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Thermal-balanced integral model for pyrolysis and ignition of wood

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Abstract−The pyrolysis and ignition of wood is of great importance to understand the initial stage of combustion, helping control the occurrence and spread of unwanted building and forestry fires. The development of a thermal-balanced model is introduced for examining the analytical relationship between the ignition time and external heat flux. The critical heat flux, one of the important fire-retardant characteristics of combustible solid, is determined from a correlation study between the ignition time and external heat flux. One of the thermal-balanced integral models, considering the effect of surface heat losses, average absorptivity and moisture content, is employed to give the prediction of surface temperature rise, ignition time and ignition temperature of the Aspen. The results show that the model readily and satisfactorily predicts ignition temperature and ignition time of wood with different moisture contents.

Key words: Thermal-balanced Integral Model, Ignition, Critical Heat Flux, Moisture Content

INTRODUCTION

The combustion of wood is sometimes tightly related to the occurrence and spread of horrible building and forestry fires. The pyrolysis and ignition of wood is the initial stage of combustion, the understanding of which would help to control the unwanted building or forestry fires. A large number of experimental and theoretical studies concerning pyrolysis and ignition of wood have been reported in the literature, regarding the temperature rise of the solid, volatile evolution during the process, ignition time, ignition temperature and so on [1,2].

The commonly-observed phenomenon of pyrolysis and ignition of wood is described as follows [3]: when the surface of wood board is exposed to external heating source (thermal radiation or convection from hot gases), heat is conducted from the surface to the inside. Temperature at different depths of the solid is then be increased against time. Consequently, the solid undergoes thermal decomposition - a chemical degradation process to produce char and combustible gases. The combustible gases released from the exposed surface enter a ‘gas phase’ to mix with oxygen. Under the favorable condition(s), a flame on the surface is generated. It is called “ignition” once the flame appears. The ignition initiated by a pilot energy source (e.g., a small gas flame or an electric spark) located in the vicinity of the exposed surface of the solid is termed as “piloted ignition,” while the one without a piloted source is called spontaneous ignition. The favorable condition is defined as the “ignition criterion.” The ignition temperature, defined as the surface temperature of solid when ignition occurs, is well-established to be the ignition criterion for the relevant predictions.

Different models for achieving precise predictions of pyrolysis and ignition of wood in the literature can be categorized into two types: thermal-balanced integral models [4-11] and numerical models [12-14]. For thermal-balanced integral models (mostly for describing the piloted ignition), the analytical expression for the key characteristics, such as surface temperature rise of solid, ignition time and ignition temperature can be obtained through the integration of the energy-balanced equation(s), but no chemical information for the pyrolysis process is involved. For numerical models, the chemical kinetic schemes and the conservation of mass and heat transport are coupled and the parameters are predicted through the numerical methods.

The thermal-balanced integral model has been developed for several decades. It is not as precise as the numerical models but is applicable for fire-engineering utilization, since the relationship between characteristics of pyrolysis and ignition and the affecting factors is demonstrated through the analytic expressions [1,15]. The development of the thermal-balanced integral models will be introduced in this work, involving the determination of surface temperature rise (T), ignition temperature (T_{ig}) and ignition time (t_{ig}). The analytical expression of ignition time from the thermal-balanced integral models is vigorously discussed and estimated by the experimental results in previous studies. The critical heat flux (q_{cr}), defined as the maximum heat flux for combustible solid not to be ignited, is determined through the correlation study between the ignition time and heat flux. Finally, one of the thermal-balanced integral models is employed to predict the surface temperature rise, ignition time and ignition temperature of Aspens with different moisture content under different heat fluxes.

EXPERIMENTAL SETUP

The experimental system for investigating pyrolysis and ignition of solid fuels was introduced in the previous study [16,17]. The heat flux was firstly set and confirmed by a hand-style calorimeter. The shaped sample (100 mm*100 mm for the surface and 15 mm for

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the depth) was placed on the sample holder, where only the surface was subjected to the external radiation and other faces were insulated by asbestos. Four thermocouples were placed in the depth of 1 mm, 7 mm and 14 mm of sample to record the surface temperature, middle temperature and bottom temperature. The ignition time was recorded by the timer once the flame appeared on the surface of sample. If no flame could be observed within 30 min, it was estimated that no ignition would occur.

