



# Approximate analytical solutions for temperature based transient mass flux and ignition time of a translucent solid at high radiant heat flux considering in-depth absorption



Junhui Gong<sup>a,\*</sup>, Yabo Li<sup>a</sup>, Jinghong Wang<sup>a</sup>, Jing Li<sup>b</sup>, Yixuan Chen<sup>a</sup>, Juncheng Jiang<sup>a</sup>, Zhirong Wang<sup>a,\*</sup>

<sup>a</sup>Nanjing Tech University, College of Safety Science and Engineering, Nanjing, Jiangsu 210009, China

<sup>b</sup>University of New Haven, Henry C. Lee College of Criminal Justice and Forensic Sciences, Department of Fire Science & Professional Studies, West Haven, CT 06516, United States

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## ABSTRACT

Most studies, employing ignition temperature as the ignition criterion, utilized surface absorption of radiant incident heat flux in analytical models when investigating the ignition mechanism of solid combustibles. However, in-depth absorption exerts its influence on ignition time significantly for translucent solid, especially at high radiant heat flux. In this work, we extend the previous researches from surface absorption to in-depth absorption to develop an approximate analytical ignition model using critical mass flux instead of critical temperature. An approximation methodology is proposed during derivation to study the in-depth absorption scenario. The comparison among this model, available experimental data of black PMMA in the literature and previous numerical simulations indicates that the proposed model provides relatively high accuracy in predicting ignition time. Furthermore, the pure surface absorption circumstance is also reexamined and compared with the classical ignition theory. The results show that surface absorption hypothesis accelerates the total mass flux, which consequently shortens the ignition time. However, in-depth absorption assumption eliminates the heat accumulation on surface and results in good prediction for ignition time at high heat flux. For in-depth absorption, the absorption coefficient affects the heat penetration depth and temperature distribution in this layer which consequently affects the thermal degradation reaction rate, mass flux and finally ignition time. Meanwhile, the ignition time considering both surface and in-depth absorption is discussed, and the relationship with pure surface and in-depth absorption conditions is obtained.

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## 1. Introduction

Radiant heat feedback from flame to unburnt solid combustibles controls the thermal degradation, ignition and subsequently the fire propagation. Therefore, numerous studies have been conducted to investigate the pyrolysis and ignition mechanism of various types of materials. The majority focused on bench scale experiments in which the radiant heat flux is relatively low [1], and the heat flux is assumed to be totally absorbed by exposed surface, namely surface absorption. With this simple ablation theory [2], ignition is expected to occur when the surface tempera-

ture rises to a critical value, ignition temperature. This hypothesis is capable for infrared opaque materials at relatively low heat flux, and it was used extensively in the last decades. However, for translucent solid, in-depth absorption plays an important role during pyrolysis and ignition process, especially at high radiant heat flux [1,3–11].

For in-depth absorption, incident heat flux is absorbed through the material gradually and it attenuates exponentially, which can be described by the Beer–Lambert's law. The absorption capability of a specified material is characterized by an in-depth absorption coefficient, or radiant extinction coefficient, which quantifies the absorption of thermal radiation per unit path length within the medium. The in-depth absorption, reflection and transmission of radiative flux in semitransparent materials are complex problems which involve optical properties of materials, type and operating temperature of heater, thickness of sample, multiple

\* Corresponding authors.

E-mail addresses: [gjh9896@njtech.edu.cn](mailto:gjh9896@njtech.edu.cn) (J. Gong), [wangzhirong@njtech.edu.cn](mailto:wangzhirong@njtech.edu.cn) (Z. Wang).

## Nomenclature

$A$	constant in Eq. (13)
$B$	constant in Eq. (13)
$C$	constant in Eqs. (49), (60), (67) and (71)
$C'$	constant in Eqs. (53) and (62)
$C_s$	specific heat
$e$	Euler number
$f$	function
$h_c$	convection heat transfer coefficient
$h_R$	radiation heat transfer coefficient
$\Delta H_v$	heat of decomposition
$k$	thermal conductivity
$l$	characteristic length scale of pyrolysis
$L$	thickness of sample
$m''$	total mass flux
$\dot{q}''_{ext}$	incident heat flux
$r$	reflectivity of top surface of sample
$R$	ideal gas constant
$S_v$	rate of volatiles generation in solid
$t$	time
$T$	temperature
$x$	spatial coordinate
$Z$	pre-exponential factor

