IGNITION OF WOOD-BASED MATERIALS BY THERMAL RADIATION

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ABSTRACT

Ignition is the initial stage of burning the materials. Consequent flame spread over the materials, heat release rate, fire spread across the rooms, and other issues for building fires all depend on that. Ignition of cellulose materials is commonly classified as smoldering or glowing ignition (self-heating ignition) and flaming ignition including piloted and spontaneous ignition. Numerous studies on this topic were reported in the literature. A review on ignition of wood will be reported in this paper.

Ignition temperature, critical mass flux of volatiles, time to ignition, critical heat flux and critical heat release were measured experimentally and applied as key ignition criteria for theoretical analysis. Quantitative study on modeling smoldering ignition of cellulosic materials is not yet well understood. As experimental data is inadequate, this part is only briefly discussed. Models of flaming ignition were well developed from those well validating experimental data. However, most of the flaming ignition models of wood were only on the solid phase. Gas phase phenomena during ignition should be further examined for developing flaming ignition models.

1. INTRODUCTION

As cellulose materials are widely used in the construction industry such as partitions and furnishings, better understanding on pyrolysis, ignition, combustibility, heat release rate and fire spread would be helpful for building fire hazard assessment and fire protection.

The ignition of those cellulose materials, especially wood, has been studied for over a century. Ignition is the initial stage of burning the materials, and directly related to the consequent flame spread, heat release rate, fire spread, and other safety issues for building fires. Ignition with a flame at the surface of a material exposed to external heating, such as a pilot source or a hot wall, is called flaming ignition. This mode of ignition is driven by the flammable vapor produced by the thermal decomposition of the solid. Another mode that the solid is subjected to self-heating under a low heat flux from the external environment or inadequate oxygen is called smoldering or glowing ignition (self-heating ignition). In smoldering cigarettes, self-heating ignition is not due to thermal decomposition but oxidation of the solid. This phenomenon is not so common for non-porous materials.

Comparing to smoldering or glowing ignition (self-heating ignition), the more common mode of ignition, flaming ignition, is closely related to the fire behaviors of materials. It would affect the thermal phenomena of real building fires. In this paper, the flaming ignition of cellulose materials is discussed in more detail. Only a brief overview is devoted to self-heating ignition.

Flaming ignition can be further divided into piloted and spontaneous ignition, depending on whether there is an ignition source, such as a spark or a flame. There are many works reported in the literature. The earliest systematic studies on the spontaneous ignition of solid were carried out by Bixel et al. [1] in 1910, and those on piloted ignition were conducted by Prince [2] in 1915. The thermal conduction equation was first applied by Bamford et al. [3] for analyzing ignition. A mathematical method was developed by Lawson and Simms [4] in 1960s for predicting ignition, being the early data-correlation method. Since then, the study can be classified as experimental studies, detailed mathematical modeling, and correlation studies. A detailed review was presented by Babrauskas [5].

2. EXPERIMENTAL STUDIES ON IGNITION

Experimental studies might be taken as the first step to understand how the materials behave under a fire. Measured data can be applied as ignition criteria for further theoretical studies. Key ignition criteria identified for cellulosic materials are surface ignition temperature, critical mass flux of volatiles, time to ignition and critical heat flux.

### Surface Ignition Temperature (Critical Ignition Temperature)

The surface ignition temperature T_{ig}, an important characteristic of ignition of cellulosic materials, is one of the criteria used for describing ignition occurrence. The sample such as wood will be ignited when the surface temperature reaches T_{ig}. Although this concept originated from experiments might not be entirely correct, results can be applied in modeling the burning process. For example, ignition is assumed to occur when the surface temperature reaches a constant value T_{ig} deduced from correlation studies under different radiant heat fluxes. Therefore, measuring the ignition temperature experimentally is the starting point of studying the ignition of materials such as wood.

As reviewed by Babrauskas [5], such studies started in the 19th century. There are two different definitions of 'critical ignition temperature':

- The temperature of the surface at the time of ignition.
- The minimum temperature of a furnace containing the specimen to ignite.

A summary on T_{ig} is compiled as number distribution curves in Figs. 1 and 2. It is observed that the critical ignition temperature for wood varied from 210 to 497 ^{o}C in Fig. 1a and mostly from 310 to 360 ^{o}C in Fig. 1b for piloted ignition; and from 220 to 510 ^{o}C in Fig. 2a and mostly from 240 to 400 ^{o}C in Fig. 2b for autoignition. Note that there is one value lying outside the range. Such a wide spread might be due to the following reasons:

- The definition of ignition temperature.
- The design of the test apparatus.
- The experimental operating conditions including piloted, incident heat flux, air flow and other factors.
- The conditions of sample such as moisture content and orientation.
- The species of wood (as density, specific heat and thermal conductivity were not considered).
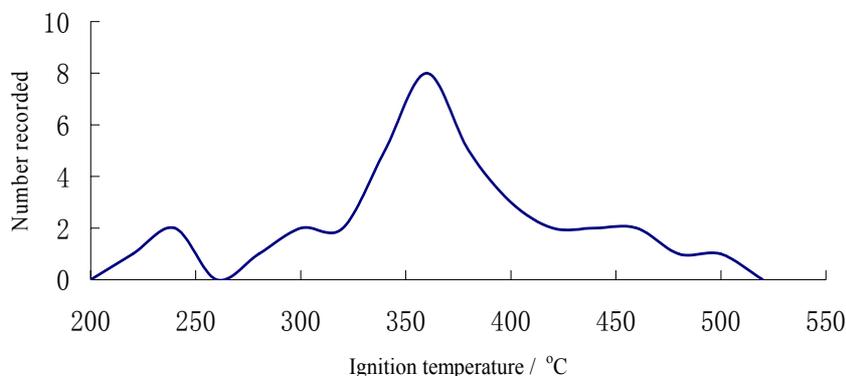
(a) Number distribution
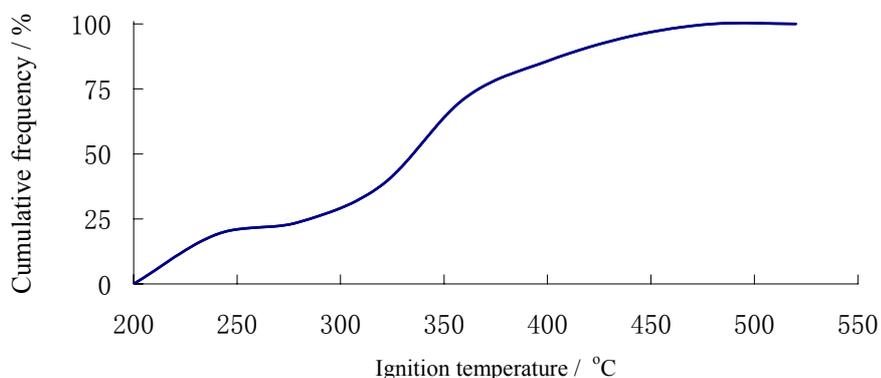
(b) Cumulative frequency