Aspen sample with moisture content of 3.2%, 12.6%, 24.7% and 36% was tested in the apparatus under the heat flux of 10 kW/m^2 and 40 W/m^2. Each experiment was run twice. More runs would be launched if the data was estimated to be unreasonable.

THEORY

In thermal-balanced integral models, the wood sample is heated from one side by thermal radiation and assumed to be a semi-infinite, opaque and inert solid. The process of pyrolysis and ignition (mainly the temperature rise) is described by an energy-balanced equation together with boundary conditions for the control volume of the solid [11]. The equation is then integrated with respect to the space variable and then time variable, giving the analytical expressions of surface temperature rise and ignition characteristics (i.e., ignition time and ignition temperature).

Here, the thermal-balanced integral models are orderly introduced when more key factors (such as radiant heaters, surface heat losses and moisture content) are taken into account. Some of the key factors influencing the process of pyrolysis and ignition of wood are summarized from the literature:

- The types of the radiant heater
- External heat flux
- Thermal properties of solid
  Thermal properties of solid such as thermal conductivity, density, specific heat and the related properties of thermal inertia and thermal diffusivity
- Air flow around the specimen
- Moisture content
- Specimen size and thickness
- Orientation of the sample
- Sample absorptivity
- Pilot size and position (if applicable)

1. Model 1: The Basic Theory for Thermal-balanced Integral Model

The simplest thermal-balanced integral model commonly used for pyrolysis and piloted ignition of wood is the one-dimensional conduction model [18]. The surface heat losses during the process were ignored. A fixed surface temperature was suggested as the criterion for piloted ignition. The thermal-balanced equation of the model is expressed as:

$$\frac{\partial T}{\partial t}=\alpha\frac{\partial^2 T}{\partial x^2} \tag{1}$$

The boundary and initial conditions are:

$$t=0;\ T=T_0 \tag{2}$$

$$t>0;\ -k\frac{\partial T}{\partial x}=q_e,\quad \text{for } x=0 \tag{3a}$$

$$t>0;\ T=T_0,\quad \text{for } x=\infty \tag{3b}$$

The surface temperature rise is estimated to be [18]:

$$T_s(t)-T_0=\frac{2q_e}{k}\left(\frac{\alpha t}{\pi}\right)^{1/2} \tag{4}$$

As $T_s(t)=T_{ig}$, the ignition time t_{ig} is:

$$t_{ig}^{-1/2}=\left(\frac{4}{\pi}\right)^{1/2}\frac{q_e}{\sqrt{k\rho c}(T_{ig}-T_0)} \tag{5}$$

Another two expressions (Eqs. (6) and (7)) were proposed by Moghtaderi et al. [19] and Spearpoint and Quintiere:

$$t_{ig}^{-1/2}=\left(\frac{4}{3}\right)^{1/2}\frac{q_e}{\sqrt{k\rho c}(T_{ig}-T_0)} \tag{6}$$

$$t_{ig}^{-1/2}=\left(\frac{3}{2}\right)^{1/2}\frac{q_e}{\sqrt{k\rho c}(T_{ig}-T_0)} \tag{7}$$

The analytical expression for ignition time (t_{ig}) given by Eqs. (5), (6) and (7) are of the same form, differing only by a numerical coefficient.

2. Model 2: Considering Effect of Surface Heat Losses

The heat losses on the sample surface were considered in the thermal-balanced integral model [20], where the heat losses on the solid surface were expressed by Newton's law of cooling (Eq. (8)) and the sample was assumed to be inert, opaque and semi-infinite. The fixed surface temperature was also considered to be the ignition criterion. The boundary conditions for this model are:

$$t>0;\ -k\frac{\partial T}{\partial x}=q_e-h_c(T-T_0),\quad \text{for } x=0 \tag{8}$$

