ONE-DIMENSIONAL MODEL OF PYROLYSIS AND IGNITION OF MEDIUM DENSITY FIBERBOARD SUBJECTED TO TRANSIENT IRRADIATION

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Abstract. Medium density fiberboard (MDF) is an engineered wood product that is widely used in the interior design of buildings and in furniture because of its good performance, ease of use and cost efficiency. However, like all wood products, MDF poses a fire risk. While the literature contains a lot of studies for wood pyrolysis and burning, MDF has not been thoroughly investigated yet. In this work, we study the pyrolysis of MDF subjected to transient irradiation in the form of parabolic pulses. While the majority of studies in literature employ a constant heat flux, we use transient irradiation to obtain a more comprehensive case. A one dimensional model was set up in GPyro, a generalized pyrolysis code. The model uses heat and mass transfer and temperature dependent properties for each material. We use a kinetics scheme that includes drying and 4 competing reactions in which the four components of MDF (lignin, cellulose, hemicellulose and resin) decompose into char. For the surface temperature, the model predictions experiments show very good agreement with experimental measurements that were performed in an FPA (Fire Propagation Apparatus).

1. INTRODUCTION

Medium density fiberboard (MDF) is an engineered wood product (EWP) that is widely used in the built environment. It is manufactured by binding wood fibers with wax or resin under high temperature and pressure conditions [10]. Due to this, its thermal properties and fire behavior are different than the properties and behavior of natural wood. Fire is a major risk for wood products, and that is no different for EWP, therefore it is essential to have a solid understanding of how EWP in general and MDF in particular behaves when subjected to a fire. There are many studies in the literature that deal with the pyrolysis and
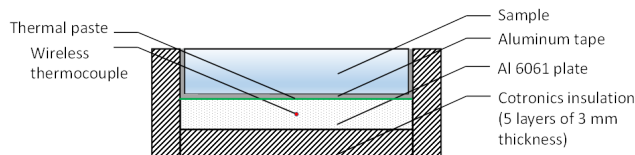
Figure 1. Sketch of the MDF sample placed in the FPA for the constant and transient irradiation experiments

ignition of wood but only a handful that look at the ignition of MDF. The recent experimental work of Li et al. looked to measure various properties of virgin MDF and its produced residues (char) when subjected to fire, such as heat of pyrolysis [9], density thermal conductivity and specific heat [7]. Huang et al. [4] studied computationally the influence of transient flame and physicochemical properties on the burning behavior of MDF.

One of the simplifications used in the majority of studies in the literature is the assumption of a constant irradiation from the heat source. While this is convenient due to its simplicity, this case is singular and does not reflect more possible fire scenarios. Transient irradiation is a more comprehensive case, thus analyzing dynamic heat transfer effects and how they impact solid-phase ignition criteria is a relevant topic. There are are studies [11] that have used transient heating scenarios for piloted ignition of different materials such as polymers and wood. However, as the studies mentioned before use constant heating scenarios, only one other work in literature looks at piloted ignition under transient irradiation for MDF [1]. Agarwal et al. [1] use transient irradiation in the form of linearly varying irradiation to validate the optimized thermal properties of MDF obtained through inverse modelling of constant irradiation scenarios.

