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DETERMINATION OF FIRE CHARACTERISTICS OF SPRUCE WOOD BY NEW MEDIUM-SCALE LABORATORY METHOD

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ABSTRACT

The paper is focused on the evaluation of spruce wood (*Picea abies* L.) used in building construction using the new medium-scaled test method, which is a modification of the standard test method according to standard STN EN ISO 11925-2. The significance of the new medium-scale test method lies in its accessibility compared to standard test methods and in the ability to test samples of various dimensions (lengths up to 1 meter) at different angles of exposure to the heat source. The new medium-scale method is based on exposing the samples (300 × 100 × 100 mm) to a 1 kW flame source for 1800 s. The test setup was placed on the laboratory scale with thermocouples placed in the samples for the duration of the test. This enabled us to measure the mass loss, temperature courses, charred layer depth, and charring rate. With this method, the mentioned parameters were determined for three different angles of inclination (0°, 45°, 90°) for the samples, which simulate the actual placement of a wooden building element in a structure. Values of mass loss ranged from 3.33 ± 0.62% (0° angle) to 4.66 ± 0.33% (90° angle). The temperature courses at the angles of inclination 90° and 45° were similar. Nevertheless, at the 90° angle, the maximum temperature reached was 75.6°C lower. The charring rate reached its maximum value of 0.49 $\mathrm{mm \cdot min^{-1}}$ at an inclination angle of 45°. The results showed the influence of the angle of inclination and wood grain directions on fire characteristics.

Keywords: angles of inclination of the samples; charred layer; lignocellulosic material; mass loss; temperature courses.

INTRODUCTION

The paper is focused on the evaluation of spruce wood (*Picea abies* L.) Nowadays, many factors influence the choice of building materials. In addition to suitable physical and mechanical properties, environmental impact is essential in evaluating materials (Kadlicová *et al*., 2017). Wood, thanks to its unique combination of properties, such as easy processing and good physical and mechanical properties, has been and remains a very important lignocellulosic material used as a construction material (Popescu and Pfriem, 2020). It is a material characterized by a relatively inhomogeneous, anisotropic structure and consists of a complex of macromolecular substances (cellulose, hemicelluloses, lignin) and extractive substances (Dietenberger, 2002). The structures of the mentioned polymers can vary significantly depending on the type of wood. Wood polymers of coniferous trees have a different structure compared to those of deciduous trees (Lowden and Hull, 2013).

The main components of wood – cellulose, hemicelluloses, and lignin – are to some extent susceptible to damage by abiotic influences (UV radiation, water, sun, oxygen), biological pests (fungi, insects, bacteria), and degradation processes when exposed to higher temperatures – fire (Reinprecht, 2016). The use of wood in construction is often questioned precisely because of its flammability. Flammability is a general term that describes the properties of a material in response to fire. It cannot be expressed by a single value because it is influenced by several parameters (Giudice and Canosa, 2017; Quintiere, 2017). Flammability assessment methods are essential in evaluating materials and flame retardants. Most experiments commonly used aim to determine the following fire properties of materials: ease of ignition; flame spread rate; heat release rate; and the rate of development, quantity, and composition of smoke released in individual phases of the fire. According to several authors, the most important parameter for determining fire hazard is the Heat Release Rate (HRR) (Friedman *et al.*, 2003; Lyon and Walters, 2002).

Currently, fire protection of materials is an integral part of the design and construction of a wide range of buildings and products. Medium-scale testing of materials and products is a key process for assessing performance and ensuring fire resistance. These tests provide valuable information on the reaction of materials to high temperatures and intense thermal loads, enabling them to be identified and optimized.

A large number of standardized and non-standardized test methods are used for testing materials. Standardized test methods are primarily used to demonstrate compliance with the requirements imposed on a material or product by applicable legal regulations. Non-standardized test methods are primarily used in science and research, but also in determining the causes of fires (Martinka and Balog, 2014).