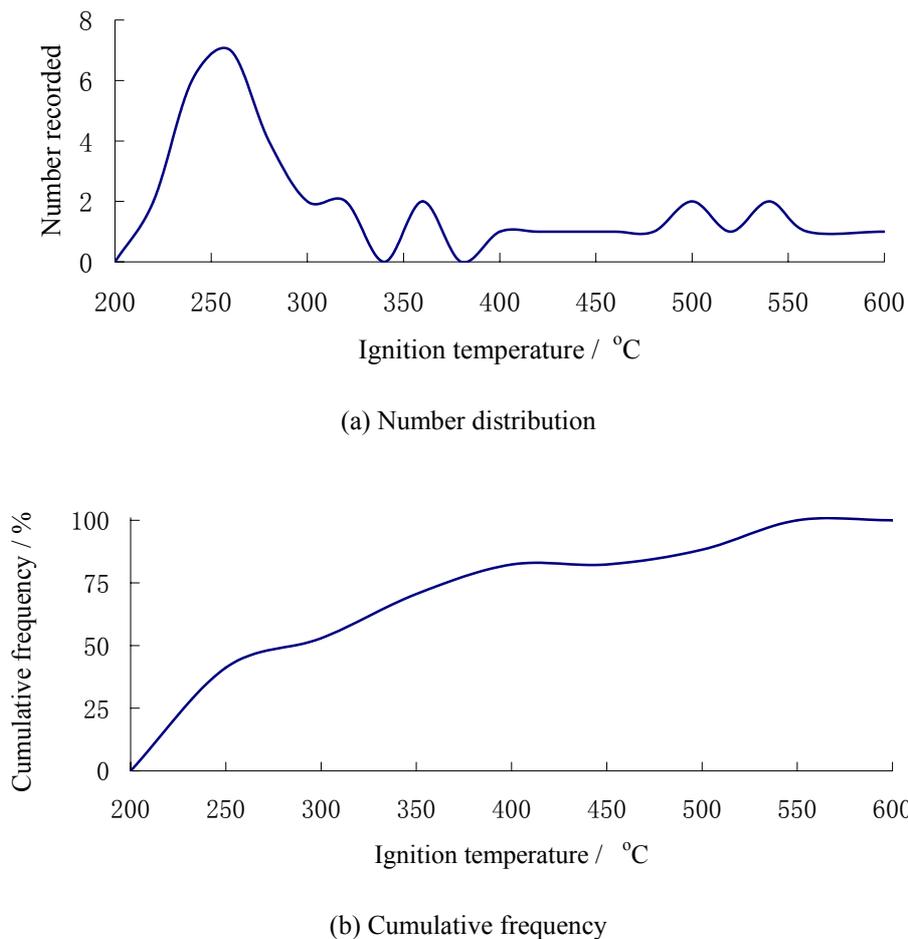**Fig. 1: Review on piloted ignition temperature of wood [5]**

(a) Number distribution

(b) Cumulative frequency

Fig. 2: Review on spontaneous ignition temperature of wood [5]

Two types of apparatus were developed for "ignition only" tests:

- Sample is placed in a furnace as proposed by Setchkin [6] in 1949.
- Burning the sample in open air under thermal radiation, testing with the cone calorimeter is an example [7].

But the basic division depends on a preferred specimen size for each test. As in Fig. 3, values of T_{ig} for piloted ignition should not be higher than those for autoignition, unless the equipment was not developed properly. Autoignition temperature under radiant heating would give a wider range. It appears that design of the apparatus would affect autoignition more than for piloted ignition.

Ignition temperature is also affected by experimental conditions such as air flow velocity and the incident radiant heat fluxes. The piloted ignition temperature was found by Atreya and Abu-Zaid [8] to increase as the velocity increased. For a heat flux of 35 kWm^{-2} and air velocity increasing from 0.1 ms^{-1} to 1 ms^{-1}, the ignition temperature might be increased by 15 K. Therefore, the critical surface temperature might be taken as 558 K under such conditions. Spontaneous and piloted ignition temperature of several cellulosic materials, black rubber and polyurethane foam were measured by Smith and King [9] in exposing the samples to radiation heat flux of 5 to 105 kWm^{-2} from two quartz lamps of a long wavelength infrared pyrometer. The surface ignition temperature was observed to decrease with increasing radiant heat flux for the cellulosic materials. Results are similar to those reported by Atreya et al. [10]. In contrast to the works by Hopkins [11], ignition temperatures for Redwood increased only when the heat flux was less than 21 kWm^{-2}. Similar results were reported by Spearpoint and Quintiere [12] on calculating the ignition temperature in regions of the same fluxes using the piloted ignition integral model.
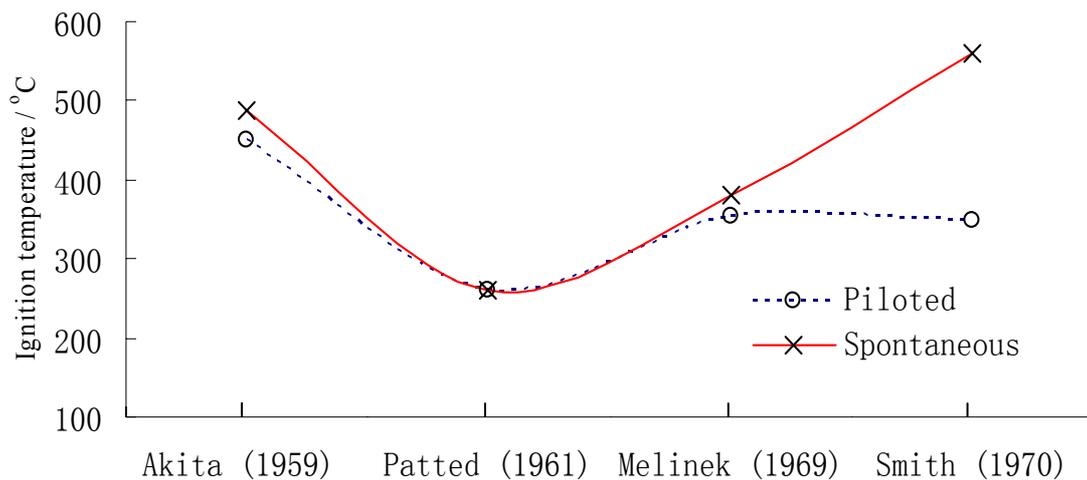
Fig. 3: Comparison between piloted and spontaneous ignition temperature of samples by different investigators [5]

