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Pyrolysis and spontaneous ignition of wood under time-dependent heat flux

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ABSTRACT

This work investigates experimentally and theoretically the effect of time-dependent incident heat flux (HF), which is more reasonable in fire-like environment, on thermal degradation process of wet pine wood. A feedback method was utilized to generate a time-dependent heat flux by controlling the output power of radiative heater. Both quadratic and linear heat fluxes were studied in this study. Comparison between measured heat fluxes and designed values indicates that the method provides high accuracy. Measurements of temperature distribution at different depths of material, ignition time and mass loss rate were implemented in the tests to examine the effects of time-dependent heat fluxes. Additionally, analytical model and numerical model were developed to predict the pyrolysis behaviors, and good agreement exists between the experimental and simulational results. Results showed that the heat penetration layer is restricted to a thinner depth for HF with higher increasing rate. A linear relationship was found between ignition time and HF parameters, which is also validated by experimental data and reexamined by constant heat flux circumstance. Mass loss rate was affected significantly by the changed heat flux compared with constant scenario. Furthermore, critical mass flux, which keeps almost unchanged, can be employed as ignition criterion due to the fact that the ignition temperature increases with increasing heat flux, which also certifies the conclusions of other researchers.

1. Introduction

Combustion of solid fuel has been an important subject in the field of fire safety engineering [1]. When heated, the surface and inner temperature of fuel rises, leading to pyrolyzing, release of combustible gas and finally combustion while the critical conditions for ignition are met. Researches on characteristics of early stage of fire help to prevent the fire disaster and reduce the corresponding danger. One of the most interesting materials to be examined is wood which plays an important role in building fires and wildfire [2]. Various experiments and models [3–9] have been conducted so far to study the pyrolysis and burning behavior of wood considering different factors, such as external energy source, materials and environmental conditions, etc. In this paper, we focused on the effect of incident heat flux (HF) that is very important for the process of energy transfer. Numerous studies have been done against this problem under the condition of standard time-temperature curve prescribed by ASTME 119 [10] or ISO 834 [11] for purpose of interchangeable data. However, the HF used in the literature was often set to be constant while it varies with the growth of a fire in a practical fire environment. Therefore, it will be more rational to study the pyrolysis and ignition of wood under variable HFs. Some researchers did the experiments of different materials under simple variable HFs, trying to get more practical results. Bilbao [12] carried out an experimental study on the fire behavior of wood exposed to decreasing HFs that came from the thermal radiation of a flame produced in an accidental release of materials. Results showed that the decreasing rate of HF had little influence on ignition time. As heat-release rate is generally time-dependent in fire, Yang [13] did the experiments under linearly-dependent HFs, demonstrating an agreement of power function between the ignition time and the increasing rate of the HFs. Ji [14] gave the ignition criteria of wood under linearly increasing HFs according to experiment and simulation, showing that wood ignites when the surface temperature reaches 500 °C and the increasing rate of HF is larger than 0.06 kW/(m^2·s). In these work, the HF can only be linearly-increasing due to the simple controlling method. More real fire environments still need to be studied, but logical design of HFs is not found in previous literature, so we need to develop a routine to get more complex HF, which will certainly be helpful to get further understanding of the influence of HF on the pyrolysis behavior of wood.

In this paper, we extend the work in [15–19] by designing two kinds of time-dependent HFs, namely linearly and quadratically-increasing HF that are more reasonable in a practical fire environment and more

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Nomenclature

A	Pre-exponential factor (s^{-1})
a	Group a
b	Group b
C	Specific heat ($J\,kg^{-1}\,K^{-1}$)
E	Activation energy ($kJ\,mol^{-1}$)
H	Enthalpy per unit mass ($kJ\,m^{-3}$)
HF	Heat flux ($W\,m^{-2}$)
h_{conv}	Convection coefficient ($W\,K\,m^{-2}$)
k	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_D	Darcy's coefficient ($m^3\,s\,kg^{-1}$)
L	Thickness of sample (mm)
m	Mass ($kg\,m^{-2}$)
$\dot{m}''$	Mass flux ($kg\,m^{-2}\,s^{-1}$)
M	Molar mass of gas ($g\,mol^{-1}$)
p	Pressure (Pa)
P	Power (kW)
$\dot{q}''$	Heat flux ($kW\,m^{-2}$)
t	Time (s)
Q	Reaction heat ($J\,kg^{-1}$)
R	Universal gas constant ($J\,mol^{-1}\,K^{-1}$)
T	Temperature (K)
x	Spatial variable (mm)
Y	Moisture content (%)

