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# Experimental tools applied to ignition study of spruce wood under cone calorimeter

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## Abstract

A study of wood ignition was performed using a dedicated experimental setup including a cone calorimeter. This setup mainly includes a non-intrusive metrology by infrared camera, enabling an accurate surface temperature measurement and a fast visible camera (3000 fps), used to observe the “auto” ignition location. The study was carried out in vertical orientation only. Fast visible camera pictures showed three types of ignition: auto-ignition close to the exposed surface, auto-ignition far from the exposed surface and ignition piloted by the cone coil. Ignition occurred only above  $45 \text{ kW}\cdot\text{m}^{-2}$ . Besides, for low heat fluxes, no ignition occurred but it was possible to observe a transition between pyrolysis solely, without combustion, and smoldering combustion for a sample surface temperature around  $400 \text{ }^\circ\text{C}$ .

Keywords: *Ignition of wood; cone calorimeter; surface temperature; IR thermography.*

## 1 INTRODUCTION

For fire safety concerns in construction domain, study of fire behavior and flame propagation in wood structures is relevant, owing to wood flammability. Overall, wood structures can exhibit a good performance under fire conditions thanks to the charring behaviour that results in a slow in-depth heat propagation and, under specific conditions, an ability to self-extinguish [1, 2]. A recent review performed by Bartlett *et al.* [3] presents the state of the art on burning behaviour of wood for structural applications. In particular, this review reports factors influencing the wood degradation with regards to material properties itself (including pyrolysis, moisture transport, charring), system properties (like sample orientation for instance) and thermal exposure (including ignition and extinction). It appears that numerous parameters are involved in the burning process of timber, underlining the complexity for real tall buildings application. Among all these parameters, the present work aims at studying the ignition phenomenon in cone calorimeter tests, and more precisely auto-ignition, i.e. ignition without any external source of energy inducing ignition when pyrolysis gases form a flammable mixture with air (ignition piloted by a spark or a pilot flame).

Ignition criteria were widely studied for many years and a state of the art was proposed by Babrauskas [4]. Most of the studies were conducted in piloted mode, looking for the conditions for which pyrolysis produces enough gas to allow and maintain flaming combustion, whatever the cause of ignition. Results obtained with piloted ignition are less scattered than without, because ignition will occur as soon as pyrolysis gases and air are in good proportion. That is why piloted ignition occurs at lower heat fluxes and surface temperatures as compared to the case when the ignition is not piloted. Concerning the heat flux, the piloted ignition occurs for flux in  $10\text{--}15 \text{ kW}\cdot\text{m}^{-2}$  range whereas auto-ignition occurs in  $25\text{--}33 \text{ kW}\cdot\text{m}^{-2}$  range for a horizontal sample orientation [3]. For vertical orientation, higher fluxes are necessary to ignite wood samples ( $28 \text{ kW}\cdot\text{m}^{-2}$  for piloted ignition and  $63\text{--}79 \text{ kW}\cdot\text{m}^{-2}$  for auto-ignition,

according to Hottel and Wilkes work's [5]). Moreover, for identical applied heat flux, times-to-ignition are always shorter in the horizontal orientation [3, 6, 7]. Bartlett *et al.* [3] suggested that it could be explained both by an increase of sample convective cooling and by pyrolysis gases dilution in vertical orientation. Nevertheless, in real fire situations, there are many cases where flammable products are subjected to high radiative fluxes but where no external "ignition" source (like a flame) is present near the exposed material. It becomes consequently relevant to study when and where the spontaneous ignition can occur. In previous studies, ignition criteria were studied with regards to critical heat flux necessary to achieve auto-ignition and to surface temperature at ignition [4, 8, 9]. Nevertheless, in existing works, some aspects are poor or less addressed, in particular the two following points:

- The first one concerns the ignition location. Indeed, one wonders if ignition occurs in the core of air/pyrolysis gases mixture, or at sample surface, or even near the cone calorimeter hot coil. In this last case, ignition can be considered to be piloted by the coil, and then not to be a true spontaneous ignition. Crémona [10] pointed out that this type of ignition can happen for the cone calorimeter oriented horizontally. In the second case, ignition is piloted by the sample surface, but this ignition is not due to an external cause and ignition can still be considered to be spontaneous. Such an ignition driven by the sample hot surface was reported by Kashiwagi *et al.* [11]. Boonmee and Quintiere [8] highlighted that two kinds of ignition occur in vertical orientation when using a cone calorimeter: a flaming ignition for high heat fluxes and a glowing ignition for low heat fluxes. In that work, glowing ignition term was used when ignition comes from the surface at very long time, while flaming ignition term was used when ignition occurs at short time in the core of combustion gases.
- The second one concerns the sample surface temperature at ignition. Indeed, in many works, this temperature is measured by thermocouples. Yet, such a measurement is subjected to several causes of inaccuracy because a good thermocouple/surface thermal contact is difficult to achieve, since thermocouple is both subjected to the air/pyrolysis gases flow and exposed to the radiative heat flux coming from the cone. Some papers reported surface temperatures measured thanks to pyrometers [8, 12] which more likely measure a "true" surface temperature. These measurements are always higher (between 400 and 600 °C) than temperatures measured with thermocouples (between 250 and 400 °C) [3].