2. IGNITION EXPERIMENTS

The experiments used in this work were conducted in the FM Global Fire Propagation Apparatus (FPA). The MDF sample of a thickness of 30 mm was placed onto an aluminium plate of 25 mm thickness, used for a better defined bottom boundary condition, and then covered in 5 layers on the bottom and 3 layers on the side of Cotronics insulation that minimize the heat losses to the environment. The surface temperature was read using an infrared pyrometer and the mass loss was recorded using the load cell. A wireless thermocouple was inserted in the aluminium plate to measure the in-depth temperature. The ethylene-air pilot was placed 10 mm above the sample surface and 10 mm away from the perimeter of the specimen. A sketch of the prepared sample is shown in Fig. 1. Unlike the majority of studies in literature, this work investigates samples exposed transient irradiation. Parabolic irradiation curves that imitate both the growth and the decay are chosen to illustrate a case that challenges the assumptions of constant irradiation used in the majority of the literature. The validation of the heater controller is shown in Fig.2.
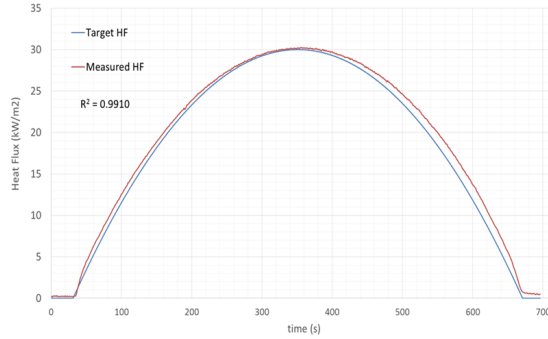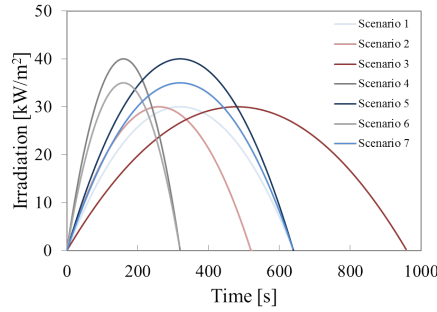
Figure 2. Heater controller validaton

Figure 3. Summary of the parabolic irradiation curves used in the experiments and described in Table 1

A number of 7 parabolas are used, as shown in Fig. 3, with the addition of a constant irradiation scenario of 20 kW/m^2 which was done to validate the setup and provide a link to literature. The two varying parameters of the parabolic curves are the time to peak and the peak irradiation. Four times to peak were used in the investigation, ranging from 160 s to 480 s and the peak irradiations are 30, 35 and 40 kW/m^2. The details about the peak irradiation time to peak which characterize the parabolas are summarized in Table 1. Time to ignition was observed visually and it varies from 161 s in Scenario 4 to 408 in Scenario 0 (constant irradiation).

3. PYROLYSIS MODEL

3.1. Governing equations and boundary conditions

The setup and sample were modelled using the open-source code Gpyro [6]. The governing equations are listed as follows: condensed-phase mass conservation (Eq. (1)), species conservation (Eq. (2)) and the energy equation (Eq. (3)). Thermal equilibrium between the condensed-phase and the gas phase is assumed. The

Scenario number	Time to peak (s)	Peak irradiation (kW/m^2)	Time to ignition (s)
0	constant	20	408
1	320	30	280
2	260	30	256
3	480	30	360
4	160	40	161
5	320	40	224
6	160	35	180
7	320	35	252

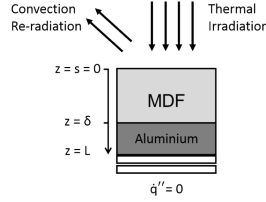**Table 1.** Summary of the parabolic irradiation scenarios

Figure 4. The computation domain used in the Gpyro simulations: the irradiation is applied to the top of the MDF sample, the bottom boundary is considered adiabatic

shrinkage of the sample was taken into account. As shown in the literature [3], in-depth radiation is important for wood for certain wavelengths, but not the ones of the FPA quartz tubes. Therefore the in-depth radiation was not taken into account. The reaction rate is expressed by the Arrhenius equation, Eq. (4).

$$\frac{\partial \bar{\rho}}{\partial t} = -\dot{\omega}'''_{fg} \tag{1}$$

$$\frac{\partial (\bar{\rho} Y_i)}{\partial t} = -\dot{\omega}'''_{di} \tag{2}$$

$$\frac{\partial (\bar{\rho} \bar{h})}{\partial t} = \frac{\partial}{\partial z}\left(\bar{k}\frac{\partial T}{\partial z}\right) + \sum_{i=1}^{K}(-\dot{\omega}'''_i)\Delta H_s \tag{3}$$

$$\dot{\omega}'''_i = \bar{\rho} Y_{A,k} A_k exp(-E_k/RT)^n \tag{4}$$

where ρ is the density $(kg/m^3\})$, t is time (s), Y is mass fraction, ω is the reaction rate per unit volume (*fg* stands for formation of gases, *di* for destruction of species), k is the thermal conductivity (W/mK), T is temperature (°C), z is the depth (m), ΔH is the heat of pyrolysis (kJ/kg), A is the pre-exponential factor (s^{-1}), E is the activation energy (kJ/mol), n is the reaction order, R is the universal gas constant.