The temperature rise of the sample surface was estimated by Simms [5], giving the similar analytical solution as Model 1 [18]:

$$T_s-T_0=\frac{q_e}{h_c}(1-\exp\tau^2\operatorname{erfc}\tau) \tag{9}$$

Where $\tau=h_c(t/k\rho c)^{1/2}$ is defined as the cooling modulus. Multiplying to both sides of Eq. (9) gives:

$$\frac{q_e t^{1/2}}{(T_s-T_0)(k\rho c)^{1/2}}=\frac{\tau}{(1-\exp\tau^2\operatorname{erfc}\tau)} \tag{10}$$

As the cooling modulus (τ) tended to be zero (heat losses at the solid surface were ignored), the right term of Eq. (10) could be approximately expanded to be:

$$\exp\tau^2\operatorname{erfc}\tau=1-\frac{2}{\pi^{1/2}}\tau+f(\tau^3)+\ldots\approx 1-\frac{2}{\pi^{1/2}}\tau \tag{11}$$

Substituting Eq. (11) into Eq. (10) gives:

$$\frac{q_e t^{1/2}}{(T_s-T_0)(k\rho c)^{1/2}}\rightarrow\frac{\pi^{1/2}}{2} \tag{12}$$

It could be found that Eq. (12) is the same as Eq. (5) in the simplest model if the heat losses on solid surface are ignored.

When both convective and radiative heat losses on the surface of solid were considered, an equivalent heat transfer coefficient (h_{eq}) was defined [8] and employed in the later thermal-balanced integral models [10,21] as:

$$q_l=h_c(T_s-T_0)+\varepsilon\sigma(T_s^4-T_0^4)=h_{eq}(T_s-T_0) \quad (13)$$

The boundary conditions were expressed as:

$$t>0;\ -k\frac{\partial T}{\partial x}=q_e-h_{eq}(T-T_0),\ \text{ for } x=0 \quad (14)$$

As t_{ig} tends to be infinity, the critical heat flux is the incident heat flux equal to the convective and radiative heat losses on the surface:

$$q_{cr}=q_l=h_c(T_{ig}-T_0)+\varepsilon\sigma(T_{ig}^4-T_0^4) \quad (15)$$

Eq. (1) in the Model 1 was solved with the boundary condition of linear heat loss on the surface (when $h_{eq}=h_c$ in Eq. (8)). Thus, the analytical expression of surface temperature rise should be of the same form as Eq. (9) given by Simms [20]. A number of truncation exercises on the expanded terms were carried out to approximate the right term of Eq. (9), giving the following correlationship-equation from the best-fitting examination:

$$t_{ig}^{-0.547}=\frac{1}{0.73}\frac{(q_e-q_{cr})(h_{eq}^2)^{0.547}}{(k\rho c)^{0.547}q_{cr}} \quad (16)$$

For the case of non-linear (both convective and radiative) heat loss given by Eq. (15), the predicted data was analyzed by plotting log(τ) against log(q_e/q_{cr}) for different ignition temperatures. Eq. (16) appears to be valid for the case of non-linear heat losses.

Another analytical solution of ignition time correlated with heat flux was given for thermally thick materials by Mikkola and Wichman [9], considering both convective and radiative heat losses:

$$t_{ig}^{-1/2}=\left(\frac{4}{\pi}\right)^{1/2}\frac{(q_e-q_{cr})}{(k\rho c)^{1/2}(T_{ig}-T_0)} \quad (17)$$

where q_{cr} was determined by Eq. (15) with a given ignition temperature [14].

3. Model 3: Considering Effect of Average Absorptivity

The absorption factors for different wood species, paper and cotton were found by Simms et al. [22]. The average absorptivity was mainly determined by the distribution of the energy versus wavelength of the radiant heat source. The value (average absorptivity) for natural wood was found to be fairly constant by the same radiant heat source, since spectral absorptance for different natural woods was quantitatively same [7].

