行政院國家科學委員會專題研究計畫成果報告
零重力場下火焰延燒特性研究
Flame Spread Over Thermally-Thin Solid Fuel Under Zero-Gravity

計畫編號：NSC 89-2212-E-009-058
執行期限：八十九年八月一日至九十年七月三十一日

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中文摘要

本計畫主要針對熱薄型固體燃料處在無重力之狀態下，火焰傳播的特性作一數值模擬。研究結果顯示，根據燃料厚度的不同，火焰傳播的型態可分為兩部分，當燃料厚度小於臨界厚度時，火焰傳播速度會隨著厚度變薄而降低，然而當燃料厚度大於臨界厚度時，火焰傳播速度則會隨著厚度增加而降低，其關鍵機制在於當燃料厚度小於臨界厚度時，由於燃料本身無法提供足夠的燃料蒸汽供作燃燒之用，因此火焰會越來越弱，最終將會熄滅，而當燃料厚度大於臨界厚度時，影響火焰傳播速度最重要的因素是氣相對燃料的熱傳量，燃料厚度增加要裂解出相同的燃料蒸汽，勢必須要更多的熱量，若熱傳量不足，裂解出的燃料蒸汽也就相對減少，造成火焰傳播速度降低。另外我們發現固相燃料可依溫度分為三個區域，分別為：預熱區，劇烈裂解反應區及等溫區，在預熱區中，固相溫度逐漸提升，在劇烈裂解反應區中，火焰回饋的熱量主要用來做裂解反應之用，而在等溫區中，固相溫度保持在裂解溫度直到燃料燒盡。在氧濃度對火焰傳播速度影響方面，研究結果顯示，在高氧濃度的環境下，火焰傳播速度較快，在 $0.2 \le Y_{O\infty} \le 0.45$ 時，兩者有一關係式：$\overline{V_f} = 6.38 Y_{O\infty}^{\ \ 1.01}$，而熄滅氧濃度為 $Y_{O\infty} = 0.14$。

關鍵詞：火焰傳播，熱薄型燃料，無重力場，燃料厚度，外界氧濃度

Abstract

The project aims at simulating and studying the flame spread phenomena over a thermally thin solid fuel in a purely zero-gravitational field. There are two different regions of flame spread against the solid fuel thickness. In the first regions, $\bar{2} \le \bar{2}_{cr}$, the flame-spread rate increases with solid fuel thickness. But in the second region, $\bar{2} \ge \bar{2}_{cr}$, the flame-spread rate gradually decreases as the solid fuel thickness increases. The controlling mechanisms in these two regions are the nature of solid fuel and heat transfer from gas phase, respectively. The solid fuel can be divided three zones according to solid phase temperature profile. They are the preheat zone, intense pyrolysis zone and constant temperature zone. In the preheat zone, the solid phase temperature raises continuously and pyrolysis does not occur yet. In the intense pyrolysis zone, the large parts of energy feedback from flame are used to pyrolyze fuel vapors so the pyrolysis reaction is intense. In the constant temperature zone, the solid fuel temperature maintains pyrolysis temperature until burnout. The flame-spread rate is faster in the higher oxygen concentration environment. The relationship between flame-spread rate and oxygen concentration is found to be $\overline{V_f} = 6.38 Y_{O\infty}^{\ \ 1.01}$ within the range of $0.2 \le Y_{O\infty} \le 0.45$. The predicted extinction limit is at $Y_{O\infty} = 0.14$.

Keywords: flame spread, thermally-thin fuel, zero gravity, fuel thickness, oxygen index

Introduction

The project aims at simulating and studying the flame spread phenomena over a thermally thin solid fuel in a purely zero-gravitational field. It is motivated from previous series of studies [1,2,3], which investigated the structure and behaviors of spreading flame over the thermally-thin solid fuel subjected different gravity intensity. However, no consideration so far is taken for accounting on the exactly zero gravity environment. Experiments and model prove that the flame behavior is affected by ambient oxygen concentration. As ambient oxygen concentration increases the flame-spread rate have the same tendency. If ambient oxygen concentration is lower than a critical value, the flame will extinct [4,5,6].

