THERMAL DEGRADATION AND IGNITION OF WOOD BY THERMAL RADIATION

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ABSTRACT

Thermal degradation and ignition of selected wood samples will be studied in this paper. Firstly, experiments were conducted on samples of surface size 100 mm by 100 mm and thickness 15 mm thick. The samples of moisture content varied from 5% to 44% were exposed to uniform heat flux from 20 to 70 kW/m^2. Temperature profiles, mass loss rate, ignition temperature and ignition time of wood were all examined.

A partial differential equations (PDE) model was then proposed to study the effect of heat flux on the pyrolysis and ignition of wood with different moisture content. The heat of thermal decomposition and effect of evaporation of water were also considered in the model. It is observed that temperature distributions, mass loss rate and ignition time predicted by this PDE model matched the experiments well. Results were also compared with an integral model predicting ignition characteristics based on energy balance and ignition criterion. This sample integral model did not give good predictions because most of the physical and chemical effects were not yet included under experimental conditions.

KEYWORDS: Temperature distribution, Mass loss rate, Ignition temperature, Ignition time, Criterion, PDE model, Integral model

NOMENCLATURE

A Pre-exponential factor (s^{-1})
c Thermal capacity (J/kgK)
E Reaction active energy (J/mol)
H Reaction heat (J/kg)
h Thermal convective coefficient (W/m^{2}K)
K Reaction
k Reaction rate (s^{-1})
L Thickness of the sample (mm)
Q'' Energy Source (W/m^2)
q'' Heat flux (kW/m^2)
R Universal gas constant (J/molK)
T Temperature (K)
t Time (s)
X Moisture content
x Distance from the upper surface (mm)
α Average absorptivity
λ Thermal conductivity (W/mK)
ρ Density (kg/m^3)
σ Stephen-Bolzman constant
ε Emissivity

δ   Control volume (m)

Subscripts

0   Initial
1   Char formation
2   Volatiles formation
3   Water evaporation
c   Char
e   External
g   Volatile
l   Liquid
r   Reaction
s   Solid
v   Vapor
w   Wood
conv   Convective
ig   Ignition
loss   Loss

INTRODUCTION

A good understanding on the combustion mechanisms of wood is very important for modeling building fires and developing timber products.   Pyrolysis and ignition of wood is the initial stage of combustion.   The subsequent fire growth and flame spread would be affected.

Thermal decomposition of wood and other cellulosic materials was widely studied in the literature[1-5].   It was generally accepted that wood begins to lose its water of constitution until the temperature exceeds 100 ^{o}C.   Weight loss is slow up to 200 ^{o}C and the evolved gases are difficult to ignite.   Lignin and hemicellulose of wood undergo glassy transition in this range.   The pyrolysis is thought to be endothermic and results in evolution from 200 ^{o}C to 280 ^{o}C.   Mixtures of carbon dioxide, water vapor and acetic acid would be evolved.   The wood specimen would pyrolyze rapidly from 280 ^{o}C to 500 ^{o}C.

If the fuel and oxygen mixed within the flammability limit, wood will be ignited.   Ignition of these pyrolyzed gases with or without an external pilot energy source (such as a nearby open flame or electrical spark) can be classified as piloted or spontaneous ignition.   As described by Janssens [6] and Babrauskas[7], factors affecting the ignition of materials can be classified as external and internal factors.   The area of exposure, uniformity of radiant heater, heating rate, air draught and total pressure of gas phase are examples of external factors.   Internal factors include the moisture content, grain orientation, surface absorptivity, thermal properties, diathermancy, permeability and void fraction.

The objective of this paper is to study the effect of some key factors on the process of pyrolysis and ignition of the solid experimentally and theoretically.   When wood samples were subjected to different external heat fluxes (a uniform temperature over the solid surface), temperature at different points and solid mass loss were recorded.   Some key ignition characteristics such as time to ignition and ignition temperature would also be investigated in this paper.   A partial differential equations (PDE) model including the heat of thermal decomposition and effect of evaporation of moisture content was developed to examine the effect of heat flux on the pyrolysis and ignition of wood with different moisture content.   Finally, the time to ignition predicted by the PDE model was compared with the typical integral model describing ignition characteristics by an algebraic expression.

THE EXPERIMENTS

Experiments on thermal degradation and spontaneous ignition of different species of wood were carried out under an air atmosphere in the modified cone calorimeter [8]. The sample of wood was cut into size of 100 mm by 100 mm and 15 mm thick heated horizontally inside a $380 \times 380 \times 460$ mm refractory steel furnace. In this way, one side of the wood sample was subjected to uniform heat flux from 20 to 70 kW/m^2. The other sides were insulated with asbestos. Pyrolysis and ignition of birch with different moisture content under a certain heat flux were also studied in the experiments.