The model proposed by Wesson et al. [7] included the effect of average absorptivity, and the boundary conditions were described as:

$$-k\frac{\partial T}{\partial x}=\bar{\beta}q_e,\ \text{ for } x=0 \quad (18)$$

The analytical relationship between ignition time and heat flux is estimated to be:

$$t_{ig}=C\frac{\rho^a\{\text{erf}[L/2(\alpha t)^{1/2}]\}^b}{(\bar{\beta}q_e)^d} \quad (19)$$

Eq. (19) was fitted by the least-square method for the cases under both flame heating and tungsten lamps heating, giving:

$$t_{ig}=35\frac{\rho^{0.9}\{\text{erf}[L/2(\alpha t)^{1/2}]\}^{1/2}}{(\bar{\beta}q_e)^{2.8}} \quad (20)$$

Since the radiative and convective heat losses were not included in Eq. (20), another analytical expression considering the effects of the heat losses was proposed as:

$$t_{ig}^{-1/2}=\left(\frac{4}{\pi}\right)^{1/2}\frac{(\bar{\beta}q_e-q_{cr})}{(k\rho c)^{1/2}(T_{ig}-T_0)} \quad (21)$$

Where the boundary conditions were:

$$-k\frac{\partial T}{\partial x}=\bar{\beta}q_e-h_{eq}(T-T_0)=\bar{\beta}q_e-h_c(T-T_0)-\varepsilon\sigma(T^4-T_0^4),\ \text{for } x=0 \quad (22)$$

4. Model 4: Considering Effect of Moisture Content

As described by Maclean [23], Moisture content of wood was related to its oven dry mass and defined as:

$$MC(\%)=\frac{M_w-M_{w,d}}{M_{w,d}}\times 100 \quad (23)$$

With the presence of moisture content, the values of the thermal properties, such as thermal conductivity and specific heat, were changed to different extents. Moreover, the extra energy was required to vaporize the water, referred as the heat of drying. Ignition time was thus delayed and critical heat flux might be increased [10].

The thermal-balanced integral model considering effect of moisture content on pyrolysis and ignition of wood was firstly proposed by Simms and Margaret [6]. The effects of moisture content were mainly expressed to change the thermal properties (k, ρ, c) of sample, where the heat of wetting (ΔW) and the latent heat (H) were involved. The specific heat c_m of wet wood was expressed as:

$$c_m=c_0+\{\Delta W+0.01[H+(100-T_0)\times 4200]MC\}/T_{ig} \quad (24)$$

Effect of moisture content on thermal conductivity of wood was measured and given by Maclean [23]:

$$k_m=4.2\times 10^{-5}\{\rho_0(4.78+0.102MC+0.57)\} \quad (25)$$

Neglecting solid volume changes would give the density of wet wood as:

$$\rho_m=(1+0.01MC)\rho_0 \quad (26)$$

Considering the heat losses on the solid surface and the effect of average absorptivity for the model, the ignition time related to heat flux could be expressed similarly as Eq. (21):

$$t_{ig}^{-1/2}=\left(\frac{4}{\pi}\right)^{1/2}\frac{(\bar{\beta}q_e-q_1)}{(k_m\rho_m c_m)^{1/2}(T_{ig}-T_0)} \quad (27)$$

Where surface temperature rise can be illustrated as:

Table 1. The physical properties of the woods for thermal-balanced integral model

Wood species	Thermal conductivity (k) ($Wm^{-1}K^{-1}$)	Density (ρ) (kgm^{-3})	Specific heat (c) ($Jkg^{-1}K^{-1}$) [20]
Oak [20]	0.1632	660	1422
White wood [20]	0.1087	470	1422
Mahogany [7]	0.1338	560	1422
Pine [24]	0.1255	500	1422
Douglas fir [11]	0.0962	455	1422
	0.0872	340	1422

$$T_s - T_0 = \frac{\bar{\beta} q_e t^{1/2}}{\sqrt{\pi}/2(k_m \rho_m c_m)^{1/2} + h_{eq} t^{1/2}} \quad (28)$$

Here, the ignition temperature (T_{ig}) is estimated to be the surface temperature when ignition commenced.

The above thermal-balanced integral models would be estimated by the previous experimental data in the next section, while the thermal properties of the involved samples are listed in Table 1.

