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Abstract

The aim of the present work was to improve the study of wood self-extinguishment under cone calorimeter thanks to a dedicated experimental setup. A cone calorimeter was modified into a double sliding cone calorimeter in vertical orientation for studying samples extinguishment. With this new setup, the external heat flux can be quickly switched from a high to a low value seeking for the heat flux leading to the sample extinguishment. Samples were first submitted to different heat fluxes (60, 82.5 and 93.5 $kW.m^{-2}$) leading to auto-ignition. After different exposure times (6, 9, 15 and 18 minutes), the heat flux was suddenly reduced to a lower value (between 38.5 to 60 $kW.m^{-2}$) by sliding from one cone to the other one. All in all, 206 tests were performed varying heat fluxes and exposure time. This large number of test made it possible to carry out a statistic study and to deduce a critical Mass Loss rate and a critical heat flux for self-extinguishment. The critical heat flux for self-extinguishment varied from 44 to 51 $kW.m^{-2}$ depending on the heat flux that was used to ignite the sample. These critical heat fluxes were found weakly dependent on the time during which the sample was exposed to the high flux. Time-to-extinguishment was between 40 seconds and 100 seconds. Mass Loss Rate Per Unit Area (MLRPUA) for which self-extinguishment occur was found to be equal to 3.95 $g.m^{-2}s^{-1}$ and this value is almost independent on experiment parameters (exposure time and heat flux).

Keywords: *Self-extinguishment of wood; double cone calorimeter; infrared camera*

1 INTRODUCTION

The use of wood material in facade construction or in building structures appears to be a supportive solution for sustainability development concerns. Although wood is a combustible material, it is anyway used in building construction thanks to a long duration resistance to fire (compared to a metallic structure for instance) and because of its potential ability to self-extinguish under favourable conditions which still have to be determined accurately. Consequently, the study of flaming self-extinguishment of wood is more and more addressed with both fundamental and empirical approaches. A review of available contributions was reported and summarized by Bartlett [1]. For instance, in a recent paper, Emberley *et al.* [2] performed tests at large scale and found that a wooden structure could self-extinguish during a fire when the maximum incident heat flux is reduced below 45 $kW.m^{-2}$. However, in some particular cases the conditions for self-extinguishment could never be achieved. This was observed by several authors [3, 4, 5] who studied extinguishment phenomenon in a full-scale Cross Laminated Timber (CLT) compartment. These works focused on CLT delamination during the tests. Delamination is a stochastic phenomenon that generates the fall of burning wood and exposing additional fuel. Therefore, the delamination contributes to feed the fire and to expose some virgin wood to the heat flux, avoiding conditions for self-extinguishment to occur. Moreover, the experimental study made by McGregor showed that self-extinguishment did not occur for a large compartment made entirely of wood [3].

Studies were also carried out at smaller scale, using a cone calorimeter or a Fire Propagation Apparatus (FPA), to estimate useful parameters such as heat flux and critical Mass Loss Rate Per Unit Area (MLRPUA) at self-extinction [6]. Emberley *et al.* [7] measured a critical MLRPUA from 2.65 to 8.28 $g.m^{-2}.s^{-1}$ and a critical heat flux between 24.1 to 56.6 $kW.m^{-2}$ according to wood species. That paper concluded that the self-extinguishment is independent on wood densities or on the imposed heat flux. Using a FPA, Bartlett *et al.* [4] performed experiments by decreasing the imposed heat flux of the FPA (corresponding to a FPA temperature decreasing) until the self-extinguishment was observed. A critical MLRPUA equal to 3.48 $g.m^{-2}.s^{-1}$ and a critical heat flux equal to 31 $kW.m^{-2}$ was found in this way (at ambient oxygen concentrations) [4]. These experiments, at small scale, have determined critical values for extinguishment after MLR decrease, at steady state. Recently, the present authors have conducted experiments in which the wood was first exposed to a high heat flux and then to a null one [8]. These tests showed that the critical MLR depends on the exposure time. Indeed, critical MLR values were high for low exposure time because char was just started to form, constant when the MLR is at its steady state and low for long exposure because of the thick char layer. Finally, Crielaard *et al.* [9] studied the smouldering extinguishment by shifting sample from one cone with a heat flux of 75 $kW.m^{-2}$ to another between 0 to 10 $kW.m^{-2}$ varying air flow. These two cones were horizontally oriented. The critical heat flux for self-extinguishment of smouldering is below 5 to 6 $kW.m^{-2}$. A 0.5 $m.s^{-1}$ airflow led to quicker extinguishment than with no airflow while a 1 $m.s^{-1}$ airflow led to maintain the flame at 6 $kW.m^{-2}$. In that work MLR data could not be provided since the sample had to be moved from the first cone to the second one.

The aim of the present work was to study the flaming self-extinguishment of spruce wood exposed to heat fluxes provided by two vertically oriented cone calorimeters. For that purpose, the initial cone calorimeter setup was modified by adding a second cone. This new device is very useful for studying sample extinguishment, by suddenly sliding from one cone to the second one, while continuing to record the mass loss. It allows to provide an accurate characterisation of both the critical heat flux and the MLR for self-extinguishment. The setup is completed by a precision scale to record the mass loss and an infrared camera to measure the surface temperature during the tests [10]. In the following, the experimental setup and the material will be first described. Then, results related to the heat flux and the MLR at self-extinguishment will be presented and discussed.

2 Materials and Methods

2.1 Samples and double sliding cone calorimeter

The experimental setup used for this study is presented in figure 1. It is based onto a usual cone calorimeter in vertical orientation which was modified by fixing two cones on a sliding ball bearing table. This allows to switch fast from one heat flux (coming from one of the cones at a fixed temperature) to another heat flux (coming from the other cone at a different temperature). The sample is put in the sample holder which is laid on a precision scale. The main advantage of this setup is that the mass (and then the Mass Loss Rate) can be measured continuously, even when switching from one flux to the other. Moreover, as described in a previous paper [11], the surface temperature is measured using an infrared camera looking from the cone hole. Hence, with this setup, the sample surface temperature can also be measured, except during two short instants when the coil passes between the camera and the sample.

