行政院國家科學委員會專題研究計畫成果報告

熱厚型固相燃料在重力場中之引燃及向下火焰延燒之研究

Ignition and Transition to Flame Spread Over a Thermally-Thick Solid Fuel in a Gravitational Field

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摘要

本計畫係以數值分析方法來研究重力場中自然對流環境下，纖維質材料平板之引燃及火焰傳播現象。研究結果顯示，垂直燃料平板之引燃及火焰傳播歷程可以分成兩個階段，第一個階段是加熱階段，第二個階段是火焰發展階段，此階段主要包含了引燃過程及一個過渡的過程。在加熱階段，固態燃料的最高溫度會隨加熱時間增加而上升，但其上升速率有減小的趨勢，這主要是由於在加熱階段後期，固態燃料開始進行裂解反應所造成。在火焰發展階段的引燃過程，因為在加熱階段累積的預混可燃氣體發生化學反應，釋放出大量的熱，因此，在引燃過程氣相溫度會在短時間內急劇上升。同時火焰的型態也在引燃過程中由預混火焰快速的轉變為擴散火焰（火焰前端除外）。在過渡的過程中，火焰同時扮演引燃源及熱源的角色，用來加速固態燃料的裂解，並維持火焰的存在。此外，研究結果亦顯示延長加熱時間可使材料從一暫態引燃轉變成持續性的引燃。針對不同厚度的材料，研究結果發現，當厚度小於2.5mm時，引燃延遲時間會隨厚度增加而增加，但當厚度大於2.5mm時，引燃延遲時間與固態燃料的關係則視外加熱源的加熱速率而定，當加熱速率小於固態燃料內部的熱擴散速率時，引燃延遲時間會隨厚度增加而增加。反之，則厚度變化對引燃延遲時間造成的影響非常小。

Abstract

This project numerically investigates the ignition behaviors of vertically oriented cellulosic materials subjected to a radiant heat flux in a normal gravitational field. The entire process is delineated into two distinct stages. In the heating up stage, the maximum temperature increases with time but at a decreasing rate because of the pyrolysis reaction. The flame development stage consists of ignition and transition processes. In the ignition process, the maximum temperature in gas phase increases dramatically within a short period of time because a large amount of heat is generated from chemical reaction of the accumulative, flammable mixture. The flame is in a transition from a premixed flame to a diffusion one, except for the small region around the flame front. For the effect of varying the heating duration on ignition behavior, prolonging the imposed radiative heat time leads the ignition from a transition one to a persisting ignition. The effect of varying the solid fuel thickness indicates that the ignition delay time increases with an increase of solid fuel thickness while $\bar{\delta}_s \leq 2.5$mm. For $\bar{\delta}_s \geq 2.5$mm, the relationship between ignition delay time and solid fuel thickness depends on external heating rate. If the external heating rate is the same order as the heat diffuse rate in the solid fuel, the ignition delay time increases with an increase in solid fuel thickness. If the external heating rate is greater than the heat diffuse rate, the ignition delay time remains nearly a constant.

Introduction

This work investigates the ignition behaviors of a vertically oriented solid fuel subjected to a radiant heat flux under a natural convective environment in a normal gravitational field. Although such process plays an important role in natural fire growth, previous modeling studies of solid fuel ignition phenomena only considered the following topics: simple flow fields, such as stagnation point flow [1] and potential flow in microgravity environment [2] [3]; solid fuel energy conservation [4]; and one-dimensional assumptions [5]. There are no sophisticated models to describe the detailed interaction between the gas phase transport/chemical process and the solid fuel heating/pyrolysis process.

In light of above developments, this study develops a time-dependent combustion model to simulate and study the process of radiative autoignition and subsequent transition to flame spread over a vertically oriented solid fuel. The parametric studies change the solid fuel thickness ranging from the thermally-thin to thermally-thick fuels, the peak values of externally imposed flux values, and the heating periods. This study concentrates mainly on providing further insight into the detailed ignition processes and their respective controlling mechanisms.

Mathematical Model

Figure 1 illustrates the physical configuration of two-dimensional ignition over a vertically oriented solid fuel. At time t<0, the system is quiescent. When $t \geq 0$, an external heat flux in Gaussian distribution is imposed on the solid surface. The mathematical model for gas phase includes a set of time-dependent, fully elliptic conservation equations for continuity, momentum, energy, and species, an equation of state, and an expression of viscosity variation with temperature. They are coupled with the solid phase energy and mass conservation equations at the interface. The study adopts an Arrhenius-type expression describing the fuel consumption rate for the chemical reaction in gas phase, and the process that decomposes solid fuel into volatiles and char.

