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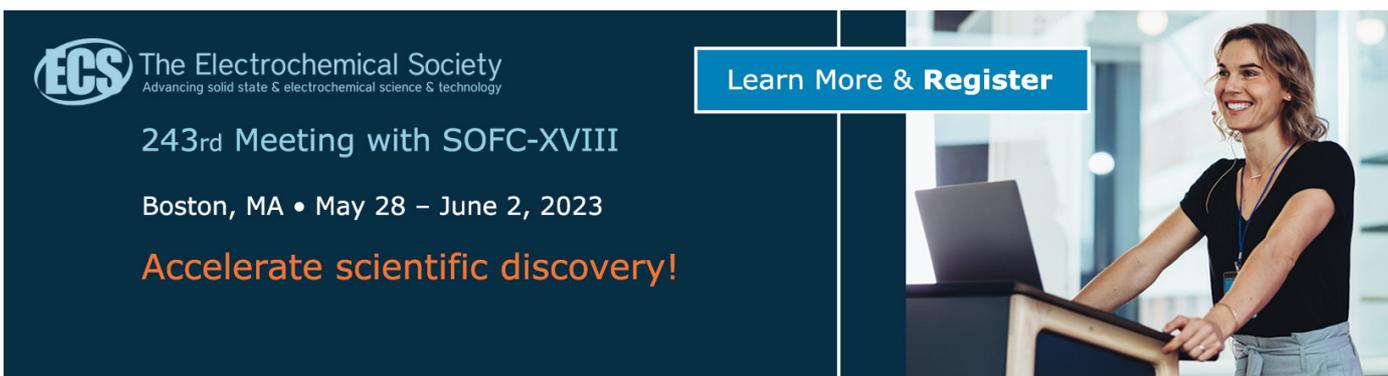
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An engineering model for ignition and extinction of wood flames using bench-scale data

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ABSTRACT

Predicting the fire spread in wooden structure buildings widely uses engineering tools such as computational fluid dynamics (CFD) simulation softwares. These softwares mix several physical models to address a wide range of phenomena, such as heat and mass transfer, pyrolysis, combustion or fluid dynamics. These models must be kept as simple as possible to limit the modelling costs.

The behaviour of wooden materials under fire conditions has been extensively studied for several years. The existing studies mainly focuses on the characterization of ignition of these materials. Several physical parameters have been examined, notably ignition time and temperature or critical ignition flux. In particular, ignition temperature has been shown a very elusive quantity (Babrauskas [1]). Some more recent work (Shen [2]) stated on the complexity to use theoretical models to predict ignition phenomena at an engineering level.

Wood extinction has been much less studied. This issue raises as a major question in recent work for building fire safety studies, as it is a key parameter to demonstrate robustness against fire. It is commonly agreed that self-extinction of wood occurs in most cases when the external thermal aggression stops (Emberley [3]). The physical phenomena leading to extinction are still under study.

This work proposes a criterion-based model of wood products ignition, pyrolysis and extinction with a very simple approach. The proposed criterion is built on test data measured on cross laminated timber and plywood panels, and identifies a burning region in the domain (Surface temperature) vs. (Net heat flux at the surface). This model has been incorporated into a CFD simulation software and used to model a large-scale fire of a plywood facade. It produced good outcomes for plywood fire spread predictions with very few modelling costs.

KEYWORDS:

Ignition; extinction; cone calorimeter; modelling; heat transfer; CFD.



INTRODUCTION

The prediction of wood based material ignition and extinction when exposed to fire conditions is of prime interest for fire engineering studies. Indeed, the fire hazards in wooden structures are directly related to the wood contribution to fire. Moreover, the fire resistance studies of wooden structures rely on the capacity of wood fire to extinct when the external thermal flux decreases.

The present study focuses on piloted ignition and flame extinction. Indeed, this work aims at giving engineering criteria to predict ignition and extinction: As piloted ignition is easier to achieve than spontaneous ignition, a criterion based on the former gives worst case estimations maximizing the safety level. Smouldering extinction could be of interest for a fire safety study, as smouldering also transforms wood into char and destroys its resistance. It is not studied here because this phenomenon is very different from flaming and cannot be included in the same disappearance criterion. Its potential influence is discussed in Crielaard [4].

This work intends to give a simpler criterion than pyrolysis model but for both wood ignition and extinction phenomena, whereas prescribed heat release rate models cannot predict extinction. This criterion can then be used in a Computational Fluid Dynamics (CFD) software in order to more accurately predict flame ignition and extinction in fire resistance studies.

Although moisture content is known to have major influence on ignition (Moghtaderi [5]), it is not studied here. It could be included in a future work.

