Chapter 7

Wood of Coniferous Trees: Reaction to Fire

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Additional information is available at the end of the chapter

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Abstract

This thesis investigates the reaction of wood of selected coniferous wood species (pine, fir, spruce, larch) to fire. The fact that coniferous wood might be taken from various parts of the tree, i.e., branches, trunk, or root, is also taken into consideration. We study changes in selected properties in relation to fire—weight loss, relative burning rate, charred layer, and (a)/(b) ratio. Results are then statistically evaluated.

Keywords: coniferous wood, fire, mass loss, testing methods, reaction to fire

1. Coniferous wood in forest fire

Climatic changes in Europe brought about a new phenomenon—forest fires. Fires regularly occur mainly in southern Europe—in Portugal, Spain, Greece, southern France, Croatia, and Mediterranean islands.

Slovakia is no exception—there were 136 recorded fires in 2016 causing the damage of 96,665 €. The worst situation came about in 2012 with 517 fires occurring on 170 ha of forest cover. The material damage came up to 793,860 €.

The most common causes of fires are campfires and the burning of grass, dry vegetation, waste, and trash. Statistics show exact causes of fires, size of the area, and damage done to vegetation. One of the biggest fires on the territory of Slovakia broke out in a hard to access mountain ridge. It was probably caused by unruly guests setting up fire on the mountain ridge near a tourist path. The fire claimed human lives. It emerged in the locality of Krompľa, on the border of Hrabušice and Betlanovce, not far from the national nature reserve Tri kopce. The terrain made it impossible for the fire equipment to reach the area. According to the estimates, 10 ha of forest burnt down. The territory, along with Záhorie, was the area with the most frequent reoccurrence of forest fires even in the past. Although forest fires were quite common in our territory in the past, they were not of such large scale and economic consequences [1, 2].

Due to climate change, the intensity of forest fires has risen. In addition, forest fires are influenced by more factors: slope of forest terrain, cardinal points, wind and fuel—tree types, their age, branch proportion, trunk, and root system.

The thesis treats the issue of fuel response of four selected types of coniferous wood and their reaction to thermal stress in constant conditions. The four types of trees are as follows: Scotch pine (*Pinus sylvestris L.*), European silver fir (*Abies alba Mill.*), Norway spruce (*Picea abies* (*L.*) *Karst.*), and European larch (*Larix decidua Mill.*). These conditions simulate an emerging fire.

Anticipated contribution of the thesis is to recommend fire protection measures based on risk assessment of the type and quantity of fuel in a forest area. The issue became relevant after the wind-whirl in the High Tatras in November 2004 and the subsequent fires in 2005. Of the 13 fires, the largest occurred on July 30, 2005 (e.g., **Figure 1**) [3, 4].

Figure 1. Fire of calamity in High Tatras, July 30, 2005.

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2. Overview of current situation

2.1. Wood: flammable material

Wood is obtained mainly from treelike plants. Different parts of the tree (root, trunk, and tree crown) have different functions and usability.

Chemistry in a live tree indicates chemical composition of necrotic cells (cell walls and lumens—intercellular spaces). From a chemical viewpoint, wood is a complicated complex of heterogeneous biopolymers (90–97%) so-called major components accompanied by smaller quantities of accompanying components (3–10%). Main components of wood are represented by saccharide share (65–75%), composed of cellulose (40–50%), and hemicelluloses, plus aromatic share formed by lignin (15–35%). Accompanying (accessory) components of wood are formed by organic substances, monomers and polymers, as well as by inorganic ones. In addition to organic substances, which are an essential part of wood, wood also contains mineral substances creating ash during combustion.

Cellulose is a high molecular polysaccharide consisting of B-D-anhydro-derivate of beta-D glucopyranose (1➔4) [5]. For wood, the average polymerization degree of natural cellulose evaluated viscosymetrically is 4000–5500. One part of cellulose chains remains in amorphous arrangement while continuous transition between crystalline and amorphous share can be observed. Cellulose chains are maintained by hydrogen bonds between hydroxy groups of neighboring cellulosic chains.

Hemicelluloses are composed of heteropolysaccharides with lower polymerization degree (mostly 100–200). The main components are pentose and hexose: L-rhamnose, L-fructose, L-arabinose, D-xylose, D-mannose, D-glucose, and D-galactose. Hemicelluloses are amorphous and contain neutral or acidic cross-linked fibers. Coniferous plants contain glucomannans, the main hemicellulose component. Depending on the type of plant, their amount ranges from 20 to 30% [6]. Lignin is a benzenoid component of some plants containing benzene core with propane chain, phenolic hydroxyl groups, and forms a three-dimensional macromolecule.

2.2. Wood characteristic after thermal degradation

2.2.1. Change in chemical composition

There are materials entering the reaction with oxygen (e.g., metals) or which, in the first stage of heating, change their chemical composition, or the composition of their core building elements, produce flammable gases and begin to burn. Wood belongs to this category too. Main components of wood degrade at different temperatures affecting the whole process of combustion.

Hemicelluloses will decompose under temperatures ranging between 170 and 240°C. They are the least resistant to thermal decomposition. By regulating wood heating, we may achieve reduction of hemicelluloses without reducing its strength, resulting in an increase in dimensional stability of wood [7, 8].

