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DETERMINATION OF CHARRING RATE OF OAK WOOD

Alena Párničanová – Martin Zachar – Danica Kačíková – Lucia Zacharová

ABSTRACT

This paper deals with the determination of selected fire properties of oak wood, i.e., charring rate, which is used in practice to model and investigate the fire causes. Thermal loading was carried out using a measuring apparatus described in Utility Model No. 9373 registered by the Industrial Property Office of the Slovak Republic. Oak wood samples with dimensions of 40 × 50 × 50 mm (l × w × t) were thermally loaded by a heat flux of 15, 20, 25 and 30 $kW \cdot m^{-2}$, using a ceramic infrared heater. Two methods of determination of the charring rate, based on reaching the temperature of 300 ºC in individual depths in a specific time and according to the thickness of the charred layer formed in a time interval of 1800 s measured using a caliper were compared. Both methods confirmed that the charring rate is increasing with increasing thermal loading. The charring rate determined based on the temperature of 300 ºC ranged from 0.65 to 0.88 $mm \cdot min^{-1}$. According to the second method, the charring rate reached values from 0.41 to 0.86 $mm \cdot min^{-1}$. More accurate results were achieved by applying the method of determination of the charring rate based on the charred layer measured by a caliper. However, the method of determination of the charring rate using thermocouples can be considered less subjective because the temperature is measured automatically, using thermocouples compared to manual measurement using a caliper. The obtained results can be used as input data for computer-supported modeling of indoor fires.

Keywords: thermal loading; oak wood; charring rate; charred layer.

INTRODUCTION

Currently, wood is used as a construction material because it is affordable (Hrovatin, 2005). Wood is a material that loses its mechanical properties due to thermal loading. Therefore, it is important to ensure the strength and longevity of buildings, as well as to pay attention to their fire resistance (Zanatta *et al*., 2018).

As a result of the thermal loading, charring occurs in the process of pyrolysis, which takes place at high temperatures and constant pressures in an oxygen-free environment for the thermal decomposition of wood as an organic material (Kravetz *et al*., 2020, Qin *et al.*, 2021, Richter *et al*.,2019).

The charring temperature is approximately 300 ºC at which a charred layer of wood is formed (Booth, 1987, White, Nordheim 1992, Chen *et al*., 2016, Findorák *et al*., 2016).

The charring rate of wood is influenced by several parameters such as wood density and moisture, external heat flux and oxygen concentration in the ambient air, as well as the type of wood and the burning direction (Salmen *et al*., 2011, Cachim *et al*., 2008, Njankouo

et al., 2004, Mikkola, 2007). According to STN EN 1995-1-2 (Eurocode 5), it is important to know the value of the charring rate, which enters into the calculation of the fire resistance of wooden constructions. The charring rate is determined based on the charring depth and the time of exposure to thermal loading (Martinka *et al*., 2018). In addition, it is also an essential parameter in investigating the causes of fire, which is in line with NFPA 921: 2021 (NFPA 921: 2021).

In accordance with NFPA 921:2017, the charring rate of wood under laboratory conditions and exposure to a heat source from one side is determined from 0.17 $mm \cdot min^{-1}$ to 4.23 $mm \cdot min^{-1}$ (NFPA 921: 2021). In line with EN 1995-1-2 2, the proposed charring rate of solid and glued laminated softwood and beech is constant, approximately 0.6 $mm \cdot min^{-1}$, and decreases with increasing density (Friquin, 2011). The value of the charring rate of grown/solid and glued laminated hardwood and beech with a bulk density greater than 450 $kg \cdot m^{-3}$ is 0.50 $mm \cdot min^{-1}$ (Špilák, 2018).

The charring rate is not constant. At the beginning of burning, the charring rate is usually faster than the rate after the formation of the charred layer, because the charred layer acts as an increasing thermal insulation between the exposed surface and the pyrolyzed wood, which results in degression of the charring rate during the first phase of combustion. Once the first few millimeters of charring are formed, the rate is constant (Friquin, 2011).

The aim of the paper is to determine the charring rate of oak wood based on data measured by progressive laboratory methods. Two methods of measurement were compared. The first one based on the temperature of 300 ºC reached at a certain depth, in a certain time and the second one based on the thickness of the charred layer formed in a time interval of 1800 s.

MATERIALS AND METHODS

The measurement was carried out using a measuring apparatus described in Utility Model No. 9373 registered by the Industrial Property Office of the Slovak Republic. The apparatus consists of a ceramic infrared heater with a power of 1000 W, control device METREL HSN0203 (Metrel d.d. Horjul) and digital scale Radwag PS 3500.R2.M connected to a PC.

