Numerical analysis of the effect of fuel load on downward flame spread

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Abstract. This paper performs parameter studies varying sample thickness and volume density to investigate the effect of surface density on downward flame spread using Direct Numerical Simulation (DNS). Surface density is a significant property that affects fuel loads on the fuel surface greatly. The results reveal that all the thin fuels of 70 – 180 g/m² attain a steady state, which means that the flame base and pyrolysis front move downstream with the same rate. Moreover, the propagating rates of the flame base and pyrolysis front decrease with the increasing surface density. Subsequently, the flame contour and flame heat feedback in preheated region are studied. Along the flame base downstream, dimensionless flame standoff distance grows gradually till a peak reaches at appropriately \((Z-Z_b)/Z_f\) of 0.23, and then is reduced to a minimum near the flame front. Radiative heat flux occupies the dominant position upstream the flame base, and its distribution with normalized space \((Z-Z_b)/Z_f\) is established.

The present paper together with previous works can provide further understanding on the effect of fuel loads on downward flame spread.

1. Introduction

Downward flame spread over flammable solid materials is one of the fundamental problems in the fire accidents, and it involves the coupling of chemical reaction and heat transfer progress. Although most works focuses on flame spread over the thermally thick materials [1-5], thin solid fuel has also attracted much attention owing to the flammability.

Previous works tend to examine the effect of flows flied [6-8], buoyancy [9], and sample measurement [10, 11] on downward flame spread over thin fuel, while studies on fuel load on the sample surface are comparatively less researched. De Ris [6] developed an analytical model for flame spread in the forced opposed-flow, where both an exact solution in the thick limit and an approximate solution in the thin limit were obtained. Hirano et al. [7] elucidated the controlling mechanism that causes the instability of downward flame spread in air free flow experimentally, and concluded that the spreading flame would be extinguished once the free-stream velocity was above that of the stable flame-spread limit. Olson and Miller [8] made a comparison of opposed and concurrent microgravity-flame spread over thin fuel oriented vertically in forced convective flow, and presented a correlation to predict flame spread rate. Altenkirch et al. [9] gauged buoyancy effects on flame spread down thermally thin paper samples through varying the ambient oxygen content, ambient pressure, and acceleration of gravity, and found that a dimensionless spread rate correlates well with Damkohler number. Kurosaki et al. [10] and Itoh et al. [11] studied the effect of the fuel width and separation...
distance on downward flame spread along parallel paper sheets theoretically and experimentally, and concluded that FSR depends more the separation distance than the fuel width.

For the thin fuels, surface density, the product of sample thickness and volume density, is a significant property that determines fuel load on the fuel surface. Difference in the fuel load can affect the burning process greatly. Blasi [12] employed a quasi-steady, two-dimensional mathematical model to simulate downward flame spread over thin fuel, in which three main regions of flame spread are established based on the dependence of flame spread rate (FSR) on sample thickness. Lin and Chen [13] conducted numerical analyses to investigate the effect of sample thickness on downward flame spread, and identified the controlling mechanism and critical feature for downward spreading-flame. However, the above mentioned studies merely focus on varying the sample thickness to examine how the fuel loads influence downward spreading flame. Numerically varying sample thickness and volume density using DNS to match the thin sample with varied surface densities is considered the extension to the original approaches.

This paper, therefore, performs parameter studies varying the surface density of thin fuel to model downward flame spread through DNS. Flame standoff distance and heat feedback to the fuel surface are examined, and a correlation that characterizes the radiation heat feedback in preheated region with normalized space was established. The present paper together with the previous works can further deepen our understandings on the effect of fuel loads on downward flame spread, and guide future fire spread modeling.

2. Numerical model
A two-dimensional DNS based on an open-source code [14, 15], Fire Dynamics Simulation (FDS) 5.5.3, revision 7052, was applied to examine the effect of fuel loads on flame spread by varying the sample thickness and volume density. The model is a Computational Fluid Dynamics program which can be used to simulate the fire-driven fluid flow by solving the Navier-Stokes equations. Also, the model employs the one-step, second-order finite-chemistry rate for the gas combustion, the one step pyrolysis for solid fuel, and the 1D heat conduction in the solid phase.