Cellulose is more resistant to thermal stress than hemicelluloses. The decomposition rate of cellulose is moderate up to 250°C. Intensive decomposition of cellulose is observed at the temperatures of 250–300°C. It leads to disruption of links in the main chain according to a radical mechanism; the tail link of cellulose turns into levoglucosan [9].

Lignin is the most resistant to thermal decomposition. Process of the thermal decomposition of lignin is divided into two stages. In the first stage, labile ether alkyl links decompose at the temperatures of 300–320°C. The second stage is an active decomposition of lignin at the temperatures of 350–390°C. The structure of macromolecules is disrupted and volatile products are being released. Formation of volatile products is lower than with cellulose. Decomposition rate is slowing down by increasing the temperature and is followed by accumulation of condensing aromatic structures in the solid phase [10].

Wood exposed to temperatures higher than 288°C (temperature generally assumed as charring temperature) can be divided into five degradation zones [11]. The variety of the decomposition of main wood components and characteristic reactions in different temperature intervals lead to differentiation of burning process into several stages.

2.2.2. Changes in anatomical structure

The anatomical structure itself, individual cell elements, affects the process of combustion, its first phase—ignition—in particular. It results mainly from chemical composition and geometric shape of cellular elements, their size, and their number.

2.2.3. Changes in physical characteristics

In addition to chemical composition, physical properties of wood and wood-based materials significantly influence the course of combustion. Each physical property has an impact on burning, though not to the same degree.

The thesis does not represent a comprehensive assessment of physical properties during wood combustion. The following properties have been chosen: wood density, its surface, moist level, thermal properties, and geometric shape.

The thicker the material is (the same volume, but it is heavier), the more energy is needed for ignition and combustion. Some claims distinguishing flammability levels of woody plants according to their density are wrong. Chemical composition is more important, e.g., woody plants with higher content of hemicelluloses are easier to be ignited even if they have higher density level. With the same chemical composition (same percentage represented by the main wood components), the impact of density on ignition and burning manifests itself. The impact of density on ignitability is more significant with large wood-based materials [12].

Surface of the material (its quality) is another physical characteristic, which significantly affects combustion. Wood, capillary-porous material, is rough on the surface. The roughness depends on working as well as on the anatomical structure of wood. Besides roughness, surface quality also depends on anatomical defects, defects resulting from working, mechanical damage, dirt, etc., changing the surface quality. Surface quality mainly affects thermal conductivity α. The smooth and high-quality surface reflects the energy of radiation source and flame source thus making it more difficult for the wood to be ignited compared to the rough surface under the same test conditions.

From the point of view of quality, working is as important as the color of wood. The natural color of the wood (including tropical woody plants) comprises the entire color range. Thermal degradation causes color changes. The light color of wood gradually darkens and finally turns black, charred layer. The intensity of darkening depends on heat rate and temperature—several authors treated the subject. The color change is brought about by polysaccharide degradation (hemicelluloses and cellulose). The final stage, creation of charred layer, occurs in every single case. The charred layer is of black color, a good absorbent of thermal radiation. Its chemical composition and porous structure is, at the same time, a bad heat conductor. Therefore, charred layer represents auto-retarding nature of wood, which is taken into consideration in practice.

Color change also influences wood quality. Charred layer is formed due to changes at all levels: changes in chemical composition, supermolecular structure, anatomical structure, as well as macroscopic structure. An interesting study was introduced by who monitored changes in chemical composition of wood immediately after removing the charred layer [13].

As mentioned above, charred layer has an auto-retarding character and plays a role in the process of wood burning of load-bearing structures. We assume that it will play its role in forest fires too, but it is not clear whether this property will have positive or negative impact. As the fire progresses, charred layer remains in relatively cold environment preventing the girder or other wooden building elements from burning. During forest fire, charred layer smolders mostly in the root system situated in overheated soil. Environment cools down very slowly. Air flow is caused by climatic conditions, or is caused by temperature differences caused by the fire. This flow can also bring about secondary combustion of unburnt fuel (e.g., **Figure 2**).

2.3. Coniferous wood in forest fires

Forest fire is an extremely harmful factor that is detrimental to all components of forest biocenose, biotope as well as plant and animal component. It is a sudden, partially, or fully uncontrolled time and space-limited emergency event, which has a negative impact on all social functions of forest. It causes direct and indirect damages and, according to the method of its development, it belongs to anthropogenic (which are more common in Slovakia) or natural harmful factors. It is a complex of physico-chemical phenomena based on unstationary (changing in space and time) processes of combustion, gas exchange, and heat transfer [14].

In general, forest fires are mainly caused by natural conditions and man himself. They are often caused by human negligence, failure to observe fire protection measures—no fire, no smoking, no grass burning, no brushwood burning, playing with matches, etc.—or by underestimating the danger when making an open fire. Cases of arson are very rare.

Figure 2. Color change of wood and its estimated thermal degradation (after removing charred layers, cuts of 1 mm in thickness have been made).

In addition, these fires are more dangerous since they occur in the areas which are hard to access for fire brigade and their equipment, with insufficient or unfit resources of water for fire fighting purpose, and require enormous deployment of people, special fire, or aviation technology [15].