The boundary conditions are:

Gas Phase

At $x = x_{min}$:

$$u \cong 0 \quad , \quad v \cong 0 \quad , \quad T = 1 \quad , \quad Y_F = 0 \quad , \quad Y_O = Y_{O\infty}$$

At $x = x_{max}$:

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial T}{\partial x} = \frac{\partial Y_F}{\partial x} = \frac{\partial Y_O}{\partial x} = 0$$

At $y = y_{max}$:

$$\frac{\partial u}{\partial y} = 0 \quad , \quad \frac{\partial v}{\partial y} = 0 \quad , \quad T = 1 \quad , \quad Y_F = 0 \quad , \quad Y_O = Y_{O\infty}$$

Solid phase

At $x = x_{min}$:

$$T_s = 1$$

At $x = x_{max}$:

$$\frac{\partial T_s}{\partial x} = 0$$

At the mid-plane of the solid fuel bed:

$$\left.\frac{\partial T_s}{\partial y}\right|_{y=0} = 0$$

Interface conditions:

$T_i = T_{Si}$

$$K_s \left.\frac{\partial T_{si}}{\partial y}\right|_{y=\delta_s} = \mu \left.\frac{\partial T_i}{\partial y}\right|_{y=\delta_s} + q_{ext} + \sigma.\varepsilon\left(T_s^4 - T_\infty^4\right)$$

$u=0$, $m_S'' = \rho_i v_i$

$$m_i'' Y_{Fs} = m_i'' Y_{Fi} - \frac{\mu}{Pr\sqrt{GrLe}} \cdot \left.\frac{\partial Y_F}{\partial y}\right|_{y=\delta_s}$$

$$m_i'' Y_{Os} = m_i'' Y_{Oi} - \frac{\mu}{Pr\sqrt{GrLe}} \cdot \left.\frac{\partial Y_O}{\partial y}\right|_{y=\delta_s}$$

where $Y_{Fs} = 1$, $Y_{Os} = 0$

The numerical scheme adopts the SIMPLE algorithm [6] and was thoroughly described by Lin [7]. The selected non-dimensional computational domain and grids are 444.5 x 133.5 and 230 x 89, respectively. An SGI INDIGO2 workstation, located at National Chiao Tung University, performed the computations using a minimum time step value of $\Delta t=10$, corresponding to 0.0548 sec. dimensionally.

Results and discussion

The selected solid fuel is a cellulosic material. The ignition and transition to flame spread process over the solid fuel can be divided into two stages according to the relationship between maximum temperature and time as shown in Fig. 2: (I) heating up stage, during which the maximum temperature, occurred nearly at interface, is increased with time, but with a decreasing rate, because pyrolysis reaction becomes active in the later stage. In the heating process, the heated region is enlarged and the flammable mixture preparing for the following ignition is generated. Also, the maximum induced flow velocity is increased with time because the increasing temperature gradient. (II) flame development stage, which includes ignition and transition processes. The ignition process is characterized by a sharp increase in maximum temperature. Such an increase is attributed to that a large amount of heat is generated from chemical reaction of the accumulative, flammable mixture. Meanwhile, the flame is in a transition from a premixed flame to a diffusion flame, except in a small region just around the flame front. The induced flow ahead of the flame's leading edge is retarded by the local high-pressure plateau, as generated by the thermal expansion attributable to active combustion. Thereafter, this high-pressure plateau accelerates the flow towards downstream. In the transition process, the maximum temperature decreases from the highest value since the large amount of flammable mixture is almost consumed. The flame is fully developed into a diffusion flame except in a small upstream region. In addition to the externally imposed heat, the flame serves as the heat source to pyrolyze the solid fuel further to sustain itself. The observation reveals that the upward flame front travels faster than the downward flame front (Fig.3), because the heat transfer from the flame to the unburnt fuel is rendered more difficult by the gas flow moving against the propagating flame.

