

## Article

# Flammability Properties of the Pyrolysis Gas Generated from Willow Wood

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**Abstract:** Willow wood presents a real interest for biomass pyrolysis due to its fast growth, renewability, and high energy density. Following the pyrolysis of willow wood in an inert atmosphere, a multi-fuel gaseous mixture was obtained, with the following composition (by volume): 38.20% CO/21.87% H<sub>2</sub>/17.44% CH<sub>4</sub>/1.15% O<sub>2</sub>/17.15% CO<sub>2</sub>/4.19% N<sub>2</sub>. The propagation of laminar premixed flames in these *multifuel* mixtures with air was investigated numerically for initial temperatures from 298 to 500 K, initial pressures from 1 to 20 bar, and fuel equivalence ratios between 0.60 and 2.00. The combustion of these gaseous mixtures as free laminar premixed flames was simulated by means of the INSFLA package and an extended reaction mechanism with 592 elementary reactions and 53 species. The modelling of the gas-phase combustion delivered several important parameters: the laminar burning velocities,  $S_{li}$ , the maximum flame temperatures,  $T_{fl,max}$ , the flame front thicknesses,  $d_{fl}$ , and the peak concentrations of the main reaction intermediates. The obtained parameters, discussed in correlation with the initial pressure and temperature, afforded the determination of the overall activation parameters of *multifuel* oxidation with air.

**Keywords:** multifuel; laminar burning velocity; flame temperature; flame front thickness



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## 1. Introduction

Willow wood is an excellent choice for biomass pyrolysis due to its fast growth, renewability, and high energy density. This process involves heating the willow wood to high temperatures in an oxygen-free environment, often an inert atmosphere, leading to the thermal decomposition of the wood and the generation of solid, liquid, and gaseous biofuels. Biochar (the solid product) is a carbon-rich material that can enhance soil fertility, while bio-oil (the liquid product) is a dark brown liquid that can be utilized as a fuel or chemical feedstock. The gaseous product is a mixture of carbon monoxide, hydrogen (known also as syngas), and other gases that can be employed as a fuel for power generation or as a chemical feedstock. The composition of this gaseous product varies considerably depending on the pyrolysis conditions and the feedstock type [1].

The use of biofuels as alternative energy sources has been increasing in recent years, as they are seen as a more sustainable and environmentally friendly alternative to traditional fossil fuels. However, the use of complex fuel mixtures in power generation, automotive industries, and aviation transportation raises concerns about the chemical and safety aspects of their combustion. As a result, researchers have been focusing more on the study of the safety aspects of complex fuel mixtures.

A key parameter that is of particular interest in the design of industrial processes is the laminar burning velocity ( $S_{li}$ ). This parameter condenses several pieces of information about the reactivity and the exothermicity of the system, which are critical factors in

ensuring the safe and efficient use of these alternative fuels [2]. The laminar burning velocity is a measure of the rate at which a flame front travels through a combustible mixture in the absence of turbulence. This parameter is essential for designing and optimizing combustion processes, as it influences the rate of energy release, the flame stability, and pollutant emissions. Therefore, the laminar burning velocity is a critical parameter for the design of industrial processes, as it helps to ensure that the combustion process is both efficient and safe.

There is a wealth of burning velocity information in the literature, which includes data obtained from simulations as well as experimental studies involving various fuels under different operating conditions. The experimental studies can be divided into two groups. The first group includes measurements conducted on stationary flames, such as Bunsen burners, or a derivative of that method. The second group involves measurements conducted on non-stationary flames in tubes, and later in low-aspect closed vessels. Regardless of the techniques employed, numerous studies have been conducted on CH<sub>4</sub> [3–5] and CH<sub>4</sub>/H<sub>2</sub> [6–8], on binary mixtures such as CH<sub>4</sub>/CO [9], natural gas/H<sub>2</sub> [8], and CO/H<sub>2</sub> [10–14], and on ternary mixtures [15]. Experimental laminar burning velocity data for multi-fuels with four components (CO/CO<sub>2</sub>/H<sub>2</sub>/N<sub>2</sub>) have been provided by Varghese and Kumar [16], and those with five components (H<sub>2</sub>/CO/CO<sub>2</sub>/CH<sub>4</sub>/N<sub>2</sub>) have been provided by Oliveira et al. [17].