According to the type of flammable substances, forest fires belong to class A, fires of solid substances of organic origin. Forest fire can be characterized as a process of burning of the whole array of organic materials which form forest cover. At temperatures of 80–150°C, water in the tissue and wood is lost. At the wood self-ignite is at the temperature of about 300°C. At the temperatures above 450°C, gases, which are being released from wood, ignite in contact with the outside air and at the temperatures above 600°C, wood itself becomes a source of combustion. During burning, temperature of flame comes up to 700–800°C. In the process of burning of a tree crown of coniferous tree, temperatures rise up to 1000°C with the height of the flame up to 100 m. In the process of burning of coniferous forest, the temperature of the flame comes up to 1300°C.

Forest fires are divided according to different criteria. In forestry as well as fire practice, they are most commonly divided into:

- underground fires,
- ground fires, and
- ring fires.

The above-mentioned types of fires are described in details. Fire in the area hit by wind-whirl has its own specific features, which do not allow its unequivocal inclusion into the above-mentioned classification. A new category has been formed, fire of devastated area. This type of fire is characterized as follows:

- Surface of the fire is not differentiated according to height as in the above-mentioned division; it is made up of broken wood, uprooted trees, standing trees, remnants of decaying trees (dead wood), herb cover, and forest floor.
- Distribution of wood material is uneven, wood is stacked in layers several meters high "including" parts of tree crowns with assimilation apparatus also in ground layers.
- After processing such wood, a large number of logging waste remains in the area representing a potential risk resulting in formation and spread of fire.
- Ignition followed by combustion may be area-wide, long-term (lasting several days), throughout the whole area of the fire, not only in its "head" (principle of a bonfire or "pyre").
- Devastated area is, compared to other types of fire, difficult to access because of temporary cessation of forest transport networks and piled-up wind-throw mass.

Therefore, it is imperative to be aware of all aspects and risks of forest fires, their development and behavior, system of prevention, monitoring, modern, effective, ecological, economic and safe fire-fighting methods as well as consequences and methods of their elimination or clean-up [16].

3. Wood: flammable material

The thesis treats the issue of forest fires, explaining causes of its formation and rapid development. Its objective is to examine the reaction of different conifers to forest fire. Forest fires (ring, ground, and underground fires) were quite common on other continents, but nowadays, they are becoming a problem in Europe too, particularly its southern regions. Fire in devastated area has not been mentioned in any foreign written source. In the area affected by wind-whirl, the "forest" (blown down trees) is burning but in a different form and in a different way than with common forest fires. Results of the thesis may be incorporated into fuel models that can model this type of fire for fire and rescue services. Heat sources and conditions of the experiment characterize change in wood properties during its thermal degradation. Branch, trunk, and root have been exposed to these heat sources and their influence on the development of fire has been observed.

The goal of the thesis is to find out, assess, and compare the reaction of selected coniferous woody plants to conditions simulating fire. Fire in the experiment is seen as forest fire. This is given by the selection of tree parts (branch, trunk, and root), which means all forms of fuel are represented such as crown, above-ground, ground segments as well as fire of devastated area.

Thermal stress represents one source of ignition. Homogeneity of the source—one heat, radiant source has been designed for this purpose so that the results were comparable and selected evaluation criteria were influenced by the fuel type only.

Distance—position of fuel (test specimen) from the heat source was chosen so that the temperature of the source may manifest itself and, at the same time, the sensitivity of the measurement has been ensured. Therefore, the difference between the distances is 5 mm only.

Evaluation criteria—are the fundamental changes in physical parameters (weight loss, thickness of charred layer, relative burning rate, and (a)/(b) ratio—represents relative burning rate divided by the time the highest relative burning rate was measured).

The given criteria, qualitative selection of fuel and evaluation criteria shall determine the sensitivity of the selected coniferous woody plants to the reactions simulating fire conditions.

Phrasing of those objectives of the thesis is based on several initiatives, including, in particular, my personal experience, as well as the discussions and tutorials with experts of state administration bodies and many experts from practice.

When drawing up the doctoral thesis, several methods of research were used: analysis, synthesis, abstraction, comparison, induction, and deduction.

In the initial stage, analysis, comparison, and synthesis were used, whereas in the final phase, the methods of induction and deduction, comparison and subsequent formulation of regularities of the given phenomena have been applied [17].

Using system approach, the research of the thesis has been carried out in the following three stages:

- Collection, sorting, and data processing

All necessary information has been obtained from various sources. We utilized all available resources from documentary records and bibliographic research to bibliographic literature, scientific articles from professional journals, proceedings from various conferences, information from various seminars, scientific and research thesis, reports of state administration and other institutions, internet resources and, last but not least, personal tutorials or other forms of communication with officers of some state administration bodies and institutions (in particular Department of Fire Prevention, County Departments of Fire and Rescue Services, Faculty of Wood Sciences and Technology in Zvolen). While sorting, studying, and processing the information, analytic, and synthetic method have been used, contributing to the subtheoretical knowledge and conclusions.

- Synthesis of partial results

After further sorting, partial results of analyses performed provide basis for formulating synthetic knowledge in the given field.

- Application of acquired knowledge

In the final phase, the knowledge and conclusions we came up with were arranged in mutual contexts so as to provide and enable theoretical and practical applicability while improving the phenomena monitored.

4. Methods

4.1. Coniferous wood after thermal degradation

Test specimens were made up from four selected types of coniferous woody plants: Scotch pine (*Pinus sylvestris L.*), European silver fir (*Abies alba Mill.*), Norway spruce (*Picea abies* (*L.*) *Karst.*), and European larch (*Larix decidua* Mill.).

