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Char depth of several wood species under single or double heat exposures

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Abstract. For many engineering and fire investigation applications, understanding the behaviour of materials exposed to fire often relies on fairly simple measurements (*e.g.* char thickness) to deduce the quantities of interest (*e.g.* fire size or duration) by trying to account for a number of complex phenomena (*e.g.* influence of wood species, dimensions or moisture content). The aim of the work presented here is to analyse the charring process as a function of different experimental parameters, mainly a varying heat flux. The robustness lies in the large number of cone calorimeter experiments, as the char characteristics of 783 samples were measured. The results show promising correlations between the char depth (combination of missing and remaining char thicknesses) and the cumulative exposure, which represents the energy received by the sample, for a single or a double exposure and independently of the other experimental conditions.

1. Introduction

Fire investigation is a complex field due to the destructive nature of a fire, which erases most of the evidences and leaves investigators with only traces on the remaining materials, which can vary greatly depending on a number of parameters (origin and history of the fire, boundary conditions ...). Investigations are mainly based on observations or direct measurements of degraded or decomposed materials, such as the char depth of wood. The latter is highly dependent on the wood species and the fire conditions. The most commonly used data for investigation is the char layer thickness, but two other measurements can provide additional data, namely the remaining wood and the char that has burned and thus disappeared due to the char oxidation. The latter remains largely unexplored, despite its important role in defining boundary conditions, as the surface exposed to the incident heat flux retreats with time. This missing layer is included when considering the char depth, which is the position of the char front relative to the initial surface of the sample, *i.e.* the sum of the missing and remaining char thicknesses.

The position of the char depth can often be determined by measuring the in-depth temperature with thermocouples following the isotherm at 300 °C or by direct measurement by cutting the sample after exposure to fire [1]. Results obtained by the first method depend on how the



thermocouples are implanted in the wood and for the second on the experimenter and the instrument used (ruler, probe, image processing). In addition, the determination of the char depth also depends on the position at which the measurement is taken. Indeed, even with small samples, the value of the char depth can sometimes vary by more than 50 % when the incident heat flux is controlled [2]. For wood, the charring rate used is very often taken to $0.65 \text{ mm}\cdot\text{min}^{-1}$, although it varies with numerous parameters [1, 3, 4]. Finally, most studies have been carried out using either a prescribed temperature curve as a function of time (ISO 834) or a single controlled heat flux (cone calorimeter, FPA). On the other hand, there are few studies focusing on char depth with variable heat fluxes. Lizhong *et al.* [4] studied the effect a heat flux increasing linearly on the charring rate and showed that it can doubled when the slope varied from 0.2 to $0.57 \text{ kW}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

In this context, a study using cone calorimeters was performed to investigate char formation and combustion for a large number of wood species under different conditions, including two successive controlled heat fluxes. The results are compared to observations made for a single exposure [2].

2. Materials and Methods

The results presented were obtained during several experimental campaigns carried out at LEMTA (Laboratoire Énergies et Mécanique Théorique et Appliquée, Nancy) and LCPP (Laboratoire Central de la Préfecture de Police, Paris). The following sections present their main features.

2.1. Wood samples

Eight wood species were studied: poplar, spruce, fir, larch, particleboard (composed of resin and pine chips), oak, beech and ipe. These wood species cover a very wide range of densities, from $327 \text{ kg}\cdot\text{m}^{-3}$ for poplar to $1100 \text{ kg}\cdot\text{m}^{-3}$ for ipe. Ipe, oak, beech and poplar are hardwoods whereas larch and spruce are softwoods. It should be noted that larch is almost as dense and hard as some hardwoods such as oak and beech, while poplar has properties similar to softwoods, *i.e.* it is light and soft. All samples sizes were $10 \times 10 \times 5 \text{ cm}^3$ (except particleboard which was 3 cm thick) and had a moisture content close to 10 %. The grain orientation was perpendicular to the heat flux and there were no pre-existing cracks that could have influenced the char formation [5]. A total of 582 samples from LEMTA and 201 from LCPP were initially used in this study. Table 1 shows the number of samples and the density of each species.

Table 1: Number and density of the eight studied wood species.

