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Concurrent flame spread over discrete thin fuels

JeanHyuk Park, Jared Brucker, Ryan Seballos, Byoungchul Kwon, Ya-Ting T. Liao*

Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, OH, United States

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ABSTRACT

An unsteady two-dimensional numerical model was used to simulate concurrent flame spread over paper-like thin solid fuels of discrete configurations in microgravity (0 g with 20 cm/s) and in normal gravity (1 g). An array of ten 1 cm-long fuel segments was uniformly distributed in the flow direction (0 g) or in the vertical direction (1 g). A hot spot ignition source was applied at the upstream leading edge of the first fuel segment. The separation distance between the fuel segments was a parameter in this study, ranging from 0 (corresponding to a continuous fuel) to 3 cm. Using this setup, the burning characteristics, spread rate of the flame base, and the solid burning rate were examined. The flame base spread rates in both 1 g and 0 g cases increase with the separation distance. This is due to the flame jumping across the gaps. For the solid burning rate, the dependency on the separation distance is different in 1 g and 0 g cases. At a flow velocity of 20 cm/s in 0 g, the flame reaches a limiting length and the flame length is approximately the same for all fuel configurations. As the separation distance increases, the heating length (the fuel area exposed to the flame) decreases, resulting in a decreasing total heat input and a decreasing solid burning rate. In 1 g, the flame is long and extends to the last fuel segment before the first fuel segment burns out. This suggests that the heating length is approximately the same in all simulated cases (~total fuel length). However, the flame standoff distance decreases when the separation distance increases. This results in an increasing total heat input and an increasing solid burning rate. Terrestrial experiments were conducted to validate the 1 g model. The experimental results agreed reasonably with the model predictions of burning characteristics, burn durations, and flame spread rates.

1. Introduction

Discrete (or discontinuous) fuel configurations consist of multiple fuel segments separated by non-combustible materials or air gaps. In many practical situations, discrete fuel configurations better represent the fuel load arrangement than a continuous fuel configuration would. Examples of real-world discrete fuels include wildland forest trees, urban buildings, commodities stored in warehouses, and balconies in multi-story apartment buildings. Flame spread across discrete fuel can have very different characteristics from that of continuous fuel. The presence of spaces between the combustibles can serve as barriers and decrease the probability of flame spread [1,2]. However, when the flame does spread, the spread rate for discrete fuels can be higher than for continuous fuels. Many studies suggest that the flame spread rate increases when the fuel element separation distance increases [3], or when the fuel loading (mass per volume) decreases [4]. Some studies suggest that there is an optimal fuel percentage (or porosity) for flame spread [2,5]. Thus, the fire safety concerns for discrete fuel elements can be higher than for continuous fuels. Understanding how fires spread over discrete fuels is crucial for fire safety.

Many studies have been performed on various configurations of discrete fuel elements including horizontal [1,2,4,6,7], vertical [3,5], and sloped [8,9]. For example, Vogel and Williams [6] performed experiments of flame propagation along a horizontal array of vertically oriented matchsticks (with the heads removed). They explored the propagation boundary in terms of matchstick height and separation distance. A theoretical model was also proposed based on a constant ignition temperature and a previously obtained flame standoff profile. Agreement between the theory and the experiment suggested that convective effects are of primary importance in flame propagation at matchstick size scales. Prahl and T'ien [7] studied flame spread across vertically oriented matchsticks in the presence of forced convection (in both concurrent and opposed directions). They presented the necessary conditions for flame propagation in a non-dimensional plot of the separation distance (non-dimesionalized by the matchstick height) and the wind velocity (non-dimensionalized by the natural convection velocity). Watanabe et al. [2] conducted an experiment of flame spread along thin combustible solid (filter paper) with randomly

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* Corresponding author.
E-mail address: yating.liao@case.edu (Y.T. Liao).

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distributed pores. For pore-scales smaller than the flame preheat length, their results showed that the flame spread rate increases with the paper porosity and reaches a maximum value at 20–30% porosity. They hypothesized that this is due to reduction of the paper superficial density. After 40% porosity, the spread rate decreases, and reaches zero at 60% porosity. The authors explained that the formation of pore clusters prevent the flame from jumping over the pores. Also, with more pores the heat input to the paper fuels is reduced.

For upward flame spread, Gollner et al. [3] performed experiments on vertical arrays of horizontally protruding wood matchsticks. They investigated the influence of separation distance between the fuels on flame spread, time to burnout, and mass loss rates. Miller and Gollner [5] conducted experiments on upward flame spread over vertical arrays of alternating lengths of PMMA and insulation. They found that the flame spread rate peaks at around 67–89% fuel percentage (ratio of the fuel length to the total length), and that there is a fuel percentage limit below which the flame fails to spread. They also found that the fuel mass loss rate per burning area negatively correlates with the fuel percentage. They theorized that air entrainment by the flame plays a significant role as it promotes oxygen convection, reduces the flame standoff distance, and intensifies the heat feedback to the fuel.

