Upward Flame Spread over Discrete Fuels

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Abstract

Upward flame spread over discrete fuels has been analyzed through experiments on vertical arrays of alternating lengths of PMMA and inert 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 fraction of exposed area consisting of fuel (i.e., the fuel coverage f) was below unity. A maximum flame spread rate was observed for $f = 0.67$, possibly due to a delayed thickening of the boundary layer or increased air entrainment. In arrays with $f \leq 0.5$, the flame spread rate decreased; in fact, deceleration of the pyrolysis front was observed. This behavior indicates that a homogeneous fuel bed approximation, which might be applicable when f is near unity, would be highly unsuitable for arrays with low fuel coverage. 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 f . This provides further support to the hypothesis that decreased thickening of the boundary layer, which would lower the flame standoff distance, plays a causal role.

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

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

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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]
f	Fuel coverage (area of array consisting of exposed fuel)
f_{crit}	Critical fuel coverage (lower limit of fuel coverage at which flame will not successfully spread)
$\dot{m}''_{fuel}$	Mass loss rate per burning area [g/s m ²]
$\dot{m}''_{total}$	Mass loss rate per total pyrolysis area [g/s m ²]
a, b	Coefficients in Eq. 8 employed to develop a logarithmic fit for the flame spread rate [cm/s]
$width$	Width of the tested fuel (20 cm).
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.

43 Some previous research related to wildfire spread has focused on regimes
44 where assumptions of a homogeneous fuel bed can be taken. Thomas [2, 3] de-
45 veloped correlations for porous fuel beds under external forced flow scenarios. He
46 determined that the rate of horizontal flame spread was inversely proportional
47 to the bulk density of fuel for both scenarios. Dupuy [4] performed experiments
48 with flame spread over various fuel beds and reaffirmed the trend for the flame
49 spread rate to decrease with fuel density. Rothermel [5] characterized flame
50 spread in porous fuel beds in his mathematical model for wildland fuels in 1972.
51 In addition to hypothesizing a slower rate of flame spread for densely packed
52 fuels, he also theorized a decrease in the spread rate as fuel density decreased
53 beyond a certain threshold. In the loose arrangement, a lack of fuel and heat
54 losses would result in slower spread rates. Therefore, it was hypothesized that
55 there would be an optimal fuel density for flame spread, and experimental re-
56 sults confirmed this correlation. Rothermel characterized the fuel density as
57 a packing ratio, which measures the fraction of the fuel array volume that is
58 occupied by fuel. The optimal packing ratio for flame spread rates varied based
59 upon the type and size of the fuel.

60 Some research has also been conducted on discrete fuels in which an assump-
61 tion of homogeneity is not readily appropriate. Watanabe et al. [6] looked at
62 flame spread across horizontal, combustible filter paper perforated with holes,
63 and a gap that spanned the entire apparatus (perpendicular to the direction of
64 spread) was deemed a slit. The probability for a flame to traverse a slit was
65 closely related to whether the slit length exceeded the pre-heat length, with
66 greater slit lengths resulting in low flame spread probabilities. An increase in
67 the flame spread rate was also observed as porosity increased from 0% to ap-
68 proximately 20-30%. Any further increase in porosity led to a decrease in the
69 spread rate until approximately 50-60% porosity, at which point the flame failed
70 to spread. Abe et al. [7] continued similar work on horizontal filter paper, find-
71 ing that the probability for the flame to spread across the filter paper was again
72 related to the number of slits formed.

73 Arrays of matchsticks (with the heads removed) have been utilized to study

74 flame spread along discrete fuels [8, 9, 10, 11]. Recently, Gollner et al. examined
75 discrete fuel behavior through an investigation of vertical matchstick arrays [12].
76 Flame spread over vertical arrays was found to be a function of spacing between
77 the matchsticks. In all tests with spacing, power law dependencies were assumed
78 due to buoyant acceleration. As the spacing between matchsticks was increased,
79 the flame spread rate also increased. Even though the distance between fuel
80 elements became larger, the flame attained unobstructed impingement onto the
81 next fuel element, resulting in faster spread. Furthermore, in all setups where
82 the spacing was greater than 0 cm, the pyrolysis front actually accelerated over
83 the height of the array. Convective heat transfer correlations were found to
84 nearly predict the burning behavior of this accelerating pyrolysis front.

