

Research of Charring and Resulting Char in Natural and Treated Timber

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Abstract – Wood is a material widely used for construction purposes, which has quite a number of advantages in comparison with other materials – it is light, strong, resistant to impacts and vibration, easy to process, etc. However, one of the largest drawbacks of wood – it is flammable. In case of fire in wooden buildings or buildings made of timber structures, the most noticeable feature of combustion is charring of these structures. This property is important in identifying the cause of a fire. Therefore, it is necessary to relate charring of timber structures with certain significant effects of fire, such as its duration and temperature. It is also important to identify whether timber has been treated with fire retardant solutions before the fire break-out. The article analyses the wood properties that have influence on combustion and charring processes. The indicators of charring, and calorific values, the electrical resistance and electrical capacitance were determined for char resulting in natural and treated timber under different conditions. Microscopic examination was carried out. The research results were summarised by conclusions.
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I. Introduction

Wood is a unique anisotropic porous substance of plant origin where the volume of pores takes 50–75 % of the wood volume. It has quite a number of advantages in comparison with other materials: it is solid and can bear high loads. At the same time it is light, has low heat conductivity, easy to process, etc.

The drawbacks of wood: it absorbs much water, decays, deforms under the influence of humidity, and one of the largest drawbacks – it is flammable [1]. As a rule, reaction to fire of timber structures is decreased by treating them with fire retardant solutions. Quite a number of works have been dedicated to research of efficiency and durability of fire retardant solutions [2]–[9]. The main mass of completely dry wood (about 99 %) consists of organic substances. In addition to organic substances, wood contains some mineral substances (salines), which turn to ash after wood has been burnt.

Regardless of tree species, there are 49–50 % of carbon, 43–44 % of oxygen, about 6 % of hydrogen and 0.1–0.3 % of nitrogen in completely dry wood. Carbon, hydrogen and oxygen form complex organic substances, such as cellulose, hemicellulose, lignin and the so-called extractive substances (resins, gums, fat, tannides, pectins, etc.) [10]. The composition of wood depends on botanic origin, growing conditions, species and the age of a tree and other factors [2], [11], the prevailing proportion of its components is as follows 50 % of cellulose, 25 % of hemicellulose and 25 % of lignin. The substances that are included in the composition of wood are of various structure and different thermal resistance [12].

Referring to the research data obtained by various authors, the thermal decomposition of wood components takes place at different temperatures: hemicellulose at 200–325 °C, cellulose at 220–375 °C, lignin at 250–500 °C [13]–[18].

The research was carried out under different conditions and combustion is influenced by the types of the substance (tree) [19] as well as the speed of temperature increase [2], [20]–[22] and environment (oxidising or reducing gases) where the substance is studied [23], [24]. The thermogravimetric analysis is used for research of thermal decomposition and combustion mechanism and kinetics of natural, fire retarder treated timber and its products, thus simulating conditions that are likely to occur during a fire.

Combustion as a phenomenon can take various forms (fuming, smouldering, flaming, explosion); however in the end they all come down to a chemical reaction between a flammable substance and oxygen present in the atmosphere. Proper use of this reaction results in much benefit (power, heat resources) but, if uncontrolled, it can cause both serious material damage and human death. [12]. Fire is a complex phenomenon: its course and effects depend on a number of interrelated factors. In case of fire in wooden buildings and buildings made of timber structures, the most noticeable result of combustion and extinction is charring of timber and its products. This result is important in identifying the cause of fire. Therefore, it is necessary to relate charring of timber and its products or structures with particular significant effects of fire, such as its duration and temperature [25].

Since timber is in fact a rather complex substance, its pyrolysis and combustion are influenced not only by its various properties but also by environmental factors.

In addition to that, the dynamics of fire development is determined by various fire factors, and all the listed circumstances make it difficult to determine combustion duration and timber temperature.

Under fire conditions, timber experiences pyrolysis (thermal destruction). Pyrolytic gas typically flames up as soon as it rises up to the surface of charred timber.

Further combustion and mechanical degradation of char finally destroys or splits the outer layers of char off.

The charring rate is in fact linearly dependent on time. The temperature of char layer formation averages 300 °C [26]. Charring of timber is closely related to the combustion characteristics of wood components – hemicellulose, cellulose and lignin, which influence formation of char. The majority of char is formed during combustion of lignin [12].