Studies on the laminar burning velocity of mixtures that may have in their composition some of H<sub>2</sub>/CO/CH<sub>4</sub>/O<sub>2</sub>/N<sub>2</sub>/CO<sub>2</sub> at variable concentrations are presented in the literature by Di Benedetto et al., Kobayashi et al., Basco et al., Francisco et al., and Zhang et al. [18–23], and studies on the laminar burning velocity of liquid fuels obtained from the pyrolysis of biomass (e.g., rice husk) at high initial pressures and temperatures are presented by Xu et al. [24,25]. From the study by Di Benedetto et al. [18] on CH<sub>4</sub>/O<sub>2</sub>/N<sub>2</sub>/CO<sub>2</sub> and H<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub>/CO<sub>2</sub> mixtures, it was observed that the presence of CO<sub>2</sub> has a strong influence on the whole process, through the specific heat of the mixtures (leading to a decrease in the flame temperature and burning velocity) and through the chemical kinetics of the process. A study on the fuel composition and initial pressure influences on the laminar flame speed of H<sub>2</sub>/CO/CH<sub>4</sub> bio-syngas was presented by Zhou et al. [26].

Earlier research has indicated that the laminar burning velocity of syngas in air is notably affected by the presence of hydrogen in the fuel mixture, owing to its superior laminar burning velocity when combusted with air in comparison to conventional gaseous fuels [27,28]. Furthermore, the introduction of diluents, such as nitrogen and carbon dioxide, to the fuel mixture can significantly reduce the laminar burning velocity due to the inerting properties of these gases [28–30]. A study about explosions of syngas/CO<sub>2</sub> mixtures in oxygen-enriched air was presented by Salzano et al. [31].

The aim of the present paper is to calculate the laminar burning velocities at various initial conditions (temperature, pressure, and composition) for *multifuels* obtained from the pyrolysis process of willow wood (temperature of the pyrolysis process: 800 °C). The experiments were carried out in a fed-batch reactor under nitrogen atmosphere. The data referring to experimental pyrolysis methods applied to the current research study have already been detailed by Ionescu et al. [32]. Therefore, here, only the obtained results concerning the gaseous phase (obtained following the process of the pyrolysis of willow wood at a temperature of 800 °C) will be presented and discussed. The work focuses mainly on the gas resulting from pyrolysis. The composition of the gaseous mixture obtained by the pyrolysis processes of willow wood, experimentally determined by GC, is the following: [CO] = 38.20 vol%; [H<sub>2</sub>] = 21.87 vol%; [CH<sub>4</sub>] = 17.44 vol%; [O<sub>2</sub>] = 1.15 vol%; [CO<sub>2</sub>] = 17.15 vol%; and [N<sub>2</sub>] = 4.19 vol%. Along with these, other components were observed in very small concentrations, which were neglected. In the paper, this mixture was named: “*multifuel A*”. Other *multifuels* obtained by willow wood pyrolysis have close compositions in relation to *multifuel A*, so their behavior was not considered of interest for the present paper.

## 2. Computing Program and Methodology

The laminar burning velocities characteristic for the free laminar premixed flames of gaseous mixtures was computed by the package INSFLA, developed by Warnatz, Maas, and coworkers [33–35], for the simulation of flame propagation in fuel–air mixtures, under various conditions. The present case examined premixed laminar free flames under radiative energy losses. The mechanism CH4-C4, using 53 chemical species which participate in 592 elementary reactions [34], was run, using updated values of several rate coefficients for rate-limiting reactions of propane–air oxidation, as given by Heghes [36]. The runs were performed for the combustion of the *multifuel* (a mixture named *multifuel A*) with air at various initial pressures from 1 bar to 20 bar and various initial temperatures from 298 K to 500 K. As input data, the thermochemical properties of chemical species, as given in [37], were used; their transport coefficients were calculated according to [35].

## 3. Results and Discussion

The results of calculations delivered by the INSFLA package on premixed laminar flames of *multifuel A* with air, at different initial conditions (concentration, pressure, temperature), taking into account radiative losses, are shown in Figures 1 and 2. The data were plotted against the equivalence ratio,  $\varphi$ , defined as:

$$\varphi = \frac{[\text{fuel}]}{[\text{oxygen}]} / \left( \frac{[\text{fuel}]}{[\text{oxygen}]} \right)_{\text{st}} \quad (1)$$

where the index “st” refers to a stoichiometric mixture, whose components (fuel (*multifuel A*) and oxygen) burn completely to CO<sub>2</sub> and H<sub>2</sub>O.

Figure 1 shows the influence of the initial temperature,  $T_0$ , and equivalence ratio,  $\varphi$ , on: (a) laminar burning velocities,  $S_u$ , (b) the flame temperature,  $T_{fl,max}$ , and (c) the flame front thickness,  $d_{fl}$ , of the mixture between *multifuel A* and air at  $p_0 = 1$  bar, while Figure 2 shows the influence of the initial pressure,  $p_0$ , and equivalence ratio,  $\varphi$ , on: (a) laminar burning velocities,  $S_u$ , (b) the flame temperature,  $T_{fl,max}$ , and (c) the flame front thickness,  $d_{fl}$ , of the same mixture at  $T_0 = 298$  K.

