄ C ₂ H ₆ C ₃ H ₈ C ₄ H ₁₀	A comprehensive review of measurements and data analysis of laminar burning velocities for various fuel + air mixtures	2018	Konnov et al. [62]
	Biogas	Laminar burning and flammability limits in biogas: A state of the art	2014	Pizzuti et al. [65]
		Laminar burning velocity and flammability limits in biogas: A literature review	2016	Pizzuti et al. [66]
		Laminar burning velocity of biogas-containing mixtures. A literature review	2021	Giurcan et al. [67]
	Syngas	A review of laminar flame speeds of hydrogen and syngas measured from propagating spherical flames	2020	Han et al. [64]
Fuel–H ₂ –air	CH ₄	Progress in combustion investigations of hydrogen enriched hydrocarbons	2014	Tang et al. [31]
		Kinetic and dynamic analysis of hydrogen enrichment mixtures in combustor systems—A review paper	2016	Emami et al. [68]
		Measurements and data analysis review of laminar burning velocity and flame speed for biofuel/air mixtures	2021	Abdulraheem et al. [69]
	C ₃ H ₈	Progress in combustion investigations of hydrogen enriched hydrocarbons	2014	Tang et al. [31]
		Kinetic and dynamic analysis of hydrogen enrichment mixtures in combustor systems—A review paper	2016	Emami et al. [68]
		A review of laminar burning velocity and flame speed of gases and liquid fuels	2017	Khudhair et al. [61]
	Biogas	Laminar burning velocity of biogas-containing mixtures. A literature review	2021	Giurcan et al. [67]

However, no reviews regarding the laminar burning velocities of H₂-enriched *n*-C₄H₁₀–air mixtures have been reported yet. Therefore, this review fills a critical gap in the combustion domain regarding the laminar burning velocities of *n*-C₄H₁₀–H₂–air flames, presenting a comparison of existing experimental and computed results. In addition, a detailed analysis of the data regarding the dependence of the laminar burning velocities of these gaseous mixtures on their equivalence ratio, initial pressure and temperature, and hydrogen content is given. The laminar burning velocity is an important feature of H₂-enriched *n*-C₄H₁₀–air mixtures' combustion characteristics affecting the performance and design of combustion devices. Additionally, this parameter is involved in flame stabilization and extinction, predicting pollutant production, and determining the heat release rate. Given that combustion systems do not always work under standard conditions, research carried out under different initial conditions (temperature, pressure, compositions) must be taken into account.

In this sense, the present work was structured as follows:

1. Introduction;
2. Experimental methods used to obtain the laminar burning velocities of *n*-C₄H₁₀–H₂–air mixtures;
3. Numerical methods used to obtain the laminar burning velocities of *n*-C₄H₁₀–H₂–air mixtures;
4. Laminar burning velocities of H₂-enriched *n*-C₄H₁₀–air mixtures:
 - 4.1 Effect of the mixture equivalence ratio;
 - 4.2 Effect of hydrogen addition;

- 4.3 Effect of the initial temperature;
- 4.4 Effect of the initial pressure.
5. Challenges and future perspectives;
6. Conclusions.

2. Experimental Methods Used in Obtaining the Laminar Burning Velocities of n -C₄H₁₀-H₂-Air Mixtures

Experimental investigation of the laminar burning velocities of hydrogen-enriched n -C₄H₁₀-air mixtures was performed by using several well-established methods including both stationary flames (e.g., flat-flame burner method, heat flux method, and diverging channel method) and non-stationary flames (e.g., spherical expanding flame method under isobaric or isochoric conditions). In the case of stationary flames, the reactants were introduced into the reaction zone, while in the case of non-stationary flames, the reaction zone was introduced into the reactants and, thus, the laminar burning velocities were obtained [14,16]. All reported experimental results were conducted at an initial pressure of 1 bar.

Sher and Ozdor [15] provided the first experimental investigation of the laminar burning velocities of n -butane-air mixtures using measurements at various initial temperatures (298–420 K) using a flat-flame burner. This experimental technique allowed the measurements of lower laminar burning velocities that are obtained in the case of mixtures with a composition close to the explosion limit being used at low gas flow rates. Sher and Ozdor [15] used n -C₄H₁₀-air mixtures with an equivalence ratio between 0.5 and 1.2 in the presence of a low hydrogen content (up to 9.3 vol%). Later, Jithin et al. [27] and Sankar et al. [28] obtained the experimental laminar burning velocities of H₂-enriched n -C₄H₁₀-air mixtures using the heat flux method. This experimental method allowed performing accurate measurements of the laminar burning velocity at elevated initial pressures [70]. The authors [27,28] reported the laminar burning velocities for n -C₄H₁₀-air mixtures having equivalence ratios between 0.7 and 1.3, an initial temperature of 298 K, and a hydrogen content up to 60 vol%.

Another experimental technique used by researchers to obtain the laminar burning velocities of n -butane-hydrogen-air mixtures is the diverging channel method [27]. This method allows measurement of the laminar burning velocities of a flammable mixture at elevated temperatures. This experimental technique was used by Jithin et al. [27] who performed experiments on n -C₄H₁₀-air mixtures enriched with various hydrogen amounts having equivalence ratios from 0.7 to 1.3, ambient initial pressure, and initial temperatures up to 450 K.

The spherical expanding flame method was used by Tang et al. [51] and Zitouni [55] to obtain the laminar burning velocities of H₂-enriched n -C₄H₁₀-air mixtures under ambient initial conditions, various equivalence ratios, and various amounts of hydrogen. This experimental method allowed obtaining the laminar burning velocities from a single experiment for a large domain of temperatures and pressures. Tang et al. [51] performed experiments in a 5.3 L cylinder, while Zitouni [55] performed experiments in a 35 L cylinder. Both studies were performed on mixtures having equivalence ratios between 0.6 and 1.5, an initial temperature of 298 K, and various hydrogen contents.

