

## Article

# Influence of Coniferous Wood Conditioning by Pulsed Electric Field on Its Combustion Heat Characteristics

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**Abstract:** The article presents the impact of sawdust conditioning from coniferous trees with a pulsed electric field (PEF) on the characteristics of the combustion heat. The study used four variants of electric field parameters, i.e., (I) 300 discharges with an electric field intensity of  $25 \text{ kV}\cdot\text{cm}^{-1}$ , (II) 150 discharges with an electric field intensity of  $25 \text{ kV}\cdot\text{cm}^{-1}$ , (III) 300 discharges with an electric field intensity of  $30 \text{ kV}\cdot\text{cm}^{-1}$ , (IV) 150 discharges with an electric field intensity of  $30 \text{ kV}\cdot\text{cm}^{-1}$ . It should be noted that the interval between successive discharges was 10 sec and it was constant for each variant of the experiment. A change in the characteristics of the heat of combustion was found under the influence of a pulsed electric field on sawdust from coniferous trees in each period of the measurement. The highest temperatures were achieved by the interaction of a pulsed electric field with a discharge pulse of  $30 \text{ kV}\cdot\text{cm}^{-1}$  and the number of discharge cycles amounting to 300, whereas significantly lower temperature values were recorded with the discharge electric field intensity of  $25 \text{ kV}\cdot\text{cm}^{-1}$ . It was found that the longest times from the moment of ignition to reaching the maximum temperature were obtained for the material after the influence of PEF with an electric field intensity of  $30 \text{ kV}\cdot\text{cm}^{-1}$  and the number of pulses 300 (IV combination), while the shortest time of the analyzed interval was stated for the first combination of the experiment (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and a number of pulses 150). The use of a pulsed electric field allows modeling the combustion time of a homogeneous material, which enables the improvement of the process control possibilities, and is also important information for the design of devices intended for biomass combustion.

**Keywords:** wood; conifer; pulsed electric field; calorific value



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## 1. Introduction

Currently, in many countries, the production of energy from biomass constitutes the largest share in the structure of the use of renewable energy, and biomass is believed to be most likely to increase the use of this fuel as a source of renewable energy [1–4]. Statistically, biomass is one of the three most important sources of fuel used for generating electricity and thermal applications [2]. Nowadays, many modern technologies are used on a global scale to effectively convert biomass into heat, steam energy, as well as liquid and gaseous biofuels [5–8]. Due to the high potential of wood to be used for commercial biofuel production, it is expected to continuously increase wood resources, especially so-called energy plantations. However, from an economic point of view, these production systems are not financially advantageous, and the clones of trees such as willows and poplars produced by cultivation programs do not grow fast enough to obtain profitable biofuel production [9]. The net amount of biomass in wood depends on the tree species but also on the available amount of solar energy, the amount of energy captured by the plant, the efficiency of photosynthesis conversion or the loss of biomass as a result of plant life processes [10]. The most important parameters characterizing wood and other thermally transformed fuels in terms of their energy use are combustion heat and calorific

value [11,12]. These parameters may differ significantly even within the same fuel, which is affected by many factors, and so, for example, pinewood in air-dry conditions may reach values from  $18.6 \text{ MJ}\cdot\text{kg}^{-1}$  [13] to  $20.54 \text{ MJ}\cdot\text{kg}^{-1}$  [14]. The heat of fuel combustion decreases with increasing water content, which in the case of wood is stored in the cell walls and in the spaces between dead cells [15,16]. When determining the heat of combustion with the use of a calorimetric bomb, the time and temperature of the medium receiving heat from the bomb body are automatically recorded [17]. As a result of this registration, a time–temperature characteristic is created. Measurement of the temperature of individual periods of the combustion process enables to determine the so-called corrected temperature rise needed to estimate the calorific value. In turn, the duration of individual periods is used to determine the so-called amount of heat exchange in the calorimeter, which allows defining the correction for heat exchange between the calorimeter and the thermostat [18].

It should, however, be noted that there are indications suggesting that the characteristics of the heat of combustion can be modified by proper conditioning of the biological material [19–23]. The most popular methods of pretreatment of organic substances include thermal treatments, which, while improving the conditions of mass transfer, simultaneously cause several unfavorable changes in the product, e.g., irreversible changes in color or degradation of biologically active compounds [24–26]. One of the most promising nonthermal pretreatment techniques prior to drying is the use of high voltage pulses that generate a time-varying electric field—pulsed electric field (PEF) [26–28]. The interaction with a pulsed electric field causes changes in the structure of the cell membrane called electroporation, which is a process of creating new or enlarging already existing membrane pores. The perforation of the natural structure of the cell membrane facilitates the diffusion of water and components dissolved in it. This reduces the resistance to mass movement (accelerates many processes, e.g., drying or osmotic dehydration) and improves the extraction conditions [29–31].

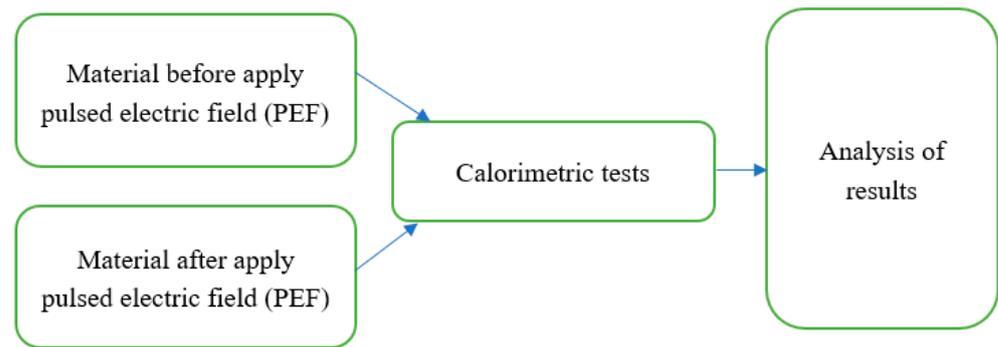
The aim of the presented research was to determine the impact of the pulsed electric field on the characteristics of the combustion heat of the selected biological material and further to determine the combustion curve for each combination of the experiment.