Flame spread is a fire characteristic that affects the entire combustion process. The rate of fire development also depends on how quickly the flame can spread across the surface of a flammable material. Flame spread can be considered as a progressive ignition in which the leading edge of the flame acts as both a heat source and an initiation source. The rate of flame spread can depend on a material's physical properties and chemical composition. Unlike the surfaces of liquids, the surface of a solid can be oriented in any direction, which can significantly affect flame spread. This is especially true for flame spread, as it is controlled by the mechanism that transfers heat ahead of the burning zone, which is strongly influenced by the surface geometry and slope (Drysdale 2011; Huang *et al.,* 2015; Kobayashia *et al.,* 2017; Pizzo *et al.,* 2009).

The flame spreads over the material's surface immediately after ignition, but it spreads faster when it is an upward flame on a vertically oriented fuel surface. This is due to the change in the physical interaction between the flame and the unburned fuel when the fuel orientation changes, i.e., the direction of propagation of the released flammable gases changes (upward) relative to the direction of flame propagation (Quintiere, 2017; Drysdale, 2011).

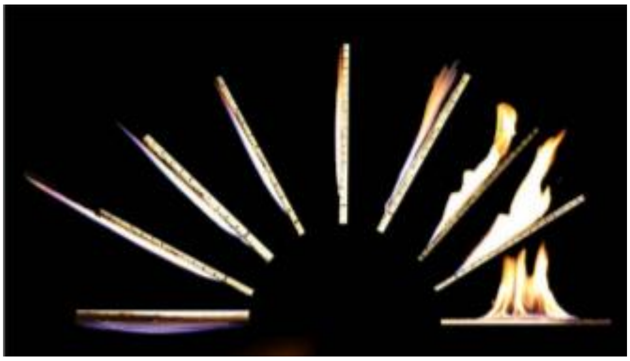

Fig. 1 Flame propagation at different angles of inclination (Gollner *et al.,* 2017).

One important fire property of wood is its charring rate. It is influenced by several parameters, such as wood density, moisture content, and wood type (Martinka *et al.*, 2018; Salmen *et al.,* 2011). The charring rate values are important because, according to STN EN 1995-1-2: Eurocode 5 (2010), the charring rate is a key factor in calculating the fire resistance of wooden structures, which is of interest to building safety experts who study the loss of load-bearing capacity of wooden beams and columns in post-fire conditions (Richter *et al*., 2019). Eurocode 5, parts 1–2, presents several models for calculating the fire resistance of wooden structures. These models are based on the hypothesis that wood charring occurs at temperatures above 300°C (Babrauskas, 2005). In addition to the charring rate, the charring depth is considered an important parameter of the fire resistance of wooden structures, as it allows determining the size of the residual cross-section of wood, which is used to determine the fire resistance of a wooden structure (Cachim and Franssen, 2009). The charring rate is defined as the ratio of the depth of the char layer formed on the timber to the fire duration (Frangi and Fontana, 2003). The charring rate is determined by measuring the charring depth and the duration of thermal exposure.

In previous research, we used the test method according to Utility Model No. 9589 – "Device for determining the speed of flame spread over the surface of polymer materials and a method for this determination" (Kmeťová *et al.,* 2022). Based on the research results, a medium-scale test method was developed, and fire characteristics on larger samples were verified. The comprehensive assessment of the material is focused on its behavior under various conditions.

The aim of the work is an experimental comparison of the thermal resistance of the selected lignocellulosic material - spruce wood, when loaded with a flame source, depending on the angle of inclination of the sample. For the experiment, we chose three different angles of inclination for the sample (0°, 45°, and 90° relative to the tested flame).

MATERIALS AND METHODS

The experiment was conducted using Norway spruce (*Picea abies* L.) samples. The samples were collected from tree trunks harvested in the Forest Enterprise territory belonging to the Technical University in Zvolen, in the central part of the Slovak Republic, during April 2024. A total of 15 samples were used for the experiment, in the shape of a prism with dimensions of 300 mm (tangential) × 100 mm (radial) × 100 mm (transverse). Before the experiment, the moisture content of the samples was 10.19 ± 0.11% and the density 481 ± 2 $kg\cdot m^{-3}$. Moisture content and density were determined gravimetrically.