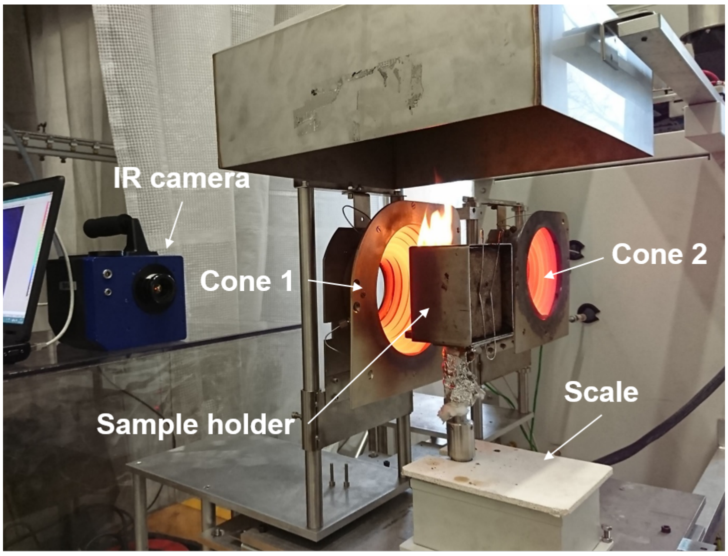


Figure 1: Experimental setup with a flaming wood sample exposed to 82.5 kW.m^{-2} (coming from cone 1). Cone 2 is adjusted to a lower heat flux (here 60 kW.m^{-2}).

The selected material was spruce wood and sample sizes were 100×100 mm with a 50 mm thickness, so the sample is thermally thick. Sample average density was about 480 kg.m^{-3}, given for an average moisture content around 9 %. As specified in the standard ISO 5660-1, samples were wrapped with two layers of aluminum foil, except their top side exposed to the radiative flux. The distance between the sample and the heater was 25 mm. The sample was considered ignited with the appearance of the flame and in contrary extincted with the flame extinguishment. Radiative heat fluxes emitted by the cones were controlled before each test thanks to a Schmidt-Boelter fluxmeter (by Medtherm). The heat flux was considered correct when the value was ± 0.5 kW.m^{-2} from the desired flux. The heat fluxes initially chosen were 60, 82.5 and 93.5 kW.m^{-2} but we noted during a calibration of the fluxmeter made a posteriori that the values indicated by the fluxmeter were underestimated by 10 %. The values given everywhere in the following of the paper are therefore the values given by the fluxmeter corrected for this error. In this study, samples were exposed vertically during 6, 9, 15 and 18 minutes to external constant heat fluxes between 60 and 93.5 kW.m^{-2} for the first exposure. Then the second cone was slid in order to expose the sample to a lower heat flux (between 38.5 and 60 kW.m^{-2}). This second exposure lasted 5 min. At least three experiments were performed per pair of heat flux (example 60 kW.m^{-2} for the first and 38.5 kW.m^{-2} for the second) and exposure time. A total of 206 tests were performed. Figure 2 shows the heat flux evolution measured by the fluxmeter during the double cone sliding. The transition between the two cones is shorter than 5 seconds.

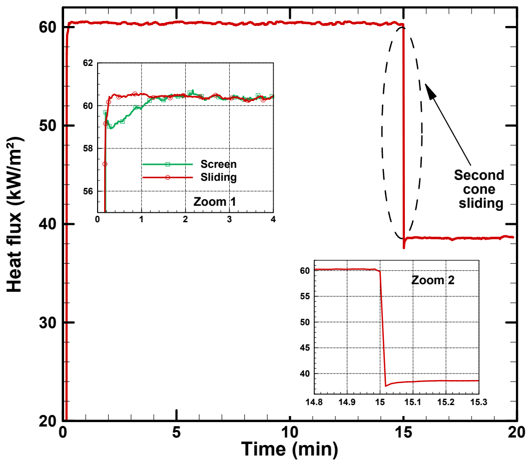


Figure 2: Heat flux evolutions with a first heat flux equal to 60 kW.m^{-2} during 15 min, followed by a lower heat flux (38.5 kW.m^{-2}) during 5 min.

Figure 2 shows that the heat flux increases very fast when the fluxmeter is exposed to the cone calorimeter and reaches a plateau at the chosen nominal value, here equal to 60 kW.m^{-2}. This is an additional advantage of the present setup involving sliding cones compared to the original cone calorimeter. Indeed, in that one an insulating shield is used to prevent the sample to be directly exposed to the radiative flux emitted by the cone, mainly during the initialization step of the test (baseline acquisition of the mass cell). When this screen is in front of the cone coil, heat losses are reduced (compared to the heat losses without the screen), and the electrical power required to maintain the cone coil at the temperature setpoint is reduced. When the insulating cover is removed, losses suddenly increase, the cone temperature decreases, and as a result the emitted flux also, as shown in figure 2 (green curve, zoom 1). So it takes some time (almost one minute) for the cone temperature to reach the setpoint again. These heat losses were already observed and described in [12]. In the proposed modified device, the screen is no longer needed because the cone is translated in front of the sample. In this way the desired heat flux measured by the fluxmeter is stable from the very beginning of the experiment.
After 15 minutes, the second cone, adjusted to a heat flux equal to 38.5 kW.m^{-2}, is slid in front of the fluxmeter. The desired heat flux measured by the fluxmeter is quickly stable, about 10 s after sliding, and equal to the desired value, as seen in figure 2 (zoom 2).

2.2 Surface temperature measured by infrared camera

A multispectral infrared camera (Orion SC7000 by FLIR) was used for measuring surface temperature of samples during tests. This measurement is non-intrusive and makes it possible to study the temperature field evolution on a large surface unlike a thermocouple put on the surface which measures only a punctual temperature. Moreover the temperature measured by a thermocouple can be affected by radiation coming from the cone or a bad contact between the thermocouple and the surface, since wood is degrading during the test, producing char and

cracks [13].
The camera was equipped with a specific optical bandpass filter at 3.9 μm (2564 cm^{-1}), which is outside emission bands of combustion gases (CO_2 and H_2O) present in the flame of the wood sample [14]. In this spectral band, only soot can emit, and since the optical thickness of flames involved in cone calorimeter experiments is very small, the flame can be considered as almost transparent [10]. The surface temperature is calculated using the inversion of Planck's law after a preliminary calibration of the camera with a blackbody. In the present work, we paid more attention to the temperature measured at time long enough such that all the sample surface is made of char. An emissivity equal to 0.95 was chosen for char. Figure 3 shows the temperature field obtained for one test for which the heat flux was equal to 82.5 kW.m^{-2} during 900 s and 44 kW.m^{-2} after.

