The Pyrolysis and Heat Release Rate of Wood Exposed to Weak External Heat Flux for Long Times

Chen Xiaojun*, Yang Lizhong, Ji Jingwei and Fan Weicheng

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230026, Anhui Province

Abstract

Pyrolysis and heat release rate of wood exposed to a weak external heat flux for long times is experimentally and theoretically studied in this paper. Experimental measurements have tested the effect of an external heat flux on the pyrolysis and heat release rate of wood using a cone calorimeter particularly with a small heat flux. Differences in the pyrolysis and heat release rate of wood under strong and weak heat fluxes are discussed. A mathematical model is developed to predict the pyrolysis of wood and time to ignition, also the model provides the temperature at each point of the solid before ignition, which is also used to explain the mechanism of the pyrolysis of wood exposed to weak external fluxes for long times.

1. Introduction

Despite the fact that "the plastics age" is now about a half-century old, lingo-cellulosic materials such as woods are still a very dominant form of combustibles. The pyrolysis and combustion of charring materials, such as wood, is a complex interplay of chemistry, heat, and mass transfer. The rate of pyrolysis of a solid material (especially a charring material) is a major factor affecting the spread of a fire, because it determines the rate of heat release by the fire. Because of the importance and complexity of the pyrolysis of charring materials, there is a substantial volume of work on the ignition, pyrolysis, burning, and charring of wood and cellulosic materials, both experimentally and theoretically [1–8].

The average heat release rate (AHRR) and the peak heat release rate (PHRR) are two important parameters for the flammability evaluation of wood, fire performance design and fire hazard evaluation for a specific building. Although many experiments concerning heat release of wood have been reported [9–10], there is less research concerning the relationship between the average heat release rate and the external heat flux levels. Hao C. Tran determined the burning behavior of wood with a modified OSU apparatus at a range of heat fluxes from 15 to 55 kW/m^2 and

Corresponding Author- Tel.: +86-551-3601661;
Fax: +86-551-3601669
E-mail address: xjchen@ustc.edu.cn

presented a linear relationship between the AHRR and the external heat flux levels in 1992[11]. Based on his further work, he also presented a series of linear formulas to forecast the AHRR of wood in Babrauskas et al.'s monograph ''Heat Release in Fires'' [12]. These formulas made it easier to estimate the heat release rate of wood in a certain fire environment and the fire loads of a building. It is also a simple and practical method for fire hazard evaluation and fire performance design.

2. Characteristic of heat release rate of wood in cone calorimeter

In this work, four kinds of wood (oak, kempas, cherry, and beech) were tested with a cone calorimeter (Cone 2A) both under a weaker heat flux (20 kW/m2) and stronger heat fluxes (30, 40, 50 kW/m2). These wood samples were conditioned in a room at 293K and 65% relative humidity. The moisture content of these samples is about 0.12 kg/kg. Density of oak, rosewood, cherry wood and beech is 650, 850, 625 and 700 kg/m3, respectively. The wood samples were made into wood blocks with a size of 10 cm wide, 10 cm long and 1.6 cm thick. All samples were tested three times at per heat flux level in the horizontal orientation and the average value was adopted in this paper. Samples were wrapped in a single layer of aluminum foil, placed into the sample holder with a retainer frame and backed by noncombustible ceramic fiber insulation blanket. According to ISO 5660, these measurements ensure a standardized heat flow boundary condition for the test samples. The results in Fig.1 show that the relationship between the average rate of heat release (from ignition to extinguish) and the external heat flux is more of a parabolic than a simple linear relationship. Actually, Tran's linear formula [11] is approximately true at higher heat fluxes. From Fig. 1, for the woods tested, the minimum critical heat flux is 30 kW/m^2, after which there is a clear linear relationship between the average rate of heat release and the heat fluxes. Of all of these heat fluxes, the maximum rate of heat release is 20 kW/m^2. Table 1 shows that all the woods tested needed more than 20 minutes to catch fire at 20 kW/m^2, 4 to 30 times longer than that under other heat fluxes.

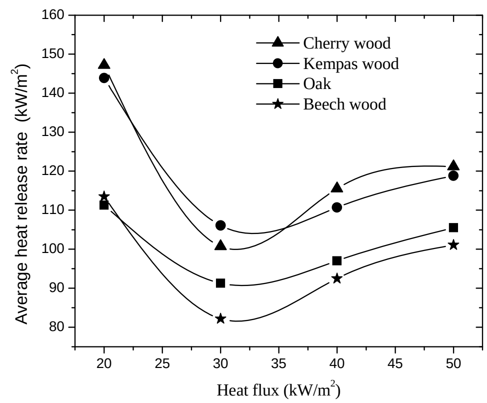

Fig.1. Average Heat Release Rate of wood and Heat Flux.