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

90 The primary objective of this study is to empirically analyze important pa-
91 rameters associated with upward flame spread over discrete fuels. This will
92 naturally involve a disconnected pyrolysis front, which changes the distribution
93 of the mass flux released by the fuel. The flame itself will then be subject to dif-
94 ferent entrainment patterns, and it is possible for increased oxidizer to become
95 available due to the gaps in the pyrolysis front. It is not fully known how the
96 flame dynamics change in such a scenario: notably, it is not readily identifiable
97 where a disconnected pyrolysis front should be modeled as a single flame emit-
98 ted by a porous fuel or as multiple fires anchored at discrete fuel elements. The
99 spacing of the fuel will influence which region of the flame has the greatest effect
100 on the unburnt fuel; for example, significant spacing in a large fire may put the
101 unburnt fuel in a zone where radiation becomes more important. If the spacing
102 is beyond a certain threshold, extinction of the flame may even occur. In turn,
103 the outcomes of all these scenarios are subject to the transient development of
104 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 vertical 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 apparatus (91.5 cm) vertically. These shims were used to hold alternating blocks of PMMA and insulation board against the apparatus, leaving a horizontal exposure width of 20 cm. All blocks of PMMA and insulation were approximately 1.27 cm (0.5 in) in thickness. Blocks of PMMA represent the discrete fuel elements, and vertical lengths of either 4 or 8 cm were employed in tests. Pieces of insulation, which would be placed between the PMMA blocks, functioned as the ‘spacing’ or ‘gaps’ of inert material above and below each block of PMMA.

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. 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

Figure 1: Photograph of apparatus and associated data acquisition equipment, including the mass balance, camera, and infrared camera.

134 fps. Before tests, the centerline exhaust velocity of the small hood was mea-
 135 sured with a hot wire anemometer and recorded. To avoid variability due to
 136 externally-imposed flows, the centerline exhaust velocity was consistently kept
 137 between 2.0 to 2.5 m/s in the exhaust opening (10-cm diameter).

138 2.2. Establishment of a Discrete Fuel Array

139 The experimental apparatus was designed to fit arrays with different sizes of
 140 alternating fuel and insulation. 10 cm above the mass balance (22 cm above the
 141 table surface), bolts served as base pegs to hold a 10-cm-tall piece of insulation
 142 in the apparatus. This clear distance was established so that air from below the
 143 array could be entrained in a consistent fashion.

144 Fig. 2 displays a schematic of the experimental setup. The first piece of
 145 insulation was followed by a block of PMMA that was 2 cm in height. This
 146 block of fuel served as the ignition source for all experiments and was imme-
 147 diately followed by a 2-cm length of insulation. All experiments retained this
 148 bottommost arrangement to maintain consistency in ignition and preheating.

Figure 2: Fuel array configuration for a 4-cm fuel/1-cm spacing test. The left side of the diagram depicts a front view while the right side depicts a side view. Only the region demarcated as the fuel array was manipulated between tests.

149 Above this bottom region was the fuel array, which was the physical parameter
 150 manipulated between tests. A fuel array consisted of fixed sizes of fuel and in-
 151 insulation, stacked one upon the other in an alternating pattern. This pattern was
 152 maintained until approximately 30-35 cm from the bottom of the ignition block.
 153 Fig. 3 displays several example fuel arrays. In order to quantify the amount of
 154 fuel in each discrete array, we created a parameter f , the fuel coverage of the
 155 array. The fuel coverage is simply the hypothetical fraction of the array surface
 156 area consisting of exposed fuel. For example, a test with 4-cm slabs of fuel and
 157 1-cm spacing would possess a fuel coverage of $f = (4\text{cm})/(4\text{cm} + 1\text{cm}) = 0.8$.
 158 This quantity succinctly reveals the basic structure of the discrete fuel array,
 159 and it will be employed to compare results from different arrays.

160 Finally, a sheet of insulation board, 27 cm in length, was placed above the
 161 fuel array. This maintained a flush inert surface above the fuel array so that
 162 flame dynamics would not be altered by a sudden change in the vertical surface.