In the following, study of wood auto-ignition is addressed regarding: i) if it occurs either in gases or near the sample surface, and in which proportion; ii) if false spontaneous ignition (ignition piloted by the coil) can occur or not when using a cone calorimeter. A contactless measurement using an infrared camera was implemented in order to obtain a reliable surface temperature.

The studied material was spruce laminated wood (glulam) which is a recombination of solid wood for large scale structural applications. This material is elaborated by gluing together, in the wood grain direction, purged laminated wood. The obtained glulam can be considered like solid wood if wood layers and glue are correctly chosen [13, 14]. In some cases, the glulam can experience delamination. This is an important issue because the delamination can lead to a further increase of sample degradation or even a re-ignition of wood [15] which can penalize the use of glulam for structural purposes. In cone calorimeter tests, as small size samples are tightened in sample holder, the delamination is generally not observed.

The basic composition of the setup included a vertically oriented cone calorimeter and a precision scale used to record mass loss during tests. A fast visible camera was used for catching the ignition location during tests. Some tests were performed with a sapphire window put between sample and cone calorimeter coil in order to avoid a possible contribution of the cone coil on wood auto-ignition. An infrared camera was used to observe the radiation emitted from wood samples surface during thermal degradation experiments. Infrared images were post-processed involving a subtraction method between successive images, to withdraw high incident flux from the cone calorimeter partly reflected by the sample. Then, an identification step was implemented linking the rise in intensity between two time steps with the increase of sample surface temperature [16].

## 2 MATERIALS AND METHODS

### 2.1 Samples and cone calorimeter

Figure 1 presents the experimental setup. This configuration allows applying the heat flux and measuring both mass loss with a scale (Mass Loss Rate Per Unit Area (MLRPUA) deduced) and surface temperature with the infrared camera which looks to the sample through the cone hole.

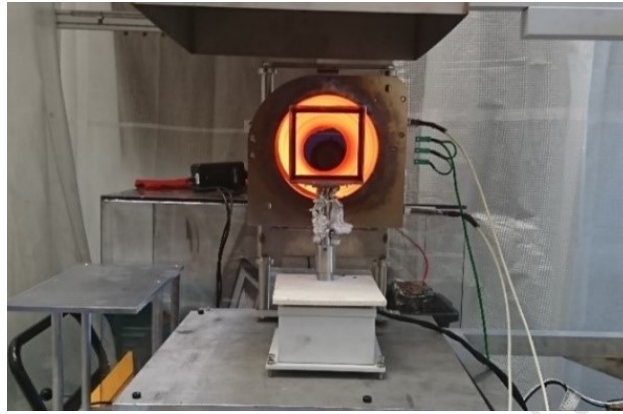


Figure 1: Experimental setup (In this photograph the sample was not put in the sample holder in order to see the cone aperture. The infrared camera looks to the sample through this aperture).

The selected glulam material was made with two layers of spruce wood with a 25 mm thickness, glued with melamine-urea-formaldehyde (MUF). Sample sizes were  $100 \times 100$  mm with a 50 mm thickness. The sample average density was about  $480 \text{ kg.m}^{-3}$ , 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 sample and heater was 25 mm. Samples were exposed vertically to the radiative heat flux between 15 and  $85 \text{ kW.m}^{-2}$  during one hour. The radiative heat flux emitted by the cone was controlled before each test thanks to a Schmidt-Boelter fluxmeter (Medtherm). The heat flux was considered correct when value was  $\pm 0.5 \text{ kW.m}^{-2}$  from the desired flux.

### 2.2 Ignition location by fast visible camera

A fast visible camera (Photron APX-RS) was used in order to study the ignition location. The camera was set to 3000 frames per second, which allowed recording 1.3 seconds in its buffer. An example of recorded pictures obtained during ignition is presented in figure 2.

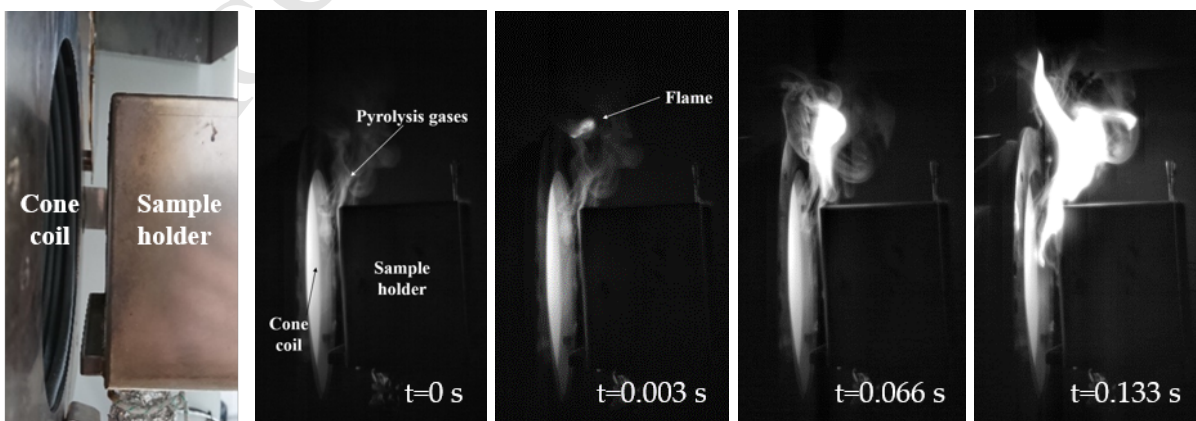


Figure 2: Auto-ignition far from the exposed surface (flaming ignition) at  $75 \text{ kW.m}^{-2}$ .

