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Study of Ignition and Extinction of Spruce Glulam Exposed to a Radiative Flux

Terrei L.^{1,*}, Acem Z.¹, Lardet P.², Georges V.², Boulet P.¹, Parent G.¹

¹ LEMTA, UMR CNRS 7563, Université de Lorraine, France

² Université Paris-Est, Centre Scientifique et Technique du Bâtiment (CSTB), France

*Corresponding author's email: lucas.terrei@univ-lorraine.fr

ABSTRACT

Wood-based materials, which are more and more used in building construction, are often characterized by the normative tests such as cone calorimeter. Measurements of ignition time, mass loss or heat release rate, and temperatures are usually performed. The degradation dynamics of samples depends on a large number of variables (humidity, density, scale sample, experimental conditions), and it can induce flaming ignition. The autoignition phenomenon has already been studied, but opinions concerning the involved physical processes remain controversial. The ability of wood to self-extinguish in case of fire is also an important issue, especially concerning structure mechanical strength. The purpose of the present work is to study thermal degradation of glulam in the cone calorimeter with the dedicated experimental setup. In particular, we focus on ignition, extinction, and re-ignition. The cone calorimeter with vertical sample orientation was modified to study extinction and re-ignition so that the external heat flux can be quickly switched off. The samples were exposed to the heat fluxes at four values in the range from 15 to 75 kW/m². For the low heat flux, the transition was observed between pyrolysis and smoldering combustion at the temperature about 400 °C. The ignition only occurred at the heat flux higher than 55 kW/m². For 55 kW/m², re-ignition was not consistent and random. However, for the highest flux, re-ignition occurred for each new exposure to the external heat flux. Both the ignition and extinction times increased at each exposure. Char layer delays the ignition.

KEYWORDS: Cone calorimeter, extinction, ignition, re-ignition.

INTRODUCTION

Wood is one of the oldest building materials because of its cost effectiveness, mechanical properties and ease to implement. Currently, among available solutions, wood appears to be an interesting material because of its environmental advantages. There is a global rise of wood-based materials in structure as well as in architecture. It now becomes a viable alternative to concrete and steel for modern structures.

Before their usage, building materials are subjected to fire tests at different scales [1]. Cone calorimeter is one of them. It is a standard test (ASTM and ISO) useful for measuring the Mass Loss Rate (MLR), Heat Release Rate (HRR), ignition time and ignition temperature [2].

For fire safety concerns in construction domain, the study of fire behavior and flame propagation in wood structures is important due to its flammability. Nevertheless, some previous studies have shown that wood can exhibit encouraging resistance to fire, especially slow in-depth propagation and ability to self-extinction [3]. This ability is essential particularly for the rescue intervention or the structure resistance.

The fire behavior of wood has been widely studied for several years, mainly with regard to ignition criteria [4]. The sample exposure to an external heat flux or a flame leads to pyrolysis process within the sample, releasing pyrolysis gases. This process depends on several parameters such as moisture, density, heat flux and experimental conditions. It is consequently very difficult to clearly identify and characterize “the ignition conditions” [5, 6], even if it is well known that ignition occurs when the pyrolysis products, at a sufficient concentration, reach their flash point. The wood degradation by radiative heat flux leads to the formation of a char layer. Many studies have shown that the char layer tends to reduce the degradation process. Indeed, during the sample degradation, the heat release rate and mass loss rate decrease when the char is formed [7, 8]. This phenomenon is attributed to the forming of the char layer protecting the virgin wood from the direct exposure to heat flux. The flaming self-extinction of wood is also a process that generates an increase of interest. Some experiments were realized at the fire compartment and at cone calorimeter scale to estimate heat flux and critical MLR at self-extinction [9, 3]. Bartlett et al. [10] used fire propagation apparatus (FPA), and determined a critical mass loss rate below $3.48 \text{ g}/(\text{m}^2 \cdot \text{s})$ and an incident heat flux below $31 \text{ kW}/\text{m}^2$ conducting to the auto-extinction of samples (at ambient oxygen concentrations). In similar tests using cone calorimeter, Emberley et al. [11] reported a critical mass flux between 2.65 to $8.28 \text{ g}/(\text{m}^2 \cdot \text{s})$ and a critical heat flux between 24.1 to $56.6 \text{ kW}/\text{m}^2$ according to wood species. These values are determined after MLR decrease, at steady state.

