A REVIEW ON IGNITION OF CELLULOSE MATERIALS UNDER EXTERNAL HEAT FLUX

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ABSTRACT

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

The 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. Models of flaming ignition are well-developed from those well-validated experimental data. However, most of the flaming ignition models of wood are only on the solid phase. New theory on gas phases should be developed for further studying flaming ignition, especially the spontaneous ignition of wood.

Quantitative study on modeling smoldering ignition of cellulosic materials is not yet well understood as experimental data are inadequate. This part is only briefly discussed.

1. INTRODUCTION

As cellulose materials are widely used in the construction industry such as for partitions and furnishings, better understandings of 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 heat, 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 external environment or inadequate oxygen is 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 (self-heating ignition), the more common mode of ignition, flaming ignition, is closely related to the fire behavior of the 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 or 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 by Bixel and Moore [1] in 1910, and piloted ignition by Prince in 1915. The thermal conduction equation was first applied by Bamford [2] for analyzing ignition. A mathematical method was developed by Lawson and Simms [3] in 1960s for predicting ignition, being the early data-correlation method. Since then, the studies can be classified as experimental studies; detailed mathematical modeling; and correlation studies.

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, critical heat flux and critical heat release rate.
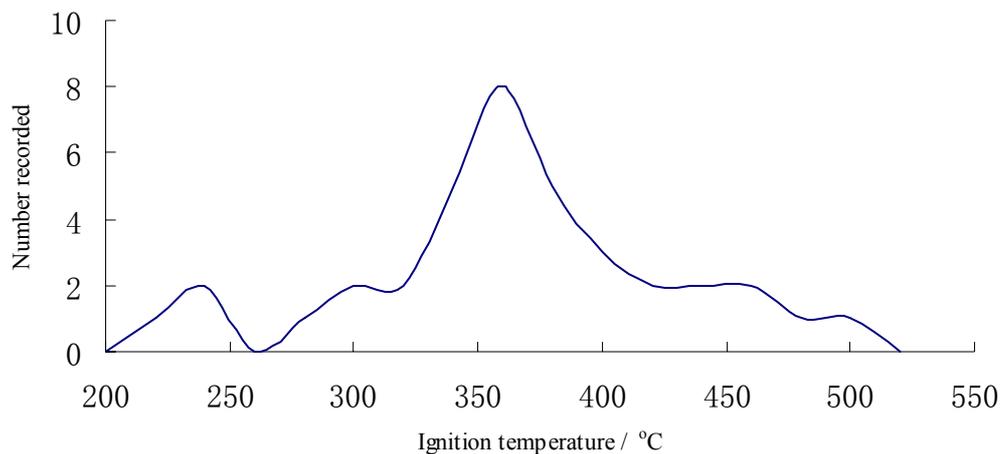
Surface Ignition Temperature (Critical Ignition Temperature)

The surface ignition temperature T_{ig}, an important characteristic of ignition of cellulosic materials, is one of the criteria used for describing ignition. 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, the 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 [4], such studies started from the 19th century to the present moment. A summary is reported in the literature and compiled as a number distribution for T_{ig} in Figs. 1 and 2. It is noted that there are two different definitions of 'critical ignition temperature':

