Upward Flame Spread over Discrete Fuels

Colin H. Miller, Michael J. Gollner

aUniversity of Maryland Department of Fire Protection Engineering
3106 J.M. Patterson Building
University of Maryland
College Park, MD 20742-3031

Abstract

Upward flame spread over discrete fuels has been analyzed through experiments on vertical arrays of alternating lengths of PMMA and insulation board. By manipulating the lengths of the PMMA fuel and the insulation, trends relating flame spread to fuel loading were assessed.

The peak upward flame spread rate was observed in non-homogeneous fuel arrays where the percentage of exposed fuel area was below unity. In arrays with fuel percentages between 67-89%, it was hypothesized that increased air entrainment, which subsequently modifies heating rates, resulted in a maximum flame spread rate. Below these fuel percentages, the flame spread rate decreased. At very low fuel percentages, deceleration of the pyrolysis front was observed. This behavior indicated that a porous fuel bed approximation, which might be applicable when the fuel percentage is near unity, would be highly unsuitable for the markedly discrete behavior observed at low fuel percentages. Trends for the mass fluxes and flame heights were also assessed, and it was noted that the mass loss rate per burning area was negatively correlated with fuel percentage.

A method for approximation of the fuel spread rate at various fuel percentages was also proposed. This estimate requires reasonable estimates for the homogeneous flame spread rate and the lowest fuel percentage that sustains spread.

Keywords: upward flame spread, discrete fuels, PMMA, vertical wall fire

*Corresponding author
**Phone Number: 301-405-6667 (Michael J. Gollner)
Email address: ubertus@umd.edu (Colin H. Miller)
Nomenclature

$x_{p,fuel}$ Fuel pyrolysis zone (vertical length of burning regions only) [cm]

$x_{p,inert}$ Inert pyrolysis zone (vertical length of the insulation between burning regions) [cm]

$x_{p,total}$ Total pyrolysis zone (vertical length of burning region including both fuel and insulation) [cm]

$A_{burn}$ Burning area (fuel surface area involved in pyrolysis) [m$^2$]

$\dot{m}$ Mass loss rate [g/s]

$V_p$ Flame spread rate (advancement rate of total pyrolysis zone) [cm/s]

$V_{p,fuel}$ Fuel spread rate (advancement rate of fuel pyrolysis zone) [cm/s]

$(fuel \%)$ Fuel percentage (area of array consisting of exposed fuel)

$(fuel \%)_{crit}$ Critical fuel percentage (lower limit of fuel percentage at which flame will not successfully spread)

$\dot{m}_{\dot{m}}^{\prime\prime}_{fuel}$ Mass loss rate per burning area [g/s·m$^2$]

$\dot{m}_{\dot{m}}^{\prime\prime}_{total}$ Mass loss rate per total pyrolysis area [g/s·m$^2$]

$a, b$ Coefficients in Eq. 9 employed to develop a logarithmic fit for the flame spread rate [cm/s]

$x$ Represents fuel percentage as the independent variable in Eq. 9

Abbreviations

PMMA Poly(methyl methacrylate)

1. Introduction

A typical fuel load in a wildland environment consists of many discrete, non-homogeneous fuels, which can be concentrated in varying densities. Similarly, a warehouse typically features units of commodities which are stored in various discrete arrangements, covering up to 90% of the available floorspace [1]. In the event of a fire, flames can spread horizontally between commodities or vertically in the typical rack storage scenario. In the urban environment, multi-story buildings possess exterior levels and balconies, which present additional high-risk discrete flame spread scenarios. For this reason, it is important to understand expected phenomena of discrete fire spread, addressing whether discretization of fuels will accelerate, decelerate, or extinguish a spreading fire. An understanding of the associated geometry is essential to predicting fire behavior. The following study delves into an investigation of discrete fuels via empirical
analysis of vertical flame spread, a canonical configuration for fire research.

Some previous research related to wildfire spread has focused on regimes where assumptions of a homogeneous fuel bed can be taken. Thomas [2, 3] developed correlations for porous fuel beds of various materials under external forced flow scenarios. He determined that the rate of horizontal flame spread was inversely proportional to the bulk density of fuel for both scenarios. This means that, for the range of arrays that were studied, an increased density of fuel actually inhibited flame spread; indeed, this implies that the spread of the fire is most likely oxygen-limited. In 1995, Dupuy [4] performed experiments with flame spread over various fuel beds and reaffirmed the trend for the flame spread rate to decrease with fuel density. Rothermel [5] characterized flame spread in porous fuel beds in his mathematical model for wildland fuels in 1972. In addition to hypothesizing a slower rate of flame spread for densely packed fuels, he also theorized a decrease in the spread rate as fuel density decreased beyond a certain threshold. In the loose arrangement, a lack of fuel and heat losses would result in slower spread rates. Therefore, it was hypothesized that there would be an optimal fuel density for flame spread, and experimental results confirmed this correlation. Rothermel characterized the fuel density as a packing ratio, which measures the fraction of the fuel array volume that is occupied by fuel. The optimal packing ratio for flame spread rates varied based upon the type and size of the fuel.

Some research has also been conducted on discrete fuels in which an assumption of homogeneity is not readily appropriate. These experiments involved flame spread across discrete fuel elements as opposed to flame spread across a homogeneous material or fuel bed. Watanabe et al. [6] looked at flame spread across horizontal, combustible filter paper perforated with holes (non-combustible regions). For the two-dimensional array of perforated filter paper, a gap that spanned the entire apparatus (perpendicular to the direction of spread) was deemed a slit. The probability for a flame to traverse a slit was closely related to whether the slit length exceeded the pre-heat length, with greater slit lengths resulting in low flame spread probabilities. An increase
in the flame spread rate was also observed as porosity increased from 0% to approximately 20-30%. Any further increase in porosity led to a decrease in the spread rate until approximately 50-60% porosity, at which point the flame failed to spread. Abe et al. [7] continued similar work, utilizing filter paper with randomly distributed pores to simulate urban fires, which have regions of fuel (e.g., buildings) and areas that lack fuel (e.g., streets, empty lots). The filter paper was perforated with pores of 4 and 8 mm, and porosity levels of 40-60% were considered. The probability for the flame to spread across the filter paper was again determined to be very closely related to the number of slits formed, and the number of slits was positively correlated to porosity.