## 2. Materials and Methods

The paper analysis biological material in the form of sawdust from three coniferous trees, i.e., spruce, fir and larch. The sawdust was subjected to a pulsed electric field with an electric field intensity of  $25 \text{ kV}\cdot\text{cm}^{-1}$  in two variants of the number of capacitor discharges, i.e., 150 and 300, an electric field intensity of  $30 \text{ kV}\cdot\text{cm}^{-1}$ , where two variants of the number of discharges were also applied, i.e., 150 and 300. The time between successive discharges amounted to 10 s and was the same for each variant of the electric field intensity and the number of discharges. Research on the heat of combustion and calorific value of biological material was carried out in the Laboratory of Experimental Research Techniques for Biological Products and Raw Materials of the Faculty of Production and Power Engineering at the University of Agriculture in Krakow, accredited by the Polish Center for Accreditation with number AB 1698.

Figure 1 presents a simplified schematic diagram of the conducted experiment. It should be noted that each type of sawdust was also tested in the so-called blank test, in the case of which sawdust was not subjected to the pulsed electric field.

The interaction with the pulsed electric field was conducted on the test stand (Figure 2), which generates a pulsed electric field with an electric field intensity from  $0 \text{ kV}\cdot\text{cm}^{-1}$  to  $30 \text{ kV}\cdot\text{cm}^{-1}$ . The described stand was constructed by ERTEC-Poland, then the device was significantly modified by the authors of this publication due to the specifications of the research carried out. The electric field intensity magnitude adjustment is smooth thanks to the use of a multiturn potentiometer. The energy of a single discharge can be ranged from 18 J to 270 J depending on the magnitude of the electric field intensity and the duration of the discharge.



**Figure 1.** Schematic diagram of the experimental procedure.



**Figure 2.** Ertec Su-1 test stand.

The stand includes a capacitor with a capacity equal 0.25 mF, and the frequency of the generated discharges depends on the interaction electric field intensity and up to  $10 \text{ kV} \cdot \text{cm}^{-1}$ , the frequency of discharges may be at least 1 Hz, while in the case of electric field intensity exceeding  $10 \text{ kV} \cdot \text{cm}^{-1}$ , the minimum frequency of discharges is 0.33 Hz. The station is equipped with proprietary software based on the LabVIEW platform, which allows you to program the sequences of activities and output parameters during the impact of the pulsed electric field on the material collected in the cell and then archives the data.

The material subjected to the pulsed electric field is inserted into an element called a stationary sterilization cell (Figure 3), made of Teflon, in the form of two interconnected cylinders, with the bases of these cylinders made of a material with good electrically conductive properties (stainless steel). The cell has a capacity of 20 mL. After filling it with the test substance, the cell is closed thanks to the applied threaded connection. Then it is placed on the electrode, and the second electrode is lowered onto its opposite base after the discharge chamber is closed.

In the device used, there is the possibility of generating pulses of exponential shape. Figure 4 demonstrates the electrical diagram of the device, and Figure 5 shows the shape of the generated pulses.

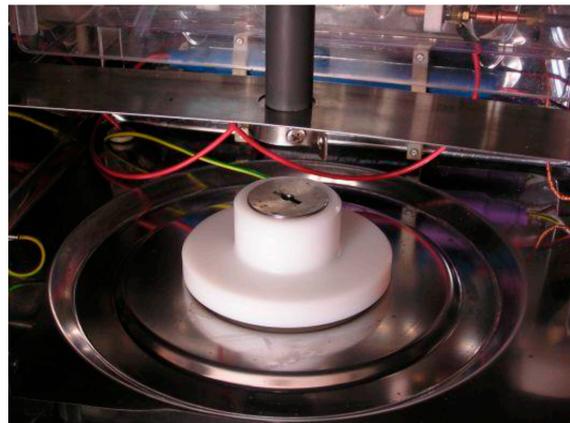


Figure 3. Stationary cell located inside the pulsed electric field (PEF) conditioning chamber.

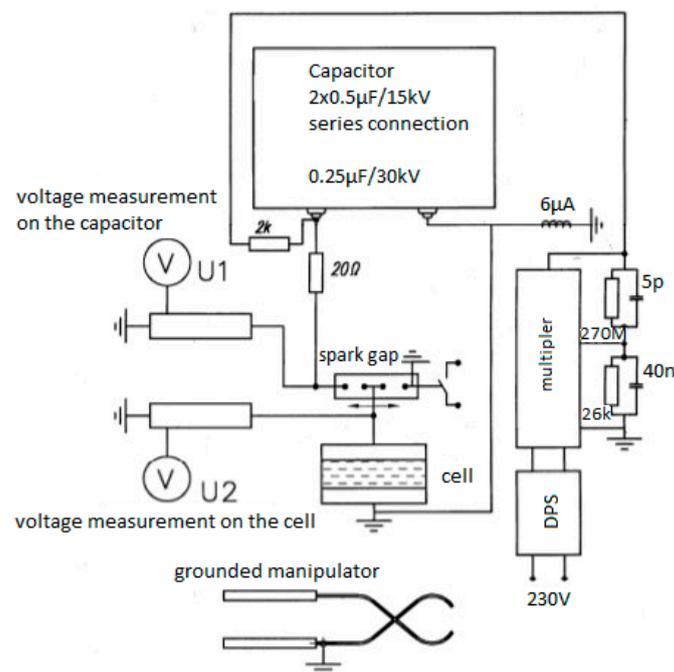


Figure 4. Schematic diagram of an electrical system for generating PEF pulses with an “exponential” shape [32].