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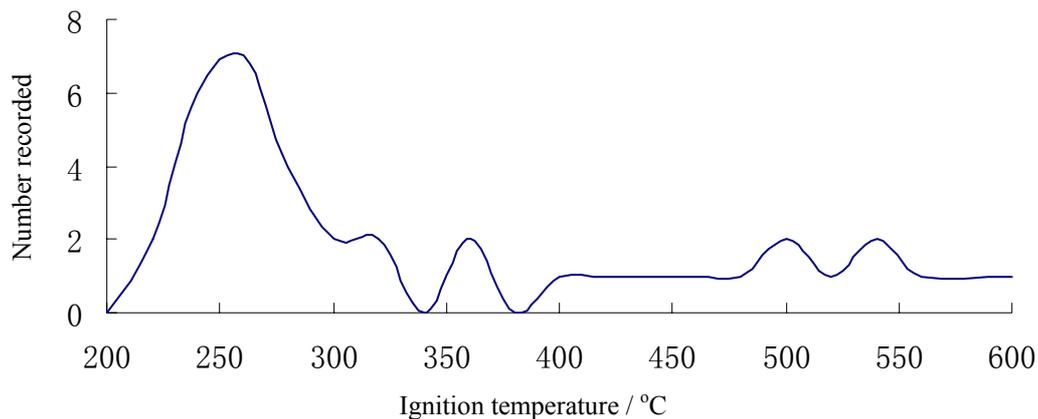- The minimum temperature of a furnace containing the specimen to ignite.
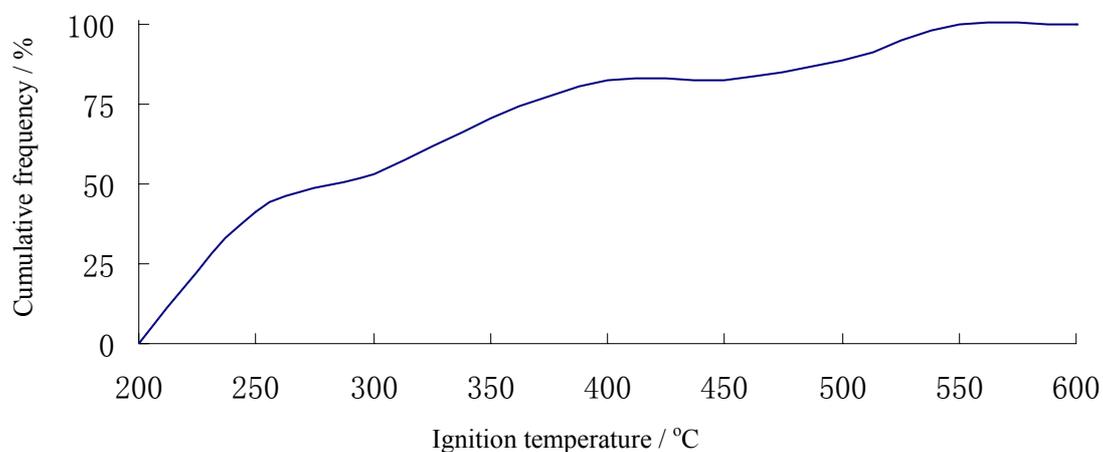

(a) Number distribution
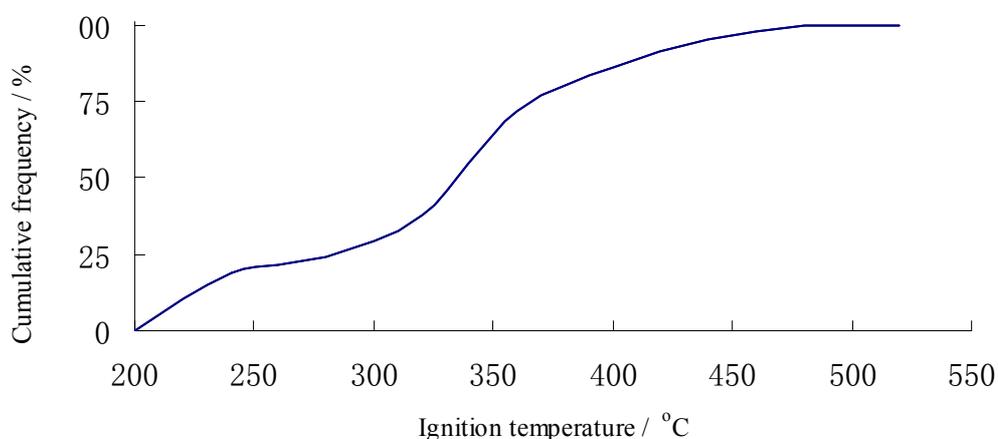
(b) Cumulative frequency