The material studied here was laminated wood (glulam) of spruce which is a re-composition of solid wood for structural wood of great lengths. This material is composed with laminated wood purged, joined then glued together in the direction of the wood grain. The glulam can be considered like solid wood if the wood layers and the glue are correctly chosen [12, 13].

The aim of this work is the study of the auto-ignition, auto-extinction and re-ignition of the glulam exposed to heat fluxes provided by a vertically oriented cone calorimeter. For that purpose, the cone calorimeter was modified to study sample extinction and re-ignition by suddenly applying or withdrawing the heat flux. This modification was useful for studying samples extinction and re-ignition by suddenly applying or withdrawing the heat flux. A precision scale was used in order to record mass loss and to calculate MLR during the test. In addition, the radiation from the surface of wood samples during thermal degradation was recorded through the cone aperture thanks to a multispectral infrared camera. Infrared images were post-processed, involving a subtraction method between successive images, to withdraw the high incident flux from the cone calorimeter partly reflected by the sample. Then, the increase in intensity between two times steps was used to compute the increase of surface temperature as described in [14]. For each test, time-to-ignition and time-to-extinction was recorded and linked with surface temperature and MLR to determinate the critical MLR of extinction.

EXPERIMENTAL SETUP

Samples and cone calorimeter tests

Figure 1 presents the experimental setup. In addition, to remove suddenly the heat flux, this configuration allows to measure continuously the surface temperature with the infrared camera. The selected glulam material was made of spruce glued with melamine-urea-formaldehyde (MUF). The sample sizes were $100 \times 100 \text{ mm}$ with a 50 mm thickness. The sample moisture content was 9% corresponding to an average density of $480 \text{ kg}/\text{m}^3$. As specified in the standard ISO 5660-1 [15], the samples were wrapped with two layers of aluminum foil, except the top side exposed to radiative flux. After, the sample is placed in the sample holder with a ceramic plate behind the back side. The distance between the sample and the heater was 25 mm . The samples were exposed vertically to external constant heat fluxes between 15 and $75 \text{ kW}/\text{m}^2$. The cone emission could be assumed to be close to those of a blackbody [16]. The sample was considered ignited with the appearance of the

flame, recorded by a fast camera to deduce the ignition origin. Once ignited, samples continued to be exposed to heat flux for different times (5, 10, 30 and 60 minutes) in order to observe the impact on the extinction.

The radiative heat flux emitted by the cone was controlled before each test thanks to a Schmidt-Boelter fluxmeter (by Medtherm). The heat flux was considered correct when the value was $\pm 0.5 \text{ kW/m}^2$ from the desired flux. In the original cone calorimeter device, an insulating screen is used to prevent the sample from being exposed to the radiative flux emitted by the cone, mainly during the initialization step of the test (acquisition of the baseline 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 screen is removed, losses increase, the temperature of the cone decreases, and as result the emitted flux also. So it will take a while for the temperature of the cone to reach the setpoint again. In the proposed modified device, the screen is no longer needed. The cone is simply translated in front of the sample. In this way the desired heat flux is stable from the beginning of the experiment. Figure 2 compares the heat evolution for the two configurations with an exposure of 75 kW/m^2 during 5 minutes.