These previous studies provide insight on how flames propagate in certain discrete fuel arrangements. Some studies also contain theoretical formulations of the observed phenomena. However, to our knowledge there are no numerical studies to link the theory to the experiments and to provide a comprehensive understanding of this process. Numerical modeling offers several attractive features, such as providing access to variables that cannot be easily measured (e.g. heat flux distributions on the sample surfaces, local solid burning rate, flow velocity field). Also, it allows theory to be tested. The objective of this work was to use numerical tools to gain a thorough understanding of burning and flame spread processes over an array of discrete fuel elements. In particular, the effects of gaps and the mechanisms that cause a faster flame spread over discrete fuel configurations were investigated. We focused on the concurrent flow configuration and flat thin fuel elements. Two scenarios were considered: upward flame spread in buoyancy-driven flow in normal gravity (1 g cases) and concurrent flame spread in purely forced flow at 20 cm/s in zero gravity (0 g cases). In normal gravity, buoyancy flow confounds the fire growth process and may impede observation of certain fundamental underlying physical processes. Performing 0 g simulations helps us to gain a comprehensive understanding of flame spread characteristics. The flow speed used in the 0 g cases (20 cm/s) is what is typically observed in orbiting spacecraft. This flow is due to air circulation used to keep the atmosphere well mixed and to provide cooling for electronics. Therefore, the 0 g results are also relevant to fire safety in space.

Last, experiments were performed to validate the 1 g model. Detailed simulation results and selective experimental data are presented in this paper.

2. Numerical modeling

The model configuration for the upward flame spread (1 g) case is shown in Fig. 1. An array of ten fuel samples is placed vertically. The fuel samples are separated by gaps of air. The separation distance between samples (gap size) is a variable ranging from 0 (continuous setup) to 3 cm in different simulation cases. The length of each fuel sample is 1 cm, so there are 10 cm of the total fuel length in all simulations. In other words, the total fuel mass is constant while the total fuel span (defined as the distance between the bottom of the lowest fuel segment and the top of the highest fuel segment) varies in different fuel-gap configurations. The fuel sample is modeled after Whatman filter paper with material properties of cellulose. The filter paper's thickness is measured to be 0.23 mm. In the numerical model, the fuel is assumed to yield 10% of mass (chemically inert char) during the combustion process. To ignite the sample, a hotspot (corresponding to a hot wire in two-dimensional simulations) at 1000 °C is applied 0.1 mm below the first sample (see Fig. 1) for 3 s.

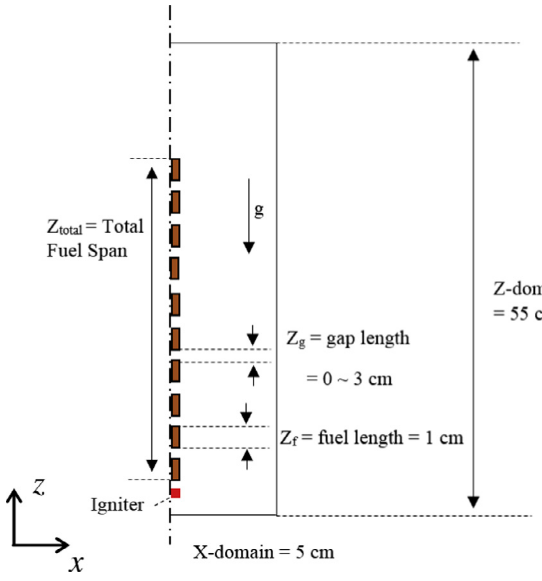

Fig. 1. Numerical model configuration.

Two-dimensional Direct Numerical Simulation was performed using an open-source code, Fire Dynamics Simulator (FDS) 6.2.0, revision 22,352. The model included one-step finite-rate gas-phase combustion, one-step first-order solid pyrolysis, and gray gas radiation for all gas species. The gas and solid thermo-physical properties, the kinetic parameters of the gas-phase reactions, and solid pyrolysis model used in this work are the same as those in [10,11]. Parameters that are not FDS default values are listed in Table 1. Details of the model setup and parameters can be found in [10,11].

To save computational time, the sample half-thickness plane (dash-dot-line in Fig. 1) is assumed to be symmetric. Therefore, only half of the flow domain is simulated and half of the solid thickness is used. The computational domain ranges from 0 to 55 cm in the fuel length direction (z-direction, where $z = 4$ cm corresponds to the bottom edge of the first fuel sample) and from 0 to 5 cm in the fuel thickness direction (x-direction, where $x = 0$ cm corresponds to the sample half-thickness plane). The grid sizes are $\Delta x = 0.7576$ mm and $\Delta z = 1.421$ mm, resulting in $66 \times 387 = 25{,}542$ grids. Grid dependence studies were performed for both continuous and discrete fuel cases. Increasing the grid number to 132×1000 (~5.2 times of the original grid number) resulted qualitatively in the same flame spread processes with less than 5% difference in burn durations [11].

In the purely forced flow simulations (0 g cases), all simulation conditions and models are identical to those in 1 g simulations except that a forced flow at 20 cm/s is applied in the fuel length direction (positive z-axis).

3. Computational results

3.1. Upward flame spread across discrete fuel samples

Upward flame spread with four different fuel-gap configurations, including the continuous case, was simulated. A video that compares the simulation results of all cases is included in the Sup-