Figure 3: Schematic of fuel array configurations from four example tests. The fuel coverage is the ratio of the fuel surface area to the total exposed area within the fuel array. Tested fuel coverage values included 0.4, 0.5, 0.67, 0.8, 0.89, and 1.

163 2.3. Ignition Procedure

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

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

176 2.4. Flame Height Processing Technique

177 Image processing of front-view video from the Casio camera was employed
178 to calculate flame height. Each frame from the raw video was converted to
179 grayscale, and an average grayscale image was developed from 125 frames (rep-
180 resenting a 5 second period). Each pixel in this image was then scanned, with
181 pixels of higher brightness considered activated (i.e., from a scale of 0 to 1, 0.05
182 was chosen as the activation threshold for each pixel). Subsequently, if 10%
183 of the pixels in a horizontal line spanning the fuel array were activated, this
184 line was determined to have a positive flame presence. This litmus test was
185 applied to all horizontal lines spanning the apparatus height. The largest ver-
186 tical distance with a continuous flame presence was then determined to be the
187 representative flame height. This process proved repeatable and reliable in all
188 tests when the ambient filming conditions were sufficiently dark.

189 2.5. Infrared Thermography

190 By tracking the temperature contour corresponding to the ignition temper-
191 ature, an effective pyrolysis front can be located to determine the flame spread
192 rate. Determination of the location of the pyrolysis front by means of a tem-
193 perature measurement has been performed in various studies [13, 14, 15].

194 Our initial experimental approach relied on thermocouples melted directly
195 to the surface of the PMMA along the centerline. However, thermocouples
196 would occasionally become detached from the surface and extend into the flam-
197 ing region, artificially raising the measured temperature and perturbing the flow
198 of hot gases. Moreover, this process proved incredibly tedious as experimental
199 repeatability necessitated the making and fitting of hundreds of new thermocou-
200 ples. Infrared (IR) thermography was determined to be a more suitable choice
201 for experimentation. Thermal imaging cameras can take instantaneous temper-
202 ature measurements at a wide viewing angle, which makes thermographic data
203 more versatile than point measurements provided by thermocouples.

204 Because combustion gases have finite transmittance, the temperature read-
205 out of the IR camera is not necessarily indicative of the true temperature of

206 an object behind the flame. Previous researchers [13, 14, 15, 16, 17, 18] have
 207 employed IR filters in order to filter out emission bands from carbon dioxide,
 208 which emits strongly at 2.7 and 4.3 μm , and water vapor, which emits strongly
 209 at 2.7 and 6.3 μm [19]. Soot, on the other hand, has a continuous emission
 210 spectrum, so it is possible for a very sooty flame to affect temperature measure-
 211 ments of a surface behind the image. Nevertheless, Parent et al. [17] performed
 212 experiments on a vertically mounted PMMA slab of identical width to this
 213 experiment, and, when analyzing IR images, they found that the background
 214 contribution of the soot was hardly visible, minimally affected the extracted
 215 temperatures, and contributed quite homogeneously. In addition, Forsth and
 216 Roos [20] found that, for our emission range, PMMA is not far from being a
 217 blackbody, and Sohn et al. [21] have successfully used an assumed emissivity of
 218 0.92 to obtain accurate readings from infrared images. Previously, Urbas and
 219 Parker [15] successfully applied an infrared pyrometer in the range of 8-12 μm
 220 to measure the surface temperature of burning wood specimens. Given that our
 221 camera’s spectral response lies within the range of Urbas and Parker’s camera,
 222 this was a promising precedent, especially since PMMA should produce fewer
 223 soot emissions than burning wood.

224 Validation of our temperature measurements, nonetheless, had to be at-
 225 tempted. Therefore, several tests were simultaneously instrumented with ther-
 226 mocouples and recorded by the IR camera. After several small-scale tests were
 227 conducted, an assumed PMMA emissivity of 0.92 was found to give reasonable
 228 temperature readings for the infrared images, where accuracy was a measure of
 229 similarity to thermocouple values. Fig. 4 displays four temperature profiles from
 230 both the IR camera and the thermocouples from a validation test in which the
 231 IR spot measurements were taken at the approximate thermocouple locations.
 232 In total, 9 thermocouples were employed in this test, and the average percentage
 233 difference between the absolute temperatures from the IR data and those from
 234 the thermocouples was 3.4% at the time of ignition (i.e., when raw data from the
 235 IR camera first indicated 573 K). Differences of this magnitude were determined
 236 to be acceptable. Infrared images and measurements produced a picture of the