$$wet\ wood \rightarrow dry\ wood + water\ vapour \qquad (drying)$$
$$hemicellulose \rightarrow char + pyrolyzate \qquad (hc)$$
$$cellulose \rightarrow char + pyrolyzate \qquad (cc)$$
$$lignin \rightarrow char + pyrolyzate \qquad (lc)$$
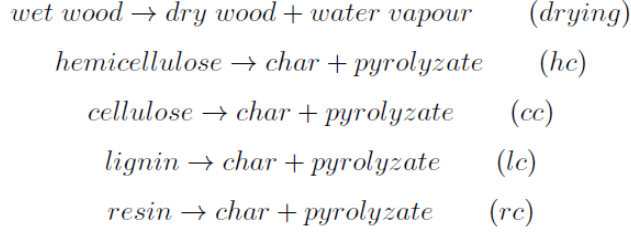$$resin \rightarrow char + pyrolyzate \qquad (rc)$$

Figure 5. The kinetics scheme used in the one-dimensional model; the abbreviation of the reaction step is written inparenthesis

The domain for the one-dimensional model of the cone experiments is shown in Fig. 4 and is made of a layer of MDF with a thickness of 30 mm and a layer of aluminium of 25 mm thickness. The ceramic insulation layer was not modelled, but it provides the adiabatic bottom boundary condition (z = L)(Eq. (5)). The top surface (z = 0) is exposed to the heat flux (Eq. (6)). Keeping a balance between accuracy and simulation time, the final values of the domain parameters are a cell size of 0.01 mm and a time step of 0.05 s [11].

$$(z = L) \qquad -\bar{k}\frac{\partial T(L)}{\partial z} = 0 \tag{5}$$

$$(z = 0) \qquad -\bar{k}\frac{\partial T(0)}{\partial z} = \bar{\varepsilon}\dot{q}_e^{"} - h_c(T_s - T_0) - \bar{\varepsilon}\sigma(T(0)^4 - T_0^4) \tag{6}$$

where ϵ is the emissivity and q_e is the external irradiation.

3.2. Chemical kinetics

The kinetics scheme and parameter values were proposed by Li, Huang et al., [8] to which a drying step step was added. First, the sample undergoes the drying process, after which each of the four components of MDF (cellulose, hemicellulose, lignin and resin) decompose into char and volatiles. The values for the pre-exponential factor, activation energy, heat of pyrolysis and reaction order are summarized in Table 2.

3.3. Model Parameters

The solid properties used in the simulations are listed in Table 3. The thermal conductivity and specific heat capacity of MDF and of char vary with temperature and are taken from Li et al [7]. The density of char is taken from Li et al, while the density of MDF is measured prior to the experiment. Because shrinkage is taken into account, the density does not vary with temperature. The surface emissivity of MDF is taken from Boulet et al [2]. No parameter fittings were used.

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Kinetic constants				
	Log A	**E**	**ΔH**	**n**
Drying	8.12	67.8	270	2.37
hc	12.9	165	256	2.4
cc	13.6	189	256	0.84
lc	16.3	238	256	10.4
rc	13.6	149	256	4.7
Units	log (1/s)	kJ/mol	kJ/kg	-
Reference	[8]	[8]	[9]	[8]

Table 2. Kinetic constants used in the modelling, following the kinetic scheme of Lie et al.