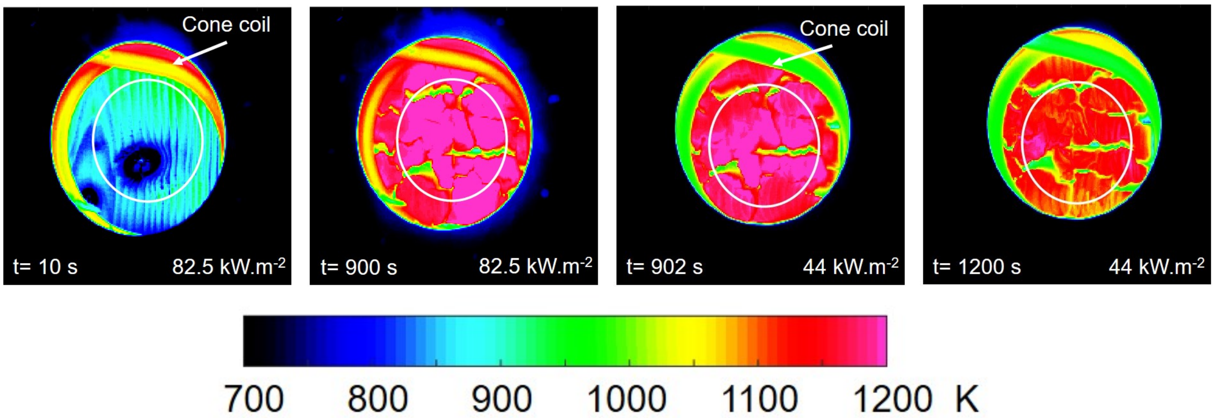


Figure 3: Temperature field in Kelvin and studied area (white circle) at different exposure time for two different external heat fluxes (82.5 kW.m^{-2} up to 900 s and 44 kW.m^{-2} from 902 s to 1200 s).

The white circle corresponds to the studied area, where the mean surface temperature was calculated. The temperature field on the surface is quite homogeneous, except for temperatures estimated into cracks. The temperature of the second cone, which is adjusted to a lower heat flux, is lower than the temperature of the first cone which is adjusted to a high flux. This cone temperature decrease is well seen in figure 3, between the image taken at t= 900 s, just before switching and the image taken at t= 902 s, just after switching. For this test flame extinguishment occurred approximately 60 s after flux switching. We note that the sample surface temperature remained quite high ($\pm$ 1150 K) even a long time after the flame extinguishment, due to the heat flux brought to the sample by the cone, and the additional heat due to the char oxydation [11, 15, 16].

3 Flame self-extinguishment after one given exposure time

3.1 Heat flux for wood self-extinguishment

Some tests were performed to determine the different parameters significant wood self-extinguishment. As explained before, the sample was exposed to a first high heat flux inducing auto-ignition. After 15 minutes, the cones was slid and the sample was exposed to a lower heat flux. Table 1 presents the results of 95 tests carried out with a fixed first exposure time equal to

15 minutes. This table gathers if self-extinguishment occurred or not, and the proportion of self-extinguishment, for different pairs of heat fluxes.

Table 1: Results of tests performed. In columns, the heat flux (kW.m^{-2}) applied to the sample during the first step. In rows, the heat flux (kW.m^{-2}) applied to the sample during the second exposure (†: flame extinguishment, √: no flame extinguishment, -: no test). Percentage of self-extinguishment is also added.

Flux 2 \ Flux 1	60	82.5	93.5
60	-	√ √ √: 0 %	√ √: 0 %
55	-	-	√ √ √: 0 %
52	-	√ √ √ √ √ √ √ √: 0 %	√ √ √ √ √ √ † †: 25 %
49.5	√ √ √ √: 0 %	† † † √ √ √ √ √: 37.5 %	† † † † † √ √ √: 62.5 %
47	√ √ √ √ √ √ √ †: 12.5 %	† † † † † † √ √: 75%	† † † † † † † †: 100 %
44	† † † † † † √ √: 75 %	† † † †: 100 %	-
41	† † † † † † † †: 100 %	-	-
38.5	† † †: 100 %	† † † †: 100 %	-

This table shows that the heat flux required to sustain the flame increases when the first heat flux increases. To illustrate this, for a second heat flux equal to 47 kW.m^{-2} self-extinguishment was observed systematically when the first heat flux was equal to 93.5 kW.m^{-2} whereas the flame persisted overwhelmingly when the first heat flux was equal to 60 kW.m^{-2}. This phenomenon can be explained because using a larger heat flux during the first 15 minutes of the test leads to a larger sample degradation and thus a thicker char layer. Consequently, the heat flux required to degrade the remaining virgin wood and to release enough pyrolysis gases to maintain the flame has to be higher. That is why the critical heat flux for self-extinguishment is higher for 93.5 kW.m^{-2} than for 60 kW.m^{-2}. Near the critical heat flux wood self-extinguishment is not systematic for a given second heat flux. The explanation comes from the state of the wood sample surface. Indeed, the flame maintenance is controlled by a sufficient amount of pyrolysis gases leaving the sample. This gases release is driven by the imposed heat flux but depends also on the cracks size. Consequently, when the imposed heat flux is near the limit between the wood self-extinguishment and the flame maintenance, the cracks size and depth will have a determining role. This is illustrated in figure 4 which shows two spruce samples after 15 minutes of exposure to 93.5 kW.m^{-2}.

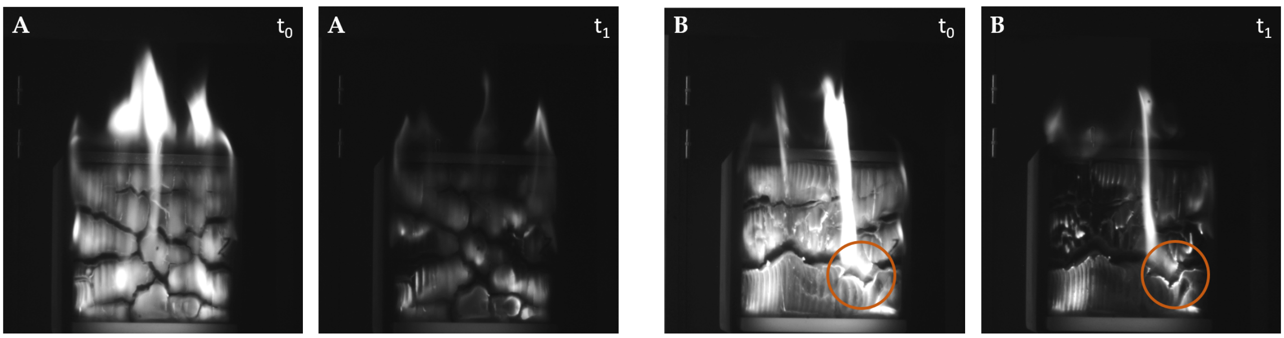


Figure 4: Pictures of two wood samples (A and B) after 15 minutes of exposure to 93.5 kW.m^{-2}. t_0: time where the heat flux is removed, t_1: 20 s after t_0.

For a same experimental protocol, the two samples look different. In particular sample B presents a large crack from which enough pyrolysis gases escape so that a flame can be sustained

longer. The cracks formation cannot be controlled, that is why the samples self-extinguishment can vary significantly from one test to another even if performed in the same conditions.
To handle such a variability, tests were carried out up to eight times for heat fluxes pairs near the critical heat flux, as shown in table 1, and a statistical analysis was performed. Figure 5 shows the proportion of cases in which extinguishment was observed as a function of the second heat flux. The measurements (symbols) as well as shape-preserving interpolations (dashed lines) are shown.