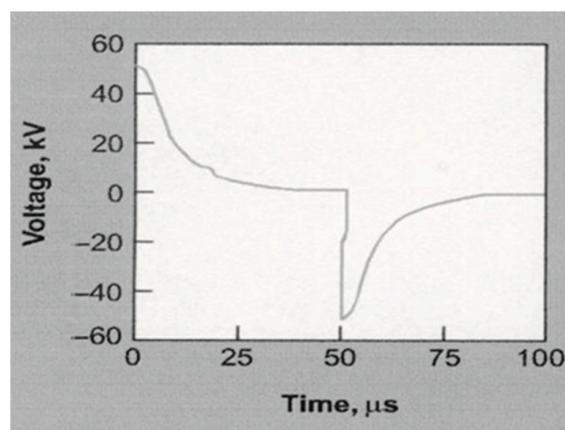
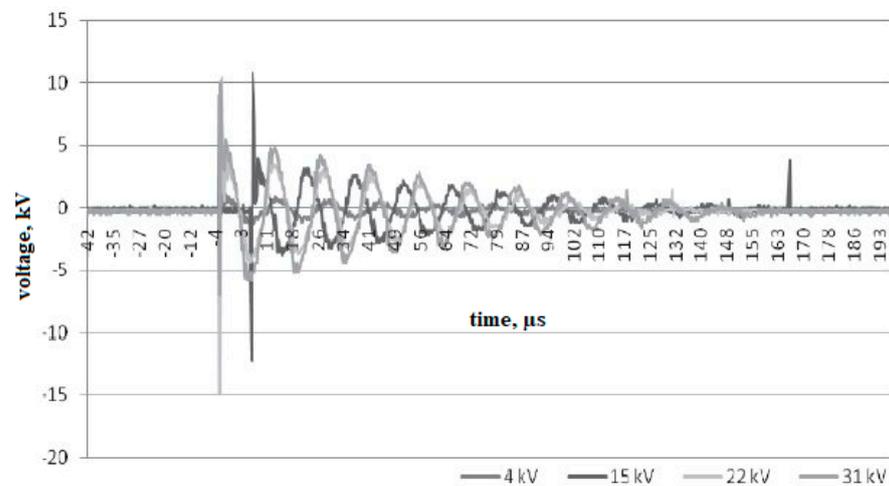


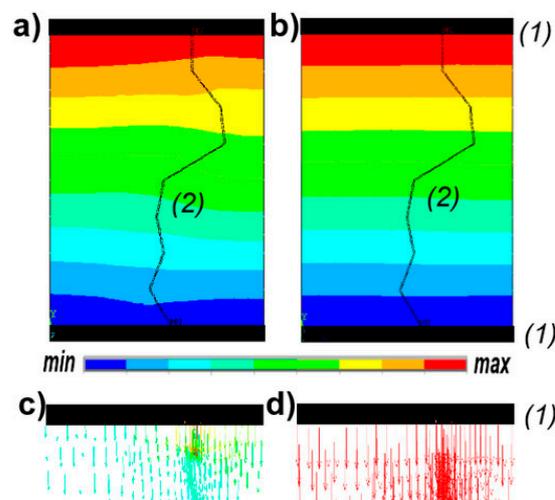
Figure 5. The assumed shape of a bipolar “exponential” pulse [32].

The electrical properties of the station in question were tested with the use of the polish Twelve Electric company AS3-mini-network parameter analyzer, equipped with a RIGOL Technologies DS1204B three-phase digital oscilloscope for recording voltage and current waveforms. On the basis of the collected results, it was determined that the average energy consumption for generating a single impulse is 65.6 mJ. During the tests, values ranging from 56.5 mJ to 71.3 mJ were measured, and the determined value of the coefficient of variation was 6.9%. During the measurements of the parameters of the generated high voltage pulse, the value of the initial electric field intensity was changed in the range from 4 to 30 kV·cm<sup>-1</sup>. The recorded waveforms are summarized in Figure 6. The recorded waveforms present the oscillating course of changes in the voltage value of the generated pulse. Its initial amplitude depends on the adopted voltage that triggers the pulse. The time during which the oscillations of the generated impulse were suppressed for all tested impulses amounted to approx. 150–160 μs.



**Figure 6.** Voltage pulse as a function of time changes depending on the voltage [32].

Figure 7 presents the visualization made in ANSYS [33], and in particular: distribution of the electric potential in the range from 0 kV to 30 kV (a,b) and the gradients of electric field intensity (c,d) in the vicinity of electrodes (1) for the break time value of 0.5 s (a,c) and 1 s (b,d) from previous discharge. It also demonstrates the figure geometry of the previous discharge channel (2).



**Figure 7.** Electric potential distribution (a,b) and electric field gradients (c,d) distribution for nonlinear parameters ( $\epsilon$ ,  $\rho$ ) after 0.5 s (a,c) and 1 s (b,d) from previous discharge. 1—electrode; 2—geometry of previous discharge channel [33].