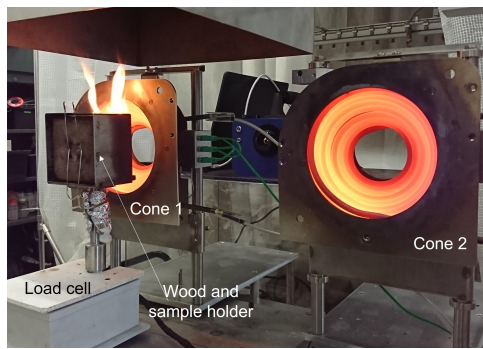
	Poplar	Spruce	Fir	Larch	Particleboard	Oak	Beech	Ipe
Number of samples	170	26	51	135	44	169	130	58
ρ min - max ($\text{kg}\cdot\text{m}^{-3}$)	327-377	390-560	–	540-765	–	556-811	642-786	900-1100
Mean ρ (\pm std $\text{kg}\cdot\text{m}^{-3}$)	355 ± 15	471 ± 52	500	652 ± 63	660	707 ± 81	710 ± 35	950 ± 35

2.2. Experimental setup

At LEMTA, wood samples were tested using a double cone heater in vertical orientation, without pilot. Specimens were placed at a distance of 25 mm from the cone heater surface, and were exposed to incident heat fluxes from 15 to $85 \text{ kW}\cdot\text{m}^{-2}$. Each sample was wrapped in aluminum foil on all sides not exposed to the heat flux. The test set-up allowed the wood to be exposed to one or two incident heat fluxes for prescribed times [6]. Figure 1a shows the experimental setup of the double cone calorimeter on its sliding system. More details on the operation of the double cone calorimeter can be found in a study which was devoted to wood extinction [6]. At

LCPP, wood samples were exposed to a conventional cone calorimeter (single heating element) in horizontal orientation, with a pilot and for incident fluxes between 20 and 80 kW.m⁻², for 3 to 45 min [2]. These experimental devices allowed the samples to be subjected to different conditions:

- A single heat flux for a prescribed time, in a vertical configuration without a pilot or in a horizontal configuration with a pilot. In this condition the second heating cone of the LEMTA was not used.
- Two heat fluxes using the LEMTA device, the first heat flux causing auto-ignition (55, 75 or 85 kW.m⁻²) for a given time (6, 9, 15 or 18 min) and a second lower heat flux for 5 min [6].



(a) Double sliding cone heater.



(b) The three regions that can be defined.

Figure 1: Experimental setup at LEMTA and example of a sample.

As shown in previous studies [7, 8, 2], wood degradation can be the same for a short exposure to a high heat flux or a long exposure to a low heat flux. In order to compare these exposures, the concept of cumulative exposure (CE , (MJ.m⁻²)), similar to the local fire severity [8], is introduced:

$$CE = \int_0^{\tau} \dot{q}(t)'' dt \quad (1)$$

where $\dot{q}(t)''$ is the incident heat flux (kW.m⁻²) and τ is the exposure time (s). In Eq. (1), the cumulative exposure is the total thermal energy received by the sample since the beginning of the exposure. It can be directly related to the amount of energy causing damage. For example, a CE of 28 MJ.m⁻² could be caused by a single exposure at 80 kW.m⁻² for 6 min, or a double exposure to 55 kW.m⁻² for 6 min and then 30 kW.m⁻² for 5 min. For all the experiments performed, the CE varied between 1.65 and 270 MJ.m⁻².

2.3. Char measurement

After each test, the sample was cut in half and measurements were taken in the centre of the sample (Fig. 1b). Although the measurement can depend on the location [2], it was decided here to measure the thickness at the centre of the samples due to the very large number of tests. A caliper gauge was used to measure the thickness of the char layer and of the remaining virgin wood. These measurements were then used in conjunction with the original sample thickness to deduce the char regression. In accordance with most of the literature, the combination of char regression and char layer (*i.e.* missing and remaining char) is referred to as char depth. Outliers were removed from the analysis by detecting, over the entire dataset, char layer, virgin wood or char depth measurements that were more than 1.57 times the interquartile range of the entire

dataset. These points may be due to problems during the experiments, or simply some extreme experimental conditions that were less replicated than others.

3. Results

It is important to note that for LEMTA samples, exposed vertically and without pilot, the sample auto-ignition was only observed for $45 \text{ kW}\cdot\text{m}^{-2}$ at long exposure times (more than 45 min). This means that only char oxidation was present at lower heat fluxes [9]. On the other hand, for LCPP samples exposed horizontally with an ignitor and for heat fluxes greater than or equal to $20 \text{ kW}\cdot\text{m}^{-2}$, all showed flaming ignition. Figure 2 gives an example of the thicknesses of the remaining char layer, virgin wood and missing char for several wood species as a function of the heat fluxes applied. This figure only groups together samples exposed to a single heat flux for 40 min. Each point represents one test.