Figure 4: Raw data obtained from thermocouples and the infrared camera for a sample validation test.

pyrolysis front that was much clearer than thermocouple measurements, which exhibited occasional dramatic fluctuations. 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. These diagnostic locations are visible in Fig. 5 along with simultaneous images of the visible flame and a graph of the measured temperature. In this image, IR temperature measurements clearly indicate that the pyrolysis front is traversing the uppermost block of PMMA.

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 $x_{p,total}$, refers to the distance associated with both the burning PMMA and the insulation that

Figure 5: Simultaneous images of a visible flame, an infrared image with diagnostic locations, and a graph of the IR measurement location vs. the measured temperature. Results taken from the spreading phase of 8-cm fuel/4-cm spacing test #2. The graph, which indicates ignition temperature, confirms that the pyrolysis front is spreading across the uppermost block of PMMA.

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 equation

$$x_{p,total} = x_{p,fuel} + x_{p,inert}. \quad (1)$$

Fig. 6 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:

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

Figure 6: Graphical representation of a vertical array of discrete fuels.

$$x_{p,inert} = \sum_i x_{p,inert(i)} = x_{p,inert(1)} + x_{p,inert(2)}. \quad (3)$$

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

$$A_{burn} = x_{p,fuel} * width. \quad (4)$$

265 The flame spread rate, V_p , is another parameter that must be clarified for
 266 discrete cases. This refers to the velocity at which the pyrolysis front travels
 267 across a surface. In discrete fuel configurations, it must be realized that the
 268 pyrolysis front will reach the edge of one unit of fuel and temporarily halt. If
 269 more fuel is located nearby, the flame will steadily raise the temperature of this
 270 adjacent unit until it also begins to pyrolyze and ignite; a new pyrolysis front
 271 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 rate (or flame spread velocity), V_p will refer to the total vertical distance traversed by the pyrolysis front over time. More succinctly,

$$V_p = \frac{d(x_{p,total})}{dt}. \quad (5)$$

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.

A quantification of the rate at which the pyrolysis front consumes fuel is also relevant. This parameter will be termed the fuel spread rate (or fuel spread velocity), $V_{p,fuel}$, and it refers to the distance *of fuel* traversed by the pyrolysis front over time. Unlike the flame spread rate, calculation of the fuel spread rate excludes non-combustible regions. $V_{p,fuel}$ is calculated by ignoring the inert regions of the spacings and looking only at the vertical distance of fuel consumed, $x_{p,fuel}$, such that

$$V_{p,fuel} = \frac{d(x_{p,fuel})}{dt}. \quad (6)$$

Under a homogeneous flame spread scenario (no spacing), $V_{p,fuel}$ will necessarily be equal to V_p ; however, $V_{p,fuel}$ will always be less than V_p for discrete fuels. The fuel spread rate 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 rate 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 rate 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.

294 4. Flame Spread Rate

295 4.1. Results

296 The pyrolysis height, $x_{p,total}$, was calculated under the conjecture that the
297 pyrolysis temperature of PMMA was 300°C, an assumption utilized by previous
298 researchers [22]. A consistent inflection point in the transient temperature data
299 was observed at this temperature, supporting the claim that ignition occurs in
300 this region. Temperature data from infrared images was smoothed by means
301 of a polynomial fit; subsequently, the intersection of this fit with 300°C was es-
302 tablished as the ignition time for each respective height. Average flame spread
303 rates (V_p and $V_{p,fuel}$) were determined by applying a linear fit to plots of height
304 vs. ignition time. Because the fuel array could be influenced too heavily by
305 early or late spread behavior, we compared spread rates determined from mea-
306 surements over the entire array to spread rates evaluated using only the middle
307 portion of the array (i.e., between 10 and 25 cm in height). These two methods
308 obtained spread rates that differed by an average of 8.8%, with the most signif-
309 icant differences being observed in fuel arrays with low fuel coverage. Despite
310 this difference in reported magnitude, no difference in trends was observed, and
311 it was determined that obtaining the flame spread rate from a linear fit of the
312 entire height of the fuel array was appropriate. An example fit from this process
313 is displayed in Fig. 7.