Figure 4 displays the histories of maximum temperature for various heating periods under the same incident heat flux distribution. In Case 1, the externally radiative heat is imposed and maintained for the entire computational time. For Case 2, the incident heat flux is terminated at t=770 and it is at t=1030 for Case 3. This finding indicates that if the incident heat flux does not keep heating the solid fuel after ignition initiation occurs (t=770); no persisting ignition existed. Such an ignition is simply a transient phenomenon because the resultant flame cannot provide sufficient energy to overcome the heat loss and sustain itself into the later stage. On the other hand, if the radiative heat is imposed until the transition process starts, such as Case 1 and Case 3, the flame can sustain itself for persisting ignition. This trend corresponds to the observation in the experimental works of Kashiwagi [8].

This work also explores the dependency of ignition delay time on solid fuel thickness, varying from δ_s=0.360(0.5 mm) to 3.605(5mm). Three peak heat flux values (3.5W/cm^2, 5W/cm^2, and 6.5W/cm^2) with the same half width of 1 cm are selected to further explore the effects of solid fuel thickness and external heat flux on solid fuel ignition behaviors. According to the prediction(Figure 5), the ignition delay time increases with an increase of solid fuel thickness when δ_s< 1.802 (2.5 mm) for all three peak heat flux values. This occurrence is attributed to that the larger volumetric heat absorption retards the temperature rise in solid fuel, which, in turn, slows down the solid fuel pyrolysis reaction, further delaying ignition. For 1.802(2.5mm) $\leq \delta_s \leq$ 3.244(4.5mm), the ignition delay time remains constant for the high and medium peak flux values. In this domain, if the external heating rate is greater than that of the heat diffusion rate inside the solid, then the temperature distributions are similar and the pyrolysis regions are nearly the same. Consequently, the ignition delay times are more or less the same. For the peak flux equal to 3.5W/cm^2, the ignition delay time increases with an increase of solid fuel thickness since the external heating rate is the same order as the heat diffusion rate.

計畫成果自評

本研究內容與原計畫相符、計畫內容豐碩，並已發表於 “Combustion Science and Technology”(in press) 及 The Second Asia-Pacific Conference on Combustion, (P540-544)

Reference

1 Amos, B. and Fernandez-Pello, A. C., “Model of the ignition and flame development on a vaporizing combustible surface in a stagnation point flow: ignition by vapor fuel radiation absorption,” Combust. Sci. Technol., Vol. 62, pp. 331-343(1988)

2. Nakabe K., Mcgrattan K.B., Kashiwagi T., Baum H.R., Yamashita H., and Kushida G., “Ignition and transition to flame spread over a thermally thin cellulosic sheet in a microgravity environment, “Combust. Flame, Vol. 98, pp. 361-374(1994)

3. Mcgrattan K.B., Kashiwagi T., Baum H.R., Olson S.L., “Effect of ignition and wind on the transition to flame spread in a microgravity environment,” Combust. Flame., Vol. 106, pp. 377-391(1996)

4. Bradley H. H., JR, “Theory of ignition of a

reactive solid by constant energy flux," Combust. Sci. Technol., Vol. 2, pp. 11-20(1970)

5.Gandhi, P. D. and Kanury A. M., "Thesholds for spontaneous ignition of organic solids exposed to radiant heating," Combust. Sci. Technol., Vol. 57, pp. 113-128(1988)

6. Patankar, S. V., Numerical Heat Transfer and Fluid Flow, Hemisphere, London. (1980)

7.Lin, Pei-Hsun, Proposal for Ph.D dissertation, Department of Mechanical Engineering, National Chiao-Tung University, Hsin Chu, Taiwan 300(1998)

8. Kashiwagi, T., Effects of sample orientation on radiative ignition, *Combust. Flame.*, Vol. 44, pp. 223-245(1982)

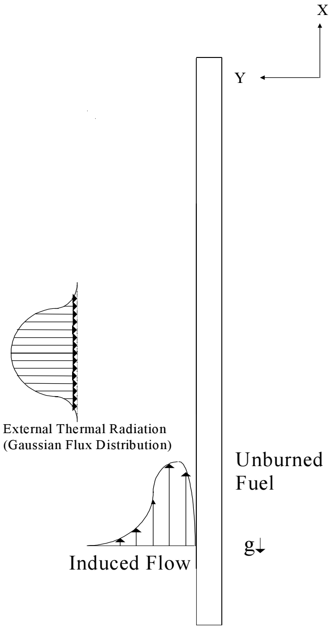

Figure 1. Configuration of radiative ignition of a vertically-oriented solid fuel