Arrays of matchsticks (with the heads removed) have been utilized to study flame spread along discrete fuels [8, 9, 10, 11]. Recently, Gollner et al. examined discrete fuel behavior through an investigation of vertical matchstick arrays [12]. Flame spread over vertical arrays, or the advancement of the ignition front, was found to be a function of spacing between the matchsticks. When the spacing was 0 cm, a linear fit was applied, but, as the spacing was increased to a maximum of 1.4 cm, power law dependencies were assumed due to buoyant acceleration. As the spacing between matchsticks was increased, the flame spread rate also increased. Even though the distance between fuel elements increased, the flame attained unobstructed impingement onto the next fuel element, resulting in faster spread. Furthermore, in all setups where the spacing was greater than 0 cm, the pyrolysis front actually accelerated over the height of the array. Convective heat transfer correlations were found to nearly predict the burning behavior of this accelerating pyrolysis front.

It should be noted that nearly all previous experiments on flame spread over discrete fuels have been conducted with thermally thin fuels. Thermally thin fuels exhibit minimal internal thermal gradients, which can significantly alter the ignition process. In the following experiments, we take a new approach, employing thermally thick fuels in a canonical upward flame spread configuration.

The primary objective of this study is to empirically analyze important parameters associated with upward flame spread over discrete fuels. This will
naturally involve a disconnected pyrolysis front, which changes the distribution of the mass flux released by the fuel. The flame itself will then be subject to different entrainment patterns, and it is possible for increased oxidizer to become available due to the gaps in the pyrolysis front. It is not fully known how the flame dynamics change in such a scenario: notably, it is not readily identifiable whether a disconnected pyrolysis front should be modeled as a single flame emitted by a porous fuel or as multiple fires anchored at discrete fuel elements. Not only is the pyrolysis zone disconnected, but also the unburnt fuel ahead of the flame front. The spacing of the fuel will influence which region of the flame has the greatest effect on the unburnt fuel; for example, significant spacing in a large fire may put the unburnt fuel in a zone where radiation effects become more important. If the spacing is beyond a certain threshold, extinction of the flame may also occur. In turn, the outcomes of all these scenarios are subject to the transient development of the flame front.

By examining parameters that are necessarily intertwined with the flame spread, an understanding of expected discrete flame spread behaviors can be obtained. Throughout this study, particular attention is focused on the relationship between the flame spread rate and the streamwise lengths of fuel and spacing. This relationship can elucidate the influence of factors relevant to flame spread over discretized fuels. Further correlations, including the mass loss rate and the flame height, are also studied. Results will further an understanding of discrete fuels, a common scenario for many real-world conflagrations.

2. Experimental Setup and Procedure

2.1. Test Apparatus and Experimental Design

A 0.91-meter tall apparatus, pictured in Fig. 1 was developed to support discrete fuels in a vertical orientation while allowing for surface temperature measurements, video footage, and mass loss measurements. An aluminum frame was built to hold Superwool 607 insulation in a 90° vertical position. 2.5-cm wide aluminum shims were bolted on top of the insulation and ran the length of the
Figure 1: Photograph of apparatus and associated data acquisition equipment, including the mass balance, camera, and infrared camera.

apparatus (91.5 cm) vertically. These shims were used to hold alternating blocks of PMMA and insulation board against the apparatus, leaving a 20-cm exposure width for the PMMA and the insulation. The PMMA and insulation board were cut and sized for each experiment. This vertical fuel-holding apparatus was then placed upon a mass balance, with the base of the setup held 12 cm above the surface of the table. Mass data was measured via the mass balance and sent to an adjacent computer. This setup was safely positioned under a small exhaust hood and fitted with vertical, flameproof draperies on three sides, leaving the front section exposed. A Casio Exilim camera was positioned in front of this setup in order to record the flame height progression at 25 fps. A FLIR Thermacam SC3000 with a spectral response of 8 to 9 µm was also positioned in front of the setup; this camera operated using a 100-500°C filter with a user-imposed image refresh rate of 4 fps. The exhaust airflow was measured and kept at a constant low velocity between tests.
2.2. Establishment of a Discrete Fuel Array

The experimental apparatus was designed to fit arrays with many different lengths of alternating fuel and insulation. 10 cm above the mass balance (22 cm above the table surface), bolts served as base pegs to hold the first piece of insulation in the apparatus. A 10-cm clear distance was established by the first piece of insulation so that air entrained below the array could pass upward consistently and exhibit minimal perturbations (Fig. 2).

This first piece of insulation was followed by a block of PMMA that was 2 cm in vertical length. This block of fuel served as the ignition source for all experiments and was immediately followed by a 2-cm length of insulation. All experiments retained this same basic structure for the bottommost region of the apparatus to achieve relative consistency in ignition and preheating over multiple tests.

The subsequent fuel array was then varied based on the scenario to be tested.
Every fuel array possessed consistent lengths of fuel and insulation, stacked one upon the other in an alternating pattern. For example, the standard setup in tests of 4-cm fuel and 1-cm insulation lengths is displayed in Fig. 2. Note that a fuel-spacing-fuel-spacing pattern is followed within the array until approximately 34 cm from the bottom of the ignition block. All tests maintained this alternating pattern until approximately 30-35 cm from the bottom of the ignition block. Because the pyrolysis front can accelerate as it travels up the apparatus, a consistent array height was maintained to allow for proper comparisons between tests.