Although specimen orientation would affect the ignition temperature, there is not much experimental data to support that. Surface temperatures at piloted ignition of vertical and horizontal samples of red oak and mahogany were measured by Atreya et al. [10] using fine chromel-alumel thermocouples. The thermocouple junctions were placed and fixed securely to the surface of the samples. An average ignition temperature of 375 °C was found for mahogany under both vertical and horizontal orientations. The value for red oak was 365 °C. But from the experimental results of Fangrat et al. [13], the average values of surface ignition temperature recorded for the same type of material in different orientations varied over the wide range of 100 K or more. Values for vertical orientation are usually much higher than those for the horizontal samples. Such results agreed with the predictions using the integral model by Spearpoint and Quintiere [12]. There might be different mechanisms of ignition for horizontal and vertical samples. Further, moisture content is another factor affecting the critical ignition temperature. Ignition temperatures varied from 290 °C to 356 °C with a mean 353 °C as reported by Dietenberger [14] on changing samples with different moisture contents by a cone calorimeter. It was concluded by Jassens [15] that T_{ig} increased by 2 °C when moisture content of the sample increased by 1%. Such small variation might not be important for wood samples seasoned down to moisture content lower than 20%.

In general, the surface ignition temperature was described by Tran and White [16] as 'a very elusive quantity and difficult to measure accurately'. The main problem is associated with the use of infrared pyrometry where the surface emissivity changes with thermal decomposition upon ignition to give

crack, shrinkage or other deformations. Further works should be on designing a suitable apparatus and reviewing the measuring procedure. For example, the position of placing the thermocouple junction to the solid surface and fixing it securely are the key points.

Critical Mass Flux of Volatiles (Critical Mass Loss Rate)

The critical pyrolysates mass flux, interpreted as a critical mass flow of volatiles sufficient to support a nascent flame, is another proposed criterion for ignition. The concept was firstly suggested by Bamford et al. [3] in 1946. The mass loss rate was calculated as a function of time, and then correlated with experimental observations. A proposed criterion that piloted ignition would occur is when the mass flux m'' of pyrolysates releasing from the surface (i.e. mass loss rate of the sample) reaches a value of 2.5 gm^{-2}s^{-1}.

By following Bamford et al., the values of mass loss rate of the sample produced by thermal decomposition under piloted ignition conditions were investigated for both cellulosic and foamed materials. It appears that most of the works, especially those conducted by Terwarson et al. [17], Drysdale and associates [18-20] in 1980s, were focused on polymeric materials. Very few works were concerning cellulosic materials.

The critical mass loss rate required for piloted ignition for several electric cable specimens was reported by Tewarson et al. [17] to be lying from 2.6 to 4.8 gm^{-2}s^{-1}. A critical value of mass loss rate of 1.9 gm^{-2}s^{-1} was reported by Thomson and Drysdale [18] for piloted ignition of plastics. It is difficult to measure such low values of mass loss

rate accurately and the results might vary in different experiments. The lower reported values might be more accurate than the higher ones. For example, a higher value of 4 to 5 $gm^{-2}s^{-1}$ was found by Deepak and Drysdale [19] for PMMA. Later, a value of 1.9 $gm^{-2}s^{-1}$ was found by Thomson and Drysdale [18] after upgrading the apparatus. The values are related to the species of materials and the testing conditions, such as air flow velocity and oxygen content. Effects of some variables including air flow rate and oxygen concentration on the critical mass loss rate for PMMA tested in horizontal orientation were studied by Rasbash et al. [20].

The mass loss rates of several wood samples at ignition were measured by Koohyar et al. [21]. The critical value was found to be from 1 to 22 $gm^{-2}s^{-1}$, suggesting that $m_{cr}^{"}$ is higher than 7.5 $gm^{-2}s^{-1}$, much higher than that deduced by Bamford et al [3]. Another series of tests on wood were conducted by Melinek [22] to deduce the mass loss rates under both piloted and spontaneous ignition. A simple numerical model of the ignition was proposed with the mass loss rate of the sample determined from a one-step Arrhenius reaction as:

$$m^{"}(t) = (\rho(t) - \rho_c)A\exp\left(\frac{-E}{RT}\right) \qquad (1)$$

The transient mass loss rate curve rose to give a peak and then decreased gradually due to consuming the reactants. The peak of the curve would give the possible ignition and the shape of the curve determines whether the flame can be sustained. Subsequently, as suggested by Kanury [23], this criterion would give some information in determining the combustible fuel to air mixture ratio as flammability limit f in a boundary layer induced by a heated solid surface. The free convectively induced air mass flux was estimated as $\rho_g(g\alpha_g\beta\Delta T)^{1/3}$. The critical fuel mass flux $m_{cr}^{"}$ is given in terms of f by:

$$m_{cr}^{"} = f\rho_g(\alpha_g\beta\Delta T_g)^{1/3} \qquad (2)$$

Values of f were determined from literature and based on the result, this criterion on critical mass flux deduced by Bamford et al. [3] was found to be only a necessary condition for ignition to occur. Additional information on either a pilot heat source or a high enough temperature to give spontaneous ignition is required to get the sufficient conditions.

However, very few experimental works were reported on exploring the concept of critical mass flux or critical mass loss rate. Values of mass flux available were found to be scattered over a wide range, not yet good enough to deduce correlations.

Ignition Time

There are many factors affecting the time to ignition of solid wood t_{ig}. The species itself, sample orientation, moisture content, ambient conditions and the available experimental data are all important in deriving correlating expressions.

A basic relationship on t_{ig} is:

$$t_{ig} \quad \propto \quad \lambda\rho c(T_{ig} - T_0)^2 \qquad (3)$$

If the ignition temperature is taken as a constant, the relationship becomes:

$$t_{ig} \quad \propto \quad \lambda\rho c \qquad (4)$$

That means that the ignition time can be determined directly by the thermal inertia ($\lambda\rho c$). A similar result was also pointed out by Babrauskas [24]. Therefore, the time to ignition of different materials might be determined by their relative values of thermal inertia, not by the ignition temperatures. However, thermal inertia of the sample is difficult to measure accurately during ignition, which should be further studied.

The effect of orientation of materials on ignition time has also been studied in the literature. Two sets of time to ignition were found by Fangrat [13] for horizontal orientation: the time to ignition in the gas phase t_{ig} measured by a cone calorimeter; and the time to ignition in the solid phase t_{is} derived from the surface temperature profiles. The time to ignition in the solid phase was 3 to 5 s shorter in all cases. But such differences were not observed when the sample was orientated vertically. Moisture content was shown by Peck [25] to affect the ignition time. Note that the thermal physical properties of the sample depend on the moisture content, and more heat is required to remove the moisture. Thus, the time to ignition would be extended when the moisture content increases.