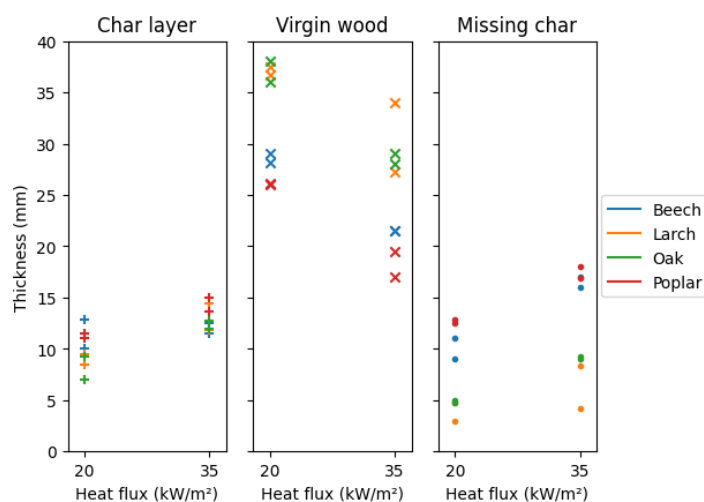


Figure 2: Remaining char, virgin wood and missing char thicknesses for a single exposure during 40 min.

From this example, it can be logically noticed that the char layer increases with the heat flux whereas the remaining wood decreases, but more importantly, that, for any given heat flux, (i) the char layer of each species spans a short range of about 3 mm, whereas (ii) the virgin wood thickness depends greatly on the species with differences as large as 12.4 mm here. A consequence is that measuring only the char thickness might not provide all the information about the wood degradation and that the missing char thickness, which depends on both heat flux and on wood species, must also be taken into account. These differences in char oxidation could be due to differences in the char structure and / or external conditions, and must still be investigated. Figure 2 represents only one exposure time for two imposed heat fluxes. It becomes difficult to show clear correlations when time is added as a variable, and even more difficult when heat fluxes and times are varied during a test.

As described previously (Eq. 1), the CE can be used to account for the two variables affecting the exposure (time and heat flux). So far, the CE showed to be a useful quantity for single exposures (one time, one heat flux) [2]. In order to move towards more representative tests, it is interesting to investigate whether CE allows to describe char measurements (thickness, virgin wood) for samples subjected to two successive exposures. Figure 3 presents the char depth (sum of the missing and remaining char thicknesses) as a function of cumulative energy for a few species.

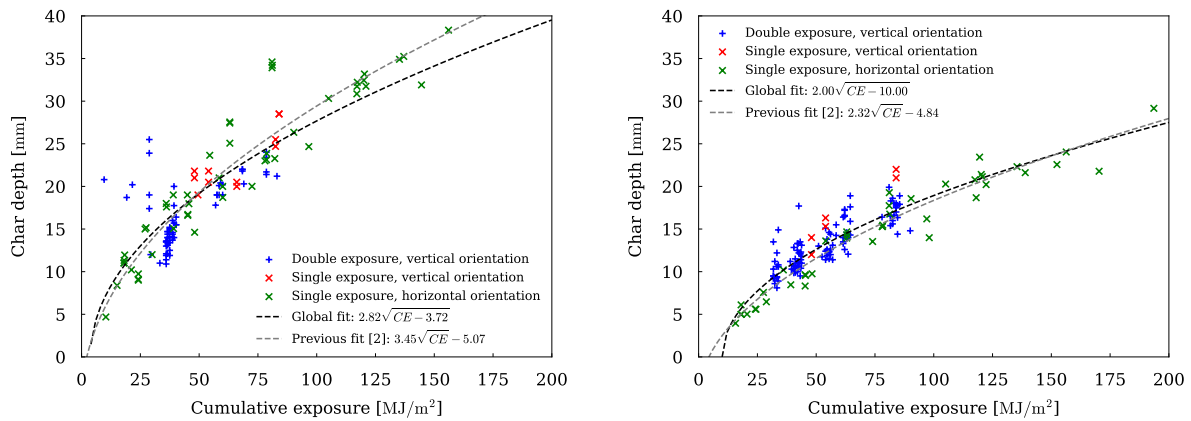


Figure 3: Examples of char depth as a function of the total cumulative exposure. Left panel: beech (124 tests), right panel: oak (162 tests).

