

行政院國家科學委員會專題研究計畫成果報告
水平熱厚型固相燃料在重力場中之引燃及火焰延燒之研究
Ignition and Transition to Flame Spread Over a Horizontally
Oriented Thermally-Thick Solid Fuel in a Gravitational Field
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中文摘要

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，水平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。研究結果發現，水平燃料平板的引燃時間要比垂直燃料平板的引燃時間來的短，這是因為在水平燃料平板，高溫之可燃氣並不會受到因重力所引起之誘導流所稀釋冷卻，此外也發現在低重力場的情況下，水平燃料平板的引燃時間要比高重力場下來的短，其原因是在高重力場中誘導流較強的緣故。

關鍵詞：熱厚型固態燃料，引燃，水平火焰延燒，重力場

Abstract

This study numerically investigates the ignition behaviors of horizontally oriented cellulosic materials subjected to a radiant heat flux under a natural convective environment. The process can be divided into two stages: (I) Heating up stage, during which the maximum temperature is increased with time. (II) Flame development stage, which includes ignition and transition processes. The ignition process is marked with a sharp increase in maximum

temperature. 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. In the transition process, the flame continuously spreads out, formed the so-called opposed flame spread. Since there is time lags between solid fuel pyrolysis and gas phase chemical reaction, the pyrolysis front overtakes the flame front in the initial heating process. Once the situation in the vicinity of the flame front reach the ignition status, the flame moves forward quickly, and the flame front moves to nearly the same position as the pyrolysis front position.

The ignition delay time is shorter for horizontal solid fuel than for vertical one under the same external heat flux. It is because the resultant high temperature region is not cooled and flammable mixture is not diluted by the induced flow for horizontal solid fuel. For various gravity level, the ignition delay time is decreased with a decrease in gravity level because of larger flow velocity induced in high gravity environment.

Keywords: thermally thick solid fuel, ignition, horizontally flame spread, gravity

Introduction

This study investigates the ignition and transition to flame spread behaviors of a horizontally oriented solid fuel subjected to a radiant heat flux under a natural convective environment in a normal gravitational field. In fact, it is motivated from a previous project [1], which studied the ignition behaviors of a vertical solid fuel under the same environment. For the problems associated with solid fuel ignition characteristics, previous modeling studies only considered the following topics: solid fuel energy conservation [2]; gas phase transport/chemical process (the transient

heating/pyrolysis process in solid fuel is ignored) [3]; one-dimensional assumptions [4]; and potential flow in microgravity environment [5] [6]. Although fires are generally driven by natural convection, no sophisticated models are available to describe the complicated interaction between gas and solid phases during the ignition process under a natural convective environment in a gravitational field. Therefore, this work concentrates mainly on establishing a more complete combustion model to study the detailed process for ignition and subsequent flame spread over a thick solid fuel.

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 horizontally oriented solid fuel. Then, the predicted results are used to compare with ones for the vertical solid fuel obtained previously by Lin and Chen [7]. Besides, the parametric study is based on changing gravity level. The main purpose is to provide further insight into the detailed ignition processes for horizontal solid fuel and to understand their respective controlling mechanisms.

Mathematical Model

Figure 1 illustrates the physical configuration of two-dimensional ignition over a horizontally oriented solid fuel. Because a symmetrical condition is applied in the middle plane, the computations are carried out on a half plane. 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 $x = x_{\min}$:

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

At $x = x_{\max}$:

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

At $y = y_{\max}$:

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

Solid phase

At $x = x_{\min}$:

$$T_s = 1$$

At $x = x_{\max}$:

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

At the back-plane of the solid fuel bed:

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

Interface conditions:

$$T_i = T_{si}$$

$$K_s \left. \frac{\partial T_{si}}{\partial y} \right|_{y=\ell_s} = \left. \frac{\partial T_i}{\partial y} \right|_{y=\ell_s} + q_{ext} + \pm \mathcal{E}(T_s^4 - T_\infty^4)$$

$$u = 0, \quad m_s'' = \rho_i v_i$$

$$m_w'' Y_{Fs} = m_w'' Y_{Fw} - \frac{\ll}{\text{Pr} \sqrt{GrLe}} \cdot \left. \frac{\partial Y_F}{\partial y} \right|_w$$

$$m_w'' Y_{Os} = m_w'' Y_{Ow} - \frac{\ll}{\text{Pr} \sqrt{GrLe}} \cdot \left. \frac{\partial Y_O}{\partial y} \right|_w$$

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

The numerical scheme adopts the SIMPLE algorithm [8] and was thoroughly described by Lin [9]. The solution obtained by the grid distribution of 129 x 159 (corresponding to a non-dimensional computational domain of 222.5 x 296.8) with a time step $\Delta t = 10$ (equal to 0.0548 sec. dimensionally) is acceptable; this set is also an optimal combination for the following computations. An SGI INDIGO2 workstation, located at National Chiao Tung University, performed the computations.

