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# UNIVERSITY OF CALIFORNIA, SAN DIEGO 

## Studies on Upward Flame Spread

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy<br>in Engineering Sciences (Mechanical Engineering) by<br>Michael J. Gollner

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The dissertation of Michael J. Gollner is approved, and it is acceptable in quality and form for publication on microfilm and electronically:
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$\qquad$

Chair

University of California, San Diego

2012

## DEDICATION

To Agnieszka, whose love and support have made this journey through graduate school possible.

## EPIGRAPH

We all, regardless of the scale of the fire out of control, have been awed by the power of the demon thus released by nature and bumbled by the relatively puny efforts of man's extinguishment operations.
"Fundamental Problems of the Free Burning Fire" by Howard W. Emmons

There is no better, there is no more open door by which you can enter the study of natural philosophy, than by considering the physical phenomena of a candle.
"The Chemical History of a Candle" by Michael Faraday

Fire is the best of servants, but what a master!
"Past and Present"
by Thomas Carlyle

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## NOMENCLATURE

## Symbols

| $a$ | exponent constant (-) |
| :---: | :---: |
| A | surface area ( $\mathrm{cm}^{2}$ ) |
| $B$ | mass-transfer number of the fuel |
| C | constant in $\dot{q}^{\prime \prime}$ correlation |
| $C_{1}$ | constant in $x_{p}$ correlation |
| $C_{2}$ | constant in $x_{f}$ correlation |
| $c_{p}$ | specific heat capacity per unit mass |
| $d$ | matchstick thickness |
| $D$ | molecular diffusion coefficient |
| $f$ | stoichiometric fuel-to-air mass ratio |
| $g$ | acceleration due to gravity |
| $h$ | heat transfer coefficient |
| $\Delta H_{c}$ | heat of combustion per unit mass of fuel consumed |
| $\Delta H_{p}$ | heat of pyrolysis |
| $k$ | thermal conductivity |
| $\ell$ | average horizontal distance over which oxygen diffuses |
| $l_{t h}$ | thermal penetration depth |
| $L$ | matchstick length |
| M | mass |
| $\dot{m}$ | fuel mass-loss rate |
| $n$ | vertical matchstick position |
| $\overline{\mathrm{Nu}}_{d}$ | Nusselt number, $h d / k$ |
| Pr | Prandtl number, $\nu / \alpha_{t}$ |
| $\dot{Q}$ | heat-release rate |
| $\dot{q}$ | heat flux |
| $r$ | regression length |
| $r_{f}$ | radial flame standoff distance |
| $r_{s}$ | radius of cylinder at time $t$ |
| $R^{2}$ | coefficient of determination |
| $\mathrm{Re}_{d}$ | Reynolds number, ud/ $\nu$ |
| $S$ | spacing between matchsticks |
| $t$ | time |
| $t_{\text {spread }}$ | spread time to the top of the matchstick array |
| $t_{\dot{m}_{\text {peak }}}$ | time to peak mass-loss rate |
| $t$ | time |
| $T$ | temperature |
| $u$ | velocity |
| $u_{z}$ | average vertical velocity |


| $V_{p}$ | pyrolysis front velocity |
| :--- | :--- |
| $w$ | number of columns across |
| $x$ | height |
| $x_{f}$ | Flame height |
| $x_{p}$ | Pyrolysis height |
| $y_{f}$ | Flame standoff distance |
| $Y_{O_{2}, \infty}$ | ambient $\mathrm{O}_{2}$ mass fraction |

## Greek Symbols

| $\alpha$ | Entrainment coefficient |
| :--- | :--- |
| $\alpha_{m}$ | mass diffusivity |
| $\alpha_{t}$ | thermal diffusivity |
| $\beta$ | volumetric thermal expansion coefficient |
| $\delta_{B L}$ | boundary layer thickness |
| $\eta$ | power-law correlation exponent |
| $\phi$ | flame liftoff angle |
| $\rho$ | density |
| $\nu$ | kinematic viscosity |
| $\mu$ | dynamic viscosity |
| $\theta$ | angle of inclination |
| $\tau$ | $t^{\prime} / t$ |

## Subscripts

0
initial
burnout
chemical
flame
gas
ignition
initial
mixing
pyrolysis
re-radiation
solid
ambient

## Superscripts

| $\prime$ | per unit width |
| :--- | :--- |
| $\prime \prime$ | per unit area |

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## PUBLICATIONS

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M.J. Gollner, K.J. Overholt, A.S. Rangwala, J. Perricone, and F.A. Williams. Warehouse commodity classification from fundamental principles. Part I: Commodity and burning rates. Fire Safety Journal, 46(6):305-316, 2011.
K.J. Overholt, M.J. Gollner, J. Perricone, A.S. Rangwala, and F.A. Williams. Warehouse commodity classification from fundamental principles. Part II: Flame heights and flame spread. Fire Safety Journal, 46(6):317-329, 2011.
M.J. Gollner, Y. Xie, M. Lee, Y. Nakamura, and A.S. Rangwala. Burning behavior of vertical matchstick arrays. Combustion Science and Technology, 184(5):585607, 2012.
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## FIELDS OF STUDY

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Studies in Combustion
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Studies in Environmental Fluid Mechanics
Professors Jan Kleissl and Paul Linden.
Studies in Fire Protection Engineering
Professor Ali S. Rangwala.
Studies in Applied Mathematics
Professors Eric Lauga and Stefan Llewellyn Smith

# ABSTRACT OF THE DISSERTATION 

## Studies on Upward Flame Spread

by

Michael J. Gollner<br>Doctor of Philosophy in Engineering Sciences (Mechanical Engineering)<br>University of California, San Diego, 2012<br>Professor Forman A. Williams, Chair

Experimental techniques have been used to investigate three upward flame spread phenomena of particular importance for fire safety applications. First, rates of upward flame spread during early-stage burning were observed during experiments on wide samples of corrugated cardboard. Results indicated a slower acceleration than was obtained in previous measurements and theories. It is hypothesized that the non-homogeneity of the cardboard helped to reduce the acceleration of the upward spread rates by physically disrupting flow in the boundary layer close to the vertical surface and thereby modifying heating rates of the solid fuel above the pyrolysis region. The results yield alternative scalings that may be better applicable to some situations encountered in practice in warehouse fires.

Next, a thermally thick slab of polymethyl methacrylate was used to study the effects of the inclination angle of a fuel surface on upward flame spread. By performing experiments on 10 cm wide by 20 cm tall fuel samples it was found that the maximum flame-spread rate, occurring nearly in a vertical configuration, does not correspond to the maximum fuel mass-loss rate, which occurs closer to a horizontal configuration. A detailed study of both flame spread and steady burning at different angles of inclination revealed the influence of buoyancy-induced flows in modifying heat-flux profiles ahead of the flame front, which control flame spread, and in affecting the heat flux to the burning surface of the fuel, which controls fuel mass-loss rates.

Finally, vertical arrays of horizontally protruding wood matchsticks were used to investigate the influence of the spacing of discrete fuel elements on rates of upward flame spread. Rates of upward flame spread were found to increase dramatically for spacings between 0 cm and 0.8 cm and experienced only a slight increase thereafter. Based on these observations, the influence of convective heating was hypothesized to dominate this spread mechanism, and predictions of ignition times were developed using convective heat-transfer correlations. Mass-loss rates followed a similar pattern and were predicted along with matchstick burnout times using a droplet burning theory extended for a cylindrical geometry.

## Chapter 1

## Introduction

### 1.1 Motivation for Fire Research

Scientific advances in the understanding of combustion and fire phenomena have greatly benefited mankind, allowing increased control of desired energy resources and prevention of some devastating fire phenomena. Despite these significant advances, catastrophe related to the unwanted combustion of fuels remains an ever-present danger. Research efforts, such as the "Home Fire Project" of the 1970's in the United States demonstrated the impact scientific research can have on the prevention and mitigation of unwanted fires [1]. Despite these advances, there is still more work to be done. Some fields of fire science remain entirely enigmatic, while others have become reasonably understood, yet are still continually challenged by recent advances in other areas such as the increased use of plastics, regulations on halogenated fire retardants, increasing magnitudes of warehouse storage arrangements and continued development in the wildland-urban interface. This dissertation will specifically focus on upward fire spread, where buoyantlypropelled flows aid the transfer of heat ahead of a burning fuel, advancing the fire front at a rate that typically accelerates with time, making this an important field of study for safety applications.

In light of previous advances in the study of fire, an important question is whether it is still worthwhile to continue fire research? To answer this question, it is important to first review some current trends in fire safety. In 2010, U.S. fire
departments responded to an estimated 1,331,500 fires. These fires caused 3,120 civilian deaths and 17,720 civilian injuries. In the same year, 72 firefighters were fatally injured while on duty [2]. There were also 78,150 firefighter injuries in 2009. Beyond obvious life-safety aspects, the total cost of fire in 2008 came to an extraordinary $\$ 362$ billion, or $2.5 \%$ of the U.S. Gross Domestic Product [3].

While the life-safety cost of fire has reduced significantly over the past few decades, the cost in human life is still far too high. Moreover, the enormous financial burden placed on homeowners, businesses and governments as a results of these devastating fires continues to mount year after year. In an era of increased awareness of sustainability and environmental consciousness, the decision to more efficiently prevent and extinguish fires also has an important environmental component. Unwanted fires pollute air and waterways, release significant amounts of "carbon emissions" and require significant fossil-fuel resources for prevention, fire fighting and cleanup, issues that must be addressed in the future if we are to continue striving for some form of environmental sustainability. The motivation to continue research in the field, therefore, should seem obvious. More efficient methods of fire protection engineering have the possibility to reduce costs while increasing the safety of the general population and surrounding environments, perhaps even paying for itself in costs that would have been lost to fire.

### 1.2 The Flame Spread Problem

When a solid or liquid fuel surface is sufficiently heated, flammable vapors are either evaporated (liquid fuels) or pyrolyzed (solid fuels), liberating them from the fuel surface and into the gas phase. When the fraction of flammable vapors in the surrounding atmosphere becomes sufficiently large enough, a spark or enough thermal input will cause the fuel and oxygen mixture to ignite in the gas phase. Sometimes the heat generated by the ensuing flame will not be capable of maintaining the supply of fuel vapor to the gas phase and the mixture will simply "flash", quickly extinguishing. If, however, the heat from the flame to the fuel surface or another applied source of thermal energy is capable of sustaining the necessary
flow of flammable vapors from the fuel to the gas phase, sustained combustion of the fuel will proceed.

Gaseous vapors diffusing from either the solid or liquid-phase fuel surface react with diffused atmospheric oxygen at a thin flame sheet, appropriately called a diffusion flame. The rate at which the combustion process proceeds is then governed by the rate at which fuel vapor is liberated and diffused from the solid or liquid phase and from the fraction of the heat flux generated from these fuel vapors that is received by the burning surface. Describing the gas-phase combustion of fuel vapors and generated heat fluxes primarily requires description of fluid-dynamic effects which control the structure of the diffusion flame, chemical-kinetic effects which govern the rate of reaction and radiative effects from soot produced within the flame. Description of any liquid fuel vaporization is complicated, however that of a solid fuel becomes ever-more complicated because so many effects, radiative absorbtion, chemical kinetics, charring, etc. contribute to this process. While recent attempts have begun to numerically model the pyrolysis process within some solid fuels [4], often it is necessary to apply simple approximations to these complex problems in order to describe relevant macro-scale physics. These assumptions often include infinite reaction rates in the gas phase and a constant temperature for ignition of the fuel surface, $T_{i g}$. The first assumption is typically very accurate for fire problems because reaction times are orders of magnitude greater than flow and diffusion times, however, a constant ignition temperature ignores many relevant effects within the solid phase. Despite introducing these errors from $T_{i g}$, this assumption is usually more than accurate enough when describing processes such as flame spread.

Fundamentally, fire spread occurs because of some type of communication between a burning region and nearby, unburnt fuel [5]. This communication can occur because of one of many different heat-transfer mechanisms, however all modes require a requisite heat flux per unit area, $\dot{q}^{\prime \prime}$ to be applied to the nonburning fuel in order for spread to occur. The flame-spread rate, $V_{p}$ is then the rate at which this expanding combustion zone, called the pyrolysis zone, moves through a fuel bed.