As can be seen in figure 2, ignition phenomenon is very fast and occurs for this test far from the exposed surface. Indeed, it is seen in the picture at  $t = 0.003$  s, that the fire point is located within the gas phase far from exposed surface. Once ignition occurred, the flame spread all over the flammable mixture in about 0.1 s (see picture at  $t = 0.133$  s). The fast visible camera is very useful for determining the ignition type. A specific study linking time-to-ignition to ignition type and exposed heat fluxes will be presented and discussed below.

### 2.3 Surface temperature measured by infrared camera

Surface temperatures are usually measured using thermocouples. However, these measurements are punctual and could be affected by the heat sink along the thermocouple wire or the bad contact between thermocouple and sample. This contact seems all the more difficult to maintain because wood is degrading during the test, producing char and cracks [17]. For the present work, a multispectral infrared camera (Orion SC7000 by FLIR) was used for measuring the surface temperature of samples during tests. This non-intrusive measurement allows studying temperature field evolution on a large surface while avoiding contact problems. During infrared measurements, the flame between the infrared camera and the sample surface can lead to mismeasurement of temperature. Some studies showed that emission by flames is predominant in specific wavelengths where major combustion gases ( $\text{CO}_2$  and  $\text{H}_2\text{O}$ ) can emit [18]. Outside these bands, 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 outside gas emission bands [16]. The camera had a filter wheel to select desired wavelengths. The selected wavelength was  $3.9 \mu\text{m}$  ( $2564 \text{ cm}^{-1}$ ), which is outside emission bands of combustion gases. Such a measurement method was already successfully performed by authors' group on other materials [16]. Once the camera signal is acquired, it is converted to a spectral intensity, thanks to a preliminary calibration of the camera involving a blackbody, and the temperature is calculated using the inversion of Planck's law. The emissivity for wood was studied in [19]. It is shown that the wood emissivity at  $2564 \text{ cm}^{-1}$  is close to 0.9 and that it does not vary more than  $\pm 5 \%$  around this value when the wood deteriorates under a heat flux. According to Chaos [20], a misestimate of the emissivity in the 0.8-1 range can lead to an error of 8 % in the surface temperature. Figure 3 shows the temperature field obtained for two different tests (20 and  $55 \text{ kW}\cdot\text{m}^{-2}$ ) at 120 s exposure. The white circle corresponds to the studied area, where the mean surface temperature was calculated. For the test at  $55 \text{ kW}\cdot\text{m}^{-2}$ , we can observe that emission of flame is actually negligible (i.e. not visible in the IR image) at the selected wavelength ( $3.9 \mu\text{m}$ ). The temperature field at surface is quite homogenous, except for the temperature estimated into cracks (in yellow).

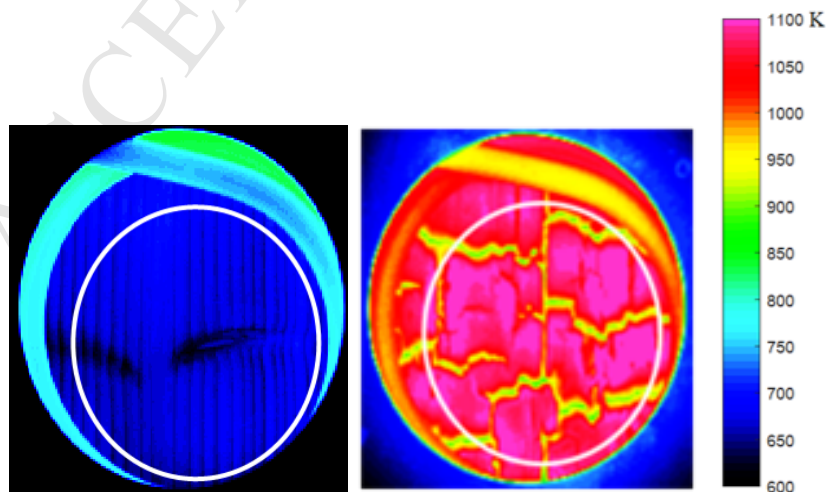


Figure 3: Temperature field in Kelvin and studied area (white circle) at 120 s for two different external heat fluxes ( $20 \text{ kW}\cdot\text{m}^{-2}$  (left) and  $55 \text{ kW}\cdot\text{m}^{-2}$  (right)).



Surface temperature evolutions obtained from the IR camera and a sheathed K-type thermocouple (1 mm diameter) located at the surface center are plotted in Fig 4. In a general way, surface temperature increases more or less quickly before reaching a plateau, near 800 °C for tests performed at 55 kW.m<sup>-2</sup>, which is in good agreement with Shi and Chew [9]. At 1250 s, when the flame appears, a sudden increase of the surface temperature is observed for both types of measurement. Nevertheless this increase is low, about 20 K. Indeed, at cone calorimeter scale, the additional heat flux brought by the flame ( $q_f$ ) is less than 1 kW.m<sup>-2</sup> accordingly to a calculation based on Law's [21] work<sup>1</sup>. For the same reason, it will be shown later that the mass loss rate is almost unchanged when the flame appears.