Oak wood samples were prepared from the trunk of the sessile oak (*Quercus patraea*) harvested during summer in the Slovak Republic. At the time of harvesting, the trunk was 110 years old, and the trunk diameter was 410 mm. The samples were sawn in tangential directions to dimensions of 50 × 40 × 50 mm (l × w × t). Samples without anatomical defects were dried in a drying oven and subsequently adjusted to a moisture content of 10 +/- 0.15 %. The density of test samples was 681 ± 0.33 $kg \cdot m^{-3}$. The surface of the samples was prepared by mechanical processing – sawing.

First, the place where the initiation burner was fixed during the measurement of each sample was marked. Subsequently, 4 holes were drilled with a 2 mm drill bit in the center of each sample at a distance of 10 mm from each point. Before the measurement thermocouples were inserted into each hole in the sample. The thickness of the samples prepared in this way was measured using a caliper at 9 different places (Fig. 1) to determine the average thickness of samples. This measurement served in the next steps to determine the thickness of the charred layer.

Subsequently, each sample was weighed and the heat flux was noted at which each sample was tested. The heat flux values were 15, 20, 25 and 30 $kW \cdot m^{-2}$, where 10 samples for each heat flux value were used, a totally 40 samples.

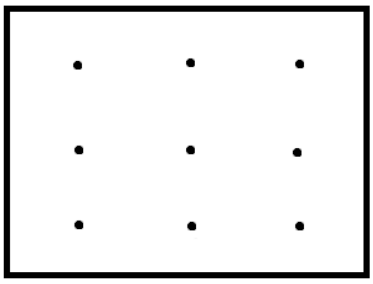

Fig. 1 Illustration of 9 different points on a sample (authors).

Before starting the measurement and placing the sample under the ceramic infrared heater, the moisture content of the sample was calculated as the ratio of the weight of wet wood to the weight of absolutely dry wood. The samples used in the measurement were dried at a temperature of 103+/-2 ºC to a constant weight.

The sample prepared this way was placed on a stand, 30 mm under the infrared heater. The stand was placed on the scales, which recorded the mass loss. The propane burner was turned on, the flame of which was placed 10 mm above the sample, the place that was marked in advance. The stopwatch was turned on and we waited for initiation on the sample surface. When the sample started to burn, the propane burner was pulled away. The temperature course was measured using the ALMEMO 710 measuring device and four K-type thermocouples with a thickness of 0.5 mm, placed in the sample at a depth of 10 mm (T1), 20 mm (T2), 30 mm (T3) and 40 mm (T4) from the thermally loaded surface. Measurement of each sample took 30 minutes. Based on the measured temperature on the thermocouples (T1, T2, T3 and T4), the charring rate was determined according to equation (1).

$$\beta_0 = \frac{d_{char}}{t} \tag{1}$$

Where: β_0 - charring rate (mm·min^{-1}),
d_{char} - charred layer (mm),
t - time of thermal loading (min).

After thermal loading of the samples, the charred layer was removed manually. Subsequently, the samples were measured again with a caliper at the same nine points as it was done before the thermal degradation of the sample. The thickness of the charred layer was calculated as the difference of the average thickness of the samples before testing and the average thickness of the samples after the experiment and removing the charred layer.

RESULTS AND DISCUSSION

The charring rate of the oak samples based on the time and the depth at which we reached the temperature of 300 ºC was calculated. Based on the measured values, the average values of the charring rate in the time interval from 0 s to 960 s (Table 1) was determined. Table 1 shows the calculated charring rate of the oak samples in the time interval 0 s to 960 s, because during the thermal loading (0 s to 1800 s) a temperature of 300 °C only on T1 in time of 960 s was reached.

Tab. 1 Charring rate of samples in time intervals at a depth of 10 mm.

Heat flux ($kW \cdot m^{-2}$)	Time to reach the temperature of 300 ºC (s)	Charring rate in time interval from 0 to 960 s ($mm \cdot min^{-1}$)
15	930	0.65
20	920	0.65
25	740	0.81
30	690	0.87

At a heat flux of 15 $kW \cdot m^{-2}$, the charring rate in the time interval from 0 to 960 s reached the lowest values i.e. 0.65$mm \cdot min^{-1}$. At a heat flux of 20 $kW \cdot m^{-2}$, the charring rate was slightly higher, i.e., 0.6522 $mm \cdot min^{-1}$. At a heat flux of 25 $kW \cdot m^{-2}$, the average charring rate was 0.81 $mm \cdot min^{-1}$. The highest value of the charring rate 0.87 $mm \cdot min^{-1}$ was reached at a heat flux of 30 $kW \cdot m^{-2}$. The relationship between the average charring rate of oak wood in the time interval from 0 to 960 s and the heat flux density is shown in Fig. 2.