METHODS AND MATERIALS

Specimens preparation

Two types of wood specimens were selected from spruce cross laminated timber (CLT) and from okoume and birch plywood. Okoume and birch samples were taken from the raw material of the test setup used by Duny [6]. The samples were 100 x 100 mm wide. CLT samples were 50 mm thick and plywood samples were 18 mm thick.

All the samples were conditioned in controlled environment at 50 % relative humidity and 23°C.

They were wrapped with aluminum foil except for the top side exposed to the radiative flux. The specimens were framed by a steel edge frame as specified in ISO 5660-1.

Thermocouples type K with wire thickness of 1 mm and type FC08K with pliable metal for surface junction were used at the exposure surface of wood. The sensors were directly stapled into wood as showed on the picture below. This kind of measurements can affect the thermocouple reading. Some further work with measurements based on infrared devices is still in progress.



Fig. 1. Sample and sensor preparation.

Apparatus

The cone calorimeter was used according to ISO 5660-1. During the experiment, the fan flow rate was kept about 24 l/s and the quantity of heat release rate (HRR) as a function of time was determined directly by the oxygen depletion with a gas analyser. The cone temperature was correlated for different preliminary calibration tests, using a fluxmeter at the position of the sample.

Procedure

The specimen was exposed horizontally 25 mm below the cone heater. The incident heat flux \dot{q}_{inc} was set to values between 20 and 75 kW/m².

The surface temperature T_s and heat rate release were recorded during the test. A sample was considered ignited in this study when a visible flame was first observed. Spark plug was used as a pilot source until the appearance of flame. From the ignition time, the test was run for 2 or 10 min and then stopped by decreasing the external heat flux to 10 kW/m². The extinction time was considered when the visible flame disappeared. The phenomenon of smouldering was noticed but not studied. Table 1 sums up the procedure at each step.

Table 1. Measurements during each test step.

Step	Description	Data measurements
Ignition	Sample placed under the cone heater. \dot{q}_{inc} constant	Ignition temperature ($^{\circ}\text{C}$)
Combustion	Several minutes exposure. \dot{q}_{inc} constant	HHR (kW/m^2) Burning duration (s)
Extinction	\dot{q}_{inc} decreased to $10 \text{ kW}/\text{m}^2$ after 2 or 10 minutes of exposure.	Extinction temperature ($^{\circ}\text{C}$) Cone heater temperature ($^{\circ}\text{C}$)

EXPERIMENTAL RESULTS

Ignition step

The surface temperatures at ignition T_{ig} are presented in Table 2. Each line corresponds to a single test.

Table 2. Ignition temperatures.

CLT		Birch plywood		Okoume plywood	
\dot{q}_{inc} (kW/m^2)	T_{ig} ($^{\circ}\text{C}$)	\dot{q}_{inc} (kW/m^2)	T_{ig} ($^{\circ}\text{C}$)	\dot{q}_{inc} (kW/m^2)	T_{ig} ($^{\circ}\text{C}$)
20	422	15	352	15	348
25	416	25	434	25	311
25	341	50	288	50	295
25	328	75	266	75	277
50	279				
50	225				
75	268				
75	149				

T_{ig} is significantly reduced when \dot{q}_{inc} increases. This trend is slightly stronger for CLT.

Combustion step

The heat release rate was recorded during combustion for the three wooden materials. For plywood specimens, a complete burning was performed. Figure 3 depicts HRR variation during combustion with $\dot{q}_{inc}=50 \text{ kW}/\text{m}^2$.

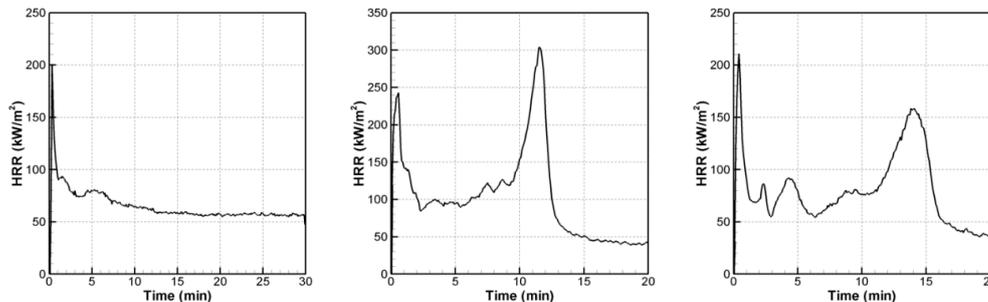


Fig. 2. HRR measurements – from left to right: CLT, birch plywood and okoume plywood.