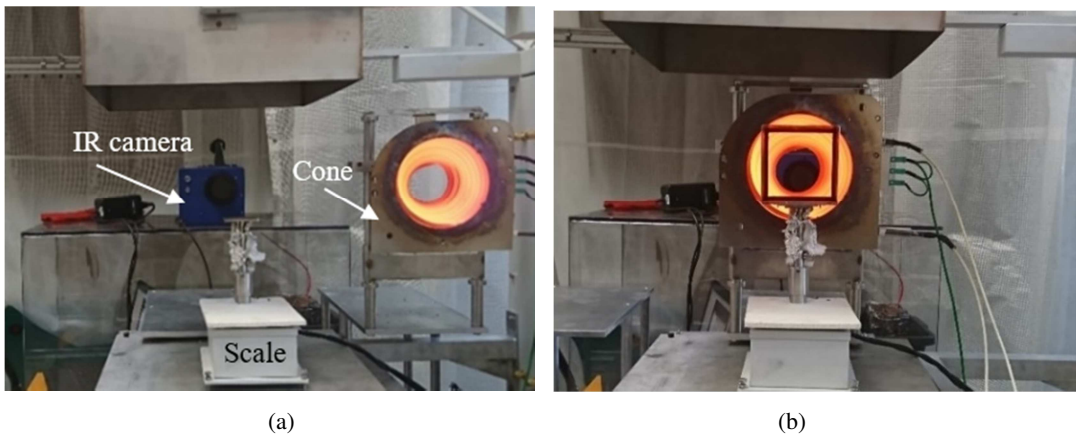


Fig. 1. Experimental setup: (a) the sample is not exposed to the cone; (b) the sample holder is exposed to the cone (the sample is removed from the sample holder to make the cone aperture visible). The infrared camera looks to the sample through this aperture).

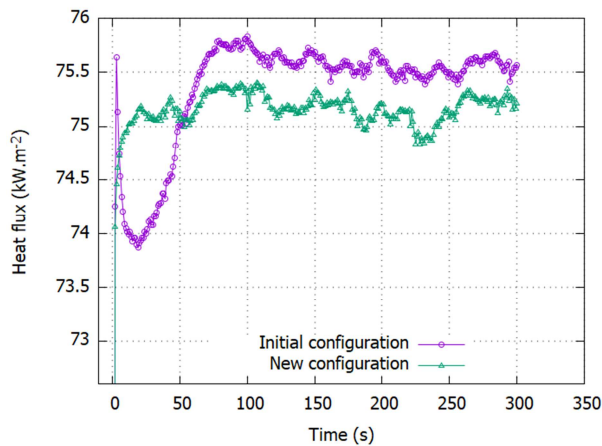


Fig. 2. Heat flux measured for the initial and new configurations (75 kW/m^2).

Variations of heat flux are different during the first hundred seconds. For the new cone configuration, heat flux increases rapidly to the desired value and then remains constant. For the initial configuration, when the shield is removed, heat flux increases before decreasing suddenly due to the increase of heat losses as explained before. The desired heat flux is achieved after 90 s. Thanks to this new setup we can ensure a steady heat flux from the very beginning of tests.

Temperature measurement

Surface or ignition temperatures are usually measured using thermocouples. However, these measurements are punctual and could be inaccurate due to the heat sink along the thermocouple wire, direct exposition to the cone radiation or to poor contact between the thermocouple and the sample. This contact seems all the more difficult for the wood that is degrading, producing char and cracks [17]. In this work, surface temperatures were measured thanks to a multispectral infrared camera (Orion SC7000 by FLIR). This non-intrusive measurement allows studying temperature field evolution on a large surface. The contact problem is also eliminated. In fire safety, this measurement is increasingly used [18, 19], especially owing to its accuracy. During infrared measurements, the flame between the infrared camera and the sample surface may lead to mismeasurement of the temperature. Some studies have shown that the emission by flames is observed to be predominant in specific wavelengths where major combustion gases (CO, CO₂ and H₂O) can emit [20]. 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 in these specific wavelengths. For the present study, the selected wavelength filter for IR camera is 3.9 μm (2564 cm⁻¹), which is outside the emission bands of combustion gases and corresponds to a wavelength where wood emissivity remains almost constant around 0.9 during degradation [16]. This type of measurement was already successfully performed by our team on other materials. More details are presented in [14].

Figure 3 shows the temperature field for a test at 55 kW/m² when ignition occurs. The white circle corresponds to the studied area where the mean surface temperature is calculated. At 0.32 s, field temperature is homogenous and constant. This temperature increases during sample exposure. At 74 s, there is the flame presence and some cracks (in yellow) appear. The field temperature is quite the same even if the cracks temperature is lower than that of the exposed surface.