Fig. 1: Review on piloted ignition temperature of wood

(a) Number distribution

(b) Cumulative frequency

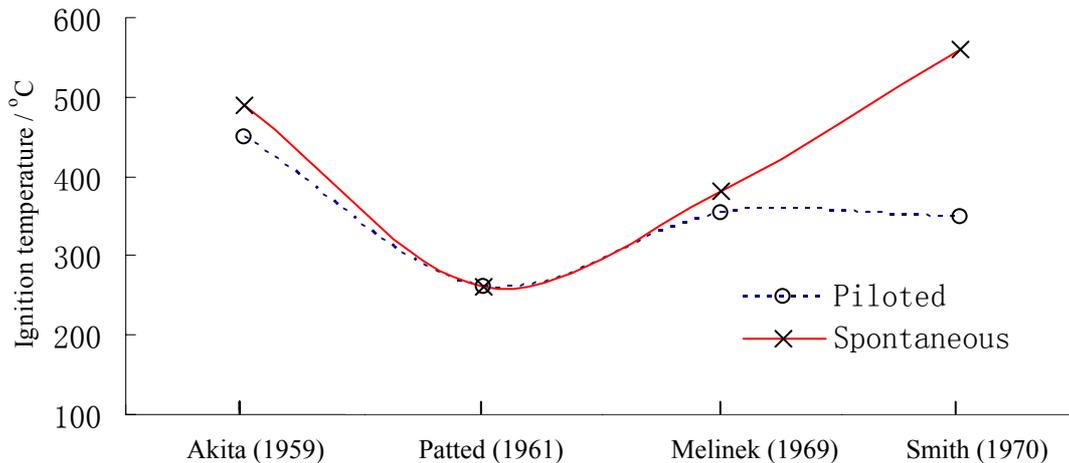**Fig. 2: Review on spontaneous ignition temperature of wood**

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:

- Definition of ignition temperature.
- Design of the test apparatus.
- Experimental operating conditions including piloted, incident heat flux, air flow and others.
- Conditions of sample such as moisture content, orientation.
- Species of wood (without considering density, specific heat or thermal conductivity).

In general, there are two types of apparatus developed for "ignition only" tests:

- Sample is placed in a furnace such as the one developed by Setchkin [5] in 1949.
- Burning the sample in open air under thermal radiation, such as in the cone calorimeter [6].

But the basic division depends on a preferred specimen size for each test. As in Fig. 3, the 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 the design of the apparatus would play a very important role in autoignition than for piloted ignition.

Fig. 3: Comparison between piloted and spontaneous ignition temperature of samples by different investigators

Ignition temperature is also affected by the experimental conditions such as air flow velocity and the incident radiant heat fluxes. The piloted ignition temperature was found by Atreya and Abu-Zaid [7] to increase as the velocity increased. For a heat flux of 35 kWm^{-2} and an air velocity increasing from 0.1 ms^{-1} to 1 ms^{-1}, the ignition temperature might be increased by 15K. Therefore, the critical surface temperature might be taken as 558K under such conditions. Spontaneous and piloted ignition temperature of several cellulosic materials, black rubber and polyurethane foam were measured by Smith and King [8] in exposing the samples to radiation heat fluxes 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. The results are similar to those reported by Atreya et al. [9]. In contrast to the works by Hopkins [10], the ignition temperatures for Redwood increased only when the heat flux was less than 21 kWm^{-2}. Similar results were reported by Spearpoint [11] in calculating the ignition temperature in regions of the same fluxes using the piloted ignition integral model.

Although the specimen orientation would affect the ignition temperature, there are not much experimental data to support that. The surface temperatures at piloted ignition of vertical and horizontal samples of red oak and mahogany were measured by Atreya et al. [9] 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 ^{o}C was found for mahogany under both vertical and horizontal orientations. The value for red oak was 365 ^{o}C. However, from

the experimental results of Fangrat et al. [12], 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. The 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 et al. [11]. 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 of 353°C as reported by Dietenberger [13] on changing samples with different moisture contents by a cone calorimeter. It was concluded by Jassens [14] that T_{ig} increased by 2°C when the moisture content of the sample increased by 1%. Such a 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 [15] 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

the critical mass flow of volatiles sufficient to support a nascent flame, is another proposed criterion for ignition. The concept was first suggested by Bamford et al. [2] 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. the 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 Drysdale et al. in 1980s, were focused on polymeric materials. Very little works were on cellulosic materials.

The critical mass loss rate required for piloted ignition for several electric cable specimens was reported by Tewaron et al. [16] 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 Drysdale and Thomson [17] for piloted ignition of plastics. It is difficult to measure such low values of mass loss rate accurately and the results might be varied 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 [18] for PMMA. Later, a value of 1.9 gm^{-2}s^{-1} was found by Drysdale and Thomson 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. The effects of some variables including air flow rate and oxygen concentration on the critical mass loss rate for PMMA tested in the horizontal orientation were studied by Rasbash et al. [19].