The new medium-scale non-standard test method represents another modification of STN EN ISO 11925-2. Using this method, samples can be exposed to the flame at different angles (0°, 45°, and 90°), which, in our case, simulates the effect of fire on various wooden structural elements in the structure (rafters, wooden beams, wooden columns). For each angle of inclination, 5 samples were tested. In the experiment, the sample is exposed to the flame for 1800 s, and the determined parameters are then monitored for 120 s without flame exposure. The advantage of the proposed method is mainly the possibility of testing samples of larger dimensions and changing angles, since the original STN EN ISO 11925-2 test method allows measurements only in the vertical orientation of the samples. Another advantage is the recording of weights and temperature curves during measurement.

The proposed test method allows for simultaneous measurement of multiple parameters (sample weight, ambient temperature, temperature inside the sample), which are continuously recorded. From the measured values, we can calculate and determine other selected fire characteristics of the material (relative mass loss, depth of the charred layer, charring rate, temperature courses in the sample cross-section). The designed device allows for making medium-scale tests; its scheme is shown in Figure 2.

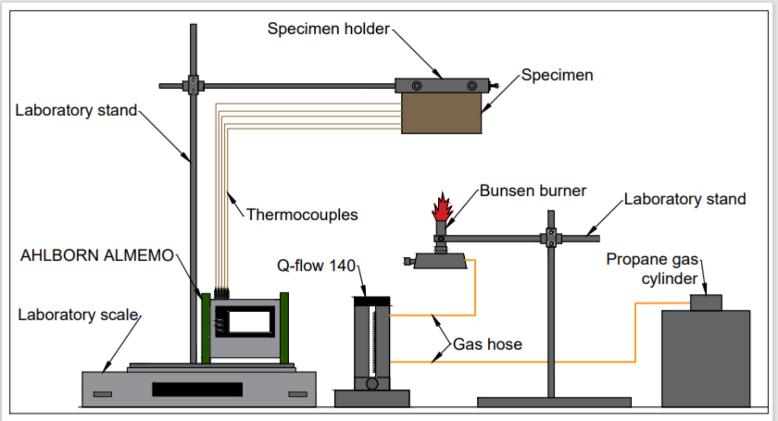

Fig. 2 Scheme of aparature.

The method consists of exposing the tested material to a constant load from a flame source – a Bunsen burner, the power of which can be regulated using a propane flow regulator (Vögtlin Q-flow 140). The burner's energy source was a pressure vessel filled with propane, with a flow rate set to 0.65 Nl·min^{-1} (Nl·min^{-1} stands for "normal liter per minute"). The burner power was determined based on the equation (Rantuch *et al.,* 2023):

$$\dot{Q} = 1.82 \times 10^{-2} \times LHV_v \times \dot{V}_{SLPM} \quad (\mathrm{kW}) \tag{1}$$

Where: LHV_v $\dot{V}_{SLPM}$ – fuel flow; SLPM – Standard liter per minute; LHV_v – lower heating value of the fuel measured at 25 °C and 101.325 kPa. We set the power of the flame source to approximately 1 kW, with a 20 cm flame in the transition area.

During the entire experiment, the sample weight was recorded using a precision balance (RADWAG WLC 60/120 C2/K), from these values we subsequently calculated the mass loss based on the equation:

$$\delta_m(\tau) = \frac{m\ (\tau_0) - m\ (\tau)}{m\ (\tau_0)} \cdot 100 \quad (\%) \tag{2}$$

Where: $\delta_m(\tau)$ – relative mass loss over time (τ); $m\ (\tau_0)$ – sample initial weight (g); m (τ) – sample weight at time (τ) (g).