The char depth measured after a single (red and green marks) or a double exposure (blue marks) are well represented by the CE . Moreover, the trends are well described by the fit proposed in Ref. [2], *i.e.* char depth = $a\sqrt{CE - CE_{crit}}$, inspired by the relationship between the propagation time of a thermal disturbance and the characteristic depth of propagation in the transient regime. CE_{crit} is the value below which there is no charring. In particular, the Fourier number relates this time to the square of the characteristic depth (or the square root of time to the characteristic depth). Since the time is the integration variable used to obtain the CE , it seems quite natural that the char thickness associated with the depth of the 300 °C isotherm should be related to the square root of CE . All the data were fitted by this equation (experiments from LCPP and LEMTA), and previous fits, made only on experiments from LCPP, are also provided when available (dashed dotted curves). Both are very similar, although the new datasets from LEMTA were obtained in quite different conditions: single or double exposure, but also orientation, ignitor, etc. This trend is also true for the other wood species presented here, as illustrated in Fig. 4 which gives an overview of all the data used in this study and the fits that were obtained.

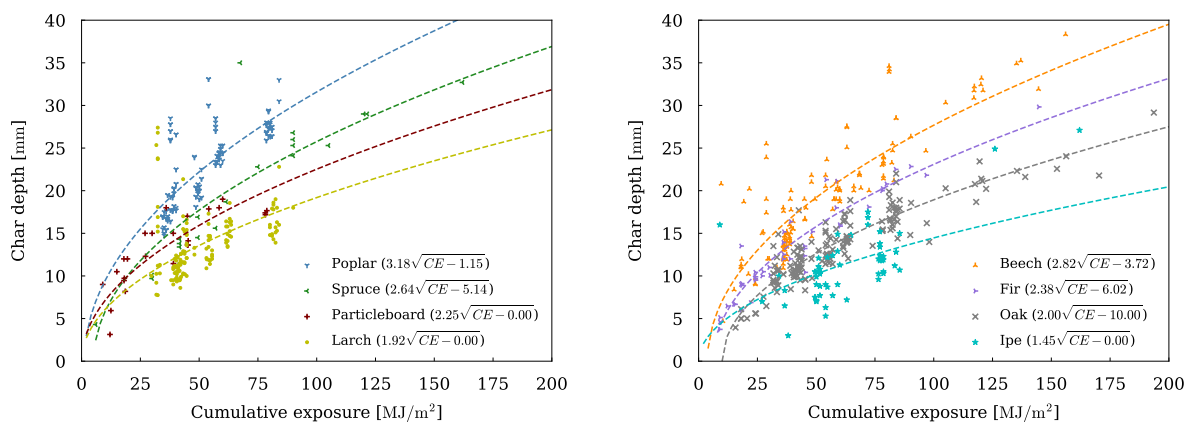


Figure 4: Char depth as a function of the total cumulative exposure (split out for better readability).

The fit quality, represented here by the root-mean-square error (RMSE) varies depending on the species, and must be further investigated. The coefficients a and CE_{crit} will also not be discussed in detail here, but it can be noted that the char depth evolution appears to be, at least in part, related to the wood density, with faster charring for poplar (least dense here) and slower charring for ipe (most dense here). However, this aspect needs to be further investigated, as some species show a different behaviour, for example beech ($\sim 710 \text{ kg.m}^{-3}$) which has a very similar charring rate as spruce ($\sim 471 \text{ kg.m}^{-3}$).

4. Conclusion

The aim of the present work was to investigate trends in the charring of various wood species in the controlled conditions provided by the cone calorimeter. Numerous experiments, carried out at LEMTA and LCPP, were analysed (783 samples). Experimental conditions such as heat flux(es), exposure time(s), sample orientation and the presence of a pilot were varied. A cumulative exposure was calculated for each experimental condition. The evolution of the char depth seems to follow a similar trend for all the experiments for a given wood species. This is even more remarkable and encouraging given that numerous samples were subjected to two consecutive exposures, which is a step towards more realistic heat sources. No clear influence of the other changes in experimental conditions (*e.g.* orientation, pilot) was observed in the analysis presented here. Despite the large volume of experiments presented in this work, the variability observed in some of the data remains significant. In the future, other parameters (char layer thickness, missing char thickness) will be compared with the CE to determine new correlations based on post-fire measurements. Finally, char comparisons will be made for experiments with and without oxygen in order to study the char oxidation process.

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