Fuels can be solid combustibles, pools of flammable liquids, porous fuel beds or discrete, separated items, the latter two being relevant in wildland-fire scenarios. The rate of fire spread through any of the above fuel beds can be fundamentally described by taking an energy balance across the flame front,

$$
\begin{equation*}
V_{p} \rho \Delta h=\dot{q}^{\prime \prime}, \tag{1.1}
\end{equation*}
$$

where $V_{p}$ is the flame-spread rate, $\rho$ the density of the fuel bed and $\Delta h$ the difference in thermal enthalpy (per unit mass) between the unburnt and burning fuel. This equation has been called the fundamental equation of fire spread $[5,6]$. Neglecting phase changes and assuming a constant ignition temperature, $T_{i g}$ the flame-spread rate can be written in a more familiar form,

$$
\begin{equation*}
V_{p}=\dot{q}^{\prime \prime} / \rho c_{p}\left(T_{i}-T_{0}\right), \tag{1.2}
\end{equation*}
$$

where $c_{p}$ and $T_{0}$ are the specific heat capacity and initial temperature of the fuel, respectively. Because $\rho c_{p}\left(T_{i}-T_{0}\right)$ tends to be a pre-defined property of the fuel, the heat flux to unburnt fuel, $\dot{q}^{\prime \prime}$ arises as the primary quantity controlling flame spread and will also be the primary focus of this work.

### 1.3 Outline of the Dissertation

The work resulting in this dissertation was first motivated by a study of the flammability properties of stored warehouse containers, as part of an effort to develop a rational basis for assessing the flammability or relative fire hazards of these containers [7-9]. In a warehouse setting, containers or "commodities" are stacked to heights sometimes exceeding 15 meters, in facilities with enormous floor area, creating a dangerous environment with large sources of fuel that are difficult for emergency personnel to reach. Detrimental effects of recent warehouse fires have included deaths of firefighters, damage to local environments, and harsh economic penalties for building owners and insurance interests, even in facilities fully protected to modern codes and standards [10-12]. Compounding this risk potential in these occupancies is the flat, upright configuration of stored goods
and their arrangement which creates exceptionally long vertical flue spaces. This configuration exhibits high rates of fire spread, especially enhanced within flue spaces where the flow is channeled and radiates, producing longer flames.

A key aspect of characterizing the flammability of a group of vertically stored materials is to predict the relative rates of upward spread. We have performed experiments involving a corrugated cardboard carton containing crystalline polystyrene cups. This constitutes a standard item used for sprinkler testing in the fire-protection industry [12]. Distinct stages of burning were identified, first involving the outer corrugated cardboard alone, then inner packaging material, and last the stored polystyrene as well [8]. It is during the first stage of this burning, involving upward spread over a vertical surface of corrugated cardboard, that the greatest potential for extinguishing a warehouse fire initiated by this type of combustion presents itself. Predicting the time necessary for flames to spread upwards, and thus the duration of this critical initial period of fire growth (often lasting only 1-2 minutes) is therefore an important component of classifying the hazards of commodities and developing a general model of fire growth in warehouse configurations. Spread behavior during this initial period of fire growth is the topic of the investigation reported in Chapter 2.

Based on the results in Chapter 3, the significant factor controlling upward flame spread, the heat flux, was emphasized under the influence of inhomogeneous materials. Another important factor influencing $\dot{q}^{\prime \prime}$ is the buoyancy direction relative to the fuel surface, which modifies the flow behavior increasing the separation distance between the flame and fuel surface and modifying radiative heat flux fractions. 10 cm wide by 20 cm tall samples of polymethyl methacrylate were ignited at inclined angles to undergo both flame spread and steady burning, investigating how the change in buoyancy direction modifies the flame-spread rate, mass-loss rate, flame standoff distance and heat fluxes to unburnt fuel ahead of the burning front.

Results indicate that flow effects significantly modify heat fluxes to unburnt fuel and hence flame-spread rates. For positive inclinations, where flames reside above the fuel surface, radiation begins to become an important fraction of heat
transfer even at this small scale. Heat fluxes to the burning fuel, however, do not follow the same trend as heat fluxes to the unburnt fuel, leading to a peak in fuel mass-loss rates close to a pool-fire configuration and peak flame-spread rates when the flame rests below a fuel surface, slightly inclined from the vertical. Additional flow effects, such as entrainment flows on the side of the fuel sample push flames closer to the side of the fuel surface, increasing mass-loss rates at the edge of the sample leading to important three-dimensional flow effects.

Finally, experiments on arrays of horizontally-protruding matchsticks (with heads removed) sought to provide a useful scale model of fire behavior through discrete fuel elements. Flames were found to spread faster through further-spaced arrays, at a rate accelerating over time, illustrating how the rate of flame spread is so greatly influenced by the heat-process between flames and unignited fuel. The flame spread process was modeled using convective heat-transfer correlations based on matchstick configurations and mass-loss rates and burnout times were predicted using a droplet burning theory extended for a cylindrical fuel element.

### 1.4 Summary

In summary, three different problems in upward flame spread will be addressed: spread over corrugated cardboard, spread along inclined fuel surfaces and between discrete fuel elements, namely matchsticks. Through these studies a further understanding of how the heat flux ahead of burning fuel influences upward flame spread will be presented.

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## Chapter 2

## Review of Steady Burning and Upward Flame Spread

### 2.1 Steady Wall Flames

Upward flame spread along vertical solid combustible surfaces occurs as a consequence of heat transfer from the flames to the unignited fuel. Heights of flames adjacent to burning fuel surfaces therefore are important in upward spread. Kosdon et al. [1] and later Kim et al. [2] developed similarity theories to describe laminar boundary-layer combustion adjacent to a vertical flat plate, employing experimental data on vertical cylinders to support the similarity hypothesis. More recent theoretical work has addressed additional phenomena, such as oxygen leakage leading to flame extinction [3]. Flame heights from such steady-burning theories can be deduced by evaluation of the maximum height of the stoichiometric surface, and a method for estimating transfer numbers experimentally for spreading flames by using the similarity solutions has been reported [4]. Buoyancy causes this height to extend above the maximum height of the pyrolyzing fuel. Pagni and Shih [5] refined the description of the combusting plume and termed excess pyrolyzate the gaseous fuel present above the height of the pyrolyzing surface. An increase in the mass of the excess pyrolyzate increases the flame height, thereby increasing rates of upward flame spread in wall fires. These authors formulated and solved con-
servation equations in the region numerically. Later, Annamalai and Sibulkin [6] obtained approximate analytical solutions to the laminar boundary-layer equations from Pagni and Shih's formulation for the flame height and flame spread rates by assuming polynomial profiles.

Most of these papers also report experimental results. Numerous experiments [7-16] have been performed subsequently on steady-burning wall flames using both solid fuel surfaces and gaseous line and wall-fire burners to investigate relationships among flame heights, burning rates, and incident heat fluxes. Among the most thorough work, Ahmad and Faeth [7] performed such experiments in the turbulent regime on steadily burning, vertical fuel-soaked wicks and compared their results to numerical solutions of boundary-layer equations. Their work established a unified correlation of laminar and turbulent burning-rate measurements for steady wall fires on the basis of a modified Froude Number.

Delichatsios hypothesized a simplified flame-height correlation on the basis of dimensional analysis, suggesting that the flame height depends only on the total heat-release rate per unit width of a wall fire [8, 17]. This relationship,

$$
\begin{equation*}
x_{f} \sim\left(\dot{Q}^{\prime}\right)^{2 / 3}, \tag{2.1}
\end{equation*}
$$

has been observed (with $\dot{Q}^{\prime}$ in the range of $20-100 \mathrm{~kW} / \mathrm{m}^{2}$ ) during experiments on gaseous line burners [9-11], gaseous wall-fire burners [7, 8, 13-16] and vertical samples of solid polymethyl methacrylate (PMMA) and wood at varying levels of external heat flux $[9,11,12,14]$, although earlier results of Markstein and de Ris [18] suggested a power of $1 / 2$ instead, so some differences in exponents may be encountered.

To understand the basis of equation 2.1, consider a turbulent wall plume with an entrainment coefficient $\alpha$, the local ratio of the tangential velocity of incoming air to the average upward velocity in the plume. If $f$ denotes the mass of fuel required to react with a unit mass of air, that is, the stoichiometric fuel-to-air mass ratio, then a mass balance indicates that the burning rate per unit width can be represented as

$$
\begin{equation*}
\dot{m}^{\prime}=f x_{f} \alpha \rho_{a} u_{z} \tag{2.2}
\end{equation*}
$$

where $x_{f}$ is the flame height, $\rho_{a}$ the density of ambient air, and $u_{z}$ the average vertical velocity, which can be estimated as $u_{z}=\sqrt{x_{f} g}$ for a buoyant plume, where $g$ is the acceleration of gravity ${ }^{1}$. The basis of the simple estimate in equation 2.2 should be self-evident since the factor multiplying $f$ on the right-hand side is just the product of the average horizontal mass inflow rate per unit area with the height of that area. Similar reasoning could be applied to a vertical axisymmetric jet for which the total mass flow rate would be given by including as as an additional geometrical factor on the right-hand side, the jet circumference. Solving for the flame height reveals the scaling

$$
\begin{equation*}
x_{f}=\left[\dot{m}^{\prime} /\left(\rho_{a} \alpha f \sqrt{g}\right)\right]^{2 / 3} \tag{2.3}
\end{equation*}
$$

which leads to equation 2.1 because the heat-release rate per unit width for steady burning, $\dot{Q}^{\prime}$ is the product of the fuel mass-loss rate per unit width, $\dot{m}^{\prime}$ and the heat of combustion per unit mass of fuel consumed, $\Delta H_{c}$.

While equation 2.1 has strong experimental support for large turbulent wall flames, having $\dot{Q}^{\prime}>30 \mathrm{~kW} / \mathrm{m}^{2}$, recent experimental results in a range of lower heat fluxes have suggested a change in the steady relationship between heatrelease rates and flame heights for tests below approximately $20 \mathrm{~kW} / \mathrm{m}^{2}$. Tsai and Drysdale [16] performed experiments on vertical PMMA samples and a gasfired burner with several mounting configurations and for all samples found a distinctly linear relationship between total heat-release rates and flame heights when $\dot{Q}^{\prime}$ was less than $20 \mathrm{~kW} / \mathrm{m}^{2}$. It is reasonable that the dependency of $x_{f}$ on $\dot{Q}^{\prime}$ should be stronger at these smaller scales. If the flow is laminar, then the oxygen reaches the reaction zone by molecular diffusion, and in equation 2.2 , the inflow velocity $\alpha u_{z}$ should then be replaced by a diffusion velocity, $D / \ell$, where $D$ is a molecular diffusion coefficient, and $\ell$ is an average horizontal distance over which oxygen diffuses. As was pointed out by Roper [20], this horizontal distance

[^0]can be estimated as an average volume flow rate per unit width, $\dot{m}_{f} /\left(f \rho_{f}\right)$ (where $\rho_{f}$ is an average gas density in the flame), divided by an average buoyant velocity, $\sqrt{x_{f} g}$. Substitution of these estimates into equation 2.2 yields
\[

$$
\begin{equation*}
x_{f}=\left(\dot{m}_{f}^{\prime}\right)^{4 / 3} /\left(\rho_{f} \rho_{a} f^{2} D \sqrt{g}\right)^{2 / 3} \tag{2.4}
\end{equation*}
$$

\]

in place of equation 2.3 , which would yield

$$
\begin{equation*}
x_{f} \sim\left(\dot{Q}^{\prime}\right)^{4 / 3} \tag{2.5}
\end{equation*}
$$

in place of equation 2.1. Since the flow, however, is unlikely to be perfectly laminar, a result intermediate between equations 2.1 and 2.5 may be expected. In fact, Tsai and Drysdale [16] reported exponents of 0.98 to 1.25 , depending on sample mounting, in their relationship between heat-release rates and flame heights.

### 2.2 Upward Flame Spread

The general model for upward flame spread, represented graphically in Figure 2.1a, consists of three primary regions, the pyrolysis zone, extending to height $x_{p}$, where ignited material burns and contributes fuel to rising flames, the combusting plume, the region $x_{f}-x_{p}$, where unburnt fuel (excess pyrolyzate) from the pyrolyzing zone continues to burn and heat unignited solid fuel, and a buoyant plume above $x_{f}$ carrying combustion products and entrained air above the combustion region. The spread process is driven by the heat flux from the flame to unignited material above the pyrolysis front [21]. Because the rate of upward flame spread is nearly always orders of magnitude larger than that of downward or lateral flame spread, these processes can often be neglected in the analysis of upward flame-spread scenarios.