HRR first reaches a peak at ignition, then drops and keeps a steady level during the combustion step. Based on these results, heat release rate can be considered as not depending on incident heat flux during most of the combustion duration. For plywood series, the total burning time can be deduced from the measurements. A second HRR peak occurs just before extinction, when residual wood and char is almost completely cracked leading to an increase of material surface participating to the pyrolysis (Delichatsios [7]).

Extinction step

In this step, extinction is studied by decreasing \dot{q}_{inc} . The heat flux decrease rate is not adjustable but imposed by the inertia of the cone heater. \dot{q}_{inc} value is deduced from the cone temperatures measurement. Table 3 presents the surface temperature at extinction T_{ext} . Each line corresponds to a single test.

Extinction temperatures are higher than ignition temperatures. No clear trend is visible compared to incident heat flux.

Table 3. Extinction temperatures.

CLT			Birch plywood			Okoume plywood		
Exposure time (min)	\dot{q}_{inc} (kW/m ²)	T_{ext} (°C)	Exposure time (min)	\dot{q}_{inc} (kW/m ²)	T_{ext} (°C)	Exposure time (min)	\dot{q}_{inc} (kW/m ²)	T_{ext} (°C)
2	25	554	2	16	448	2	21	450
	26	547		19	486		30	585
	21	522		27	554		38	601
10	31	541						
	32	629						

ANALYSIS

Net heat flux formulation

The present work aims at identifying surface heat transfer phenomenological criterion at ignition and extinction. As both these phenomena are related to wood heating, a net heat transfer balance must be considered to identify the main phenomena.

For each test series presented above, the net heat flux \dot{q}_{net} at ignition or extinction is estimated with Eq. 1. Flame irradiance \dot{q}_f has been estimated following Eq. 2 (Law [8]).

$$\dot{q}_{net} = h(T_g - T_s) + \varepsilon(\dot{q}_{inc} + \dot{q}_f - \sigma T_s^4) \quad (1)$$

$$\dot{q}_f = (1 - e^{-0.3t_f}) \sigma T_g^4 \quad (2)$$

σ being the Stefan-Boltzman constant. The other parameters are defined in Table 4 with the hypothesis taken for each case.

Table 4. Hypothesis for \dot{q}_{net} calculations

Parameter	Symbol	Ignition	Extinction
Gas temperature (°C)	T_g	50.0	800.0
Heat transfer coefficient (W/m ² /K)	h	20.0	20.0
Emissivity (-)	ε	0.9	0.9
Flame thickness (m)	t_f	-	0.1
Flame irradiance (kW/m ²)	\dot{q}_f	-	2.2

The resulting values are presented in Fig. 3.

For CLT, a clear trend can be identified with a strong ignition temperature decrease when the net heat flux increases. This trend is less clear for plywoods. Extinction temperatures are higher than ignition temperatures. It comes from the insulating effect of the char layer on the pyrolysis.

The net heat flux at ignition for low values of incident heat flux is close to zero. For a low irradiance, the time to ignition is high, and surface heat transfer is close to equilibrium. It is therefore consistent to measure quasi-null values.

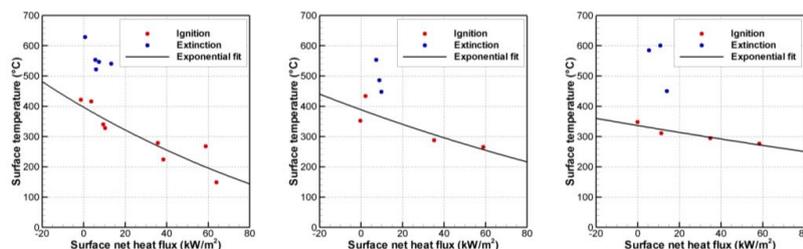


Fig. 3. T_{ig} vs. \dot{q}_{net} correlation – from left to right: CLT, birch plywood and okoume plywood.

It has been chosen to correlate the absolute temperature at ignition to the net heat flux with an exponential law as presented in Eq. 3. T_0 and \dot{q}_0 are the fitting parameters. Resulting curves are described in Fig. 3.

$$T_{ig} = T_0 \cdot e^{-\dot{q}_{net}/\dot{q}_0} \quad (3)$$

For engineering purpose, extinction points have conservatively not been considered for the correlation. It leads to a worst-case estimation of the burning time, because it underestimates the temperature to extinction.

Phase space interpretation

The T_s vs. \dot{q}_{net} plane can be interpreted as a phase space of the local surface heat balance. This space is divided by the criterion line fitted above. The sample surface follows a trajectory in this space during fire, and burning occurs for the parts of the trajectory above the criterion line. The trajectories are governed by Eq. 1. As the surface temperature increases, the net flux decreases.

