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Full Length Article

Approximate analytical solutions for transient mass flux and ignition time of solid combustibles exposed to time-varying heat flux

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ABSTRACT

An approximate analytical model was established in this study to predict the transient mass flux and ignition time of solid combustibles exposed to time-dependent exponentially increasing heat flux. Critical mass flux was employed as the ignition criterion in the developed model. A new approximation strategy was used to simplify the complicated exact solution and to derive explicit correlations between ignition time and heat flux. Linear and quadratic heat fluxes were focused and the conclusions under other heat fluxes can be extended through analogy. An equivalent ignition temperature, involving critical mass flux, thermodynamics and chemical kinetics, was found in this study. The negative square root of ignition time is linearly proportional to the heat flux at ignition time. Under linear and quadratic heat fluxes, the ignition heat flux increases with $a^{1/3}$ and $a^{1/5}$ (a is a constant in the heat flux expression), respectively, whereas the total heat absorbed by the solid before ignition is proportional to $a^{-1/3}$ and $a^{-1/5}$, respectively. The capability of the proposed model was validated by another analytical model, numerical simulations and experimental data of black PMMA (Polymethyl Methacrylate) and pine wood. Furthermore, the effect of surface heat loss on the predictions of the proposed model was estimated and parametric study based on critical mass flux was implemented.

1. Introduction

Prediction of thermal decomposition and ignition of solids exposed to incident radiant heat flux is of particular importance in fire risk evaluation and controls. In many theoretical studies such as the classical ignition theory, constant incident heat flux was utilized as a boundary condition at condensed phase. However, in accidental fires time-varying heat flux is the most frequent condition and there is a deficiency of relevant investigation in the literature aiming at revealing the ignition mechanism of such circumstance [1]. Both growth of fire and flame spread in buildings or forest fires would lead to a time-varying heat flux exposure to unburnt combustibles [1], and the ignition delay time is thus a critical parameter in estimating the subsequent spread rate.

Ignition of solid materials under constant heat flux has been studied extensively by previous investigators, including theoretical and numerical models. Lawson and Simms's model [2] is a classical analytical solution considering only heat conduction and has been modified by many other researchers [3–10]. In all these analytical models, ablation theory [2] is used for ignition, which assumes that ignition occurs only when the surface temperature of solid increases to a critical value, namely ignition temperature. The main flaw of this ignition criterion is that this hypothesis is only introduced for simplification and the ignition mechanism at gas phase is not considered. Furthermore, the surface temperature at the ignition time actually increases with increasing incident heat flux, which has been validated by experimental measurements [11,12]. Comparatively, critical mass flux is a more reliable ignition criterion considering the lower flammability limit of pyrolyzate and is generally employed in the numerical models [13,14]. Introducing thermal degradation reaction, taking place mainly in heat penetration depth in which large temperature gradient exists, into analytical model would lead to unsolvable problem when integrating the transient total mass flux through temperature solution. Lautenberger [11] tried this challenge and conducted a pioneering investigation coupling critical mass flux in analytical solution through an approximate strategy under constant heat flux.

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Nomenclature

A, B	constants in Eq. (17)
a, b	coefficients in time-varying heat flux
C	constant in ignition time correlations
C_P	specific heat ($Jg^{-1}K^{-1}$)
e	Euler number
f,*g*	functions
h	heat loss coefficient ($Js^{-1}m^{-2}K^{-1}$)
ΔH_v	heat of decomposition (Jg^{-1})
k	thermal conductivity ($Js^{-1}m^{-1}K^{-1}$)
L	thickness of sample (m)
m''	total mass flux ($gm^{-2}s^{-1}$)
Nu_L	Nusselt number
$\dot{q}''_{ext}$	external heat flux ($Js^{-1}m^{-2}$)
R	ideal gas constant ($Jmol^{-1}K^{-1}$)
Ra_L	Rayleigh number
S_v	rate of volatiles generation in solid (s^{-1})
t	time (s)
T	temperature (K)
x	spatial coordinate (m)
Z	pre-exponential factor (s^{-1})