Until 1500 s, the temperature given by the thermocouple and the infrared camera are in pretty good agreement, even if the thermocouple underestimates the surface temperature by a few dozens of degrees, mainly when the temperature variation is fast, as a consequence of the thermal inertia of the thermocouple. The discrepancy between the two types of measurements increases for the largest times. Given that the sample surface burns, the contact between the thermocouple and the surface can no longer be ensured, resulting in a decrease of measured temperature. In addition, the thermocouple signal becomes more and more "noisy" since it is subjected to temperature variation of surrounding, caused by the turbulence of hot gases in the flame. Although widely used, we show here that the surface temperature measured by a thermocouple can lead to great uncertainty (fig. 4). For sake of accuracy, the surface temperature measurement by IR camera is preferable. This, of course, means that radiative properties have to be known, especially the sample emissivity, which may vary during the degradation process. A parametric study of sample emissivity was also done. Three values of emissivity (0.88, 0.90 and 0.95) were chosen in typical range of variation of wood emissivity during its thermal degradation, as reported by Boulet *et al.* [19]. For two tests performed at 20 and 55 kW.m<sup>-2</sup>, the temperature variation due to the emissivity uncertainty is below 20 °C in the worst case, which is very reasonable. Moreover, figure 4 shows a decrease of temperature around 1500 s because the sample surface is degrading during test and the contact with thermocouple disappears. This phenomenon was already described in [23]. Consequently, when the ignition occurs at long time, the thermocouple could not measure the surface temperature at ignition.

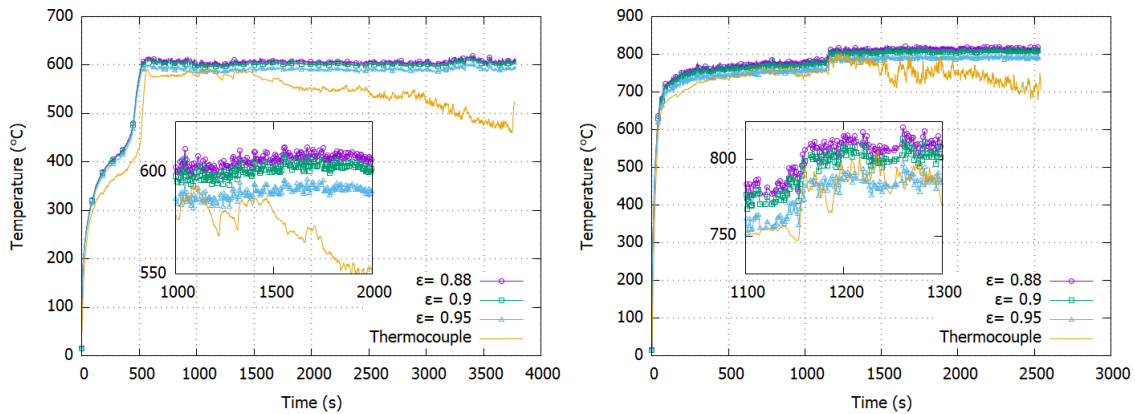


Figure 4: Time evolution of the surface temperature for two different external heat fluxes (20 kW.m<sup>-2</sup> (left) and 55 kW.m<sup>-2</sup> (right)) calculated with the infrared camera for 3 values of emissivity and measured with a thermocouple located at the surface center.

<sup>1</sup>The formula given by Law,  $q_f = (1 - e^{-0.3t_f})\sigma T_g = 0.3 \text{ kW.m}^{-2}$  with  $T_g = 900 \text{ °C}$  for a wood flame according to [22] and  $t_f$  (flame thickness)= 1 cm. The same formula gives  $q_f = 1 \text{ kW.m}^{-2}$  for a flame temperature of 1300 °C, which is a very large ceiling value for  $T_g$ .

## 2.4 Sapphire window

To avoid a possible ignition of pyrolysis gases by the hot cone calorimeter coil, a sapphire window, transparent in infrared range (up to  $5\ \mu\text{m}$  wavelength), was inserted between the cone and the sample. The window, with 20 cm diameter (equal to the cone external diameter) and 5 mm thickness was mounted on a thin steel support. As the mean transmittance of the window is around 60 %, the cone temperature has to be increased to obtain the desired heat flux. Consequently, tests were performed only at 45 and 55  $\text{kW}\cdot\text{m}^{-2}$ , because higher heat fluxes cannot be achieved with the sapphire window. The distance between sample and cone was set to 45 mm in order to ensure a good circulation of pyrolysis gases.

## 2.5 Mass loss measurements

As specified by the standard ISO 5660-1, a precision scale with a 0.1 g resolution was used for the mass loss measurement. As pointed out above, for some tests, the original cone calorimeter setup was modified to include a sapphire window between the cone coil and the sample. It might be asked whether the mass loss measurement is affected or not by this modification. Figure 5 shows mass loss rates per unit area (MLRPUA) evolutions for the two different configurations, with or without the sapphire window. Tests were performed at 55  $\text{kW}\cdot\text{m}^{-2}$  during one hour.