The objective of this study is to explore the mechanism of flame spread over the thermally thin solid fuel in quiescent, zero gravity environment by changing fuel thickness in detail. And in this special condition, the ambient oxygen concentration is the key parameter to affect the flame spread rate. So its effect is also considered.

Mathematical Model

As shown in Fig.1, which presents the schematic configuration of flame spread model, the flame is stabilized on the side of the fuel bed with a quenching layer (frozen reaction zone) in between. The governing system for the fuel now becomes steady with translation velocity $\overline{V}_f$. The governing equations for gas phase includes 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 $x = x_{\min}$:

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

At $x = x_{\max}$:

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

At $y = y_{\max}$:

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

At $y = 0,\ x_{\min} \le x < 0$:

$$u = 1,\ T = T_s,\ m_w'' = {}^{o}{}_{w} v_w$$

$$m_w'' Y_{Fw} = m_w'' + \frac{\text{«}}{\Pr \operatorname{Re} Le} \left. \frac{\hat{o}Y_F}{\hat{o}y} \right|_w$$

$$m_w'' Y_{Ow} = \frac{\text{«}}{\Pr \operatorname{Re} Le} \left. \frac{\hat{o}Y_O}{\hat{o}y} \right|_w$$

At $y = 0,\ 0 < x \le x_{\max}$:

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

Solid phase:

At $x = x_{\min}$: ${}^{o}{}_{s} = 1,\ T_s = 1$

At $x = 0$: ${}^{o}{}_{s} = {}^{o}{}_{sf},\ k_s \left. \frac{\hat{o}T_s}{\hat{o}x} \right|_{0^-} = \text{«} \left. \frac{\hat{o}T}{\hat{o}x} \right|_{0^+}$

The SIMPLE algorithm [7] is adopted to develop the numerical algorithm. According to the grid test procedures, a 220 x 70 non-uniform grid is adopted in this study. The computation is performed on a PC at National Chiao Tung University.

Results and discussion

Figure 2 displays the flame-spread rate as a function of solid fuel half thickness in the range of $0.0015\,cm \le \bar{2} \le 0.02\,cm$. There are two different regions of flame spread against the solid fuel thickness. In the first region, $0.0015\,cm \le \bar{2} \le 0.006\,cm$, the flame-spread rate increases with solid fuel thickness. This phenomenon is violation of the traditional concept that the flame-spread rate is faster over a thinner solid fuel. This is because that in this region the solid fuel is too thin to pyrolyze enormous fuel vapor to provide combustion so that the flame becomes weaker. When $\bar{2} < 0.0015\,cm$ the flame does not exist anymore. In the second region, $0.006\,cm < \bar{2} \le 0.02\,cm$, the flame-spread rate gradually decreases as the solid fuel thickness increases. Because the thicker fuel is needed more energy to raise its temperature and pyrolyze fuel vapor into air to form the flammable mixture. The gas phase temperature adjacent the solid fuel surface is quenched by solid fuel. When the solid fuel becomes thicker the gas phase temperature adjacent the solid fuel surface will decreases. So the gas phase conduction from flame to solid fuel is weaker so that the vaporization fuel vapor is less and the flame-spread rate is decrement. In this region the flame spread is heat transfer controlled. The trend in the second region is in qualitative agreement with the thermal theory by de Ris [8] for thermally thin fuels. The de Ris theory [8] predicted the flame-spread rate is an inverse proportion with fuel thickness. But the de Ris theory [8] cannot predict the same trend in the first region. We define the critical half thickness $\bar{2}_{cr}$ as the fastest flame-spread rate at this half thickness. But this value is not a constant. For different solid fuels this value is change. In this study $\bar{2}_{cr}$ equals 0.006 *cm.*