Figure 7: Example of linear fit applied to a fuel array with 8-cm-tall PMMA and 1-cm-tall insulation board. Experimental data is shown in black while the linear fit is displayed as a dashed red line. The slope of the line represents the flame spread rate.

314 A flame spread rate and fuel spread rate for each fuel array was determined
 315 from 3 to 4 tests. For each test, all ignition times were normalized by setting
 316 the ignition time of the first measurement location as time $t = 0$. Subsequently,
 317 heights of temperature measurements were plotted vs. ignition times using
 318 combined data from identical fuel arrays, and a linear fit of all data points
 319 yielded the flame spread rate (V_p) as the slope. The fuel spread rate ($V_{p,fuel}$)
 320 was likewise determined from a plot of fuel pyrolysis heights vs. ignition times.
 321 The flame spread rate and the fuel spread rate are plotted vs. the fuel coverage,
 322 f , in Fig. 8 for all fuel arrays. Based on a linear regression, a 95% confidence
 323 interval for the slope was established; this confidence interval is displayed for
 324 each point as an error bar.

Figure 8: Flame spread rate and fuel spread rate plotted vs. fuel coverage for the 4-cm PMMA, 8-cm PMMA, and homogeneous arrays.

4.2. Discussion

Fig. 8 reveals an approximate peak in the measured flame spread rate at $f = 0.67$. The general trend for the flame spread rate to peak at a fuel coverage below unity indicates that there is an optimum fuel coverage for flame spread. In typical homogeneous wall flames, the blowing and heat release from pyrolyzing fuel contributes to the ‘thickening’ of the boundary layer. In discrete spread, the presence of inert spacing may delay the ‘thickening’ of the boundary layer. This phenomenon would subsequently lower the flame standoff distance and increase the heat flux to the surface, increasing the flame spread rate for values of fuel coverage below unity. In essence, this phenomenon would be the opposite effect observed in peeling cardboard, where fuel protruded into the flow and prematurely thickened the boundary layer [23]. Front and side air entrainment may also play a role if inert material provides a favorable environment for increased mixing of fuel and oxidizer.

Although Rothermel [5] examined three-dimensional fuelbeds, he also observed a peak in the flame spread rate at an intermediate quantity of fuel. Watanabe et al. [6] found that filter paper with 20-30% porosity exhibited the

342 fastest flame spread rate. An ‘optimal fuel configuration’ was observed in all
 343 these studies, including our own, but this quantity can change depending on
 344 the size and nature of the fuel. For example, the addition of sidewalls could
 345 reduce the amount of side air entrainment, shifting the optimal fuel coverage.
 346 A narrower fuel array could increase the influence of side entrainment. The
 347 optimal fuel coverage may also change for dissimilar fuels. Regardless, our re-
 348 search clearly indicates that the fuel coverage of the array is a significant player
 349 in the flame spread rate. For the canonical problem of upward flame spread on
 350 a vertical wall, this had never been demonstrated experimentally. The ability
 351 for fire to propagate faster over discrete fuels with spacing, even in a thermally
 352 thick configuration, is one very important extrapolation from these results. This
 353 implies that the distribution of fuel, not just fuel properties and fuel loading, is
 354 a significant driver of fire hazard.

355 Returning to Fig. 8, a significant decline in the flame spread rate is observed
 356 when the fuel coverage is decreased from 0.67. This represents the transition
 357 point at which the inert spacing no longer assists the flame spread process, but
 358 actually impedes it.

359 Meanwhile, the fuel spread rate, $V_{p,fuel}$, exhibits a clear positive correlation
 360 with the fuel coverage f , attaining a maximum value of 0.087 cm/s in the
 361 homogeneous case. This correlation implies that fires in a homogeneous scenario,
 362 although they may spread slower than a scenario with an optimal fuel coverage,
 363 will more quickly involve greater quantities of fuel.

364 For identical values of f , a remarkably close agreement in behavior was
 365 observed regardless of whether 4 or 8-cm-tall PMMA blocks were employed.
 366 This demonstrates that trends for spread rate scale with the fuel coverage (f),
 367 not with gap height. The fuel coverage is clearly an important parameter in
 368 predicting flame spread behavior, and future experiments could confirm whether
 369 this relationship scales to larger fires.