Greek

α	Thermal diffusivity
β	Coefficient in heat flux
ε	Emissivity
ζ	Porosity
λ	Coefficient in heat flux
ρ	Density ($kg\,m^{-3}$)
σ	Stefan-Boltzman constant
θ	Relative temperature
χ	Coefficient in adjusting the heat flux

Subscripts

0	Initial condition
∞	Ambient environment
a	Active material
cri	Critical
dry	Dry wood
g	Gas
ig	Ignition
in	Incident
l	Water
net	Net energy
$mois$	Moisture
s	Solid
v	Pyrolyzed volatile
w	Wood

robust than that in Ref. [15] with improved controlling algorithm. Linearly-increasing HFs are designed for the fundamental research, and quadratically-increasing HFs are designed according to Heskestad [20], where it is found that heat release rate increases quadratically in the early stage of fire. Under the designed HFs, wet white pine that is very common in our surroundings is chosen as the sample to conduct the experiments. Temperature distribution, ignition time and mass loss rate are studied. Also, theoretical and numerical model, considering the time-dependent heat flux, were developed to predict the ignition behaviors. The aim of this paper is to systematically study the basic effects of time-dependent HFs on the pyrolysis of wet white pine.

2. Materials and methods

2.1. Materials

50 × 50 mm square white pine wood samples with measured moisture of 10.3% were employed in the experiments, and the thickness is 20 mm. The samples were first wrapped by a double-layer fiberglass fabric and aluminum foil on sides and bottom surface to guarantee the insulated boundary condition, and then were mounted in a 100 × 100 × 50 mm refractory holder before tests. A volume of 53 × 53 × 23 mm was designed on the holder to fix the specimen. Thus, one dimensional scenario was achieved. The top surface of the samples and holder are in exactly the same position below heater during tests, namely 10 cm. Detailed information about thermodynamics of the wet pine wood is listed in Table 1.

2.2. Calibration of time-dependent incident HF

The experimental apparatus utilized in pyrolysis and ignition tests are illustrated in Fig. 1. Six silicon carbide bars were employed as the radiation source to generate the HF. To validate the uniformity of the HF of heater on top surface of samples during tests, a Schmidt-Boelter HF gauge was used in the experiments to obtain the measured HF in 5 locations on the horizontal position equivalent to top surface of sample. The HF gauge, with measurement range of 0–100 $kW\,m^{-2}$, was calibrated before the experiment by the first metrology and measurement institute of China Aerospace Science and Technology Corporation. Constant HF was used in this validation process for simplification, and same conclusions can be derived for time-dependent HF. Four locations were selected at the corner of the holder and the left one is in the center. The uncertainty of the measured HF was found to be lower than 10%, which indicates that the uniformity of HF is acceptable for the tests. Also for the center one, additional measurement was conducted 5 mm, maximum value of the regression depth during tests, below the other tests to examine the influences of regression of wood. No more than 3% of the HF decay was found, and thus the effect can be neglected.

For time-dependent HF, the output power of heater can be controlled to increase continuously from 0 to 55 kW by computer with a heat-flux module. The real-time value of the HF gauge is recorded by computer through the heat-flux interface to construct the feedback loop for controllable HF.

In Ref. [15], the HF during the heating process when constant output power was applied was regarded to be linearly time-increasing. The simple controlling method fails when more complex HF is needed. A feedback method is adopted here to generate more flexible HF. A series of experiments under different constant output power were

Table 1
Thermodynamics parameters of white pine wood used.

Parameter	Value	Unit	Ref.	Parameter	Value	Unit	Ref.
$\rho_{w,dry}$	450	$kg\,m^{-3}$	[21]	w_w	89.7	%	*
$C_{p,w,dry}$	1950	$Jkg^{-1}\,K^{-1}$	[22]	w_{mois}	10.3	%	*
$C_{p,mois}$	4200	$Jkg^{-1}\,K^{-1}$	[22]	T_0	300	K	*
h_{conv}	10	$Wm^{-2}\,K^{-1}$	[22]				