It is important to note that the pieces of insulation were always slightly thicker than the PMMA blocks, which affected the flushness of the array along the vertical face. Confounding effects of these perturbations in vertical flushness did not manifest themselves in overall trends when PMMA blocks were at least 4 cm. Tests with smaller PMMA blocks were found to be inconsistent, which was likely a result of the many perturbations associated with the large number of fuel-to-insulation transitions. These tests were discarded.

Finally, a sheet of insulation board, 27 cm in length, was placed above the fuel array. This maintained a flush inert surface above the fuel so that flame characteristics such as flame height would not be affected by a sudden change in the vertical surface.

2.3. Ignition Procedure

For our experiments, we minimized the amount of preheating to the fuel array during the ignition phase by employing a heat shield. The heat shield utilized a small sheet of metal that was wedged between the ignition block and the 2 cm insulation above it. A sheet of plywood sheet sheathed in metal also leaned against the apparatus at an angle 45° from the vertical (displayed in Fig. 2). As the ignition block was heated, this heat shield forced hot convective gases away from the apparatus.

Before ignition, the centerline exhaust velocity of the small hood was measured with a hot wire anemometer and recorded. The airflow in the exhaust
system could vary significantly due to changes in damper settings at other locations in the laboratory; moreover, the level of exhaust was found to be a probable source of variability in the observed flame spread rates. For this reason, the centerline exhaust velocity was consistently kept between 2.0 to 2.5 m/s (1.8 to 2.2 * 10^{-4} m^3/s) in the exhaust opening (10-cm radius).

To achieve ignition, two blowtorches were applied directly to the ignition block, above which the heat shield was positioned. Approximately 15 seconds after uniform burning of the ignition block was attained, the heat shield was removed and the flame was allowed to naturally spread up the vertical face of the apparatus.

2.4. Flame Height Processing Technique

In order to avoid changes in the measurement technique between tests, a computerized method was employed to calculate flame height. Each frame from the raw video was converted to grayscale, and an average grayscale image was developed from 125 frames (representing a 5 second period). Each pixel in this image was then scanned, with pixels of higher brightness considered activated (i.e., from a scale of 0 to 1, 0.05 was chosen as the activation threshold for each pixel). Subsequently, if 10% of the pixels in a horizontal line spanning the fuel array were activated, this line was determined to have a positive flame presence. This litmus test was applied to all horizontal lines spanning the apparatus height. The largest vertical distance with a continuous flame presence was then determined to be the representative flame height. This process proved repeatable and reliable in all tests when the ambient filming conditions were sufficiently dark.

2.5. Infrared Thermography

By tracking the temperature contour corresponding to the ignition temperature, an effective pyrolysis front can be located to determine the flame spread rate. Determination of the location of the pyrolysis front by means of a temperature measurement has been performed in various studies [13, 14, 15], and this process is based on the concept of an ignition temperature.
Our initial experimental approach relied on thermocouples, which were melted directly to the surface of the PMMA along the centerline. However, thermocouples would occasionally become detached from the surface and extend into the flaming region, artificially raising the measured temperature and perturbing the flow of hot gases. Moreover, this process proved incredibly tedious as experimental repeatability necessitated the making and fitting of hundreds of new thermocouples. Consequently, infrared (IR) thermography was determined to be a more suitable choice for experimentation. Thermal imaging cameras can also take instantaneous temperature measurements at a wide viewing angle, which makes thermographic data more versatile than point measurements provided by thermocouples. We utilized a FLIR Thermacam SC3000 for our experiment, which operates in the 8-9 µm range.

Because combustion gases have finite transmittance, the temperature readout of the IR camera is not necessarily indicative of the true temperature of an object behind the flame. Previous researchers [13, 14, 15, 16, 17, 18] have employed IR filters in order to filter out emission bands from carbon dioxide, which emits strongly at 2.7 and 4.3 m, and water vapor, which emits strongly at 2.7 and 6.3 µm [19]. Soot, on the other hand, has a continuous emission spectrum, so it is possible for a very sooty flame to affect temperature measurements of a surface behind the image. Nevertheless, Parent et al. [17] performed experiments on a vertically mounted PMMA slab of identical width to this experiment, and, when analyzing IR images, they found that the background contribution of the soot was hardly visible, minimally affected the extracted temperatures, and contributed quite homogeneously. In addition, Forst and Roos [20] found that the PMMA emission range is not far from being a black surface, and Sohn et al. [21] have successfully used an assumed emissivity of 0.92 to obtain accurate readings from infrared images. Previously, Urbas and Parker [15] successfully applied an infrared pyrometer in the range of 8-12 m to measure the surface temperature of burning wood specimens. Given that our camera’s spectral response lies within the range of Urbas and Parker’s camera, this was a promising precedent, especially since PMMA should be less affected by soot emissions than
burning wood.

Validation of our temperature measurements, nonetheless, had to be attempted. Therefore, tests were simultaneously instrumented with thermocouples and recorded by the IR camera. After several small-scale tests were conducted, an assumed PMMA emissivity of 0.92 was found to give reasonable temperature readings for the infrared images, where accuracy was a measure of similarity to thermocouple values. Fig. 3 displays four temperature profiles from both the IR camera and the thermocouples from a validation test in which the IR spot measurements were taken at the approximate thermocouple locations. In total, 9 thermocouples were employed in this test, and the average percentage difference between the absolute temperatures from the IR data and those from the thermocouples was 3.4% at the time of ignition (i.e., when raw data from the IR camera first indicated 573 K). Differences of this magnitude were determined to be acceptable. In comparison with the thermocouples, infrared images and measurements revealed a much clearer picture of the pyrolysis front location. Smoother overall fits for temperature data were afforded by the infrared images, which did not suffer from the occasional dramatic fluctuations of the thermocouples. It was also possible to take more temperature measurements per test, and these measurements were taken from 2-cm-wide lines along the center of the apparatus (see Fig. 4). All temperature data referenced in this project are derived from infrared thermography.