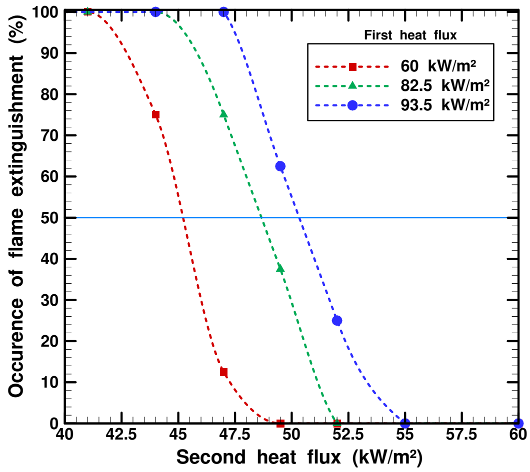


Figure 5: Percentage of flame extinguishment according to the heat flux applied to the sample during the second step (for different heat fluxes applied during the first step).

The critical heat flux was defined as the value below which we observe more than 50 % of flame extinguishment (using the interpolation curve). This critical heat flux is equal to 45, 49.5 and 51 $kW.m^{-2}$ for respectively a first heat flux equal to 60, 82.5 and 93.5 $kW.m^{-2}$. Consequently, these tests show that for a high first heat flux, the heat flux required to sustain the flame must be higher.

3.2 Time-to-extinguishment

For each test, the time-to-extinguishment, corresponding to the time when the flame completely disappeared, was recorded. Table 2 shows the mean time-to-extinguishment observed for all the cases tested.

Table 2: Mean time-to-extinguishment (s) when self-extinguishment occurs depending to exposed heat fluxes (†: flame extinguishment, $\surd$: no flame extinguishment, -: no test).

Flux 2 \ Flux 1	60	82.5	93.5
52	-	-	†: 110±10
49.5	-	†: 93 ±9	†: 98±10
47	†: 100	†: 82±27	†: 89±26
44	†: 92±23	†: 57±12	-
41	†: 58±16	-	-
38.5	†: 36±4	†: 55±9	-

Logically, for a given first flux, i.e. for a given column of the table, the lower the second flux, the shorter the mean time-to-extinguishment is. Indeed, since a given heat flux is required to get enough pyrolysis gases to sustain the flame, the lowest the heat flux, the fastest the MLR decreases under the critical value. In all the cases, the mean time-to-extinguishment did not exceed 120 s after sliding the cone.

3.3 Surface temperature

Figure 6 presents the evolutions of mean surface temperature (errors bars corresponding to the standard deviations obtained from three tests) for the same two cases presented in the previous section, i.e. a first heat flux equal to 93.5 kW.m^{-2} during 15 min followed by a second heat flux equal to 47 or 60 kW.m^{-2}.

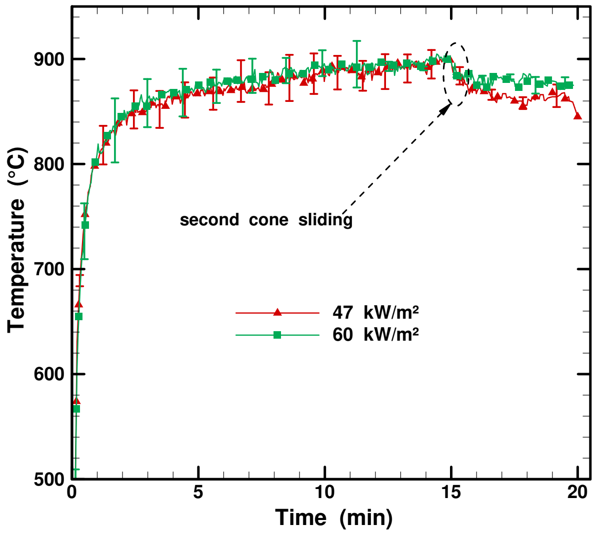


Figure 6: Surface temperature evolution with a first heat flux of 93.5 kW.m^{-2} during 15 min, followed by a lower heat flux (60 or 47 kW.m^{-2}) during 5 min.

At the beginning of the test the surface temperature increases first fast up to a temperature near 800 °C. This is followed by a more gradual rise up to 900 °C. After 15 minutes, the heat flux is switched to the lower value. As a consequence of this heat flux decrease, the surface temperature starts to decrease and a new temperature of equilibrium is reached. The temperature decrease is logically higher when the heat flux decrease is larger. 95 tests were performed. For each test, the temperature was averaged over a period of 245 seconds, taken 30 seconds after the cone was slid. The results are gathered in Table 3. In this table, are indicated the average and the standard deviation of the time averaged temperature obtained during the different tests performed for one heat fluxes pair. No indicated standard deviation means that only one or two tests were available.

Table 3: Surface temperature (°C) after sliding the cone depending on exposed heat fluxes (†: flame extinguishment, √: flame maintenance, -: no test).

Flux 2 \ Flux 1	60	82.5	93.5
60	-	√: 874±3	√: 879±1
55	-	-	√: 862±11
52	-	√: 854±10	†: 850; √: 866±6
49.5	√: 805±18	†: 843±4; √: 849±8	†: 837±9; √: 853± 7
47	†: 792 √: 792±7	†: 833±6; √: 845±3	†: 841±31
44	†: 763±24; √: 786±16	†: 840±11	-
41	†: 776±9	-	-
38.5	†: 789±4	†: 820±13	-

The reported surface temperatures at extinguishment are rather high, around 800 °C. Indeed, the incident heat flux remains large and the smouldering combustion continues (glowing embers) that explains why the temperature remains high. Logically, the new equilibrium temperature is somewhat lower when the second heat flux is lower. But the surface temperature by itself doesn't appear to have a critical impact on the flame extinguishment. For instance the flame can sustain for a surface temperature equal to 786 °C (first flux equal to 60 kW.m^{-2}, second flux equal to 44 kW.m^{-2}) whereas extinguishment can be observed for a surface temperature equal to 843 °C (first flux equal to 82.5 kW.m^{-2}, second flux equal to 49.5 kW.m^{-2}). However, it is noted that for a pair of heat fluxes for which extinguishment was or wasn't observed, the surface temperature was somewhat lower when the sample self-extinguished.

3.4 Mass Loss Rate for wood self-extinguishment

The mass loss was recorded for each test. Figure 7 presents a typical MLR evolutions for a first heat flux equal to 93.5 kW.m^{-2} during 15 min followed by a second heat flux equal to 47 or 60 kW.m^{-2}.