Thermocouples were placed inside the sample at different depths on 1 mm, 7 mm and 14 mm. The transient mass of the solid was measured by an electronic balance under the specimen holder. The temperatures and the mass of solid were recorded every 1 s. Ignition time was recorded as soon as a flame was observed on the solid surface. No ignition would be claimed if flame was not seen within 1200 s. Tests would be repeated if there are problems on the data recorded.

The temperature distribution and mass loss rate of Brazilian pear under 20 kW/m^2 heat flux were examined in Fig. 1. It was found that the process of thermal degradation was similar to that described before. Firstly, water evaporated as the surface temperature reached 100 ^{o}C, but no temperature plateau was found and the temperature increased continuously. From 200 s to 700 s, pyrolysis of the solid was slow as the temperature of most layers of the solid was between 180 and 280°C. It was observed that the solid pyrolyzed rapidly from 700 s to 1400 s, where the temperature of most layers was between 280 to 450°C. Finally, the solid decayed after 1500 s as the temperature was above 500°C.
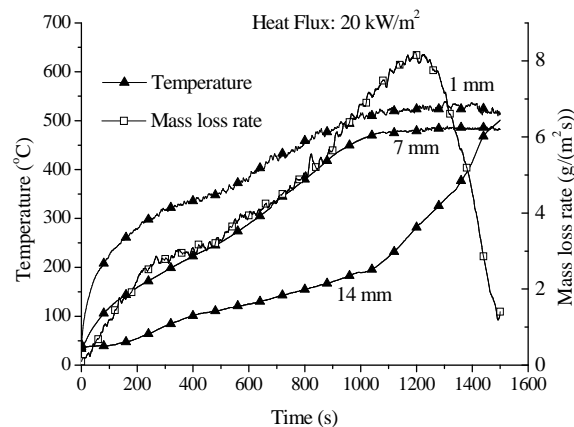

FIGURE 1. Temperature distribution and mass loss rate of Brazilian pear (MC = 15%)

It was obvious that there was a mass loss rate plateau from 200 s to 600 s. This was mainly due to the char layer insulation to resist heat energy transferred into the inert of solid, and thus delayed the pyrolysis of wood. The function of inert pressure resulted in the shrinkage of the char layer. This made the radiant heat energy easily penetrate into the solid and led to steep temperature rise and mass loss of the solid. The pyrolysis (mass loss rate) of the solid was rapid after 700 s.

THE MATHEMATICAL MODEL

A wood slab subjected to a radiant heat flux on one side was modeled. As the surface of the solid was heated (the other side was adiabatic), the wood was first dried and then pyrolyzed by radiant and conductive heat transfer. Pyrolysis of wood to water vapor, gas and char formed a one-step, multi-global reaction schemes for pyrolysis of wet wood (Fig. 2). A small portion of the pyrolysis

gases and water vapor moved inward, while the greater portion passes through the char layer and left from the upper surface of solid. Ignition was assumed to be initiated as the surface temperature reached a certain value [2,9-11].
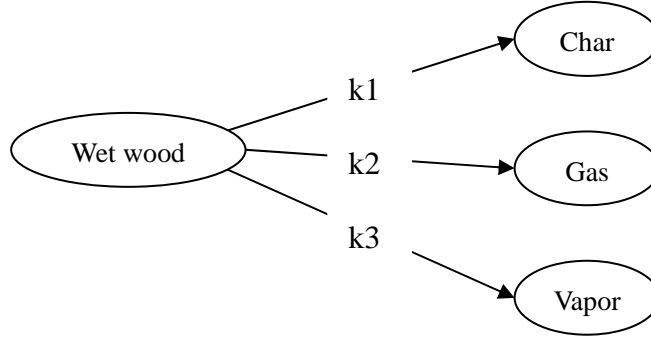
FIGURE 2. The one-step multi reactions of pyrolysis of wet wood

The assumptions for the mathematical model of wet wood are listed as follows: (1) The wood slab is considered to be a one-dimensional, thermally thick, opaque and semi-infinite solid fuel. (2) The heat and mass transport of the gases and vapor inside the solid is ignored. (3) Evaporation of water inside the wet wood is reasonably taken into account as a chemical reaction as the moisture content is below the fiber saturation point (FSP commonly 30%[12]). And there is no recondensation of water vapor inside the solid. (4) The chemical reactions for pyrolysis of wet wood are described by the first-order Ahhrenius Law. (5) Heat losses from re-radiation and convection on the solid surface are included in the model. (6) Volume shrinkage of the solid is neglected in the process of pyrolysis. (7) A fixed surface temperature T_{ig} is considered to be the ignition criterion. Based on the experimental results, a certain value of $450^{\circ}C$ was suggested to be the criterion value for spontaneous ignition of wood, a little lower than that of $525\ ^{\circ}C$ proposed by Bilbao et al. [11].