Ambient conditions would play an important role in measuring the time to ignition as reported by Bilbao et al. [26]. The time to ignition decreased with increasing heat flux; and increased with the velocity of the air due to surface cooling and dilution of the combustible gases.

Critical Heat Flux

The critical heat flux $q_{cr}^{"}$ is also suggested as another criterion for ignition of wood [27]. It can be determined experimentally by exposing the samples to different incident heat fluxes and

observing whether ignition occurs or not. The critical heat flux is somewhere between the lowest incident heat flux to give ignition and the highest heat flux where ignition did not occur. However, it is expected that the value will be sensitive to the geometry, moisture content and orientation of the sample. All these factors would affect heat and mass transfer inside the solid.

In the experimental studies by Moghtaderi [28], the critical heat flux of wood was found to be varied for different species, and the value was influenced by the moisture content for the same species. The samples would require much more heat for drying prior to ignition. Low-flux ignition and ignition of wood with different grain orientations were studied by Spearpoint [12]. Almost all ignition results available for specimens with the heat source orientated along and across the grain directions were analyzed. For exposures along the grains, $q_{cr}^{"}$ was found to be 12.5 kWm^{-2} for redwood; and less than 12 kWm^{-2} for maple. But for ignition across the grain of maple, the lowest flux at which ignition occurred was 8 kWm^{-2}. No ignition occurred at 7 kWm^{-2}, giving $q_{cr}^{"}$ of 7.5 kWm^{-2} for ignition across the grain of maple. The value for ignition across the grain of redwood was not explored in detail, but should be below 9 kWm^{-2}.

In contrast to piloted ignition, not so many works were reported on autoignition of wood under radiant heat fluxes. Early experimental studies by Simms [29] concluded that insufficiently long testing time for spontaneous ignition might give a wider range of $q_{cr}^{"}$. The value for piloted ignition should not be higher than that for autoignition.

Values of critical heat flux for ignition were calculated by Lawson and Simms [4]. The critical heat flux was calculated by extrapolating from the curve plotting $t_{ig}^{-1/2}$ versus $q_e^{"}$. Value for piloted ignition of vertical samples was deduced to be 12 kWm^{-2} by Lawson and Simms [4]. Similarly, a higher value was reported by Quintiere [30].

Several tests should be carried out to measure the critical heat flux accurately, especially for spontaneous ignition. The exposing time required for determining whether ignition will not occur is another factor. Selection of a 'failure to ignite' criterion is quite subjective. The extrapolating method might be more practical, and should be developed for accurate critical heat flux.

Other Characteristics of Ignition

Many other criteria were reported for ignition. A single value of heat release rate was proposed by Kokkala and Baroudi [31]. The combustible gases above the sample must be heated up to the flame temperature for initial combustion (ignition) to occur, and then sustained. Heat balance on this gas volume suggests that the product of the mass loss rate with the heat of combustion (or heat release rate) of the fuel volatiles is the governing factor. Therefore, the heat release rate becomes a reasonable criterion. However, the measured data were scattered because the mass loss rate is difficult to measure.

The critical char depth was proposed by Sauer [32] to be a criterion for determining ignition of wood. Charring is assumed to start at any depth when the volatiles concentration W falls to a certain value W_c. Correlations of dimensionless mass loss and char depth were deduced. The following damage function of the form was proposed by Williams [33] for deriving a correlation for charring:

$$W_c = \int \delta \exp(E_A / RT).dt \qquad (5)$$

However, it is difficult to apply the above expression for practical application.

Spontaneous ignition was suggested by Simms [34] to occur at the time and location once turbulence is first established in the gas stream. If turbulence is generated, the mixing of the volatiles with the air is enhanced. But this may not be a fundamental criterion, and so not widely used. A model of the solid phase of spontaneous ignition was considered by Devrall and Lai [35] with ignition occurred when the gas temperature first became higher than the solid surface temperature. Ignition is predicted to occur when the radiative heat is equal to the conductive heat loss of solid surface and twice the heat of the reactions. Again, these criteria are not practical as these values are not easy to measure.

More than one criterion was proposed by Rasbash [36] for determining whether ignition occurs. Many criteria have to be relied upon because ignition theory cannot yet be developed from the first principle. The mathematical model requires not only fundamental physical properties.

3. THEORETICAL STUDIES ON IGNITION

Many works were reported on theoretical studies for both smoldering and flaming ignition. A mathematical theory of ignition was initially developed by Semenoff [37] in 1928 for some gas mixtures. There, ignition or explosion is basically independent of the heat balance between the heat generated by the reaction and the heat lost to the surroundings. The theory is applicable to slower

ignition (smoldering ignition) of solid such as wood. Exothermic reactions at slow rate play an important part under certain conditions such as under a very low external heat flux. In contrast, flaming ignition would require a relatively higher heat flux for both piloted and spontaneous ignition. The external incident heat flux plays a more important role.

Modeling Smoldering (Glowing) Ignition

Smoldering ignition of cellulosic materials is due to self-heating of the solid under extremely low external heat flux or low ambient temperature. Smoldering of a porous charring solid is controlled by two factors: availability of oxygen to the smoldering front and the heat losses from it. The velocity of smoldering and the peak temperature are the key parameters. The process of smoldering is controlled by many physical processes and chemical mechanisms. There are a combination of endothermic (non-oxidation) and exothermic (oxidation) chemical reactions in the pyrolysis and combustion zones, diffusion of oxygen to the smoldering zone, diffusion of reaction products (vapors) away from the sources, and heat transfer.

A mathematical model of thermal smoldering ignition of wood was proposed by Thomas et al. [38]. The critical sizes of solid that would give smoldering ignition at any given temperature was predicted by using physical and chemical kinetic constants. A single exothermic reaction with simple heat transfer kinetics was used.