Table 1. Ignition time and heat flux

Heat flux (kW/m^2)	Ignition time (s)			
	Oak	Kempas	Cherry	Beech
20	1348.55	1699.62	1611.51	1489.92
30	214.30	443.39	193.97	159.16
40	111.09	133.77	83.31	79.04
50	61.42	79.35	49.79	49.02

3. Brief description of the mathematical model

In early works[5,6] we presented a modified model of pyrolysis for charring materials under an external heat flux. The computational fluid dynamics (CFD) model mainly includes one pyrolysis rate equation and two conservation equations.

The pyrolysis rate equation is:

$$\frac{d\rho_s}{dt} = -A\left(\frac{\rho_s - \rho_c}{\rho_w - \rho_c}\rho_w\right)^n \exp\left(\frac{-\mathrm{E_a}}{\mathrm{RT}}\right)$$

the mass conservation equation is:

$$\frac{\partial M_g}{\partial x} = \frac{\partial \rho_s}{\partial t}$$

and the energy conservation equation is:

$$\rho_s C_{ps}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_s \frac{\partial T}{\partial x}\right) + M_g C_{pg}\frac{\partial T}{\partial x} + \frac{\partial \rho}{\partial t}\left[Q + h_g + \frac{h_c \rho_c}{\rho_w - \rho_c} - \frac{h_a \rho_w}{\rho_w - \rho_c}\right]$$

the boundary condition is :

$$-k_s \frac{\partial T}{\partial x}\Big|_{x=0} = q'' - h(T_{sur} - T_0) - \varepsilon\sigma(T_{sur}^4 - T_0^4)$$

and the initial condition is

$$T = T_0\,, \rho = \rho_0\,, M_g = 0 \quad (t = 0)$$

With the above equations the parameter $\rho_s(x,t)$, $M_g(x,t)$ and $T_s(x,t)$ can be predicted. The solution of the model provides the temperature at each point of the solid and the local solid conversion.

4. Discussions

From Fig.1 and table 1 we can see that a clear linear relationship between the average rate of heat release and the high heat fluxes(>30kW/m^2). But The AHRR is highest at 20 kW/m^2.In order to explain the interesting phenomena, we should know the chemical composition of wood and the burning process in the cone calorimeter, then investigate how does the heat flux affect the heat release of wood by calculating the temperature field of wood at ignition time.

Following Formula is the most simple heat release rate model of wood:

$$\dot{Q}(t) = \dot{m}'' \cdot \chi_A \cdot H_c$$

where, H_c is the combustion heat of volatiles and χ_A is the combustion efficiency (<1.0).

The chemical composition of wood determines H_c and the heat transfer process determines the mass loss rate of wood.

According to the Arrhenius equation described reaction rate:

$$w_s = -\frac{\partial \rho_s}{\partial t} = A\rho_a^n \exp\left(\frac{-E_a}{RT}\right)$$

where n is the reaction index, E_a is the reaction active energy and A is the pre-exponential factor.

The time for mass decrease from an initial mass, m_0, to some other mass, m, can be calculated by integration of Arrhenius kinetic expression for a first reaction rate:

$$t = -\frac{\ln\left(\frac{m - m_f}{m_0 - m_f}\right)}{A \times \exp\left(\frac{-E_a}{RT}\right)}$$

Where t is time, m_f is final mass, m_0 is initial mass.

Table 2．Effect of different kinetics and temperature on reaction time

	250℃	300℃	350℃
$E_{a1} = 145 kJ/mole$ $A_1 = 7.4\times10^9/s$	1.9289×10^{4}s	1051s	91s
$E_{a2} = 225 kJ/mole$ $A_2 = 4.8\times10^{16}/s$	2.9079×10^{5}s	3181s	72s

Table 2 shows the effect of different kinetics and temperature on reaction time. Here the ultimate char yield m_f =20%. In order for material to lose 70% of its original mass at a constant temperature of 250℃, it would take about several days.

This means that the pyrolysis kinetics is the controlling mechanism at this condition. When temperature is 350℃ , it only takes minutes. This means at this temperature the transport phenomena is the controlling mechanism. Fig.3 gives the effect of different kinetics on the wood pyrolysis process. From fig. 3 we can see that at low heat flux (20 kW/m^2), the kinetics has significant effect on wood pyrolysis process. While at higher heat flux (≥ 30kW/m^2), the effect of kinetics is neglectable.

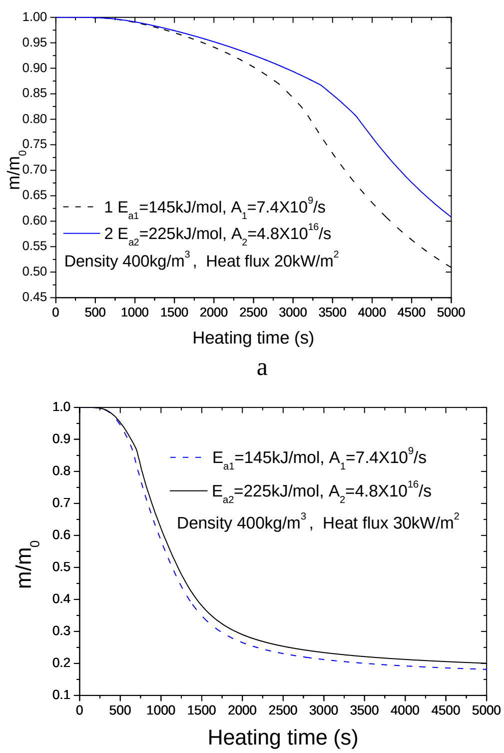

Fig. 3. Calculated effect of different kinetics on wood pyrolysis under different heat flux