3. Definition of Discrete Flame Spread Parameters

One of the first issues associated with discrete fuels involves discontinuities along the pyrolysis zone. Typically, the pyrolysis zone is continuous and easily defined as the distance over the burning material. However, in a discrete fuel configuration, it is now conceivable that the burning region will consist of multiple sections of disconnected fuels. For this reason, different regions of the pyrolysis zone must be defined. The total pyrolysis zone, or $x_{p,\text{total}}$, refers to the distance associated with both the burning PMMA and the insulation that
Figure 3: Raw data obtained from thermocouples and the infrared camera for a sample validation test.

Figure 4: Sample infrared image, taken from the spreading phase of 8 cm fuel/4 cm spacing test #2. Note that the horizontal lines along the centerline of the apparatus display the locations of the temperature measurements made by the software during post-processing.
may lie between. The fuel pyrolysis zone, \( x_{p,fuel} \), is the total vertical distance of burning PMMA fuel; this distance represents the true pyrolysis region. Lastly, the inert pyrolysis zone, \( x_{p,inert} \), consists of the insulation that lies in between the burning PMMA. All three definitions would then be related by the following equation,

\[
x_{p,\text{total}} = x_{p,fuel} + x_{p,inert}
\]  

Fig. 5 displays a side-view diagram of a vertical fuel array with alternating lengths of fuel and inert material. The total pyrolysis zone consists of three blocks of fuel contributing to the fire along with two sections of the inert wall. \( x_{p,fuel} \) and \( x_{p,inert} \) can be determined from our previous definitions, which lead to the following equations:

\[
x_{p,fuel} = \sum_i x_{p,fuel(i)} = x_{p,f(1)} + x_{p,f(2)} + x_{p,f(3)}
\]

\[
x_{p,inert} = \sum_i x_{p,inert(i)} = x_{p,inert(1)} + x_{p,inert(2)}
\]

In the typical upward flame spread scenario, the burning area is computed as the product of the total pyrolysis region and the width of the burning material. In discrete flame spread, a more appropriate burning area, \( A_{burn} \) would be

\[
A_{burn} = x_{p,fuel} \times \text{width}.
\]

This new burning area should be utilized to determine the mass flux of fuel from the surface via the common equation

\[
\dot{m}'' = \frac{\dot{m}}{A_{burn}}.
\]

The flame spread rate, \( V_p \), is another parameter that must be clarified for discrete cases. This refers to the velocity at which the pyrolysis front travels across a surface. In discrete fuel configurations, it must be realized that the
Figure 5: Graphical representation of a vertical array of discrete fuels.

pyrolysis front will reach the edge of one unit of fuel and temporarily halt. If more fuel is oriented nearby, the flame will steadily raise the temperature of this adjacent unit until it also begins to pyrolyze and ignite; a new pyrolysis front will then spread across its surface. These discontinuities in the spread of the pyrolysis front complicate measurement of the spread rate, $V_p$. Throughout the remainder of this paper, the flame spread velocity (or flame spread rate), $V_p$, will refer to the total vertical distance traversed by the pyrolysis front over time. This distance was previously defined as $x_{p, total}$, which includes both combustible and non-combustible regions. Defined this way, the flame spread rate continues to be the rate at which flame spreads across the fuel arrangement in the direction of interest. However, a quantification of the rate at which the pyrolysis front moves across the fuel is also relevant. This parameter will be termed the fuel spread velocity (or fuel spread rate), $V_{p, fuel}$, and it refers to the distance of fuel traversed by the pyrolysis front over time. Unlike the flame spread velocity, calculation of the fuel spread velocity excludes any non-combustible region. This fuel spread rate is calculated by ignoring the inert
regions of the spacings and looking only at the vertical distance of fuel consumed, $x_{p, fuel}$. Under a homogeneous flame spread scenario (no spacing), this velocity will necessarily be equal to the spread rate; however, $V_{p, fuel}$ will always be less than the spread rate for discrete fuels. The fuel spread velocity is an important parameter because it indicates how quickly a certain quantity of fuel is becoming involved in the flame spread process. A fast fuel spread velocity indicates that a significant amount of fuel is quickly contributing to the overall heat release rate of a fire. On the other hand, a fast flame spread velocity may or may not indicate that a large amount of fuel is burning because calculation of $V_p$ includes inert regions for discrete scenarios. Distinction of these two parameters will be maintained in subsequent discussions. As a form of further clarification, the following equations succinctly define the flame spread and fuel spread velocities:

$$ V_p = \frac{dx_{p, total}}{dt} \quad (6) $$

$$ V_{p, fuel} = \frac{dx_{p, fuel}}{dt} \quad (7) $$

4. Results

4.1. Flame Spread Rate

The pyrolysis height $x_{p, total}$, which is the distance between the advancing pyrolysis front and the bottom of the ignition block, had to be quantified in order to determine $V_p$ and $V_{p, fuel}$. $x_{p, total}$ was calculated under the conjecture that the pyrolysis temperature of PMMA was 300°C, an assumption that has been utilized by previous researchers [22]. When the PMMA reached this temperature, a consistent decrease in temperature rise was observed, supporting the claim that the ignition temperature was approximately in this region. This postulation enabled the following measurement technique: As the flame traversed the fuel array, infrared thermography captured average temperatures of 2-cm-wide sections along the centerline of the apparatus. The derived temperature data was then smoothed by means of a polynomial fit; subsequently,
the intersection of this fit with 300°C was established as the ignition time for each respective height. These ignition times represent the instants at which the pyrolysis front reached a certain height. Given these ignition times over the height of the array, average flame spread rates were determined by applying a linear fit to each test.