The thermal conduction equation on temperature T in the solid sample is:

$$\nabla^2 T = \frac{1}{a}\frac{dT}{dt} - \frac{q_i^{''}(T)}{\lambda} \tag{6}$$

It is assumed that the heat generation $q_i^{''}(T)$ is due to single reaction described by the Arrhenius law:

$$q_i^{''}(T) = -\Delta H_i A \rho^n \exp(-ER/T) \tag{7}$$

The boundary conditions are:

$$x = \pm L, \quad h_c(T_S - T_\infty) = -\lambda \frac{dT}{dx} \tag{8a}$$

$$x=0, \quad \frac{dT}{dx} = 0 \tag{8b}$$

Dimensionless quantities are:

$$\delta = \frac{\Delta H_i A E^2 L \rho_0^{\,n}}{\lambda R T_\infty^{\,2}}\exp(-E/RT) \tag{9a}$$

$$\theta = \frac{E(T - T_\infty)}{RT_\infty^{\,2}} \tag{9b}$$

$$\alpha = h_c L / \lambda \tag{9c}$$

$$z = x / L \tag{9d}$$

$$\tau = at / L^2 \tag{9e}$$

$$B = \frac{\Delta H_i}{\rho c}\frac{E\rho_0}{RT_\infty^{\,2}} \tag{9f}$$

The dimensionless forms of equations are:

$$\nabla^2 \theta = \frac{d\theta}{dt} - \delta w^n e^\theta \tag{10a}$$

$$\frac{dw}{d\tau} = -\frac{\delta}{B} w^n e^\theta \tag{10b}$$

where w is the ratio of ρ / ρ_0.

The critical value of thermal smoldering ignition of solid is δ_{cr}. Relationships between the specimen size and the minimum temperature for ignition, and between the specimen size and the maximum temperature rise due to self-heating are predicted by the model. However, only single exothermic reaction was considered in the model. The gas phase phenomena were ignored.

A modified model for smoldering ignition of porous materials (furniture which consists of a thin fabric layer over a thickly foam padding) was proposed by Mitler and Walton [39]. During the process of solid smoldering, up to three reactions for materials and diffusion of gases were included.

Thermal conduction of the solid without radiation heat transfer can be determined in terms of the volumetric heat source S as:

$$\rho \frac{\partial cT}{\partial t} = \nabla(\lambda \cdot \nabla T) + S \tag{11a}$$

$$S = \sum H_i r_i + Q_v \frac{\partial \rho}{\partial t} \tag{11b}$$

Values of ρ, c, λ and S varied with positions and temperature. Up to three reactions were proposed for changing the virgin material through thermal degradation and oxidative pyrolysis. The char would then be oxidized to ash. Gases might be migrated to affect the heat transfer and hence the

temperature distribution. The diffusion for oxygen into the reactive region would change the reaction rate. Without convection, the density ρ_i for the ith species is governed by:

$$\frac{\partial \rho_i}{\partial t} = div(D_{i0} grad \rho_i) + S_i \qquad (12)$$

where S_i is the mass source for the ith species.

The diffusivity of O_2, D_O was obtained from the literature and the boundary conditions for mass transfer of oxygen O_2 are described as:

$$m_{O_2}^{"}(x,y) = k_{gas}[Y_{O,\infty} - Y_{O,s}(x,y)] \qquad (13a)$$

$$k_{gas} = \rho_{O,\infty}\gamma \qquad (13b)$$

$$u_O = D_O \left(\frac{\partial Y}{\partial x}\right)_s = \gamma(Y_{O,\infty} - Y_{O,i}) \qquad (13c)$$

Mass transfer at the boundary was calculated by TMPSUB [39] to get the value of γ. TMPSUB is the software developed for solving ordinary differential equations including those describing the physical and chemical kinetics of the heating and smoldering process. Results on the predicted ignition temperature and time to ignition agreed with the experiments. However, moisture effect was not considered in the model.

Another smoldering model of the porous cellulosic material (cigarette) was proposed by Rostami et al. [40]. This model is similar to the one suggested by Muramatsu et al. [41] with the virgin material taken as four pyrolysis reactants and moisture. The evaporation-pyrolysis zone was presented by four steps on pyrolysis of tobacco, char oxidation and water evaporation. Volatiles and water vapor were produced upon heating the solid, leaving char residues and ash. Heat transfer in the gas phase and exchange with solid phase were included in this model.

Energy equations for the solid and gas phase are:

$$(1-\phi)\rho_s c_s \frac{\partial T_s}{\partial t}$$
$$= \nabla \cdot (\lambda_s (1-\phi)\nabla T_s) + h_{s-g}(\frac{A}{V})(T_s - T_g) + S_s \qquad (14a)$$

$$\frac{\partial}{\partial t}(\rho_g \phi h_g) + \nabla \cdot (\rho_g u h_g)$$
$$= \nabla \cdot (\lambda_g \phi \nabla T_g) + h_{s-g}(\frac{A}{V})(T_g - T_s) + S_g \qquad (14b)$$

where h_{s-g} is the gas-solid interface heat transfer coefficient, A is the surface area and V is the volume of the material matrix. Heat exchange between the solid and gas phase interface depended on A/V.

The kinetic constants for pyrolysis are required in the model suggested by Muramatsu et al. [41] for predicting the peak temperature for both gas and solid phase, the smoldering velocity (the burn rate) and the density variation in a smoldering process. The predicted results agreed with experiments on some variables such as the temperature distributions and the smoldering velocity. In fact, accuracy of the predictions depends strongly on the number of empirical input parameters such as the porosity ϕ, activation energy E and pre-exponential A.

Quantitative study on smoldering ignition of cellulosic materials is not yet well understood as experimental data is inadequate. Experiments on smoldering are expensive and time-consuming. An experimental database for smoldering ignition of cellulosic materials should be developed for validating mathematical models.

Modeling Flaming Ignition of Wood from External Radiant Heating

The initiation of flaming combustion may be piloted or spontaneous. Piloted ignition occurs in the presence of an ignition energy source, such as a flame or an electrical spark. This phenomenon of piloted ignition plays very important role in fire safety engineering, as it occurs at relatively lower critical surface temperature. Most of the previous tests and hence the theories were on the piloted ignition problem, while few works focused on spontaneous ignition. There are two groups of theories for the piloted ignition models: detailed partial differential equation models and integral models. Based on the assumptions and simplifications, these models can be further classified into two subgroups. The first subgroup includes only the solid phase phenomenon and most of the models [26,28,44] are under this group. The second subgroup considers both the solid and gas phase phenomenon and their coupling effects [12].

3.2.1 Subgroup 1: Solid phase only

As observed in most of the bench-scale tests on piloted ignition, it is considered that gas phase physical and chemical phenomena in are relatively insignificant by comparing with those in the solid phase. This is because oxygen is sufficient for gas phase reactions. In this subgroup, only solid phenomena were included in the flaming ignition model of wood. Volatiles produced from the solid

would leave from the exposed surface immediately. The oxygen concentration in gas phase was taken to be constant and sufficient for the reactions. Factors affecting the ignition of wood such as external heat flux, air velocity, moisture, orientation and species were considered respectively or comprehensively in the models.