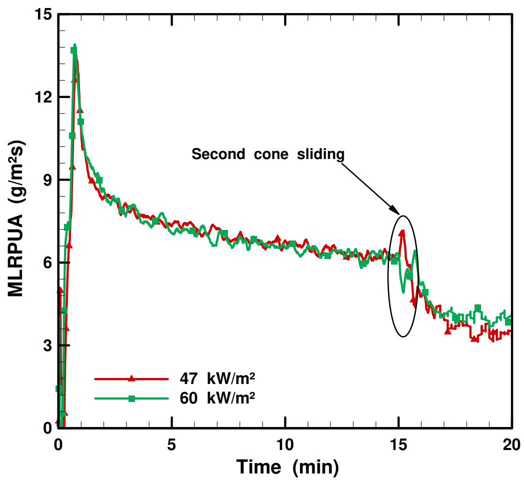


Figure 7: MLR evolutions with a first heat flux of 93.5 kW.m^{-2} imposed during 900 s, followed by two lower heat fluxes (60 and 47 kW.m^{-2}) imposed during 5 min.

MLR evolutions are similar during the first part during which the heat flux is the same. A peak is observed at the beginning of the test, followed by a gradually decrease all along the 15 minutes of exposure. This is a classical MLR behavior already described in [1, 17] for instance. At 15 minutes, the second cone, with a lower heat flux, is slid in front of the sample. It results in a logical MLR decrease. Approximately 100 s after switching the heat flux, a new steady state is observed, slightly above 4 g.m^{-2}s^{-1} for the test for which the second heat flux was equal to 60 kW.m^{-2}. For the test for which the second heat flux was equal to 47 kW.m^{-2}, the new steady state was around 3.5 g.m^{-2}s^{-1}. Flame self-extinguishment occurred for the second case (heat flux equal to 47 kW.m^{-2}) but not for the first one (heat flux equal to 60 kW.m^{-2}). Even in the case for which flame extinguishment occurred, the MLR does not decrease to zero because pyrolysis continues, as well as smouldering combustion. Figure 8 presents the steady state MLRPUA measured 100 s after the second heat flux was applied to the sample surface.

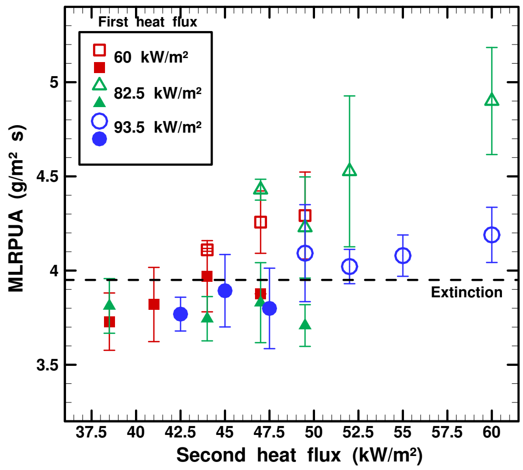


Figure 8: MLRPUA measured after the cone sliding (empty mark: no flame extinguishment, plain mark: flame extinguishment).

Tests for which flame extinguishment occurred are represented with plain marks, and with empty marks when extinguishment did not occur. It is quite clearly seen in this figure that a critical value for the MLRPUA can be determined around 4 g.m^{-2}s^{-1}: flame extinguishment occurred almost every time the MLRPUA was below this critical value, and almost never when it is above. This critical MLRPUA is consistent with those obtained by Emberley *et al.* [6, 7] and slightly higher than those reported by Bartlett *et al.* [4]. Below this value, the degradation process and thus the MLR are too weak to get enough pyrolysis gases released to sustain the flame. It is worth noting that this value is the same whatever the exposure heat flux used in the first part of the test.

4 Influence of the exposure time on sample self-extinguishment

The measurements performed so far were presented only for one exposure time (15 minutes) to the high heat flux. However, the exposure time might affect the determined parameters especially when the wood decomposition is not yet in steady state. Tests were performed by submitting the sample to the high heat flux during different exposure times: 6 min (38 tests), 9 min (36 tests) and 18 min (37 tests). These times were chosen to avoid the transient state, since the goal of this work was to determine if exposure time has or not an influence on wood extinguishment once the steady state were reached. After this time, the second cone set at a lower heat flux was slid in front of the sample and MLR, heat flux and time for wood self-extinguishment were measured. Times-to-extinguishment were measured between 30 and 120 seconds that is similar to values measured previously and reported in table 2. Heat fluxes and MLR results are presented and discussed in the next two sections.

4.1 Critical heat flux

As for the tests carried out with a 15 min duration and presented in section 3.1, for a second heat flux near the critical heat flux extinguishment or flame persistence was not systematic. Figure 9 shows the occurrence of flame self-extinguishment as a function of the heat flux for different exposure times. The self-extinguishment critical heat flux is defined as before, i.e. the heat flux for which the extinguishment probability is higher than 50 % (value obtained from the interpolation curve).