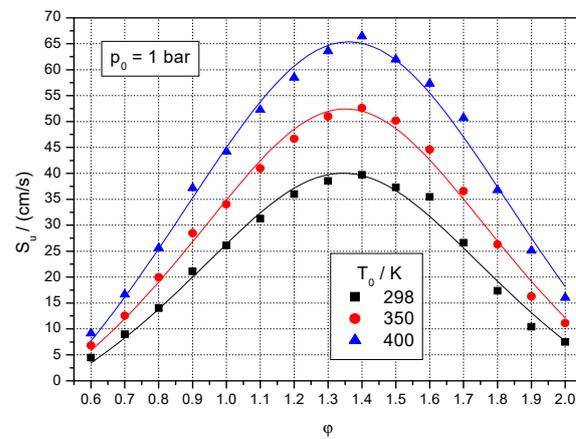
The normal burning velocity is influenced by the initial conditions of the flammable mixture (concentration, temperature, and pressure). The peak burning velocity  $S_{u,max}$  was obtained at the same composition ( $(\text{multifuel A}) = 30.1\text{--}31.6$  vol%;  $\varphi = 1.30\text{--}1.40$ ) for all initial temperatures and/or pressures. The variation in the burning velocity of *multifuel A* with air, at different concentrations, pressures, and initial temperatures, can be seen in Figures 1a and 2a. As the initial pressure increases, a decrease in the burning velocities is observed, and as the initial temperature increases, an increase in the burning velocities is observed.

The variation in the maximum temperatures in the flame front  $T_{fl,max}$ , as a function of the concentration of the studied mixture in air at different initial pressures and temperatures, is represented in Figures 1b and 2b. It can be observed that the maximum temperature in the flame front,  $T_{fl,max}$ , reaches the highest value in the field of the most reactive mixtures close to the equivalence ratio  $\varphi = 1.10$ . The values of maximum temperatures in the flame front register higher values with the increase in the initial pressure, while the initial temperature has a less significant influence on  $T_{fl,max}$ .

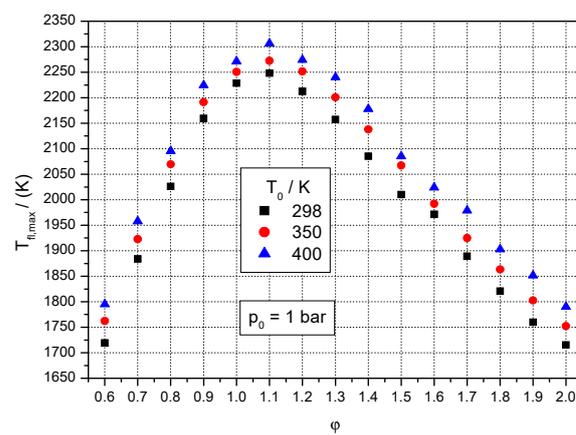
In Figure 1b, the ratio  $(T_{fl,max})_{400\text{ K}} / (T_{fl,max})_{298\text{ K}}$  was 1.019 for the stoichiometric mixture. In Figure 2b, the ratio  $(T_{fl,max})_{10\text{ bar}} / (T_{fl,max})_{1\text{ bar}}$  was 1.016 for the same mixture.

Similar to the burning velocity and the flame temperature, the flame front thickness,  $d_{fl}$ , depends on the initial conditions of the flammable mixture (concentration, temperature, and pressure). The variation in the flame front thickness as a function of the initial temperature at different initial pressures of *multifuel A* with air at different equivalence ratios is represented in Figures 1c and 2c. The lowest values of the flame front thickness  $d_{fl}$  are observed in the range of rich mixtures ( $\varphi = 1.30\text{--}1.40$ ) depending on the initial pressure. With the increase in the initial pressure, a decrease in the values of the flame front thickness is observed, and the same behavior is also found in the case of an increase in the

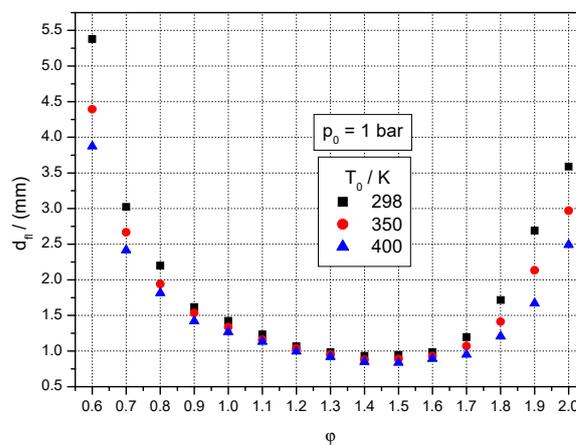
initial temperatures, i.e., the thickness of the flame front decreases with the increase in the initial temperature.