RESULTS AND DISCUSSION

1. The Determination of the Critical Heat Flux for Piloted Ignition of Wood

The correlationship between ignition time and external heat flux is well expressed from the thermal-balanced integral models, facilitating the determination of the critical heat flux. With regard to the definition of critical heat flux of combustible solid ($t_{ig} \rightarrow \infty$, or $t_{ig}^{-1/2} \rightarrow 0$), the value ($q_{cr}$) could be obtained from the intercept of linear fit of $t_{ig}^{-1/2}$ against q_e with x-axis. An example on piloted ignition data of different wood samples reported by previous investigators is shown in Fig. 1. The critical heat flux was estimated to be about 12 kWm^{-2} for whitewood heated by a gas-fired radiant panel by Simms [20]. The value was over 18 kWm^{-2} for mahogany exposed to tungsten lamps by Wesson et al. [7]. Data by Bluhme [24] for thermally thick pine gave the critical heat flux of approximately 13 kWm^{-2}. The critical value for Douglas fir (5 cm thick) measured in a cone calorimeter by Spearpoint and Quintiere [11] was about 12.5 kWm^{-2}. Different critical heat fluxes might be due to different wood species and different types of radiant heaters.

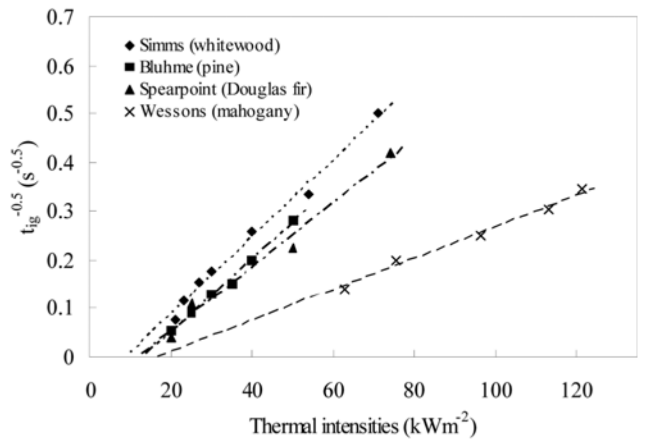

Fig. 1. The (piloted) ignition data by Simms [20], Wessons et al. [7], Bluhme [24] and Spearpoint and Quintiere [11].

The correlationship between ignition time and heat flux for different radiant heaters is shown in Fig. 2, showing that the result for mahogany radiated by gas-fired panel (average absorptivity tended to be 1) lay above that radiated by tungsten lamps (average absorptivity was 0.44). With the given h_c=10 Wm^{-2}K^{-1}, ε=1 and T_{ig}=360 °C for Eq. (22), the average absorptivity of different radiant heaters for giving best fit with experimental data is estimated to be 0.95 for mahogany under gas-fired panel [20], 0.46 for oak under tungsten lamps [7], and 0.88 for pine under electrical heater [24]. The critical heat flux for mahogany heated by a gas-fired panel was similar to the value for pine radiated by an electrical heater, because of the similar average absorptivity. The value of critical heat flux was about 13 kWm^{-2}, similar to 12 kWm^{-2} determined by the experimental data and 12.2 kWm^{-2} predicted by Eq. (15). A higher predicted critical heat flux of about 28 kWm^{-2} was obtained for oak radiated by tungsten lamps, due to the low average absorptivity. This suggested that the effect of average absorptivity on pyrolysis and ignition was not so important when the average absorptivity was close to 1. But if the average absorptivity was relatively low, its effect should be included in the thermal-balanced model.

2. The Sensitivity of Ignition Temperature for Predicting Piloted Ignition Time of Wood

The ignition time was predicted under different heat fluxes (from 12 to 70 kWm^{-2}) with a given ignition temperature of 360 °C by Eqs. (16) and (17). The predicted data was plotted as t_{ig}^{-n} versus q_e and compared with the experimental data in Fig. 3. It was shown that the prediction by Eq. (17) matched better with the experimental data of oak than that by Eq. (16). Ignition time of whitewood was also predicted by Eq. (5) from the model without surface heat losses (Model 1); and by Eq. (17) from the model with radiative and convective heat losses (Model 2). Predictions were compared