Even when edge effects are irrelevant, so that the vertical combustible sample effectively is of infinite width (as in the present study), a wide variety of upward spread behavior can occur, depending upon the nature of the combustible material [23] and the vertical dimension of the surface. Much attention has been devoted to thermoplastics, PMMA being the material investigated most widely. For such


Figure 2.1: (a) Theoretical description of 2-D upward flame spread [22]. (b) Description of measured flame and pyrolysis heights observed from a representative front video frame. As shown in the figure, $x_{f, \max }$ is defined as the top of an attached yellow flame, $x_{f, a v g}$ the mean height of the flame across the sample width, and $x_{p, a v g}$ the mean height of the pyrolysis front across sample width.
materials, when the flames are small and laminar, the spread rate from both theory and experiment for thermally thick materials obeys $x_{p} \sim t^{2}$ [24-26] (although one set of experimental results [25] correlates better with $x_{p} \sim t^{1.7}$ ), but when the flames are large and turbulent, $x_{p}$ increases exponentially with time [24, 27, 28]. Cellulosic materials generally behave quite differently. At small scales, for thermally thick materials, it has proven to be difficult to achieve reasonable accuracy in determining the functional dependence of $x_{p}$ on $t$, the results being sensitive to the manner of initiations and the type of cellulosic. A simple linear dependence, $x_{p} \sim t$, appears to apply for wood, within the accuracy of the data [27, 29, 30]. At later times, unless the material is sufficiently thin that burnout at the bottom becomes important [30] (leading finally to a constant upward spread rate), char eventually builds up to such an extent that upward spread stops, and self-extinguishment occurs $[27,30]$. Sufficiently intense external radiation can, however, lead to continued spread [30, 31].

Upward flame spread is quite complex. Models must address the burning
rate of the fuel below $x_{p}$, the time-dependent temperature field in the condensed phase above $x_{p}$, and the heat flux from the gas to the solid above $x_{p}$. Even the simplest solid materials that experience only time-dependent heat conduction up to a fixed surface temperature required for ignition, thereby being readily amenable to an approximation of a constant heating time for ignition during upward spread, in general must be described by difference-differential equations [18], which predict a stepwise, "leapfrogging" spread [24] that can approach continuous spread behavior, describable by ordinary differential equations [27] only at long times [18, 27]. When charring is important, more complicated descriptions of the behavior of the fuel in response to the heating above $x_{p}$ are needed [27].

Because of the overall complexity of the upward spread process, simplifications of the description of the spatial dependence of the heat flux from the gas to the solid above $x_{p}$ are prevalent in the literature. The gas flow in that region, involving combustion of the excess pyrolyzate, is complicated and not amenable to similarity approximations with a high degree of accuracy, even for laminar flow. In early work, Sibulkin and Kim [32] assumed a constant heat flux to the wall between $x_{p}$ and $x_{f}$ and a flux decaying exponentially with height in the nonreacting plume above $x_{f}$, but in later work, Annamalai and Sibulkin [6] ignored this exponential tail, employing only a constant heat flux over the distance $x_{f}-x_{p}$, an approximation that is very common elsewhere in the literature [18, 27, 30]. A considerable amount of information actually is available on heat fluxes to walls as functions of height above the burning area in wall fires, and such detailed information has been employed in numerical algorithms calculating upward flame spread [28]. Full numerical simulations are beginning to appear more frequently now [33, 34]. Simplified models of the spread process that make rough approximation ignoring these details generally invoke a constant heat flux between $x_{p}$ and $x_{f}$ and zero heat flux above $x_{f}$, assuming that the shape of the heat-flux distribution will not affect the predictions significantly.

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## Chapter 3

## Upward Flame Spread over Corrugated Cardboard

### 3.1 Introduction

As part of a study of the combustion of boxes of commodities, rates of upward flame spread during early-stage burning were observed during experiments on wide samples of corrugated cardboard. The rate of spread of the flame front, defined by the burning pyrolysis region, was determined by visually averaging the pyrolysis front position across the fuel surface. The resulting best fit produced a power-law progression of the pyrolysis front, $x_{p}=C_{1} t^{\eta}$, where $x_{p}$ is the average height of the pyrolysis front at time $t, \eta=3 / 2$, and $C_{1}$ is a constant. This result corresponds to a slower acceleration than was obtained in previous measurements and theories (e.g. $\eta=2$ ), an observation which suggests that development of an alternative description of the upward flame spread rate over wide, inhomogeneous materials may be worth studying for applications such as warehouse fires. Based upon the experimental results and overall conservation principles it is hypothesized that the non-homogeneity of the cardboard helped to reduce the acceleration of the upward spread rates by physically disrupting flow in the boundary layer close to the vertical surface and thereby modifying heating rates of the solid fuel above the pyrolysis region. As a result of this phenomena, a distinct difference was observed
between scalings of peak flame heights, or maximum flame tip measurements and the average location of the flame. The results yield alternative scalings that may be better applicable to some situations encountered in practice in warehouse fires.

Under the conditions of the experiments investigated here, charring of the cellulosic corrugated cardboard is mild, providing a good indication of the arrival of the pyrolysis front (by observing blackening of the face), but not extending significantly above the pyrolysis front to impede spread. In addition, while burnout at the bottom of the cardboard begins towards the end of the upward-spread tests, it is not extensive enough to necessitate its inclusion in the description of the spread, and, moreover, the soon-to-follow involvement of combustion of the commodity [1] overpowers the effects of burnout in the fire history.

### 3.2 Modified Description of Heat Flux

From the one-dimensional time-dependent heat-conduction equation for a semi-infinite solid of density $\rho$, heat capacity per unit mass $c_{p}$ and thermal conductivity $k$, it can be shown that with heating at the surface by a time-dependent heat flux per unit area $\dot{q}^{\prime \prime}$, beginning with a uniform temperature $T_{0}$ at time zero, the surface temperature $T$ at time $t$ is given by [2]

$$
\begin{equation*}
T=T_{0}+\frac{1}{\sqrt{\pi k \rho c_{p}}} \int_{0}^{t} \frac{\dot{q}^{\prime \prime}}{\sqrt{t-t^{\prime}}} d t^{\prime} \tag{3.1}
\end{equation*}
$$

If the material begins to pyrolyze at a fixed pyrolysis temperature $T_{p}$, then by introducing the nondimensional variable $\tau=t^{\prime} / t$, it becomes clear that the integral

$$
\begin{equation*}
I=\int_{0}^{1} \frac{\dot{q}^{\prime \prime} \sqrt{t}}{\sqrt{1-\tau}} d \tau \tag{3.2}
\end{equation*}
$$

must be a constant, determined by the material properties. Under the assumption that the heat-flux distribution above the pyrolysis zone has the power-law variation

$$
\begin{equation*}
\dot{q}^{\prime \prime}=C / x^{1 / 3}, \tag{3.3}
\end{equation*}
$$

Equation 3.2 implies that the time $t$ of arrival of the pyrolysis front will obey

$$
\begin{equation*}
x_{p}=C_{1} t^{3 / 2} \tag{3.4}
\end{equation*}
$$

where $C_{1}$ is a constant. Under the approximation that the flame height $x_{f}$ is proportional to the burning rate per unit width $\dot{m}^{\prime}$ and that $\dot{m}^{\prime}$ is proportional to $x_{p}$, this result also yields

$$
\begin{equation*}
x_{f}=C_{2} t^{3 / 2}, \tag{3.5}
\end{equation*}
$$

where $C_{2}$ is a constant. These variations will be seen to fit the present data best. It may be noted that, with heat transfer controlled by convection, Equation 3.3 implies a boundary-layer thickness that increase with height in proportion to $x^{1 / 3}$, which is in contrast with the classical similarity solution for natural convection, giving an $x^{1 / 4}$ dependence and $x_{p} \sim t^{2}$. The reasons for this difference will be discussed after the experimental results are presented.

### 3.3 The Experiments

The surface tested was the front face of a package of single-walled corrugated cardboard of dimensions $530 \times 530 \times 510 \mathrm{~mm}$. The inside of the carton was compartmentalized by corrugated cardboard dividers to create cells containing polystyrene cups. Other details of the overall experiment are available elsewhere [1] but are not relevant to the present study. Measurements addressed in this study were restricted to flame spread over the first 30 cm of the front surface, so that exposure of the interior of the commodity, burnout, and spread over the rear surface of the cardboard have not yet begun. Moreover, since the sample width exceeded 500 mm , effects of the width on flame heights and on upward spread, which have been addressed in the literature (much of it recent) [3-9] need not be considered here; the width no longer plays a role when it is greater than about $300 \mathrm{~mm}[6,9]$ so that, during the portion of the overall experiment considered here, the cardboard face is effectively of infinite width. The front face was made of approximately 3 mm thick single-ply corrugated cardboard (a schematic diagram of which is shown


Figure 3.1: Cross-section of ' C ' Flute corrugated cardboard [10, 11] used in the experiments.
in Figure 3.1) with its flues oriented vertically. The gross density of the corrugated board has been reported as $0.12 \mathrm{~g} / \mathrm{cm}^{3}$, and the top layer paper density 0.48 $\mathrm{g} / \mathrm{cm}^{3}$ [10].

The package was placed on top of a load cell that measured mass with an accuracy of $\pm 0.5 \mathrm{~g}$. A Sony HD digital camcorder recording at 29.97 fps was positioned in front of the test apparatus to record flame heights and to visually observe the progression of the pyrolysis front. A digital SLR camera was also positioned on the side of the apparatus to record the flame shape close to the fuel surface. The setup was placed under a 1 MW hood to capture burning fumes and embers. Ignition was achieved by adding 4 mL of n -heptane to a strip of glass fiber board approximately 1 cm tall, 0.35 m wide by 3 mm in depth. The wetted wick igniter was held by an aluminum u-channel that was positioned adjacent to and below the lower front edge of the commodity. The video cameras and a data acquisition system used to record load cell readings were started before ignition of the commodity. The data acquisition system and camcorders were synchronized with a stopwatch used to determine the offset between instrument start time and ignition start time. Experimental time begins when the strip is piloted at the centerline of the commodity's front face.

### 3.4 Experimental Results

### 3.4.1 Flame Heights

Experimentally, the simplest method of determining flame heights has been by marking a ruler on the side of a combustible sample, and observing the arrival
of the flame at set markers to determine the flame height, as was done in the work of Tewarson and Ogden [12]. Similar methods have been used by Orloff et al. [13] and by Tsai [8]. Saito et al. determined flame heights by inspecting regularly time-spaced frames from front video footage and reasoned that this method is analogous to performing measurements at every frame obtained [14]. FernandezPello [15] used shutter settings with still photography to resolve flame heights, a somewhat manual method to average over the effects of flame intermittency. To increase precision, Audouin et al. [16], Rangwala et al. [6] and Consalvi et al. [17] all applied thresholds of video images to determine the extent of the flame. Consalvi et al. also related the flame height to the heat flux imparted to a solid by comparison with a numerical model of the process.

Visual assessments of flame locations were performed in the present work as the flame spread up the front face of corrugated cardboard to approximately 30 cm in height. Frames from front video during upward flame spread were imported into Matlab, and then the location of the flame was visually selected utilizing zoomed video frames at 15 points across the width of the front face and recorded by computer software. The height of the flame front at each position was defined as the peak of the visible yellow flame at that location. Although a threshold could be implemented for flame heights, it was found to make little difference in the results.

Averaged flame heights from four tests are shown in Figure 3.2. Deviations in the flame height across the width of the sample are indicated by a shaded gray region above and below these points. The turbulent fluctuating nature of flames causes significant scatter, indicated by an increasing region of deviation over time. Although fluctuations could be decreased by using more uniform materials, such as PMMA, or by introducing sidewalls to limit entrainment effects that disturb the flow, that would exclude the real-world effects of interest here. The growth of the deviations throughout time is important, and observation of these deviations aids in the understanding of early-stage upward fire propagation over practical cellulosic materials. Time-averaging of video frames, as is often performed in steady pool-fire experiments, cannot be applied usefully to these quickly spreading flame fronts.


Figure 3.2: Flame heights for four tests assessed visually across the width of the front face of corrugated cardboard. Points represent averages over the horizontal distance for each test, the line is the average of all the tests, and the shaded region defines boundaries of the standard deviation.