Before the samples were placed in the chamber of the Ertec Su-1 stand, the standardized material was stabilized in accordance with the EN 14780:2011 standard (tested material was unified and brought to the air-dry state). Then, within each species of wood, two groups were distinguished, one of which was the so-called control test, where the pulsed electric fuel was not applied, while the other was subjected to the pulsed electric field. In both cases, the moisture content in the analytical state was determined in accordance with EN ISO 18134-3:2015 standard [34]. The test portion of the material (minimum 1 g weighing to the nearest 0.1 mg.) is dried at a temperature of  $(105 \pm 2) ^\circ\text{C}$  in the air atmosphere until the constant mass is achieved. Constant mass was defined as a change not exceeding 1 mg in mass during a heating period of 60 min. The percentage of moisture was calculated from the loss in mass of the test portion. In addition, for the sample that was subjected to the pulsed electric field interaction, the moisture content of the wood was determined again before the combustion heat test was conducted. Such a procedure made it possible to exclude the influence of the differentiation of the controlled and processed material moisture content on the basis of the obtained results of the combustion heat. The value of 0.1% was adopted as the limit of repeatability. The combustion heat of the tested biological material was determined with the use of a calorimetric bomb combustion method, based on the EN ISO 18125:2017 standard [18]. A weighed portion of the analysis sample ( $1 \pm 0.1$ ) g was burned in high-pressure oxygen (the bomb filled to 3 MPa by pure oxygen with an assay of at least a volume fraction of 99.5%, and free from the combustible matter) in a bomb calorimeter. The effective heat capacity of the calorimeter was determined in calibration experiments by combustion of certified benzoic acid under similar conditions, accounted for in the certificate (ambient temperature equal to  $25 ^\circ\text{C}$ ). The corrected temperature rise was established from observations of temperature before, during and after the combustion reaction took place. Water (distilled,  $1.0 \pm 0.1$  mL) was added to the bomb initially to give a saturated vapor phase prior to combustion, thereby allowing all the water formed, from the hydrogen and moisture in the sample, to be regarded as liquid water. For this purpose, the polish Precyzja-Bit company calorimeter (model KI 12Mn) was used (Figure 8a), which allowed the determination of changes in the temperature of the liquid in the calorimetric vessel with an accuracy of  $0.001 ^\circ\text{C}$ . The capacity of the calorimetric vessel in the device equal to 2.7 L. Due to the methodology used and the low-density of sawdust, the material had to be compressed with a manual press (Figure 8b) before taking measurements. Only such a prepared portion could be used to make measurements.



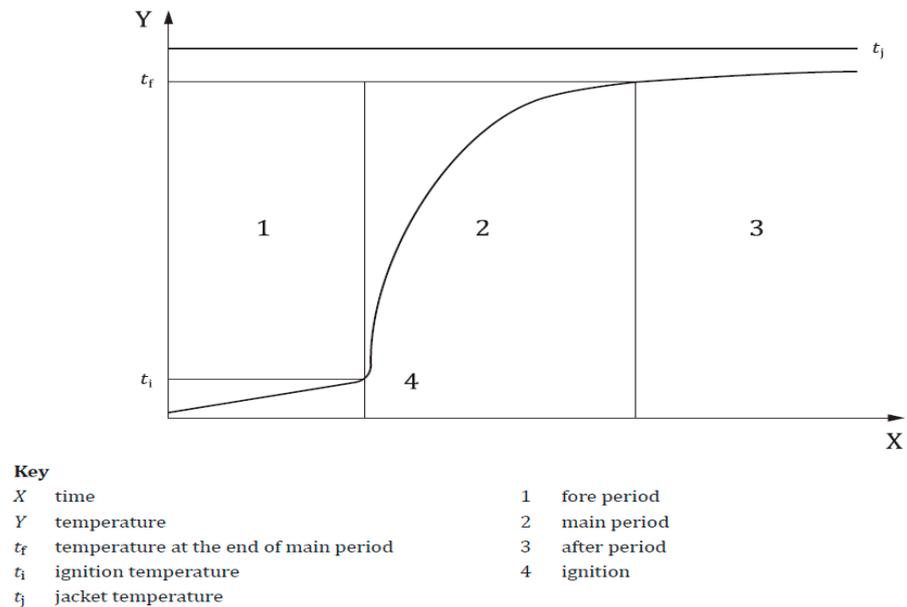
(a)



(b)

**Figure 8.** Elements of the stand for determining the heat of combustion: (a) calorimeter, (b) manual press.

The calorimeter measured and then automatically records three characteristic temperature points and three basic periods in the time–temperature course of the combustion process, as shown in Figure 9.



**Figure 9.** Example time–temperature curve from EN ISO 18125:2017-07 [18].

The exact value of the heat of combustion was determined using the Formula (1) [18], where  $q_{v,gr}$  is the gross calorific value at constant volume of the fuel as analyzed, in  $J \cdot g^{-1}$ ;  $\varepsilon_{(n)}$ —is the mean value of the effective heat capacity of the calorimeter as determined in the calibrations, in  $J \cdot K$ ;  $\theta$ —is the corrected temperature rise, in  $K$ ;  $Q_{fuse}$ —is the contribution from the combustion of the fuse, in  $J$ ;  $Q_{ign}$ —is the contribution from the oxidation of the ignition wire, in  $J$ ;  $Q_N$ —is the contribution from the formation of nitric acid (from liquid water and gaseous nitrogen and oxygen, in  $J$ ;  $Q_s$ —is the correction for taking the sulfur from the aqueous sulfury acid to gaseous sulfur dioxide, in  $J$ ;  $m_1$ —is the mass of the sample of the fuel, in  $g$ ;  $m_2$ —is the mass of the combustion aid, in  $g$ ;  $q_{v,2}$ —is the gross calorific value at constant volume of the combustion aid, in  $J \cdot g$ .