The temperature course was recorded using K-type thermocouples (NiCr-Ni thermocouples) with a measurement range of -40 °C to 1200 °C. The location of the thermocouples in the samples is shown in Figures 3 and 4. During exposure of the sample to the flame at 90° and 45°, the thermocouples' locations within the sample remained the same. A total of 11 thermocouples (TC0 to TC10) were used (fig. 4). These thermocouples were placed from the side (300 × 100 mm) of the sample at a depth of 5 cm in the sample. The placement was on three levels – two levels were 3 cm away (on both sides) from the middle of the side into which the thermocouples were inserted into the sample, and one level was always 0.5 cm away from the center of the sample. During exposure of the sample to the flame at 0°, the thermocouples' locations within the sample differed. A total of 15 thermocouples (TC0–TC14) were used (Fig. 3). Thermocouples were placed on both sides of the sample at a depth of 5 cm, so that the temperature was measured along the same line as the flame. In addition, the ambient temperature was recorded during the experiment, reaching 19.5°C. An ALHBORN ALMEMO 2290-8710 V7 (Ahlborn Messund Regelungstechnik GmbH, Holzkirchen, Germany) was used to record the temperatures. Samples at angles of 90° and 45° were exposed to the surface, in the center of the sample in a tangential section, and samples at an angle of 0° were exposed to the lower edge of the sample in a tangential/transverse section.

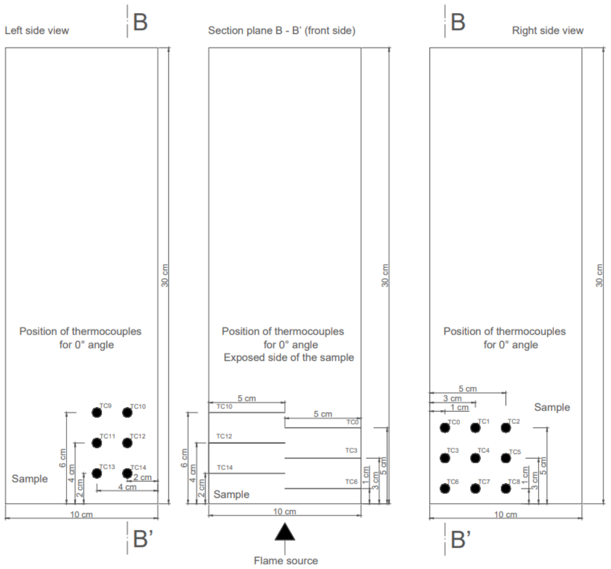

Fig. 3 Schematic of thermocouple placement at 0° inclination angle of sample.

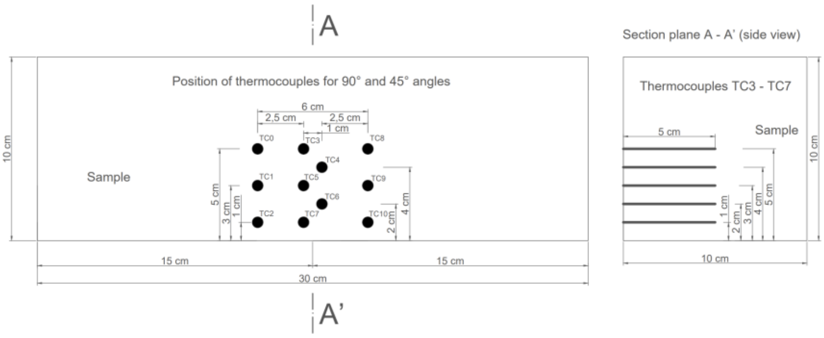

Fig. 4 Schematic of thermocouple placement at 45° and 90° inclination angle of sample

The depth of the char was measured after the experiment was completed and the char was scraped off, using a digital depth gauge (MarCal 30 EWRi) to determine the difference between the original dimensions of the sample and its dimensions after the experiment. The charring rate was determined by calculating the depth of the char and the time of exposure to thermal stress. Figure 5 shows a diagram of the locations where the char was measured.