	Temperature-dependent properties			
	Value	Exponent Value	Units	Reference
Thermal conductivity k	0.12	0.49	W/mK	[7]
Density ρ	605	-	kg/m^3	measurement
Specific heat capacity c_p	1489	0.85	J/kgK	[7]
Surface emissivity of MDF ϵ	0.8	-	-	[2]
Thermal conductivity of char k_{char}	0.09	3.90	W/mK	[7]
Density of char ρ_{char}	330	-	kg/m^3	[7]
Specific heat capacity of char $c_{p,char}$	600	1.15	J/kgK	[7]

Table 3. Modelling parameters for MDF

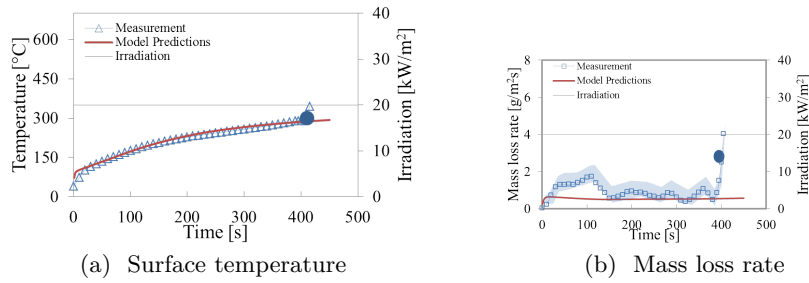(a) Surface temperature

(b) Mass loss rate

Figure 6. Comparison between the measurements and the model predictions for surface temperature and mass loss rate for constant irradiation (Scenario 0)

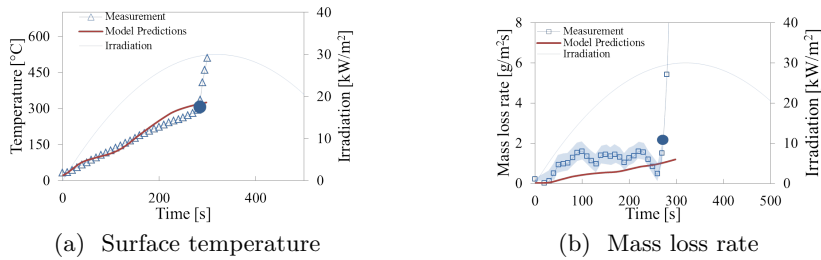(a) Surface temperature

(b) Mass loss rate

Figure 7. Comparison between the measurements and the model predictions for surface temperature and mass loss rate for the transient irradiation (Scenario 1)

4. RESULTS

For the constant irradiation scenario, the comparison between the experimental measurements and the model predictions are shown in Fig. 6. The surface temperature prior to ignition is predicted excellently by the model. The model slightly underpredicts the mass loss rate in the initial phase, but goes on to predict well prior to ignition.

Considering the good predictions in the constant irradiation model, it is interesting to see how the transient irradition scenario behaves. Fig. 7 shows the model predictions in the transient irradiation scenario with time to peak of 320 s and peak irradiation of 30 kW/m^2. Like in the constant irradiation scenario, the surface temperature prediction is very good, with the mass loss rate being underpredicted by the model. Considering that this model has no fittings, only measured values from literature sources, its performance is very good. Also, the accuracy of mass loss rate measurements in the FPA is better when the readings are very frequent [5], so potential errors induced experimentally might also contribute to the small discrepancy between predictions and measurements.
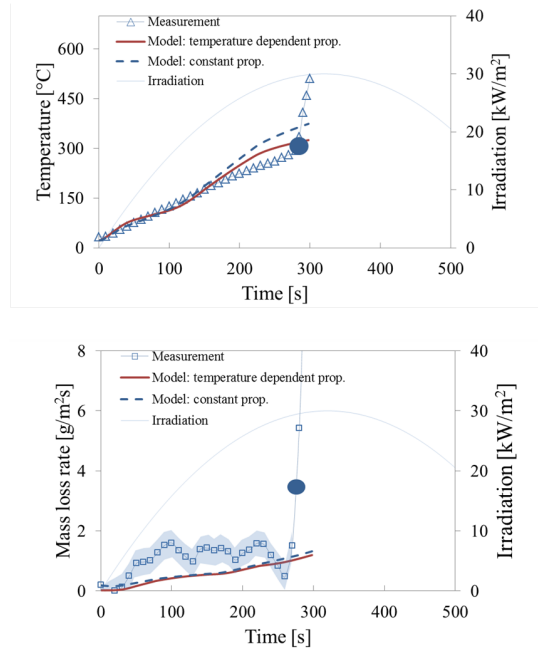
Figure 8. The influence of using temperature dependent properties: surface temperature and mass loss rate variation