Test specimens were prepared from 1-m-long trunks (pine, fir, spruce, larch). After dressing the trunks—removing the bark and cutting it into boards—the process of drying to constant moisture of 8 ± 2% followed. The boards of 10×12×150 mm were then cup up. No surface finish was used for the test specimens. Test specimens from branches and roots have been cut in the same way as the trunk. The diameter of the branches and roots was 60 mm. See **Figures 3–7**.

Figure 3. Scotch pine (*Pinus sylvestris L.*).

Figure 4. European silver fir (*Abies alba Mill.*).

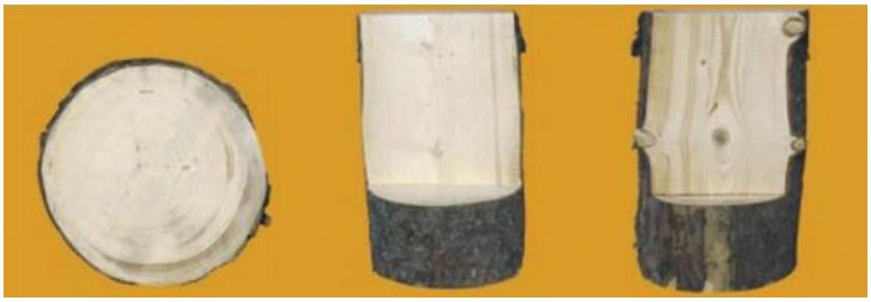

Figure 5. Norway spruce (*Picea abies (L.) Karst.*).

Figure 6. European larch (*Larix decidua Mill.*).

4.2. Heat load

4.2.1. Apparatus

Simple device—consisting of scales, asbestos boards (to protect scales against heat radiation), stand, support frame, radiant heat source (radiator), and clamp holder for test specimens—was used for the experiments.

The apparatus (e.g., **Figure 8**) is composed of electronic weighing scales, Sartorius Basic plus type BDBC from Sartorius AG Company, I. class of accuracy with non-automatic weighing instruments, measuring with an accuracy of two decimal places and the maximum weight 2100 g [18].

Figure 7. Testing samples.

4.2.2. Radiant heat source

Infrared heater is used as a heat radiation source. Heat transfer from the heater was carried out by diffusion of electromagnetic radiation of 0.75–12 Jm of wavelength which is, after being absorbed by a solid, transformed into heat. Infrared heater of T-5 class by Electro Prague was used for the experiment. The heater is of a flat shape, bent slightly into arch shape in the direction of the longitudinal axis of the body. Radiation was given off by the front side, back side, and front edges of the heater. Side edges of the heater were neglected due to their low significance in heat transfer. The emitting body is made from special ceramics, cordierite. The material is highly resistant to sudden changes of temperature with differences in temperatures greater than 70°C as well as resistant to high temperatures (1100°C).

The emitting body is equipped with a thin aluminum parabola. Electromagnetic radiation is common in the nature as every single body emits it. Wavelength or frequency depends on the temperature of the solid. As the temperature of the solid changes, its color changes as well [18].

Dimensions and parameters of the heater (e.g., **Figure 9**):

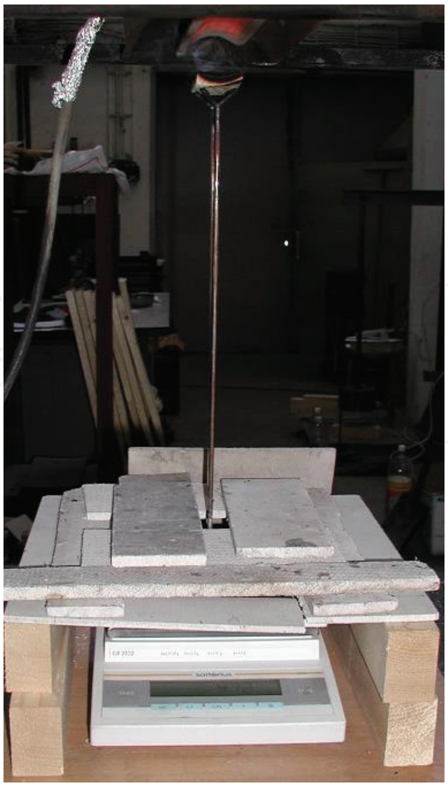

Figure 8. Apparatus.

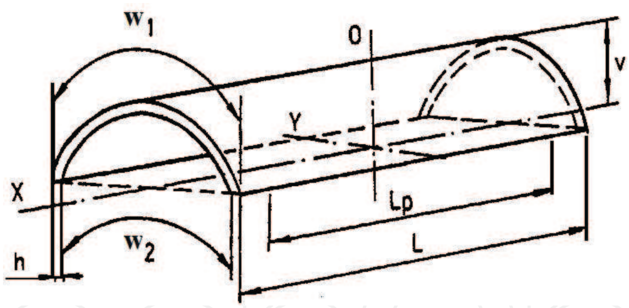

Figure 9. Dimensions and parameters of the heater.

