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Analytical prediction of pyrolysis and ignition time of translucent fuel considering both time-dependent heat flux and in-depth absorption

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ABSTRACT

This contribution reports an approximate analytical model to predict transient mass flux and ignition time of translucent fuel, black poly(methyl methacrylate) (PMMA), subjected to a time-dependent incident heat flux, at^b, where t is time and a and b are constants. The model can be easily extended to other non-charring translucent solids. The model takes into account in-depth absorption of thermal radiation in the condensed phase, which is typically ignored in the analytical formulations. Both critical temperature and critical mass flux were employed as the ignition criteria to examine their effects on the predictions. The model was validated using exact numerical solutions and experimental data, and compared with earlier analytical models based on the assumption of surface absorption. Linear and quadratic heat fluxes were considered for validation and discussion. The results show that surface absorption accelerates the pyrolysis process and leads to higher mass flux and shorter ignition time with respect to the in-depth absorption case. The discrepancy between the predicted transient mass fluxes of these two absorption modes increases with increasing a. The ignition heat flux increases with increasing a and decreases with increasing b for both surface and in-depth absorption cases. However, the critical energy is independent of heat flux in in-depth absorption scenario. Furthermore, parametric studies of in-depth absorption coefficient and critical mass flux were conducted to investigate their effects on the quality of the model predictions. Also, the equivalent ignition temperature was calculated and compared with the experimental values. It is expected that the developed model will find its use in performance-based design applications.

1. Introduction

Thermal degradation and ignition of fuel subjected to an external incident heat flux play important roles in fire occurrence and the subsequent propagation. The majority of the previous studies, including experimental, numerical and analytical ones, focused on constant heat flux and surface absorption by assuming that the condensed phase is opaque. It was hypothesized that all the net delivered energy is absorbed by the surface and ignition takes place only when a critical surface temperature is achieved, namely the classic ablation theory [1]. However, translucent solids are used extensively in building industry, and for these materials in-depth absorption must be taken into account to correctly predict the ignition process [2–10]. Furthermore, a time-dependent feedback heat flux from flame is a more frequent scenario in reality due to the growth and spread of fire [11]. Consequently, it is essential to develop the ignition theory to take into account the time-dependent nature of the incident heat flux.

Four ignition criteria can be found in the literature as reported by Vermesi [10]: critical temperature, critical mass flux, critical energy and time-energy squared. The first two were commonly used in analytical and numerical models, respectively. When employing surface absorption and critical temperature in classical ignition theory for thermally thick solids under constant heat flux, the inverse square root of ignition time is linearly proportional to the incident heat flux [1]. In most analytical studies, critical temperature was used as the ignition criterion and the pyrolysis in the condensed phase was ignored.

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Nomenclature

a, b	coefficients in heat flux expression
A, B	coefficients in Eq. (13)
C	constant
C_P	specific heat capacity ($Jg^{-1}\ K^{-1}$)
e	Euler number
f	function
h	heat loss coefficient ($Js^{-1}m^{-2}K^{-1}$)
k	thermal conductivity ($Js^{-1}m^{-1}K^{-1}$)
L	Laplacian operator
$\dot{m}''$	mass flux ($gm^{-2}s^{-1}$)
p	variable in Laplace transformation
$\dot{q}''$	incident heat flux ($Js^{-1}m^{-2}$)
Q	critical energy (Jm^{-2})
t	time (s)
T	temperature (K)
T_a	activation temperature (K)
x	spatial coordinate (m)
Z	pre-exponential factor (s^{-1})

Greek symbols

α	thermal diffusivity (m^2s^{-1})
δ	heat penetration depth (m)
ε	emissivity
θ	relative temperature (K)
Θ	Laplace transform function
κ	in-depth absorption coefficient (m^{-1})
ρ	density (gm^{-3})
τ	integral variable
σ	Stefan-Boltzmann constant ($Js^{-1}m^{-2}K^{-4}$)

Subscripts

0	ambient condition
c	convection
cri	critical
ig	ignition
in	in-depth absorption
$mass$	critical mass flux
r	reference
R	reradiation
$surf$	surface absorption
$temp$	critical temperature