Charring of timber is also dependent on the heat load applied on the structural surface and change in the value of heat load depending on the length of thermal exposure [27]. In our opinion, the uniform charring depth can be obtained by exposing timber to different temperatures for various periods of time. However, the uniform charring depth can also result from timber exposure to different conditions of pyrolysis. It is therefore not appropriate to estimate combustion duration, which is used for identification of the fire source, only by charring depth.

In Lithuania, to determine the charring time of timber structures, the depth of char on charred wooden structure and the electrical resistance of char are measured. Using the derived dependencies on the basis of the measured values of the char depth and electrical resistance [26], and considering the original thickness and moisture content of a timber structure, the charring time, which is used to prediction of a fire source location, is estimated.

However, this measuring method is not widespread, as it requires special equipment to be used. It is also essential to determine whether the charred timber has been treated with fire retardant solutions before fire.

The aim of the work is to investigate how the calorific value of char resulting from wood of different species at different temperature changes and determine how the value of the electrical resistance vary depending on whether it has or has not been treated with fire retardant solutions, as well as measure the electrical resistance of resulting char as charring time changes with wood of various species used for combustion.

II. Test Equipment and Methods

II.1. Tested Materials and their Characteristics

For experiments softwood (pine, fir) and hardwood (aspen, oak) were used. Before tests, wood was conditioned according to the requirements of LST EN 13238:2010 [28].

The moisture content in the specimens did not exceed 15 %, the moisture content was determined using a

moister meter HPM 2000. For treating purposes the fire retardant solution BAK-1 was used.

II.2. The Special One-Side Heating Equipment

To identify charring peculiarities in wood of different species at different temperatures, special one-side heating equipment was used [26], [29]. This equipment ensures the simulated one-side heating of the test specimen up to 950°C. The equipment consists of one-side heating device, heat controller, instrumentation and equipment for recording the readings (Fig. 1).

The principle of the experiment was to heat the specimen on one side based on dependency of temperature on time specified in and regulated by LST EN 1363-1:2000 [30].

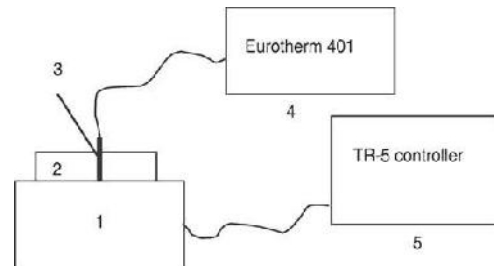


Fig. 1. The principal scheme of the one-side heating equipment that has been used for one side heating tests: 1 — one-side heating apparatus; 2 — fragment of the tested structure; 3 — temperature and heat flow measuring equipment; 4 — Eurotherm 401 recorder; 5 — TR-5 controller for regulation of temperature in the heating chamber

The height and width of the wood specimens was 210 mm and 150 mm respectively, the thickness varied from 47 mm to 59 mm. Both natural wood and wood treated with fire retardant solution BAK-1 (with consumption 500 ml/m², coated with a brush on all sides). Using the described equipment, the wood specimens prepared for investigation were exposed to heating for a specific pre-set period of time τ , min. (5, 10, 20, 30 and 45). During this period, the average heating temperatures shown in Table I were reached. After this period the specimen was removed from the chamber followed by its extinguishing with a fire blanket.

The char formed during these tests was used for further research.

II.3. Calorimetric Bomb Method

Research of the resulting char was followed up by the test method described in LST EN ISO 1716:2010 *Reaction to fire tests for products – Determination of the gross heat of combustion (calorific value)* [31].

The essence of this test is to determine how much heat is released by completely burnt wood or charcoal.

The course of research was as follows. Any dust and ash was brushed off from the specimen of charred wood, and up to 5 mm of the top char layer was taken with a knife in different points on the specimen. Char was ground with a pestle in a mortar.

Ground char was placed into an open vessel.

The vessel with char was conditioned to the constant mass in a laboratory furnace at the furnace temperature of about 60 °C. For research purposes 0.5–1.0 grams of char conditioned to the constant mass and ground in such a manner that the diameter of the ground particles did not exceed 500 µm was used.

Three tests were performed with resulting char from one specimen. Three specimens were heated for the same period of time; therefore the calorific value of char was calculated as the arithmetic average of nine specimens.

The calorific value of natural wood or wood treated with fire retardant solutions and dried to the constant mass in a laboratory drying chamber at the temperature of 60 °C was also determined (about 25 cm² of treated wood surface area was shaved off to get 1 g of treated wood chips).