Now we inspect the different distribution of internal temperature in the wood during the heating-up period. Fig. 4 gives the calculated inner temperatures of wood 200 s after heating and also the experimental results given by Suuberg et al. [13]. From Fig. 4, for woods of the same density, the stronger the external heat flux, the higher are the temperatures of the surface, the inside of the wood, and also the temperature gradient. This is due to the

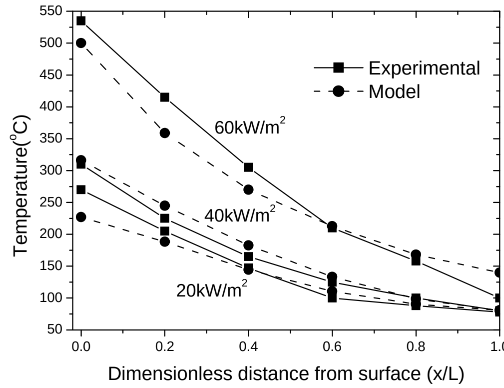

Fig.4. Comparison of predicted and experimental temperature profiles (458kg/m^3, *t*=200s)

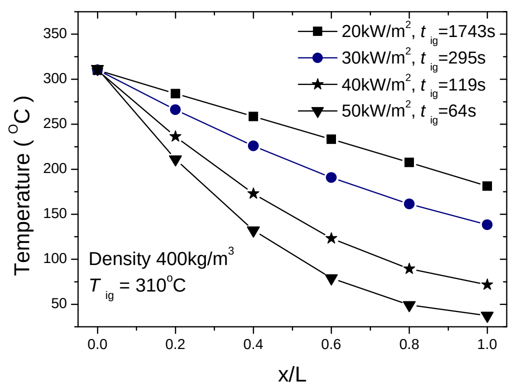

Fig. 5 The distribution of the inner temperature of wood

accumulation of heat absorbed by the surface.

Fig. 5 describes the calculated inner temperature distributions of wood at the occurrence of ignition. As can be seen from Fig. 5, when the external heat flux is 20 kW/m^2, the time needed for ignition is very long (1743 s); thus the temperature is relatively high and the inner temperature gradient is small, because of a long heating time. In fact, the lowest temperature reaches almost 180°C. On the other hand, when the external heat flux is 50 kW/m^2, the wood is ignited after a very short time (64 s). In this case, the surface temperature rises more quickly and the inner temperature gradient is very high. From Fig. 5, the lowest temperature is 30°C and almost equals the ambient temperature. However, the temperature is much lower than that at 20 kW/m^2.

Fig 6 gives the average inner temperature of a wood occurrence of ignition under different heat flux . From fig 6 we can see that the lower heat flux the higher average inner temperature is.

Based on this analysis, it can be said that the average inner temperature of the wood decreases rapidly when the external heat flux is increased. It takes long time for wood to ignition when heat flux is low (20kW/m^2). And the inner temperature is relative high. This result in rapidly pyrolysis rate and heat release rate when wood is ignited. In addition, the ignition temperature has a great effect on the ignition time of a wood.

5. Conclusion

Transport limitations play a significant role in overall pyrolysis and combustion properties of large size wood material. The mainly important factor that influences the mass loss rate and time to ignition of wood is external heat flux and initial sample density especially external heat flux. The higher heat flux results in higher temperature and deeper temperature gradient, the pyrolysis wave is much thinner. The lower density wood is a better heat insulator which results in earlier onset of pyrolysis and the surface temperature increases more quickly.

The average heat release of wood is quite different at different heat flux levels. The interior part of wood had higher temperatures, less moisture and a higher decomposition rate at a lower heat flux level when the sample was ignited.These factors lead to a greater AHRR of wood.

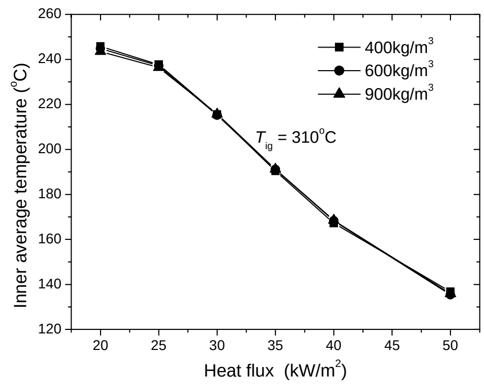

Fig. 6. The average inner temperature of wood

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