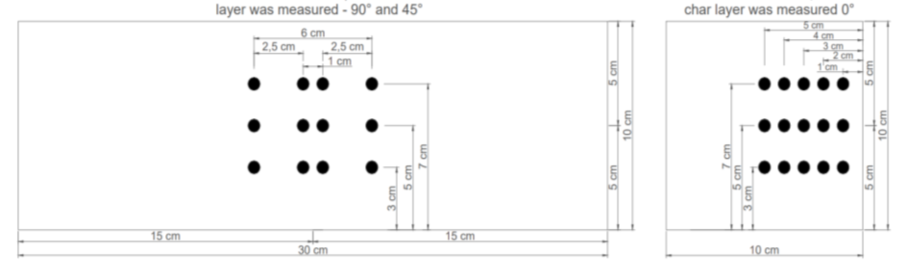

Fig. 5 Charred layer measurement scheme.

RESULTS AND DISCUSSION

Figure 6 shows a visual representation of the samples after the experiment was performed, and Figure 7 shows photo documentation of the samples after the charred layer was scraped off.

Fig. 6 Photo documentation of samples after the experiment.

Fig. 7 Photo documentation of samples after scrapped of the charred layer (0°. 90°, 45°).

During the experiment, the samples burned. The sample's angle of inclination affected the pattern of flame spread along its surface. According to the results (Figs. 6 and 7), when the samples were stressed at 0 °, the flame not only spread along the front side of the samples but also down the sides of the samples. Also, depending on the angle of inclination of the sample, we see an observable difference (in terms of burn-in), which was also in the charred layer. While at 90 ° the flame penetrated their inner layers, at 45 ° it remained on the surface and spread upwards. The spread of the flame was also influenced by the direction of the wood grain. Neither sample group continued to burn after the flame was removed.

Kmeťová *et al.* (2022) in a study aimed at comparing the thermal resistance of a selected lignocellulosic material - spruce wood, applying a progressive laboratory test method. Using this method, the flame spreads over the surface of the selected material, and the mass loss when the sample is exposed to a small, directed flame is determined. The laboratory test results showed a significant effect of the sample's angle of inclination (0°, 45°, 90°) on the evaluation criteria.

Gollner *et al.* (2017), also addressed the effect of sample flow and inclination on flame propagation across solid fuels. Upward flame spread is best studied, with various theories available to describe many aspects of the process. But even in this well-studied configuration, work is still needed to refine these results and address key areas of interest.

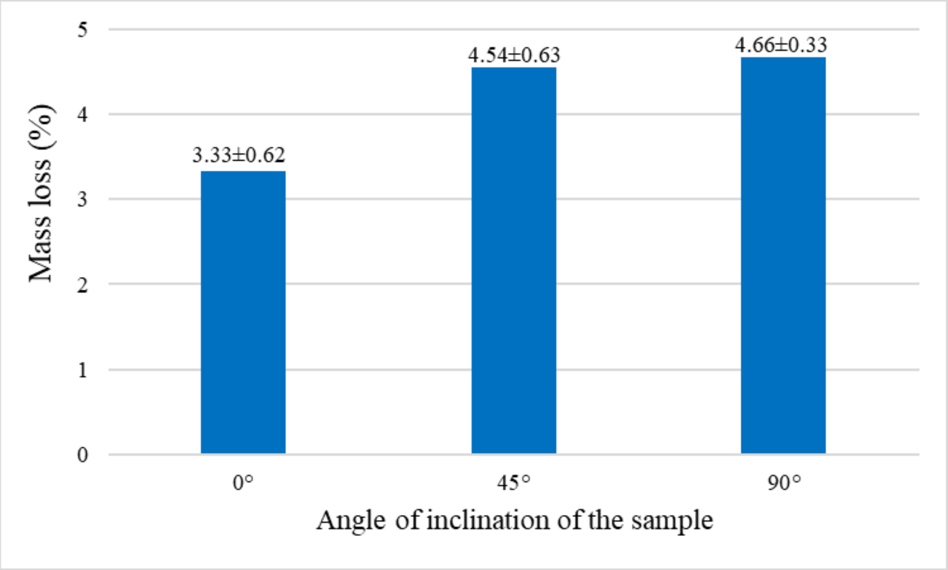

Fig. 8 Relative mass loss of tested samples (average ± SE).