It was noted that a linear fit applied to points along the entire height of the fuel array could be influenced too heavily by either the ignition region or compounded acceleratory effects at the top of the apparatus. Consequently, these linear fits were also compared to linear fits from the middle portion of the fuel array (i.e. between 10 and 25 cm in height). It was found that the measured flame spread rates between a total linear fit and a linear fit of the middle portion differed by an average of 8.8%, with more significant differences being observed in the tests with low fuel percentages. When spread rate data from each of these methods were plotted, no difference in trends was observed; only slight differences in reported magnitude were witnessed. Consequently, it was determined that obtaining the flame spread rate from a linear fit of the entire height of the fuel array was appropriate for this study.

Once 3 to 4 individual tests with identical fuel array patterns (i.e., same fuel length and spacing) were completed, a flame spread rate and fuel spread rate was determined. For each test, all ignition times were normalized by setting the time where the first location ignited as time \( t = 0 \). Subsequently, all ignition heights from identical test cases were plotted vs. ignition times, and a linear fit of all data points yielded the flame spread rate \( V_p \) as the slope. The fuel spread rate \( (V_{p,\text{fuel}}) \) was likewise determined from a plot of fuel pyrolysis heights vs. ignition times. Based on a linear regression, a 95% confidence interval for the slope was established; this confidence interval is displayed for each point in Figs. 6-7 as an error bar.

The fuel percentage of the array was then used to compare results from different discrete fuel arrays. The fuel percentage is simply the hypothetical percentage of the array surface area consisting of exposed fuel. For example, a test with 4 cm slabs of fuel and 1 cm spacing would possess a fuel percentage
of \((\text{fuel length} / \text{total length}) = (4 \text{ cm})/(4 \text{ cm} + 1 \text{ cm}) = 80\%\). This quantity succinctly reveals the basic structure of the discrete fuel array. Both the flame spread rates \(V_p\) and the fuel spread rates \(V_{p,\text{fuel}}\) were plotted against fuel percentages in Figs. 6-7.

![Graph showing flame spread rate and fuel spread rate vs. fuel percentage for 4-cm fuel and homogeneous arrays.](image)

Figure 6: Flame spread rate and fuel spread rate plotted vs. fuel percentage for the 4-cm fuel and homogeneous arrays.

Plotting flame spread rate vs. fuel percentage provides perhaps the most intuitive quantification of results. For 4-cm slabs of fuel (Fig. 6), the spread rate slowly starts to increase from the homogeneous case as spacing is increased. This spread rate peaks at around a 67% fuel composition, in the scenario where 2-cm spacing was employed. This represents the optimal spread rate configuration for fuel arrays with 4-cm PMMA blocks. As the fuel percentage is lowered from this optimal configuration, a significant decline in spread rate is observed. Tests with 4-cm fuel and 4-cm spacing, representing a fuel composition of 50%, exhibit a spread rate that is 0.05 cm/s slower than the homogeneous case. This trend of decreased speed with increased spacing should continue until a threshold value is reached, upon which flames will no longer successfully spread up the apparatus.

For the fuel arrays with 8-cm PMMA blocks, a nearly identical trend is observed (Fig. 7).
Figure 7: Flame spread rate and fuel spread rate plotted vs. fuel percentage for the 8-cm fuel and homogeneous arrays.

The fuel spread rate is also a function of the fuel percentage. As the percentage of fuel in the array increases, $V_{p,\text{fuel}}$ increases. This trend is observed for all points in both the 4-cm fuel and the 8-cm fuel arrays, as shown in Figs. 6, 7, 8, and 9. A maximum fuel spread velocity is attained for the homogeneous tests at 0.087 cm/s, which necessarily coincides with the homogeneous flame spread rate as well. Both the 4-cm fuel and 8-cm fuel arrays exhibit a minimum fuel spread velocity of approximately 0.02 cm/s at a fuel percentage of 40%. The positive correlation of fuel spread rate with fuel percentage is consistent across all tests.

4.2. Flame Height

Flame heights for each test were computed from video footage via MATLAB processing. An 8th-order polynomial fit smoothed flame height data, and a normalized start time was developed based on the time when the lowest temperature measurement reached the pyrolysis temperature (300°C). Flame heights vs. time are plotted in Figs. 8 and 9 for the 4-cm fuel and 8-cm fuel arrays, respectively. The homogeneous case (no spacing) is also included in both figures. For the first 200 seconds, flame heights for all tests are nearly the same, increasing...
from 12 to 37 cm in height. After this, some tests exhibit a deceleration in the flame spread rate, beginning with the largest spacing. By 400 seconds, the homogeneous case possesses the largest flame height.

4.3. Mass Loss Rates

Mass loss rates for each test were determined from the mass loss data. By eliminating outliers and applying an 8th-order polynomial fit, the mass loss rates for each test were determined. In order to compare the mass loss rates at various
times of the test, the starting point for every test was normalized as the point when the first temperature measurement of the fuel array reached the pyrolysis temperature (300°C). Mass loss rates from identical fuel arrays were averaged to determine a representative mass loss rate for each fuel configuration.

![Figure 10](image1.png)

**Figure 10:** Mass loss rate vs. time for all 4-cm fuel arrays and the homogeneous tests.

![Figure 11](image2.png)

**Figure 11:** Mass loss rate vs. time for all 8-cm fuel arrays and the homogeneous tests.

Figs. 10 and 11 display mass loss rates plotted vs. time. All tests exhibit comparable mass loss rates for the first 200 seconds, increasing from 0.05 g/s to 0.11 g/s. After this point, the mass loss rates for the low fuel percentage tests...
drop off, and every other test becomes eventually outpaced by the homogeneous case. The mass loss rates exhibit consistently positive slopes, indicating that the steady burning period has not yet been reached. Nevertheless, the negative concavity of each mass loss rate towards the latter period of all tests indicate that a steady mass loss rate is being approached due to the conclusion of the spread phase.