The mass loss rates of several wood samples at ignition were measured by Koohyar et al. [20]. 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}. The value is much higher than that deduced by Bamford et al. Another series of tests on wood was conducted by Melinek [21] 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 the 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 [22], 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:

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

The values of f were determined from the literature and based on the result, this criterion on critical mass flux deduced by Bamford et al. [2] 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. The 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:

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

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

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

That means that the ignition time can be determined directly from the thermal inertia ($\lambda\rho c$). A similar result was also found by Babrauskas [23]. The ignition temperatures for common combustible solids vary only over a limited range from 300 to 500 °C. The thermal inertia of wood might vary by a factor of 100. Therefore, the time to ignition of different materials might be determined from

their relative values of thermal inertia, not from the ignition temperatures. However, thermal inertia of the sample is difficult to measure accurately during ignition. Variations of thermal inertia of the sample during ignition should be 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 et al. [12] for horizontal orientation: the time to ignition t_{ig} in the gas phase measured by a cone calorimeter; and the time to ignition t_{is} in the solid phase 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 et al. [24] to affect the ignition time. Note that the thermal physical properties of the sample depend on the moisture content. Further, more heat is required to remove the moisture. Therefore, the time to ignition would be extended when the moisture content increases.

Ambient conditions play an important role in measuring the experimental time to ignition as reported by Bilbao et al. [25]. 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. It is concluded that ignition time depends on the air velocity and radiative heat flux.

Critical Heat Flux

The critical heat flux $q_{cr}^"$ is also suggested to be another criterion for ignition of wood. 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 would 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 the surface heat transfer.

In the experimental studies by Moghtaderi [26], the critical heat flux of wood was found to be varied for different species. However, the value is not affected by the moisture content. The reason is due to the long exposure time under the critical conditions. The samples would require much more heat for drying before ignition. Low-flux ignition and ignition of wood with different grains were studied by Spearpoint [11]. Almost all ignition results available for specimens with the heat source orientated along and across the grain directions were analyzed. For exposure 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}. 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 much works were reported on autoignition of wood under radiant heat fluxes. Early experimental studies by Simms [27] concluded that insufficient long testing time for spontaneous ignition might give a wider range of $q_{cr}^"$. The value for piloted ignition should not be higher than for autoignition.

Another method was proposed by Lawson and Simms [4] to obtain the values of critical heat flux for ignition of vertical samples of wood. For the times to ignition t_{ig} under different radiant heat fluxes $q_e^"$, plotting $1/t_{ig}^{1/2}$ versus $q_e^"$ and extrapolating t_{ig} to infinitely large would give the critical heat flux. The value for piloted ignition of wood was deduced to be 12 kWm^{-2}. By measuring different surfaces under a range of external heat fluxes and by using direct ignition data on $q_e^"$ and t_{ig}, a value higher than that by Lawson and Simms was deduced by Quintiere [28].

Resources are required for experimental studies. Several tests should be carried out to measure the critical heat fluxes, especially for spontaneous ignition. The exposure time required in determining whether ignition will 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 obtaining 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 [29]. 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 the heat release rate) of the fuel volatiles is the governing factor. Therefore, the heat release rate becomes a reasonable criterion. However, the measured data are scattered because the mass loss rate is difficult to measure.

The critical char depth was proposed by Sauer [30] to be a criterion for 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. A damage function of the form was proposed by Williams [31] for deriving a correlation for charring:

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

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

Spontaneous ignition was suggested by Simms [32] 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 [33] 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 were proposed by Rasbash [34] 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.

In general, there are several criteria for ignition. But these criteria might not be useful for numerical modeling or correlation studies. Experimental studies are necessary to give data for modeling the ignition process.

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 [35] 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 in slow rate play an important part under certain conditions such as under very low external heat flux. In contrast to smoldering ignition, 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

The smoldering ignition of cellulosic materials is due to the 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 loss 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.

Based on such assumptions, a mathematical model of thermal smoldering ignition of wood was proposed by Thomas [36]. The critical size 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:

$$\nabla^2 T = \frac{1}{a}\frac{dT}{dt} - \frac{q_i^{"}(T)}{\lambda} \qquad (6)$$

It is assumed that the heat generation $q_i^{"}(T)$ is due to a single reaction described by the Arrhenius law:

$$q_i^{"}(T) = -\Delta H_i A \rho^n \exp(-ER / T) \qquad (7)$$

The boundary conditions are:

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

$$x = 0, \quad \frac{dT}{dx} = 0 \qquad (8b)$$

Dimensionless quantities are:

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

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

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

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

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

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

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}. The 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 Henri et al. [37]. 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 from the volumetric heat source S as:

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

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

The values of ρ, c, λ and S varied with the 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 oxidated 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:

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

where S_i is the mass source for the ith species.