(a)

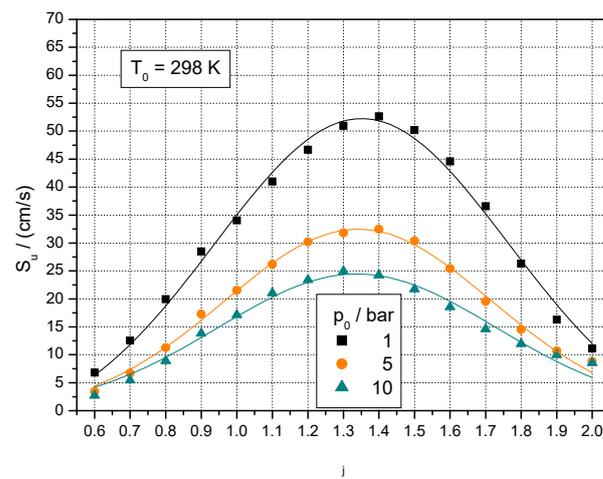


(b)

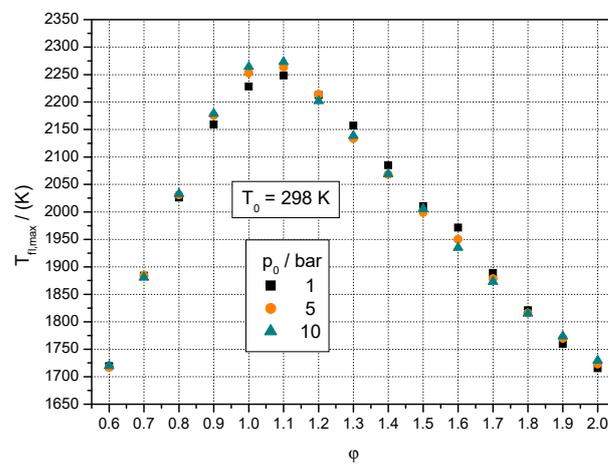


(c)

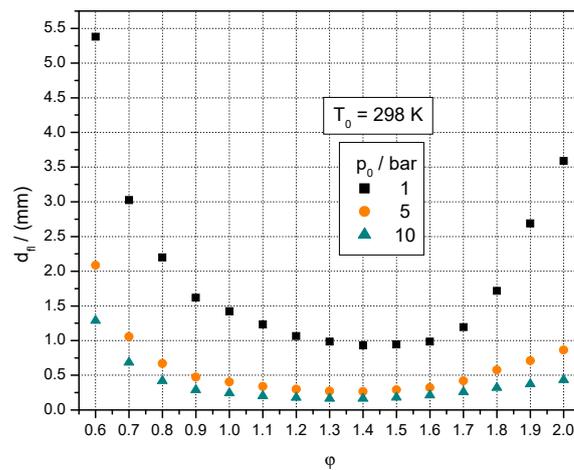
**Figure 1.** The influence of initial temperature,  $T_0$ , and equivalence ratio,  $\phi$ , on: (a) laminar burning velocities,  $S_u$ , (b) flame temperature,  $T_{fl,max}$ , and (c) flame front thickness,  $d_{fl}$ , of multifuel A with air at  $p_0 = 1$  bar.



(a)



(b)

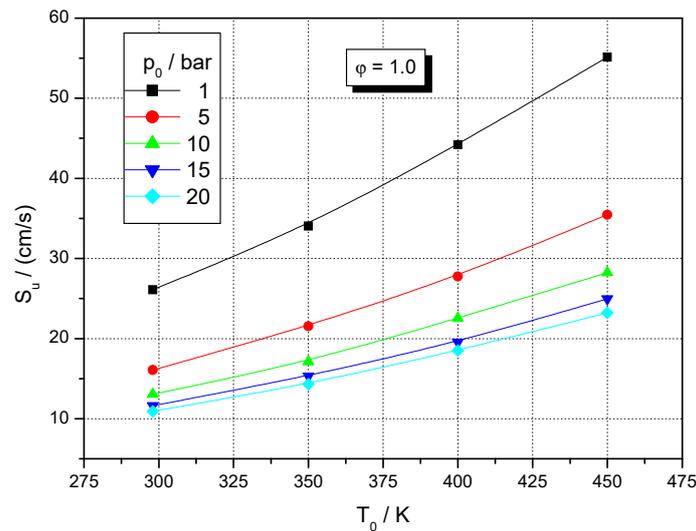


(c)