5. Analysis

5.1. Flame Spread Rate Discussion

The general trend for flame spread rate to peak at a fuel percentage below unity indicates that there is an optimum fuel percentage for flame spread. It is quite likely that entrainment plays a significant role in determining this optimum value. For the fastest flame spread case, a favorable fuel-to-oxidizer ratio may be provided by the gaps in the discretized fuel. These gaps can increase the amount of air entrained from both the front and the sides of the fuel array, so that the most efficient mixing would occur at an optimal fuel percentage. It is also conceivable that increased entrainment of air could intensify heating by reducing the flame standoff distance.

An increase or decrease in the optimal fuel percentage will reduce the flame spread. The ‘optimal’ configuration is a loose term, and it will change depending on the size and nature of the fuel. For example, the addition of sidewalls could hypothetically reduce the amount of side entrainment, which could shift the optimal fuel percentage. A narrower fuel array could also increase the influence of entrainment from the sides. The optimal configuration for a dissimilar fuel choice may occur at a different fuel percentage. Nevertheless, an optimal fuel percentage will be defined as that which leads to the highest flame spread rate for this experimental configuration.

The trend for this optimal configuration to occur at a specific fuel percentage is similar to the findings of Rothermel [5], who found an optimal packing density for dead vegetative fuelbeds. Watanabe et al. [6] also found that fil-
ter paper with 20-30% porosity exhibited the fastest flame spread rate. Both of these studies, although they examined significantly different experimental configurations, found optimal configurations for the flame spread rate.

Returning to the thermal model of flame spread, we can surmise that the flame spread rate is directly related to both the magnitude and location of the heat flux directed to unburnt fuel. Continuing along this path of deduction, one can hypothesize that an optimal entrainment configuration modifies the flame to promote pyrolysis by extending the pre-heat region and/or increasing the magnitude of the heat flux. This configuration is likely a multi-faceted function, dependent on flame characteristics, flame height, fuel location, fuel properties, etc. Regardless, our research clearly indicates that the fuel percentage of the array is a significant player in the flame spread rate. For the canonical problem of upward flame spread on a vertical wall, this had never been demonstrated experimentally. The ability for fire to propagate faster over discrete fuels with spacing, even in a thermally thick configuration, is one very important extrapolation from these results. This implies that a disjoint scattering of fuel may actually pose a greater hazard than a dense, consolidated fuel distribution.

The optimal fuel percentage occurs at 67% for the 4-cm fuel tests and between 67-89% for the 8-cm fuel tests. This peak in the flame spread rate implies that the distribution of fuel, not just fuel properties and fuel loading, is a significant driver of fire hazard.

Meanwhile, the fuel spread velocity, \( V_{p,fuel} \), exhibits a clear positive correlation with the fuel percentage, with a maximum value of 0.087 cm/s occurring in the homogeneous case. This correlation implies that fires in a homogeneous scenario, although they may spread slower than the optimal fuel percentage, will more quickly involve greater quantities of fuel.

When the fuel percentage is the result of a uniform distribution of discrete fuels, knowledge of either the flame spread rate or the fuel spread rate also allows us to calculate the other. Eq. 8 expresses how to predict the flame spread rate from the fuel spread rate:
Figure 12: Eq. 8 was used to generate estimates for the flame spread rate and fuel spread rate. Data shown is from 4-cm fuel arrays.

\[ V_p = \frac{V_{p,fuel}}{(fuel \%) \text{ }} \]  

(8)

Applying this equation to fuel spread data from 4-cm fuel arrays, estimates for the flame spread rate were plotted in Fig. 12, and they lie in relative agreement with the experimental results. Eq. 8 can also be used to estimate the fuel spread rate from the flame spread rate. This technique would likely fail if a given fuel array experienced dramatic fluctuations in the important length scales (i.e., fuel and spacing lengths).

5.2. Spread Rate Estimates Based on Limits of Spread

The fuel spread velocity exhibits a clear positive correlation with fuel percentage that could be estimated if the limits of the fuel spread rate are known. The homogeneous fuel spread velocity can be measured experimentally; additionally, our experiments with discrete fuels tend to exhibit a limit where no spread occurs somewhere around a fuel percentage of 30%. By measuring the homogeneous spread rate and assuming a fuel spread velocity of zero at a certain critical fuel percentage, \((fuel \%)_{crit}\), a logarithmic fit can be applied between these points to create an estimate of the fuel spread rate at intermediate values.
The logarithmic fit would then take the form

\[ V_{p,fuel} = a \ln(x) + b, \]  

(9)

where \( b = V_{p,homogeneous} = V_{p,fuel,homogeneous} \), \( x \) represents the fuel percentage, and \( a = -b / \ln((fuel \%)_{crit}) \). Given this estimation for \( V_{p,fuel} \), \( V_p \) can then be estimated by means of Eq. 8.

This methodology was applied to the spread rates that were obtained, and the following values were employed:

\[ V_{p,homogeneous} = 0.087 \text{ cm/s} \]

\( (fuel \%)_{crit} = 0.3 \)

Here, the homogeneous spread rate was derived from experimental results and the critical fuel percentage was estimated based on results for tests with low fuel percentage. The following constants were then obtained by applying Eq. 9:

\[ b = V_{p,homogeneous} = 0.087 \text{ cm/s} \]

\[ a = \frac{-b}{\ln((fuel \%)_{crit})} = \frac{-0.087}{\ln(0.3)} = 0.073 \text{ cm/s} \]

Plugging these results into Eq. 9, we have

\[ V_{p,fuel} = 0.087 \ln(x) + 0.073, \]  

(10)

where \( x \) is the fuel percentage and \( V_{p,fuel} \) is in cm/s. Fig. 13 plots this theoretical fit vs. experimental results for the fuel spread rate from all tests, and the theory fits the data with an \( R^2 \)-value of 0.97. Moving further, the results from the theoretical fit for fuel spread rate can be used to estimate flame spread rates via Eq. 8. Substituting Eq. 10 into Eq. 8, we obtain

\[ V_p = \frac{0.073 \ln(x) + 0.087}{x} \]  

(11)
These hypothetical flame spread rates are also plotted vs. experimental results for the flame spread rate in Fig. 13. This fit attains an $R^2$-value of 0.93.