The D_O for the diffusivity of O_2 was obtained from the literature and the boundary conditions for mass transfer of oxygen O_2 $\overset{\bullet}{m}_{O_2}^{''}$ is described as:

$$\overset{\bullet}{m}_{O2}^{''}(x, y) = k_{gas}[Y_{O,\infty} - Y_{O,s}(x, y)] \tag{13a}$$

$$k_{gas} = \rho_{O,\infty} \gamma \tag{13b}$$

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

Mass transfer at the boundary was calculated by **TMPSUB** [37] to get the value of γ. TMPSUB2 is a software developed for solving ordinary differential equations including those describing the physical and chemical kinetics of the heating and smoldering process. The 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. [38]. This model is similar to the one suggested by Muramatsu et al. [39] with the virgin material taken as four pyrolysis reactants and moisture. The evaporation-pyrolysis zone was presented by four-step on pyrolysis of tobacco, char oxidation and water evaporation. The four produced volatiles and water vapor were produced upon heating the solid, leaving two 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:

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

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

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 depends on A/V.

The kinetic constants for pyrolysis are required in the model suggested by Muramatsu 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 the experiments on some variables such as the temperature distributions and the smoldering velocity. In fact, the 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 are inadequate. Experiments on smoldering are expensive and time-consuming. An experimental database for smoldering ignition of cellulosic materials should be developed for validating the mathematical models.

Modeling Flaming Ignition of Wood From External Radiant Heating

The initiation of flaming combustion may be piloted and 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 is very important in providing fire safety, because it occurs at relatively lower critical surface temperatures. It is related to the initiation of combustion and subsequent spread and growth of fire from the small ignited source. Spontaneous ignition phenomena of cellulosic materials are not so well understood. Most of the tests and hence the theories are mostly on the piloted ignition problem. 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 of the piloted ignition model, these models can be further classified into two subgroups. The first subgroup includes only the solid phase phenomena and most of the models [25,26,42] developed are under this group. The second subgroup considers both the solid and gas phase phenomena and these coupling effects [11].

3.2.1 Subgroup 1: Solid phase only

Under normal conditions, it is considered that gas phase physical kinetics such as diffusion and chemical kinetics are relatively insignificant in comparing with those in the solid phase as observed in most of the bench-scale tests on piloted ignition. This is because oxygen is sufficient for gas reactions. In this subgroup on flaming ignition model of wood, only solid phenomena were included. The volatiles produced from the solid surface would leave immediately. The oxygen concentration in gas phase was taken as constant to be sufficient for the reactions. Factors affecting the ignition of wood, such as external heat flux, air velocity, moisture, orientation and species, were considered in the models.

A typical model of piloted ignition of wood was proposed by Moghtaderi [26]. 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 $T(x, t)$:

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

The initial and boundary conditions are:

$$T(x,0) = T(L,t) = 0 \tag{16a}$$

$$-\lambda \frac{\partial T(0,t)}{\partial x} = \alpha q_e^{"} - [h_{eq}T(0,t)] \tag{16b}$$

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

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

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

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

$$H_L = h_{eq}T_{ig} \tag{18b}$$

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

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:

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

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 properties 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 considered in the model.

The effect of air flow velocity was included in the model on ignition of wood by Bilbao et al. [25]. Ignition might be delayed due to cooling of the solid surface. 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:

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

$$(20)$$

The boundary conditions are:

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

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

where q_r'' is the radiative heat loss.

The gas phase is calculated by using the air velocity over the sample and the correlations [40] for free and forced convection over a horizontal wood slab. The model provided the temperature at each point in the solid, the local conversion of solid and the time to ignition. In general, experimental and theoretical results on 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. [41]. The 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 value was suggested as the ignition criterion for piloted ignition. A higher value was used for spontaneous ignition, depending on the species of wood.