The relative mass loss trend (Fig. 8) was similar for the 45° and 90° sample angles. We noticed a greater difference at the 0° angle of inclination compared to the other two angles. At the same time, we can state that all woody plants lost less than 6% of their original weight in 1920 seconds. We recorded the worst results for samples at a 90° angle of inclination, which lost up to 4,66% of their weight, which we attribute to the faster spread of the flame into the sample. As expected, even in the case of mass loss, the angle of sample inclination significantly influenced the thermal degradation of wood. In addition to the angle of inclination, the mass loss was also influenced by the wood grain directions.

The following figures 9-11 show the average temperature courses in samples exposed to a flame source at given angles. In all temperature profiles, after the flame was turned off (time 1800 s), the sample temperature decreased, indicating that the samples did not burn at any exposure angle. The temperature courses are significantly influenced by the location of the thermocouples, and it is clearly visible that the closer the thermocouples were to the exposed side of the sample, the higher the temperatures were.

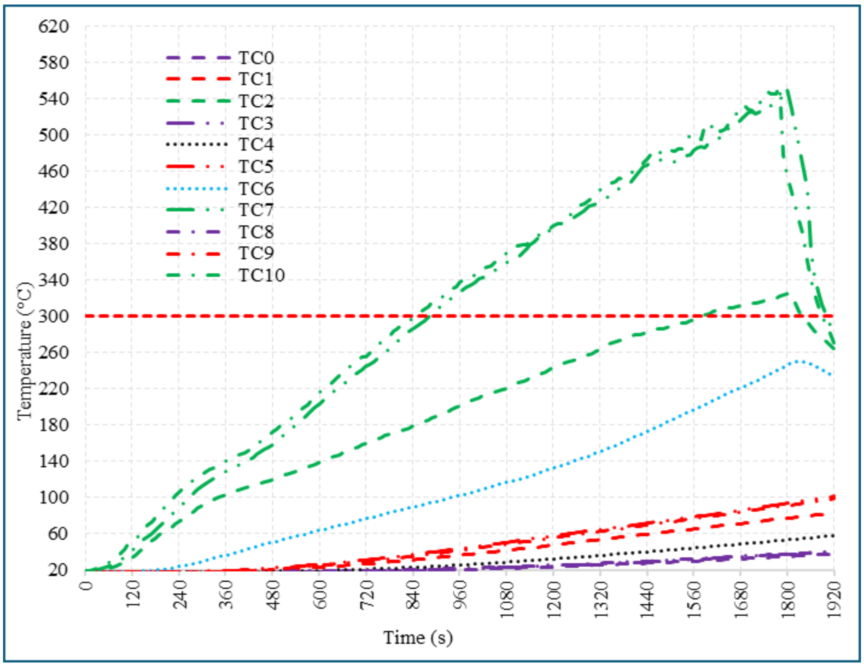

Fig. 9 Temperature courses at 90° sample inclination.