Overall, the theoretical results from estimation of the limits of flame spread fits the data remarkably well. The close fit for the fuel spread velocity reaffirms our hypothesis that no spread will occur around a limiting fuel percentage of 30%. The positive correlation of fuel spread velocity with fuel percentage is perhaps the most consistent trend in this study, and a logarithmic fit captures the expected behavior well. The fit for the flame spread velocity is reasonable as well; only slight underpredictions are observed for the higher fuel percentages.

It should also be noted that results for the 4-cm and 8-cm fuel arrays with identical fuel percentages are quite comparable. Moreover, the trends observed for the flame spread and fuel spread rates are the same. For fuels in the small range of tested sizes, it appears that relevant relationships for flame spread scale with the fuel percentage. It is not clear whether this trend would continue to scale beyond fuels in the 4-8 cm range; unfortunately, the small size of the apparatus and the lack of precision needed for smaller fuel blocks placed testing of other fuel sizes beyond the realm of this study.
5.3. Acceleration of Spread Rate

The aforementioned values for the flame spread velocity have been derived from the average rate of change in pyrolysis height across the entire fuel array. However, the rate of flame spread is not a static variable for upward flame spread, and many experiments with samples of necessary height have observed significant acceleration of the flame spread rate [13]. Our experiment is no exception. By dividing the height of the fuel array into five separate regions, we were able to look at velocities observed at various locations. A linear fit was applied to data averaged from at least 3 experiments in each region (i.e. measurement locations and ignition times) to estimate local flame spread rates.

Fig. 14 displays the local flame spread velocity vs. location for the 4-cm fuel and homogeneous fuel arrays. For the arrays with a fuel percentage of 80% and higher, a clear acceleration can be identified as the pyrolysis front advances up the apparatus. Meanwhile, the test with 2-cm spacing exhibits an unclear trend, although the velocity magnitude of the velocity in the uppermost region seems to indicate that some acceleratory effects are certainly possible. The local flame spread rates of the remaining tests, involving 4 and 6-cm spacings, seem to indicate a deceleration of the pyrolysis front. It seems that the low fuel percentage begins to have a significant impact in the later stages of flame spread. The decreased flame height may have a large effect at higher regions, where radiative effects become more pronounced and the heat transfer is no longer dominated by a laminar flame. Additional experimentation on a larger apparatus may even indicate that the upward flame spread for tests with lower fuel percentages may further decelerate or even fail to propagate at higher regions.

Fig. 15 displays the local flame spread velocity vs. location for the 8-cm fuel and homogeneous fuel arrays. Similar to the 4-cm fuel arrays, the 8-cm fuel arrays with a high fuel percentage exhibit some acceleratory effects; this is evidenced by larger local flame spread rates at higher regions of the apparatus. Meanwhile, the 8-cm fuel arrays with lower fuel percentages (i.e., arrays with 8 and 12-cm spacings) have clearly decelerated towards the top of the apparatus. These findings parallel the trends observed in the 4-cm fuel arrays.
Figure 14: Local flame spread rates vs. height for the 4 cm fuel and homogeneous tests.

Figure 15: Local flame spread rates vs. height for the 8 cm fuel and homogeneous tests.
These plots display a sharp divergence in acceleratory trends of the pyrolysis front for arrays with a low fuel percentage vs. arrays with a high fuel percentage, indicating the occurrence of different flame spread behaviors. For all discrete fuels tested, the flame spreads via a ‘jumping’ phenomenon, whereby the pyrolysis front ascends to the top of one block of fuel and momentarily halts. After a certain amount of time, the next block of fuel will be heated to the point where the pyrolysis front can effectively ‘jump’ to this block and resume its progress. At low fuel percentages, it takes a significant amount of time for this jump to occur, so the flame propagates over the discrete fuels in a very iterative fashion. Because each successive iteration (i.e., each jump from one fuel to the next) appears to take a greater amount of time, an eventual failure to spread on a larger apparatus is plausible. In contrast, the flame spread behavior for high fuel percentages is indicative of a flame that is continuously advancing and even accelerating. This divergence in behavior indicates that there is a certain fuel percentage below which fuel arrays should be treated as distinctly discrete. Above this fuel percentage, it may actually be appropriate to describe the fuel array as a partially homogeneous fuel bed.

5.4. Mass Fluxes

Two measures of the mass loss rate per unit area were obtained: the mass loss rate per total pyrolysis area ($\dot{m}_{\text{total}}''$) and the mass loss rate per burning area ($\dot{m}_{\text{fuel}}''$). Eqs. 12 and 13 demonstrate how these parameters were calculated:

$$\dot{m}_{\text{total}}'' = \frac{\dot{m}}{\text{width} \cdot x_{p,\text{total}}} \quad (12)$$

$$\dot{m}_{\text{fuel}}'' = \frac{\dot{m}}{\text{width} \cdot x_{p,\text{fuel}}} \quad (13)$$

where the width is 20 cm and $x_{p,\text{total}}$ and $x_{p,\text{fuel}}$ estimates were derived from the linear fits used to calculate flame spread rates and fuel spread rates. There are important differences between $\dot{m}_{\text{fuel}}''$ and $\dot{m}_{\text{total}}''$: $\dot{m}_{\text{fuel}}''$ is the true burning mass flux, for this parameter quantifies a burning area by neglecting the
inert sections of the fuel array. Meanwhile, \( \dot{m}_{\text{total}} \) quantifies an average mass flux for a given area. For all inhomogeneous fuel arrays, \( \dot{m}_{\text{fuel}} \) is necessarily greater than \( \dot{m}_{\text{total}} \).