$$q_{v,gr} = \frac{\varepsilon_{(n)} \cdot \theta - Q_{fuse} - Q_{ign} - Q_N - m_2 \cdot q_{v,2} - Q_s}{m_1} \quad (1)$$

In order to confirm or reject the hypothesis about the normal distribution of the examined parameter, the results of the research were subjected to the Kolmogorov–Smirnov test. Afterward, selected basic descriptive statistics were calculated in accordance with [35], significant due to the described phenomena. The statistical package Statistica 9.0 and MS Office Excel (Analysis ToolPak-VBA) were used for the calculations.

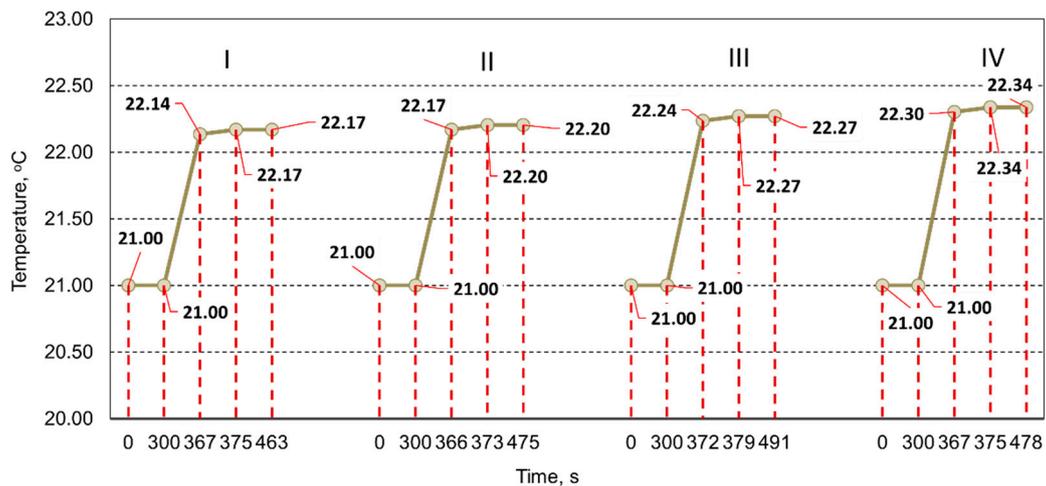
### 3. Results

Each of the tested materials (spruce, fir and larch sawdust) was subjected to a separate analysis.

#### 3.1. Spruce Sawdust

Samples of spruce sawdust constituting a control sample (without PEF influence) and after PEF treatment had a moisture value in the analytical state at the level of  $9.9 \pm 0.1\%$ . Analyzing the temperature characteristics during the combustion of biological material, which was a spruce tree previously subjected to stimulation with a pulsed electric field (Figure 10), it was found that the highest temperature was obtained in the case of PEF with an electric field intensity of  $30 \text{ kV} \cdot \text{cm}^{-1}$ , where the number of pulses amounted to

300. The lowest temperature during combustion was recorded for the test, in which the parameters of the pulsed electric field were as follows: electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and the number of pulses 150. In the case of other combinations of PEF, the values of the temperatures obtained were in the range from  $22.17 \text{ }^\circ\text{C}$  to  $22.27 \text{ }^\circ\text{C}$ . Taking into account only the values of the measured temperatures, disregarding their characteristics, it was stated that for all combinations of the experiment, the differences that arose were statistically significant and of great importance for the entire analyzed process.



**Figure 10.** Characteristics of the combustion temperature of a sample of a spruce tree conditioned with a pulsed electric field: I (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); II (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300); III (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); IV (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300).

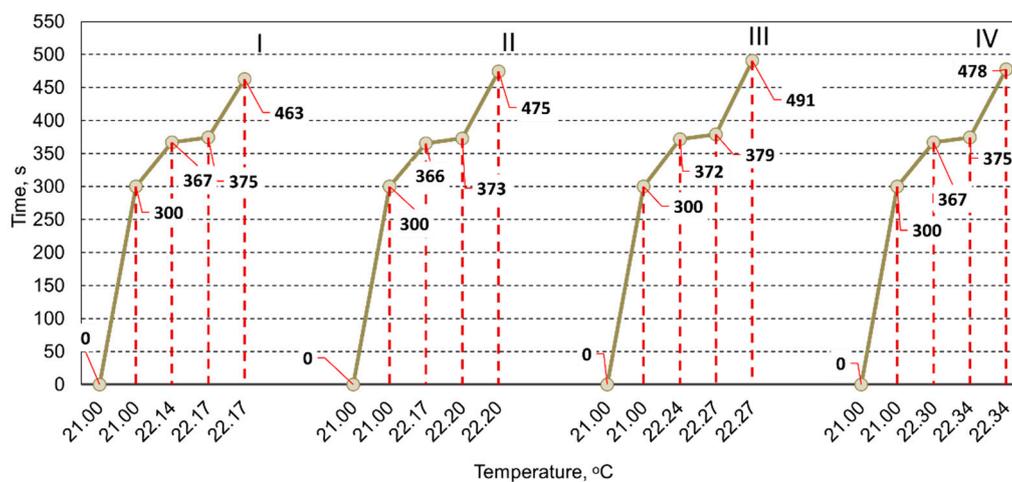
The key stimulation parameters from the point of view of temperature increase were the discharge electric field intensity and the time of exposure. It should be noted that in the case of the blank test (not subjected to stimulation with a pulsed electric field), the lowest temperatures were recorded. Even though the analyzed temperature differences in terms of absolute values constitute a small value within the range of interest for the setting phenomenon, it represents a significant proportion of the value.