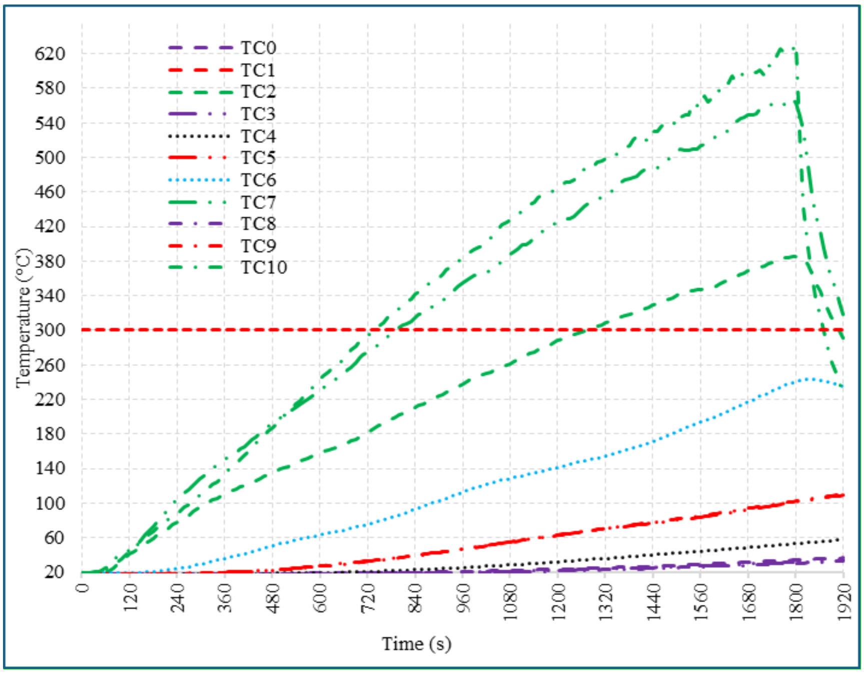

Fig. 10 Temperature courses at 45° sample inclination.

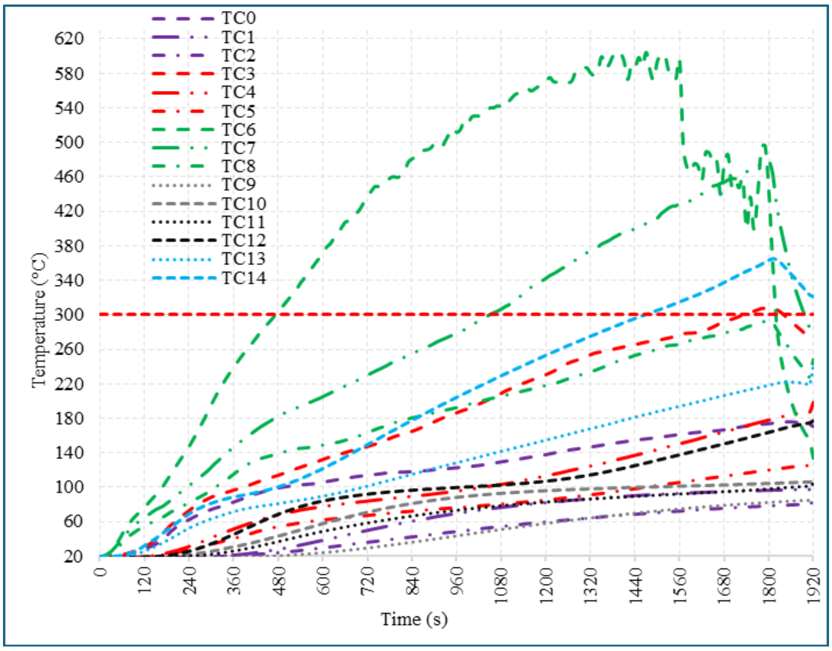

Fig. 11 Temperature courses at 0° sample inclination.