370 4.3. Spread Rate Estimates Based on Limits of Spread

371 Given a uniform distribution of discrete fuels, knowledge of either the flame
 372 spread rate or the fuel spread rate also allows us to estimate the other. Eq.
 373 7 expresses how to predict the flame spread rate from the fuel spread rate.
 374 This relationship highlights how the flame spread rate may be understood as a
 375 balance between the fuel spread rate and the fuel coverage.

$$V_p \approx \frac{V_{p,fuel}}{f} \quad (7)$$

376 In addition, Fig. 8 shows that the fuel spread rate exhibits a clear positive
 377 correlation with fuel coverage that can be estimated if the limits of the fuel
 378 spread rate are known. These limits are the homogeneous fuel spread rate,
 379 which can be measured experimentally, and the limit where no spread occurs,
 380 which occurs around a fuel coverage of 0.3 in our experiments. By measuring
 381 the homogeneous spread rate and assuming a fuel spread rate of zero at a critical
 382 fuel coverage, f_{crit} , a logarithmic fit can be developed to estimate intermediate
 383 values. The logarithmic fit would then take the form

$$V_{p,fuel} = a \ln(f) + b, \quad (8)$$

384 where $b = V_{p,homogeneous} = V_{p,fuel,homogeneous}$, f represents the fuel coverage,
 385 and $a = -b/\ln(f_{crit})$. Given this estimation for $V_{p,fuel}$, V_p can then be esti-
 386 mated by means of Eq. 7.

387 This methodology was applied using the limits of spread from our experi-
 388 ment, and the following fit was attained:

$$V_{p,fuel} = 0.073 \ln(f) + 0.087, \quad (9)$$

389 where f is the fuel coverage and $V_{p,fuel}$ is in cm/s. Fig. 9 plots this theoretical
 390 fit for $V_{p,fuel}$ vs. experimental results, and the theory fits the data with an
 391 R²-value of 0.97. Moving further, the results from the theoretical fit for $V_{p,fuel}$
 392 can be used to estimate V_p via Eq. 7. Substituting Eq. 9 into Eq. 7, we obtain

Figure 9: Plot of experimental and theoretical spread rates from all tests vs. fuel coverage.

$$V_p = \frac{0.073 \ln(f) + 0.087}{f}. \quad (10)$$

393 This estimate for V_p is also plotted vs. experimental results in Fig. 9. This fit
 394 attains an R^2 -value of 0.93.

395 Overall, the theoretical results fit the data remarkably well. The close fit
 396 for the fuel spread rate reaffirms our observations that no spread will occur at
 397 $f_{crit} = 0.3$. In many cases, this will not be known *a priori*, but a reasonable
 398 estimation can be used to develop a first-order approximation. Future exper-
 399 imentation could confirm whether this method scales to larger fires. There is
 400 some sensitivity of the fit to the estimation of f_{crit} . Assuming no spread occurs
 401 at $f_{crit} = 0.25$, V_p and $V_{p,fuel}$ are slightly overpredicted, resulting in an average
 402 percentage difference of 11% for V_p and 9% for $V_{p,fuel}$ in comparison with the
 403 experimental data. Assuming $f_{crit} = 0.35$, V_p and $V_{p,fuel}$ are underpredicted,
 404 resulting in an average percentage difference of 19% for V_p and 23% for $V_{p,fuel}$
 405 in comparison with the experimental data. In both cases, the differences were
 406 most pronounced at low values of f .

Figure 10: Acceleration of the flame spread rate vs. fuel coverage for all tested fuel arrays.

4.4. Acceleration of Spread Rate

The rate of flame spread is not a static variable for wall fires, and many experiments with samples of sufficient height have observed significant acceleration of the flame spread rate [13]. An analysis of local flame spread rates reveals that our experiment is no exception. A local flame spread rate was measured for each 4-cm-tall block of PMMA, and two local spread rate measurements were determined for each 8-cm-tall PMMA slab. Linear fits of $x_{p,total}$ vs. t , taken over 4-cm-tall regions, were used to determine local values of V_p . By calculating the change between the two uppermost local values of V_p , the acceleration of flame spread at the top of the apparatus was quantified for each fuel array.