A typical model of piloted ignition of wood was proposed by Moghtaderi et al. [28]. Ignition was assumed to occur once the surface temperature reached a certain value. Oxidation and chemical effects prior to ignition were not included. Enthalpy conservation gives the equation for temperature $T(x, t)$:

$$\rho c \frac{\partial T(x,t)}{\partial t} = \lambda \frac{\partial^2 T(x,t)}{\partial x^2} \qquad (15)$$

The initial and boundary conditions are:

$$T(x,0) = T(L,t) = 0 \qquad (16a)$$

$$-\lambda \frac{\partial T(0,t)}{\partial x} = \alpha q_e^{''} - [h_{eq} T(0,t)] \qquad (16b)$$

where h_{eq} is defined as an equivalent heat transfer coefficient:

$$h_{eq} = h_c + \varepsilon\sigma[T(0,t) + 2T_\infty][(T(0,t) + T_\infty)^2 + T_\infty^2] \qquad (17)$$

Through direct integration with respect to time, the equations become:

$$t_{ig}^{-1/2} = (q_e^{''} - H_L)/S \qquad (18a)$$

$$H_L = h_{eq} T_{ig} \qquad (18b)$$

$$S = (\frac{3}{4} k\rho c)^{1/2} f(H_L / q_e^{''})\theta_{ig} \qquad (18c)$$

where H_L represents the total heat loss from the surface at ignition and f is a function of the ratio of the total heat loss to the incident heat flux $q_e^{''}$.

The ignition temperature T_{ig} at heat fluxes may be obtained as:

$$T_{ig} = T_\infty + \left(\frac{f(1)}{f(H_L / q_e^{''})} \right) T_{cr} \qquad (19)$$

The ignition time t_{ig} predicted by this model for different species agreed with the experiments. Further, $t_{ig}^{-1/2}$ was found to be linearly related to

$q_e^{''}$. A critical heat flux can be deduced by plotting $t_{ig}^{-1/2}$ against $q_e^{''}$. It is found that the critical value varies from one wood species to another. Additionally, other key piloted ignition characteristics such as the ignition temperature and the thermal inertia can be described and analyzed from the above equations. However, the effects of air flow rate, moisture content and sample orientation were not taken account in the model.

Effect of air flow velocity was included in the model on ignition of wood by Bilbao et al. [26]. Ignition might be delayed due to the cooling of the solid surface by the air flow. The effects of water vaporization and the reactions prior to ignition were also included. The criterion for ignition was also taken as the critical ignition temperature. The energy partial differential equation is described as:

$$\frac{\partial[\rho_s c_s T_s]}{\partial t} + \frac{\partial \rho_s X}{\partial t}(-Q_v) = \lambda_s \frac{\partial^2 T_s}{\partial x^2} + (-H_s)(-r_s) \qquad (20)$$

The boundary conditions are:

$$t > 0, \ x = L, \ \ \frac{\partial T_s}{\partial x} = 0 \qquad (21a)$$

$$t > 0, \ x = 0, \ \ \lambda_s \frac{\partial T_s}{\partial x} = q_e^{''} - q_r^{''} - h_c(T_S - T_\infty) \qquad (21b)$$

where $q_r^{''}$ is the radiative heat loss.

The gas phase is calculated by using the air velocity over the sample and the correlations [42] for free and forced convection over a horizontal wood slab. The temperature at each point in the solid, the local conversion of solid and the time to ignition could be calculated by the model. In general, experimental and theoretical results on the ignition time for spontaneous ignition agreed fairly well. Better agreement was observed for piloted ignition when a relatively low heat flux and/or an air flow over the sample surface existed.

Subsequently, another flaming ignition model of wood was developed by Bilbao et al. [43]. Effect of external heat flux and the effect of water evaporation were included. However, convective flow of air and volatiles was not considered. The critical surface temperature was suggested as the criterion for piloted ignition, and a higher value was used for spontaneous ignition.

The energy balance is described for $T_s \neq T_v$ as:

$$\frac{\partial \rho_s c_s T_s}{\partial t} = \lambda_s \frac{\partial^2 T}{\partial x^2} + \left(-H_s\right)\left(-r_s\right) \qquad (22a)$$

For $T_s = T_v$, the solid temperature at each point is equal to the vaporization temperature until water is totally released:

$$\lambda_s \frac{\partial^2 T_s}{\partial x^2} = \frac{\partial [\rho_s X]}{\partial t}\left(-Q_v\right) \qquad (22b)$$

where T_v is the water evaporation temperature which is lower than that of solid decomposition.

The boundary conditions were the same as the earlier model [26]. The time to ignition for both piloted and spontaneous ignition at constant or varying heat fluxes were calculated and compared with experiments. Better agreement between the experimental and theoretical results was found for piloted ignition than for spontaneous ignition, especially at heat fluxes lower than 30 kWm^{-2}. The decreasing rate of heat flux would not only affect the time to ignition significantly, but would affect whether ignition occurred or not.

A detailed model for piloted ignition of wet wood was proposed by Moghtaderi et al. [44] to investigate the effect of water vaporization. The piloted ignition process was divided into a pre-drying phase and a drying phase. The physical configuration of the drying phase was classified as a dried zone, a wet zone, and an interface at the water vaporization temperature (T_v). Ignition was assumed to occur when the surface temperature reached the critical value T_{ig}. The heat conduction in the dried zone is governed by:

$$\frac{\partial T_d(x,t)}{\partial t} = a_d \frac{\partial^2 T_d(x,t)}{\partial x^2} \qquad (23)$$

The boundary condition is:

$$-\lambda_d \frac{\partial T_d(0,t)}{\partial x}$$
$$= q_{net}^{"} - q_e^{"} - h_c(T_d(0,t) - T_\infty) - \varepsilon\sigma(T_d^{~4}(0,t) - T_\infty^{~4}) \qquad (24)$$

The heat conduction in wet zone can be expressed by:

$$\frac{\partial T_w(x,t)}{\partial t} = a_w \frac{\partial^2 T_w(x,t)}{\partial x^2} \qquad (25)$$

The boundary condition is:

$$\frac{\partial T_w(\delta_d + \delta, t)}{\partial x} = 0 \qquad (26)$$

The Stefan boundary condition was used to describe the coupling of heat transfer between the dry and wet zones as below:

$$\lambda_d \frac{\partial T_d(\delta_d,t)}{\partial x} - \lambda_w \frac{\partial T_w(\delta_d,t)}{\partial x} = m_m^{"} Q_v \qquad (27)$$

The surface temperature, the time to ignition of material with different moisture content, water vapor mass flux and the total mass flux of the sample were predicted by the model together with Computational Fluid Dynamics (CFD). The total mass flux during the piloted ignition of wet wood appears to be a function of time only. The critical heat flux is independent of the moisture content for the same species of wood. Correlation studies on the theoretical and experimental data suggested that this differential model is reasonably accurate.