Another analyzed element was the time from the moment of ignition to the moment of obtaining the maximum temperature, the differentiation of which may indicate the measurable effect of the pulsed electric field on biological material, extending or shortening this time. Figure 11 presents the time characteristics of the individual stages of calorimetric research on a spruce tree previously subjected to pulsed electric field stimulation.

Table 1 lists the parameters presented in Figures 10 and 11.

**Table 1.** Characteristic temperature points of spruce sawdust combustion.

Point	Parameters	Combination I	Combination II	Combination III	Combination IV
Start	t [s]	0	0	0	0
measuring	T [°C]	21.00	21.00	21.00	21.00
Sample	t [s]	300	300	300	300
ignition	T [°C]	21.00	21.00	21.00	21.00
End of	t [s]	367	366	372	367
combustion	T [°C]	22.14	22.17	22.24	22.30
Temperature	t [s]	375	373	379	375
stabilization	T [°C]	22.17	22.20	22.27	22.34
End of mea-	t [s]	463	475	491	478
surement	T [°C]	22.17	22.20	22.27	22.34



**Figure 11.** Time characteristics of the individual combustion stages of a sample of spruce trees conditioned with a pulsed electric field: I (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); II (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300); III (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); IV (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300). It was found that the longest times from ignition to reaching the maximum temperature were obtained for the material under the influence of PEF with an electric field intensity of  $30 \text{ kV}\cdot\text{cm}^{-1}$  and the number of pulses 150 (III combination), while the shortest time of the analyzed interval was stated for the second combination of the experiment (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number pulses 300). Taking into consideration all the used combinations of experiments, from the point of view of the duration of individual combustion cycles, there were no statistically significant differences in the measured values. Only a slight increase in the value of time was found for the samples after the PEF exposure, where the discharge electric field intensity amounted to  $30 \text{ kV}\cdot\text{cm}^{-1}$ . It should be underlined that in the case of the first combination, the combustion time is the shortest in all measured sections.

### 3.2. Fir Sawdust

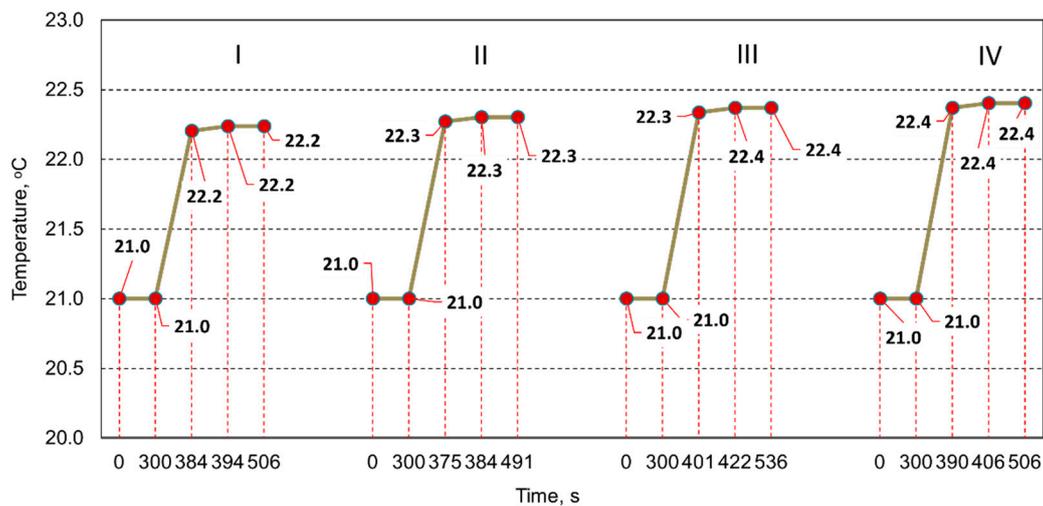
For fir sawdust in both analyzed groups (before and after the exposure to PEF) had a constant value of moisture in the analytical state equal to 8.6%. Analyzing the temperature characteristics during the combustion of biological material, which was fir sawdust previously subjected to the pulsed electric field (Figure 12), it was found, as in the case of sawdust of spruce wood, that the highest temperature was obtained in the case of PEF with an electric field intensity of  $30 \text{ kV}\cdot\text{cm}^{-1}$ , where the number of pulses amounted to 300. The lowest temperature during combustion was recorded for the test in which the parameters of the pulsed electric field were as follows: discharge electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$ , number of pulses 150. It must be emphasized that in the case of the blank (unstimulated) test, the lowest temperatures were recorded. Despite the fact that the analyzed temperature differences in terms of absolute values constitute a small value, within the variability of temperatures of the phenomenon in question, they accounted for a significant value.

In the case of the time from the moment of ignition to reaching the maximum temperature, significant differentiation was recorded, which proves the measurable effect of the pulsed electric field on the biological material. Figure 13 presents the time characteristics of the individual stages of calorimetric research on fir sawdust that were previously subjected to the pulsed electric field. It was found that the longest duration of the interval in question was obtained in the case of the impact of PEF with the parameters of the 3rd combination (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150), while the shortest time was obtained in the case of the 2nd combination of the experiment.