In that case, the tests were performed with the wood chip tablets and the calorific value was accounted for as the arithmetic average of values obtained at three tests.

II.4. Research of Electrical Resistance Measuring

The electrical resistance (R , Ω) of each specimen was measured with special equipment used for that purpose (Fig. 2).

To measure the electrical resistance of the selected char specimen, it is necessary to follow certain succession. First of all, the surface of selected specimens must be cleaned. The mass of one specimen should be at least 1 g. The specimen is placed into a separate open vessel. This vessel with the specimen is conditioned in a laboratory furnace. The furnace temperature should not exceed 105 °C. The specimens are conditioned to the constant mass. Afterwards each specimen is ground with a pestle in a marble mortar. The diameter of the ground particles did not exceed 500 µm.

The resistance metering device (ohmmeter) is used to measure the electrical resistance R , Ω of the char specimens. With the help of clamps the press is connected to the resistance metering device, as shown in Fig. 2.



Fig. 2. Equipment for measuring electrical resistance of char

Afterwards, the electrical resistance of each char specimen is measured. The sequence of actions in this procedure is as follows: the ground specimen of char (300–600 mg) is placed into the mould (Fig. 3) so that the original height of the mould without char would increase by 4 mm; the mould is seated into the press and mechanically (by turning the handle) pressed up to 3500–5000 kg/cm².

The readings of the resistance metering device are recorded. The mould is removed from the press and char is cleaned out.

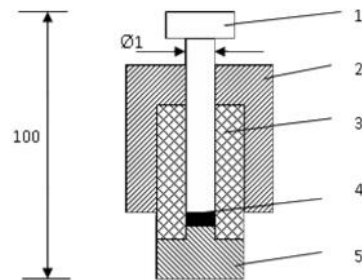


Fig. 3. Mould for char placing: 1 – plunger (HRC 55-60); 2 – guide bar; 3 – ebonite insert; 4 – char; 5 – base (HRC 55-60)

II.5. Microscopic Examination

The microscopic examination was carried out with char from pine wood (heating time was 10 and 45 min.).

This examination was carried out using the electronic scanning microscope JEOL JSM-7600F with the resolution of 1.5 nm, magnification from 25 to 1000000 times, for examination purposes voltage of 2.0 kV was used, the surface of examined specimens was plated with gold, 250x magnification was used.

II.6. Method for Measuring Electrical Capacitance of Char

The equipment used for tests (Fig. 4) consists of an electrical capacitance metering device, LCR meter E7-13, which is connected to the stainless steel electrodes with thickness of 1 mm, width of 12 mm, height of 30 mm using copper wires, the distance between the electrodes – 24 mm.



Fig. 4. Equipment used for measuring electrical capacitance

The electrical capacitance of a compound composed of distilled water and ground char or wood chips (the diameter of ground particles did not exceed 250 μm), poured into a glass vessel with a diameter of 36 mm and depth of 58 mm. The compound was composed of 50 g of distilled water and 0.1 g of wood chips or ground char from wood. About 7 cm^2 of treated wood surface area was shaved off to get 0.1 g of wood chips (the diameter of ground particles did not exceed 250 μm).

III. Overview of Results

Dependency of the calorific value of char resulting from different species of wood on the heating time is provided in Fig. 5.

The calorific value of char resulting from oak wood reaches 26.1 MJ/kg after 5 minutes of heating. After 10 minutes of heating the calorific value rises up to 29.5 MJ/kg, after 20, 30 and 45 minutes of heating the calorific values of char change slightly: after 20 min. – 33.5 MJ/kg, after 30 min. – 33.9 MJ/kg, after 45 min. – 34.0 MJ/kg. The maximum calorific value of char is after 45 minutes of heating. Even after 5 minutes of heating the calorific value of char is higher than the value of the wood itself and the determined calorific value of dry oak is 18.9 MJ/kg.