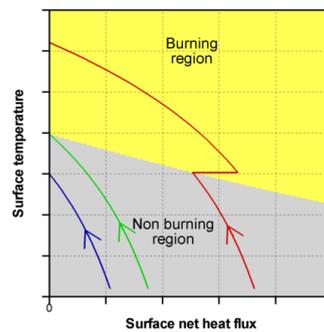


Fig. 4: Trajectory examples in heat transfer space phase

Fig. 4 presents three theoretical trajectories with constant incident heat flux, and other thermal parameters identical to those of Table 4. The first trajectory in blue occurs for a low incident heat flux value. As this value is inferior to the critical heat flux, the trajectory never crosses the criterion line, and no ignition happens.

The second trajectory in green occurs at critical incident flux. The trajectory reaches the criteria line at $\dot{q}_{net} = 0$. This point is never physically reached, as it requires an infinite heating time. Therefore, the T_0 parameter of the correlation is the ignition temperature under critical heat flux conditions, as described in [5].

The third trajectory in red occurs for a high incident heat flux value. This trajectory deviates when crossing the criterion line, because of the heat flux generated by the combustion.

EXPERIMENTAL DATA CORRELATION

Numerical model

A comparison to real scale tests has been used to validate the previous criteria line. The examined experimental data come from a series of façade fire tests in Dunny's research [6]. Three tests were performed: one with an inert façade, and two with plywood façade, respectively okoume plywood and birch plywood identical to the one tested in our work. The test setup comprised a small fire room opening on a 5 m tall façade. The source fire came from 1.5MW wood stake for 20 minutes.

The Dunny test setup has been modelled with Fire Dynamics Simulator (FDS) v6.5.2, following the rules given in his work: The wood stake HRR was specified from the inert façade test measurements, and a 10 cm mesh was used.

FDS was modified to take into account the criterion line correlated above. The criterion calculation from net heat flux is introduced during the predictor step, and the comparison to surface temperature is done during the corrector step. A constant heat release rate per unit area has been imposed, based on the mean value measured during the burning step of the cone tests.

Results comparison

The simulation results have been processed to identify the burning duration at each point of the façade, defined as the duration for which an area has experienced a surface temperature above the criterion line. Fig. 5 compares the calculated burning time for both plywood materials with the visual aspects of the façade after burning.

The unburnt area (light grey in the simulation) corresponds to the places where the wood has not ignited. The charred area (dark grey in the simulation) corresponds to the places where the wood surface has ignited and for a burning time lower than 9'30'' for birch and 11'30'' for okoume. These times were deduced from the burning durations measured with the cone tests. The completely burnt area (black in the simulation) corresponds to the zone where the wood surface presents a burning time higher than 9'30'' for birch and 11'30'' for okoume.

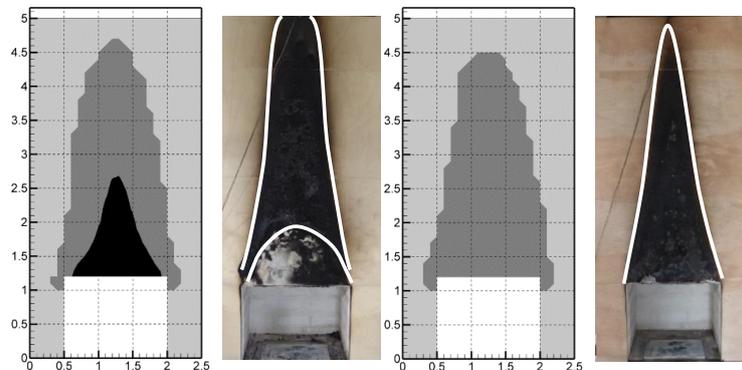


Fig. 5: Façades after burning – From left to right: Birch simulation and test, okoume simulation and test

Both facades burning are relatively well represented. The partially burnt area is slightly underestimated, whereas the completely burnt area is slightly overestimated. No complete burning is visible on okoume plywood façade during the tests (Koutaiba [9]) nor in simulations.

CONCLUSIONS

The three test series performed on wooden material gave a unique phenomenological criterion for engineering prediction of ignition and extinction. This criterion has been incorporated in FDS and proved to predict burning areas and thickness on plywood facades, with very few additional modelling costs.

It must be consolidated with two major points. First, a deeper physical analysis would improve the understanding of the cone-scale test results and the fitting of the criterion. Second, it would be interesting to correctly define the ignition and extinction criteria with precise measurement techniques. The vertical orientation with the CLT could be studied to see if a difference exists in the ignition temperature or in the correlation between surface temperature and net flux. Surface temperature could be measured over a larger area rather than with a punctual measurement with a thermocouple. The sample exposure to the external heat flux could also vary to observe the impact on the extinction time and depth of the char layer.

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