The energy conservation equation for pyrolysis and ignition of the wet wood is described as:

$$(\rho_w c_w + \rho_c c_c + \rho_l c_l)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda_s \frac{\partial T}{\partial x}) + Q_r^{''} \qquad [1]$$

Where $Q_r^{''}$ is described as the sum of reaction heat of the two pyrolysis reactions and evaporation of water and the heat brought by specific heat variation:

$$Q_r^{''} = k_1 \rho_w [\Delta H_1^0 + (c_w - c_c)(T - T_0) + k_2 \rho_w [\Delta H_2^0 \\ + (c_w - c_g)(T - T_0)] + k_3 \rho_l [\Delta H_3^0 + (c_l - c_v)(T - T_0)] \qquad [2]$$

The mass conservation equations for wood, char, volatile, liquid and vapor are listed as follows:

$$\frac{\partial \rho_w}{\partial t} = -(k_1 + k_2)\rho_w \qquad [3a]$$

$$\frac{\partial \rho_c}{\partial t} = k_1 \rho_w \qquad [3b]$$

$$\frac{\partial \rho_g}{\partial t} = k_2 \rho_w \qquad [3c]$$

$$\frac{\partial \rho_l}{\partial t} = -k_3 \rho_l \qquad\qquad [3d]$$

$$\frac{\partial \rho_v}{\partial t} = k_3 \rho_l \qquad\qquad [3e]$$

According to assumption (4), the rate of pyrolysis reactions is governed by first-order Ahhrenius Law:

$$k = A \exp(\frac{-E}{RT}) \qquad\qquad [4]$$

The initial and boundary conditions are:

$$t=0,\ T=T_0 \qquad\qquad [5]$$

$$t>0,\ x=0,\ \ \lambda_s \frac{\partial T}{\partial x} = \alpha q_e^{"} - q_{loss}^{"} \qquad\qquad [6]$$

$$q_{loss}^{"} = \sigma\varepsilon(T^4 - T_0^4) + h_{conv}(T - T_0) \qquad\qquad [7]$$

$$t>0,\ x=L,\ \ \lambda_s \frac{\partial T}{\partial x} = 0 \qquad\qquad [8]$$

A variation for the solid thermal conductivity with solid conversion (η) was assumed as:

$$\lambda_s = \eta\lambda_c + (1-\eta)\lambda_w \qquad\qquad [9]$$

$$\eta = \frac{\rho_c}{\rho_s} = \frac{\rho_c}{\rho_c + \rho_w} \qquad\qquad [10]$$

The parameters utilized to solve the model were obtained either by using other experimental systems or from the literature. The kinetic parameters for different pyrolysis reactions of wet wood are given in Table 1 and thermal properties for wood, char, gas, liquid and water vapor are given in Table 2.

TABLE 1. Kinetic parameters for pyrolysis reactions and process of drying

Pyrolysis reactions	A (s^{-1})	E (kJ/mol)	Ref.	ΔH_i^0 (kJ/kg)	Ref.
Wood $\xrightarrow{k1}$ Char	7.38×10^5	106.5	13	-420	14
Wood $\xrightarrow{k2}$ Gas	1.44×10^4	88.6	13	-420	14
Drying process					
Moisture $\xrightarrow{k3}$ Vapor	5.13×10^{10}	88	15	-2440	16

Moreover, the average absorptivity of wood in spite of the species was approximately unity under cone calorimeter (electrical heater), obtained by Wessons et al. [17].   The emissivity value of wood slabs, 0.78, was given by Costa [18] and considered to be constant during the experiment.   The value for convective coefficient of the solid surface was taken as 10 W/m²K from the literature [10].