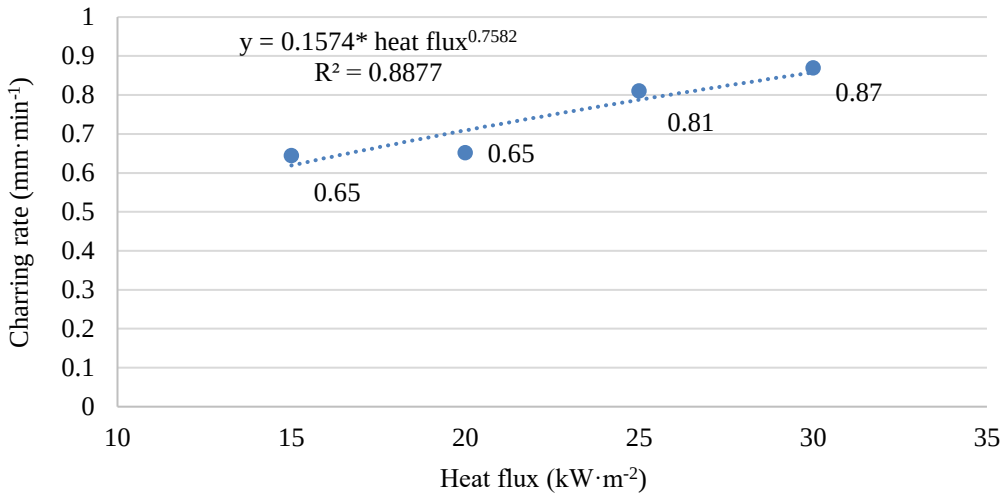

Fig. 2 Average charring rate in the time interval from 0 to 960 s.

One of the most important fire properties of wood is the charring rate (Martinka *et al.*, 2018). It is influenced by a heat flux, but also by moisture content and oxygen concentration in the air (Xu *et al.*, 2020). Our experiment confirmed that the charring rate increases with increasing heat flux acting on samples, which is also in accordance with the results of authors (Kačíková and Makovická-Osvaldová, 2009, Martinka *et al.*, 2018).

The charring rate of the oak samples was determined based on the thickness of the charred layer, which was measured using a digital caliper. We determined the average values of the charring rate in the time interval from 0 s to 1800 s (Table 2).

Tab. 2 Charring rate of test samples in the time interval 0 to 1800 seconds.

Heat flux (kW·m^{-2})	The orginal thickness of the sample (mm)	Thickness of the sample after charring (mm)	Thickness of the charred layer (mm)	Charring rate (mm·min^{-1})
15	49.53	37.27	12.26	0.41
20	49.66	33.10	16.56	0.55
25	49.65	26.12	23.53	0.78
30	49.67	23.89	25.78	0.86

We calculated the thickness of the charred layer of the test samples based on equation (3), i.e., depending on the thermal loading. At a heat flux of 15 kW·m^{-2}, the smallest charred layer was formed, i.e., 12.26 mm. At a heat flux of 20 kW·m^{-2}, the charred layer was larger, i.e., 16.56 mm. At a heat flux of 25 kW·m^{-2}, the charred layer was 23.53 mm. The most extensive charred layer, i.e., 25.78 mm was achieved at a heat flux of 30 kW·m^{-2}. Measurement of the charred layer using a caliper confirmed the assumption that the charring rate increases with increasing heat flux. The relationship between the average charring rate of oak wood in the time interval from 0 to 1800 s and the heat flux density is shown in Fig. 3.