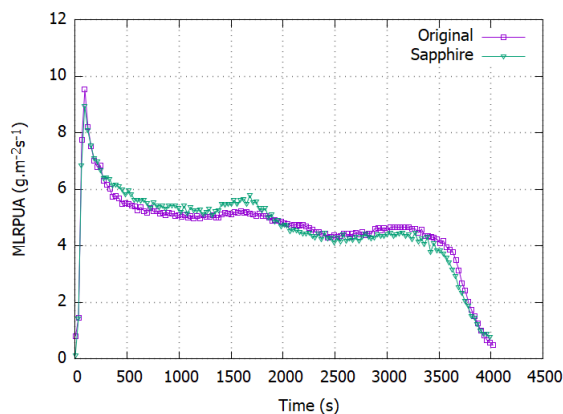


Figure 5: MLRPUA for tests with performed at 55  $\text{kW}\cdot\text{m}^{-2}$  in different configuration.

Caption “Original” in legend stands for a test performed in the original configuration (i.e. without sapphire window and cone coil temperature at 800 °C) and caption “Sapphire” refer to tests carried out with the sapphire window (cone coil temperature at 950 °C). It appears that MLRPUA evolutions are very similar. It can be thus considered that tests with the sapphire window are carried out in similar conditions than without.

## 3 APPLICATION TO THE IGNITION STUDY OF GLULAM UNDER CONE CALORIMETER

The setup was applied to the study of glulam degradation, especially the ignition type and the corresponding surface temperature at ignition. For each test, samples were exposed to the heat flux during one hour. After one-hour exposure, the heat flux was removed. Tests were carried out at different radiative heat fluxes, between 15 and 85  $\text{kW}\cdot\text{m}^{-2}$  in order to study flaming combustion or smoldering combustion. In the following, results are split in two parts focusing on flaming or smoldering combustion respectively.



### 3.1 Study of flaming combustion

#### 3.1.1 Type of ignition and time to ignition

As explained above, the time-to-ignition is defined as the moment when a flame appears. At this time, the surface temperature is often referred to the ignition temperature. However, it is difficult to explain conditions which lead to ignition. In this study, we planned to find out if the ignition always corresponds to a real auto-ignition as it is often claimed or if it can occur when pyrolysis gases encounter the hot cone coil. For that purpose, the ignition location was recorded by a fast camera. In our tests, in vertical orientation, ignition occurred when the sample was exposed to a heat flux above  $45 \text{ kW}\cdot\text{m}^{-2}$ . Figures 2, 6 and 7 present fast visible camera pictures for tests performed at 55 and  $75 \text{ kW}\cdot\text{m}^{-2}$ . Recorded pictures show three types of ignition: auto-ignition distant from the exposed surface (Fig. 2), auto-ignition close to the exposed surface (Fig. 6) and ignition piloted by the cone coil (Fig. 7).

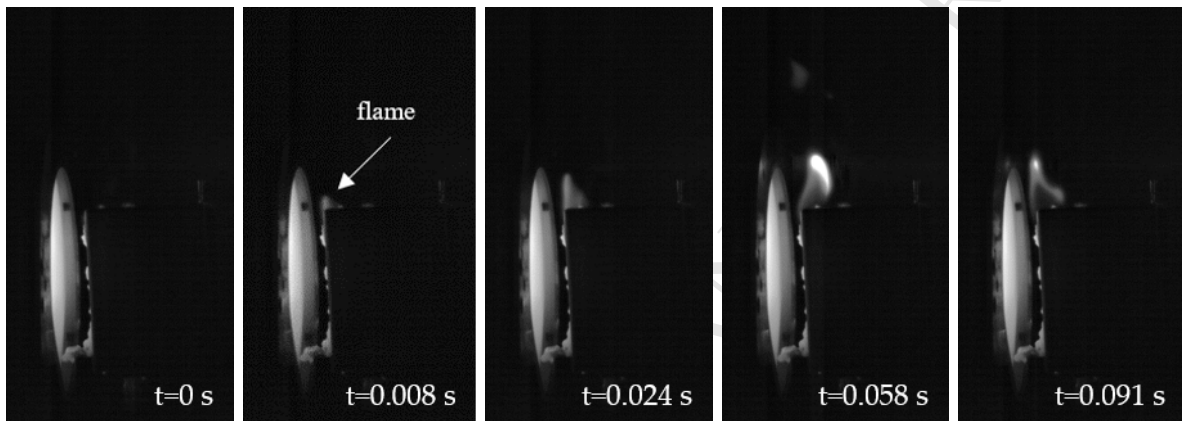


Figure 6: Auto-ignition close from the exposed surface (glowing ignition) at  $55 \text{ kW}\cdot\text{m}^{-2}$ .