Details on the weaknesses and strengths of these experimental methods together with their accuracy and uncertainties can be found elsewhere [62,67,71,72]. However, in Table 3, a brief description of their advantages and disadvantages is presented.

Overall, it can be said that the experimental determination of the laminar burning velocities of n -C₄H₁₀-air flames enriched with H₂ was usually performed at an initial pressure of 1 bar, initial temperatures from 298 to 450 K, equivalence ratios ranging from 0.5 to 1.5, and H₂ contents from 0 to 60 vol%. In Table 4, a summary of the experimental techniques used to obtain the laminar burning velocities of n -C₄H₁₀-air flames enriched with H₂ at $p_0 = 1$ bar are given.

Table 3. Brief description of the experimental methods' advantages and disadvantages.

Stationary flames	Flat burner	Advantages	- a simple method - measurements at different initial pressures and compositions
		Disadvantages	- only lower laminar burning velocities are measured - composition close to the explosion limit
	Heat flux	Advantages	- direct method - measurements at various pressures
		Disadvantages	- not suitable for mixtures with high laminar burning velocities at high pressures, difficulties in flame stabilization appear - difficulties in obtaining laminar burning velocity at elevated temperatures
	Diverging channel	Advantages	- the hydrodynamic stretch is negligible - various initial temperatures and fuel concentrations - allows accurate measurements of quenching distance
		Disadvantages	- apparition of heat losses - apparition of stretched flames
Spherical expanding flames		Advantages	- a single curve registered in a short time - measurements at high pressures/temperatures and various initial compositions - measurements in vessels with different volumes and shapes
		Disadvantages	- expensive and complex equipment is involved - stretch corrections are necessary - implies dedicated equations for laminar burning velocity calculation - heat losses to the vessel's wall

Table 4. Experimental techniques used by researchers to obtain the laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ –air flames enriched with H_2 , at $p_0 = 1$ bar.

Technique	Initial Conditions			Reference
	φ	p_0 (bar)	T_0 (K)	
Flat-flame burner	0.5–1.2	1.0	298–420	Sher and Ozdor [15]
Heat flux method	0.7–1.3	1.0	298	Jithin et al. [27]
	0.8–1.3	1.0	298	Sankar et al. [28]
Diverging channel method	0.7–1.3	1.0	300–450	Jithin et al. [27]
Spherical expanding flames	0.6–1.5	1.0	298	Tang et al. [51]
	0.7–0.9	1.0	298	Zitouni [55]

3. Numerical Methods Used in Obtaining the Laminar Burning Velocities of $n\text{-C}_4\text{H}_{10}$ – H_2 –Air Mixtures

Although the experimental investigations give sufficient information about the laminar burning velocity of a fuel–air mixture, they are laborious, expensive, and involve a large amount of raw material and time. Therefore, in addition to experimental measurements, another possibility to obtain the laminar flame velocities of flammable gaseous mixtures, used by researchers in the combustion field, is by conducting theoretical and numerical simulation studies. Dedicated programs that involve various kinetic mechanisms are usually necessary to study 1D freely propagating flames under various initial conditions such as fuel or diluent concentration, equivalence ratio, initial temperature, and/or pressure.

Thus, besides the experimental procedures used by researchers to determine the laminar burning velocities of hydrogen-enriched n -butane–air flames, numerical methods were also used to obtain this important combustion feature using various computing packages [27,28,52–55]. These computing packages use not only different reaction mechanisms but also involve numerous reactions and species.

For $n\text{-C}_4\text{H}_{10}\text{-H}_2$ -air flames, investigators used the following mechanisms: Aramco 2.0 mechanism [27,28], a mechanism that describes the combustion of H_2 and its mixtures with CO (syngas) or C1-C2 hydrocarbons; San Diego [55] and modified San Diego mechanisms [29,53], optimised mechanisms for studying the autoignition and flame propagation occurring in different hydrocarbon mixtures; GRI Mech (version 1.2) [73], designed to compute mainly natural gas flames; and USC Mech II [52–55], a mechanism applied to numerous combustion scenarios that include the oxidation of C1-C4 hydrocarbons, hydrogen, and carbon monoxide. A more detailed description of these mechanisms was made in other works [62,67,74].

Computations regarding hydrogen-enriched n -butane-air flames were undertaken under various initial conditions (pressures of 1–20 bar, temperatures of 298–450 K, and various compositions (equivalence ratios between 0.5 and 1.5, H_2 content between 0 and 60 vol%)). Table 5 provides information about the various chemical reaction mechanisms used by researchers to obtain the laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ -air flames enriched with H_2 .

Table 5. Chemical reaction mechanisms and initial conditions involved in computing the laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ -air mixtures enriched with H_2 .

Mechanism	Initial Conditions			Reference
	φ	p_0 (bar)	T_0 (K)	
Aramco 2.0	0.7–1.3	1.0	300–450	Jithin et al. [27]
	0.8–1.3	1.0	298	Sankar et al. [28]
USC Mech II	0.8–1.3	1.0	298	Sankar et al. [28]
	0.6–1.5	1.0	298	Tang et al. [51]
	0.8–1.3	1.0	298	Cheng et al. [52]
	0.7–1.3	1.0	298	Ren et al. [53]
	0.6–1.3	1.0	300	Aravind et al. [54]
	0.7–0.9	1.0	298	Zitouni [55]
San Diego	0.7–0.9	1.0	298	Zitouni [55]
Modified San Diego	1.0	1.0	298	Veetil et al. [29]
GRI Mech 1.2	0.7–1.4	1.0–20.3	300	Sung et al. [73]