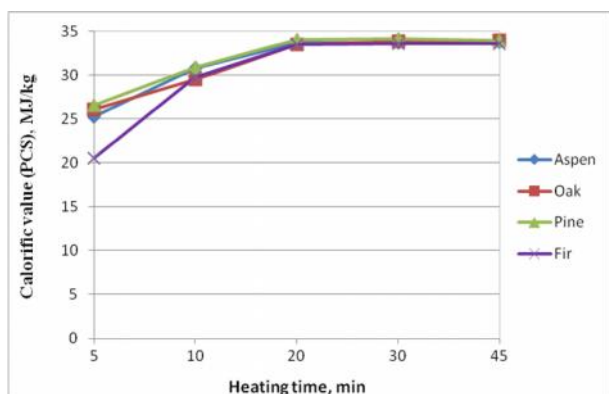


Fig. 5. Average dependency of calorific value of char resulting from different species of natural wood on heating time

The calorific value of char resulting from aspen wood is 25.3 MJ/kg after 5 minutes of heating, after 10 min. – 30.8 MJ/kg, after 20, 30 and 45 minutes of heating the calorific values are similar – 33.7 MJ/kg, 33.7 MJ/kg and 33.8 MJ/kg respectively. The calorific value of dry aspen wood is 18.7 MJ/kg. The calorific value of char resulting from pine wood is 26.5 MJ/kg after 5 minutes of heating, after 10 min. – 30.9 MJ/kg, after 20, 30 and 45 minutes of heating the calorific values are 34.1 MJ/kg, 34.1 MJ/kg and 34.0 MJ/kg respectively. The calorific value of dry pine wood is 20.0 MJ/kg. The calorific value of char resulting from fir wood is 20.5 MJ/kg after 5 minutes of heating, and the value of dry fir wood is 19.5 MJ/kg, the difference is only 1.0 MJ/kg, whereas for some species the difference in the calorific values is 6.5 MJ/kg – 7.2 MJ/kg. After 10 minutes of heating the

calorific value of fir char is 29.8 MJ/kg, after 20 min. – 33.5 MJ/kg, after 30 min. – 33.6 MJ/kg, after 45 min. – 33.6 MJ/kg. After 5 minutes of heating the highest calorific value was of char resulting from pine wood (26.5 MJ/kg), the lowest value was attributable to fir (20.5 MJ/kg), the difference between the highest and the lowest values was 6 MJ/kg. After 10, 20, 30 and 45 minutes of heating the differences between the lowest and the highest values were not big: after 10 min. – 1.4 MJ/kg, after 20 min. – 0.6 MJ/kg, after 30 min. – 0.5 MJ/kg, after 45 min. – 0.4 MJ/kg. The calorific value of char resulting from different species of wood after they are heated for 20 minutes and longer (the reached average heating temperature $\geq 780^\circ\text{C}$) are within range of 33.5 MJ/kg and 34.1 MJ/kg. This small change in the calorific values at the temperature higher than 780°C can be explained by the data obtained by another author [32]. According to Demirbas [32], during the fir wood charring up to the temperature of 777°C , the resulting char residue in the elemental composition is 91.2 % of carbon, 1.5 % of hydrogen, 4.0 % of oxygen, 0.1 % of nitrogen, 3.1 % of ash, and if heated to the temperature of 877°C – 92.1 % of carbon, 1.2 % of hydrogen, 3.3 % of oxygen, 0.1 % of nitrogen, 3.3 % of ash. The composition of fir wood before tests was: 51.9 % of carbon, 6.1 % of hydrogen, 40.9 % of oxygen, 0.3 % of nitrogen. If wood is heated at the temperature above 780°C , changes in the elemental composition of the resulting char residue are slight; therefore the differences between the calorific values are not big. Namely the calorific value depends most of all on the amount of carbon, hydrogen and oxygen in the material. The dependency of the calorific values of char resulting from fir wood treated with the fire retardant solution BAK-1 on heating time are shown in Figure 6.

The lowest calorific value of char was determined in the specimens heated for a period of 5 minutes – 9.3 MJ/kg, and the highest value was after 45 minutes – 32.9 MJ/kg. After 10 min. of heating the calorific value was 22.3 MJ/kg, after 20 min. – 24.7 MJ/kg, and after 30 min. – 29.4 MJ/kg. It was determined that the calorific value of char resulting from the natural wood was higher than that of char resulting from wood treated with BAK-1 solution after 5, 10 minutes of heating and respectively longer.

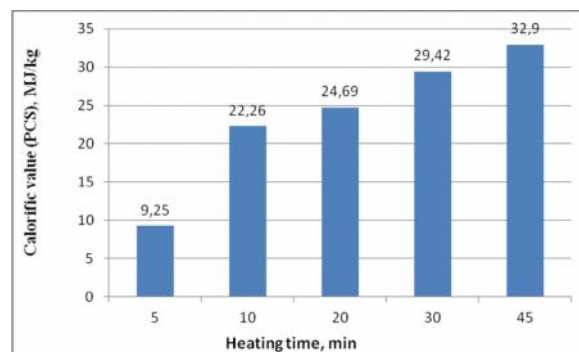


Fig. 6. Average calorific values of fir wood coated with fire retarder BAK-1

The dependency of the electrical resistance values of char resulting from different species of wood on heating time are shown in Table I.