The effect of sample orientation was studied in the spontaneous ignition model of wood suggested by Kashiwagi [45]. Ignition was assumed to occur when light started to emit from flaming as observed by a photomultiplier. The governing equation is:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} \qquad (28)$$

- Before decomposition $(0 < t < t_0)$, the boundary condition is:

$$-\lambda \frac{\partial T}{\partial x} = \alpha q_e^{"} - \varepsilon\sigma(T^4 - T_\infty^{~4}) - h_c(T - T_\infty) \qquad (29a)$$

- After decomposition $(t > t_0)$, the boundary condition is:

$$-\lambda \frac{\partial T}{\partial x} = \alpha q_e^{"} - \varepsilon\sigma(T^4 - T_\infty^{~4}) - h_c(T - T_\infty) + (-H_s)(-r_s) \qquad (29b)$$

The expression for h_c was taken as an average coefficient over the characteristic length of a heated slab, driven by natural convection.

- For vertical sample:

$$h_c = 0.54(\lambda/D)(Gr\,\mathrm{Pr})^{1/4} \qquad (30a)$$

- For horizontal sample:

$$h_c = 0.555(\lambda/D)(Gr\mathrm{Pr})^{1/4} \qquad (30b)$$

where D is diameter of the irradiated area.

The surface temperature and the ignition temperature for both vertical and horizontal samples were predicted by this model. The ignition temperature and the critical heat flux for ignition of the horizontal sample are lower than those of the vertical sample. However, the predicted results were not validated by the experimental data.

Similar results were obtained by Spearpoint and Quintiere [12] in using an integral model for the piloted ignition of wood. Effects of species, orientation and heat flux were considered in the model. Ignition was assumed to occur when the surface temperature reached a critical value T_{ig}. Conservation of energy for a control volume gives:

$$\rho c \left[\frac{d}{dt} \int_{o}^{\delta} T(x)dx - T_0 \frac{d\delta}{dt} \right] = q^{''}(t) \qquad (31)$$

The boundary conditions are:

$$x=0, \quad -\lambda \frac{\partial T}{\partial x} = \alpha q_e^{''} - \varepsilon\sigma(T^4 - T_\infty^{\;4}) - h_c(T - T_\infty)$$
$$(32a)$$

$$x=\delta, \quad \lambda \frac{\partial T}{\partial x} = 0 \qquad (32b)$$

After algebraic manipulation, the following was derived:

$$t_{ig} \approx \frac{2}{3} k\rho c \left(\frac{T_{ig} - T_\infty}{q_e^{''}} \right)^2 \qquad (33)$$

For the time to ignition extended to infinitely long, the critical heat flux for ignition was determined:

$$q_{cr}^{''} = \sigma(T_{ig}^{\;4} - T_\infty^{\;4}) + h_c(T_{ig} - T_\infty) \qquad (34)$$

Analysis for convective heat loss in the model for piloted ignition by Delichatsios et al. [46] gave:

$$t_{ig} = \frac{\pi}{4} k\rho c \left(\frac{T_{ig} - T_0}{\overset{\bullet}{q}_e^{''}} \right)^2 \qquad (35)$$

The coefficient $\pi/4$ might give a more exact solution than that proposed by Spearpoint and Quintiere [12]. Additionally, T_{ig} and thermal inertia could be calculated through the value of $\overset{\bullet}{q}_{cr}^{''}$ and t_{ig} derived from the model by Spearpoint. Thus, the time to ignition, the critical heat flux of different species and the ignition temperature for piloted ignition for different sample orientations

were all predicted. The results agreed with the experiments, especially on the time to ignition for different species under different heat fluxes and grain orientations. These mathematical equations would give a more scientific procedure to study the characteristics such as t_{ig}, $\overset{\bullet}{q}_{cr}^{''}$ and T_{ig} of flaming ignition of wood.

Only the solid phase phenomena were considered in the above models. The criterion for ignition was taken as the critical surface temperature of solid in most of the models. In fact, the solid and gas phase were coupled at the exposed surface of the sample during ignition. Therefore, gas phase phenomena such as interface energy exchange between the solid and gas phase, and the diffusion of gases at the surface of the sample should be considered.

3.2.2 Subgroup 2: Both solid and gas phases

The flaming ignition process is governed by the coupling between the solid and gas phase events. The model for the flaming ignition of wood proposed by Tzeng et al. [47] included the effect of gas diffusion, but not the heat transfer between the gas phase and solid phase. The mass emission rate from the combustible solid was assumed to be a known function of time in this one-dimensional model. The conservation of energy is governed as:

$$\rho_s c \frac{\partial T}{\partial t} + \rho_g u \frac{\partial T}{\partial x} =$$
$$= \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) + (-H_F)A\rho_g^{\;2}Y_F Y_O \exp(-E/RT)$$
$$(37)$$

The conservation of species is described as:

$$\rho_g \frac{\partial Y_F}{\partial t} + \rho_g u \frac{\partial Y_F}{\partial x} = \frac{\partial}{\partial x}(\rho_g D \frac{\partial Y_F}{\partial x}) - A\rho_g^{\;2}Y_F Y_O e^{-E/RT}$$
$$(38a)$$

$$\rho_g \frac{\partial Y_O}{\partial t} + \rho_g u \frac{\partial Y_O}{\partial x} = \frac{\partial}{\partial x}(\rho_g D \frac{\partial Y_O}{\partial x}) - r_O A\rho_g^{\;2}Y_F Y_O e^{-E/RT}$$
$$(38b)$$

ρ, λ, c_p and D are assumed to be constant to simplify the equations.

The boundary conditions are:

$$x=0, \quad \frac{\partial Y_F}{\partial x} = M(Y_F - Y_{F,S}), \frac{\partial Y_O}{\partial x} = M(Y_O), T = T_S$$
$$(39a)$$

$$x=\delta, \quad Y_F = 0, Y_O = Y_{O,\infty}, T_g = T_\infty \qquad (39b)$$

where M is the mass transfer coefficient.

Time to ignition, surface temperature of the solid, the fuel mass flux related to ignition source location and the minimum fuel mass flow rate were predicted. As the surface temperature increased, both the minimum fuel flow rate for sustained piloted ignition and the minimum distance of the ignition source were observed to decrease. However, the predicted results had not yet been validated by experiments.