4. Laminar Burning Velocities of H_2 -Enriched $n\text{-C}_4\text{H}_{10}$ -Air Mixtures

The laminar burning velocity is a main characteristic that describes combustion phenomena and provides physico-chemical information on the reactivity, exothermicity, and diffusivity of a given mixture. It alters or even determines the burning rate of a given fuel-oxidizer mixture and characterizes many premixed flame phenomena (e.g., extinction, flash back, blow off). Additionally, the laminar burning velocity is an important feature necessary to the chemical kinetic mechanism validation and development of surrogate fuel models [57,75,76]. Furthermore, this parameter is important in the scaling and modelling of turbulent premixed flames; therefore, accurate values of laminar burning velocities, especially at elevated initial conditions (pressures and/or temperatures), are necessary. Furthermore, the laminar burning velocity obtained under standard conditions (298 K and 1 bar) is an important parameter that characterises the combustion properties of a fuel and is useful for understanding the underlying chemistry. Therefore, precise values of laminar burning velocities are a necessity regardless of whether they were obtained experimentally or from calculations.

Studies undertaken by researchers in the combustion field to obtain the laminar burning velocities of $n\text{-C}_4\text{H}_{10}\text{-H}_2$ -air mixtures have been obtained using both experimentation and computation. An overview of these methods is presented in Figure 2.

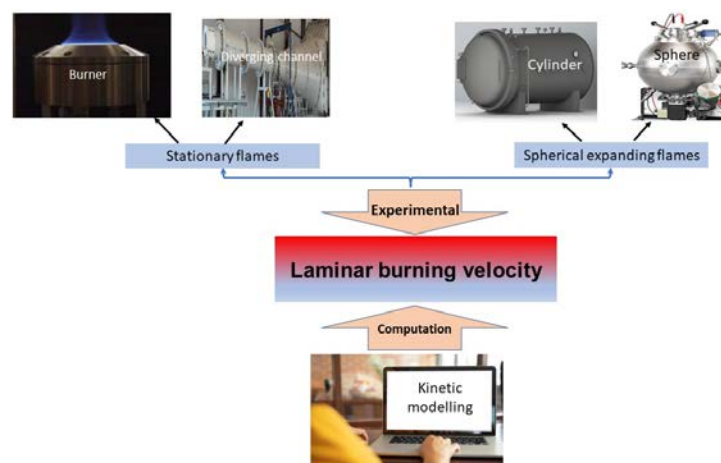


Figure 2. Methods used to obtain the laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ -air flames.

As demonstrated earlier, the laminar burning velocity depends on a series of factors such as the composition, initial temperature and pressure of the combustible gaseous mixture, the presence of inert or active additives, and the type of oxidant in which the combustion occurs [9,50,62].

In the following chapters, the dependence of the laminar burning velocity of H_2 -enriched $n\text{-C}_4\text{H}_{10}$ -air mixtures on some of these parameters is discussed.

4.1. Effect of the Mixture Equivalence Ratio

The laminar burning velocity depends upon the composition (equivalence ratio) of the mixture under investigation. The effect of the mixture equivalence ratio on the laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ -air mixtures was investigated using both experiments and computation, as was previously mentioned. The range of equivalence ratios examined by researchers includes both lean and rich mixtures.

In Figure 3, the measured laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ -air flames enriched with 40 vol% H_2 from measurements performed using the heat flux method and diverging channel method, respectively, at ambient initial conditions are presented versus the equivalence ratio. We can observe that the data presented in Figure 3 agree well with each other, within experimental errors. As mentioned by Faghih and Chen in their paper [72], there are many disagreements concerning the experimental values of the laminar burning velocities reported by those who performed research in this field. These differences can be observed even in the case of a mixture with the same composition that is studied using the same experimental technique (or the same vessel volume and shape) and under the same initial conditions.

Usually, the experimental laminar burning velocities are necessary to validate and develop chemical kinetic mechanisms. For $n\text{-C}_4\text{H}_{10}$ -air flames enriched with hydrogen, researchers also performed a series of numerical calculations using certain mechanisms as described above.

Figure 4 depicts the laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ -air mixtures enriched with 20 vol% H_2 obtained by computations with two different kinetic mechanisms, at different equivalence ratios. The results from Figure 4 were also obtained under ambient initial conditions. The scattering of the computed data can be attributed to the different kinetic mechanisms involved in the computation. Each mechanism is different from the other by, for example, the number of elementary reactions that are taken into account or the number of species involved in the combustion process. Thus, this can lead to different values of the laminar burning velocities even for the same mixture or the same initial conditions.

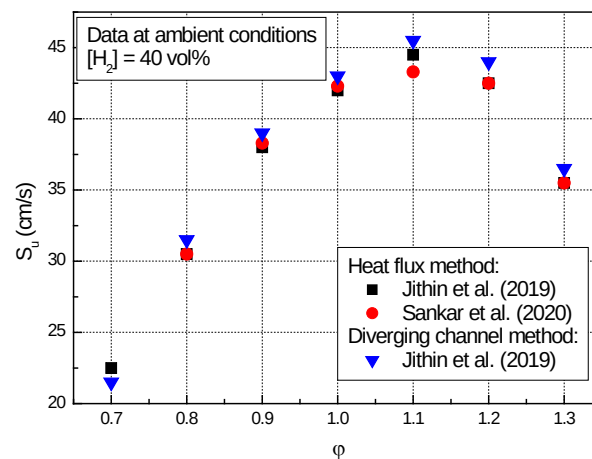


Figure 3. Experimental laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ –air mixtures enriched with 40 vol% H_2 versus the equivalence ratio. Data taken from Jithin et al. [27] and Sankar et al. [28].