The electrical resistance of char resulting from any species of wood – oak, aspen, pine or fir – after 5 and 10 minutes of heating is higher than $2 \cdot 10^8 \Omega$. More accurate determination was not possible as the resistance metering equipment can be used to measure resistance only up to $2 \cdot 10^8 \Omega$. After 20 minutes of heating the electrical resistance was lower than after 5 or 10 minutes. The lowest resistance value is attributable to char resulting from oak wood – $3.1 \cdot 10^5 \Omega$, and the highest value is attributable to char from fir wood – $9.0 \cdot 10^5 \Omega$. The electrical resistance of char resulting from aspen wood is $8.5 \cdot 10^5 \Omega$, and that from fir wood is $3.6 \cdot 10^5 \Omega$.

TABLE I
VALUES OF CHAR RESULTING FROM DIFFERENT SPECIES
OF WOOD ON HEATING TIME

Heating time, min	Average electrical resistance, Ω			
	Oak	Aspen	Pine	Fir
5	$>2 \cdot 10^8$	$>2 \cdot 10^8$	$>2 \cdot 10^8$	$>2 \cdot 10^8$
10	$>2 \cdot 10^8$	$>2 \cdot 10^8$	$>2 \cdot 10^8$	$>2 \cdot 10^8$
20	$3.1 \cdot 10^5$	$8.5 \cdot 10^5$	$3.6 \cdot 10^5$	$9.0 \cdot 10^5$
30	$3.8 \cdot 10^4$	$5.4 \cdot 10^2$	$2.4 \cdot 10^4$	$2.3 \cdot 10^3$
45	26.9	108.4	3.3	11.8

When wood is heated for 30 minutes, the tendency for the electrical resistance to get lower is still maintained.

The lowest resistance value is attributable to char resulting from aspen wood – $5.4 \cdot 10^2 \Omega$, from fir – $2.3 \cdot 10^3 \Omega$, from pine wood – $2.4 \cdot 10^4 \Omega$, and the highest value is attributable to char from oak wood – $3.8 \cdot 10^4 \Omega$.

When wood is heated for 45 minutes, the electrical resistance changes from 3.3 to 108.4 Ω . The lowest resistance value is attributable to char resulting from pine wood, and the highest value – from aspen wood. The lowest resistivity value after 45 minutes of heating is even $6.1 \cdot 10^7$ times lower than that after 5 or 10 minutes.

Figs. 7 and 8 present the microscopic pictures of char resulting from pine wood (in Fig. 7 the heating period is 10 minutes and in Fig. 8 is 45 minutes). After 10 minutes of heating some defects are observed on the surface of char from pine wood, however the surface itself is uniform and free of cracks. After 45 minutes of heating individual pine rings, which are thin and cracked show up. The pictures just confirm the research carried out by Demirbas [32] that as the temperature rises the components of wood decompose and disappear, whereas the remaining amount of carbon is increasing.

Figure 9 shows the average values of the electrical capacitance measurements in a compound composed of chips of natural and treated wood and distilled water.

The values of the electrical capacitance of compound composed of chips from natural wood and distilled water differ insignificantly and make the difference of about 0 nF. The values of the electrical capacitance of the compound composed of chips from wood treated with fire retardant solution *BAK-1* with consumption of 250 ml/m² and distilled water are higher than those of the

compound with chips of natural wood. The lowest value of the electrical capacitance was obtained with the compound with chips from oak wood ~4.3 nF, whereas the highest value was attributable to the chips from aspen wood ~13.4 nF, chips from pine wood ~7.1 nF, chips from fir wood ~12.0 nF.