Average mass loss rates per unit area were estimated over the time period when the linear fit for \( x_{p,\text{total}} \) occupied 10-25 cm in height. This region is the middle of the fuel array, and the associated time period represents the middle portion of the spread phase. Both \( \dot{m}_{\text{fuel}} \) and \( \dot{m}_{\text{total}} \) were averaged over this period, and the results are plotted vs. fuel percentage in Figs. 16 and 17. For all tests, \( \dot{m}_{\text{total}} \) is nearly constant during the spreading phase, hardly deviating from around 3 g/s\cdotm^2. However, \( \dot{m}_{\text{fuel}} \) appears to be negatively correlated with fuel percentage. The highest results for \( \dot{m}_{\text{fuel}} \) actually occur for the tests with the lowest fuel percentage, climbing to over 5 g/s\cdotm^2.

These results imply that, during the spreading phase, the fuel from the arrays with more spacing are releasing more pyrolyzed gases per surface area of fuel. Because \( \dot{m}_{\text{fuel}} \) is equivalent to the imparted heat flux divided by the effective heat of gasification [23], it stands to reason that a higher heat flux per unit area is being imparted over the fuel surface of arrays with low fuel percentages. This
could be the result of a decreased flame standoff distance due to modified air
entrainment patterns, which would allow a greater heat flux to be delivered to
the fuel array. The higher local mass flux of gases at lower fuel percentages will
assist the flame in overcoming the obstacles to spread provided by inert spacing.
The mass flux data further supports the argument that the flame spread rate is
dependent on the entrainment of fresh oxidizer.

One could argue that these results are skewed because they are derived from
a linear fit for $x_{p,fuel}$. It is certainly true that the actual burning area does
not follow a strictly linear growth, particularly in the low fuel percentage tests;
in these tests, an iterative jumping phenomenon is observed as the pyrolysis
front halts at the top of one block of fuel while the next block of fuel is slowly
heated to its pyrolysis temperature. Regardless, the results for the mass fluxes
should still hold because they have resulted from an average of results over a
significant span of time. The discrepancies in the instantaneous calculation of
the burning area should have only minor effects on the results displayed here
because the linear fit for $x_{p,fuel}$ provides an adequate measure of the average
burning region.

Furthermore, analysis of IR images revealed that the shape of the pyrolysis
front does not appear to deviate much when different fuel arrays are employed. This qualitative assessment should assuage concerns that the predicted trend is a result of width differences in the actual burning region between tests. Although the accuracy of the numerical values provided are debatable, it seems unlikely that the observed trends are erroneous.

Other experimentalists have also examined mass loss rates per unit area for upward flame spread over a homogeneous PMMA slab. Gollner et al. [22] obtained a value of 4 g/s·m² for a spreading mass loss rate and 6 g/s·m² for a steady mass loss rate in experimental work on 10 x 20 cm vertical PMMA slabs. Experimental results from our research indicate a value of 3.5 4 g/s·m² for the spreading phase and nearly 5 g/s·m² towards the latter end of the data collection period. Considering this period was terminated before a maximum mass flux could be obtained, our results agree very well with Gollner et al.s. Some researchers have recorded higher steady mass fluxes for PMMA, notably Ohtani et al. with 8 g/s·m², Singh et al. with 8.90 g/s·m², and Kulkarni et al. with 9 g/s·m² [24, 25, 26]. Regardless, these values were obtained with laminar flames across samples of significantly smaller size, so the higher mass loss rates are not surprising.

6. Conclusion

This study has analyzed upward flame spread over discrete fuels by studying vertical arrays of alternating lengths of PMMA and insulation. By manipulating the lengths of the fuel and insulation, important trends related to flame spread were assessed.

Perhaps the most noteworthy finding is the trend for the flame spread rate to peak at a fuel percentage below unity. It has been hypothesized that increased air entrainment due to the larger spacing between fuels plays a significant role in this behavior. If extrapolation of these results is possible, the implication would be that fuel loads with greater spacing between discrete fuels could represent a greater fire hazard than a concentrated distribution of fuel.
It was also discovered that the fuel spread rate follows a readily identifiable trend, which consists of a positive correlation with fuel percentage. Moreover, this study revealed that a reliable estimation of the fuel spread rate for various fuel percentages can be developed with knowledge of the homogeneous fuel spread rate and a reasonable assessment for the limiting fuel percentage. In turn, the flame spread rate can be approximated for a given fuel array if the fuel spread rate is known. This methodology may serve as a useful foundation for estimates of flame spread rates over non-homogeneous fuels.

The mass loss rate per burning area was found to be negatively correlated with fuel percentage. These results imply that a higher heat flux is being imparted over the fuel surface. The increased mass flux at low fuel percentages likely contributes to the aforementioned trend for the flame spread rate.

For low fuel percentages, it was discovered that the time for the pyrolysis front to spread to the next block of fuel could be significant. Furthermore, the lower fuel percentages witnessed a deceleration of the pyrolysis front after each successive jumping iteration. Higher fuel percentages still exhibited the expected acceleration of the pyrolysis front as it moves upward. This divergence of behavior indicates that the conditions in the more developed stages of upward flame spread may lead to different results. Additionally, the divergence of results indicates that there is a fuel percentage below which an assumption of near-homogeneity is invalid; consequently, the fuel configuration should be identified as distinctly discrete.

Acknowledgments

The authors would like to acknowledge financial support for this work from the John L. Bryan Chair in Fire Protection Engineering.

References