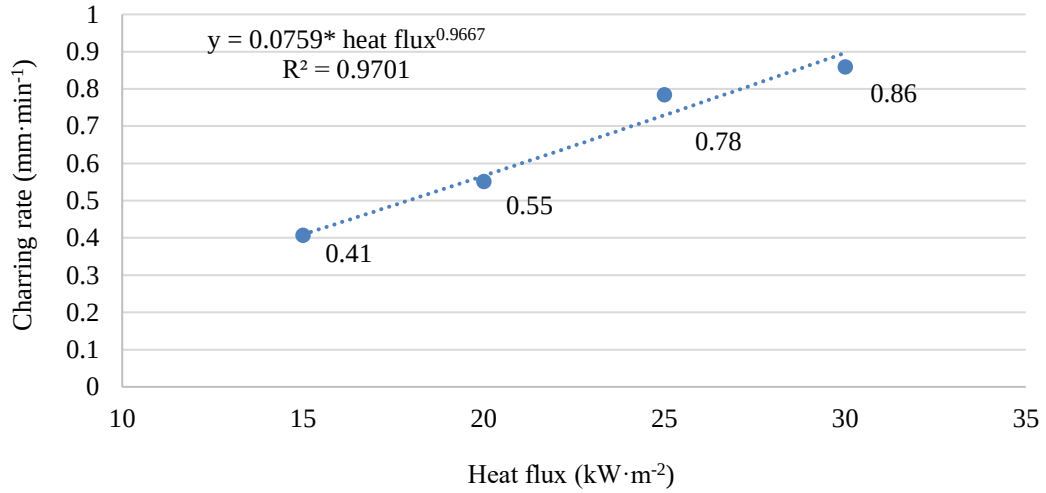

Fig. 3 Average charring rate in the time interval from 0 to 1800 s.

The charring rate was determined based on the charred layer and the time of exposure of the samples to thermal loading. It was confirmed that the charring rate increases with increasing heat flux, as in the case of determination of the charring rate based on achieved temperature of 300 ºC (thermocouple T1). At a heat flux of 15 kW·m^{-2}, the charring rate reached the lowest value, i.e., up to 0.41 mm·min^{-1}. At a heat flux of 20 kW·m^{-2}, the charring rate was slightly higher, i.e., 0.55 mm·min^{-1}. At a heat flux of 25 kW·m^{-2}, the average charring rate was 0.78 mm·min^{-1}. The highest value of the charring rate 0.86 mm·min^{-1} was achieved at a heat flux of 30 kW·m^{-2}.

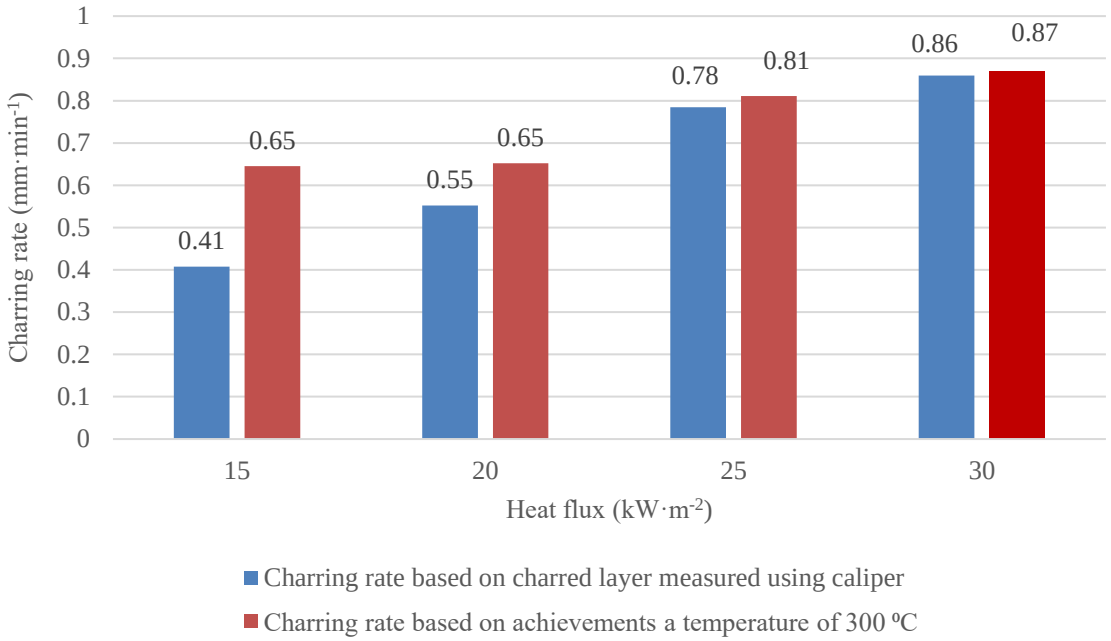

Fig. 4 Comparison of charring rates measured by different methods.

A comparison of two different methods of measurement showed similar values of the charring rates (Fig. 4). Different charring rates were achieved only at a heat flux of 15 kW·m^{-2}. The value of the charring rate of 0.65 mm·min^{-1} was reached by applying the measurement methods based on the charring temperature. Using the second measurement method (based on charred layer), the charring rate reached 0.41 mm·min^{-1}. This difference could be caused by the low heat flux (15 kW·m^{-2}) and the longer time of initiation of the tested samples. Considering the different values of the charring rate at a heat flux of 15 kW·m^{-2}, and the subsequent comparable results reached at a heat flux of 20, 25 and 30 kW·m^{-2}, we can state that more accurate results were achieved by applying the method of determination of the charring rate based on charred layer measured by caliper.