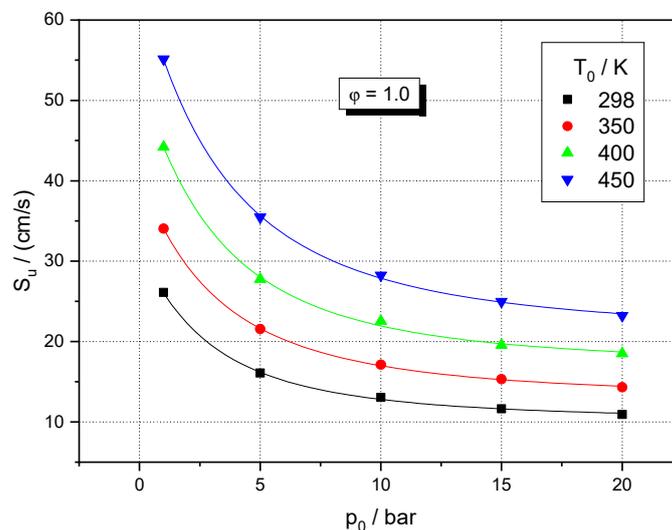
**Figure 2.** The influence of initial pressure,  $p_0$ , and equivalence ratio,  $\phi$ , on: (a) laminar burning velocities,  $S_u$ , (b) flame temperature,  $T_{fl,max}$ , and (c) flame front thickness,  $d_{fl}$ , of multifuel A with air at  $T_0 = 298$  K.

The burning velocities obtained for flames at higher initial pressures and temperatures are given in Figure 3 ( $\varphi = 0.9\text{--}1.0$ ) vs. the initial temperatures at various initial pressures ( $p_0$ : 1–20 bar) and in Figure 4 ( $\varphi = 1.0$ ) vs. the initial pressures at various initial temperatures ( $T_0$ : 298–450 K).

The lines in Figures 3 and 4 are the best-fit correlations of the computed burning velocities with the initial pressure or temperature. The burning velocities decrease with the initial pressure increase and increase when the initial temperature increases.



**Figure 3.** Computed burning velocities of *multifuel A* with air mixtures, for 24.7% *multifuel A* concentrations ( $\varphi = 1.0$ ), vs. the initial temperature, at various initial pressures ( $p_0$ : 1–20 bar).



**Figure 4.** Computed burning velocities of stoichiometric *multifuel A* with air mixture (24.73% or  $\varphi = 1.0$ ) vs. the initial pressure, at various initial temperatures ( $T_0$ : 298–450 K).

The dependence of  $S_u$  on the initial pressure of fuel-oxidant mixtures can be described quantitatively in the form of a power law; thereby, the data were analyzed according to the following empirical equation [38,39]:

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

where  $S_{u,ref}$  is the normal burning velocity at  $p_{ref}$ , the reference pressure, and  $\beta$  is the baric coefficient. Choosing  $p_{ref} = 1$  bar as the reference pressure, the baric coefficients of normal burning velocities for mixtures of *multifuel A* with air with different concentrations were calculated by a non-linear regression analysis of  $S_u = f(p)$  data. Some values that are characteristic of these mixtures at various initial temperatures are given in Table 1. The baric coefficients of normal burning velocities for *multifuel A* with air mixtures at different  $T_0$  ( $T_0$ : 298 K, 350 K, 400 K) have values within the range  $-0.283, \dots, -0.385$ . The usual values from the literature for the baric coefficient,  $\beta$ , are between  $-0.500$  and  $-0.120$  for single fuel–air mixtures at 300 K [39–43].

**Table 1.** Baric coefficients ( $-\beta$ ) of normal burning velocities for mixtures of *multifuel A* with air at various equivalence ratios ( $\varphi$ : 0.7–1.6) and different initial temperatures.

$T_0$ (K)	298	350	400
$\varphi$			
0.7	$0.385 \pm 0.002$	$0.374 \pm 0.014$	$0.360 \pm 0.007$
0.8	$0.334 \pm 0.006$	$0.352 \pm 0.002$	$0.331 \pm 0.003$
0.9	$0.311 \pm 0.007$	$0.312 \pm 0.003$	$0.317 \pm 0.009$
1.0	$0.301 \pm 0.001$	$0.293 \pm 0.009$	$0.291 \pm 0.002$
1.1	$0.289 \pm 0.007$	$0.285 \pm 0.007$	$0.283 \pm 0.008$
1.2	$0.300 \pm 0.005$	$0.289 \pm 0.019$	$0.283 \pm 0.014$
1.3	$0.303 \pm 0.012$	$0.304 \pm 0.011$	$0.291 \pm 0.007$
1.4	$0.328 \pm 0.013$	$0.323 \pm 0.023$	$0.323 \pm 0.023$
1.5	$0.349 \pm 0.007$	$0.342 \pm 0.031$	$0.319 \pm 0.023$
1.6	$0.415 \pm 0.011$	$0.368 \pm 0.019$	$0.345 \pm 0.013$

Similarly, the dependence of  $S_u$  on the initial temperature of fuel–oxidant mixtures has the form [40,44,45]:

$$S_u = S_{u,ref} \left( \frac{T}{T_{ref}} \right)^\alpha \quad (3)$$

where  $S_{u,ref}$  is the normal burning velocity at  $T_{ref}$ , the reference temperature, and  $\alpha$  is the thermal coefficient. Using the ambient temperature as the reference, the thermal coefficients,  $\alpha$ , of normal burning velocities for *multifuel A* with air mixtures were calculated by a non-linear regression analysis of  $S_u = f(T)$  data. Some values that are characteristic of the examined *multifuel A* with air at various initial pressures are given in Table 2. The thermal coefficients at  $p_0 = 1$  bar range from 1.66 to 2.31, values within the domain characteristic of hydrocarbon–air mixtures. The usual values for the thermal coefficient  $\alpha$  of  $S_u$  for fuel–air mixtures at 1 bar are between 1.50 and 2.40 [42,43,46,47].