Despite the significant scatter of flame heights, averaged values of flame heights were similar for all four tests. This suggests that the small-scale behavior of the flame is repeatable when averaged. This average flame height is representative of the average vertical extent of the combusting plume, which is the region that imparts the main heat flux to the virgin solid fuel ahead of the flame. The flame tip, or maximum flame height seen anywhere across the width of the face, is less representative of the average heat-flux region, but it is shown in Figure 3.3 since it has often been referred to as the "flame height" in previous studies and therefore is useful for comparisons [17]; it is noticeably (perhaps $50 \%$ ) higher than the average shown in Figure 3.2, but the differences would be much less in more uniform, idealized experiments.

Average and maximum flame heights for all four tests were averaged, shown


Figure 3.3: Maximum or flame-tip heights, measured as the peak of attached yellow flames at each time step for four tests. Errors are not shown in the figure because single values were selected for each test, but estimated magnitudes of errors in the selection technique are $3-4 \mathrm{~cm}$.
together in Figure 3.4. Deviations between averaged values from the tests are now indicated by a shaded gray region above and below sampled points. Both flame heights follow a similar trend. To aid in assessment of analytical models and to generate empirical results, various fits to the experimental data are investigated. From Figure 3.4 it can be seen that a power-law fit, $x_{f}=C_{2} t^{\eta}$, with $\eta=3 / 2$, agrees best with the data

Figures 3.5 and 3.6 show $\log -\log$ plots of data in Figures 3.4 and 3.9, respectively, including exponential as well as power-law fits. These plots provide greater separation of different predictions and so help in selecting the best results. The exponent, $\eta$ for fits to average flame and pyrolysis heights was found to lie between $\eta=1.4-1.8$ for average flame heights, between $\eta=1.1-1.5$ for maximum flame heights, and $\eta=1.3-1.5$ for pyrolysis heights within a $95 \%$ confidence in-


Figure 3.4: Averaged flame heights and maximum flame heights combined for all four tests. Deviations between the maximum or average value for each test are denoted by a shaded gray region above and below test points. Unlike the shaded region in figure 3.2, the shading here refers only to the standard deviation between the averaged values of the four runs. Power-law fits to experimental data are also shown as dashed lines.
terval. Therefore, the selection of $\eta=1.5$ was deemed the most reasonable value to use in analysis, as it lies within the $95 \%$ confidence intervals of all measured data. Exponential fits are provided here in Figures 3.5 and 3.6 to illustrate their poor fit, but they were not included in Figures 3.4 and 3.9 because they did not represent the data well.

A summary of least-squares fits applied to experimental data is provided in table 3.1. Coefficients for power-law fits to averaged experimental data are shown along with $R^{2}$ values representing the goodness-of-fit. Best-fits, as found by a least-squares fitting algorithm as well as fits to specific powers, $\eta=1.5,2,3$ are


Figure 3.5: log-Time versus log-Height plot of the average and maximum flame heights with several possible power-law fits shown. A power-law fit with $\eta=1.5$ closely represents both maximum and average flame height data. Circles denote averaged flame height locations between all four tests, and dots averaged values from each experiment. An exponential fit to the data does not fit experimental data well.
provided for reference.

### 3.5 Additional Fits to Experimental Data

### 3.5.1 Burning-Rate Relationships

Scaling analyses presented in Section 2.1 relate flame heights to fuel massloss rates for steadily burning wall fires. Characteristic gas-phase flow times are short enough compared with spread rates that quasi-steady approximations should be reasonable. Fuel mass-loss rates, $\dot{m}$, were determined by differentiating polyno-


Figure 3.6: log-Time versus log-Height plot of the pyrolysis height with several possible fits to the function is shown. The best fit to the data appears to be a power-law fit close to $\eta=1.5$. Circles denote averaged pyrolysis locations between all four tests, and dots averaged values from each experiment. An exponential fit to the data does not fit experimental data well.
mial fits to mass-loss data collected by a load cell at the base of the experimental apparatus. Additional details of the methods used for the mass-loss data, including the original data, can be found elsewhere $[1,18]$. Fuel mass-loss rates were then converted into heat-release rates per unit width, $\dot{Q}^{\prime}=\dot{m} \Delta H_{c} / w$, where $w$ denotes the width of the sample, and the heat of combustion $\Delta H_{c}$ was assigned the constant value $13.2 \mathrm{~kJ} / \mathrm{g}$, associated with corrugated cardboard [19]. Figure 3.7 displays the resulting relationship between the heat-release rates and both average and maximum flame heights.

In Figure 3.7, vertical and horizontal error bars around each experimental point indicate the range of values of the flame height and the heat-release rate, respectively between the four experimental tests. The data points shown represent

Table 3.1: Coefficients of least-squares fits applied to experimental flame and pyrolysis heights data, where $x_{p}$ and $x_{f}$ are in cm . Power-law fits are shown, of the form $x=C t^{n}$. Exponential fits are not shown because they were all far beyond acceptable error limits.

| Fit | $\eta$ | $C$ | $R^{2}$ |
| :--- | :--- | :--- | :--- |
| $x_{f, \text { avg }}$ best fit | 1.6 | 0.062 | 0.97 |
| $x_{f, \text { avg }}$ fit | 1.5 | 0.090 | 0.97 |
| $x_{f, \text { avg }}$ fit | 2 | 0.014 | 0.95 |
| $x_{f, \text { avg }}$ fit | 3 | 0.00032 | 0.80 |
| $x_{f, \max }$ best fit | 1.4 | 0.28 | 0.97 |
| $x_{f, \max }$ best | 1.5 | 0.16 | 0.97 |
| $x_{f, \max }$ fit | 2 | 0.025 | 0.90 |
| $x_{f, \max }$ fit | 3 | 0.00056 | 0.67 |
| $x_{p, \text { avg }}$ best fit | 1.4 | 0.10 | 0.99 |
| $x_{p, \text { avg }}$ fit | 1.5 | 0.073 | 0.99 |
| $x_{p, \text { avg }}$ fit | 2 | 0.011 | 0.93 |
| $x_{p, \text { avg }}$ fit | 3 | 0.00027 | 0.71 |

the average between these tests, and least-squares fitting was applied to these average values to derive correlations in terms of power-law functions. The best-fit power-law function for the average flame height was found to have an exponent of 1.1 , with an $R^{2}$ value of 0.99 , and the maximum flame-height data were found to have an exponent of 0.9 , with an $R^{2}$ value of 0.98 . Within a $95 \%$ confidence interval, the exponent of the average flame height data could lie between 1.0 and 1.3, and the exponent of the maximum flame height data could lie between 0.8 and 1.0. Fits to the averaged experimental data, therefore, suggest an exponent of unity, within the accuracy of the measurements.

Some of the flame-tip results from the literature also are shown in Figure 3.7. The power law [20] most strongly supported in the literature for $\dot{Q}^{\prime}>20$ $\mathrm{kW} / \mathrm{m}^{2}$ is seen to lie well within the results of the presented data in that range but to predict heights above our error limit at lower values. The linear correlation of steady-burning measurements [5] for $\dot{Q}^{\prime}<20 \mathrm{~kW} / \mathrm{m}^{2}$ is consistent with our data there but would begin to fall above our error limit at the highest heat-release rates. The somewhat lower slope of our best-fit linear correlation for $\dot{Q}^{\prime}<40$


Figure 3.7: Maximum flame heights (flame tips) and flame heights averaged across the width of the front face as functions of the heat-release rate. Errors (increasing over time) for flame heights and heat-release rates are shown as vertical and horizontal error bars, respectively. Solid lines are linear least-squares fits, and flame-tip results from the literature are shown for ${ }^{a}$ Gas-fired wall burner [5] (dotdash curve), ${ }^{b}$ Gas-fired line burner [20] (dashed line), ${ }^{c}$ PMMA spreading wall fire [5] (triangles).
$\mathrm{kW} / \mathrm{m}^{2}$ is seen in Figure 3.7 to encompass, within error estimates, data [5] on upward spreading wall fires. In the size ranges of our experiments, there thus may be a small tendency for flame-tip heights to fall below the best steady-burning correlations. It becomes clear from the results in Figure 3.7 that, in addressing the average flame heights most relevant to average spread rates, a linear correlation with a slope significantly less than that of the best available correlation in the literature for idealized experiments is needed. This smaller slope seen in Figure 3.7 is employed in the following considerations.

### 3.5.2 Pyrolysis Heights

Because corrugated cardboard distinctly changes in color from light brown to black once charring occurs, the pyrolysis front location is easy to distinguish visually at each time step. Frames from front video during upward flame spread were imported into Matlab, and then the location of the pyrolysis front was visually selected along 15 points across the width of the front face and recorded by computer software. In some cases, one or two points on the edge of the sample did not ignite and thus were not pyrolyzing; these points were therefore neglected for the entire test. A section of at least the middle 35-40 cm remained uniformly spreading and therefore was analyzed for the duration of all four tests.

Spatially averaging the measured locations of the pyrolysis front across the width of the front face results in a mean pyrolysis height, shown in Figure 3.8. Despite the uniform ignition at the base of the front face, natural deviations in the makeup of the cardboard, the onset of turbulence, entrainment, and other realworld effects on this wide surface result in advancement of the front that is not entirely uniform. The deviations between the averaged heights measured across the width of the sample for each time step are indicated by a shaded gray region above and below the averaged values. These deviations grow over time, as the onset of turbulence occurs and smaller deviations from earlier in the tests grow in magnitude, and they cannot be avoided without artificially modifying the test apparatus. The average values shown are of interest for testing spread-rate models.

Analyzing captured video footage through computer software, such as by distinguishing thresholds between unburned and burnt material in theory could be an improved method of analysis, although it proved to be unnecessarily complicated. Flames fluctuated, partially obscuring views of the pyrolysis front, and smoke and charred pieces caused an initial test of using a threshold to determine pyrolysis heights to be exceedingly inaccurate. Therefore, the simpler, though more labor-intensive process of manually selecting the pyrolysis location was implemented. Other methods, such as using a 10.6 micrometer bandpass filter on an infrared imaging camera, as Arakawa et al. [21] did, could be ideal and facilitate threshold analysis of data by removing influences of the flame and detecting tem-


Figure 3.8: Pyrolysis heights for four tests assessed visually across the width of the front face of corrugated cardboard and averaged. Deviations between measurements across the face are indicated by a shaded gray region above and below experimental measurements.
perature change along the solid fuel surface. In view of the limited resolution and large expense of such equipment, however, visual imaging was deemed sufficient for these small-scale measurements.

The average or mean pyrolysis front location for all four tests was determined by averaging the locations from each test and is shown in Figure 3.9. Deviations across the front face in each of four tests were combined with deviations between tests and are presented as a shaded gray region in Figure 3.9. Just as in data for each individual test, errors grow slightly as time progresses and deviations both across the face and between tests occur. A maximum height of the pyrolysis front, indicating the highest point advancement across the front, averaged across four tests is also shown as a line above the average pyrolysis heights. It is seen from Figure 3.9 that this maximum value almost precisely follows the peak of the


Figure 3.9: The pyrolysis front location, averaged over four experimental tests is shown as triangular points. A shaded gray region above and below the points indicate deviations between tests and across the width of the front face for each sampled point. Maximum pyrolysis heights are shown above the tip of the gray region, assessed as the maximum height of the pyrolysis front at a sampled time, averaged over four tests. Power-law fits to the average pyrolysis front, with time dependencies $\eta=1.5$ and 2 are shown.
standard deviation bars above the average pyrolysis heights. This indicates that the range in which pyrolysis heights exist at each time step is fairly small, within the vertical error bars, and analysis of the peak pyrolysis height does no more than represent the maximum deviations present. It thus is not analyzed further in this study. A similar exercise could be conducted (with similar results) for the lower limit of pyrolysis heights.

From Figure 3.9 it can be seen that a power-law fit, $x_{f}=C_{2} t^{\eta}$, with $\eta=3 / 2$, agrees best with data, a conclusion further supported by the log-log plot and additional information given in the appendix.


Figure 3.10: Ratio of the average flame height over pyrolysis height as a function of heat-release rate per unit width. Experimental scatter is indicated by a shaded gray region above and below averaged values.

### 3.5.3 Relationship between Flame and Pyrolysis Heights

Several upward-spread theories rely on a power-law correlation of flame height with pyrolysis height of the form $x_{f} \sim a x_{p}^{m}[13,14,22]$. Figure 3.10 shows the ratio of the flame height to the pyrolysis height as a function of the heatrelease rate. The lower heat-release rates occure at early times and are affected by the ignition process, which causes some pyrolysis as the flames develop. Soon, however, after that initial increasing period during which $\dot{Q}^{\prime}<15 \mathrm{~kW} / \mathrm{m}^{2}$, the ratio of the flame height to the pyrolysis height appears to reach a steady value of approximately 1.4 , corresponding to $m=1$ in the preceding proportionality. The relationship of this observation to the other results is described below.