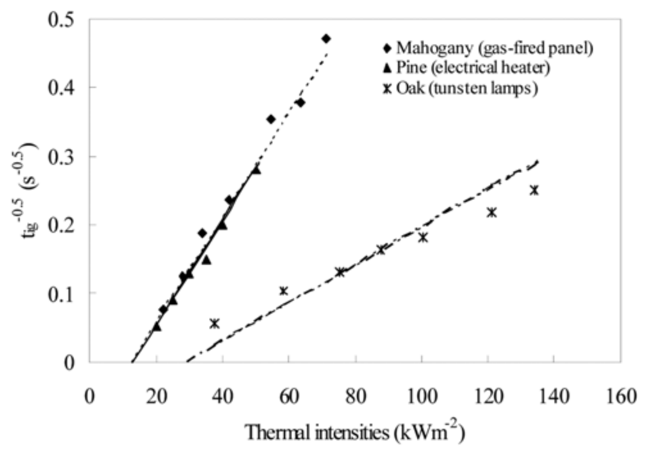

Fig. 2. Piloted ignition data by Simms (oak) [20], Wesson et al. (mahogany) [7] and Bluhme (pine) [24] compared with the predictions by Eq. (21).

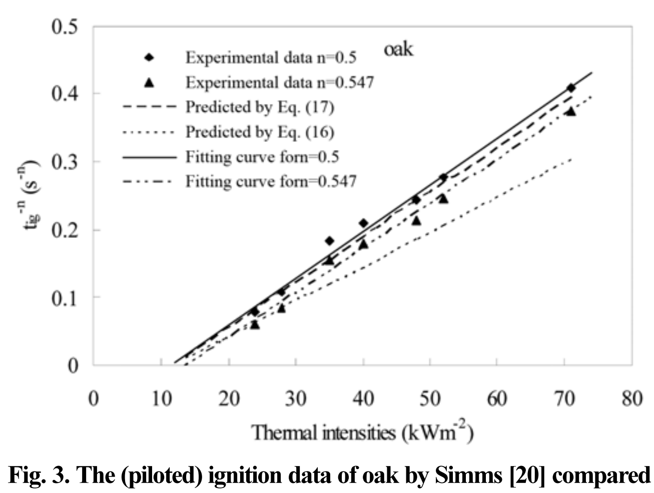

Fig. 3. The (piloted) ignition data of oak by Simms [20] compared with the predictions by different solutions from the Model 2.

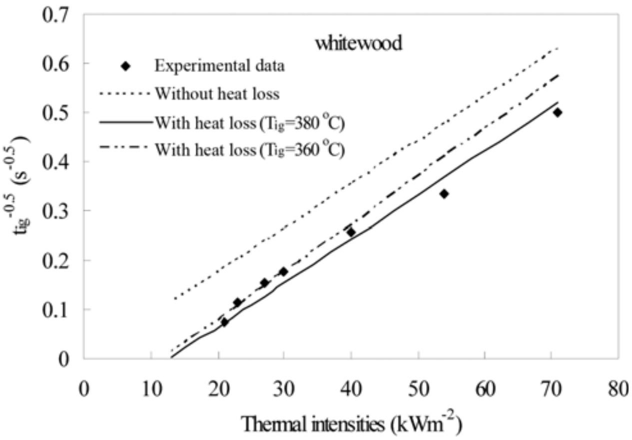

Fig. 4. The (piloted) ignition data by Simms [20] compared with the predictions by Eq. (5) and Eq. (17).

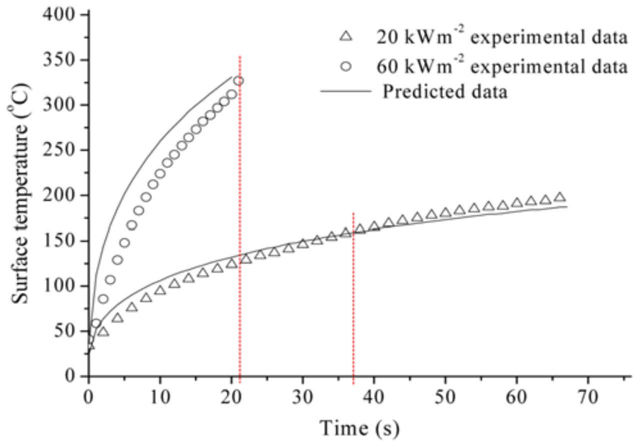

Fig. 5. The comparison of the experimental and predicted surface temperature of Aspens under 20 kWm^{-2} and 60 kWm^{-2}.