**Table 2.** Thermal coefficients ( $\alpha$ ) of normal burning velocities for mixtures of *multifuel A* with air at various equivalence ratios ( $\varphi$ : 0.70–1.60) and different initial pressures.

$p_0$ (bar)	1	5	10
$\varphi$			
0.7	$2.107 \pm 0.013$	$2.245 \pm 0.096$	$2.309 \pm 0.026$
0.8	$2.018 \pm 0.102$	$2.035 \pm 0.051$	$2.137 \pm 0.065$
0.9	$1.933 \pm 0.043$	$1.913 \pm 0.065$	$1.862 \pm 0.008$
1.0	$1.811 \pm 0.089$	$1.861 \pm 0.023$	$1.886 \pm 0.111$
1.1	$1.754 \pm 0.042$	$1.753 \pm 0.020$	$1.739 \pm 0.005$
1.2	$1.652 \pm 0.021$	$1.779 \pm 0.047$	$1.759 \pm 0.054$
1.3	$1.696 \pm 0.024$	$1.742 \pm 0.015$	$1.829 \pm 0.050$
1.4	$1.745 \pm 0.001$	$1.827 \pm 0.039$	$1.878 \pm 0.080$
1.5	$1.704 \pm 0.077$	$1.937 \pm 0.115$	$1.907 \pm 0.112$
1.6	$1.661 \pm 0.135$	$2.033 \pm 0.038$	$2.210 \pm 0.107$

Both the baric and thermal coefficients depend on the composition of the fuel–oxidant mixtures and on the range of pressures and initial temperatures for which they are determined.

From the variation in the burning velocities against the initial pressure and temperature, the overall kinetic parameters (apparent activation energy and overall reaction order) of the combustion reaction can be determined [39,40,45,48]. These global kinetic parameters are of importance in the CFD (Computational Fluid Dynamics) modeling of explosion propagation under various confinement conditions.

The variation in the calculated burning velocities with the total initial pressure and temperature of *multifuel A*–air flames afforded the determination of the overall activation parameters of the *multifuel*–oxygen reaction occurring under flame conditions. The overall reaction orders,  $n$ , were determined from the baric coefficients,  $\beta$ , of the calculated burning velocities according to the following equation [49]:

$$n = 2(\beta + 1) \quad (4)$$

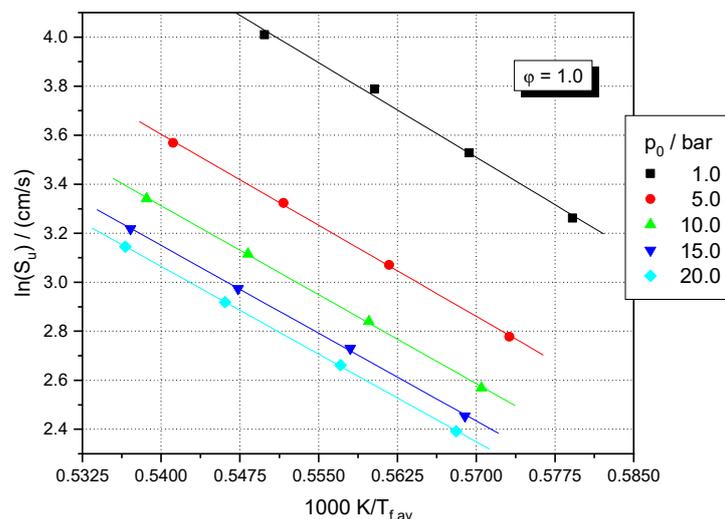
The overall activation energies,  $E_a$ , of the *multifuel A* reaction with oxygen under flame conditions were determined according to the following equation [48]:

$$\ln S_u = \text{const} - \frac{E_a}{2R\overline{T_{f,p}}} \quad (5)$$

where  $\overline{T_{f,p}}$  is the average temperature in the flame front, computed by means of the adiabatic flame temperatures of the isobaric combustion  $T_{f,p}$  [48] as:

$$T_{f,av} = T_0 + 0.74(T_f - T_0) \quad (6)$$

The plots of the computed laminar burning velocities versus the reciprocal adiabatic flame temperatures of stoichiometric *multifuel A* with air mixture (24.73% or  $\phi = 1.0$ ) are given in Figure 5. The slopes of the linear correlations gave the overall activation energies.