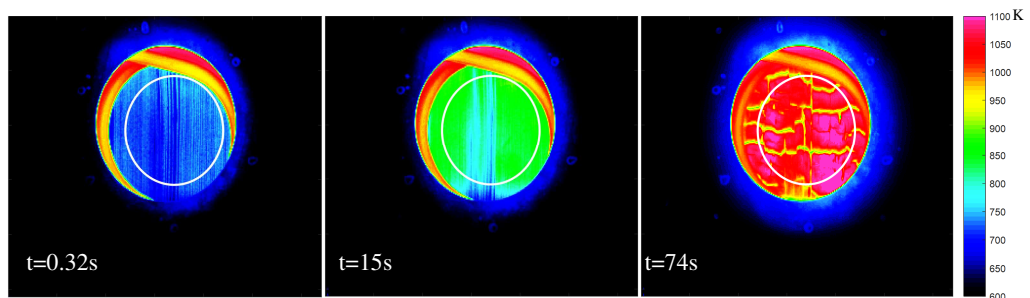


Fig. 3. Temperature field in Kelvin and studied area (white circle) for one test at 55 kW/m².

RESULTS

Samples were exposed to three external heat fluxes (15, 55, 75 kW/m²). Flame ignition was observed only for tests at 55 and 75 kW/m². For the test at 15 kW/m², only smoldering combustion was observed. In the following, after first showing the benefits of the new setup, regarding the stability of the supplying heat flux, we will first present results regarding smoldering combustion only. Then we will focus on the ignition/extinction/re-ignition studies.

Study of smoldering combustion (no flame)

For tests with a 15 kW/m^2 external heat flux, total exposure time was 3600 s. After this time, the cone was removed. Tests were repeated three times. During these tests, no flame appeared but the smoldering combustion phenomenon was observed as discussed below. Figure 4 shows MLR and surface temperature evolution provided by the IR camera.

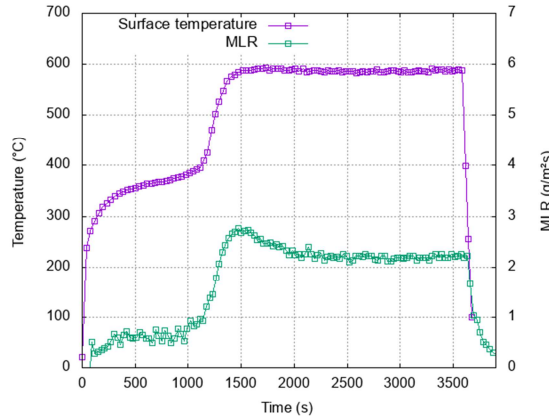


Fig. 4. MLR and surface temperature for tests without ignition

In a general way, MLR first increases to a maximum. Then MLR decreases, as the char plays the role of an insulator layer that reduces heat transfer within the sample, before reaching a plateau. At 1100 s MLR suddenly increases. This increase is also observed for the temperature for which the transition occurs at around $410 \text{ }^\circ\text{C}$. This phenomenon corresponds to the beginning of the smoldering combustion of the char that leads to an additional amount of released energy. Finally, the surface temperature reaches a plateau at around $600 \text{ }^\circ\text{C}$ at 1500 s, corresponding to a constant MLR of $2.1 \text{ g}/(\text{m}^2 \cdot \text{s})$.

Study of ignition and extinction

Tests were also carried out with higher radiative heat fluxes for which ignition occurs. After different time of exposure, the cone was slid in order to measure the extinction time of the sample. Figure 5 shows the MLR and the surface temperature of sample evolutions for tests under 55 and 75 kW/m^2 for one hour of exposure.