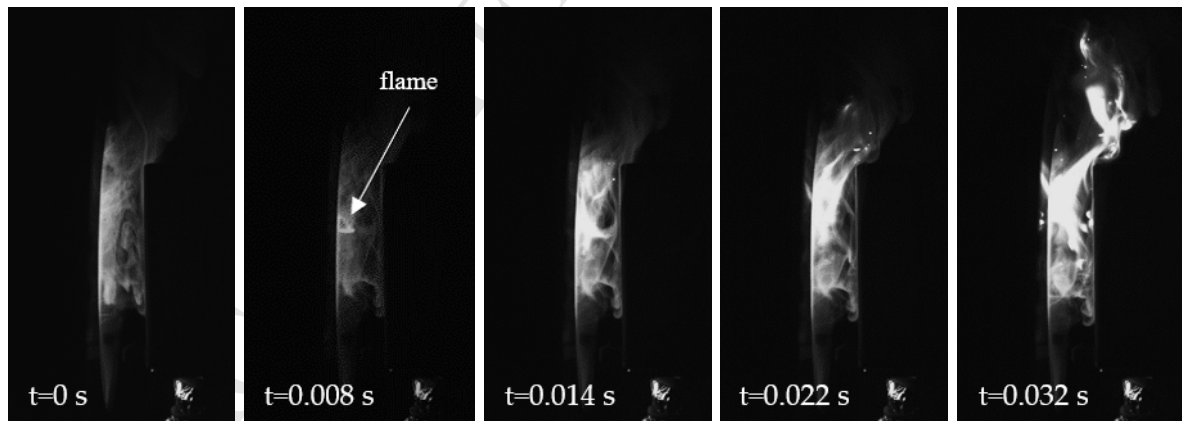


Figure 7: Ignition piloted by cone coil at  $75 \text{ kW}\cdot\text{m}^{-2}$ .

Statistics of ignition location (in percent) and time-to-ignition ( $t_{ig}$ ) in seconds are gathered in Table 1 for tests performed at 45, 55, 75 and  $85 \text{ kW}\cdot\text{m}^{-2}$ .

Table 1: Ignition origin and time-to-ignition in function of submitted heat flux.

|                                      | 45 kW.m <sup>-2</sup> |                     | 55 kW.m <sup>-2</sup> |                     | 75 kW.m <sup>-2</sup> |                     | 85 kW.m <sup>-2</sup> |                     |
|--------------------------------------|-----------------------|---------------------|-----------------------|---------------------|-----------------------|---------------------|-----------------------|---------------------|
|                                      | 10 films              |                     | 31 films              |                     | 28 films              |                     | 26 films              |                     |
|                                      | Tests                 | t <sub>ig</sub> (s) | Tests                 | t <sub>ig</sub> (s) | Tests                 | t <sub>ig</sub> (s) | Tests                 | t <sub>ig</sub> (s) |
| No ignition                          | 60 %                  | -                   | -                     | -                   | -                     | -                   | -                     | -                   |
| Auto-ignition far from the surface   | -                     | -                   | 87 %                  | 25-43               | 78 %                  | 11-17               | 70 %                  | 10-13               |
| Auto-ignition close from the surface | 40 %                  | 2790-3400           | 6.5 %                 | 1216-1726           | -                     | -                   | -                     | -                   |
| Ignition piloted by coil             | -                     | -                   | 6.5 %                 | 33                  | 22 %                  | 9-13                | 30 %                  | 8-11                |

For tests at 45 kW.m<sup>-2</sup>, the ignition was not systematic and occurred always close to the exposed surface. Times-to-ignition were high (above 2790 s) and rather dispersed. Above 45 kW.m<sup>-2</sup>, ignition occurred for each test and, as expected, increasing heat flux decreases time-to-ignition. For tests at 55 kW.m<sup>-2</sup>, the ignition is located predominantly far from the exposed surface with a time-to-ignition lower than one minute. However, for two tests (over 31 performed), ignition happened close to the surface with a large time-to-ignition (1216 s and 1726 s). For the two highest heat fluxes, ignition could be piloted by the cone coil, especially due to the increasing temperature of coil. It also appears that the ignition location has not a significant impact on time-to-ignition even if this time is slightly shorter when the ignition is piloted by the coil. Given these first results, two kinds of behavior can be highlighted:

- at low heat fluxes, ignition occurs close to the surface at a rather long time;
- at high heat fluxes, ignition occurs far from the exposed surface at a short time.

It seems obvious that the cone coil can affect ignition condition at high heat fluxes. Consequently, a sapphire window was put between sample and cone calorimeter to avoid pyrolysis gases to reach the cone coil. Table 2 presents corresponding statistics of ignition location and time-to-ignition. For each heat flux, ten films were recorded with the fast camera.

Table 2: Ignition location and time-to-ignition for tests performed with sapphire window.

|                                      | 45 kW.m <sup>-2</sup> |                     | 55 kW.m <sup>-2</sup> |                     |
|--------------------------------------|-----------------------|---------------------|-----------------------|---------------------|
|                                      | Tests                 | t <sub>ig</sub> (s) | Tests                 | t <sub>ig</sub> (s) |
| No ignition                          | 40 %                  | -                   | -                     | -                   |
| Auto-ignition far from the surface   | -                     | -                   | 10 %                  | 55                  |
| Auto-ignition close from the surface | 60 %                  | > 2500              | 90 %                  | > 1200              |
| Ignition piloted by coil             | -                     | -                   | -                     | -                   |

At 45 kW.m<sup>-2</sup>, results are comparable to tests performed without the sapphire window. Ignition was not systematic and times-to-ignition are long and dispersed, within the same range as for tests without window. On the contrary, at 55 kW.m<sup>-2</sup>, results are different. Indeed, for tests without sapphire window, flaming occurred in a very short time and was mainly located far from the exposed surface. With the window, flaming origin is mainly located close to the exposed surface and ignition occurs at long times.

### 3.1.2 Mass loss rate and surface temperature

Surface temperature was recorded for each tests. Figure 8 shows the surface temperature of samples measured with the IR camera when ignition occurred versus time-to-ignition for 91 experiments.