Results and discussion

Similar to the classification for vertical

solid fuel ignition behaviors [7], the whole process is divided into two distinct stages according to the relationship between maximum temperature and time as show in Figure 2. They are (I) Heating up stage, and (II) Flame development stage. The first stage begins when the external radiative heat flux starts to impose on the fuel surface, and it ends as the ignition to occur. In the heating process, the heated region is enlarged and the flammable mixture preparing for the following ignition is generated. The flame development stage includes both the ignition and transition processes. The occurrence for ignition initiation is defined as the instant when the specified reaction rate, 10^{-4} g/cm³.s, first appears in gas phase. The ignition process starts from ignition initiation. 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 transition process starts when the maximum temperature reaches its highest value in ignition process.

The ignition delay time is shorter for horizontal solid fuel than for vertical one under the same external radiant flux (Table I). This trend is consistent with the observation in the experimental works by Kashiwagi [10]. In horizontal mode, in upstream (-x) the heat conduction is against the incoming cold convection, however, the convection near the symmetrical plane rises upward due to the impingement of two equal strength but opposed induced flows at the plane of $x = 0$. Also the volatile flow from pyrolyzing surface are injecting to the flow field. A symmetrical thermal plume is formed. From the characteristics of these two flow fields mentioned above, the heat in upstream carried by convection is accumulated in the middle plane of $x = 0$ due to the stagnation plane resulted from impingement in horizontal mode. Therefore, under the same incident heat flux the temperature rise in solid fuel is expected faster for horizontal mode, consequently, so does for earlier ignition.

The changing in gravity level effects the potential of buoyant force, which in turn, effect the induced flow motion. It dominant the resultant distributions of temperature and fuel /oxygen mass fraction. Table II

indicates the ignition delay times increase with an increasing in gravity level. The interface maximum temperatures at ignition also show similar trend. On the other hand, the pyrolysis distance decreases with an increase in gravity level. It is because larger flow velocity induced in high gravity environment lead much heat loss to the environment, and the heat accumulated region near the symmetry line and the surface is smaller than in low gravity environment.

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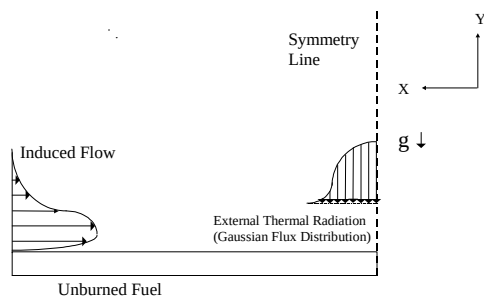


Figure 1. Configuration of radiative ignition of a horizontal solid fuel

Table I Effect of solid fuel orientations on ignition characteristics

Computed results Mode	Ignition Delay Time (s)		
	PEAK FLUX =3.5w/cm ² (Case 1)	PEAK FLUX =5w/cm ² (Case 2)	PEAK FLUX =6.5w/cm ² (Case 3)
Horizontal	8.161	3.615	2.027
Vertical	9.749	4.217	2.246
Computed results Mode	T_{simax} (interface maximum temperature at ignition)		
	PEAK FLUX =3.5w/cm ² (Case 1)	PEAK FLUX =5w/cm ² (Case 2)	PEAK FLUX =6.5w/cm ² (Case 3)
Horizontal	2.20	2.25	2.29
Vertical	2.22	2.26	2.29

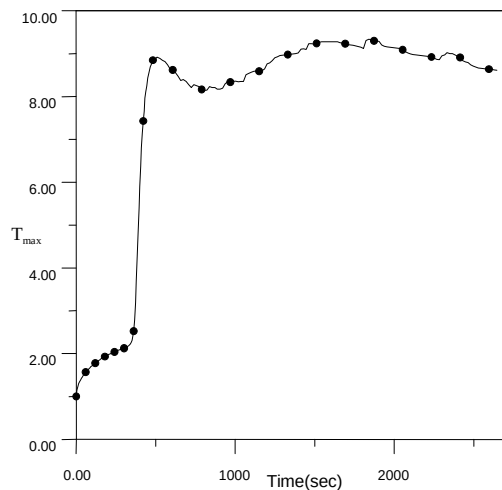


Figure 2 Time history for maximum temperature (T_{max})

Table II Effect of gravity level on ignition characteristics

G	Ignition Delay Time (s)	Pyrolysis length	T_{simax}
0.25	3.105	0.569	2.21
0.5	3.304	0.509	2.25
0.75	3.483	0.450	2.25
1	3.615	0.431	2.25
2	3.920	0.396	2.27
3	5.069	0.393	2.30
4	5.314	0.364	2.32