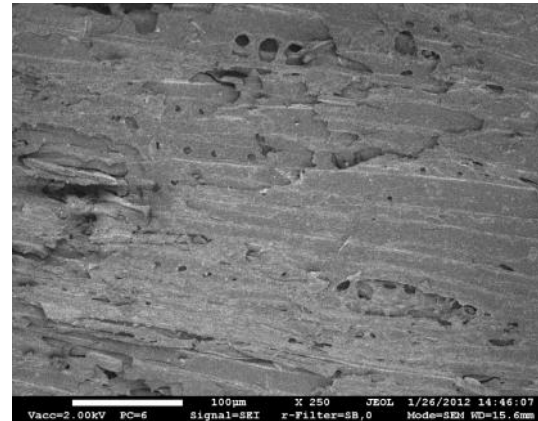


Fig. 7. Picture of pine wood after 10 minutes of heating

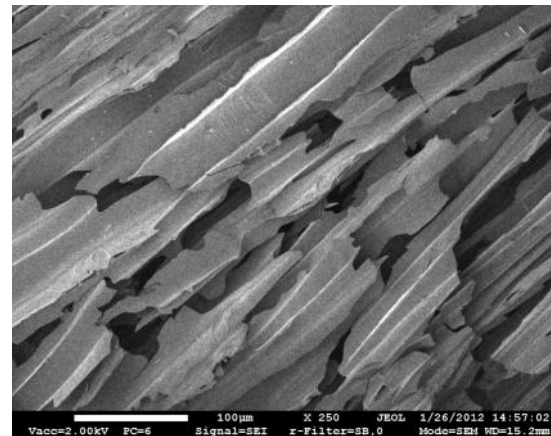


Fig. 8. Picture of pine wood after 45 minutes of heating

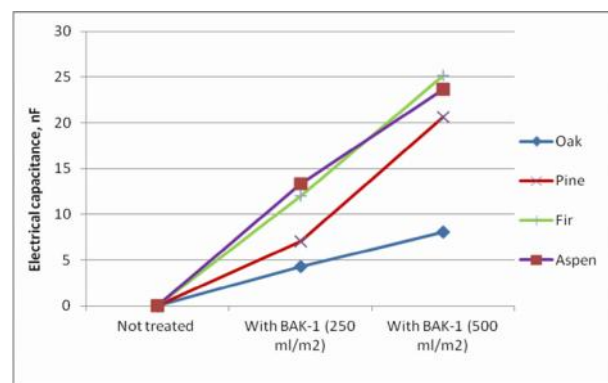


Fig. 9. Average values of electrical capacitance of compound composed of chips from natural and treated wood, and distilled water

The values of the electrical capacitance of the compound composed of chips from wood treated with fire retardant solution *BAK-1* with consumption of 500 ml/m² and distilled water are higher by 1.8-2.9 times than

the values of the electrical capacitance of the compound composed of chips from wood treated with consumption of 250 ml/m². The lowest value of the electrical capacitance was obtained with the compound with chips from oak wood ~8.0 nF, whereas the highest value was attributable to the chips from fir wood ~25.2 nF, chips from pine wood ~20.6 nF, chips from aspen wood ~23.7 nF. As the electrical capacitance depends on the area, shape of conductor surface, the distance to the other conductor and environment, and in case of research carried out only environment was subject to changes, it can be said that during research any changes in the electrical capacitance were influenced only by environment, i.e. changes in the amount of fire retardant solutions.

Furthermore, the electrical capacitance of the compound composed of distilled water and ground char from natural fir wood or fir wood treated with fire retardant solution BAK-1 (with consumption of 450 ml/m²) heated for a different period of time. The average values are presented in Table II.

The electrical capacitance of the compound composed of char from natural fir wood and distilled water varies within the range of picofarads.

The electrical capacitance of the compound with char resulting from fir wood varies from 15 pF to 45 pF, the highest electrical capacitance is observed after 10 minutes of heating, and the lowest is observed after 30 minutes of heating. After 5 minutes of heating the electrical capacitance of the compound is 39 pF, after 20 min. – 33 pF, after 45 min. – 42 pF.

TABLE II
AVERAGE VALUES

Heating time, min	Average electrical capacitance, F	
	Fir	Fir (treated BAK-1)
5	39×10^{-12}	42×10^{-9}
10	45×10^{-12}	22×10^{-9}
20	33×10^{-12}	12×10^{-9}
30	15×10^{-12}	4×10^{-9}
45	42×10^{-12}	1×10^{-9}

The electrical capacitance of the compound composed of char from fir wood treated with fire retardant solution BAK-1 and distilled water varies within the range of nanofarads. Unlike char from untreated fir wood, the electrical capacitance of the compound with char from treated fir wood changes in the following manner – the electrical capacity decreases as the heating duration increases. After 5 minutes of heating the electrical capacitance of the compound is 42 nF, after 10 min. – 22 nF, after 20 min. – 12 nF, after 30 min. – 4 nF, after 45 min. – 1 nF. The largest difference between the measurements of the electrical capacitance for the compound composed of char from natural and treated fir wood and distilled water is obtained namely depending on whether wood has been treated or not. The electrical capacitance of the compound with char from untreated fir wood was measured in picofarads, and that from treated wood – in nanofarads. This difference is important for

investigation of fires in buildings with timber structures, the method could be used to identify whether timber structures have been treated with fire retardant solutions before the fire.