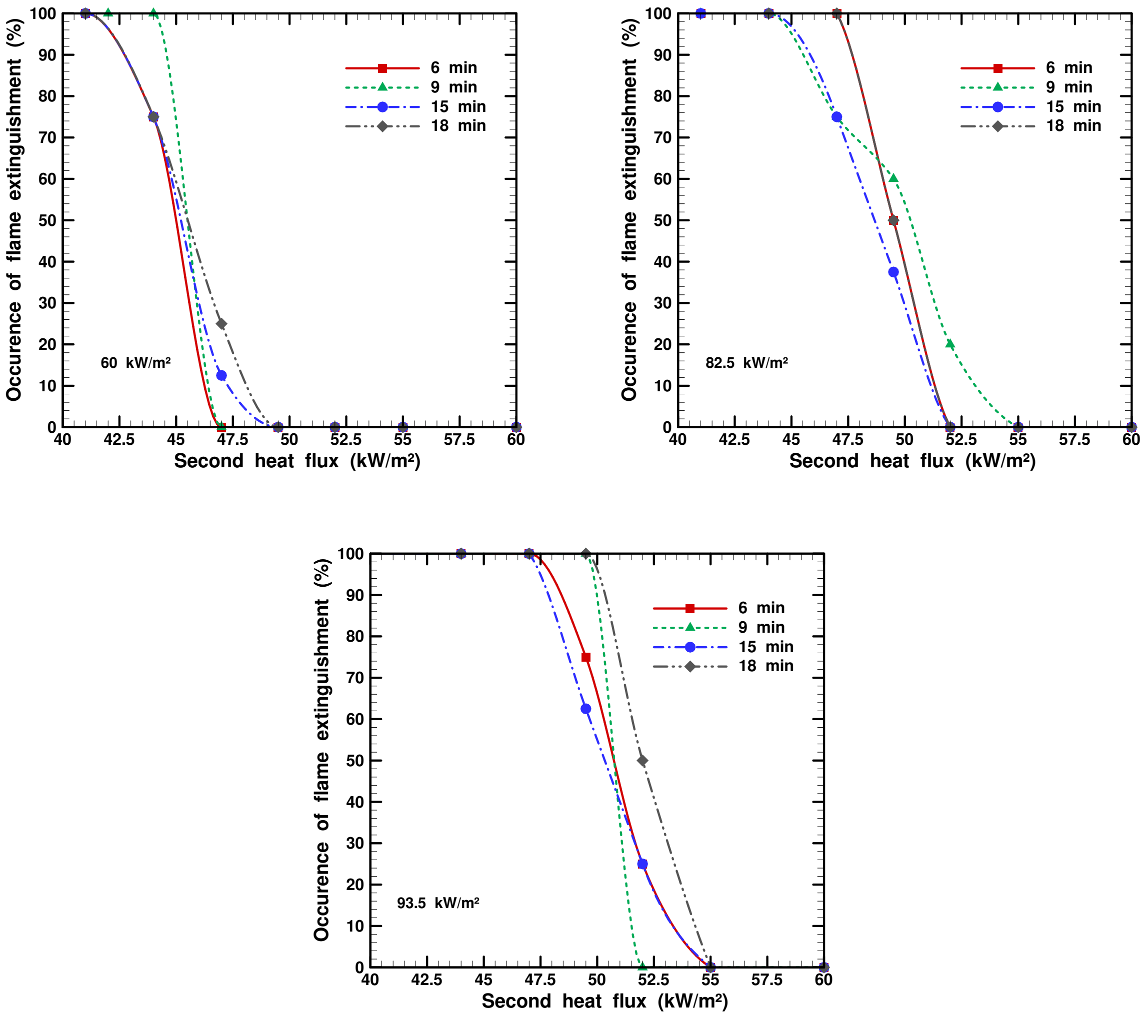


Figure 9: Percentage of flame extinguishment as a function of the heat flux applied to the sample during the second step, for different exposure heat fluxes and different exposure times.

As shown in figure 5, the heat flux required to sustain the flame increases with the first applied heat flux. For example, for an exposure time of 6 minutes, the heat flux for a 50 % probability of flame extinguishment is respectively equal to 45, 49.5 and 51 kW.m^{-2} for a first heat flux of 60, 82.5 and 93.5 kW.m^{-2}. However, we can see that these critical heat fluxes leading to self-extinguishment are almost identical whatever the exposure time to the first heat flux: it varies by a maximum of 2 kW.m^{-2} when the exposure time varies from 6 to 18 minutes. This means that multiply by three the exposure time does not modify significantly the self-extinguishment critical heat flux. Figure 10 shows the heat flux for self-extinguishment as a function of the probability of self-extinction. Two probabilities are selected to determined the critical heat flux for self-extinguishment: 50 % arbitrary and 100 % for fire safety.

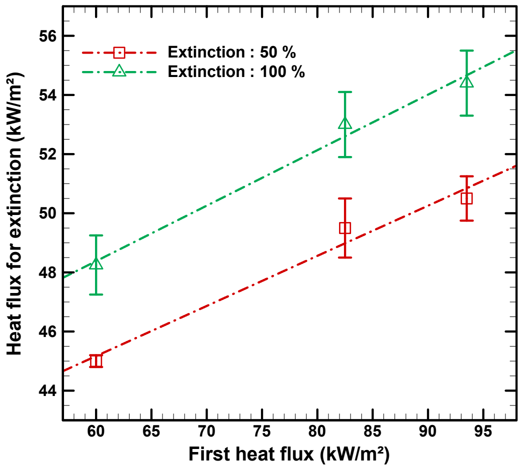


Figure 10: Heat flux for flame extinguishment according to the probability to self-extinguishment.

The heat flux for self-extinguishment increases quasi linearly time with the first heat flux irrespective to the exposure. The values of critical heat flux for self-extinguishment around 10 % when the probability for flame extinguishment switch between 50 % and 100 %. The critical heat flux is determined between 48 and 54.5 kW.m^{-2} for a probability of self-extinguishment of 100 %. The dependence of the critical extinction flux on the exposure heat flux but its quasi independence with the exposure time seems astonishing at first glance. The most obvious explanation as to why the critical flux varies is the char layer thickness. Indeed, the char layer acts both as a thermal insulator that limits the heat flux transmitted to the virgin wood layer and as a barrier to the release of pyrolysis gases. It explains why the critical heat flux increases when the exposure heat flux increases, since the thickness of char layer should increase too. But we can expect that the thickness of the char layer, and thus the critical heat flux, also increases with exposure time, which is not the case. To solve this paradox, we cut the samples in half to measure the thickness of the char layer. Figure 11 presents the critical heat flux as a function of the measured char thickness for the different exposure times.

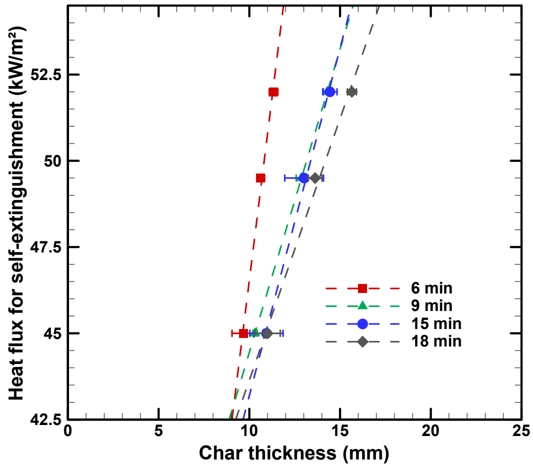


Figure 11: Critical heat flux as a function of the measured char thickness for different exposure times.

The first finding is that the critical flux increases linearly with the thickness of the char layer, which validates the hypothesis of the major influence of the char layer on the critical flux. The second result is that the thickness of the char layer doesn't increase with exposure time if this one is larger than 9 min. That is why the critical heat flux does not increase also when the exposure time increases. The explanation is that, in steady state, the char layer regression due to the smouldering combustion is almost equal to the front charring rate, so that a constant char thickness is reached and thus the critical heat flux doesn't depend on the exposure time. When the exposure heat flux increases, the charring rate increases too, as well as the regression rate, but anyway the char layer in steady state is thicker. The authors are aware that this result may very well be specific to spruce wood and therefore not general. For other wood species, the thickness of the char could very well increase with exposure time.

4.2 Mass Loss Rate

As for section 3.4, the mass loss was recorded and the MLRPUA calculated to determine a self-extinguishment critical MLRPUA as a function of the second heat flux for different exposure heat fluxes and exposure times. Results are presented in fig. 12 for exposure times equal to 6, 9 and 18 min. Results obtained for exposure time equal to 15 were already shown in fig. 8.