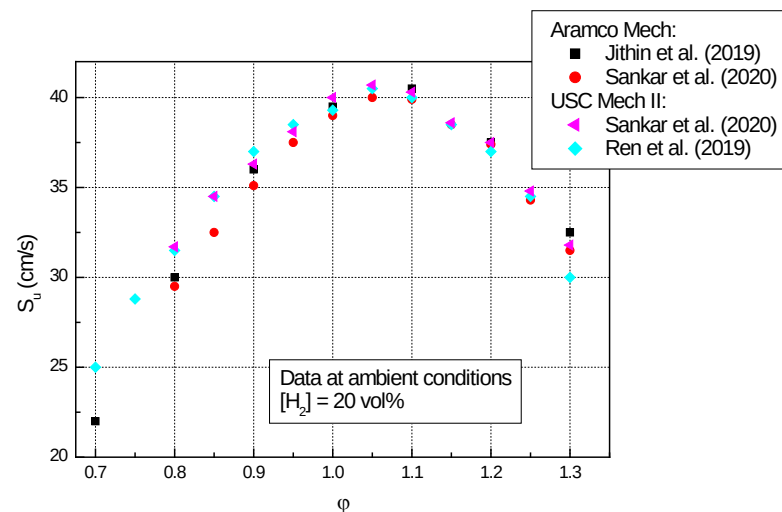


Figure 4. Computed laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ –air mixtures enriched with 20 vol% H_2 versus the equivalence ratio. Data taken from Jithin et al. [27], Sankar et al. [28] and Ren et al. [53].

As shown in Figures 3 and 4, the experimental and computed laminar burning velocities present a typical behaviour when their dependence on the equivalence ratio is studied. It is a parabola having a maximum usually at an equivalence ratio around 1.1–1.2 because of dissociation processes that occur in the flame front.

To express the dependence of the laminar burning velocity upon the equivalence ratio, various expressions have been proposed in the literature [77–80], many of them using polynomial expressions. Marshall et al. [81] found that the quartic polynomial expression gives the best results. Additionally, they concluded that the temperature and pressure dependence of the laminar burning velocity is a function of the equivalence ratio. On the other hand, other researchers have observed that the laminar burning velocity follows the same trend as the adiabatic flame temperature [28] and that the adiabatic flame temperature plays a significant role in the laminar burning velocity [78,82].

Comparing the measured laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ –air flames having various equivalence ratios (obtained at ambient initial conditions) with the computed ones, a good agreement is generally observed. This can be seen in Figure 5, wherein data from measurements and computations with various kinetic mechanisms on $n\text{-C}_4\text{H}_{10}$ –air mixtures enriched with 60 vol% H_2 are given.

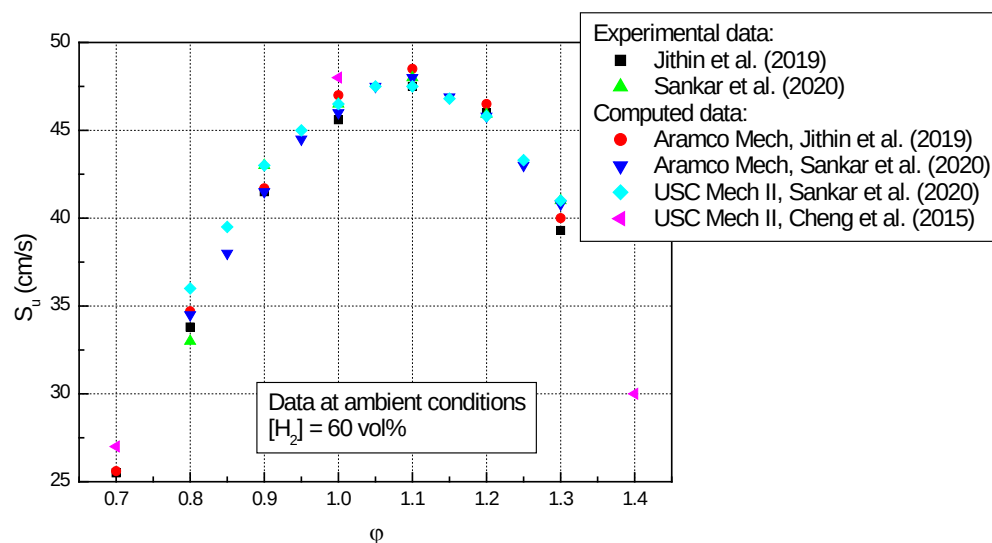


Figure 5. Experimental and computed laminar burning velocities of $n\text{-C}_4\text{H}_{10}$ –air mixtures enriched with 60 vol% H_2 versus the equivalence ratio. Data taken from Jithin et al. [27], Sankar et al. [28] and Cheng et al. [52].

In a recent paper [83], the accuracy of different kinetic mechanisms (GRI Mech 3.0, Aramco Mech 1.3, USC Mech II, HP Mech, etc.) was considered. The authors observed that the mechanism with the highest accuracy for simulating methane–air flames under engine-relevant conditions was Aramco Mech 1.3, but also that the other mechanisms can provide reasonable results that can contribute to a detailed description of combustion processes that occur in fuel–oxidant mixtures, especially when there is no possibility of safe experimentation. Therefore, it is necessary to use computation to fill the gaps that exist, especially those in extreme conditions of high temperatures and pressures, to develop industrial applications.

4.2. Effect of Hydrogen Addition

Over the years, researchers have used various ways to express the hydrogen content of a $n\text{-C}_4\text{H}_{10}$ –air mixture such as the following: hydrogen concentration expressed as % volume [15,27–29,53,55], hydrogen mole fraction (x_{H}) [52], and relative hydrogen ratio (R_{H}) [51,54,73]. However, all these studies showed that the laminar burning velocity increases when more hydrogen is added, regardless of how the amount of hydrogen added to the mixture was expressed [51]. This behaviour is attributed to the change in the thermal diffusivity of the mixture under study, which increases with the amount of hydrogen added to the mixture. For this research, this trend can be seen in Figure 6, wherein the laminar burning velocities collected from experimental measurements versus hydrogen concentration expressed as vol% are plotted. Another set of representative results are given in Figure 7, wherein data obtained from computations are presented.