**Figure 5.** Computed laminar burning velocities vs. the reciprocal adiabatic flame temperatures of stoichiometric *multifuel A* with air mixture (24.73% or  $\phi = 1.0$ ). Each dataset contains results computed at various initial temperatures and various initial pressures ( $p_0$ : 1–20 bar).

The results characteristic of the studied mixtures of *multifuel A* with air are given in Tables 3 and 4.

The overall reaction orders are only slightly influenced by the initial temperature; they range between 1.23 and 1.43, similar to those of other gaseous fuel–air mixtures: ethylene [50], ethane [45], and propene [51].

Table 4 shows the values of the apparent activation energies of the *multifuel A* with air at different equivalence ratios between  $\varphi$ : 0.70 and 1.60. It is observed that the overall activation energy ranges between 257 and 428 kJ/mol for variable initial pressures between 1 and 10 bar and variable equivalence ratios between  $\varphi$ : 0.70 and 1.60.

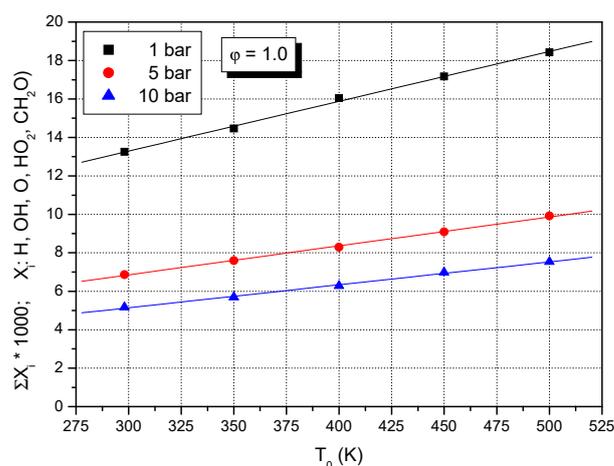
**Table 3.** Overall reaction orders,  $n$ , of *multifuel A* with air mixture at various equivalence ratios ( $\varphi$ : 0.70–1.60) and various initial temperatures ( $T_0$ : 298 K, 350 K, 400 K).

$T_0$ (K)	$n$										
	$\varphi$	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	1.60
298 K		1.23	1.33	1.38	1.40	1.42	1.40	1.39	1.34	1.30	1.17
350 K		1.25	1.30	1.38	1.41	1.43	1.42	1.39	1.35	1.32	1.26
400 K		1.28	1.34	1.37	1.42	1.43	1.43	1.42	1.35	1.36	1.31

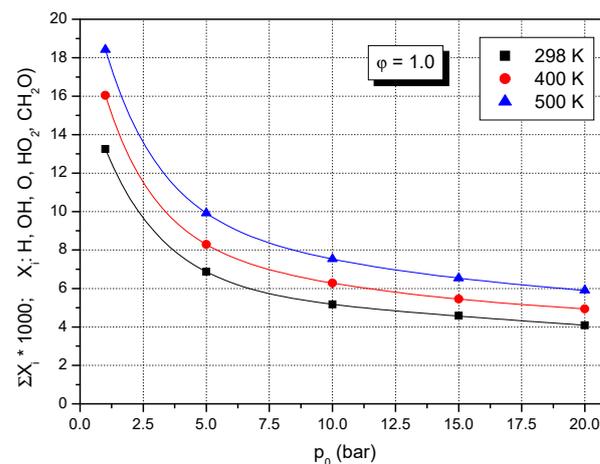
**Table 4.** Overall activation energies,  $E_a$ , of *multifuel A* with air mixture at various equivalence ratios ( $\varphi$ : 0.70–1.60) and various initial pressures ( $p_0$ : 1 bar, 5 bar, 10 bar).

$p_0$ (bar)	$E_a$ (kJ/mol)										
	$\varphi$	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	1.60
1 bar		290	335	374	428	386	339	284	249	258	300
5 bar		304	338	363	412	372	365	306	282	277	311
10 bar		300	329	365	402	384	311	249	302	310	300

Figures 6 and 7 present the sum of the computed peak mass fractions of several reactive species (H, OH, O, HO<sub>2</sub>, CH<sub>2</sub>O) in the flame front of the stoichiometric *multifuel A* with air mixture (24.73% or  $\varphi = 1.0$ ) vs. the initial temperature at various initial pressures (1 bar, 5 bar, and 10 bar) (Figure 6) and vs. the initial pressure at various initial temperatures (298 K, 400 K, and 500 K) (Figure 7). It is observed that, if the initial temperature increases, then the sum of the peak mass fractions of the examined reactive species in the front increases (Figure 6), while if the initial pressure increases, the sum of the peak mass fractions of these species decreases (Figure 7).