with the experimental data of Whitewood in Fig. 4. It was found that the predicted values for ignition time by Eq. (5) were not correct enough. A fixed ignition temperature (T_{ig}) as the ignition criterion was adjusted so that the theoretical curve of Eq. (17) in Fig. 4 could give the best fit over the experimental data of Whitewood. The value of 380 °C for predictions by Eq. (17) was considered to be more reasonable. Similarly, different ignition temperatures as the ignition criterion for other wood species (340 °C for oak, 360 °C for mahogany and 380 °C for whitewood) were determined to give better fitting between the experimental data and predictions.

3. The Application of Model 4 for Pyrolysis and Spontaneous Ignition of Wet Wood

Model 4, accounting for the effect of surface heat losses, average absorptivity and moisture content, would be utilized to predict the characteristics of pyrolysis and spontaneous ignition of wood (Aspens) The experimental tests on pyrolysis and ignition of Aspens with different moisture contents under different heat fluxes were carried out in the apparatus which is described in author's previous study [16]. The properties of Aspens for calculation of the thermal-balanced integral model (Model 4) are given in Table 2. The experimental results are used to examine the thermal-balanced integral model (Model 4) in terms of surface temperature rise, ignition temperature and ignition time of wet wood.

3-1. Surface Temperature

The experimental and predicted surface temperature of Aspens under 20 kWm^{-2} and 60 kWm^{-2} is compared in Fig. 5. Under the low heat flux (20 kWm^{-2}), the predicted value is initially above the experimental data and lower than the experimental data at about 37 s. In the initial stage of pyrolysis of wet wood, the (surface) temperature rise is suppressed, since more heat is consumed to vaporize the moisture. After the completion of this drying process (after 37 s), the heat absorbed by solid sample is mainly for elevating inner energy of the sample and in-depth temperatures. A similar phenomenon is observed for that under the high heat flux (60 kWm^{-2}), while the drying process is estimated to be complete around 21 s (Fig. 5). For both low and high heat fluxes, the surface temperature predicted by the thermal-balanced integral model is estimated to be matched well with the experimental data.

The surface temperature of Aspens with different moisture contents under 40 kWm^{-2} is predicted and compared with experimental data in Fig. 6. It could be found that the surface temperature rise is remarkably suppressed with the increased moisture content. The predicted data of the surface temperature of Aspens with low moisture content (3.2%) matches the experimental data very well. Comparably, the surface temperature of Aspens with high moisture content (24.7%) is initially larger than the experimental data and lower than

Table 2. The properties of Aspens for the calculation of the thermal-balanced integral model

Properties	Value	Source
Density* (kgm^{-3})	ρ=582	
Heat of wetting (kJkg^{-1})	ΔW=66.9	[6]
Latent heat (kJkg^{-1})	H=2175	[6]
Emissivity	ε=0.78	[25]
Convective coefficient (Wm^{-2}K^{-1})	h_c=10	[3]
Absorptivity	β=0.95	[7]

*The original moisture content is 14.4%

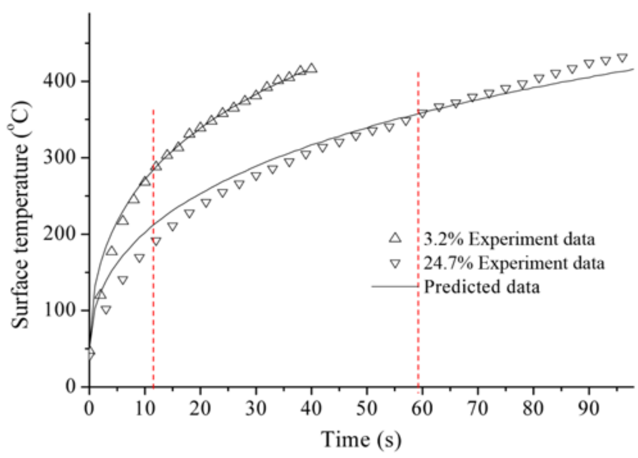

Fig. 6. The comparison of the experimental and predicted surface temperature of Aspens with the moisture content of 3.2% and 24.7% under 40 kWm^{-2}.