Lautenberger [12] introduced the thermal degradation into an analytical model under constant heat flux by invoking an approximation strategy in temperature distribution and the Arrhenius pyrolysis rate. Critical mass flux was used in that model instead of critical temperature. For translucent solids, in-depth absorption exerts its influence on ignition time significantly, especially at high radiant heat flux. And the linearity between inverse square root of ignition time and heat flux does not exist anymore [2–8]. Jiang [4] found that some in-depth absorption occurs even in the presence of the carbon black on the surface of PMMA in his experiments and suggested conducting further studies to provide analysis for combination of surface and in-depth absorption. Later, Linteris [9] and Bal [6] found that up to 60–65% of the radiation is transmitted through the carbon coating layer and is absorbed in-depth. Delichatsios [2] proposed an asymptotic solution to predict the ignition time of a translucent combustible considering both surface and in-depth absorption. Some other researchers used detailed numerical models, such as FDS [13], Gpyro [14], ThermaKin [15] and other models [3,5,6] to investigate this problem and found that in-depth absorption coefficient (or extinction coefficient) may affect the ignition time significantly. All these works addressing in-depth absorption of translucent solids are conducted under constant heat flux.

While for time-dependent incident heat flux, Didomizio [16] carried out an experimental study on ignition of wood exposed to fourth-order time-dependent heat flux and simulated the temperature distribution and ignition time by a numerical heat transfer model. Leventon [17] simulated upward flame spread over PMMA by combining an empirical variable feedback heat flux from flame to solid material [18] using a numerical pyrolysis solver ThermaKin [15]. Vermesi [10,19] experimentally and numerically studied the pyrolysis and ignition of PMMA and wood under transient irradiation by the Fire Propagation Apparatus (FPA), cone calorimeter and the numerical model GPyro [14]. In all these cases, numerical models were used to analyze the problems including in-depth absorption under time-varying heat flux. Development of an approximate analytical model with the same capability will significantly simplify the estimation process compared with numerical method.

The ignition process under time-dependent heat flux has been studied analytically by several researchers. Ji [20] developed an integral model based on Yang's [21] experimental measurements and found that the ignition time is proportional to the increasing rate of the ramped heat flux to the power of $-2/3$. Zhai [22] extended these two works to exponentially increasing heat flux. The reliability of the developed analytical model was verified by experiments employing linear and quadratic heat fluxes. Reszka [11] proposed a time-energy squared criterion when studying the ignition delay time of materials under time-dependent heat flux in forest fire. The ignition time was expressed as a function of the total energy delivered to the surface before ignition. Lamorlette [23] analytically studied the ignition of solid targets exposed to polynomial heat fluxes delivered from spreading fire fronts and provided an explicit correlation between ignition time and the polynomial coefficients. Recently, the lead author of this study developed an expression to predict the ignition time for a time-dependent heat flux [24]. All these studies employed surface absorption assumption.

Most previous analytical works dealing with solid ignition under time-dependent heat flux employed surface absorption even in translucent medium cases. When considering in-depth absorption for translucent solids subjected to time-dependent heat flux, few analytical models were reported in the literature and numerical simulation was commonly used instead. This study aims to provide an approximate analytical solution to predict the ignition time of translucent solids exposed to exponentially time-increasing heat flux. An analytical model of ignition process that takes into account in-depth absorption and time-dependent heat flux was developed and applied to a typical translucent solid, black PMMA. Both critical temperature and critical mass flux were used as the ignition criteria. Linearly and quadratically increasing heat fluxes were addressed. The experimental data of black PMMA for linear heat flux as well as the results of detailed numerical simulations were utilized to validate the proposed analytical model and the agreement was good.

2. Model development

When a non-charring polymeric solid is subjected to a time-dependent exponentially increasing heat flux, the heat transfer of this problem is illustrated in Fig. 1. Only in-depth absorption of radiative heat flux is considered in this section. In order to simplify the analysis process and obtain an explicit expression, several assumptions are