**Figure 6.** The sum of the peak mass fractions for several reactive species in the flame front of the stoichiometric *multifuel A* with air mixture (24.73% or  $\varphi = 1.0$ ) vs. the initial temperature, at various initial pressures (1 bar, 5 bar, and 10 bar).



**Figure 7.** The sum of peak mass fractions for several reactive species in the flame front of the stoichiometric *multifuel A* with air mixture (24.73% or  $\phi = 1.0$ ) vs. the initial pressure, at various initial temperatures (298 K, 400 K, and 500 K).

The variations found for the sum of the peak mass fractions of reactive species against temperature or pressure explain the variations observed for the laminar burning velocities against the temperature or pressure of the unburned mixture, reflecting the variations in the reactivity of the examined pyrolysis gas.

The topic of the present paper covers a missing gap in the field, which is the characterization of complex flammable mixtures, formed by *multifuels* and air. In recent decades, the study of alternative and clean fuels has attracted increasing attention with the depletion of fossil fuels and the strengthening of pollutant emission regulations. One of the prospective alternative fuels is the *multifuel* mixture. Such mixture, obtained from renewable sources (biomass), is recognized as one of the most promising alternative fuels. The *multifuel* mixture could be utilized in specific energy devices, such as industry gas turbines and gas engines operated at high pressures and temperatures. Still, such mixtures are poorly characterized, especially from the point of view of combustion with air, at various initial pressures and temperatures. The paper delivers the laminar burning velocities of a *multifuel*–air mixture in these various initial conditions. As a fundamental property for fuel combustion in practical energy devices, the laminar burning velocity is determined by the combined properties of the diffusivity, exothermicity, and reactivity of a fuel. The laminar burning velocity is a key parameter for describing the flame stabilization, extinction limits, flame structures, and velocity.

#### 4. Conclusions

The aim of the present paper was the numerical investigation of flame propagation in the flammable gas-phase mixture of *multifuel A* with air, the *multifuel A* being obtained by the pyrolysis of willow wood in an inert atmosphere at 800 °C. The *multifuel A* composition (by volume) is: 38.20% CO/21.87% H<sub>2</sub>/17.44% CH<sub>4</sub>/1.15% O<sub>2</sub>/17.15% CO<sub>2</sub>/4.19% N<sub>2</sub>. The propagation of the free laminar premixed flames of *multifuel A* with air was examined at initial temperatures between 298 and 500 K, initial pressures between 1 and 20 bar, and fuel equivalence ratios between 0.6 and 2.0. The numerical simulation of these flames used the package INSFLA designed for free laminar premixed flames. The laminar burning velocities,  $S_{fl}$ , maximum flame temperature,  $T_{fl,max}$ , flame front thickness,  $d_f$ , and peak concentrations of the main reaction intermediates were investigated and discussed. Based on the correlations of laminar burning velocities with the initial pressure and temperature, the overall activation parameters (overall activation energy and overall reaction order) of *multifuel A* oxidation with air were reported.

The obtained results could have an impact on the practical use of gaseous products generated from willow wood pyrolysis, since they reveal the influence of operational

parameters (initial pressure and initial temperature) on the laminar burning velocity, which in turn influences the rate of heat release and the composition of burned gases.

The examination of the results delivered the following concluding remarks:

- The influence of process parameters (initial pressure and temperature) on the laminar burning velocities of *multifuel A* mixed with air in various mixtures can be expressed as power law equations, providing a method for modeling these processes. In these equations, the thermal and baric coefficients ( $\alpha$  and  $\beta$ ) of burning velocities correspond to values that are usually characteristic of light hydrocarbons.
- The correlation between the laminar burning velocities of preheated *multifuel A* with the various air mixtures and the average flame temperature allowed for the determination of the overall activation energy. Likewise, the mathematical relationship determined between the combustion velocities and initial pressure of these mixtures at a constant initial temperature allowed for the determination of overall reaction orders. These global parameters (activation energy and reaction orders) provide valuable input data for Computational Fluid Dynamics (CFD) modeling and simulations of flame propagation under various conditions.
- The observed effects of process parameters (initial temperature and pressure) on the maximum flame temperature, the thickness of the flame, and the peak concentrations of main reaction intermediates provide valuable insight into how these parameters affect laminar burning velocities.
- The concentrations of the most important radical species in the flame front that take part in intermediate reactions under the variable initial conditions of pressure, temperature, and concentration were presented. Knowledge of radical species concentrations and of flame adiabatic temperatures, along with the determination of burning velocities, is important because they afford the comparison of experimental data with the predictions of the kinetic scheme.

Future studies should request measurements of the laminar burning velocities of *multifuel A* with air mixtures, which are necessary to validate the computed data from the present paper.

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