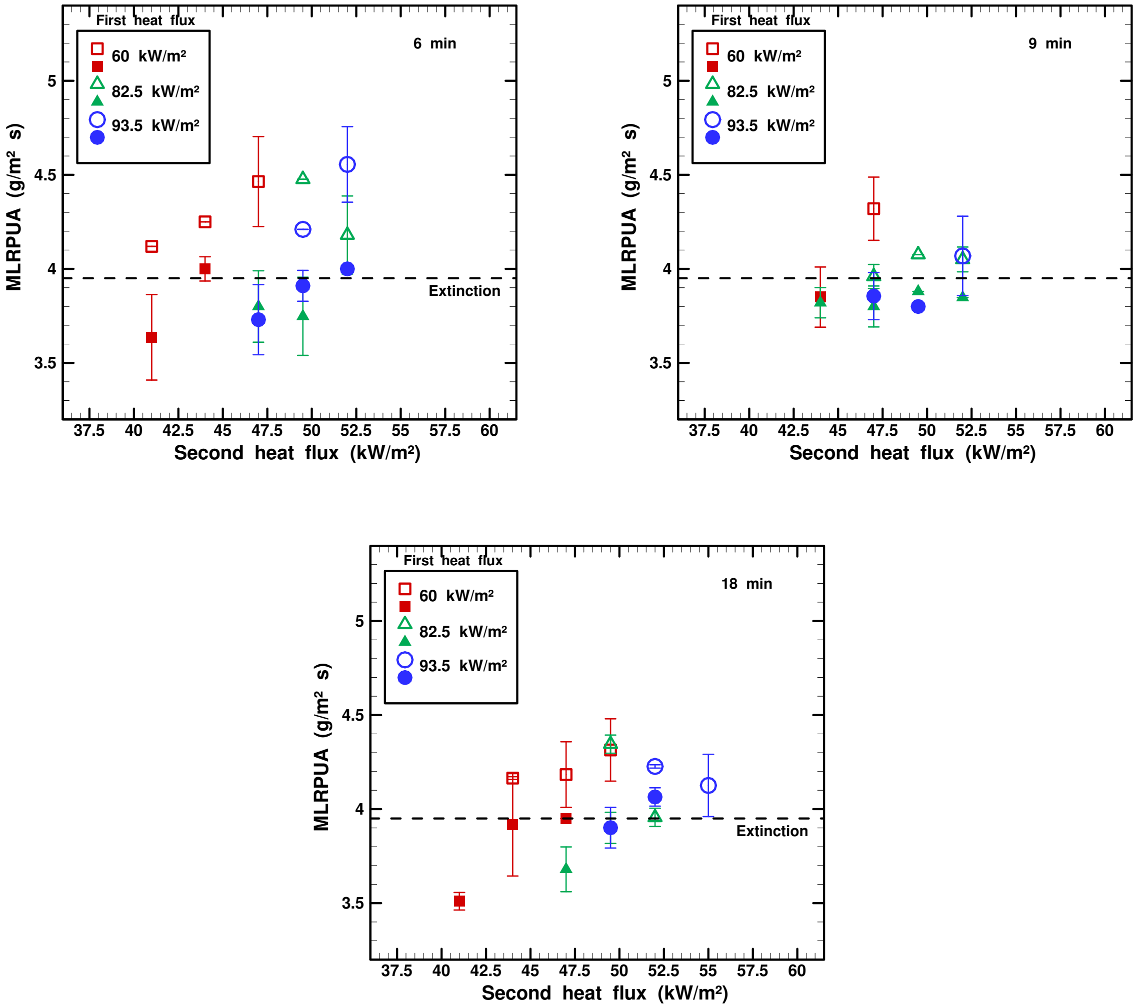
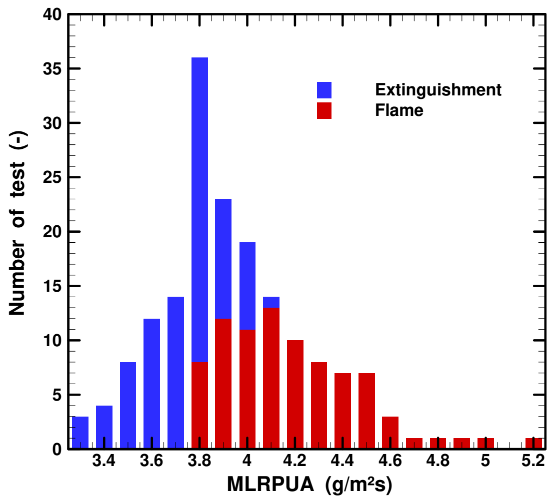


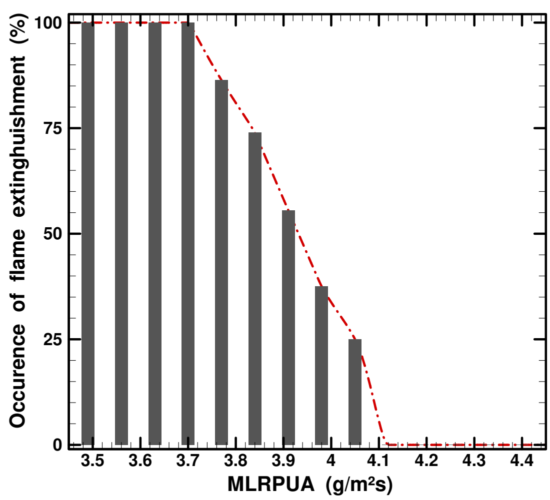
Figure 12: MLR measured after the cone sliding (empty mark: no flame extinguishment, plain mark: flame extinguishment) for four exposure times (6, 9 and 18 minutes). Results obtained for 15 minutes exposure time are presented in fig. 8.

A limit around 4 $g.m^{-2}s^{-1}$ can be drawn: above this value the self extinguishment occurs rarely and the farther the MLRPUA is from this limit, the rarer self extinguishment occurs. The opposite is observed below this limit. It is remarkable that this limit does not depend on the experiment parameters (exposure time, exposure heat flux, second heat flux). That means that a given amount of released pyrolysis gases is required to sustain the flame.

The large number of tests permitted us to perform a statistic study concerning the MLR data. All MLR values obtained during all the tests were processed to determine a self-extinguishment critical MLRPUA. Figure 13a presents the histogram showing the number of tests for which a given MLR was obtained and whether flame extinguishment (blue bar) or persistence (red bar) was observed. From this we calculated the extinguishment occurrence as a function of the MLRPUA. The result is presented in figure 13b. We retrieve the finding which was discussed previously: far below the critical MLRPUA, extinguishment probability is 100 %, and inversely far above this value extinguishment probability is null. However this allows a more precise and rigorous determination of the critical MLRPUA value. Similarly to what was done for obtaining a critical heat flux, the critical MLRPUA can be defined as the MLRPUA for which a 50 % extinguishment probability is observed. A value equal to 3.95 $g.m^{-2}s^{-1}$ was found. Moreover we can define a MLRPUA range in which extinguishment or not is not certain: it goes from 3.7 $g.m^{-2}s^{-1}$ (below this value extinguishment is almost certain) to 4.1 $g.m^{-2}s^{-1}$ (above this value, extinguishment probability is almost null).