Six thin fuels were modeled where the samples are all 20 cm long and 2 cm wide. The properties are listed in Table 1. Moreover, the solid fuel is assumed to be a cellulose-based material that yields 10% chemically inert char residues and liberates 90% combustible gas products [14-17]. To improve the simulation efficiency and save the computational time, the sample half-thickness plane (dotted line in Figure 1) is considered symmetric. Thus the half domain of 0.05 m width and 0.48 m length is modeled. To eliminate the disturbance caused by the bottom boundary of domain, the sample retains 0.08 m away from the bottom boundary. A hot ignition source with 1000 °C was applied at the sample top end. Once the sample was ignited, the hot source was withdrawn immediately.

![Figure 1. Diagram of the computational domain.](image)
The gas and solid thermo-physical properties and the kinetic parameters of gas-phase reactions [14, 16, 17] are shown below: For the gas phase, $A = 4.23 \times 10^8 \text{ m}^3\text{g}^{-1}\text{s}^{-1}$, $E = 1.13 \times 10^5 \text{kJ/kmol}$, temperature pressure $p_0 = 101325 \text{ Pa}$, heat of combustion $\Delta h_c^0 = 1.58 \times 10^4 \text{kJ/g}$, Pr = 0.7 and $T_0 = 293 \text{ K}$. For the solid phase, $A_s = 1.00 \times 10^{10} \text{s}^{-1}$, $E_s = 1.25 \times 10^2 \text{kJ/g}$, heat of reaction $\Delta h_r^0 = 752.8 \times 10^{-3} \text{kJ/g}$, $c_{ps} = 1.2 \times 10^{-3} \text{kJ/g/K}$, $k_s = 0.06 \text{W/m/K}$, emissivity $\epsilon = 1$.

Table 1. The combinations of surface density used in the model.

| Surface density(g/m$^2$) | Bulk density $\rho$ (g/m$^3$)$\times10^4$ | Thickness $d$ (m)$\times10^{-3}$ |
|--------------------------|------------------------------------------|-------------------------------|
| 70                       | 845.2                                    | 0.08                          |
| 80                       | 869.4                                    | 0.09                          |
| 100                      | 839.6                                    | 0.12                          |
| 120                      | 886.3                                    | 0.14                          |
| 150                      | 858.0                                    | 0.17                          |
| 180                      | 876.0                                    | 0.21                          |

Table 2. The rates of flame base spreading for different grid sizes in the $x$ and $z$-axis.

| Total number of grids | Grid size in $x$-direction(m) | Grid size in $z$-direction(m) | Rate of flame base moving(m/s) |
|-----------------------|------------------------------|------------------------------|--------------------------------|
| 127*720               | $3.94\times10^{-4}$          | $6.67\times10^{-4}$          | 0.0083                         |
| 127*1080              | $3.94\times10^{-4}$          | $4.44\times10^{-4}$          | 0.0086                         |
| 154*1350              | $3.25\times10^{-4}$          | $3.56\times10^{-4}$          | 0.0088                         |
| 231*1350              | $2.16\times10^{-4}$          | $3.56\times10^{-4}$          | 0.0089                         |

Prior to the simulation, grid dependence studies were performed and the resulting rates of flame base moving are shown in Table 2. The grid size of $\Delta x = 3.25 \times 10^{-4} \text{m}$ and $\Delta z = 3.56 \times 10^{-4} \text{m}$ was selected, due to the fact that increasing the total grid numbers to that of 2.3 times of the original total numbers (154*1350) causes the difference of 5.9% in the moving rate of flame base. The time step is set $1 \times 10^{-4} \text{s}$ in the DNS model [14, 16, 17] where the flame is the contour with the heat release rate larger 15000 kW/m$^3$ and the pyrolysis region is the burning rate larger 10 g/m$^2$/s.

3. Results and discussions

3.1. Flame appearance of downward spreading flame

Figure 2 shows the transient process of downward flame propagation along the representative thin fuel surface of 70 g/m$^2$. When the fuel top end is ignited completely, a flame is formed. In figure 2(a-f), the flame is observed to move downward with a constant length. From the flame base to the flame front, the flame standoff distance firstly grows till the peak appears and then decreases. Flame heat feedback to the unburnt fuel surface downstream drives the fuel to pyrolyze and liberates fuel vapor, then participating in the burning process. In the wake of the flame base moving downward, the whole flame sheet is close to the fuel surface in figure 2(d-k) where the flame front is below the fuel end. Subsequently, the flame moves gradually till it decays in figure 2j and figure 2k. Because of all the fuel being burnout, no fuel vapor was released to sustain the flame spreading, eventually resulting in the flame extinction in figure 2l.
3.2. Flame base and pyrolysis front

Location variations of the flame base and pyrolysis front with the duration time are shown in figure 3. After the ignition, locations of the flame base and the pyrolysis front vary linearly with the burning duration, suggesting that a steady flame spread process is attained. Moreover, because of liberating more combustible vapor with a little flame heat feedback, a larger rate of flame base moving is gained for the sample of smaller surface density.

