



Experimental, numerical and theoretical analyses of the ignition of thermally thick PMMA by periodic irradiation

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ABSTRACT

In this work, the pyrolysis and ignition of thermally thick poly (methylmethacrylate) material with low periodic on-off irradiation was investigated, the solid and gas absorption was ignored, an ignition time formula with periodic heating was established based on the deduced ignition time model. The results show that the surface and in-depth sample temperatures as well as the mass flux all increase during the periodic 'on' cycle prior to ignition, at the moment there is a small luminous sustained flame, followed by flame spreading. For the surface temperature, the fluctuation magnitude increases with increasing cycle time $\propto \sqrt{\tau}$. The in-depth temperature decay relating to the distance and cycle as $\propto \exp(-x/\sqrt{\tau})$. The surface and in-depth temperatures, mass flux oscillates due to the periodic on-off irradiation with a time delay, which increases with increasing cycle and in-depth distance as $\propto \sqrt{\tau}x$. The cycle has slight influence upon the surface temperature and mass flux at the moment of ignition, where the ignition temperature maintains at about 340 °C, while the critical mass flux is in a range of 1–1.4 g/m²s, which are both independent of the external heat flux. The linear relationship of successive peak surface temperature with heat flux via time $(\frac{T_s - T_0}{q_c})^2 \propto t$ in the periodic on-off heating is retained. The theoretical predictions of the periodic ignition times derived in this study are in good agreement with the experimental measurements. Finally, compared with constant heat flux, the periodic heating delays the ignition, but with increasing cycle time, the ignition time is seen to decrease, which is primarily attributed to increases in the time-averaged irradiative heat flux. The classical model over-predicts the ignition time, the prediction error is expected to increase for long time ignition with low thermal inertia, big perturbation heat flux and long cycle time.

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1. Introduction

To minimize fire hazards, it is extremely important to be able to accurately predict the pilot ignition of solid materials. However, in many practical applications, the external heat flux is not constant but periodic. Turbulent motions are common in the fire front and often generate periodic or quasi-periodic flame behavior, thus periodic or quasi-periodic fluctuations of the radiant heat flux can occur. Considering equivalent fire diameters ranging from 10^{−2} m to 5 m to account for pine needle litter fires up to crown fires, the reference frequencies are expected to be in the range 0.84–16.8 Hz, while wind/fire front interactions and wind/vegetation interactions could be responsible for a larger frequency range in the range 0.0006–0.1 Hz. Recent experimental results on fire propagation demonstrated the existence of quasi-periodic fluctuations of the heat flux involving flaming contact on the solid particles com-

posing a fuel layer that seems to be of great importance in particle ignition [1].

Many studies have examined the ignition of solid combustibles in response to constant heating [2–6], but only recently has ignition by transient irradiation received attention. Bilbao et al. [7] studied the ignition of wood by pilot and spontaneous ignition methods, applying a linearly decreasing external heat flux, and established a complex mathematical model to predict the ignition time. Reszka et al. [8] reported a method for the estimation of ignition times under linear incident heat fluxes, in which the predicted ignition time is proportional to the squared integral of the heat flux time span. Zhai et al. [9] studied the pyrolysis characteristics of poly (methylmethacrylate) (PMMA) and elm in response to a parabolic increase in heat flux and a linear increase in heat flux, determining the effects of the heat flux on the ignition time, surface temperature and mass loss. Vermesi et al. [10] studied the pyrolysis and ignition of PMMA in response to a parabolic heat flux, using both experimental trials and numerical simulations, and found that the most accurate simulations were those based on the critical mass loss rate, followed by the critical temperature. Their

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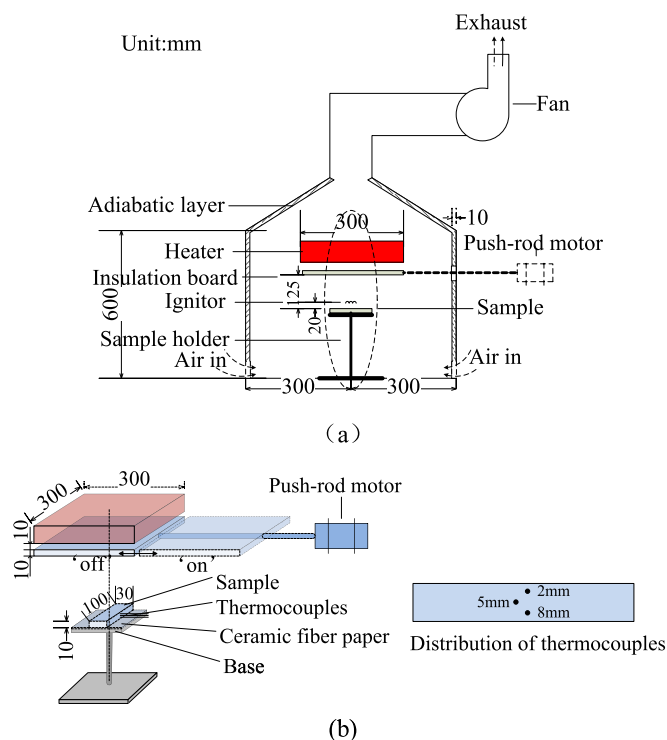


Fig. 1. The experimental set-up: the heating apparatus (a), the sample configuration and distribution of thermocouples (b).

work also suggested the novel concept of a simultaneous minimum threshold value.