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

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

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

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

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

The boundary conditions were the same as in the earlier model [25]. The time to ignition for both piloted and spontaneous at constant or varying heat fluxes were calculated and compared with the experiments. Better agreement between experimental and theoretical results was found for piloted ignition than for spontaneous ignition, especially at heat fluxes lower than 30 kWm^{-2}. Under variable heat fluxes, the decreasing rate of heat flux would not affect the time to ignition significantly, but would affect whether ignition occurred or not.

The effect of water vaporization on piloted ignition of wood was only considered inside the model, but not well analyzed nor validated. A detailed model for piloted ignition of wet wood was proposed by Moghtaderi et al. [42] on investigating 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}. 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:

$$-\lambda_d \frac{\partial T_d(0,t)}{\partial x} = q_{net}'' - q_e'' - h_c(T_d(0,t) - T_\infty) - \varepsilon\sigma(T_d^4(0,t) - T_\infty^4)$$

$$(24)$$

Heat conduction in the wet zone can be expressed as:

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

The boundary condition is:

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

The Stefan 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, time to ignition for material of 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 of the sample. 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 [43]. Ignition is 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:

$$-\lambda \frac{\partial T}{\partial t} = \alpha q_e'' - \varepsilon\sigma(T^4 - T_\infty^4) - h_c(T - T_\infty) \quad (29a)$$

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

$$-\lambda \frac{\partial T}{\partial t} = \alpha q_e'' - \varepsilon\sigma(T^4 - T_\infty^4) - h_c(T - T_\infty) + (-H_s)(-r_s) \qquad (29b)$$

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:

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

- For horizontal sample:

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

where D is the 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 for horizontal samples are lower than those of the vertical samples. However, the predicted results were not validated by experimental data.

Similar results were obtained by Spearpoint and Quintiere [11] in using an integral model for the piloted ignition of wood. The effect of species, orientation and heat flux were considered. 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:

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

$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 on convective heat loss in the model for piloted ignition by Drysdale [44] gave:

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

The coefficient $\pi/4$ might give a more exact solution as proposed by Spearpoint. In the study by Delichatsios et al. [45], when the heat flux was greater than about three times the critical heat flux (i.e. $\dot{q}_e'' > 3\dot{q}_{cr}''$), the following was derived:

$$q_{cr}'' = \frac{(q_e'')_{intercept}}{0.76} \qquad (36)$$

Additionally, T_{ig} and thermal inertia could be calculated through the value of $\dot{q}_{cr}''$ 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 sample orientations. These mathematical equations would give a more scientific procedure to study the characteristics such as t_{ig}, $\dot{q}''_{cr}$ 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 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 the 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. [46] included the effect of gas diffusion, but not the heat transfer during ignition. The mass emission rate from the combustible solid was assumed to be a known function of time in this one-dimensional model. Piloted ignition was modeled as a thin slab of gas raised to the adiabatic temperature of the mixture. The conservation of energy is governed as:

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

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:

$x = 0$,

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

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

where M is the mass transfer coefficient.

The time to ignition, surface temperature of the solid, the fuel mass flux related to the 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.

In contrast, another one-dimensional solid-gas phase model for flaming ignition was proposed by Atreya [47]. Diffusion of gases and energy conservation in the gas phase were considered. The effect of water vaporization on the ignition process was not investigated. The solid phase energy and mass conservations are:

$$\rho_s \frac{\partial h_s}{\partial t} + \rho_m \frac{\partial h_m}{\partial t} + m_s'' \frac{\partial h_g}{\partial x} = \frac{\partial}{\partial x}(\lambda_s \frac{\partial T_s}{\partial x}) + \frac{\partial q_r''}{\partial x}$$
$$+ (H_s - h_s + h_g)\frac{\partial \rho_s}{\partial t} + (H_m - h_m + h_g)\frac{\partial \rho_m}{\partial t}$$
$$(40)$$

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial \rho_m}{\partial t} = \frac{\partial m_s''}{\partial t} \quad (41)$$

The gas phase energy and species conservations are:

$$\rho_g \frac{\partial T}{\partial t} + \rho_g u \frac{\partial T}{\partial x} = \frac{\partial}{\partial x}(\frac{\lambda}{c} \frac{\partial T}{\partial x}) + \frac{1}{c}\frac{\partial q_r''}{\partial x} + \frac{H_F}{c} m_F'' $$
$$(42a)$$

$$\rho_g \frac{\partial Y_F}{\partial t} + \rho_g u \frac{\partial Y_F}{\partial x} = \frac{\partial}{\partial x}(\rho_g D \frac{\partial Y_F}{\partial x}) - m_F'' \quad (42b)$$

$$\rho_g \frac{\partial Y_O}{\partial t} + \rho_g u \frac{\partial Y_O}{\partial x} = \frac{\partial}{\partial x}(\rho_g D \frac{\partial Y_O}{\partial x}) - r_O m_F'' \quad (42c)$$