IV. Conclusion

1. The calorific values of char residue, irrespective of the heating time of natural wood, are higher than those of wood from which char residue has been obtained. The calorific value of dry wood is 18.7–20.0 MJ/kg and the calorific value of char residue already after 5 minutes of heating is 20.5–26.5 MJ/kg.
2. The calorific values of resulting char residue in natural wood increase rapidly until 20 minutes of heating. After 5 minutes of heating the calorific value reaches 20.5–26.5 MJ/kg and after 20 minutes – 33.5–34.1 MJ/kg. Later on after 30 and 45 minutes of heating the calorific values change insignificantly. Then the difference between the highest and the lowest values is about 0.6 MJ/kg.
3. The calorific value of char resulting from fir wood treated with the fire retardant solution BAK-1 is lower than that of char from natural wood heated for the same period of time.
4. The electrical resistance of char gradually decreases as wood is heated for a longer period of time. After 5 minutes of heating the electrical capacitance is $>2 \cdot 10^8 \Omega$, irrespective species of wood char resulted from, after 45 minutes – $3.3\text{--}108.4 \Omega$, the lowest value is attributable to pine and the highest – to aspen.
5. The electrical capacitance of the compound composed of distilled water and ground char from natural fir wood heated for a different period of time is about 1000 times lower than that of the compound composed of distilled water and ground char from fir wood treated with fire retardant solution BAK-1 (with consumption of 450 ml/m²) heated for a different period of time.
6. The electrical capacitance of the compound composed of distilled water and ground char from fir wood treated with fire retardant solution BAK-1 (with consumption of 450 ml/m²) gradually decreases as wood is heated for a longer period of time. After 5 minutes of heating the electrical capacitance was 42 nF, after 20 min. – 12 nF, after 45 min. – 1 nF.

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References

- [1] R. Šniuolis, *Engineering Materials* (Lucilijus, 2004).
- [2] M. Hagen, J. Hereid, M. A. Delichatsios, J. Zhang, D. Bakirtzis,

