Brief Communication

Numerical Analyses for Downward Flame Spread over Thin and Thick Fuels in a Gravitational Field

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INTRODUCTION

In analyses of opposed flame spread over thermally-thin cellulose fuels, previous investigators [1] have indicated that forward conductive heat transfer in the gas phase from flame to fuel is the controlling mechanism. As the fuel thickness increases, conductive heat transfer through the solid fuel to the virgin portion plays a critical role [2]. Suzuki et al. [3] indicated that the effect of thickness, following the corresponding flame behavior, can be classified into thermally-thin, thermally-thick, unstable, and extinction regimes. However, such effects have seldom been investigated in detail. The purpose of the present communication is to report numerical analyses of how the thickness influences the downward spreading flame over the solid fuel in a gravitational field under natural convection. The computations are performed from thin to thick fuels, with an assumed constant flame spread rate. The numerical solutions are presented as a function of thickness to identify the controlling mechanism and critical features.

MATHEMATICAL MODEL

The flame configuration closely resembles that of Duh and Chen [4]. Hence their conservation equations and boundary conditions in the gas phase used are adopted. These equations and boundary conditions are coupled with the two-dimensional solid phase conservation equations at the interface [5]. The detailed description of the mathematical model can be found in Lin [5].

RESULTS AND DISCUSSION

The solid fuel selected is a cellulose material [5]. The parametric study is based on the change of solid fuel thickness ($\bar{\delta}_s$), between 1 and 10 mm. Table 1 indicates that the predicted flame spread rate ($\bar{V}_f$) decreases with an increase in solid fuel thickness and this is confirmed by experiments, such as those of Suzuki et al. [3]. The four regimes, with different spreading flame behavior are: (I) thermally-thin, (II) transition, (III) thermally-thick, and (IV) unstable.

In regime (I), the flame spread rate is approximately inversely proportional to the thickness. Consequently, the product of $\bar{\rho}_{s_\infty}$ (virgin solid fuel density), $\bar{\delta}_s$ and $\bar{V}_f$ maintains a nearly constant value, of 1.921×10^{-4} g/mm s. The results are close to those of Suzuki et al. [3], in which the value is 1.9×10^{-4} g/mms. Even for the lower bound, $\bar{\delta}_s = 1.5$ mm, both studies are almost the same. For case A in Table 1, Fig. 1(a) shows a representative solid temperature distribution in this regime. The isotherms just ahead of the flame leading edge are almost invariant with y. The two-dimensional aspects that appear behind $x = 0$ are unlikely to affect the flame spread behavior, because the controlling mechanism in this regime is forward heat transfer in the gas phase [4].

In regime (II), although the resultant criteria τ_c, $(=\bar{\tau}(\bar{k}_s\bar{\delta}/\bar{\rho}_s\bar{C}_s\bar{V}_f)^{-1/2}$; $\bar{\tau}$: solid fuel half thickness; $\bar{k}_s$: solid fuel conductivity; $\bar{\delta}$: characteristic length; $\bar{\rho}_s$: solid fuel density; $\bar{C}_s$: solid fuel specific heat) for each case are still regarded as thermally-thin according to the definition of Lastrina et al. [6]; their flame spread rates change only slightly. Hence, this regime is defined as a transition one, from thermally-thin to thermally-thick. Figures 1(b) and 1(c) reveal that the two-dimensional aspects increase, par-

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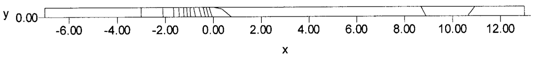
TABLE 1

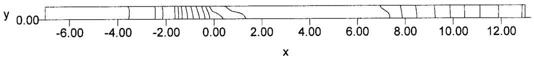
Effect of Changing Solid Fuel Thickness in Normal Environment

Case	$\bar{\delta}_s$ (mm)	τ_c	$\bar{V}_f$ (mm/s)	$\bar{\rho}_{s\infty}\bar{\delta}_s\bar{V}_f$ (g/mm.s)	Regime
A	1.00	0.588	0.684	1.915×10^{-4}	I
B	1.20	0.641	0.572	1.922×10^{-4}	
C	1.40	0.697	0.491	1.925×10^{-4}	
D	1.50	0.731	0.470	1.974×10^{-4}	II
E	2.00	0.961	0.457	2.559×10^{-4}	
F	2.20	1.023	0.429	2.643×10^{-4}	
G	3.00	1.175	0.304	2.554×10^{-4}	III
H	4.00	1.415	0.248	2.778×10^{-4}	
I	5.00	1.639	0.213	2.982×10^{-4}	
J	5.50	1.741	0.198	3.049×10^{-4}	
K	6.00	1.858	0.190	3.192×10^{-4}	
L	6.50	1.989	0.185	3.367×10^{-4}	
M	7.00	2.116	0.181	3.548×10^{-4}	
N	7.50	1.816	0.116	2.436×10^{-4}	IV
O	10.00	2.055	0.084	2.352×10^{-4}	