Total length: l = 245 mm

Working length: lp = 200 mm

Outer width: w_1 = 85 mm

Inner width: w_2 = 64 mm

Thickness: h = 5 mm

Height: v = 30 mm

Temperature (30 mm from the radiator): t = 130°C

4.2.3. Test procedure

Test procedure is as follows. Heater has been warming up for 15 min. After 15 min, a sample has been mounted into the clamp holder and exposed to radiant heat for 3 min. For each woody plant type, 15 tests will be conducted. time will be constant: set to 3 min. The only variable is the distance from the heater—30, 35, 40, 45, and 50 mm. For every single specimen, weight loss will be recorded after 15 s and relative burning rate will be calculated. In case the test specimen ignites, it will be put off after 3 min. Each test specimen will be measured before the test, including its thickness. After cooling down, charred layer will be determined. Charred layer will be removed up to the healthy/undamaged wood.

4.3. Evaluation criteria

4.3.1. Weight loss

Weight loss will be recorded while the sample is exposed to the radiant heat source. Relative weight loss will be calculated according to Eq. (1) [18].

$$\delta_m(\tau) = \frac{\Delta m}{m_{(\tau)}}.100 = \frac{m_{(\tau)} - m_{(\tau+\Delta\tau)}}{m_{(\tau)}}.100 \ [\%] \tag{1}$$

where $\delta_m(\tau)$ is the relative weight loss in time (τ) [%], $m_{(\tau)}$ is the weight of the sample in time (τ) [g], $m(\tau + \Delta\tau)$ is the weight of the sample in time ($\tau + \Delta\tau$) [g], and Δm is the difference in weights [g].

4.3.2. Charred layer

Charred layer will be determined, and the thickness of charred layer will be calculated as the ratio of original thickness of test specimen and the thickness of test specimen after the test. The percentage will be determined according to Eq. (2) [18].

$$\Delta h = 100 - \left(\frac{h_1 - h_2}{h_1}.100\right)[\%] \tag{2}$$

where Δh is the thickness of charred layer after the test/thermal stress [%], h is the thickness of the test specimen before the test [mm], and h_2 is the thickness of the test specimen after the test [mm].

4.3.3. Relative burning rate

Relative burning rate is determined according to Eqs. (3) and (4) [18]:

$$v_r = \left|\frac{\partial \delta_m}{\partial \tau}\right| [\% \ \ s^{-1}] \tag{3}$$

or numerically.

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$$v_r = \frac{\left|\delta_{m_{(\tau)}} - \delta_{m_{(\tau+\Delta\tau)}}\right|}{\Delta\tau} [\%\ \ s^{-1}] \tag{4}$$

where v_r is the relative burning rate [% s^{-1}], $\delta_{m(\tau)}$ is the relative weight loss in time (τ) [%], $\delta m_{(\tau + \Delta\tau)}$ is the relative weight loss in time ($\tau + \Delta\tau$) [%], and $\Delta\tau$ is the time interval at which weights are subtracted [s].

4.3.4. (a)/(b) ratio

Relative burning rate is an important figure; however, it is also important to know when, throughout the experiment, the peak of relative burning rate was measured. If this value is measured at an early stage, it is a material which contributes to the development of fire in an intensive way. If this happens in the final stage of the experiment, this material will have a more positive assessment. The ratio between relative burning rate and the time necessary to achieve its highest value was used in several experiments and test methods for fire protection purpose. Experimental device measured both types of data, so the thesis presents the ratio between relative burning rate (a) and the time necessary to achieve its peak (b) which has given the name to "(a)/(b) ratio," which is numerically multiplied by 106 so that the figure had better information value.

4.4. Statistical evaluation

Data obtained are processed using Statistica 7 program. Multiple factor analysis of dispersion has been used. When using multiple factor analysis of dispersion, we observed the effect of several qualitative or quantitative factors (in the given discrete values) on the values of the observed property of wood (weight loss, charred layer, the relative burning rate, and (a)/(b) ratio). In our case, the factors are as follows:

- distance of heat source from the sample,
- type of coniferous trees,
- time recorded every 15 s.

In case we prove that factors are interrelated (time and distance), their statistically significant effect will be assessed by regression analysis, see Eq. (5). [18]

$$y = ax + b \tag{5}$$

where a is the time and b is the evaluation criteria.

5. Results

To make it clear, measured values are shown in the tables.

Average values of all measurements are shown in **Table 1**.