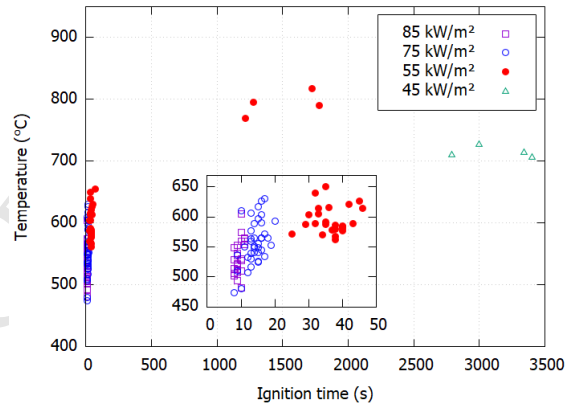


Figure 8: Surface temperature at ignition versus time-to-ignition.

Depending on heat fluxes, surface temperature at ignition laid within two intervals. For tests where the ignition occurred far from the surface (Fig. 2) or was piloted by the cone coil (Fig. 7), the surface temperature was found between 550 and 650 °C. These results are consistent with Fangrat [12] and Boonmee [8] who reported ignition temperatures (measured with a pyrometer) between 400 to 600 °C. For tests where the ignition is close to the exposed surface (fig. 6), the corresponding surface temperature range is between 710 and 820 °C. For glowing ignition, surface temperature at ignition for tests at 45 kW.m<sup>-2</sup> are lower than those at 55 kW.m<sup>-2</sup> even if times-to-ignition are longer. Indeed, in the steady state, surface temperature is close to the cone coil temperature. Consequently, for ignition

at long time, surface temperature at ignition is lower when the heat flux is low.

Figure 9 shows MLRPUA (left) and surface temperature (right) evolutions for tests between 45 to 85  $\text{kW.m}^{-2}$ . For 45 and 55  $\text{kW.m}^{-2}$ , two MLRPUA curves are plotted to describe the MLRPUA evolution when ignition location (flaming ignition: FI, glowing ignition: GI, no ignition: NI) and time-to-ignition are very different. Three tests were performed for each heat flux during one hour.

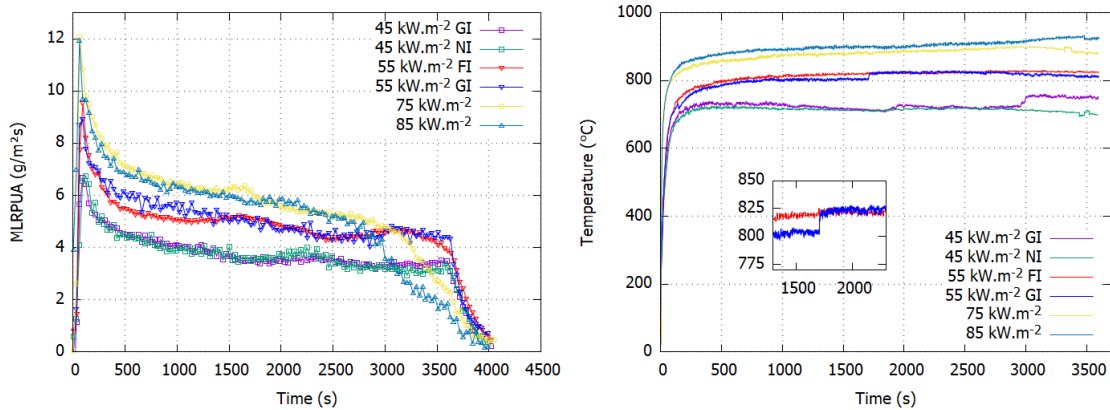


Figure 9: MLRPUA and surface temperature for tests with sample ignition (45 to 85  $\text{kW.m}^{-2}$ ).

In a general way MLRPUA first increases until a maximum. Then MLRPUA decreases, char layer formation increases, consequently the virgin wood receives lower heat flux, before reaching a constant or nearly constant value. MLRPUA and surface temperature increase are more pronounced for higher heat fluxes. However, for tests at 75 and 85  $\text{kW.m}^{-2}$ , MLRPUA evolutions tend to a constant value around 6  $\text{g.m}^{-2}\text{s}^{-1}$ . For glowing ignition (GI), at 45 and 55  $\text{kW.m}^{-2}$ , surface temperature suddenly and slightly (about 25 °C) increases when the flame appears at 1750 s and 2950 s respectively. Glowing ignition occurs when surface temperature is constant, around 720 and 790 °C for 45 and 55  $\text{kW.m}^{-2}$  respectively. This would mean that ignition at long times may occur for surface temperature higher than 700 °C. However, whatever the ignition location, no changes are observed in MLRPUA evolutions when the ignition occurred. It appears that the flame has not a significant impact on the sample degradation. Indeed, in the vertical orientation, the flame thickness is small and the additional heat flux provided by the flame is negligible compared to the heat flux coming from the cone. For the two lowest heat fluxes, heat flux removal induces a sudden decrease of the MLRPUA at 3600 s. For the two highest heat fluxes, MLRPUA decreases before the heat flux removal (at a time near 3200 s) corresponding to a total degradation of samples.