The response of solid fuel is shown in Fig. 3(a)-3(d). As shown in Fig. 3(a), the solid phase temperature distribution can be divided three zones: (a) preheat zone, (b) intense pyrolysis zone and (c) constant temperature zone. In the preheat zone, the heat flux from gas phase is totally used to raise solid fuel temperature. Due to this the temperature rises fast in this zone. In the intense pyrolysis zone, the solid fuel temperature slight decreases behind the flame tip and increase gradually. Because the large parts of energy feedback from flame are used to pyrolyze fuel vapors in this zone so that less energy is used to raise solid fuel temperature. This is confirmed from Fig. 3(b) and Fig. 3(d). Figure 3(b) and 3(d) are the distributions of solid fuel density and burning rate. As shown in these figures, the density variation is very fast and the burning rate is relative large in this zone. The density variation is less and the burning rate drops quickly in the constant temperature zone (behind the intense pyrolysis zone). In other words, the pyrolysis is intense in the intense pyrolysis zone and is weak in the constant temperature zone. In the constant temperature zone, the solid fuel temperature reaches pyrolysis temperature and maintains this temperature until burnout. We compare the response of solid fuel at different thickness. It can be found that when the solid fuel thickness increase the solid fuel temperature becomes lower in the intense pyrolysis zone (Fig. 3(a)). Because of thicker solid fuel the more energy is needed to raise its temperature and pyrolyze fuel vapors. This causing the temperature of thicker fuel is lower than one of thinner fuel. As shown in Fig. 3(c), the value of heat flux from gas phase at $\bar{2} = 0.002\,cm$ is about the same one at $\bar{2} = 0.01\,cm$ and greater than one at $\bar{2} = 0.015\,cm$. But the burning rate does not have the same trend (Fig. 3(d)). This result shows that the very thin solid fuel ($\bar{2} \le \bar{2}_{cr}$) cannot pyrolyze enough fuel to burning although the heat flux form gas phase is large. It explains why the flame-spread rate decreases when the solid fuel thickness decreases in $\bar{2} \le \bar{2}_{cr}$ region.

Figure 4 shows the flame-spread rate as a function of ambient oxygen concentration at $\bar{2} = 0.0076\,cm$. The flame-spread rate is faster in the higher oxygen concentration environment. Because the chemical reaction rate is more active in the higher oxygen concentration environment, leading to a higher flame temperature. The stronger flame let the forward gas phase conduction become more intensive and yields faster flame-spread rate. On the other hand, the predicted extinction limit is at $Y_{O\infty} = 0.14$ (extinction limit). However, Olson' experiment [5] found that the extinction limit is $Y_{O\infty} = 0.205$. The prediction of the extinction limit is lower than that by the experiment. It is because the gas phase chemistry is described by a one-step overall chemical reaction and radiation heat transfer does not consider in the numerical model. Far away from the extinction limit, the relationship between flame-spread rate and oxygen concentration is found to be $\overline{V_f} = 6.38 Y_{O\infty}^{1.01}$ within the range of $0.2 \le Y_{O\infty} \le 0.45$. The experiment by Olson [5] found $\overline{V_f} \propto Y_{O\infty}^{1.11}$ for $Y_{O\infty} \ge 0.4$.

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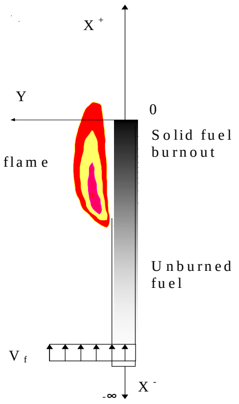