Data from Figures 6 and 7 refer to results obtained at ambient initial conditions and mixtures with stoichiometric equivalence ratios.

Tang et al. [51] conducted a study on the determination, correlation, and mechanistic interpretation of the effects of hydrogen addition on the laminar burning velocities of hydrocarbon–air mixtures. They noted that, by hydrogen addition, the burning velocity increases due to an easier diffusion of reactive species towards the flame front that occurs at the same time with an increase in the flame temperature. Tang et al. [51] concluded that all these effects are quantified through the adiabatic flame temperature, the effective Lewis number, as well as through the global activation energy.

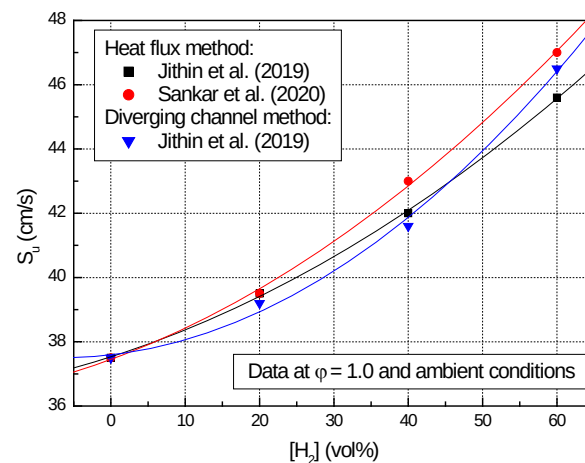


Figure 6. Experimental laminar burning velocities of stoichiometric $n\text{-C}_4\text{H}_{10}$ –air mixtures versus hydrogen concentration expressed as vol%. Data taken from Jithin et al. [27] and Sankar et al. [28].

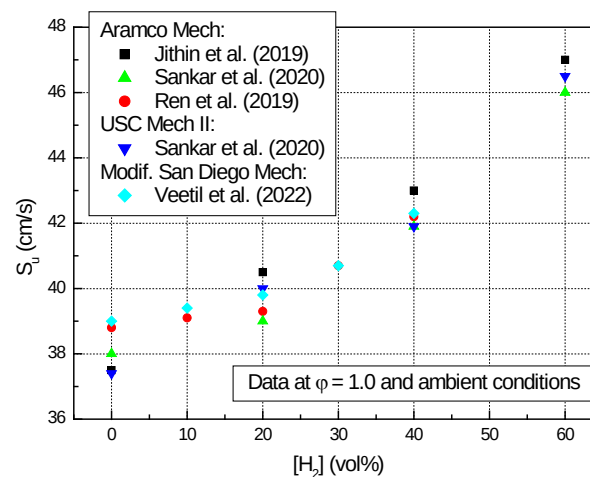


Figure 7. Computed laminar burning velocities of stoichiometric $n\text{-C}_4\text{H}_{10}$ –air mixtures versus hydrogen concentration expressed as vol%. Data taken from Jithin et al. [27], Sankar et al. [28], Veetil et al. [29] and Ren et al. [53].

A recent study [84] conducted on the effects of H_2 and CO_2 on the laminar burning velocities of methane–air flames reported that adding hydrogen to a mixture leads to chain-branching reactions that produce active radicals (O , H , and OH) by the hydrocarbons' oxidation. These chain-branching reactions represent important reactions that determine the burning rate in the case of hydrogen-enriched mixture combustion. Furthermore, Ueda et al. [84] mentioned that adding hydrogen to a fuel–oxidizer mixture also has the advantage of reducing the amount of NO emitted during combustion.

Wang and Liang [85] analysed the sensitivity coefficients of the key elementary reactions of C_3H_8 and $n\text{-C}_4\text{H}_{10}$ involved in the combustion process of hydrogen-enriched LPG–air mixtures. They noted that hydrogen addition promotes the sensitivity coefficient of the elementary reactions and increases the maximum rate of production of the free radicals O , H , and OH .

Increasing the production of the free radicals O , H , and OH leads to an increase in the heat release rate and, thus, an increase in the laminar burning velocity. However, adding hydrogen to n -butane–air mixtures influences not only the production of these free radicals but also the adiabatic flame temperature. This is an important parameter that characterizes the combustion process because it determines the amount of heat from the flame front and also acts on pollutant formation mechanisms [86]. The adiabatic flame temperature increases when the hydrogen content is increased, presenting a trend similar to that of the

laminar burning velocity, as can be seen in Figure 8. It is observed that the peak value of the adiabatic flame temperature shifts to the fuel-rich region as the hydrogen content increases. The same behaviour has been reported by researchers for the laminar burning velocities of other hydrogen-enriched fuel–oxidizer mixtures [52,87,88].

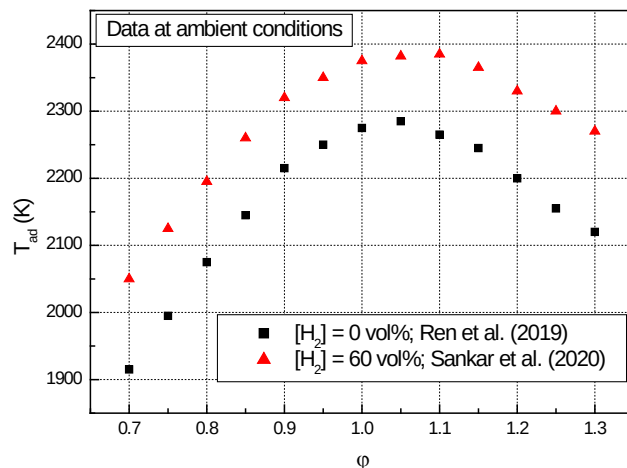


Figure 8. Adiabatic flame temperatures of n -C₄H₁₀–air mixtures and n -C₄H₁₀–air mixtures enriched with 60 vol% H₂ versus equivalence ratio. Data taken from Sankar et al. [28] and Ren et al. [53].