**TABLE 2.** Values and correlations of physical parameters used in the model

Property	Correlation/Value	Ref.
Thermal conductivity	$\lambda_s=\eta\lambda_c+(1-\eta)\lambda_w$	Assumed
(W/mK)	$\lambda_c=0.105$	3
	$\lambda_w=0.166+0.369X$	3
Specific heat	$c_w=1.95$	3
(kJ/kgK)	$c_c=1.39$	3
	$c_g=2.4$	19
	$c_l=4.18$	16
	$c_v=1.58$	3
Emissivity	$\varepsilon=0.78$	18
Convective coefficient (W/m^2K)	$h_{conv}=10$	10
Absorptivity	$\alpha=0.95$	17

By putting in the above parameters, a set of the coupled partial differential equations were numerically solved to evaluate all unknowns of the pyrolysis and ignition of wood, such as temperature distributions, mass loss rate and ignition time. Comparison of the predictions with experimental results will be discussed in next section.

TEMPERATURE PROFILES AND MASS LOSS

The temperature at different depths of birch under 20 kW/m^2 heat flux was predicted and matched experimental results well (Fig. 3). Effect of external heat flux on surface temperature was also examined by the mathematical model (Fig. 4). It was observed that surface temperature increased rapidly under high intensities due to the high temperature gradient. The predicted results under low heat flux matched experimental data better than that under high intensities. This is mainly because the materials were not opaque at the high heat flux and the effect of diathermancy of solid should be considered[2,20]. Moreover, it was found by Moghtaderi[21] that there was no obvious drying behavior during the process of pyrolysis of wet wood or before piloted ignition of wet wood for heat fluxes higher than 25 kW/m^2. And as the brief process of pyrolysis of wet wood can be observed under the higher heat fluxes, the model proposed in this paper was more valid and precise for the pyrolysis of wet wood under relatively low heat fluxes (lower than 40 kW/m^2).
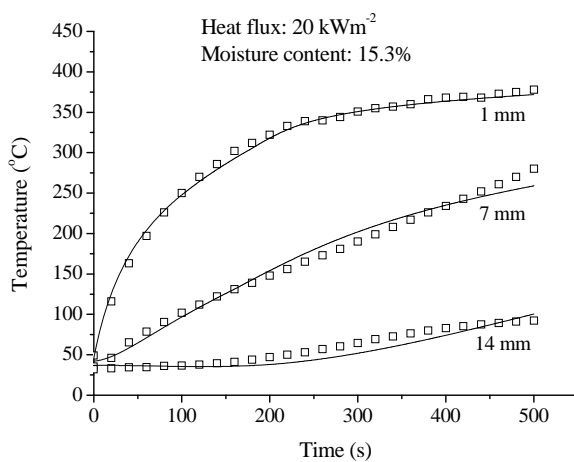
FIGURE 3. Comparison between experimental data and calculated results on temperature distribution of birch under 20 kW/m^2
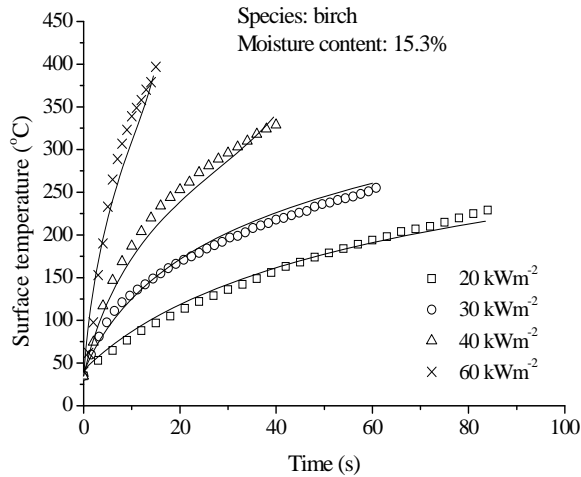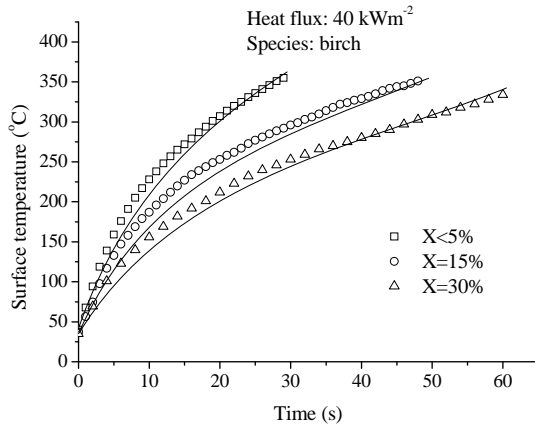
FIGURE 4. Comparison between experimental and calculated surface temperature of birch under different heat fluxes