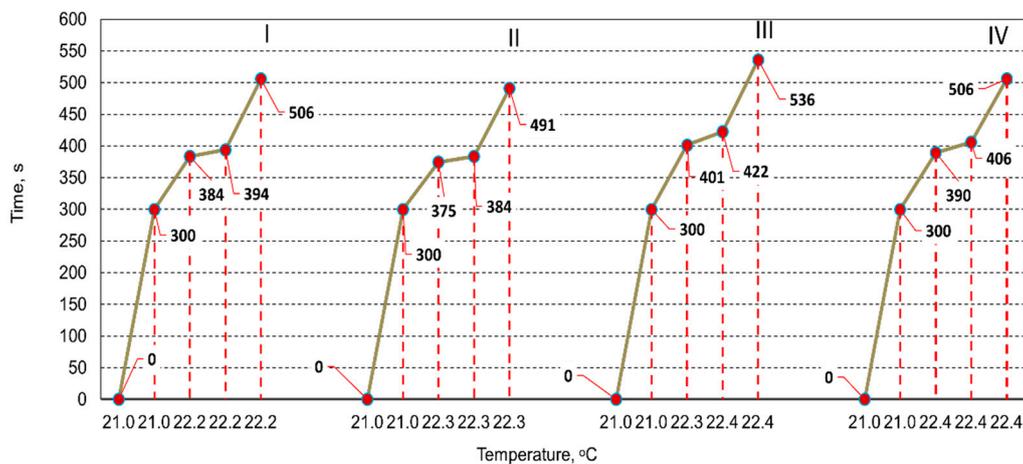
When analyzing the time of individual combustion phases, it was noted that in the case of the duration of the second phase (the difference between the values of the time recorded for the third and the second temperature), the difference in absolute value in the time sections between the material stimulated with the electric field intensity of  $25 \text{ kV}\cdot\text{cm}^{-1}$  and  $30 \text{ kV}\cdot\text{cm}^{-1}$  and the same number pulses was over 30%. In the case of the third combustion

phase, much greater relative differences were recorded in their duration, even though in absolute values, this differentiation is much smaller. It should be emphasized that there was an almost two-fold difference in the duration of the phase between the combinations of experiments I and II, and experiments III and IV, where the differentiation in the stimulation resulted mainly from the applied discharge electric field intensity, i.e., in the first two cases it was  $25 \text{ kV}\cdot\text{cm}^{-1}$ , while in the other two it was  $30 \text{ kV}\cdot\text{cm}^{-1}$ . On the other hand, the differences within the combination, where the stimulation electric field intensity was the same, the time of the analyzed phase differed only slightly despite the different number of PEF pulses. In the fourth analyzed combustion phase, its duration did not differ within the analyzed combinations of the experiment and did not exceed 10 s, which constituted less than 10% of the measured values.

Table 2 lists the parameters presented in Figures 12 and 13.



**Figure 12.** Characteristics of combustion temperature of a fir tree sample conditioned with a pulsed electric field: I (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); II (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300); III (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); IV (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300).



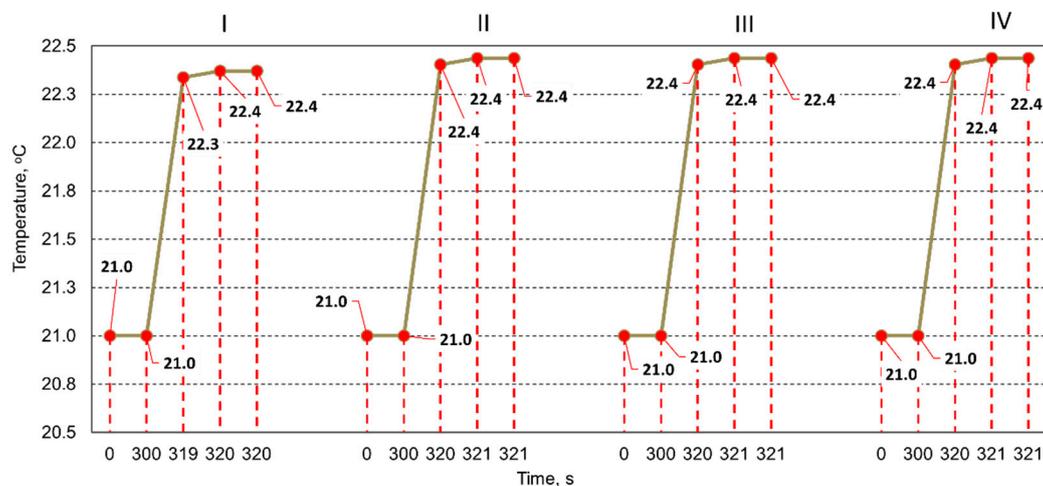
**Figure 13.** Time characteristics of individual combustion stages of a fir tree sample conditioned by a pulsed electric field: I (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); II (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300); III (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); IV (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300).