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

The boundary conditions for both solid and gas phase are:

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

$$\rho_g D \frac{\partial Y_O}{\partial x} = m_s''(Y_O) \quad (43b)$$

$$-\lambda_s \frac{\partial T_s}{\partial x} = \alpha q_r^{"} - h_c(T_S - T_\infty)$$ (43c)

$$-\varepsilon\sigma(T_S^4 - T_\infty^4) - H_s m_s^{"}$$

$x = \delta$,
$$Y_F(\delta, t) = 0, Y_O(\delta, t) = Y_{O,\infty}, T(\delta, t) = T_\infty, q_r^{"} = q_e^{"}$$
(43d)

where $m_s^{"}$ is the mass loss rate or fuel mass flux from solid, given by ρu , $\overset{\bullet}{q_e^{"}}$ is the specified external heat flux and $\overset{\bullet}{q_r^{"}}$ 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 $\frac{\partial \overset{\bullet}{q_r^{"}}}{\partial x}$ could be neglected at very large heat fluxes. In the solid phase equations, the effect of moisture was ignored. The mass loss rate of wood, the ignition temperature of solid and the fuel mass flux of wood required to ignition were all predicted by the model through the above simplifications. Under heat fluxes in the range from 20 to 40 kWm^{-2}, both the minimum mass loss rate ($m_{min}^{"}$) and T_{ig} did not depend on the heat flux, $m_{min}^{"}$ increased and T_{ig} decreased when the heat flux increased. 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 phenomena were studied in more detail. The predictions of the characteristics of ignition agreed with the experimental data to some extent. However, the solid and gas phase phenomena had to be coupled at the sample surface during ignition. Therefore, gas phase phenomena and those effects on flaming ignition should be developed for improving the models.

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. These included the ignition temperature, mass loss rate, time to ignition, critical heat flux and others. The surface ignition temperature was described as

'a very elusive quantity and difficult to measure accurately' by Tran and White. Very few methods were developed to deduce the necessary experimental data for exploring the concept of critical mass flux (critical mass loss rate). Several tests are required to measure the critical heat fluxes, especially for spontaneous ignition.

- These criteria might not be useful for numerical modeling on correlation studies. Experimental validation is necessary to measure data for modeling ignition.

- Quantitative study on smoldering ignition of cellulosic materials was not adequate in the literature. Studying smoldering of samples require prohibitive resources. There are not much experimental data available. An experimental database for smoldering ignition of cellulosic materials should be established for developing and validating the mathematical models.

- Most of the flaming ignition models of wood are only on the solid phase. Predictions agreed with the experimental data to some extent. It is complicated to couple solid and gas phase phenomena at the sample surface during ignition. New theory on gas phases should be developed for studying spontaneous ignition.

- A practical ignition model will be developed for better understanding the flame spread and fire growth to give better protection in buildings.

ACKNOWLEDGMENT

NOMENCLATURE

A	pre-exponential constant
a	thermal diffusivity, m^{2}s^{-1}
c	specific heat, kJkg^{-1}K^{-1}
D	mass diffusion coefficient, m^{2}s^{-1}
E	activation energy
Gr	Grashof number
H	heat of reaction, kJkg^{-1}
h	enthalpy, kJkg^{-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, m^{-1}

m'' fuel mass flux or mass loss rate, $gcm^{-2}s^{-1}$

Pr Prandtl number

Q latent heat, $kJkg^{-1}$

q'' heat flux, kWm^{-2}

R universal gas constant

r reaction rate, $kgm^{-3}s^{-1}$

S volumetric heat source, $kJkg^{-1}$

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

λ thermal conductivity, $Wm^{-1}K^{-1}$

ρ density, kgm^{-3}

∇ gradient with x $\left(\dfrac{\partial}{\partial x}\right)$

γ mass convective coefficient, ms^{-1}

ϕ porosity

ε surface emissivity

σ Stefan-Boltzman constant, 5.669×10^{-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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