### 3.6 Discussion of Results and Physical Observations

Both flame and pyrolysis spread rates in this study fit most closely with a power-law relationship for corrugated cardboard, having a power lower than that often found for thermoplastic materials but higher than that sometimes inferred for wood, namely, we find $x_{p} \sim t^{3 / 2}$. The data are all mutually consistent in supporting this result. Our finding (Section 2.1 and Figure 3.7) that $x_{f} \sim \dot{Q}^{\prime}$, within the accuracy of the data, is consistent with the results shown in Figures 3.4 and 3.9 and with Equations 3.4 and 3.5 , with approximately, $C_{2} / C_{1}=1.4$, according to Figure 3.9. The resulting value of the ratio $x_{f} / x_{p}$ that develops after the ignition period gives results very close to the average flame height of Figure 3.4, when use is made of the pyrolysis height of Figure 3.9, but appreciably less than the flame-tip height of Figure 3.4, which correlates better with the literature results in Figure 3.10. It becomes relevant, then, to ask why this corrugated cardboard behaves somewhat differently from other materials and exhibits lower average flame heights.

This difference appears to be mostly because the burning of this imperfect, cellulosic material, introduces complications in the burning process that are not considered in traditional models of flame spread. Observations from the side of spreading flames during the experiment reveal how differences from traditional similarity solutions may occur, namely through delamination of the top layer of fuel and its penetration into the boundary layer. Figure 3.11 shows a sample frame of corrugated cardboard with flames still residing on the front face. Unlike most thermoplastic fuels used in previous studies, and unlike more solid wood, corrugated cardboard is actually a two-layered fuel (figure 3.1) consisting of two layers of flat paper with a layer of corrugated paper in the center, glued and pressed together, leaving a significant air gap between the two flat layers. During experimentation, the front layer ignites first, followed by the back layer and inner material, which continues to smolder after progression of $x_{p}$. While the back layer of fuel is observed to remain intact throughout the duration of present experiments,


Figure 3.11: Left: Front video footage during a representative test. The blue contour across the width indicates the measured height of the pyrolysis region. Image taken from the side of a sample during a representative test. Curling of the front layer of cardboard is visible in both images, but the extent of threedimensional effects is more clearly seen in the side image.
the front layer rapidly burns off and delaminates from the corrugated and back layers, producing a "curling" effect on charred material, which physically disrupts the boundary layer above $x_{p}$. This may reduce the flame height over portions of the surface and thereby decrease the average flame height that is responsible for upward spread.

Emmons and Shen [23] observed a similar phenomenon when burning 10 cm high sheets of paper, where this charred residue of burnt paper curled upwards and penetrated the boundary layer. This process might be attributed to dual effects of pyrolysis leaving the top layer of the fuel sample adjacent to the flame much more rapidly than the inner layer, contracting the outer side and causing a slight curl (similar to what has been observed in experiments on matchsticks [24]), and the buoyant flow coming from burning material below then pushing this outer layer further outward and upward. This dual effect and the eventual hardening of charred residue produces a fairly solid obstruction that effectively increases the flame standoff distance past $x_{p}$, thereby decreasing the heat flux to the surface in
a proportion to this extension. In order to reproduce the rates of spread observed in this study, a dependence of the flame standoff distance on height, $y_{f} \sim x^{1 / 3}$ was seen to correlate the data, but this can only represent an average effect since the resulting flow clearly is not self-similar. An interesting question concerns the extent to which this similarity behavior of the averages would extend to other materials at comparable stages of upward flame spread. While these results may have some degree of generality, the present work cannot address such questions, and so future studies employing other materials would be of great interest.

### 3.7 Summary

Physical disruptions in the boundary layer, produced by delamination of the top layer of corrugated cardboard, affect the heat flux ahead of $x_{p}$, for example by increasing the average flame standoff distance. Many current flame-spread models employ a constant heat flux from the flame to unburnt surface, which may be inappropriate for the description of many different fuels at varying scales and which does not fit with a simplified description of the present observations. Instead, the spatial variation of the heat flux from the flame to the surface deserves further study for improved predictions in the future.

### 3.8 Acknowledgements

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## Chapter 4

## Upward Flame Spread of an Inclined Fuel Surface

### 4.1 Introduction

Evaluation of the fire hazard of a material often entails estimation of the material's flame-spread and heat-release rates at full scale by means of interpretation of reduced-scale tests. Maxima of these quantities are important in determining the worst-case scenario used in design of a fire-detection or suppression system [1]. In this study, the flame-spread rate and fuel mass-loss rate (proportional to the heat-release rate) were found to reach maximum values at different orientation angles, implying that the "worst-case scenario" may depend on the orientation selected for evaluation.

This study will seek to explore what controls the mass-loss rate and spread rate by investigating the spatial heat-flux profile ahead of the burning surface, the local regression of the fuel surface and the flame standoff distance over the fuel surface for upward spread and steady burning of surfaces with different orientations. For this investigation, the steady and spreading experiments are performed on polymethyl methacrylate (PMMA). Buoyancy is known to have a significant effect on the flame length, ignition and extinction limits, all of extreme importance for fire prevention and control [2], and the effect of buoyancy varies with orientation.

As the lengths of samples increase, the transition from laminar to turbulent flow behavior also plays a role. The results of this study have implications concerning designs for fire safety and may help to increase understanding of flame spread at inclinations found above or below rooftops and in wildland fire spread up sloped terrain.

### 4.2 Related Literature

While there have been many studies of upward flame spread along vertical surfaces and of horizontal flame spread along horizontal surfaces, few investigations have systematically addressed the dependence of the spread rate on the orientation angle of the surface for inclined surfaces. To date, with few exceptions all such experimental studies have focused on PMMA as a model fuel, but even for this fuel, the entire range of upward-spread inclination angles has not yet been addressed. Ito and Kashiwagi [3] report careful, detailed measurement mainly of downward flame spread along PMMA surfaces of different orientation angles, although they do include three somewhat upward orientations. Drysdale and Macmillan [4] were the first to perform upward-spread experiments systematically at different orientations. They studied both thermally thin computer cards and thermally thick PMMA samples 2-6 cm wide. Starting from horizontal spread, they found little change in the average spread rate until the angle, $90^{\circ}$ for horizontal, became about $75^{\circ}$, after which the spread rate increased substantially as the orientation of the surface approached the vertical, $0^{\circ}$, but they did not go beyond the vertical to investigate upward spread with flames below the fuel surface, orientations that are investigated here. Pizzo et al. [5] and Xie and DesJardin [6] also investigated flame spread over the surface of PMMA in the same range, $0^{\circ}$ to $90^{\circ}$, the former performing experiments on thick samples 20 cm wide, and both making 2-D numerical simulations; the latter also provide additional numerical details of the average gas-phase heat-transfer process during spread. For thermally-thin fuels, Quintiere [7] developed a flame-spread theory using a modified Grashof number to account for gravity along with heat-transfer correlations from Ahmad and Faeth [8]
and from Roper et al. [9]; experimental results were in qualitative agreement with predictions.

Steady burning experiments relevant to the present study have been performed by Ohtani et al. [10], who used square sheets of PMMA $3-10 \mathrm{~cm}$ wide and found maximum burning rates in the vertical configuration, reaching minima at the pool and ceiling configurations. Much earlier, Blackshear and Kanury [11], who used fuel-soaked wicks 10.54 cm square, also found minimum rates for the horizontal orientation and maxima for vertical orientations, consistent with these results and in qualitative agreement with more recent detailed numerical simulations by Ali et al. [12], but within experimental accuracy they report negligible differences between the vertical and ceiling orientations. Contrary to all other results, de Ris and Orloff [13], who used a gas burner 0.65 m in length, the orientation of which could be varied by rotating it, found that turbulent burning rates reached a maximum near the pool-fire configuration and minimum near the ceiling-fire configuration. They attribute their conflict with the pervious experiments, which were conducted at smaller scales, of widths less than 10 cm , to various influences, especially radiation and transition to turbulence. The differing previous results for steady burning raise questions about what should be expected in the present experiments.

### 4.3 Experimental Setup

An experimental apparatus was constructed that enables measurements to be made of flame spread and mass-loss rates on an inclined fuel surface, as shown in Figure 4.1. Two 30 cm high aluminum angle bars were mounted vertically on a load cell and connected to a rotatable aluminum sheet. This served as the test surface and measured 20 cm in width and 65 cm in height. A sheet of SuperWool insulating board, 1.27 cm thick, was attached atop the aluminum sheet. A section beginning 5 cm from the base of the surface of the insulating sheet was cut out for the fuel sample, a 1.27 cm thick, 10 cm wide, 20 cm tall sheet of Acrylite GP (PMMA), which was then mounted to the aluminum sheet with four screws.

Spacers were installed in the back of the sample to align the sample flush with the insulation and to minimize heat losses to the aluminum sheet. To permit unobstructed natural convection, which may occur in practical situations, no side walls were attached.

PMMA samples were cut precisely using a LaserCAMM, including 4 mounting holes and holes for 7 surface-mounted thermocouples. K-type thermocouples, of 0.25 mm diameter wire, were threaded through holes in the sample, bent atop the surface, and then melted flush onto the face of the surface with a heated piece of metal. Thermocouple wires were passed through a 5 cm wide opening along the length of the aluminum sheet, and their outputs were recorded at 10 Hz by a data acquisition system. This opening also facilitated observation of bubbling through the rear of the sample.

Heat fluxes were measured with an array of thin-skin calorimeters, 11 mounted along the centerline of the sample. Each sensor consisted of a 1 cm square, 1.2 mm thick 304 stainless steel plate painted matte black on the front surface, with a K-type thermocouple spot-welded to the rear of the surface. Heat fluxes were determined by numerically differentiating the measured temperature change of the rear of the sample, taking into account convective, radiative, and conductive losses [14]. Three cameras were placed around the sample to view the flame height, the flame standoff distance, and bubbling, through the front, side, and rear of the sample, respectively. The load cell measured the mass of the sample at 15 Hz with an accuracy of $\pm 0.5 \mathrm{~g}$.

Ignition of samples undergoing upward flame spread was achieved by igniting a fuel-soaked wick at the base of the sample. The fuel chosen was methyl decanoate, of which 3 mL was used. All samples were ignited at $60^{\circ}$ from the vertical, where the wick was left to burn for 2 minutes before a cover made of SuperWool insulating board was removed from the top 18 cm of the sample and the setup was rotated to the desired angle of inclination. In this manner, all samples experienced the same extent of external heat input during the ignition stage, and all had approximately a 2 cm PMMA pyrolysis height at the beginning of the experiment. Steady burning samples were ignited by a standard blowtorch, which

Figure 4.1: Experimental setup.
was passed over the surface for approximately 2 minutes until the entire surface was uniformly ignited. Measurements on steadily burning samples were taken once a constant rate of mass loss was reached, about 2 to 4 minutes after removal of the insulating board. Between four and nine tests were performed at each inclination in order to test the repeatability of the experimental results.

### 4.4 Measured Flame-Spread and Mass-loss Rate

The spread rate, $V_{p}$ was defined as the rate of increase of the pyrolysis height, which was determined from the readings of the surface-mounted thermocouples under the assumption that the pyrolysis temperature is $T_{p}=300^{\circ} \mathrm{C}$, based upon comparison of the rear-view observations of bubbling and previous measurements on Acrylite [15]. While upward flame spread is typically acceleratory, the change in spread rate over the relatively small distances measured is not great, and for consistency in comparison with previous experiments [3-6], an average spread rate between distances of 10 cm and 20 cm is employed here. Linear fits were applied to the averaged pyrolysis height to determine representative spread rates from their slopes. The points are averages for all tests and the error bars show the maximum variations between evaluating rates at 10 cm and at 20 cm for all tests. The results are shown in Figure 4.2 for $-60^{\circ} \leq \theta \leq 60^{\circ}$, along with earlier results from the literature cited previously [3-6]. Despite the evident scatter, to be expected because of the different sizes and distances studied, there is reasonable agreement with the previous work over the common range of angles measured, but the present work shows that the maximum of the curve occurs not exactly at the vertical orientation but rather at somewhat negative angles, as if a symmetrical curve were shifted slightly to the left. These new observations of $V_{p}$ in the range $-60^{\circ} \leq \theta \leq 0^{\circ}$, on the undersides of materials indicate that spread rates at $-30^{\circ}$ and $-45^{\circ}$ in fact very closely match the spread rates observed in the $0^{\circ}$ configuration, with $-30^{\circ}$ spread rates slightly higher than the averaged $0^{\circ}$ rate.