### 3.2 Study of smoldering combustion (without flame)

The experimental setup was also used for tests at lower heat fluxes. During these tests, no flame appeared but the smoldering combustion phenomenon was observed. The smoldering combustion corresponds to the flameless degradation at low temperature. Three tests were performed during one hour for each heat flux. Figure 10 shows MLRPUA and surface temperature evolutions provided from IR camera images.

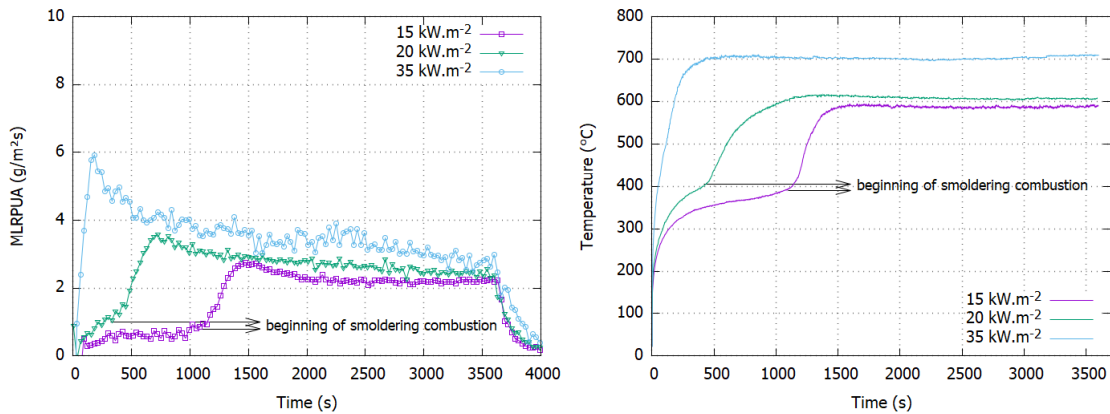


Figure 10: MLRPUA and surface temperature for tests without sample ignition (15, 20 and 35  $\text{kW.m}^{-2}$ ).

For tests at 15 and 20  $\text{kW.m}^{-2}$ , an increase of the MLRPUA is observed at 1100 s and 345 s respectively. This increase is also observed at same times for the temperature variation, around 380 °C and 410 °C respectively. This phenomenon corresponds to the beginning of the smoldering combustion that leads to an additional amount of energy release. The transition between pyrolysis to pyrolysis with smoldering combustion is more discernible for low heat fluxes (20 and 15  $\text{kW.m}^{-2}$ ). Surface temperatures measured by Urbas *et al.* at 30  $\text{kW.m}^{-2}$  with a pyrometer also showed a variation in this temperature range [17]. For tests at 35  $\text{kW.m}^{-2}$ , transition between pyrolysis with and without smoldering combustion is hardly visible because MLRPUA and temperature increase are very fast. Finally, the sudden decrease of the MLRPUA at 3600 s stands for the heat flux removal and should not be confused with the total degradation of samples.

## 4 CONCLUSION

A dedicated experimental setup was built up in order to improve the ignition study of wood under the cone calorimeter. A fast visible camera was used in order to determine the ignition location. Recorded pictures highlight that three types of ignition can occur in vertical orientation. For the highest heat fluxes (75  $\text{kW.m}^{-2}$  and above), ignition times are short (less than 20 s). Ignition occurs in most cases far from the exposed surface in the core of combustion gases, less often near the cone coil and in a few cases close from the wood surface. For the lowest heat fluxes (55  $\text{kW.m}^{-2}$  and below) auto-ignition occurs for a long exposure time and its location is close to the sample surface. When a sapphire window is added between the sample and the cone, time-to-ignition increases to very long time and ignition location is for very most cases close from the sample surface.

The surface temperature was measured with an infrared camera. This temperature was determined using a bandpass optical filter to avoid the radiation emitted by the flame. The calculation was done by inverting Planck's law, fixing the emissivity. As a consequence of increase of temperature with time, the later ignition occurs, the higher the surface temperature is at this time. When ignition occurs far from the sample surface (in space between surface and cone, or close from cone coil), time-to-ignition is short (less than 45 s) and this surface temperature is in the range 500-650 °C. When the ignition location is close to the cone coil, ignition is "piloted" by the hot coil. When ignition occurs close from the sample surface, time-to-ignition is long (larger than 1200 s) and the average surface temperature is in 700-730 °C range for a 45  $\text{kW.m}^{-2}$  heat flux and between 770 °C and 820 °C for 55  $\text{kW.m}^{-2}$ . In this case, ignition is induced by a point hotter than mean surface temperature (generally near a surface crack).

It was observed that the Mass Loss Rate is similar whatever a flame is present or not. This is a result of the negligible heat flux provided by the flame compared to the heat flux coming from the cone at this experiment scale, and especially for a cone in vertical orientation. Indeed, in this configuration,

the flame has a small thickness, and is mainly located at the upper part of the sample. For heat fluxes lower than  $45 \text{ kW}\cdot\text{m}^{-2}$ , there was no flame ignition. A transition from a pyrolysis regime without any combustion to a char combustion regime (also called smoldering combustion) was observed when the sample surface reaches a temperature between  $380 \text{ }^\circ\text{C}$  and  $410 \text{ }^\circ\text{C}$ . This transition is characterized by a sudden increase of the surface temperature due to an additional heat release by the char combustion. An increase of the MLRPUA is observed at the same time.

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## Conflict of Interest and Authorship Conformation Form

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