### Greek symbols

$\alpha$	thermal diffusivity
$\beta$	total heat loss coefficient in Eq. (24)
$\delta$	thermal penetration depth
$\varepsilon$	emissivity
$\theta$	relative temperature
$\kappa$	radiative extinction coefficient or in-depth absorption coefficient
$\lambda$	absorptivity of top surface of sample
$\xi$	dimensionless distance in Eq. (10)
$\rho$	density
$\sigma$	Stefan–Boltzmann constant
$\varphi$	dimensionless distance in Eq. (10)

### Subscripts

$A$	Case A
$B$	Case B
$c$	conduction
$comb$	combination of surface and in-depth absorption
$C$	Case C
$D$	Case D
$g$	gas phase
$ig$	ignition
$in$	in-depth absorption
$ref$	references
$s$	solid phase
$surf$	surface absorption
$v$	volatile
$\infty$	ambient condition
$0$	initial condition

internal reflections and spectral distribution effects etc. Recently, Bal and Boulet et al. [12–16] carried out successive works on these subjects experimentally employing two common standard apparatuses, Cone Calorimeter (ISO 5660 standard) and Fire Propagation Apparatus (FPA). The dependences of absorbance, attenuation coefficient, reflectivity and transmittance on wavelength bands were attained. Linteris et al. [17] measured the in-depth absorption coefficients of several polymers, including charring and non-charring ones, which provides available input parameters for subsequent

numerical studies and alternative method for measuring the coefficients.

However, we have to admit that both surface and in-depth absorption are idealized cases, and both should be considered simultaneously when examining the pyrolysis and ignition process. In Jiang et al.'s study [5], it was found that in-depth absorption exists even for the presence of coated carbon black on surface. Recently, Bal and Rein [7], Staggs [6] and Gong et al. [18,19] numerically investigated the ignition behaviors of PMMA considering both surface and in-depth absorption, and an optimized combination was obtained. Also, it was found that the traditional coating of black carbon added on the sample does not cancel in-depth radiation absorption but increases the surface absorptivity. Delichatsios and Zhang [1] modified the classical ignition theory by taking both absorption modes into account and provided some useful results.

Four ignition criteria can be found in the literature and were summarized by Vermesi et al. [20], namely critical temperature, critical mass flux, critical energy and time-energy squared. The critical temperature is reliable for a thermally thick solid exposed to a constant irradiation [21–25]. The relationship between ignition time and incident heat flux is  $t_{ig}^{-0.5} \propto q''_{ext}$ . The main criticism to this criterion includes ambiguous ignition mechanism, neglect of in-depth absorption of irradiation and the fact that surface temperature of solid increases with increasing incident heat flux, which was validated by experimental measurements [26,27]. Considering the lower flammability limit of pyrolyzate, critical mass flux is proposed as a more reliable ignition criterion. It takes into account the thermal degradation in condensed phase and is more commonly employed in numerical models. The energy criterion provides ranges of critical energy rather than a single value for each material, which states that a sample will ignite after absorbing a certain amount of energy [28]. Reszka et al. [29] and Ji et al. [30] proposed a time-energy squared criterion in which ignition delay time was expressed as a function of the total energy delivered to the surface when studying the ignition delay time of materials at time-dependent heat flux.

Although critical mass flux is a credible ignition criterion, no exact analytical solution of ignition time can be found. Almost all of the studies adopt numerical simulation when encountering this problem [4,6,7,20]. Lautenberger and Fernandez-Pello [26] developed an approximate analytical solution of ignition time for thermally thick materials employing critical mass flux as the ignition criterion. However, in his work, only surface absorption was used without considering in-depth absorption. Delichatsios and Zhang [1] developed an analytical ignition model considering both surface and in-depth absorption. Nevertheless, critical ignition temperature was used in that study rather than critical mass flux. In this paper, we extend these models with similar methodology to in-depth absorption scenario employing critical mass flux rather than ignition temperature which has been considered in our previous work [19] to provide complementary work. Also, surface absorption is reinvestigated and compared to validate such method. Furthermore, the effect of combination of surface and in-depth absorption are also discussed, and the failure of classical ignition theory in predicting ignition time at high heat flux is expected to be interpreted.

## 2. Approximate analytical model

Considering an infrared transparent medium exposed to a constant radiant incident heat flux, the heat transfer at condensed phase is illustrated in Fig. 1. In classical ignition theory, surface absorption assumption is used as shown in Fig. 1(a), namely all energy is absorbed on surface except the reflected portion. The heat through solid is conducted within heat penetration depth, estimated by  $2\sqrt{\alpha t}$ , due to temperature gradient. For pure in-depth

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