The mass-loss rates per unit area, obtained in the present study and in two previous investigations, are shown in Figure 4.3. The "steady" rates reported


Figure 4.2: Dependence of the average rate of flame spread $V_{p}$ on the inclination angle $\theta$ of the fuel surface. Here $V_{p}$ is calculated from thermocouple measurements of $x_{p}$ the pyrolysis-front position and is compared with previous experimental results by Pizzo et al. [5] and Drysdale and Macmillian [4] and numerical results by Pizzo et al. [5] and Xie and DesJardin [6]. The width of samples tested experimentally, $w$, is indicated in the figure legend.
here are averages, measured $800-1000 \mathrm{~s}$ after the uniform ignition of the entire sample, selected because the measured mass-loss rate was most constant during this period, even though the measured PMMA back-face temperature reached values as high as $80^{\circ} \mathrm{C}$ by the end of the measurement. For the spreading tests the measured mass-loss rates and pyrolyzing surface areas increase with time, and the results shown in the figure are average values at the time that the pyrolysis front reaches the top of the sample, the total sample area being employed to evaluate the rate per unit area. As may be expected, these rates are significantly less than
the "steady" rates, which are higher because of the higher average PMMA temperature associated with the deeper penetration of the thermal wave into the material at the later time [16]; at about 250 s after the "spreading" measurements shown, the recorded mass-loss rates are comparable with those of the "steady" measurements. The principal observation to be made from these results is that both sets of data exhibit the same dependence on inclination angle, with rates increasing continuously from ceiling through vertical to pool configurations. The "steady" data thus serve to demonstrate that the "spreading" results are not artifacts of the spread process but instead reflect quite general influences of the inclination angle for these experimental conditions. If results during spread had been compared at the same time after ignition instead of at the same extent of fuel involvement, there would be a tendency for the nearly constant slope of the curves to decrease with increasing angle, but the general trend would be the same.

It is noteworthy that, between the vertical and pool configurations, these results are qualitatively different from those of Ohtani et al. [10], obtained with the same fuel, shown in the figure. Those results, which pertain to steady burning of appreciably smaller samples and agree qualitatively with experiments of Blackshear and Kanury [11], are what one would expect for convection-controlled burning, because the component of gravity parallel to the fuel surface is maximum in the vertical configuration. Also, since convection-controlled rates would increase with decreasing boundary-layer thicknesses, the observed higher average mass-loss rates per unit area for the smaller samples are expected for this mechanism; in fact, data in that paper point toward a decrease in the rate per unit area with increasing size. It thus appears that in the present experiments, at least between the vertical and pool configurations, the controlling mechanism is different from that of the smaller samples.

On the other hand, the observed dependence on angle is seen in Figure 4.3 to be similar to that of de Ris and Orloff [13] over the entire range. They used a gas burner to simulate flame spread over a large fuel surface up to 65 cm in length, employing a novel technique to identify the dependence of burning rates on $B$ numbers from measurements of the heat flux to the surface. A fuel mass-


Figure 4.3: The mass-loss rates per unit area as a function of inclination angle for both steady and spreading tests in this study, along with previous data on $8 \times 8$ cm square samples of PMMA by Ohtani et al. [10] and with a 0.65 m long gas burner with $B=1$ by de Ris and Orloff [13].
transfer number of $B=1$, similar to the fuel in this present study ( $B=1.67$ [17]) is selected here from de Ris and Orloff to show for comparison. Our mass-loss rate per unit area in both steady and spreading tests over PMMA have nearly the same slopes with $\theta$ as the steady gas burner experiments, consistent with the mechanism occurring being the same. This increase in $\dot{m}^{\prime \prime}$ with $\theta$ was attributed by de Ris and Orloff to adjustments involving the importance of radiant fluxes in controlling the rates, thereby suggesting that radiant transfer is important in the present experiments. The scale of the test sample here, however, is significantly smaller than the gas-burner's dimensions, consistent with the lower rates found here, if
radiation is controlling and the radiating volume is less, but perhaps surprising in view of the magnitude of the size difference. It may suggest a greater propensity for radiant emissions from PMMA than from typical gaseous fuels.

### 4.5 Radiant-Flux Estimates

Because of these mass-loss findings, additional heat-flux measurements were made for the purpose of estimating radiant energy fluxes to steadily burning surfaces. The absence of instrumentation for direct measurement necessitated employing a roundabout, inaccurate procedure. First, heat-flux gauges were placed at various locations well outside the fire and oriented to see the entire flame, in order to obtain the total radiant power output from estimated view factors based on observed flame sizes and shapes. Next, view factors between the burning surface and the flame were estimated for each case and then employed, under the assumption of isotropic emission, to calculate the incident radiant flux. In most cases, resulting heat fluxes from different gauges based on different assumptions differed by less than a factor of two, but with the flames on the underside, at the most negative angle, visual access of the gauges without excessive heating or reflection from surfaces was difficult to achieve, and uncertainties approached a factor of 10 . Nevertheless, the order of magnitudes of the resulting fluxes were comparable with the total fluxes measured on the wall just above the burning surface and calculated as required for gasification from the measured mass-loss rate ${ }^{1}$. It thus was estimated that the radiant contribution varied from about 10 percent to about 70 percent. Moreover, a definite increase in the radiant flux with increasing angle of inclination of the surface was calculated from these results, as seen in Figure 4.4. It should be emphasized that the curve shown for the radiant flux, which lies within all error bars, is merely an estimate based on our understanding of the situation and is not a least-squares or polynomial fit, which would not be meaningful

[^1]because of the wide scatter.


Figure 4.4: Total heat fluxes over the fuel surface, $\dot{q}_{p}^{\prime \prime}$, estimated radiant energy fluxes and maximum measured heat fluxes above the fuel surface, $\dot{q}_{f, \text { max }}^{\prime \prime}$ are presented for steady burning tests. Error bars denote the standard deviation of variations between tests, except for $-60^{\circ}$ where only the most reasonable results are shown. Inset photographs of $-45^{\circ}$ and $60^{\circ}$ tests are also shown.

It is understandable, for a number of reasons, that radiant fluxes will increase with angle. The flux is mainly from soot emissions, the intensity of which will increase with increasing soot volumes and concentrations, and the soot is produced by finite-rate processes in fuel-rich zones, so that longer fuel-rich residence times lead to more soot and greater emissions. That residence time will be minimum with the flames, largely blue, underneath the fuel surface and maximum
with the flames rising above, in the pool-burning configuration. In addition, the pool-burning view angle between the flames and the burning surface is greatest, most of the yellow flames at the negative angles being adjacent to or behind inert walls. Coupled with the much thinner flame zones at negative angles, a monotonic increase of the radiant contribution with increasing angle is clearly to be expected. The increase in the rate of radiant energy transfer therefore is consistent with the burning-rate increase seen in Figure 4.3 and a viable candidate for its cause.

### 4.6 Measurement of Flame-Standoff Distances

The three-dimensional character of the flow complicates efforts to measure flame-standoff distances photographically. The side-view camera is most useful for this purpose, but it mainly senses the maximum distance, normal to the fuel surface, of emission of flame radiation, in the horizontal line of sight parallel to the surface. The horizontal variations are small between ceiling and vertical configurations, but they rapidly become large as the pool configuration is approached. Also, while some blue flames are visible near the leading edge in ceiling-like configurations, most of the flames detected are yellow. The flame characteristic that can be detected most accurately is the outer boundary of the yellow zone (or, sometimes near the leading edge, where there is no yellow, the blue zone), and for this reason that is what is recorded here. For present purposes, the "flame standoff" distance is therefore defined as the distance between the top of the yellow flame and the fuel surface, perpendicular to the fuel surface, measured by side-view images of the flame. This is more nearly a measurement of the maximum soot-emission height of the flame for orientation angles from $30^{\circ}$ to $60^{\circ}$, but much more representative of maximum-temperature positions for $-60^{\circ} \leq \theta \leq 0^{\circ}$. The distances, measured by a custom thresholding script in MATLAB on images taken during a "steady" burning regime, averaging over approximately 50 images from several tests at each angle corrected for regression of the fuel surface, are plotted in Fig. 4.6, where the shaded region defines the bounds of experimental uncertainty. Similar results are observed for "spreading" tests, as expected, but they vary a little more and could
complicate interpretations because of the spreading nature of the flame.
The "standoff distance" in Figure 4.6 remains similar for ceiling and vertical configurations and begins to linearly lift off the surface as pool configurations are approached. Underside measurements of $y_{f}$ can be interpreted from considerations of boundary layers in natural convection. In such flows, in general, it can be reasoned that it is the component of gravity parallel to the fuel surface that accelerates the flow, the normal component merely adjusting the normal pressure variation, and by dimensional analysis, characteristic lengths should then be proportional to the cube root of the ratio of the square of the kinematic viscosity to this component, which would vary inversely as the cube root of $\cos \theta$. It may then be inferred that the standoff distance should approximately exhibit such a variation, although the classical laminar boundary-layer theory for a vertical wall produces a fourth-root dependence, instead, the additional dimension modifying this simple dimensional reasoning in the boundary-layer approximation. While results also differ for turbulent boundary layers, a roughly fractional-power dependence in general is to be expected.

Comparison of the curves for the "wall fire" and negative angles in Figure 4.6 exhibit consistency with this deduction, within experimental accuracy, near the leading edge, where the flow is most nearly two-dimensional. The experimental accuracy is insufficient to determine the power, but a fractional power clearly is indicated near the leading edge. Farther along the burning surface, however, this relationship reverses, and the "wall fire" exhibits a larger standoff distance. This is consistent with the flow remaining nearly two-dimensional for the vertical configuration but becoming increasingly three-dimensional as the ceiling configuration is approached, with fluid outflow to the sides, as may be seen in the left-hand photograph in Figure 4.4, leading to a reduction in the standoff distance, which is seen to actually begin to decrease with increasing distance from the leading edge at large distances, through these three-dimensional outflow effects.

Because of this effect, the average rate of convective heat transfer to the burning fuel may decrease with increasing angle, in which case the increased radiative heat transfer rate must necessarily become responsible for the increase of

Figure 4.5: Illustrative figure showing the measurement of flame standoff distance, $y_{f}$ and the three-dimensional behavior
of the flame in $0^{\circ}$ and $60^{\circ}$ tests. The flame liftoff angle, $\phi$ is defined as the angle between the outer edge of the yellow
flame and the fuel surface.
the burning rate. A consequence of these observations is that standoff distances (but not burning rates) would behave differently for wider samples that maintained more nearly two-dimensional flow.

The sharp increase in the measured $y_{f}$ for positive $\theta$ occurs through what could qualitatively be called "liftoff" of the flame from the fuel surface by vertical buoyant acceleration. Within this region of linear increase of the "standoff distance" with distance from the leading edge, a flame liftoff angle, $\phi$ can be measured as the angle between $y_{f}$ and the fuel surface. For "steady" tests, $\phi$ is measured to be $32^{\circ}, 18^{\circ}, 10^{\circ}$ and $8^{\circ}$ for inclinations of $60^{\circ}, 45^{\circ}, 30^{\circ}$ and $0^{\circ}$, respectively; a rapidly accelerating increase in $\phi$ with $\theta$. The increase of the component of gravitational acceleration perpendicular the fuel surface causes this increase, as well as the inward "necking" of the flame, seen in the other photograph in Figure 4.4. These "standoff distances" thus are seen to be very three-dimensional phenomena and to represent mainly the behavior near the center of the fuel for angles above $30^{\circ}$.

The air entrainment from the sides causes the "necking" of the flame above the fuel sample, pushing flames at the edges of the sample closer to the fuel surface and extending $y_{f}$ above the center of the fuel. This three-dimensional behavior is the cause of the result in Figure 4.4, where constriction of the center of the $60^{\circ}$ flame is caused by increased air entrainment at the edges of the sample, an effect previously observed by Ito and Kashiwagi [3]. At underside and vertical orientations the flame shape remains fairly uniform over the fuel surface except for slight effects at the edges of the sample, but as the fuel is inclined between $30^{\circ}$ and $60^{\circ}$ three-dimensional lifting becomes increasingly important.