- Flammability assessment of fire-retarded Nordic Spruce wood using thermogravimetric analyses and concolorimetry, *Fire Safety Journal*, Vol. 44: 1053–1066, 2009.
- [3] R. Stevens, S. Daan, R. Bezemer, A. Kranenbarg, The structure – activity relationship of fire retardant phosphorus compounds in wood, *Polymer degradation and stability*. Elsevier: 832–841, 2006.
 - [4] S. T. Lebow, J. E. Winandy, Effect of fire-retardant treatment on polywood pH and the relationship of pH to strength properties, *Wood science and technology*, Vol. 33 (Issue 4): 285–298, 1999.
 - [5] K. T. Subyakto, T. Hata, S. Ishihara, S. Kawai, H. Getto, 1998. Improving fire retardancy of fast growing wood by coating with fire retardant and surface densification, *Fire mater*, Vol. 22(Issue 5):207–212, 1998.
 - [6] H. Getto, S. Ishihara, Functionally graded wood in fire endurance with basic nitrogen compounds and phosphoric acid, *Fire and materials*, Vol. 22: 77–83, 1998.
 - [7] H. A. Lecomte, J. J. Liggat, Commercial fire-retarded PET formulations e Relationship between thermal degradation behaviour and fire-retardant action, *Polymer Degradation and Stability*, Vol. 93: 498–506, 2008.
 - [8] K. H. Pawlowski, B. Schartel, Flame retardancy mechanisms of aryl phosphates in combination with Boehmite in bisphenol A polycarbonate acrylonitrile-butadienestyrene blends, *Polymer Degradation and Stability*, Vol. 93: 657–667, 2008.
 - [9] M. Grigonis, R. Mačiulaitis, V. Praniauskas, Ageing of Fire Coatings, (2012) *International Review of Civil Engineering (IRECE)*, 3 (1), pp. 71–78.
 - [10] Č. Jakimavičius, *Timber study* (Technologija, 2003).
 - [11] M. Nagrodzka, D. Maloziec, Impregnation of the wood by flame retardants, *Safety and fire technique*, Vol. 3: 69–75, 2011.
 - [12] D. Drysdale, An introduction to fire dynamics. Second edition. (John Wiley&sons, 1998).
 - [13] J. Jiang, J. Li, J. Hu, D. Fan, Effect of nitrogen phosphorus flame retardants on thermal degradation of wood, *Construction and Building Materials*, Vol. 24, Elsevier: 2633–2637, 2010.
 - [14] H. R. Taghiyari, Study on the effect of nano-silver impregnation on mechanical properties of heat-treated Populus nigra, *Wood Sci Technol*, 2010.
 - [15] T. Goodrich, N. Nawaz, S. Feih, B. Y. Lattimer, A. P. Mouritz, Hightemperature mechanical properties and thermal recovery of balsa wood, *J Wood Sci*, Vol. 56: 437–443, 2010.
 - [16] A. K. Bolling, J. Pagels, K. E. Yttri, L. Barregard, G. Sallsten, P. E. Schwarze, C. Boman, Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties, *Particle and Fibre Toxicology*, Vol. 6, 2009.
 - [17] B. Mahltig, C. Swaboda, A. Roessler, H. Bottcher, Functionalising wood by nanosol application, *Journal of Materials Chemistry*, Vol. 18: 3180–3192, 2008.
 - [18] R. Mačiulaitis, A. Jefimovas, P. Zdanevičius, Research of natural wood combustion and charring processes, *Journal of Civil Engineering and Management*, Vol. 18(Issue 5): 631–641, 2012.
 - [19] Z. Bednarek, M. Griškevičius, G. Šaučiuvėnas, Tensile, compressive and flexural strength reduction of timber in fire, *Engineering Structures and Technologies*, Vol. 1(Issue 3): 148–156, 2009.
 - [20] M. Otero, X. Gomez, A. I. Garcia, A. Moran, Effects of sewage sludge blending on the coal combustion: A thermogravimetric assessment, *Chemosphere*, Vol. 69: 1740–1750, 2007.
 - [21] S. Y. Yorulmaz, A. T. Atimtay, Investigation of combustion kinetics of treated and untreated waste wood samples with thermogravimetric analysis, *Fuel Processing Technology*, Vol. 90: 939–946, 2009.
 - [22] L. Helsen, E. Van den Bulck, S. Mullens, J. Mullens, Low-temperature pyrolysis of CCA-treated wood: thermogravimetric analysis, *Journal of Analytical and Applied Pyrolysis*, Vol. 52: 65–86, 1999.
 - [23] T. T. Fu, M. Q. Xiao, F. Chao, Investigation on combustion of fire retardant board under different N₂–O₂ mixture gas atmospheres by using thermogravimetric analysis, *Construction and Building Materials*, Vol. 25: 2076–2084, 2011.
 - [24] Y. Zhaosheng, M. Xiaoqian, L. Ao, Thermogravimetric analysis of rice and wheat straw catalytic combustion in air- and oxygen-enriched atmospheres, *Energy Conversion and Management*, Vol. 50: 561–566, 2009.
 - [25] disertacija Lipinko
 - [26] D. Lipinkas, R. Mačiulaitis, Further opportunities for development of the method for fire origin prognosis, *Journal of Civil Engineering and Management*, Vol. 11(Issue 4): 299–307, 2005.
 - [27] S. I. Taubkin, Fire and explosion, characteristics of their expertise (VNIPO, 1999).
 - [28] LST EN 13238:2010 Reaction to fire tests for building products - Conditioning procedures and general rules for selection of substrates, CEN, 2010, 11 p.
 - [29] K. Lukošius, New one side heating method for structures and its application for prediction of fire resistance of structures with separation function, Ph.D. dissertation, VGTU, Vilnius, 2004.
 - [30] LST EN 1363-1:2000 Fire resistance tests - Part 1: General requirements, CEN, 2000, 42 p.
 - [31] LST EN ISO 1716:2010 Reaction to fire tests for products - Determination of the gross heat of combustion (calorific value), CEN, 2010, 42 p.
 - [32] A. Demirbas, Carbonization ranking of selected biomass for charcoal, liquid and gaseous products, *Energy Conversion and Management*, Vol. 42(Issue 10): 1229–1238, 2001.

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