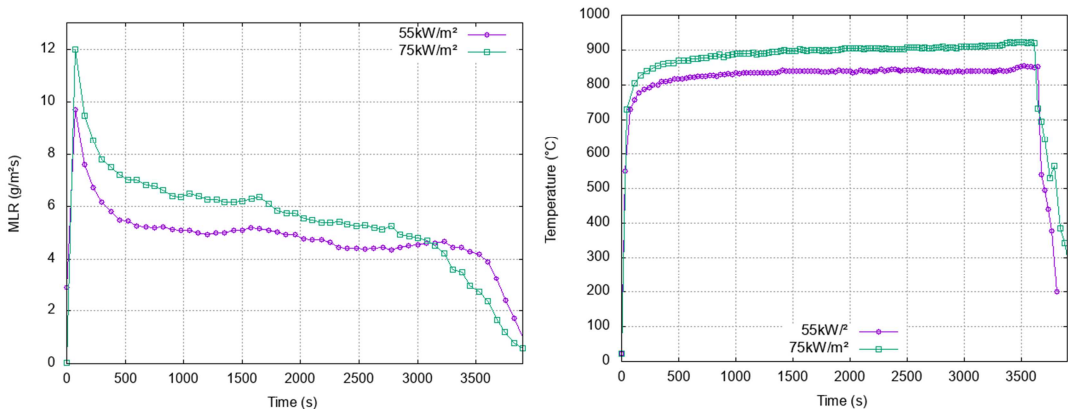


Fig. 5. MLR and surface temperature for tests with sample ignition.

Similar overall trends as previous tests without ignition are observed. The main difference is a drastic increase in MLR and surface temperature when the ignition occurs. Ignition occurs at around 15 s for the test at 75 kW/m² and around 35 s for the test at 55 kW/m². When ignition occurred, three types of ignition were observed [21]: auto-ignition close to the exposed surface, auto-ignition far from the exposed surface, within pyrolysis gases, and ignition considered piloted by the coil of the cone. These types could influence ignition time if the imposed heat flux is close to the critical heat flux allowing auto-ignition.

The corresponding temperatures at ignition were estimated at 600 °C for 75 kW/m² and 618 °C for 55 kW/m². The maximum MLR is more important for the highest flux. After ignition, MLR decreases due to the protecting role plays by the char, as discussed previously. As stated by Emberley et al. [11] and Bartlett et al. [9], MLR has two distinct states: transient and steady after 500 s even if MLR slightly decreases all along tests. For the test performed at 75 kW/m², a decrease appears at 3000 s before the cone slid. This decrease indicates that the sample is completely degraded, there is no more wood to burn.

After 3600 s of exposure to the external heat flux, the cone was slid. MLR and surface temperature decreased suddenly, and self-extinction occurred rapidly. The sample was considered extinguished when flames disappeared from the exposed surface. For the two heat fluxes where ignition occurred, samples auto-extinguished between 10 to 40 s. These extinction times are in agreement with those measured by Emberley et al. [3]. For most tests performed at 75 kW/m² during one hour, auto-extinction occurred before the cone removing because the virgin wood was already completely degraded. Table 1 shows the critical MLR for the test performed at 55 and 75 kW/m² for different time expositions.

Table 1. Critical MLR for self extinction for 55 and 75 kW/m² exposed at different times

Heat flux, kW/m ²	Critical MLR for self-extinction, g/(m ² .s)			
	5 min	10 min	30 min	60 min
75	7.26	4.97	4.94	3
55	5.9	4.94	4.7	3.7

Generally, the critical mass loss rate decreases when the exposure to the heat flux increases. It seems logical with the MLR decreasing in time. Higher values are for the lower time exposures because it was still transient MLR state and the char layer just started to form. For 5 minutes of exposure, critical MLR is higher for 75 kW/m² due to thermal aggression. From 10 to 30 minutes, in the steady state, critical MLR is quite the same whatever the imposed heat flux. It was estimated to 4.89 ±0.13 g/(m².s), in good agreement with Emberley et al. [11]. However, for one hour of exposure at 75 kW/m², most tests were already extinguished after the cone removing as explained above. For those where the flame was still present, critical MLR is lower than other exposure times because residual virgin wood is protected by the char layer.

Study of the re-ignition

The new setup allowed to switch on or off the exposed heat flux, which was useful for cycling studies. Therefore, the study of the re-ignition of samples can be performed. The experiment consisted to expose samples to a heat flux during 5 or 10 minutes. After this time, the cone was removed for 2 minutes and the extinction time was recorded. This process was repeated three times for each sample with the same heat flux. Tests were repeated three times with two heat fluxes (55 kW/m² and 75 kW/m²). Figures 7a and 7b show the evolution of the MLR obtained when the sample was exposed for 5 and 10 minutes to a heat flux of 55 kW/m².