5. DISCUSSION

An analysis was done to assess the influence of two complexity parameters, namely using temperature dependent properties and adding the drying step in the kinetic scheme respectively. Scenario 1 for transient irradiation was used in this investigation.

The influence of using properties (k and c_p) that change with time is presented in Fig. 8. Using constant k and c_p results in an overprediction of the surface temperature before ignition by a maximum of 60 °C (18%), which is a notable difference. For mass loss rate, the largest difference between the two cases is just 0.16 g, which shows that mass loss rate is not significantly influenced by the use of temperature dependent k and c_p. Therefore, the use of temperature dependent properties improves the predictions of surface temperatures slightly, but does not play a role in mass loss rate predictions.

The second parameter that was analyzed is the role of the drying step. As shown in Fig. 9, adding the drying step is much more influential than using temperature dependent properties. For surface temperature, the largest difference of 113 °C occurs around 130 s and represents around 78% more than the predicted value which uses the drying step. For mass loss rate, the difference is much higher. The slope of the curve starts later in the case without drying and increases at a much faster rate, showing a completely different behavior.
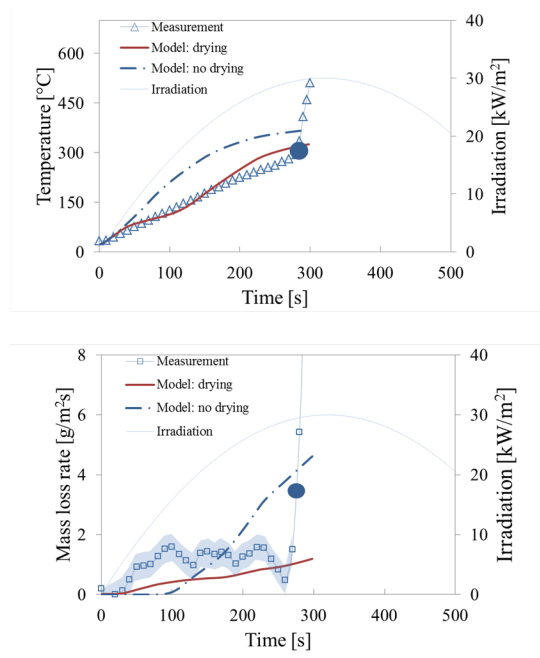
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Figure 9. The influence of using a drying step in the kinetics scheme: surface temperature and mass loss rate variation

6. CONCLUSION

A set of experiments investigating the behavior of MDF, an EWP commonly used in the built environment, prior to ignition was performed in the FPA. The samples were subjected to constant irradiation, which is the most used scenario in literature, to validate the setup and then to transient irradiation in the form of parabolic curves that simulate both the growth and the decay of the fire. Transient irradiation is a more general case of which the usually assumed constant irradiation is a particular case.

These experiments served as validation for a computational model. This one-dimensional model was then set up using thermo-chemical parameters taken from literature or measured experimentally. For both constant and transient irradiation, the model predictions show good agreement for surface temperature mass loss rate.

The model is used to investigate the influence of temperature-dependent k and c_p, as well as adding a drying set to the kinetic scheme. The former causes an overprediction in surface temperature (18%), but a negligible change in mass loss rate. The drying step, however, has a major influence both on surface temperature, where it overpredicts the surface temperature by 78% and significantly changes the behavior of the mass loss rate curve.

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