(a) Histogram.



(b) Occurrence.

Figure 13: Flame extinguishment as a function of the MLRPUA determined 100 seconds after cone sliding. Data coming for all the tests carried out whatever the exposure time and exposure heat flux (173 tests / 206 total tests performed, MLR data being not available for some tests).

5 Conclusion

A dedicated experimental setup using two heater cones was built up in order to study the flaming self-extinguishment of wood by suddenly switching from a high heat flux (leading to sample auto-ignition) to a lower heat flux in a very short time. An experimental campaign with 206 tests was led to provide an accurate characterisation of the heat flux and the critical MLRPUA for wood self-extinguishment. The critical heat flux for self-extinguishment was estimated between 44 and 51 $kW.m^{-2}$ whatever the exposure time. It was found that this value increases when the exposure heat flux is higher. By contrast, for a given exposure heat flux the critical self-extinguishment heat flux is nearly constant with exposure time. It appeared that this is explained by the char regression due to the char smouldering combustion so that the char layer reaches a nearly constant thickness in steady state. This result was found for spruce wood which was studied here, care have to be taken to not generalize to other wood species which could behave differently. The critical self-extinguishment heat flux varies linearly with the char thickness, which is one of the major findings of the present work. Near the critical heat flux, the cracks size allowing release of pyrolysis gases which maintain the flame seems to be an important parameter ruling self-extinguishment. The time-to-extinguishment was also reported. It increases when the second heat flux applied increases. This time varies from 40 seconds to 120 seconds for a sample self-extinguishment close to the critical heat flux. Surface temperature at self-extinguishment seems to have no impact on extinguishment process. The large number of tests performed made it possible to carry out a statistical study of the MLR. An extinguishment critical MLRPUA equal to 3.95 $g.m^{-2}s^{-1}$ was derived from this study, which is in good agreement with values usually found in the literature. This critical MLRPUA was found to be almost independent on the experiment parameters (exposure heat flux, exposure time), which is the second main important result of the paper.

References

[1] A. I. Bartlett, R. M. Hadden, and L. A. Bisby, "A review of factors affecting the burning behaviour of wood for application to tall timber construction," *Fire Technology*, vol. 55, no. 1, pp. 1–49, 2019.

[2] R. Emberley, C. G. Putynska, A. Bolanos, A. Lucherini, A. Solarte, D. Soriguer, M. G. Gonzalez, K. Humphreys, J. P. Hidalgo, C. Maluk, *et al.*, "Description of small and large-scale cross laminated timber fire tests," *Fire Safety Journal*, vol. 91, pp. 327–335, 2017.

[3] C. McGregor, *Contribution of cross laminated timber panels to room fires.* PhD thesis, Carleton University, 2013.

[4] A. I. Bartlett, R. M. Hadden, J. P. Hidalgo, S. Santamaria, F. Wiesner, L. A. Bisby, S. Deeny, and B. Lane, "Auto-extinction of engineered timber: Application to compartment fires with exposed timber surfaces," *Fire Safety Journal*, vol. 91, pp. 407–413, 2017.

[5] C. J. Bateman, A. I. Bartlett, R. L. Rutkauskas, and R. M. Hadden, "Effects of fuel load and exposed clt surface configuration in reduced-scale experiments," in *World Conference on Timber Engineering, Seoul, Republic of Korea*, 2018.

[6] R. Emberley, A. Inghelbrecht, Z. Yu, and J. L. Torero, "Self-extinction of timber," *Proceedings of the Combustion Institute*, vol. 36, no. 2, pp. 3055–3062, 2017.

[7] R. Emberley, T. Do, J. Yim, and J. L. Torero, "Critical heat flux and mass loss rate for extinction of flaming combustion of timber," *Fire Safety Journal*, vol. 91, pp. 252–258, 2017.

[8] L. Terrei, Z. Acem, V. Georges, P. Lardet, P. Boulet, and G. Parent, "Study of ignition and extinction of spruce glulam exposed to a radiative flux," in *Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9)*, pp. 940–949, April 2019.

[9] R. Crielaard, J.-W. van de Kuilen, K. Terwel, G. Ravenshorst, and P. Steenbakkers, "Self-extinguishment of cross-laminated timber," *Fire Safety Journal*, 2019.

[10] Z. Acem, D. Brissinger, A. Collin, G. Parent, P. Boulet, T. H. Y. Quach, B. Batiot, F. Richard, and T. Rogaume, "Surface temperature of carbon composite samples during thermal degradation," *International Journal of Thermal Sciences*, vol. 112, pp. 427–438, 2017.

[11] L. Terrei, Z. Acem, V. Georges, P. Lardet, P. Boulet, and G. Parent, "Experimental tools applied to ignition study of spruce wood under cone calorimeter," *Fire Safety Journal*, p. 102845, 2019.

[12] R. Bilbao, J. F. Mastral, J. A. Lana, J. Ceamanos, M. E. Aldea, and M. Betrán, "A model for the prediction of the thermal degradation and ignition of wood under constant and variable heat flux," *Journal of Analytical and Applied Pyrolysis*, vol. 62, no. 1, pp. 63–82, 2002.

[13] J. Urbas, W. J. Parker, and G. E. Luebbers, "Surface temperature measurements on burning materials using an infrared pyrometer: accounting for emissivity and reflection of external radiation," *Fire and materials*, vol. 28, no. 1, pp. 33–53, 2004.

[14] G. Parent, Z. Acem, S. Lechêne, and P. Boulet, "Measurement of infrared radiation emitted by the flame of a vegetation fire," *International Journal of Thermal Sciences*, vol. 49, no. 3, pp. 555–562, 2010.

[15] T. Ohlemiller, T. Kashiwagi, and K. Werner, "Wood gasification at fire level heat fluxes," *Combustion and Flame*, vol. 69, no. 2, pp. 155–170, 1987.

[16] N. Boonmee and J. Quintiere, "Glowing ignition of wood: the onset of surface combustion," *Proceedings of the Combustion Institute*, vol. 30, no. 2, pp. 2303–2310, 2005.

[17] N. Boonmee and J. Quintiere, "Glowing and flaming autoignition of wood," *Proceedings of the combustion institute*, vol. 29, no. 1, pp. 289–296, 2002.