Width effects on a vertical fuel sample have been studied by Rangwala et al. [20] and Tsai [21] previously, and in their experimental results only small changes appear to take place between widths of 10 to 20 cm . When the fuel is inclined, however, these changes may become more significant. To investigate this, regression measurements were made transversely on quenched samples. The results are shown in Figure 4.7, where the measured regression of the sample surface has been used to deduce the variation in the mass-loss rate across the


Figure 4.6: Standoff distances of steady flames when $x_{p}=20 \mathrm{~cm}$ taken by a side view camera. The angle of inclination varies from $-60^{\circ}$ to $90^{\circ}$.
sample width. Samples were cut along the width at 10 cm above the leading edge and photographed along with a scale, measuring the fuel thickness manually from photographs with ImageJ. The mass-loss rate per unit area was found from the regression length, $r$ by $\dot{m}^{\prime \prime}=r \rho_{s} / t_{b}$, where $\rho_{s}=1190 \mathrm{~kg} / \mathrm{m}^{3}$ is the density of PMMA [19] and $t_{b}$ the burning time of the sample.

While for the $-60^{\circ}$ and $0^{\circ}$ tests the regression is fairly uniform across the width of the sample, significantly higher variations in the mass-loss rates per unit area are found across the width of the sample in the $60^{\circ}$ orientation. Small edge effects are present in all samples as a result of a lip that forms between the fuel surface and insulation as the surface regresses with time. Linteris et al. found similar effects on horizontal PMMA samples when compared to vertical samples burned under imposed heat fluxes on the cone calorimeter [22]. The principal result of


Figure 4.7: Mass-loss rates from the center to edge of the fuel sample estimated from regression of the surface for steady-burning tests. Shaded regions indicate estimated error bounds.
the present measurements, however, is the large increase in the local burning rates at the edges in pool-like configurations, resulting from greatly increased convective heat transfer there by the flow drawn into the fire plume, despite the likely dominance of radiative transfer in affecting the total mass burning rate at these orientations. The edge convective enhancement adds to the nearly uniform radiant contribution.

### 4.7 Heat-Flux Distributions

To complete the experimental information used in interpreting the spreadrate results of Fig. 4.2, heat-flux distributions were obtained from the array of
gauges on the wall above the samples. While the results clearly vary with time, complete profiles above the burning fuel are obtainable only when the pyrolysis front reaches the top of the sample. Since the general character of the results is not likely to be very different over the 10 cm to 20 cm distance of interest, results are reported only for the time at which the pyrolysis front reaches the top. Heattransfer correlations of the transition length along an inclined, heated surface [23] may suggest that the flow in this experiment is mostly laminar along its length, but correlations for the convective heat flux to the fuel surface are not reliable because of large effects of differences in configurations, which change resulting correlations drastically. These effects may be similar to the "necking" and liftoff behavior which is dependent on the width and would be affected by sidewalls. The flux $\dot{q}_{f}^{\prime \prime}(x)$, which was directly measured in this study for $x=22.5$ to 47.5 cm above the leading edge of the sample, is shown in Fig. 4.8.


Figure 4.8: Heat-flux profiles ahead of the spreading fuel sample, where $x_{p}=20$ cm.

The axes of the figure are selected so that power-law fits to the decay with
height of the heat-flux profiles will appear as straight lines. The horizontal scale thus is logarithmic, like the vertical scale, even though the range of values on the horizontal scale, not much more than a factor of two, is small enough that this may not be evident initially. The dashed lines, showing best power-law fits, exclude the first two data points, nearest to the pyrolysis front, where the flux maintains the nearly constant value presumed to exist in that region of the pyrolyzing surface. It is seen that the power-law decay is quite reasonable in the region of the fit. Other fits were tested, such as exponentials, and were found to be noticeably poorer, although in some cases, especially those in which the fluxes do not change much, it is difficult to determine the best functional dependence clearly.

The power-law fits in Figure 4.8 can be expressed as $\dot{q}_{f}^{\prime \prime}(x) \sim C\left(x / x_{p}\right)^{\eta}$. For $-60^{\circ} \leq \theta \leq 0^{\circ}$, the slope of the decay in heat flux is the same, $\eta \approx-2$, with the constant $C$ decreasing with decreasing $\theta$, although perceptibly larger at $-30^{\circ}$ than at $0^{\circ}$. In flame spread over the top of inclined fuel surfaces the slope is -5 , -6 and -7 for for $30^{\circ}, 45^{\circ}$ and $60^{\circ}$, respectively. While heat fluxes near the fuel surface increase with increasing inclinations (Figure 4.4), the net average heat flux to the unignited fuel for positive inclinations is significantly lower than for negative inclinations because of this rapid decay with increasing $x$.

It is clear that for large angles, radiation controls the burning rate and the view angle to the unignited fuel surface ahead of the burning fuel also decreases with increasing angle. There is also some additional contribution of convective cooling instead of convective heating ahead of the burning fuel surface as the poolburning orientation is approached. The resulting decreased heat fluxes significantly reduce $V_{p}$ with increasing $\theta$, explaining the results in Figure 4.2 for positive angles. The opposite orientation dependencies of heat fluxes to burning and non-burning fuel is noteworthy at these positive angles. In addition, although three-dimensional flow is clearly prevalent in the experiments at these angles, the same qualitative differences between heat fluxes to burning and non-burning fuel are to be expected for very wide samples, since the "necking" and enhanced edge regression cause quantitative but not qualitative differences; the general shape in Figure 4.2 is not likely to be different for infinite width.

At negative angles, on the other hand, convective heating mainly controls both spread and burning. Despite the increasing outflow to the sides with increasing negative angles, the general behavior of decreasing spread rate and heat flux ahead as the ceiling configuration is approached, seen in Figures 4.2 and 4.8, is also expected in two dimensions, for example from the observed increase of the leadingedge standoff distance. The slightly higher heat flux at $-30^{\circ}$ compared with $0^{\circ}$ is consistent with the observed spread-rate maximum in Figures 4.2 and indicates a variation notably different from the variation of the heat flux to the burning fuel over that small range of angle. This difference may arise from the mean flow becoming more two-dimensional with increasing distance along the non-pyrolyzing surface; the outflow to the side affects the burning rate but has not yet influenced the heat flux ahead significantly at these angles. The reason for the slight increase of convective heat flux with decreasing angle near vertical is unclear but may be associated with the normal component of gravity pressing the flame closer to the fuel surface, a possibility that deserves further study. In any event, the difference of the maximum from vertical of both the angle and magnitude of the forward heat flux and spread rate are small, so the vertical configuration is useful for studying the most hazardous configuration in this respect. Thus the entire general shape of the curve in Figures 4.2 is expected to apply as well for very wide samples.

### 4.8 Summary

Effects of surface inclination on flame spread rates and burning rates were investigated using a solid PMMA fuel inclines from the vertical. It was concluded that spread rates are greatest in near-vertical orientations while burning rates are maximized in near-horizontal orientations, for the physical reasons discussed.. Three-dimensional effects were observed because experiments were designed to mimic conditions encountered in practice as closely as possible. Entrainment of air from the side of the fuel sample, described as "necking" of the flame increased heat fluxes close to the fuel edges and additional contributions of radiation are thought to be responsible for some increases in heat fluxes in positive orientations.

Despite these effects, qualitative trends were observed, including the spread-rate maximum at angles slightly less than vertical, which are general and would also apply in strictly two-dimensional configurations in the size range studied or larger, for both polymeric (and, in some respects, cellulosics, not discussed here) solid fuels like PMMA.

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## Chapter 5

## Burning Behavior of Vertical Matchstick Arrays

### 5.1 Introduction

Arrays of wooden matchsticks have proven to be useful tools to model smallscale fire-spread phenomena between discrete fuel elements. While characteristics of realistic, larger fires than those created in the laboratory can vary from what is tested at the small scale, much can still be learned from laboratory experiments, especially about the fundamental mechanisms enabling fire to spread between multiple discrete elements. To this end, matchsticks, paper arrays, and other cellulosic fuel arrays have been utilized to determine characteristics of fire spreading behavior $[1-9]$.

The majority of spread experiments through discrete fuel elements have been conducted in either horizontal or sloped configurations. Vogel and Williams [1] were the first to use vertical wooden matchsticks (with heads removed) of varying lengths and spacings to model horizontal fire spread between fuel elements, and determined necessary conditions for flame propagation as well as model the progression of the fire. A theory was developed utilizing a constant ignition temperature and flame standoff-distance profile, which achieved remarkable agreement with experimental results, supporting the contention that convective effects dom-
inate in experiments at such a small scale. Emmons and Shen [2] used a modification of this modeling technique measuring fire spread rates in a solid array of paper strips separated by increasing amounts of space. Their work presented flame-spread results through the simple geometry of paper arrays which influence the spread rate. Experiments expanding on horizontal matchstick arrays adding the influence of forced convection by Prahl and Tien [3] and Wolff et al. [7], sloped arrays by Hwang and Xie [4] and additional experiments on excelsior and paper arrays in similar, but larger configurations by Emori et al. [5], Finney et al. [9] and Weise and Biging [8] have incorporated some effects of buoyancy into the experimental and theoretical aspects of fire propagation through discrete fuel elements. An analytical analysis by Carrier et al. [6] on wind-aided fire spread through arrays suggested that convective effects dominated in this configuration, with radiative preheating only playing a role at increasingly large fuel loadings. While additional flame spread effects have been identified, no experiments have been performed or models developed where matchsticks or discrete fuel elements are oriented in an upward array to simulate upward flame spread, rather than just flame spread through elements on a vertical slope or through windy horizontal conditions.

In this study, vertical arrays of horizontally protruding matchsticks were used to investigate the behavior of upward flame spread over discrete fuel elements in the laboratory. By increasing the spacing between fuel elements, the flame spread rate can be affected by increased areas of fuel exposure to the advancing flame front. This differs from previous works, which investigated fire spread between vertical matchsticks in horizontal or slightly inclined configurations where direct flame impingement was not the primary heat transfer mechanism due to both the geometry and reduced buoyancy. Upward flame spread is perhaps the most important mode of flame spread in fire safety because it is often present in the development of a fire, and is rapid and most hazardous [10]. Upward flame spread over discrete fuel elements is a common fire scenario, and therefore the results of this work may be useful in future analyses of common fire scenarios.

### 5.2 Experimental Setup and Procedure

A series of 24 single-row experiments and 12 multiple-row experiments were performed using the experimental apparatus shown in Figure 5.1. Standard kitchen matchsticks (brand name: Penley), with heads removed and thickness $d=0.25$ cm were inserted past a thin steel plate into a sheet of fiberboard insulation, leaving $L=1.91 \mathrm{~cm}$ of wood exposed lengthwise. This length was chosen because the top of the matchsticks were far enough away from the steel plate to avoid a regime of pure wall burning, yet not long enough that they "bend" so far as to touch one another while burning, as was observed in horizontal configurations by Vogel and Williams [1]. The steel plate had a thickness of 0.5 mm and was used to provide additional structural support to the setup, although thin enough to avoid significant heat losses from the array. Matchsticks were arranged into either an equally spaced array of spacing $S$ which was varied between 0.8 and 1.2 cm or an equally spaced vertical column which was varied between $S=0.6$ and 1.4 cm . Additionally, a vertical column of matchsticks with zero spacing ( $S=$ 0.0 cm ), essentially touching one another was also tested. These spacings were chosen based upon preliminary experiments to represent the observed limits in flame-spread behavior. In arrays spaced 0.8 cm apart, matchsticks were arranged 5 wide and 11 tall, in those spaced 1.0 cm apart they were arranged 4 wide and 9 tall, and in those spaced 1.2 cm apart they were arranged 3 wide and 7 tall. Each configuration was run at least four times to ensure repeatability of the results, and values presented in this work are averages of the results. Additional setup parameters are provided in Table 5.1, with $w$ the number of matchsticks wide, $n$ the number of matchsticks tall, $M_{i}$ the initial total mass of matchsticks and $A_{i}$ the total exposed area on the surfaces of the matchsticks. A 5 cm section of fiberboard insulation extended below the matchsticks to maintain a smooth wall upstream of the fuel array.

The experimental apparatus was placed atop a load cell which has an accuracy of $\pm 0.01 \mathrm{~g}$ and 800 g capacity, used to measure and record the mass lost from the sample at half-second intervals throughout the duration of the test. Video cameras recording at 30 frames per second were positioned in front of and on the

Side View


Front View

$S=1.2 \mathrm{~cm}$

$$
S=0.0-1.4 \mathrm{~cm}
$$

Figure 5.1: Experimental setup used to test matchstick arrays. Three array setups and a generic single-column setup are shown in the front view for comparison.
side of the apparatus to observe the pyrolysis and flame front propagating. A fume hood above the apparatus removes combustion products from the laboratory without affecting flame behavior.