At an exposure angle of 90°, temperatures of 300°C were reached at the TC10, TC7, and TC2 locations at times 850 s, 880 s, and 1580 s, respectively. The maximum temperature of 554.9°C was reached at TC10 at time 1780 s. At an exposure angle of 45°, a temperature of 300°C was reached at the TC10, TC7, and TC2 locations at times 850 s, 880 s, and 1270 s, respectively. The maximum temperature of 630.5°C was reached at TC10 at time 1800 s. These results are comparable to those at a 90° exposure angle. At an exposure angle of 0°, temperatures of 300°C were reached at the TC6, TC7, TC14, and TC3 locations at times 470 s, 1050 s, 1460 s, and 1730 s, respectively. The temperature of 293.3°C was reached at thermocouple TC8 at 1800 s. This temperature can be considered as the temperature of formation of charred layer. The maximum temperature of 605.8°C was reached by TC6 at 1390 s. During the experiment, the TC6 thermocouple was observed to fall out of the samples due to its burnout. This is reflected in the temperature fluctuations shown in Fig. 11. At 90°, the samples reached lower overall temperatures than at 45° and 0°. At an angle of 90°, from the temperature course of TC10, TC7, TC6, and TC2, we can see that water evaporation occurred at 100 °C. At angles of 45° and 0°, this phenomenon is not obvious from the temperature course. This is caused by the angle at which the sample is exposed to the flame. At an angle of 90°, water evaporation occurred predominantly perpendicular to the wood fibers, while at angles of 45° and 0°, water evaporation from the sample occurred predominantly parallel to the wood fibers. For this reason, water evaporation from the sample occurred more slowly at 90° than at 45° and 0°, which led to lower overall temperatures and was reflected in the thermocouple readings (Coolier, 1992).

According to Eurocode 5 (2010), wood gradually loses its strength properties at any increase in temperature above 20 °C. At 100 °C, wood loses 35 % of its tensile strength, and at 300 °C, up to 100 %, as confirmed by several authors (Kuronen *et al.*, 2021; König, 2005; Yue *et al.*, 2022).

The depth of the charred layer at points according to the template in Figure 5 was measured. Table 1 shows the average values from all tested samples. At a 90° angle of inclination, the sample measured 18.9 mm; at a 45° angle of inclination, 22.6 mm; and at a 0° angle of inclination, 34.4 mm. The values of the charred layer are identical to the description in Figure 6. These values are also influenced by the wood's cut. From the measured charred thickness, we calculated the charred rate at 1920 s. The highest average charred rate was recorded at a 45° angle of inclination. The measured values are within the range of values of the charred rate of spruce wood reported in the available literature.

Tab. 1 Charred layer.

	0°	**45°**	**90°**
depth of the charred layer (mm)	14.90±2.18	15.90±1.20	13.20±1.70
charring rate (mm·min^{-1})	0.47±0.07	0.49±0.04	0.41±0.05

The lowest charring rate was measured for an angle of 90°. This may be related to the temperature curves – the maximum temperature reached was the lowest for the 45° and 0 ° angles of inclination. Furthermore, this result can be attributed to permeability, which affects not only water evaporation (as mentioned above) but also the charring rate. Permeability along the grain is higher than across the grain. Increased permeability increases the flow of volatiles, thereby accelerating pyrolysis. As such, it is expected that the charring rate will be greater parallel to the grain than perpendicular (Bartlett, 2018; Friquin, 2011; Moore, 2011). Based on experiments, Babrauskas (2005) found that in extensive room fires, hardwood or similar materials without gaps or joints char at rates similar to those in furnace tests, at approximately 0.50–0.80 mm·min^{-1}, which are similar to the values we obtained. The author suggests that the charring rate in real fires should not exceed these test values.

CONCLUSION

The aim of the paper was to determine the fire properties of the lignocellulosic material - spruce wood (*Picea abies* L.), due to its use as a building material. The fire properties were determined using the proposed medium-scale test method. From the results, we can conclude that the best mass-loss results were achieved at an angle of exposure to the flame source of 0°, namely 3.33±0.62%. This value is more than 1% lower than at 45° and 90°. At an exposure angle of 90°, the highest mass loss was measured – 4.66±0.33%, and, nevertheless, the best results in terms of depth of the charred layer, charring rate, and temperature profile in the sample were achieved at a 90° angle of inclination. At this angle, the samples achieved lower overall temperatures than at 45° and 0°. This phenomenon could have been caused by the angle of exposure of the sample to the flame, by the wood grain direction, and by differences in water evaporation rates depending on the sample's geometry relative to the flame.

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