In several previous studies, pilot ignition under transient heat fluxes have been determined to vary with time in either a linear or parabolic manner. Heat transfer to solid bodies during periodic heating especially for thermoforming engineering has been investigated, and the resulting surface temperatures as functions of time can be predicted using complicated mathematical models [11–13]. However, to the best of our knowledge, the deep understanding of ignition of solids in response to periodic heating with experimental investigation and theoretical analysis has rarely been examined. Recently, Lamorlette [1] investigated the applicability of the classical ignition time model (constant heat flux) for solid ignition imposed by harmonic heat flux (Fourier analysis), and showed that for thermally thick target, only slow time-varying fluctuations can affect ignition times due to the characteristic time scale of the associated kernel. But in his work, there is no explicit solution of the ignition time with harmonic external heat flux, also there is no experimental work to validate the theory.

In the present work, we conducted a series of experiments in which periodic irradiation was used both to heat and ignite PMMA specimens. In addition, numerical simulations using the COMSOL Multiphysics software package were carried out to compensate for the lack of experimental data. A model for the prediction of ignition times under a periodic on-off heat flux was established, and the effects of the on-off cycle on the surface and in-depth specimen temperatures, the mass flux and the ignition time were analyzed.

2. Experimental

A schematic of the experimental set-up is provided in Fig. 1. The combustion chamber was a cube with dimensions of $600 \times 600 \times 600$ mm, the upper part of which formed a truncated pyramid connected to a fan. This chamber was made of refractory

steel with the inner walls insulated to minimize heat loss and an observation window in one wall to allow observation of the ignition process. Small holes distributed along the base of the chamber walls allowed the ingress of ambient air and the exhaust fan generated a weak air flow through the chamber with a velocity of approximately 3 m/s.

Irradiation was provided by ten silicon carbide heaters situated parallel to one another working at 6 kW. The critical external heat flux required to ignite PMMA is in the range of $6\text{--}23 \text{ kW/m}^2$ [14].

In this work, to simplify the mathematical problem in the following theoretical analysis, the maximum local heat flux at the sample surface was designed to be 20 kW/m^2 . It is because that, for PMMA, when the radiation heat flux is lower than about 30 kW/m^2 , in-depth absorption $\kappa\delta \approx \kappa k\Delta T/\dot{q}_{ex}'' \gg 1$ (κ is the absorption coefficient; δ is the thermal penetration depth; k is the conduction coefficient), the in-depth radiation absorption can be ignored [3].

Periodic on-off irradiation was obtained by moving a 10 mm thick asbestos board in front of the heaters, using a push-rod motor moving at 9 cm/s. The board was positioned 10.5 cm above the sample surface and was able to move in or out of place in a short time. As the asbestos board was only 1.5 cm below the heater and far above the sample surface, furthermore, there is a weak upward exhaust air flow, thus, the induced disturbance of the board to the surface flowfield of the decomposed vapor was diminished to be essentially negligible.

Each PMMA sample was 100 (length) $\times$ 30 (width) $\times$ 10 (thickness) mm. The specimens were placed on a 2 mm layer of ceramic paper inside the chamber for thermal insulation. A 15 A ignition coil, 15 mm in length, was situated 20 mm above the sample as a pilot source. The effect of the heat flux provided by the pilot was determined to be negligible in a previous study [10].

Prior to each test, a water-cooled heat flux gauge (accuracy: $\pm 3\%$) was placed horizontally in the center of the chamber below the heater. By adjusting the distance between the radiometer and the heater, a local heat flux of 20 kW/m^2 was intentionally obtained. Then the sample was placed at the same horizontal position with the received heat flux. Attaching a thermocouple to the sample surface in such a way that it accurately recorded the surface temperature up to the point of ignition was extremely challenging. For this reason, the in-depth temperature profile was instead measured, using three 1 mm diameter K-type thermocouples (accuracy: $\pm 2^\circ\text{C}$) inserted tightly into three parallel holes, which has the same depth of 15 mm and diameter of 1 mm, and are 2, 5 and 8 mm horizontally below the sample surface, respectively, as illustrated in Fig. 1 (The holes are nearly at the centerline, except 5 mm hole has slight deviation to avoid measurement disturbance). This approach to temperature measurement has previously been validated by Reszka et al. [15] and Carvel et al. [16]. The resulting heat flux and temperature data were recorded by a computer at 1 s intervals. The entire sample heating process was captured using a standard digital video camera (Nikon D7100, 30 fps) through a side window, while the ignition period was recorded in detail using a high-speed camera (Photron FASTCAM Mini UX50, 1280×1024 at 500 fps). The mass flux values during these trials were very low, below the detectable range of a standard electronic balance.

A steady periodic on-off radiant flux was obtained by powering on the heaters and exhaust fan at least 10 min prior to each trial and moving the insulating board under the heaters to preheat the board. An 'off' heat flux of nil was very difficult to obtain after this preheat step. Because the sample ignition time was less than 5 min during the pyrolysis process, the periodic on-off heat flux was extremely steady, with values of 20 and 2 kW/m^2 , respectively, as shown in Fig. 2 (experiment). The trace in this figure demonstrates that the heat flux transitions formed a square wave, but there is a very short time delay between the on and off settings, which is

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