**Table 2.** Characteristic temperature points of fir sawdust combustion.

Point	Parameters	Combination	Combination	Combination	Combination
		I	II	III	IV
Start	t (s)	0	0	0	0
measuring	T (°C)	21.00	21.00	22.00	22.00
Sample	t (s)	300	300	300	300
ignition	T (°C)	21.00	22.00	22.00	22.00
End of	t (s)	384	375	401	390
combustion	T (°C)	22.20	22.30	22.30	22.40
Temperature	t (s)	394	384	422	406
stabilization	T (°C)	22.20	22.30	22.40	22.40
End of mea-	t (s)	506	491	536	506
surement	T (°C)	22.20	22.30	22.40	22.40

### 3.3. Larch Sawdust

Larch sawdust that was not subjected to conditioning had a moisture content of 8.3%, while after the PEF interaction process, the moisture decreased by 0.1%, which was within the assumed error limit. The characteristics of the temperature course during combustion in the case of sawdust from the larch tree were characterized by a very low variability within the tested combinations of pulsed electric field stimulation. Contrary to the other analyzed biological materials, no clear influence on the nature of the temperature curve and its nodal values was observed. Figure 14 shows the characteristics for each experiment combination, which are almost identical, although it should be noted that it is worth noting that slightly higher temperatures were recorded in the fourth experiment combination (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300).



**Figure 14.** Characteristics of combustion temperature of a larch tree sample conditioned with a pulsed electric field: I (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); II (electric field intensity  $25 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300); III (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 150); IV (electric field intensity  $30 \text{ kV}\cdot\text{cm}^{-1}$  and number of pulses 300).

A similar statement applies to the time of combustion, where the influence of pulsed electric field stimulation on the analyzed volume was not observed. In the analyzed case, there were no significant differences, from the point of view of the process, in time and temperature values between the biological material subjected to stimulation and the material constituting the blank sample, which was not subjected to stimulation. In the case of the time of the individual combustion phases of the material, no significant differences were also noted as a consequence, and they were not visualized.

Table 3 lists the parameters presented in Figure 14.

**Table 3.** Characteristic temperature points of larch sawdust combustion.

Point	Parameters	Combination	Combination	Combination	Combination
		I	II	III	IV
Start	t (s)	0	0	0	0
measuring	T (°C)	22.00	22.00	22.00	22.00
Sample	t (s)	300	300	300	300
ignition	T (°C)	22.00	22.00	22.00	22.00
End of	t (s)	361	378	359	381
combustion	T (°C)	22.40	22.40	22.40	22.43
Temperature	t (s)	367	400	367	402
stabilization	T (°C)	22.40	22.40	22.40	22.44
End of mea-	t (s)	455	575	486	511
surement	T (°C)	22.40	22.40	22.40	22.44

#### 4. Discussions and Conclusions

The interaction of a material with a pulsed electric field is the subject of many research interests. There are known results of studies in which this stimulation was applied to such biological materials as milk [36], egg mass [37,38], fruit and vegetable juices [39–41], cider [42,43], olive oil [44], raspberries [45], apples [46], potatoes [47], wheat [48], and even yeast [49]. There have also been many attempts to use PEF as an alternative to high-temperature extraction [50] or to improve LCB porosity in biorefineries [51].

The influence of the pulsed electric field on wood material was described in the work of Kumar et al. [52], who observed an increase in tissue porosity in the obtained results of the interaction on wood chips with an electric field of 1–10 kV·cm<sup>-1</sup>. According to the authors, the obtained results indicate an increased efficiency of the cellulose hydrolysis process, and the consequences that PEF causes in organic matter, especially in wood biomass, constitute disturbances and structural changes in the cell membrane, causing the loss of its semipermeability, thus facilitating the entry of enzymes hydrolyzing polysaccharides and lignin [30,31]. Nevertheless, the mechanism that unambiguously determines these phenomena has not been described in detail [53].

There are no studies in the literature that would prove even an attempt to determine the influence of PEF on the characteristics of the heat of combustion. Moreover, the mentioned characteristic always appears as a necessary element of calorific value measurements. However, its role is reduced to only one of the stages of the methodology used to determine the value of the heat of combustion of the tested fuel. On the other hand, from the physical and energetic point of view, both the amount of energy produced and the time in which this energy was released seems to be important. As a rule, each of these factors is considered separately, and different methodologies are used to determine them.

As noted by Rhen et al. [54], knowledge of the combustion time enables the improvement of the process control possibilities, constituting at the same time crucial information for the design of devices intended for fuel combustion. In the research on the combustion time of coal obtained in the pyrolysis process of pellets made of spruce wood sawdust, the above-mentioned author noticed that the time depended on the used material and ranged from 4.5 to 6.5 min. In the case of combustion temperature analyses, the authors [55–57] emphasize the role played by two characteristic points, which are the ignition temperature and the peak temperature. However, they note that the first of the abovementioned temperatures, in the case of biomass combustion, varies within a narrow range, while the second depends primarily on the content of volatile substances in the fuel. The analysis of the heat of combustion characteristics enables both the duration of the combustion process to be determined and the characteristic points of this process to be designated. Thus, it is a link connecting precise measurements of time and temperature separately with measurements based on the determination of these values in order to designate the heat of combustion.

It seems that the increase in tissue porosity described by the authors [30,31,52] may be the cause of changes in the combustion process of wood material, which results in differences in temperature and duration of individual periods of characteristics. It is also

not without significance that sawdust treated as a residue of forest production was used in the research and thus characterized by a greater variability of wood components, i.e., cellulose, hemicellulose, lignin and extractive substances [58,59], compared to the uniform wood material, which can be, e.g., tree trunks cleared of bark.

At present, it is impossible to precisely parameterize the process of PEF influence on the characteristics of the combustion heat of the tested fuel. Therefore, there is a need to conduct further experiments and extend the scope of research not only to other parameters of the electric field but also to various types of wood.

This research has demonstrated the influence of organic matter conditioning on the temperature characteristics, as well as time characteristics of individual combustion stages. It was also found that the decisive factor in changing the properties of sawdust is the discharge electric field intensity and, secondly, the number of discharge pulses.

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