Figure 7 shows a good repeatability in the evolution of the MLR. Table 1 gathers the ignition and extinction times in seconds. The maximum of MLR is at the first exposure, when the char layer is not yet formed. After the peak, MLR decreases before reaching a constant value. The withdrawal of the cone induces a decrease of MLR. The extinction of the sample happens in a few seconds after the cone removal. A new exposure to the heat flux results again in an increase of MLR. The latter tends towards a constant value close to that of the first exposure.

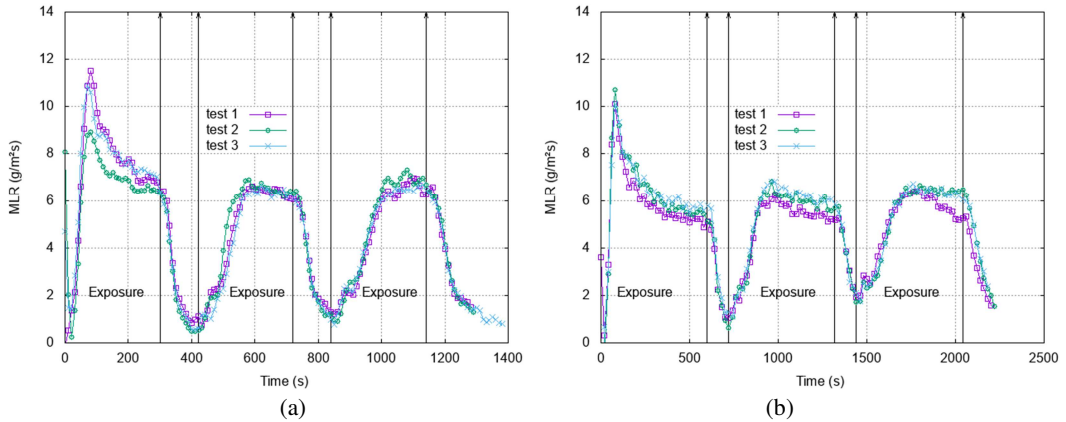


Fig. 7. MLR of tests with an exposure of 55 kW/m^2 (a) 5 min; (b) 10 min.

Table 2. Ignition time (t_{ig}) and extinction time (t_{ext}) for samples exposed to 55 kW/m^2

Tests	Exposure	5 min		10 min	
		t_{ig}	t_{ext}	t_{ig}	t_{ext}
Test 1	1 st	45	15	40	10
	2 nd	- ^a	-	180	5
	3 rd	-	-	-	-
Test 2	1 st	-	-	43	15
	2 nd	-	-	-	-
	3 rd	-	-	200	11
Test 3	1 st	40	13	51	20
	2 nd	-	-	-	-
	3 rd	240	20	140	15

^aNo Ignition occurs, Consequently there is no extinction time.

According to Table 2, re-ignition did not occur for any exposure. There was no ignition for test 2 with an exposure of 5 minutes. Ignition time increased for the second exposure. When the cone is removed, the presence of a flame does not have an impact on the evolution of MLR. The char layer seems to increase the ignition time. However, when re-ignition occurred after a new exposure to heat flux, critical MLR for self-extinction were quite the same (around 5.9 and $4.9 \text{ g/(m}^2 \cdot \text{s)}$ for 5 and 10 minutes, respectively). Figures 8a and 8b show the evolution of MLR obtained when the samples were exposed for 5 and 10 minutes to a heat flux of 75 kW/m^2 .

Figure 8 shows the good repeatability of tests. MLR evolution is very close to tests with 55 kW/m². The imposed heat flux being more important, the value of MLR peak increases. The second and third exposure lead to an increase of MLR to the same constant value.

Contrary to tests with an exposure of 55 kW/m², ignition occurs for each test. Ignition time is between 13 and 20 s for the first exposure. For the second exposure, ignition time increases of about 35 s like the extinguishment time. The re-ignition occurs close to the exposed surface in terms of cracks where the pyrolysis gases get out. Ignition time increases more for the third exposure, about 45 s for an exposure of 5 minutes and between 60 and 100 s for an exposure of 10 minutes. Samples are more degraded for the exposure of 10 minutes and the char layer is thicker. The formation of the char layer protects virgin wood and explains the increase of ignition time. However, explained for tests at 55 kW/m², critical MLR for self-extinction does not decreased after a new exposure (7.26 and 4.97 g/(m²·s) for 5 and 10 minutes respectively).