Wood	Place	Distance [mm]	Weight loss [%]	Charred layer [%]	Relative burning rate [% s^{-1}]	Max. relative burning rate [s]	(a)/(b) ratio [% s^{-2}]	Density [kg m^{-3}]
Pine	Branch	30	13.82	23.23	0.001242	160	7.76	444.83
		35	11.88	19.63	0.000869	150	5.79	451.41
		40	7.15	7.95	0.000564	130	4.34	455.94
		45	5.46	4.58	0.000413	140	2.95	463.40
		50	4.63	3.21	0.000372	82.5	4.51	435.76
	Trunk	30	71.56	100.00	0.008611	137.5	62.63	418.22
		35	14.53	15.03	0.001259	162.5	7.74	425.94
		40	13.71	9.12	0.001244	157.5	7.90	400.93
		45	9.41	6.05	0.000708	85	8.33	391.35
		50	6.98	2.51	0.000559	102.5	5.45	398.76
	Root	30	25.38	40.45	0.002707	142.5	19.00	440.58
		35	17.28	21.51	0.001972	167.5	11.77	439.43
		40	9.07	18.07	0.000834	152.5	5.47	429.81
		45	6.49	10.71	0.000641	167.5	3.83	414.79
		50	5.43	8.35	0.000448	160	2.80	412.95
Fir	Branch	30	15.20	23.92	0.001400	110	12.73	561.81
		35	10.33	17.89	0.000774	140	5.53	546.63
		40	7.34	10.27	0.000520	112.5	4.63	543.30
		45	5.16	6.40	0.001469	155	9.48	541.09
		50	4.02	4.90	0.000404	167.5	2.41	539.75
	Trunk	30	67.64	84.70	0.008461	147.5	57.36	418.78
		35	18.09	20.21	0.001654	175	9.45	442.31
		40	11.35	7.37	0.000913	145	6.30	500.71
		45	7.74	4.17	0.000644	142.5	4.52	503.22
		50	6.27	2.96	0.000510	155	3.29	483.78
	Root	30	29.34	42.14	0.004161	162.5	25.60	519.61
		35	13.62	21.47	0.001324	167.5	7.90	508.48
		40	11.54	18.66	0.001427	170	8.39	521.02
		45	7.37	9.55	0.000663	175	3.79	515.31
		50	5.60	7.67	0.000518	172.5	3.00	512.15

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Wood	Place	Distance [mm]	Weight loss [%]	Charred layer [%]	Relative burning rate [% s⁻¹]	Max. relative burning rate [s]	(a)/(b) ratio [% s⁻²]	Density [kg m⁻³]
Spruce	Branch	30	14.73	20.10	0.001217	142.5	8.54	646.95
		35	10.05	14.25	0.000801	130	6.16	589.27
		40	7.00	6.01	0.000564	137.5	4.10	609.73
		45	6.11	2.96	0.000411	145	2.84	635.59
		50	4.79	2.14	0.000445	140	3.18	2.14
	Trunk	30	86.55	100.00	0.009462	110	86.02	351.65
		35	34.38	36.32	0.001213	162.5	7.47	368.28
		40	17.77	22.94	0.001692	165	10.25	345.98
		45	9.56	5.15	0.000774	120	6.45	358.82
		50	8.34	4.84	0.000657	100	6.57	337.61
	Root	30	30.48	44.40	0.002491	150	16.61	463.25
		35	15.07	22.16	0.001506	162.5	9.27	470.60
		40	11.00	17.79	0.000913	140	6.52	560.57
		45	5.46	9.79	0.000398	132.5	3.01	483.82
		50	5.24	5.65	0.000494	160	3.09	475.86
Larch	Branch	30	14.73	21.44	0.001235	105	11.76	633.71
		35	10.05	18.24	0.000986	95	10.38	568.48
		40	5.61	10.70	0.000507	175	2.90	612.67
		45	5.47	5.65	0.000398	175	2.28	628.42
		50	3.43	2.49	0.000387	75	5.15	618.09
	Trunk	30	36.21	29.64	0.004450	147.5	30.17	434.46
		35	12.68	12.42	0.000994	145	6.85	447.53
		40	10.35	7.53	0.000866	127.5	6.79	445.06
		45	7.35	3.06	0.000599	130	4.61	457.69
		50	6.83	1.58	0.000579	140	4.14	445.85
	Root	30	23.73	37.20	0.002533	170	14.90	470.46
		35	13.72	24.62	0.001199	167.5	7.16	482.56
		40	10.14	19.45	0.000943	130	7.25	482.59
		45	6.29	11.37	0.000873	167.5	5.21	482.24
		50	4.59	6.95	0.000639	180	3.55	506.80

Table 1. Average values of all measurements [19].

5.1. Evaluation and discussion

Monitored evaluation criteria have been assessed from two aspects: woody plant type and its position. Final evaluation is represented by dependence between the evaluation criteria. Size of charred layer, relative burning rate, and (a)/(b) ratio relate to weight loss, and the dependence between them is evaluated.

In all cases, it is a linear dependency. Graphic statistical evaluation is shown in **Figures 10–12**. In **Figure 10**, the correlation relationship between weight loss and charred layer for all types of woody plants and all positions is depicted. Linear dependence is given by the value r^2, which is equal to 0.948, the value close to 1. Such close dependencies are also found with the other evaluation criteria. **Figure 11** represents a correlation between weight loss and relative burning rate $r^2 = 0.922$ and **Figure 12** shows the correlative relation of weight loss and (a)/(b) ratio where $r^2 = 0.944$. These figures show the dependency evaluation for all measurements, regardless of the position and the type of woody plant. **Tables 2** and **3** show the equations of regression in linear form for each correlation, evaluation criteria, types of woody plants and their position.

In general, it is possible to conclude that the trunk of spruce showed the worst values given the criteria, which is necessary to be taken into account from the fire fighting point of view. There are also differences between positions within one type of woody plant. This means that when reviewing the fuel in devastated area, it is necessary to assort the quantities of fuel.