When the flame base moves downward, the pyrolysis rejoin enlarge downstream and therefore causes the pyrolysis front move downward. The propagating rates of the flame base and pyrolysis front as function of surface density, as well as burning duration, are illustrated in figure 4. Both the moving rates of the flame base and pyrolysis front are nearly identical, revealing that the spreading flames along the fuel samples of 70 – 180 g/m² are all steady. A general conclusion therefore is drawn that the moving rates of the flame base and the pyrolysis front decrease with surface density studied numerically, while burning duration increases linearly.

Figure 2. The transient process of downward flame spread along the fuel surface (70 g/m²). Black line is the flame contour with the heat release rate 15000 kW/m³.

Figure 3. Variation of the position with duration time: (a) flame base, (b) pyrolysis front.
Figure 4. Average spread rate and duration time vs surface density.

Figure 5. Dimensionless flame standoff distance as a function of normalized distance $\left(\frac{Z-Z_b}{Z_f}\right)$.

3.3. Flame standoff distance and flame heat flux

Figure 5 reveals dimensionless flame standoff distance as a function of the normalized distance $\left(\frac{Z-Z_b}{Z_f}\right)$, where $D_f$ is the flame standoff distance, $\delta_x$ the minimum grid size in the $x$ direction, $Z_b$ the location of flame base, and $Z_f$ flame length. Near the flame base, standoff distance is small implying that the flame approaches the fuel surface tightly. Subsequently, it increases gradually till a peak is attained and then decays. All the samples of 70 – 180 g/m$^2$ studied in figure 5 behave similar, which clarifies that downward steady flames along thin fuel surface agree reasonably in terms of flame contour, irrespective of surface density of the sample.

Figure 6. Radiative flame heat flux as a function of the position along the fuel surface.

Flame heat feedback to the fuel surface is a driven force that drives the unburnt fuel to pyrolyzate, and thus it is essential to investigate the heat flux profile in the unburnt region. In figure S1 (Supplemental Materials S1), downward along the fuel surface and away from flame base, radiative heat flux occupies the dominant position during the flame spread downward, especially near the flame base (6.5 times of the measurement of convective heat flux).

Due to the importance of the radiative heat flux in the preheated region, correlation of the radiative flame heat flux with the normalized distance $\left(\frac{Z-Z_b}{Z_f}\right)$ is established in figure 6. It can be observed
that the flame radiative heat flux exposed on the sample surface behaves the same trend for all the samples of 70 – 180 g/m². A correlation is obtained,

$$\ln\left(\frac{\dot{Q}_{rad}}{\dot{Q}_{rad,\text{max}}}\right) = -0.75\ln\left([Z_f-Z]/Z_0\right) - 1.37$$  \hspace{1cm} (1)

Where $\dot{Q}_{rad}$ is the flame radiative heat flux to the fuel surface at the upstream position of Z, and $\dot{Q}_{rad,\text{max}}$ denotes the flame radiative heat flux at the position of flame base $Z_0$. The correlation implies that near the flame base, a higher flame radiative heat flux is exerted on the unburnt fuel surface and it would decay far from the flame base.

4. Conclusions
In this work, downward flame spread over the thin fuel was studied using DNS. Parameter studies varying the sample thickness and volume density were performed to investigate the effect of fuel loads on the flame spread process. The major findings are:

(1) Downward spreading flame undergoes a transient rise and then becomes steady for all the thin fuel studied, which implies that the flame base and pyrolysis front move with the same rate. Prior to the flame extinction, the spreading flame move downward with a constant length. When the flame base reaches the bottom of the modeled fuel, the flame eventually goes to the extinction without the fuel vapor.

(2) The moving rates of the flame base and pyrolysis front decrease with surface density while the burning duration time presents an increasing trend numerically.

(3) Dimensionless flame standoff distance presents the same trend that it achieves the peak at $(Z-Z_0)/Z_f = 0.23$ and decreases while $(Z-Z_0)/Z_f > 0.23$. It is found that the fuel loads on the surface of thin sample affects the flame appearance slightly. Downward along the fuel surface and away from the flame base, radiative heat flux from the flame to the fuel surface occupies the dominant position, and its correlation with normalized space $(Z_f-Z)/Z_f$ is developed.

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