Some of the fundamental combustion characteristics for a premixed flame are the laminar burning velocity, flame temperature, ignition delay time, and flammability limits. Adding hydrogen to hydrocarbons leads to improvements in these combustion characteristics. When the flame temperature increases, an increase in the following is observed [89]: reaction rates, thermodynamic efficiency, heat transfer rates. However, a high flame temperature promotes the production of pollutants (particularly NO) due to the fact that hydrogen oxidation produces many H radicals. H radicals have an important role in NNH intermediate production, which are mainly responsible for NO formation [84]. On the other hand, hotter combustion gases result in such combustions and the cooling losses are higher compared with a low flame temperature. This situation leads, thus, to a decrease in the efficiency of the device in which the combustion occurs [84].

The study undertaken by Aravind et al. [54] focusing on the effect of hydrogen addition on the combustion properties of LPG–air mixtures showed that hydrogen addition improves the burning characteristic of the LPG–air mixture by a linear increase in the laminar burning velocity, independent of the mixture pressure, temperature, or mixture components' fraction. The study conducted by Wei et al. [45] on hydrogen-enriched biogas–air flames also demonstrated this finding. On the other hand, Tutak et al. [44] provided a study on a hydrogen-enriched natural gas mixture and reported that hydrogen addition leads to an increase in maximum combustion pressure and temperature and to an acceleration of the natural gas combustion process.

All these studies showed that hydrogen addition leads to an improvement in the interactions between the reaction zones (and, thus, the flammability limits are extended), an improvement in the combustion stability, a reduction in the laminar flame thickness, a decrease in stretch response, and an increase in adiabatic flame temperature and laminar burning velocity.

Generally, an increase in the laminar burning velocity with an increase in hydrogen amount is due to two major effects [73]: (a) the chemical effect: an increase in hydrogen amount leads to an increase in the active radicals during the combustion process; (b) the thermal effect: adding hydrogen leads to an increase in the adiabatic flame temperature.

Thus, adding hydrogen to a fuel–air mixture leads to an increase in the laminar burning velocity, enhancing the explosion risk of that mixture; therefore, it is necessary that

the high explosive risk of these mixtures be taken into account to avoid unwanted fires and explosions.

4.3. Effect of the Initial Temperature

Usually, in most practical applications, the initial conditions (temperature and pressure) of the combustible mixture are different than ambient conditions; therefore, it is necessary to quantify the effects of these parameters on the laminar burning velocity.

The initial temperature of gaseous fuel–air mixtures represents one of the main parameters that influence the laminar burning velocity. Increasing the initial temperature of these mixtures leads to more stable flame propagation.

Sher and Ozdor [15] and Jithin et al. [27] studied the influence of the initial temperature on the laminar burning velocities of *n*-butane–air mixtures enriched with hydrogen. Sher and Ozdor [15] reported laminar burning velocities for *n*-butane–air mixtures having various equivalence ratios, enriched with a small amount of hydrogen (up to 9.3 vol%) at initial temperatures between 298 and 420 K from measurements with a flat-flame burner. Data collected from this study referring to rich *n*-butane–air mixtures ($\varphi = 1.2$) enriched with hydrogen are presented in Table 6.

Table 6. Laminar burning velocities of *n*-butane–H₂–air mixtures ($\varphi = 1.2$) at various initial temperatures from measurements with a flat-flame burner reported in the literature [15].

[H ₂] (vol%)	<i>S_u</i> (cm/s)		
	T ₀ = 300 K	T ₀ = 360 K	T ₀ = 420 K
0	40.9	59.4	85.8
1.4	46.2	68.2	96.8
2.7	50.6	77.0	105.6
4.1	55.0	83.6	116.6

Jithin et al. [27] used both experiments with the diverging channel method and computation using a dedicated program to obtain the laminar burning velocities of *n*-butane–air flames enriched with hydrogen having initial temperatures up to 450 K. Data collected from this study referring to the stoichiometric *n*-butane–air mixtures enriched with hydrogen are presented in Table 7.

Table 7. Laminar burning velocities of stoichiometric *n*-butane–H₂–air mixtures at various initial temperatures from measurements with the diverging channel method and computation reported in the literature [27].

[H ₂] (vol%)	<i>S_u</i> (cm/s)					
	T ₀ = 300 K		T ₀ = 360 K		T ₀ = 420 K	
	Exp.	Comp.	Exp.	Comp.	Exp.	Comp.
0	37.5	37.5	-	50.0	68.0	65.5
40	41.6	43.0	62.0	57.5	-	72.0

All data from Tables 6 and 7 were obtained at ambient initial pressure. As can be seen, there is an increase in laminar burning velocity as the initial temperature increases, as long as the initial composition and pressure are kept constant. Gas preheating influences the burning velocity through the flame temperature, which varies with the initial temperature and through the change in the overall reaction rate. Indeed, the temperature increase boosts the dissociation reactions that produce free radicals, thus initiating the combustion reaction [90].

Generally, there are three paths for the initial temperature to influence the laminar burning velocity [76]:

(a) Through the reaction rate and the flame temperature. Increasing the initial temperature leads to an increase in the flame temperature and, thus, the reaction rate is accelerated, resulting in an increase in the laminar burning velocity;

(b) Through the change in density. Increasing the initial temperature leads to an increase in the laminar burning velocity through a decrease in density;

(c) Through the transport property of the mixture. The transport property parameters (e.g., the heat conductivity) depend on the initial temperature.