In comparison with the results of a similar experiment testing the spruce samples, using the same method, the charring rate had an increasing trend with increasing heat flux. In the time interval from 0 s to 1920 s, the average charring rate varied from 1.00 mm·min^{-1} (at a heat flux of 15 kW·m^{-2}) to 1.84 mm·min^{-1} (at a heat flux of 30 kW·m^{-2}) (Zachar *et al.* 2021). The charring rate of spruce wood compared to oak wood may differ due to different densities. Spruce wood burns faster due to lower density when compared to oak wood.

According to Martinka *et al.* (2018) who tested spruce and pine wood exposed to a heat flux from 20 to 50 kW·m^{-2} for 0-30 minutes, the average charring rate of spruce timber was in the range from 0.73 mm·min^{-1} (heat flux of 20 kW m^{-2}) to 1.2 mm·min^{-1} (heat flux of 50 kW·m^{-2}). The average charring rate of pine timber in the same time interval from 0 to 30 min was from 0.67 mm·min^{-1} (heat flux of 20 kW·m^{-2}) to 0.87 mm·min^{-1} (heat flux of 50 kW·m^{-2}). The charring rate increased faster between 10 and 20 minutes. This may be due to the fact that if the wood is heated for a long period, heat accumulation occurs in the wood, meaning that the wood absorbs and stores heat. The accumulated heat can then promote faster burning of the wood.

The charring rate of six Chinese wood samples with densities from 0.35 to 0.69 g·cm^{-3} and moisture content of about 12 % tested by a cone calorimeter ranged from 0.604 to 0.971 mm·min^{-1} at a heat flux of 50 kW·m^{-2} and a time interval of about 10 s

(Wen *et al*., 2015). The authors reported different charring rates, which is caused by different wood density (the density of oak wood ranges from 0.6 to 0.9 $g \cdot cm^{-3}$) and also moisture content (oak wood samples were dried to absolute humidity). The value of the thermal conductivity of oak wood in the tangential direction was 0.21 $W \cdot (m \cdot K)^{-1}$ (Požgaj *et al.*, 1997). The charred layer serves as an insulation layer, the thermal conductivity of which is approximately one-sixth of the thermal conductivity of non-degraded wood. It also slows the further thermal degradation of remaining wood (Blass, 1995).

CONCLUSION

Two methods of determination of the charring rate, based on reaching the temperature of 300 ºC in individual depths, in a specific time and according to the thickness of the charred layer formed in a time interval of 1800 s measured using a caliper were compared.

Both methods confirmed that the charring rate has an increasing tendency with increasing thermal loading. The charring rate determined based on the temperature of 300 ºC, achieved a value of 0.65 $mm \cdot min^{-1}$ at a heat flux of 15 $kW \cdot m^{-2}$. According to the second method (based on charred layer measured using a caliper) the charring rate was slightly lower, i.e. 0.41 $mm \cdot min^{-1}$. Gradually, as we increased the heat flux, the charring rate also increased, up to 0.87 $mm \cdot min^{-1}$ at a heat flux of 30 $kW \cdot m^{-2}$ (first method). The charring rate determined based on the charred layer, the charring rate achieved similar value, i.e., 0.86 $mm \cdot min^{-1}$. It can be stated that more accurate results were achieved by applying the method of determination of the charring rate based on charred layer measured by caliper. However, we consider the method of determination of the charring rate using thermocouples (reaching the temperature of 300 °C) less subjective because the temperature is measured automatically, using thermocouples compared to manual measurement using a caliper. The results can be used in further research of the fire properties of wood and as input data for computer-supported modeling of indoor fires.

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AUTHORS' ADDRESSES

Alena Párničanová (Ing.)
Martin Zachar (doc., Ing., PhD.)
Danica Kačíková (prof., Bc., RNDr., MSc., PhD.)
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Department of Fire Protection
T. G. Masaryka 24
960 01 Zvolen
Slovakia
xparnicanova@is.tuzvo.sk
zachar@tuzvo.sk,
kacikova@tuzvo.sk

Lucia Zacharová (Ing., PhD.)
National Forest Centre
Forest Research Institute
T. G. Masaryka 2175/22
960 01 Zvolen
Slovakia
lucia.ambrusova@gmail.com