5.2. Theoretical and practical contribution

Scientific contribution of the thesis is to complement the data that characterize the fuel monitored for fire protection purpose. Meeting the target consists on finding out certain values that can be applied into computer models of fire. The thesis provides instructions for further experimental

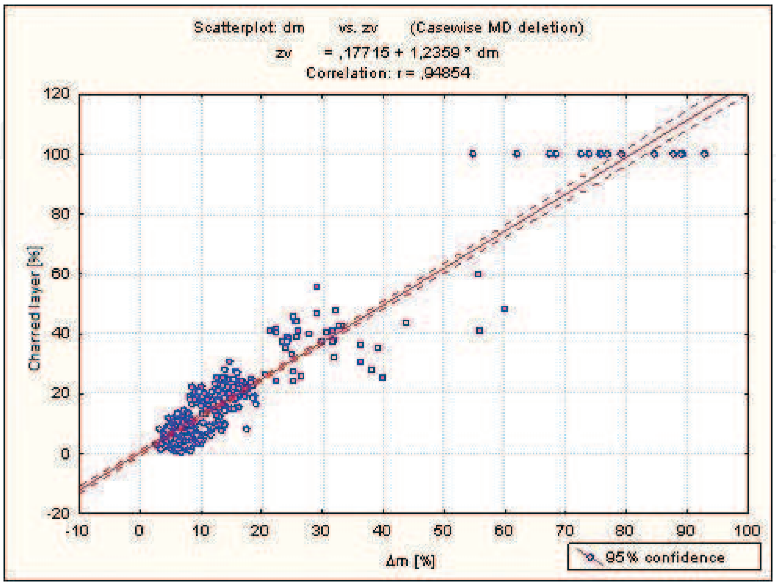

Figure 10. Correlation relations of weight loss and thickness of charred layer for all measurements (woody plants and their positions).

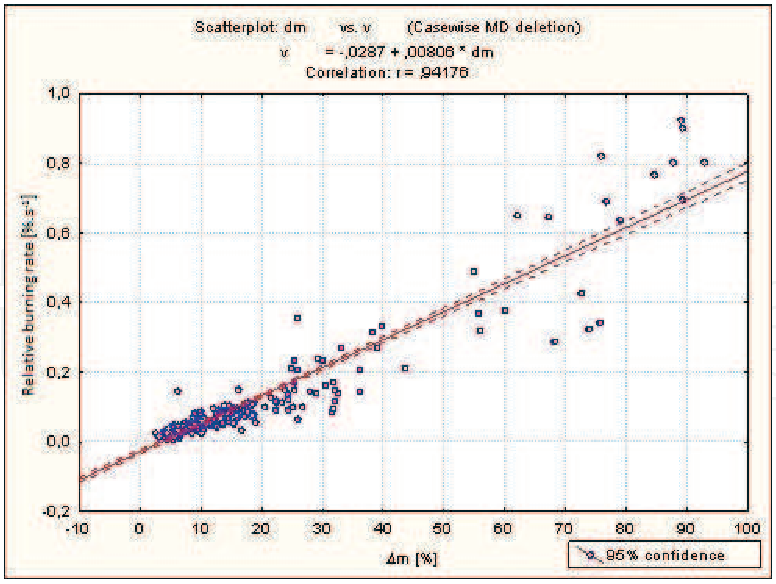

Figure 11. Correlation relations of weight loss and relative burning rate for all measurements (woody plants and their positions).

work that could be diversified into other measurements, research into further physical changes, or chemical properties of selected woody plants and their parts. The conclusions of these recommendations could then answer the question of why there are differences within a single woody plant and why there are differences within the same group of woody plants, coniferous woody plants. Moreover, evaluation of parameters of other non-wood parts seems crucial since they may contribute to rapid development of forest fire (needle layers, leaves, groups of shrubs, etc.).

A practical contribution lies in finding other properties of fuel, specification of the risks that are taken into account within operational plans, and projects for risk assessment of forest fire

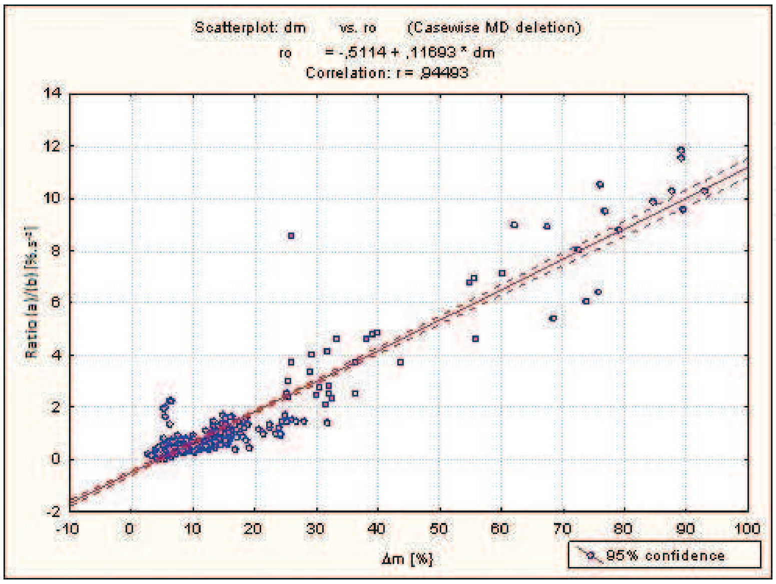

Figure 12. Correlation relations of weight loss and (a)/(b) ratio for all measurements (woody plants and their position).