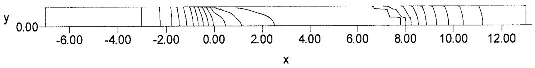
ticularly in the neighborhood of the flame leading edge. When considering two-dimensional solid conduction throughout this study, the streamwise conduction always outweighs that of the one across the fuel in the thermally-thin regime. Up to the transition regime, the latter gradually increases, due to the growing two-dimensional effect; however, its intensity is still markedly less than that of the streamwise direction. Consequently, the flame spread rate in this regime still decreases with an increasing thickness, but at a markedly slower rate than that in the thermally-thin regime. Once the conduction across the fuel becomes of the same order of magnitude as that in the streamwise direction, it enters the thermally-thick regime.



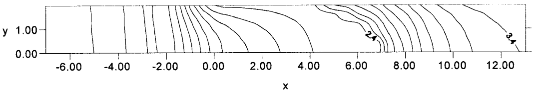
(a) Isotherm values: from 1.1 to 2.4 , ΔT= 0.1(last line :2.4)



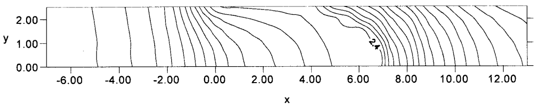
(b) Isotherm values: from 1.1 to 3.2 , ΔT= 0.1



(c) Isotherm values: from 1.1 to 3.2 , ΔT= 0.1



(d) Isotherm values: from 1.1 to 3.4 ,ΔT= 0.1



(e) Isotherm values: from 1.1 to 4.0 , ΔT= 0.1

Fig. 1. Solid fuel temperature distributions for (a) $\bar{\delta}_s = 1.0$ mm, (b) $\bar{\delta}_s = 1.5$ mm, (c) $\bar{\delta}_s = 2.2$ mm, (d) $\bar{\delta}_s = 5.5$ mm, (e) $\bar{\delta}_s = 7.0$ mm (x = 0 is designated as the location of the flame leading edge, where the fuel surface receives a maximum heat flux from gas phase ($T = \bar{T}(K)/298(K)$, $x = \bar{x}(cm)$/characteristic length(cm), $y = \bar{y}(cm)$/characteristic length (=0.1387cm))

This regime (III) complies with the criterion, $\tau_c > 1.0$, of Lastrina et al. [6]. The simulation results demonstrate that the flame spread rate decreases with an increasing fuel thickness at a decreasing rate. Particularly when 5.5 mm $\leq \bar{\delta}_s \leq$ 7 mm, the descendent rate reaches a minimum and the averaged value of flame spread rates of J, K, L and M in Table 1 is 0.19 mm/s. Close examination of Figs. 1(d) and 1(e), which display the solid temperature profiles for $\bar{\delta}_s = 5.5$ (case J) and 7.0mm (case M), reveals that these two profiles closely resemble each other near the flame leading edge area. Hence the resultant flame spread rates are expected to change only slightly in this domain. The behavior also is observed by Suzuki et al. [3]: the corresponding measurements of flame spread rate reach a constant value, equal to 0.2 mm/s for 5 mm $< \bar{\delta}_s <$ 7.5 mm.

We also find that in the thermally-thick regime the surface temperature exceeds the ambient one far upstream. Obviously, the preheat length in the solid phase surpasses that of the gas phase. This higher surface temperature is caused by energy transfer from downstream via solid heat conduction, implying that this profoundly influences the flame spread over the thick fuel. The phenomenon is confirmed by the ratio of total heat flux integrated across the half thickness in the solid at x = 0 to that from the gas phase integrated from x = 0 to far upstream. In this regime this ratio ranges from 18% ($\bar{\delta}_s$ = 3.0 mm) to 36% ($\bar{\delta}_s$ = 7.0 mm).

Regime (IV) occurs at $\bar{\delta}_s \geq 7.5$ mm. A sudden drop in flame spread rate is found between cases M and N in Table 1. Suzuki et al. [3] found that in the range 7.5 mm $\leq \bar{\delta}_s < 8.4$ mm, the flame spread becomes unstable. Thereafter, they classified an extinction regime when $\bar{\delta}_s >$ 8.4 mm, where the continual flame spread cannot progress any further. The difference between regime (IV) in this study and the unstable and extinction regimes in Suzuki et al. [3] is attributed to the facts that the present simulation is based on a constant-flame-rate assumption and the combustion model adopts a one-step overall chemical reaction.

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