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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.

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 predict 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 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. 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. Watanabe et al. [6] looked at flame spread across horizontal, combustible filter paper perforated with holes, and 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

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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)

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 on horizontal filter paper, finding that the probability for the flame to spread across the filter paper was again related to the number of slits formed.

Arrays of matchsticks (with the heads removed) have been utilized to study flame spread along discrete fuels [8–11]. Recently, Gollner et al. examined discrete fuel behavior through an investigation of vertical matchstick arrays [12]. Flame spread over vertical arrays was found to be a function of spacing between the matchsticks. In all tests with spacing, 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 became larger, 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 where 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. 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 becomes more important. If the spacing is beyond a certain threshold, extinction of the flame may even 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 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

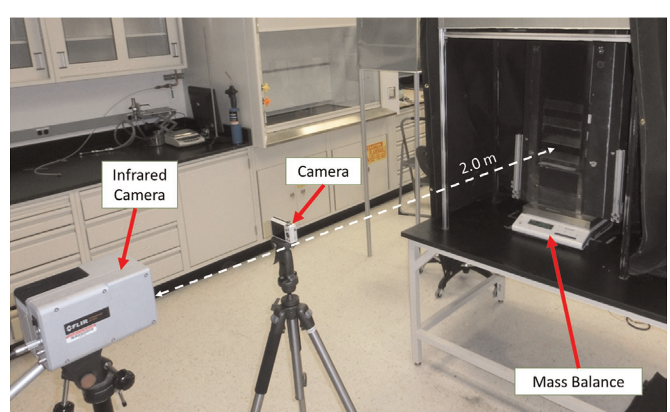

Fig. 1. Photograph of apparatus and associated data acquisition equipment, including the mass balance, camera, and infrared camera.