Criterion	Woody plant	Regression equation	Value of r^2
Thickness ofcharred layer [%]	Pine	y = 1.3824x − 1167	0.959
	Fir	y = 1.2993x − 0.2893	0.960
	Spruce	y = 1.1652x + 0.26212	0.974
	Larch	y = 0.94483x + 3.3748	0.772
Relative burning rate [% s⁻¹]	Pine	y = 0.0098x − 0.0346	0.959
	Fir	Y = 0.0051x + 0.0001	0.839
	Spruce	y = 0.0095x − 0.0488	0.949
	Larch	y = 0.0061x − 0.0053	0.852
(a)/(b)ratio [% s⁻²]	Pine	y = 0.1226x − 0.6248	0.939
	Fir	y = 0.0998x − 0.173	0.750
	Spruce	y = 0.1279x − 0.6566	0.964
	Larch	y = 0.0855x − 0.2591	0.811

Table 2. Regression equation in linear form and the r^2 value for correlations of evaluation criteria for the given types of woody plants.

Criterion	Position	Regression equation	Value of r^2
Thickness of charred layer [%]	Branch	y = 1.6639x − 2592	0.855
	Trunk	y = +1.2902x − 5718	0.972
	Root	y = +1.4117x + 1.7700	0.949
Relative burning rate [% s⁻¹]	Branch	y = 0.0048x + 0.0032	0.581
	Trunk	y = 0.0085x − 0.0415	0.902
	Root	y = 0.0059x − 0.0025	0.708
(a)/(b) ratio [% s⁻²]	Branch	y = 0.0619x + 0.0061	0.534
	Trunk	y = 0.1236x − 0.7564	0.952
	Root	y = 0.0905x − 0.1389	0.464

Table 3. Regression equation in linear form and the value of r^2 for correlations of evaluation criteria in the given positions.

or devastated area. On the basis of the above-mentioned procedures, the readiness and amenities of fire-fighting units in certain locations will be optimized. Quality evaluation of woody plants will help to ensure that, in addition to forestry assessment of the suitability of woody plants (i.e., into fire-fighting belts), it will also use other assessment such as fire-fighting.

6. Conclusion

Forest fires have always been a part of people's life on our territory. They are quite common even today and their "quality" as well as their quantity changed for the worse. They are more extensive, more difficult to extinguish in terms of intervention and fire-fighting procedures, especially in our mountain areas. Special fire-extinguishing equipment as well as aviation technology must be used. The difficulty level of intervention, its length as well as economic costs have changed. The problem needs to be dealt with comprehensively (as in every single field of multidisciplinary fire protection) meaning that it needs to be dealt with not only by using modern equipment, tactics but also by studying fuel and by conducting further scientific research.

This thesis should contribute to this solution. Evaluation of individual woody plants (found in various types of literature) was carried out for fire protection purpose assessing wood as building material. Woody plants were divided into hard and soft and/or broad-leaved and coniferous trees. The first hypothesis of our experiment supposed certain degree of homogeneity between the selected coniferous trees, or between different tree parts (branch, root, and trunk) within a single woody plant. Confirming this hypothesis (homogeneity) would mean expressing certain value that could be incorporated into model software programs of forest fire modeling (e.g., FireSite).

However, it turned out the second hypothesis has been correct: there will be differences between the selected woody plants and differences within a single tree type. This hypothesis resulted from the contrast of the first one as well as from personal experience of fire-fighters and boy scouts. Fire-fighters run into problems while extinguishing underground fires (root system burning) and every boy scout knows that to make a good bonfire, wood from root system is needed. To come up with a complex solution, all three parts (branch, trunk, and root) were suggested which is given by tree physiology. During forest fires, trunk is in a different position than when dealing with devastated area fire where trunks are in "horizontal" position. Amount of fuel of different quality (branch, root, and trunk) is possible to identify, to some extent, from forest management plans on the basis of forest cover density, age of the tree, location, growth, etc. Parameters such as how individual components of wood react to heat, fire, and how quickly they contribute to development of fire were missing. This thesis should complete these data.

The thesis results confirmed the second hypothesis: there are differences between different types of conifers such as pine, fir, spruce, and larch, even in the position within the tree (branch, trunk, root). Surprisingly, the worst results have been recorded for the most common woody plant—spruce. All parameters that have been monitored reached their peak for this tree type. Weight loss, as one of the selected parameters, was chosen since the change in this physical property represents standard and basic assessment criteria of materials which are tested for fire protection purpose. Charred layer, formed in the process of burning, a property of wood that is very welcome in wooden constructions (its auto-retardant nature, mainly in the process of burning of root system), indirectly represents the length of its burning, or more precisely smoldering. This effect is very dangerous in terms of re-ignition of forest fire.

Other monitored properties, such as relative burning rate and (a)/(b) ratio, characterize certain speed at which material shall contribute to development of fire. These four selected types of observations were statistically evaluated the way it is referred to in the previous chapter.

The results are comparable with literature, in particular in terms of charred layer thickness and burning rate. Only data for spruce wood and its trunk can be compared with other literature. Other parts of woody plants, such as branch and root, are not described in any available literature. This also applies to other types of woody plants that we monitored and which have been described for wood practice purpose, not for fire protection purpose. This thesis brings new knowledge of the above-mentioned woody plants and their behavior in fire conditions.

Such comprehensive solution can make it possible to fight forest fires that are common in our territory.

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