Moisture content is another key factor influencing the process of pyrolysis and ignition of wood. It was stated by Moghtaderi[21] that solid fuels of wood-based materials naturally contain moisture existing in two basic forms: (i) free or capillary water, and (ii) bound or hygroscopic water. The former is found in liquid form in the void of wood, most of which evaporates at the temperature of 100 $^{\circ}$C. The latter is present in the cell wall bonded to the hydroxyl groups inside the solid, and more energy is consumed to evaporate the bound water. Moreover, fibre saturation point (FSP) is defined by the saturation of the cell walls at a certain relative humidity of surrounding air, as additional water beyond FSP exists only in the form of free water.

Surface temperature of birch with different moisture content under 40 kW/m^2 heat flux was predicted and compared with experimental results in Fig. 5. No surface temperature plateau could be observed for the sample with different moisture content. This indicated that no obvious process of water evaporation was found as the heat flux was a little high or the moisture content was all below FSP. It was also observed that surface temperature of the sample with low moisture content rose more quickly than that with high moisture content. This was explained by that more heat energy was consumed to vaporize the water, and thus delay the temperature rise and the process of pyrolysis and ignition of the solid.

There is a good agreement between the predicted data and experimental results (Fig. 5). This indicated that the process of drying was reasonable to be described by the first-step Ahhrenius Law as the moisture content was not high in the solid. This was confirmed by Moghtaderi[12] that this pyrolysis model of wet wood ignores the free water and is applicable to the samples with moisture contents below the FSP having similar longitudinal and transversal dimensions. Some discrepancies between the predicted and experimental data were mainly due to the ignorance of the movement of produced gases inside the solid and recondensation of water vapor.

FIGURE 5. Comparison between experimental and calculated surface temperature of birch for different moisture content under 40 kW/m^2
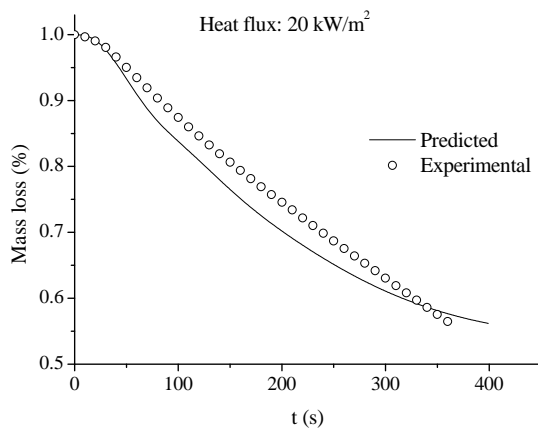
FIGURE 6. Comparison between experimental and calculated mass loss of birch

The solid conversion and water evaporation at different points of the birch under 20 kW/m^2 heat flux were calculated and using the results, total mass loss was obtained and compared with the experimental results in Fig. 6.   It can be seen that the calculated mass loss of the sample matched the experimental data well.   The obvious difference between the predicted data and experimental results after 350 s was mainly due to the ignorance of effects of volume shrinkage of the solid in this model.

IGNITION TIME

Ignition time, one of the key ignition characteristics, was widely studied in the literature [2,6,7,9,21-23]. Quantities of mathematical models for the pyrolysis and ignition of the solid, highlighting to predict ignition time, could be classified into two categories: (1) partial differential equation (PDE) model predicts ignition characteristics by numerical solutions on a group of partial differential equations including a chemical kinetic scheme coupled with heat and mass transfer equations [2,5,9,22]; and (2) integral model predicts ignition characteristics based on energy balance and ignition criterion. [10,21] The integral equation was integrated with respect to space and then time variables to give analytical expressions on ignition characteristics including ignition time, critical heat flux and ignition temperature.

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The ignition time of birch with different moisture content under 40 kW/m^2 heat flux was predicted by the PDE model and compared with experimental results in Fig. 7.   The predictions matched the experiments well, as some differences were mainly due to the criterion of a fixed surface temperature.   As the ignition temperature increased as the moisture content increased, the predicted ignition time was overestimated for the sample with lower moisture content.
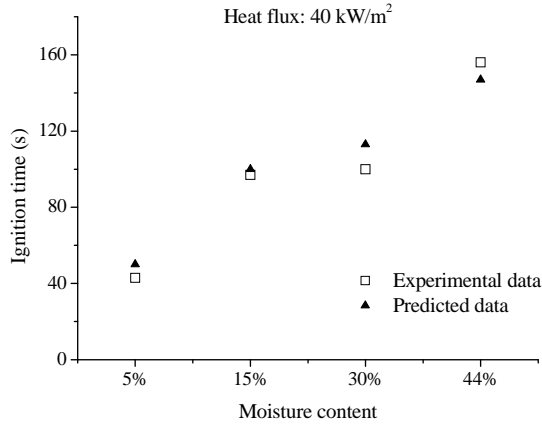
FIGURE 7. Comparison between experiments and predictions on ignition time of birch with different moisture content