Table 3. The comparison of experimental and predicted ignition temperature (T_{ig}) and ignition time (t_{ig}) of Aspens with different moisture contents under 40 kWm^{-2}

Source	Ignition temperature (°C)				Ignition time (s)			
MC	3.2%	12.6%	24.7%	36%	3.2%	12.6%	24.7%	36%
Experimental	421	449	440	475	45	97	109	156
Predicted	401	448	393	401	42.7	75.9	106.0	145

the experimental data at about 59 s. This reveals the limitation of this thermal-balanced integral model without considering the drying of moisture as a physico-chemical process.

3-2. Ignition Characteristics

The ignition temperature and ignition time of aspens with different moisture content are also predicted with a fixed surface temperature (400 °C) as the ignition criterion. The predicted values are compared with experimental data in Table 3. The predicted ignition temperature and ignition time are all in a good agreement with experimental data. It needs to be noted that the deviation between the predicted ignition time and experimental data is increased with the moisture content. This could be attributed to the selection of a fixed surface temperature as ignition criterion for the samples with different moisture contents, since the real ignition temperature is normally increased with the moisture content. However, the model is readily satisfactory for fire-engineering application, to predict ignition temperature and ignition time of solid samples.

CONCLUSIONS

Thermal-balanced integral models for pyrolysis and ignition of wood are extensively introduced, regarding the determination of surface temperature rise, ignition time, ignition temperature and critical heat flux. One of the thermal-balanced integral models is employed to give the predictions on the characteristics of pyrolysis and ignition of wood. The following conclusions were made:

• The analytical expressions correlating ignition time and heat flux from several typical thermal-balanced integral models are of the same form, which only differs from the numerical coefficient. The critical heat flux determined from the X-axis intercept of the fitting curve of $t_{ig}^{-1/2}$ versus q_e is well-established, giving the value of 12.2 kW/m^2 for the different tested wood species. This method would be of great value for assessing the fire-retardant characteristics of solid materials.

• The predictions by the model including the radiative and convective heat losses from the solid surface were sensitively affected by the selection of ignition temperature as ignition criterion. A value of ignition temperature around 360 °C was found to give the best fit between predictions and experimental points for piloted ignition of different wood species.

• Model 4, considering the effect of heat losses, average absorptivity and moisture content, might not be precise for predicting the surface temperature for the samples with high moisture content, but it is readily satisfactory for fire-engineering application.

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APPENDIX

Nomenclature/Abbreviation

L : thickness [m]
T : temperature [K]
t : time [s]
τ : cooling modulus
M : mass [kg]
m′ : mass loss rate [gm^{-2}s^{-1}]
k : thermal conductivity [Wm^{-1}K^{-1}]
ρ : density [kgm^{-3}]
c : specific heat [Jkg^{-1}K^{-1}]
α : thermal diffusivity [m^{2}s^{-1}]
q : thermal intensity or heat flux [kWm^{-2}]
h : heat transfer coefficient [Wm^{-2}K^{-1}]
β : absorptivity
ε : emissivity
σ : Stefan-Boltzmann constant [5.76*10^{-8} Wm^{-2}K^{-4}]
E : activation energy [kJkmol^{-1}]
A : pre-exponential factor [s^{-1}]
R : universal gas constant
MC : moisture content [%]
Q : reactive heat [kJkg^{-1}]
e : energy of wave
λ : wavelength [μ]
ΔW : heat of wetting [kJkg^{-1}]
H : latent heat [kJkg^{-1}]

Subscripts

0 : initial or ambient
ig : ignition
cr : critical
w : wood
d : dry
e : external
net : net
l : loss
s : surface
c : convective
eq : equivalent
m : moisture
p : pyrolysis
a : absorbed

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