C. R. Mecanique 342 (2014) 459–465

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

Quantification of ignition time uncertainty based on the classical ignition theory and Fourier analysis

Quantification de l'incertitude du temps d'ignition fondée sur la théorie classique de l'ignition et l'analyse de Fourier

Aymeric Lamorlette *

Aix-Marseille Université, CNRS, Centrale Marseille, M2P2 UMR 7340, 13451 Marseille cedex 20, France

A R T I C L E   I N F O

Article history:
Received 14 January 2014
Accepted 2 June 2014
Available online 20 June 2014

Keywords:
Heat transfer
Piloted ignition
Ignition uncertainty

Mots-clés :
Transfert thermique
Ignition pilotée
Incertitude de l'ignition

A B S T R A C T

This study aims at modeling the effect of incoming heat flux fluctuations, on solid material ignition. In order to propose a general methodology based on the classical ignition theory that can be applied to any kind of solid target, kernels accounting for the target temperature response regarding an incoming heat flux are considered for thermally thick and thin solids with low or high thermal inertia. A Fourier decomposition of the incoming heat flux is then used to calculate the target response to harmonic heat fluxes. Finally, effects of harmonic fluctuations on ignition are discussed based on the previous analytical results, allowing us to discriminate situations where ignition time is expected to be rather predictable from situations where ignition time is expected to be less predictable thanks to an uncertainty quantification of the ignition time.

R É S U M É

Cette étude a pour but la modélisation des effets des fluctuations du flux de chaleur impactant un matériau solide sur l'ignition de ce dernier. Afin de proposer une méthodologie générale, fondée sur la théorie classique de l'ignition, qui pourra être appliquée à n'importe quel type de cible, des noyaux rendant compte de la réponse en température à une sollicitation thermique sont considérés pour des solides thermiquement épais et fins, et pour de basses et hautes inerties thermiques. Une décomposition en séries de Fourier de la sollicitation est alors utilisée pour calculer la réponse de la cible aux flux harmoniques. Finalement, les effets de ces fluctuations sont discutés à partir des résultats analytiques précédents, permettant de discriminer des situations où le temps d'ignition devrait être plutôt prédictible de situations où il risque d'être moins prédictible, et ce grâce à une quantification de l'incertitude du temps d'ignition.

* Tel.: +33 491 113 811; fax: +33 491 118 502.
E-mail address: aymeric.lamorlette@univ-amu.fr.

http://dx.doi.org/10.1016/j.crme.2014.06.002
1631-0721/

1. Introduction

In the frame of fire safety applications, estimation of the flaming ignition time of solid materials is a major issue. A first approximation, often called the classical ignition theory, consists in considering ignition as two separated mechanisms: heat and pyrolysis of the solid followed by chemical reactions in the gas phase. If the pyrolysis gas flow is low with normal oxygen concentration, suggesting that ignition occurs when the solid surface temperature reaches the pyrolysis temperature, the ignition time corresponds to the time needed by the solid to heat until it begins its pyrolysis. Indeed, chemical time and mixing time are typically much smaller than pyrolysis time for piloted flaming ignition. These assumptions allow one to model ignition as a temperature rise process in the solid material, as suggested by [1]. Ignition is thus modeled as a one-dimensional heat conduction problem as proposed by [2] for thermally thick surfaces and as a zero-dimension heat transfer problem for thermally thin particles, as suggested in [3]. In order to mimic more realistic fire scenarios, an improvement of this theory is proposed in [4], where the radiant heat flux is suggested to be linearly time dependent, as suggested by [5] to take into account the time-varying heat flux on a stationary target exposed to a spreading fire front. Using this approach, the global trend of the incoming radiant heat flux can be taken into account. However, turbulent motions are common in the fire front as explained by [6] and often generate periodic or quasi-periodic flame behavior as demonstrated by [7] and [8], thus periodic or quasi-periodic fluctuations of the radiant heat flux can occur, which are not taken into account in the previously described model. These fluctuations could be responsible for ignition or fire propagation unpredictabilities, since they are not controlled in practical applications: Recent experimental results on fire propagation by [9] demonstrate the existence of quasi-periodic fluctuations of the heat flux involving flaming contact on the solid particles composing a fuel layer that seems to be of great matter in particle ignition. Moreover, the study of [10] demonstrates the effect of wind fluctuations on fire propagation, involving processes similar to those suggested in [9].

Therefore, this study aims at modeling the effect of heat flux harmonic variations on different solid targets of interest, to mimic the effect of the previously described periodic or quasi-periodic processes and investigate ignition uncertainty. The latter is defined as the harmonic flux effect on the temperature rise. It can nevertheless be noticed that if chemical and mixing time were to be considered, uncertainties due to chemistry and mixing should be added to the uncertainty due to the temperature rise, particularly when addressing ignition of the smaller targets, according to [11]. This aspect is however not investigated in this study. The suggested target could be PMMA and wood slabs, insulating foams, excelsior or pine needles, which can be classified as thermally thick or thin, with low or high thermal inertia, according to the classification suggested in [11]. Hence ignition is modeled for these solid categories. Solutions are discussed for practical fire safety applications, thus use of “practical” in this article will refer to the material thermophysical properties of PMMA, wood and insulating foams, with ignition time ranging from a few seconds to a few hundred seconds. The limit (regarding the particle size) between thermally thin and thermally thick material is set according to [12], where a radiative Biot number, depending on the incoming radiant heat flux, is considered. Indeed, a classical Biot number cannot fully account for the thermal behavior transition since heating is here due to radiative heat transfer.

In order to illustrate the incoming heat flux harmonic variation effect, an example considering the ignition under heat fluxes composed of a constant and a harmonic part is presented. Nevertheless, the methodology allows us to extend the study to heat fluxes composed of any kind of slow time-varying variations part adding any harmonic part.

2. Mathematical formulation: the classical ignition theory

This section recalls the work of [1–4,11], using a particular formalism that provides a simple expression for the target temperature response to a Fourier decomposition of the incoming heat flux, and suggesting a slight difference for low thermal inertia solids. Indeed, the study of [11] considers series expansion around $t \to \infty$, whereas this study considers a higher series expansion (in comparison with the high thermal inertia case) around $t \to 0$.

For thermally thick targets, a one-dimensional semi-infinite inert solid material is considered with one side exposed to an incoming heat flux $\Phi(t)$. The heat conduction equation is solved for the solid target, introducing $\theta(x,t) = T(x,t) - T_0$, where $T(x,t)$ is the solid temperature and T_0 the initial temperature of both the solid and its surrounding air. λ, ρ, C_p and h represent respectively the solid heat conductivity, its density, its specific heat and a total heat transfer coefficient.

For high thermal inertia solids, the associated surface heat loss can be neglected as shown in [4,11], whereas it is taken into account for low thermal inertia solids. Hence, kernel K is provided by the classical solution suggested in [2,11] for high thermal inertia solids. Since the study focuses on the surface temperature evolution, the kernel K is calculated at $x = 0$, leading to:

$$K(0,t) = \frac{2\sqrt{t}}{\sqrt{\pi \lambda \rho C_p}} \tag{1}$$

Now, considering an arbitrary function $\Phi(\tau)$ as a series of steps and using the heat diffusion equation linearity, the response $\theta(0,t)$ can be expressed as a sum of response with time offsets for an arbitrary kernel K_0:

$$\theta(0,t) = \int_0^t \frac{\mathrm{d}\Phi}{\mathrm{d}\tau} K_0(0, t-\tau)\,\mathrm{d}\tau \tag{2}$$