Figure 1. Schematic configuration of flame spread model

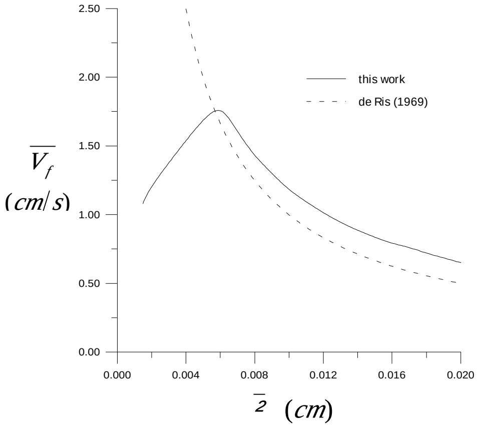
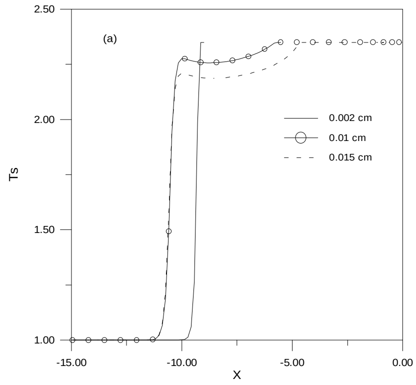


Figure 2. Flame spread rate as function of the fuel half thickness



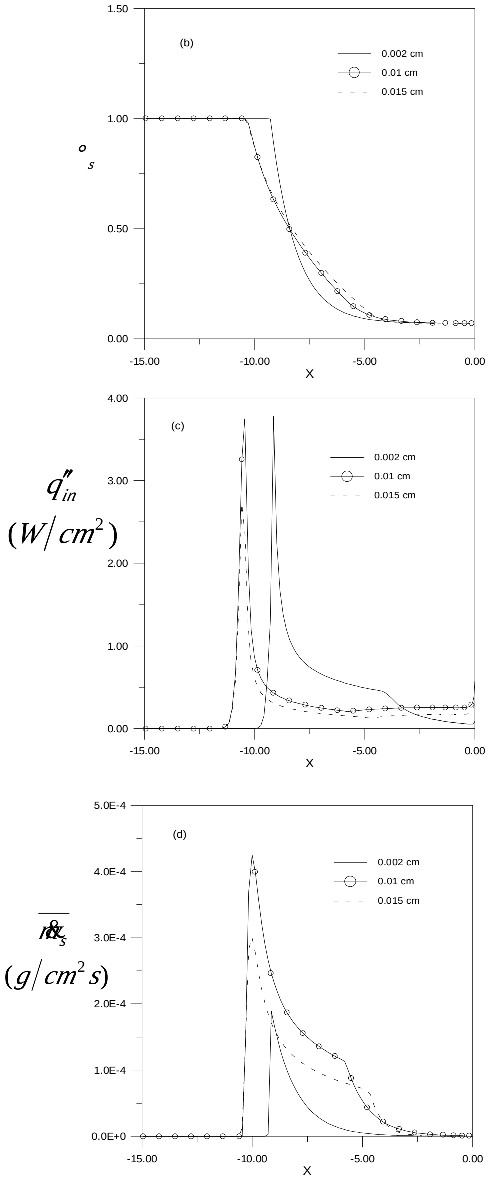


Figure 3. Distributions of (a) solid fuel non-dimensional temperature (b) solid fuel non-dimensional density (c) heat flux from gas phase (d) mass burning rate.

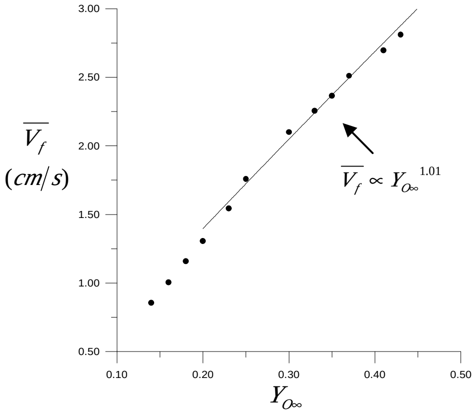


Figure 4. The flame-spread rate as a function of ambient oxygen concentration.