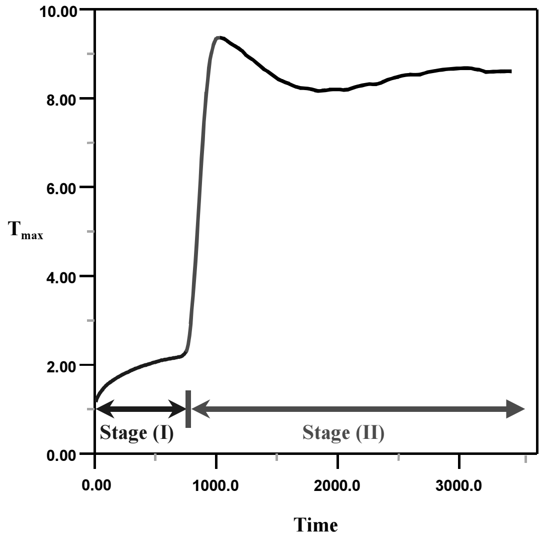

Figure 2 Time history for maximum temperature(T_{max})

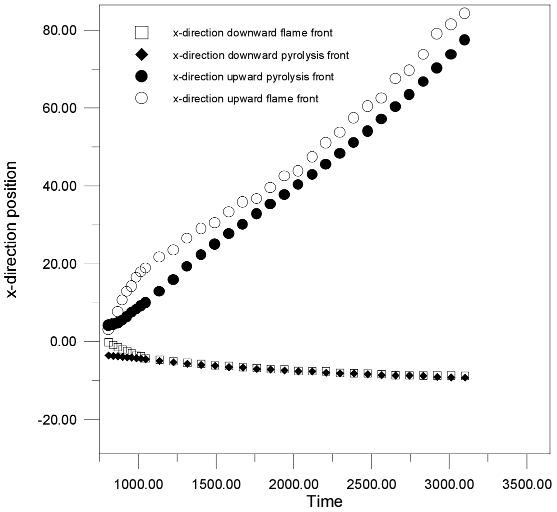

Figure 3 Upward and downward flame front and pyrolysis front positions

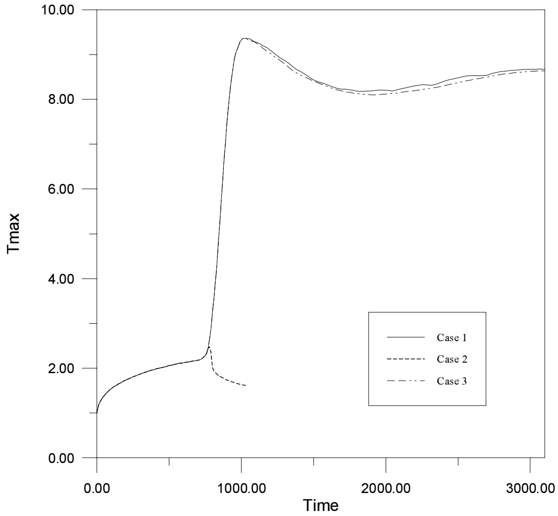

Figure 4 Effect of changing externally radiative heat imposed time on ignition behaviors

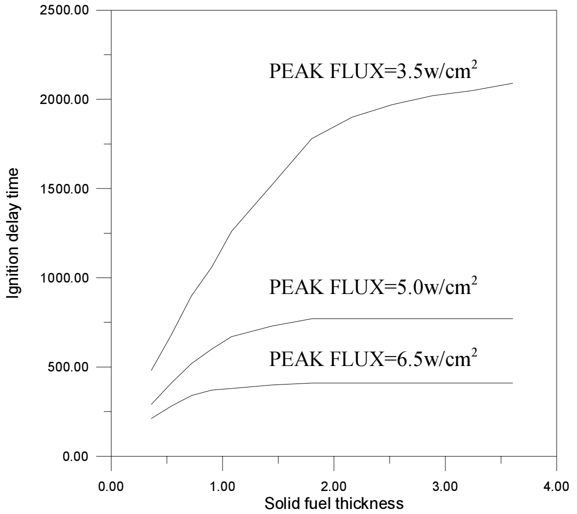

Figure 5 Relation between solid fuel thickness and ignition delay time at various heating rate