Greek symbols

α	thermal diffusivity (m^2s^{-1})
β	volumetric thermal expansion coefficient (K^{-1})
γ	surface absorptivity
δ	thermal penetration depth (m)
ε	emissivity
κ	in-depth absorption coefficient (m^{-1})
θ	relative temperature (K)
ξ	dimensionless distance in Eq. (10)
ν	kinematic viscosity (m^2s^{-1})
ρ	density (gm^{-3})
σ	Stefan-Boltzmann constant ($Js^{-1}m^{-2}K^{-4}$)

Subscripts

c	conduction
conv	convection
cri	critical value
ext	external heat flux
ig	ignition
loss	heat loss
s	solid phase
∞	ambient condition
0	initial condition

When materials are heated under time-varying incident heat flux, the thermal response and ignition behaviors differ greatly from that of constant heat flux. Recently, Didomizio [15] carried out an experimental study on ignition of wood exposed to fourth-order time-dependent heat flux by controlling the temperature of a cone heater. Meanwhile, a numerical heat transfer model was combined to compute the time-dependent temperature distribution in solid and ignition time. Leventon [16] simulated upward flame spread over PMMA by combining an empirical variable heat feedback flux from flame to solid material [17] using a numerical pyrolysis solver ThermaKin2D [18]. Vermesi [19] experimentally and numerically studied the pyrolysis and ignition of PMMA under transient parabolic irradiation by the Fire Propagation Apparatus (FPA) and a 1D pyrolysis model, GPyro [20]. In order to reduce the computation time and to provide direct insight into the ignition mechanism, other studies tried to solve this problem analytically. Yang [21] experimentally studied the ignition of some wood species under linearly increasing heat flux. Later Ji [22] 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 [23] extended these two works to exponentially increasing heat flux. The reliability of the developed analytical model was verified by experiments employing linearly and quadratically increasing heat fluxes. Reszka [1] 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. However, in all these analytical models, pyrolysis was neglected and ignition temperature was used as the ignition criterion.

In order to introduce thermal degradation process into an analytical model, we modified the approximation strategy in Lautenberger's work [11] and proposed another new approximation methodology to predict the transient mass flux and ignition time under time-varying heat flux in this study. Without this approximation method, no explicit expression for mass flux and ignition time can be attained. Critical mass flux is used as the ignition criterion, and linear and quadratic heat fluxes are addressed. Furthermore, the analytical model in Ref. [23], a numerical model previously developed by us [24] and the existing experimental data in the literature are employed for validation purpose. This work aims at providing some useful results for fundamental understanding of ignition theory of combustible solids which are widely used as ornamental and structural materials in buildings.

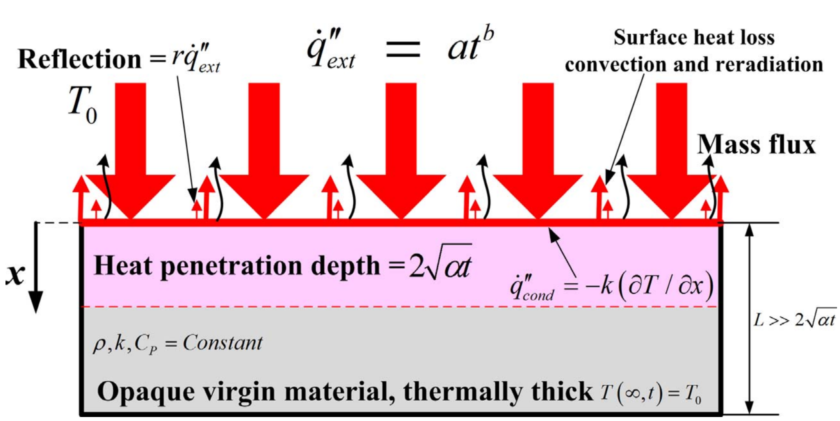

Fig. 1. Schematic of heat transfer in solid under time-dependent exponentially increasing heat flux.