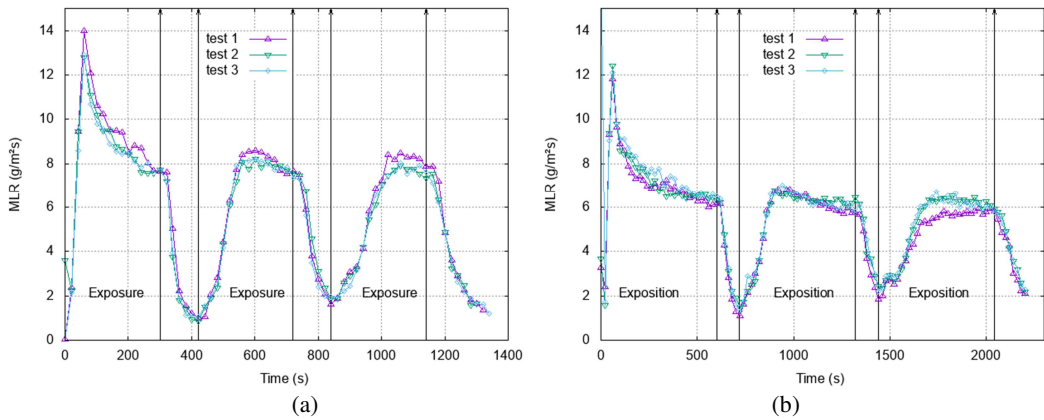


Fig. 8. MLR of tests with an exposure of 75 kW/m² (a) 5 min; (b) 10 min.

Table 2. Ignition time (t_{ig}) and extinction time (t_{ext}) for samples exposed to 75 kW/m²

Tests	Exposure	5 min		10 min	
		t_{ig}	t_{ext}	t_{ig}	t_{ext}
Test 1	1 st	20	14	14	19
	2 nd	30	20	31	10
	3 rd	40	30	80	16
Test 2	1 st	13	13	15	18
	2 nd	35	18	64	20
	3 rd	45	30	100	35
Test 3	1 st	17	18	13	20
	2 nd	30	19	40	40
	3 rd	47	30	60	50

CONCLUSION

A dedicated experimental setup was used in order to study the thermal degradation of spruce glulam under cone calorimeter. The new configuration allowed the cone to move horizontally for studying

sample extinction while measuring continuously mass loss and surface temperature. Cone removal made it possible to get a constant heat flux at the beginning of the test. The auto-ignition and the auto-extinction of the spruce glulam were studied by exposing samples to heat fluxes of 15, 55 and 75 kW/m² during different times. A precision scale recorded the mass loss during the test in order to calculate MLR. Surface temperature was also measured with a multispectral infrared camera. This temperature was determined using a filter to overcome the presence of the flame. The calculation was done by inverting Planck's law. The sample extinguishment was characterized by the disappearance of the flame.

The auto-ignition only occurred for heat fluxes beyond 55 kW/m². For tests performed at 15 kW/m², there was only smoldering combustion. MLR evolutions and surface temperature are linked and highlight well the transition from pyrolysis to smoldering combustion. The withdrawing of the cone led both to a decrease of MLR and surface temperature. The flame disappeared quickly, and the time-to-extinction was lower than one minute. The critical mass loss rate for the extinction depends on the exposure time to heat flux. For the lower exposure time, the degradation is transient and the value of critical MLR value is the highest because the char layer just started to form. This value decreases due to the constant degradation after 500 s of exposure and tends to 4.9 g/(m²·s). For one hour of exposure, the critical MLR for the self-extinction decreases since the char layer is thicker and thicker.

The new configuration of the cone enabled the study of the glulam re-ignition, too. For 55 kW/m², re-ignition was not systematic but the sample degradation seems to be the same even if there was no flame. For 75 kW/m², ignition occurred for each new exposure but ignition time and extinction time increased. The char layer plays an important role in the protection of virgin wood.

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