Fig. 10 displays these findings plotted vs. fuel coverage. Acceleratory effects are most pronounced at $f = 0.67$, which mirrors the trend observed for the flame spread rate. For $f \geq 0.67$, we see markedly positive values of acceleration; this is the expected behavior for homogeneous wall fires. However, the flame front is actually decelerating in tests where $f < 0.67$, indicated by negative values for acceleration when $f = 0.5$ and $f = 0.4$.

Fig. 10 reveals a sharp divergence in acceleratory trends of the pyrolysis front

424 for arrays with low fuel coverage vs. arrays with high fuel coverage. For discrete
 425 fuels, the flame spreads via a ‘jumping’ phenomenon, whereby the pyrolysis front
 426 ascends to the top of one block of fuel and momentarily halts. After a certain
 427 amount of time, the next block of fuel will be heated until the pyrolysis front
 428 can effectively ‘jump’ to this block and resume its progress. In arrays with low
 429 fuel coverage, it takes a significant amount of time for this jump to occur, so the
 430 flame propagates over the discrete fuels in a very iterative fashion. Because each
 431 successive iteration (i.e., each jump from one fuel to the next) appears to take
 432 a greater amount of time, an eventual failure to spread on a larger apparatus is
 433 plausible. In contrast, fuel arrays with high fuel coverage exhibit a flame that
 434 is continuously advancing and even accelerating. This divergence in behavior
 435 indicates that there is a certain fuel coverage value below which fuel arrays
 436 should be treated as distinctly discrete. Assumptions of quasi-homogeneity are
 437 clearly inappropriate for $f \leq 0.5$. Above this fuel coverage, it may actually be
 438 reasonable to describe the fuel array as a partially homogeneous fuel bed.

439 **5. Mass Fluxes**

440 Mass loss rates for each test were determined by eliminating outliers from the
 441 mass data and applying an 8th-order polynomial fit. The starting point for every
 442 test was normalized as the point when the first temperature measurement of the
 443 fuel array reached the pyrolysis temperature (300°C). Results from identical fuel
 444 arrays were averaged to determine a representative mass loss rate for each fuel
 445 array.

446 Mass loss rates were then used to generate two measures of the mass loss
 447 rate per unit area: the mass loss rate per total pyrolysis area ($\dot{m}''_{total}$) and the
 448 mass loss rate per burning area ($\dot{m}''_{fuel}$). Eqs. 11 and 12 demonstrate how these
 449 parameters were calculated:

$$\dot{m}''_{total} = \frac{\dot{m}}{width \cdot x_{p,total}} \quad (11)$$

Figure 11: Averages for $\dot{m}''_{fuel}$ and $\dot{m}''_{total}$ vs. fuel coverage. Values calculated via Eqs. 11 and 12. (Note: the difference in the mass flux values for the homogeneous test is due to the 2-cm-tall insulation board above the ignition block.)

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

where the width is 20 cm and $x_{p,total}$ and $x_{p,fuel}$ estimates were derived from the linear fits used to calculate flame spread rates and fuel spread rates.

There are important differences between $\dot{m}''_{fuel}$ and $\dot{m}''_{total}$. $\dot{m}''_{fuel}$ quantifies the burning area by neglecting the inert sections of the fuel array, so it represents the true burning mass flux. Meanwhile, $\dot{m}''_{total}$ quantifies the average mass flux for a given area. For all inhomogeneous fuel arrays, $\dot{m}''_{fuel}$ is necessarily greater than $\dot{m}''_{total}$.