The temperature dependence of the laminar burning velocity is usually expressed as:

$$S_u = S_{u,ref} \left(\frac{T}{T_{ref}} \right)^\alpha \quad (1)$$

In Equation (1), $S_{u,ref}$ represents the reference value of the laminar burning velocity at $T = T_{ref}$ and α represents the thermal coefficient of the laminar burning velocity, calculated by non-linear regression analysis of the data. In most cases, $T_{ref} = 298$ K.

For *n*-butane–air mixtures enriched with hydrogen, it was observed [27] that the thermal coefficient (α) reaches a minimum value at an equivalence ratio of around 1.1. This is the same value of the equivalence ratio where the maximum value of the laminar burning velocity is reached. Beyond this minimum value, the thermal coefficient increases for both lean and rich compositions. For various hydrogen amounts, this coefficient decreases as the amount of hydrogen in the mixture increases. This behaviour can be observed in Table 8, where results obtained for a stoichiometric *n*-butane–H₂–air mixture at ambient initial pressure are presented. For comparison, the thermal coefficients of stoichiometric H₂–air [91] and *n*-butane–air [26] mixtures are also given. It is observed that the highest value of this parameter is obtained in the case of *n*-butane–air mixtures.

Table 8. Thermal coefficients (α) of stoichiometric *n*-butane–H₂–air mixtures at ambient initial pressure reported by researchers.

Mixture	α	Reference
C ₄ H ₁₀ –air	1.61	[26]
C ₄ H ₁₀ –H ₂ –air (20 vol% H ₂)	1.45	[27]
C ₄ H ₁₀ –H ₂ –air (40 vol% H ₂)	1.37	
C ₄ H ₁₀ –H ₂ –air (60 vol% H ₂)	1.27	
H ₂ –air	1.40	[91]

4.4. Effect of the Initial Pressure

The initial pressure is another important parameter affecting the laminar burning velocity of a given fuel–oxidizer mixture. For *n*-butane–H₂–air mixtures, only data reported by Sung et al. [73] obtained from computations with the GRI Mech 1.2 mechanism are available in the literature. Naturally, a decrease in the laminar burning velocity is observed as the initial pressure increases. This behaviour is presented in Table 9, where data collected from [73] referring to stoichiometric *n*-butane–H₂–air mixtures at various initial pressures are given.

Regarding the decrease in the laminar burning velocity as the initial pressure increases, Zhang et al. [92] noted in their study that an increase in initial pressure significantly reduces the amounts of O, H, and OH free radicals within the flame front and, thus, a decrease in the flame propagation velocity under high pressure occurs. On the other hand, as the initial pressure increases, an increase in unburned gas mixture density occurs, and this is another reason for the laminar burning velocity decrease [93].

Table 9. Laminar burning velocities for stoichiometric *n*-butane–H₂–air mixtures having various initial pressures; data from computation [73].

[H ₂] (vol%)	<i>S_u</i> (cm/s)	
	<i>p</i> ₀ = 1 bar	<i>p</i> ₀ = 20.3 bar
0	43.0	16.3
1.6	44.0	17.3
3.3	47.0	18.0
4.9	49.0	18.7

The pressure dependence of the laminar burning velocity is usually expressed as:

$$S_u = S_{u,ref} \left(\frac{p}{p_{ref}} \right)^\beta \quad (2)$$

In Equation (2), *S_{u,ref}* represents the reference value of the laminar burning velocity at *p* = *p_{ref}* and β represents the baric coefficient of the laminar burning velocity, calculated, similar to the thermal coefficient of the laminar burning velocity, by non-linear regression analysis of the data. Usually, *p_{ref}* is considered 1 bar.

Representative values of the baric coefficients of the laminar burning velocities of stoichiometric *n*-butane–H₂–air mixtures [54] at ambient initial temperature are given in Table 10. Here, data referring to stoichiometric H₂–air [91] and *n*-butane–air [26] mixtures are also given.

Table 10. Baric coefficients (β) of stoichiometric *n*-butane–H₂–air mixtures at ambient initial temperature reported by researchers.

Mixture	β	Reference
C ₄ H ₁₀ –air	−1.17	[26]
C ₄ H ₁₀ –H ₂ –air	−0.30	[54]
H ₂ –air	0.60	[91]

Although the thermal coefficients of the laminar burning velocities of hydrogen-enriched *n*-butane–air mixtures depend on the hydrogen amount, the baric coefficients do not seem to depend on how much hydrogen is added to a mixture, as was concluded in the study of Aravind et al. [54].

The baric and thermal coefficients are useful inputs in estimating the laminar burning velocity and in the exploration of data consistencies of measured data sets obtained under various initial conditions. Moreover, these parameters obtained from experimental or computed data are important inputs for kinetic models' validation and for checking that the data are not affected by some random or systematic errors [94].

The laminar burning velocities of fuel–air mixtures have high importance in solving the technical problems that appear in the design of gas turbines and venting systems of pressurized vessels, especially when these are obtained at initial temperatures and/or pressures other than those in ambient conditions. Accurate results on laminar burning velocities and other explosion parameters (e.g., maximum explosion pressure, severity factor) are, thus, important features necessary to enable the safe operation of different chemical or domestic processes.

5. Challenges and Future Perspectives

Many practical applications imply initial temperatures and pressures other than those in ambient conditions. Therefore, an important direction for researchers in the combustion

field involves improving the existing data base, referring to laminar burning velocities and other combustion parameters (flammability limits, peak pressures, severity factors, pressure rise rates) at elevated temperatures and pressures.

As one can see, the literature here shows a paucity of investigations on the laminar burning velocities of hydrogen-enriched n -C₄H₁₀–air mixtures at initial temperatures and pressures different from those in ambient conditions. Therefore, the most obvious future perspectives of this study are represented by the need to carry out some experimental and theoretical investigations of these flames at sub-atmospheric pressures and at elevated pressures and temperatures.