Then, another one-dimensional solid-gas phase model for flaming ignition was proposed by Atreya [48], considering both diffusion of gases and the energy conservation in the gas phase. Effect of water vaporization on the ignition process was not investigated. The solid phase energy and mass conservations are:

$$\rho_s \frac{\partial h_s}{\partial t} + \rho_m \frac{\partial h_m}{\partial t} + m_s^{"} \frac{\partial h_g}{\partial x} = \frac{\partial}{\partial x}(\lambda_s \frac{\partial T_s}{\partial x}) + \frac{\partial q_r^{"}}{\partial x}$$
$$+ (H_s - h_s + h_g)\frac{\partial \rho_s}{\partial t} + (H_m - h_m + h_g)\frac{\partial \rho_m}{\partial t}$$

$$(40)$$

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial \rho_m}{\partial t} = \frac{\partial m_s^{"}}{\partial x} \qquad (41)$$

The gas phase energy and species conservations are:

$$\rho_g \frac{\partial T}{\partial t} + \rho_g u \frac{\partial T}{\partial x} = \frac{\partial}{\partial x}(\frac{\lambda}{c}\frac{\partial T}{\partial x}) + \frac{1}{c}\frac{\partial q_r^{"}}{\partial x} + \frac{H_F}{c}m_F^{"}$$

$$(42a)$$

$$\rho_g \frac{\partial Y_F}{\partial t} + \rho_g u \frac{\partial Y_F}{\partial x} = \frac{\partial}{\partial x}(\rho_g D \frac{\partial Y_F}{\partial x}) - m_F^{"} \quad (42b)$$

$$\rho_g \frac{\partial Y_O}{\partial t} + \rho_g u \frac{\partial Y_O}{\partial x} = \frac{\partial}{\partial x}(\rho_g D \frac{\partial Y_O}{\partial x}) - r_O m_F^{"} \quad (42c)$$

$$m_F^{"} = A\rho_g^2 Y_F Y_O e^{-E/RT} \qquad (42d)$$

The boundary conditions for both solid and gas phase are:

$$x = 0, \quad \rho_g D \frac{\partial Y_F}{\partial x} = m_s^{"}(Y_F - Y_{F,S}) \qquad (43a)$$

$$\rho_g D \frac{\partial Y_O}{\partial x} = m_s^{"}(Y_O) \qquad (43b)$$

$$-\lambda_s \frac{\partial T_s}{\partial x} = \alpha q_r^{"} - h_c(T_S - T_\infty)$$
$$-\varepsilon\sigma(T_S^4 - T_\infty^4) - H_s m_s^{"} \qquad (43c)$$

$$x = \delta,$$
$$Y_F(\delta,t) = 0, Y_O(\delta,t) = Y_{O,\infty}, T(\delta,t) = T_\infty, q_r^{"} = q_e^{"}$$

$$(43d)$$

where $m_s^{"}$ is the mass loss rate or fuel mass flux from solid, given by ρu, $q_e^{"}$ is the specified external heat flux and $q_r^{"}$ is the radiant flux on solid.

Those equations were simplified based on the physical insight. In the energy balance equation of gas phase, the term $\frac{\partial q_r^{"}}{\partial x}$ could be neglected at very large heat fluxes. In the solid phase equations, the effect of moisture was ignored. Based on the above simplifications, the ignition temperature of solid and the fuel mass flux of wood required to initiate ignition were all predicted by the model. The predicted results are very useful for exploring better criteria for both piloted and spontaneous ignition of wood.

The flaming ignition models of wood including only the solid phase phenomenon are studied in more detail. Predictions of the characteristics of ignition agreed with the experimental data very well. But, the solid and gas phase phenomena were not systematically studied and reasonably coupled at the sample surface. Therefore, gas phase phenomena and their effects on flaming ignition should be further examined for improving the mathematical models of ignition.

4. CONCLUSIONS

Ignition of wood had been studied extensively, both experimentally and theoretically. A review was reported in above and the following can be concluded:

- Several key criteria of ignition of wood have been investigated, such as ignition temperature, mass loss rate, time to ignition and critical heat flux. The surface ignition temperature was described as 'a very elusive quantity and difficult to measure accurately' by Tran and White [16]. Very few methods were developed to deduce the necessary experimental data for exploring the concept of critical mass flux (critical mass loss rate).

- Some criteria might not be useful for numerical models of flaming ignition, as they are difficult to measure or complicated to apply. Quantities of experimental validations are necessary for determining the most applicable ignition criterion for correlation

studies on flaming ignition of wood.

- Quantitative study on smoldering ignition of cellulosic materials is inadequate in the literature, and there is not much experimental data available. An experimental database for smoldering ignition of cellulosic materials should be established for developing and validating mathematical models

- Most of the flaming ignition models of wood were only on the solid phase. Predictions by the models match the experimental data well. It is complicated to couple solid and gas phase phenomena at the sample surface during ignition. New theories on gas phases should be developed for examining the flaming ignition of wood, which would give a better understanding of flame spread and fire growth.

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NOMENCLATURE

A	pre-exponential constant
a	thermal diffusivity, m^2s^{-1}
c	specific heat, $kJ\cdot kg^{-1}K^{-1}$
D	mass diffusion coefficient, m^2s^{-1}
E	activation energy
Gr	Grashof number
H	heat of reaction, $kJ\cdot kg^{-1}$
h	enthalpy, $kJ\cdot kg^{-1}$
h_c	thermal convective coefficient between the solid surface and the gas phase, $Wm^{-2}\ K^{-1}$
L	thickness, m
M	mass transfer coefficient, 1/m
$m^{"}$	fuel mass flux or mass loss rate, $g\cdot cm^{-2}\ s^{-1}$
Pr	Prandtl number
Q	latent heat, $kJ\cdot kg^{-1}$
$q^{"}$	heat flux, kWm^{-2}
R	universal gas constant
r	reaction rate, $kgm^{-3}s^{-1}$
S	volumetric heat source, $kJ\cdot kg^{-1}$
T	temperature, K
t	time, s
u	velocity, ms^{-1}
X	moisture content
Y	gas mass fraction
α	surface absorption coefficient
β	volumetric expansion coefficient
ρ	density, kgm^{-3}
λ	thermal conductivity, $Wm^{-1}\ K^{-1}$
γ	mass convective coefficient, ms^{-1}
∇	gradient with x ($\frac{\partial}{\partial x}$)
ϕ	porosity
ε	surface emissivity
σ	Stefan-Boltzman constant ($5.669\times 10^{-8}\ Wm^{-2}\ K^{-4}$)
δ	thermal penetration depth, m

Subscripts

c	char
cr	critical
d	dried
e	external
F	fuel
g	gas
i	species
ig	ignition
m	moisture
min	minimum
O	oxygen
S	surface
s	solid
w	wet
0	initial stage
∞	ambient condition

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