Mass fluxes were averaged over the time period when the linear fit for the middle portion of the spread phase (i.e., when $x_{p,total}$ occupied 10-25 cm in height). Both $\dot{m}''_{fuel}$ and $\dot{m}''_{total}$ are plotted vs. fuel coverage in Fig. 11. For all tests, $\dot{m}''_{total}$ is nearly constant during the spreading phase, hardly deviating from around 3 g/s m². However, $\dot{m}''_{fuel}$ appears to be negatively correlated with fuel coverage. The highest results for $\dot{m}''_{fuel}$ actually occur for the tests with the lowest fuel coverage, climbing to over 5 g/s m². These results imply that,

464 during the spreading phase, fuel from the arrays with more spacing is releasing
 465 more pyrolyzed gases per surface area of fuel. Because $\dot{m}''_{fuel}$ is equivalent to
 466 the imparted heat flux divided by the effective heat of gasification [24], it stands
 467 to reason that a higher heat flux per unit area is being imparted over the fuel
 468 surface of arrays with low fuel coverage. This could be the result of a decreased
 469 flame standoff distance, which would allow a greater heat flux to be delivered
 470 to the fuel array. This trend provides further support for the hypothesis that a
 471 delayed thickening of the boundary layer, which would lower the flame standoff
 472 distance, plays a causal role. The increase in local mass flux as fuel coverage
 473 is decreased will assist the flame spread rate; in fact, the optimum in the flame
 474 spread rate may be viewed as a competition between this phenomenon and the
 475 ability of a flame to traverse a gap.

476 Furthermore, analysis of IR images revealed that the shape of the pyrolysis
 477 front does not appear to deviate much when different fuel arrays are employed.
 478 This qualitative assessment suggests that the predicted trend is not a result of
 479 width differences in the actual burning region between tests.

480 Gollner et al. [22] examined mass loss rates per burning area for upward
 481 flame spread over a homogeneous PMMA slab. In their experiment, 4 g/s m²
 482 was reported as the burning rate during flame spread, which compares favorably
 483 to our values. Some researchers have recorded higher burning rates for PMMA
 484 [25, 26, 27], but higher burning rates should be expected for steady-burning
 485 laminar flames across smaller samples [28].

486 **6. Flame Height**

487 Flame heights for each test were computed from video footage via MATLAB
 488 processing. An 8th-order polynomial fit smoothed flame height data, and a nor-
 489 malized start time was developed based on the time when the lowest temperature
 490 measurement reached the pyrolysis temperature (300°C). Flame heights vs. fuel
 491 coverage are plotted in Fig. 12. For the early stages of growth, flame heights
 492 for all tests are nearly the same. Towards latter stages of spread, flame heights

for arrays with low values of f exhibit a marked decrease in growth, which is consistent with the deceleration of the pyrolysis front.

Figure 12: Flame heights vs. fuel coverage at various times during the spreading process. Towards latter stages of the test, flame heights at low values of fuel coverage can be seen to grow more slowly.

7. 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 around a fuel coverage below unity (i.e., around $f = 0.67$). It has been hypothesized that either a delayed thickening of the boundary layer or 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 consistent positive correlation with fuel coverage. A reliable estimation of the fuel spread rate for

509 various fuel coverage values can be developed with knowledge of the homoge-
510 neous fuel spread rate and a reasonable assessment for the limiting fuel coverage.
511 In turn, the flame spread rate can be approximated for a given fuel array if the
512 fuel spread rate is known. This methodology may serve as a useful foundation
513 for estimates of flame spread rates over non-homogeneous fuels.

514 The mass loss rate per burning area was found to be negatively correlated
515 with fuel coverage. These results imply that a higher heat flux is being imparted
516 over the fuel surface. This is likely caused by the inert spacing, which may delay
517 the thickening of the boundary layer and decrease the flame standoff distance.
518 The increased mass flux at low values of fuel coverage likely contributes to the
519 aforementioned trend for flame spread rate.

520 For fuel arrays with low fuel coverage (i.e., $f \leq 0.5$), it was discovered that
521 the time for the pyrolysis front to spread to the next block of fuel could be
522 significant. Furthermore, these arrays witnessed a deceleration of the pyrolysis
523 front during the later phases of flame spread. Fuel arrays with $f \geq 0.67$ still ex-
524 hibited the expected acceleration of the pyrolysis front as it moves upward. This
525 divergence of behavior indicates that there is a fuel coverage below which an as-
526 sumption of near-homogeneity is invalid; consequently, these fuel configurations
527 should be identified as distinctly discrete.

528 Finally, remarkable agreement in scaling with the fuel coverage parameter
529 was found for both 4-cm and 8-cm-tall blocks of PMMA. Future work could
530 elucidate whether scaling vs. fuel coverage remains applicable for large fires or
531 dissimilar geometries.

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