Additionally, it was observed that the laminar burning velocities of a given n -butane–H₂–air mixture under the same experimental conditions reported by different groups of researchers can lead to some uncertainties. Therefore, a systematic investigation of the effects of pressure, temperature, equivalence ratio, and hydrogen content on all propagation properties of these mixtures (maximum explosion pressures, maximum rates of pressure rise, severity factors, laminar burning velocities) is useful in assigning accurate results.

Moreover, optimization and improvement of the methods for testing laminar burning velocities, of the devices with which they are determined (e.g., burners, closed or partially closed vessels), of the equations involved in their calculation, and of flame propagation monitoring systems (e.g., high-speed cameras, ionization probes) would be beneficial for obtaining results with higher accuracy.

Over the years, results have shown not only discrepancies between experimental results obtained for the same initial compositions and conditions, but also between theoretical results provided by different kinetic modelling packages. Therefore, developing new kinetic mechanisms able to lead to better results, especially at initial temperatures and pressures other than those in ambient conditions, is indispensable.

Given these discrepancies between experimental and theoretical results, more collaboration is needed between researchers using testing methods and those using computations to establish the cause of discrepancies in laminar burning velocities and to better understand combustion processes.

The utilization of hydrogen-enriched gaseous mixtures raises another issue: the amount of hydrogen added to mixtures is not constant; it fluctuates from one application to another. These fluctuations lead to difficulties in the prediction of flame stability and laminar burning velocity that could influence the combustion performance of the devices in which the combustion occurs. Therefore, precise measurements and modelling are required to improve the combustion performance of burners, internal combustion engines, power systems, etc.

On the other hand, considering the fact that hydrogen is not found in its natural state in nature and must be produced, new production methods that allow its large-scale manufacturing (implying minimal production costs, low pollutants emissions, and high safety) are required.

An important amount of the energy we consume comes from burning fossil fuels. Actual trends in energy supply take into account the transition to alternative, cleaner fuels, such as hydrocarbons and hydrogen-enriched gaseous fuels, thus replacing conventional fossil fuels. These alternative fuels provide, among other improvements, low CO₂ emissions, high efficiency, and smooth combustion. However, the risk of unwanted fires or explosions is high due to their high flammability. Therefore, these issues lead to challenges regarding the safe handling, storage, and transportation of these alternative fuels. On the other hand, another important issue is represented by the production, storage, and transportation costs of these new alternative fuels.

Taking into account these aspects, a general conclusion that could be drawn is that further research is needed to solve all these problems.

6. Conclusions

The main objective of this work was to review the available literature regarding the laminar burning velocities of hydrogen-enriched *n*-butane–air mixtures. The laminar burning velocities obtained by researchers from experimentation and computation were discussed and analysed against the equivalence ratio, hydrogen amount, and initial temperature and pressure. The conclusions that can be drawn from this study can be summarized as follows:

- The laminar burning velocity of hydrogen-enriched *n*-butane–air mixtures has a typical behaviour characteristic for hydrocarbon–air mixtures regarding its variation with the equivalence ratio;
- The experimental laminar burning velocities of *n*-C₄H₁₀–air mixtures having various equivalence ratios (between 0.5–1.5), obtained at ambient initial conditions by various experimental techniques, agree quite well with the computed ones obtained using different kinetic mechanisms;
- At ambient initial conditions and various equivalence ratios, a scattering of the computed data was observed due to the different kinetic mechanisms involved in computations;
- At constant initial temperature, pressure, and *n*-butane–air equivalence ratio, hydrogen addition leads to an increase in adiabatic flame temperature and in laminar burning velocity; e.g., for a stoichiometric mixture with only 4 vol% H₂, the laminar burning velocity increases from 55.0 cm/s at 300 K to 116.6 cm/s at 420 K;
- For stoichiometric mixtures at ambient initial conditions, hydrogen addition increases the laminar burning velocity (either experimental or computed) from around 36 cm/s (mixtures without H₂) to around 46 cm/s (mixtures with 60 vol% H₂);
- Increases in the laminar burning velocity with increased hydrogen addition is due to the chemical effect, on one hand, and to the thermal effect, on the other hand;
- When hydrogen is added to a mixture, the production of the free radicals O, H, and OH leads to an increase in the heat release rate and, thus, to an increase in laminar burning velocity;
- At constant mixture composition and pressure, the laminar burning velocities of hydrogen-enriched *n*-butane–air mixtures increase with an increase in the initial temperature;
- The initial temperature influences the laminar burning velocity through the following: (a) the reaction rate and flame temperature; (b) the change in density; (c) the transport property of the mixture;
- The revised data showed a discrepancy between experimental and calculated laminar burning velocities obtained at various initial temperatures between 300 and 420 K;
- The thermal coefficients of stoichiometric *n*-butane–H₂–air mixtures at ambient initial pressure decrease with an increase in hydrogen amount from 1.45 (mixture with 20 vol% H₂) to 1.27 (mixture with 60 vol% H₂);
- At constant mixture composition and temperature, the laminar burning velocities of hydrogen-enriched *n*-butane–air mixtures decrease with an increase in the initial pressure; e.g., for a stoichiometric mixture with 5 vol% H₂, the laminar burning velocity decreases from 49.0 cm/s at an initial pressure of 1 bar to 18.7 cm/s at an initial pressure of 20 bar;
- An increase in initial pressure significantly reduces the amounts of free radicals (O, H, and OH) within the flame front and, thus, the flame propagation velocity decreases.

Given the fact that the mixtures under study have recently been used in micro-combustors, accurately measured or computed laminar burning velocities are necessary in the validation of kinetic mechanisms as well as in the design, testing, and performance of *n*-C₄H₁₀–H₂-fuelled devices.

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