COMPARISON WITH INTEGRAL MODEL

The typical integral model of ignition of wood was proposed by Spearpoint and Quintiere[10] based on the following assumptions:

● Ignition occurs when the surface temperature achieves a critical value.
● Solid is inert up to ignition (no chemical scheme).
● Solid is infinitely thick.

The conservation of energy for the control volume was obtained:

$$\rho_s c_s \left[\frac{d}{dt} \int_0^{\delta} T(x) - T_0 \frac{d\delta}{dx} \right] = q^{"}(t) \qquad [11]$$

Without considering the heat losses on the solid surface and volume shrinkage, equation [11] was solved into an analytical expression:

$$t_{ig} = \frac{2}{3} k\rho c \frac{(T_{ig} - T_0)^2}{q_e^{"2}} \qquad [12]$$

Similar expressions of the same form to describe time to ignition were obtained from other integral models[21,24], differing only by the numerical factors.

The comparison between PDE model, integral model and experimental results was evaluated in Fig. 8.   The predicted ignition time by PDE model was a little lower than experimental data under the low heat flux of 30 kW/m^2, while the predicted value was higher under high heat fluxes.   And the discrepancy between experimental results and predictions by the integral model was considerably obvious for the relatively low heat flux (with longer ignition time).   This might be explained by

that the surface heat losses played a significant role in energy balance of the solid under low heat fluxes, while it was only a negligible small portion under high intensities. The ignition time predicted by integral model was underestimated as heat losses on exposed solid surface were not included in the model.
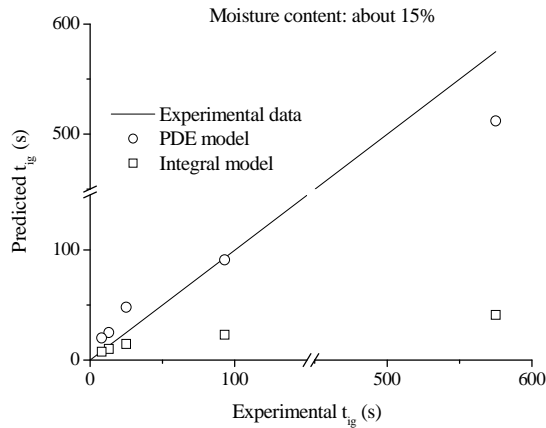
FIGURE 8. Comparison between PDE model and integral model on ignition time of birch

Thus, the integral model is applicable for the solid under higher intensities, and heat losses on solid surface under relatively lower intensities should be considered in the mathematical model. It was concluded that predictions by PDE model were more precise than those by integral model as most of physical and chemical events of pyrolysis and ignition of wood were not considered in the integral models.

However, the analytical expression deduced from the integral models of ignition of combustibles could be easily used for calculating the ignition characteristics, and the relationship among the parameters in the expression could be simply analyzed for engineering application. Thus, improving the integral model and finding new analytical solution are required in future work.

CONCLUSIONS

When a wood slab was heated, thermal decomposition of the solid fuel could be divided into four steps: (1) Water vaporized as the temperature reached 100 ^{o}C; (2) solid fuel pyrolyzed slowly at the temperature between 180 and 280 ^{o}C; (3) pyrolysis of solid was rapid as the temperature of most part of solid was from 280 to 450 ^{o}C; (4) the solid fuel decayed after the temperature above 500 ^{o}C.

The predicted temperature profiles and mass loss of the solid by the partial differential equations (PDE) model matched the experimental results very well. It was found that the pyrolysis and ignition model was applicable for the moisture content below FSP under relatively low heat fluxes. The predicted ignition time agreed well with experimental results with a fixed ignition temperature of 450°C. Some discrepancies were mainly due to the ignorance of movement of the produced volatiles and recondensation of water vapor.

Comparisons between the PDE model and integral model were also examined in this work. Predicted results by the PDE model were more precise than those by integral model, as most of physical and chemical events during the process of pyrolysis and ignition were ignored by the integral model.

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