Experiments were started by igniting the outer tips of the bottom layer of matchsticks with one standard blowtorch in the single column configurations and 2 blowtorches in multiple-column arrays. A steel plate was held between the first and second layer of matchsticks until the entire bottom row was evenly ignited, to avoid preheating downstream. Experimental time began once the steel plate was removed, resulting in rapid vertical acceleration of the flame front. The only exception to this procedure was the zero-spacing column, which could not use the steel plate as a separator. In that case, the ignition time was defined by observed flaming of the bottom matchstick (using video footage).

Table 5.1: Experimental setup and initial conditions.

| Spacing |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| $S(\mathrm{~cm})$ | Columns <br> $w$ | Rows <br> $n$ | Initial Mass <br> $M_{i}(\mathrm{~g})$ | Surface Area <br> $A_{i}\left(\mathrm{~cm}^{2}\right)$ |
| 0.0 | 1 | 31 | 2.05 | 61 |
| 0.6 | 1 | 16 | 1.06 | 32 |
| 0.8 | 1 | 11 | 0.726 | 22 |
| 1.0 | 1 | 9 | 0.594 | 18 |
| 1.2 | 1 | 7 | 0.462 | 14 |
| 1.4 | 1 | 7 | 0.462 | 14 |
| 0.8 | 5 | 11 | 2.38 | 110 |
| 1.0 | 4 | 9 | 1.63 | 71 |
| 1.2 | 3 | 7 | 0.775 | 41 |

### 5.3 Physical Observations

Upon removal of the steel plate, the flame extends above the first matchstick (or layer of matchsticks) impinging on the next matchstick directly above and begins heating. Flames from the first matchstick directly impinge across the length of matchsticks vertically above them (Figure $5.2 \mathrm{a}-\mathrm{d}$ and f), subsequently heating them and resulting in a rapid spread process that ignites the entire length
and burns until all fuel vapors have been released, shown in Figure 5.2e. Therefore, heating is accomplished by heating from flames on both sides as well as in-between matchsticks, resulting in 3-4 surfaces experiencing flame impingement before ignition, which greatly increases the rate of flame spread. The burnout process proceeds once matchsticks have lost enough fuel to no longer sustain combustion.

In single rows with zero spacing and in arrays spaced closely together ( $S=$ 0.8 cm ) the lack of spacing causes the thermal boundary layer to also flow outwards, extending the flame to reside along the sides and in front of the array, heating the sides and tips of matchsticks ahead of the pyrolyzing region until sufficient fuel vapors are gasified to sustain ignition, seen in Figures 5.2a and b. While matchsticks may ignite at the tip and burn horizontally toward the base in these small-spaced configurations, the upward spread rate is dominated by heat flux to the side of matchsticks, igniting the entire side surface and subsequently heating further matchsticks ahead. Because the heating is primarily on the sides of the matchsticks, this results in only 2 surfaces heating, which results in much lower mass-loss rates and spread rates than in spaced cases.

In experiments on horizontal matchstick arrays, Vogel and Williams [1] found that matchsticks tend to lean slightly toward the flame as it approaches, probably because of enhanced pyrolytic mass loss on the exposed side. In experiments on vertical arrays, this process was not observed. However, after the flame has passed, burned elements bend in the direction of flame propagation, similar to the horizontal case. The matchsticks bend only upwards as a result of continuing energy input, which causes further pyrolysis and mass loss on the top side. It is possible that as a result of the much more rapid combustion in the vertical configuration not enough time elapses for uneven combustion during early stages (with ignition times $\sim 1-5 \mathrm{sec}$ ), but with the long burnout time ( $\sim 10-30 \mathrm{sec}$ ), enough time elapses for these processes to become apparent, resulting in the characteristic bending upward at the end of the burning process, shown in Figure 5.2e.

Figure 5.2: Side (top) and front (bottom) video showing behavior of experiments. (a) $S=0.8 \mathrm{~cm}$ array, flame residing on face of matchstick tips, (b) $S=0.0 \mathrm{~cm}$ spacing single row, (c) $S=0.6 \mathrm{~cm}$ single row, flame spreading up matchsticks, (d) $S=0.8 \mathrm{~cm}$ single row, flame spreading up matchsticks, (e) $S=0.8 \mathrm{~cm}$ single row, matches burning out and bending upward and (f) $S=1.4 \mathrm{~cm}$ single row, flame spreading up matchsticks. Note: (b) - (f) are single-column experiments, but
holes left from arrays in the metal backing are seen in some of the front images.

### 5.4 Spread Rates

### 5.4.1 Experimental Results

In order to track the progression of ignited matchsticks, ignition was defined as a blackened underside, determined by analyzing video footage close to the side of the burning array, frame-by-frame. This method is similar to the determination of pyrolysis of Markstein and de Ris [11] on thin fuels, and is possible only at these small scales because flames are not yet large enough to obscure a view of pyolyzing fuel from a side view camcorder. Measurements from each of four tests in each single column configuration were close to one another, indicating reasonable accuracy, and they were averaged together at each time step, shown in Figure 5.3. Drawing an analogy to flame spread over continuous fuels, this sequence will be defined as a location of the pyrolysis front, $x_{p}$. Pyrolysis fronts were not able to be tracked for arrays more than one column wide because flames and neighboring matches obscure a clear view of the blackening used to detect ignition in this study. While blackening is not truly indicative of ignition, and in fact typically proceeds slightly after the first contribution to the flaming front, it provided the most accurate and repeatable method available that could reasonably compare the ignition rates between different spacings.

Models for upward flame spread predict power-law dependencies between the pyrolysis length and time of the form $x_{p} \sim t^{a}$ due to the influence of buoyancy, as reviewed by Fernandez-Pello and Hirano [12]. Accordingly, upward spread experimental results, such as those by Gollner et al. [13] have been found to fit well to these power-law correlations. In order to evaluate the applicability of upward flame spread models, as well as to compare the mechanisms influencing tests with varying $S$, a least-squares algorithm was used to apply power-law fits to ignition time data in Figure 5.3, shown as dashed curves through experimental points. Three different regimes of behavior were clearly distinguished between the 0.0 cm spacing, which experienced a linear propagation of the ignition front with time, the 0.6 cm spacing which experienced a $t^{3 / 2}$ propagation rate, and the remaining spacings which fit power-laws with the exponent from 1.6 to 1.7. As spacing increases,


Figure 5.3: Progression of the pyrolysis front. Symbols indicate visual measurement of the location of the pyrolysis front by observation of blackening of the bottom matchstick surface averaged over four tests, and dashed lines indicate power-law fits to these points. Points were not observable for arrays.
flames are more easily able to directly impinge on the lower surface of matchsticks, resulting in increased heating and shorter ignition times despite the increase in the distance between fuel elements. With $S$ over 0.8 cm , flames easily impinge all around matchsticks, and the spread rate increases with increasing spacing at a much slower rate with increased spacing.

In the 0.0 and 0.6 cm cases the observation of higher matchsticks darkening earlier than lower ones occurs because of small variabilities in the geometry of each individual matchstick. When matchsticks are placed close to one another, shown in Figure 5.2 b and c small deviations in the surface of the matchstick cause subsequent matchsticks to receive slightly more heat transfer than another, causing a faster ignition. These changes are only significant when matchsticks are very close to one another, but once they become further spaced subsequent matchsticks lie in the far plume and the shape or deviations no longer become as important.

### 5.4.2 Analysis

Vogel and Williams [1] calculated ignition times, which corresponded with flame jump times in their analysis of horizontal arrays of matchsticks. In the present experiments, ignition times are not the same as flame jump times in the horizontal configuration because as heights increase, buoyant hot gases flow at greater velocities, increasing heating rates and therefore decreasing ignition times, marked by an acceleratory behavior that was observed to proceed as $t^{1.6}$ to $t^{1.7}$ when the spacing is greater than 0.6 cm . Treatment of ignition times in horizontal arrays was accomplished with the transient heat-conduction equation alone; in contrast, in the present experiments estimates of convective heat transfer coefficients over blunt bodies may be used to estimate ignition times and therefore elucidate relevant heat transfer processes occurring.

Following the description of Fernandez-Pello [14], estimation of an ignition time for a solid must incorporate chemical, mixing and pyrolysis processes, $t_{i g}=t_{\text {chem }}+t_{\text {mix }}+t_{p}$, however the chemical time for the ignition of cellulosic pyrolyzate can be estimated and is on the order of $10^{-4} \mathrm{~s}$ and is negligible in this process. An order-of-magnitude estimate of the mixing time, $t_{m i x}$ can be accom-
plished by assuming a laminar boundary layer over the surface of the matchstick, approximated as a cylinder, where $\delta_{B L} \sim d / \sqrt{\operatorname{Re}_{d}}$. The Reynolds number, $\operatorname{Re}_{d}$ was estimated to be between 50-500 for the present experiments depending on height. If the time for diffusion to occur across the boundary layer is $\delta_{B L} \approx \sqrt{\alpha_{m} t_{m i x}}$, with $\alpha_{m}$ the mass diffusivity of gas, a mixing time can be approximated on the order of $10^{-} 1$ second for laminar flow, and is much smaller than the pyrolysis time that will be estimated.

The ignition time for a thermally thin material, i.e. one without internal thermal gradients, can be estimated when the heat flux to the material is assumed much greater than the losses to be

$$
\begin{equation*}
t_{p} \approx \rho_{s} c_{p, s} d\left(T_{p}-T_{\infty}\right) / \overline{\dot{q}^{\prime \prime}} \tag{5.1}
\end{equation*}
$$

where $\rho_{s} c_{p, s}$, the product of density and solid specific heat capacity, is a constant material property, $d$ is the fuel thickness, $T_{p}$ is the pyrolysis temperature of the fuel $\left(T_{p} \approx T_{i g}\right), T_{\infty}$ is the ambient temperature and $\overline{\dot{q}^{\prime \prime}}$ is an average heat flux per unit area imparted to the unignited matchstick while the flame resides around the surface. In these experiments, an assumption of thermally thin behavior is reasonable because the thickness of the fuel is considerably less than its thermal penetration depth, $l_{t h} \sim k_{s}\left(T_{i g}-T_{\infty}\right) / \overline{\dot{q}^{\prime \prime}} \approx 0.1 \mathrm{~mm}$, which is found using heat fluxes from convective correlations that match data. For a transient ignition process, the average heat flux in Equation 5.1 can be estimated from correlations for cross flow over a blunt body or laminar convection along a vertical plate.

The heat-transfer process is assumed to be dominated by convection, described by a heat-transfer coefficient, $h$ which will be determined by a Nusselt number correlation for $S>0$, and a Grashof number correlation for $S=0$. Typically, for a buoyant flow a Grashof number correlation should be used, but when $S$ is sufficiently larger than $d$, an upper cylinder will lie in the "far wake" of a lower cylinder. Marsters [15] found this to occur near $S / d$ greater than 2. Because details of any lower cylinders become unimportant in this far wake, the flow is approximated as cross-flow over a cylinder. Therefore, a Reynolds number must be estimated in order to use a forced-flow correlation, $\operatorname{Re}_{d}=\rho_{g} u_{g} d / \mu_{g}$, where $\rho_{g}$ and
$\mu_{g}$ are the density and viscosity of gas, respectively and $u_{g}$ is a buoyant velocity estimated from the height of the matchstick, $u_{g} \approx \sqrt{g x}$. A correlation that can be used to describe heat transfer from flames to individual matchsticks with spacing $S>0$ in this study is

$$
\begin{equation*}
\overline{\mathrm{Nu}}_{d}=0.344 \operatorname{Re}_{d}^{0.56} \tag{5.2}
\end{equation*}
$$

where $\overline{\mathrm{Nu}}_{d}=\bar{h} d / k_{g}$ is the average Nusselt number of the flow. This simplified correlation for cross-flow over cylinders was used by Albini and Reinhardt [16] to describe heat transfer from vertical flames to cylindrical, woody fuels and fairly accurately predicted ignition times in such cases, motivating its use in the present experiments. While the correlation geometry is similar to the configurations with spacings it is not the same for the zero spacing case where matchsticks touch one another and flames reside on the sides of the array. The zero spacing case is more akin to a heated, buoyant flow along two sides of a vertical wall. Heat transfer, which still occurs in a laminar regime due to small heights, can be described with a correlation for heat transfer to a vertical wall that occurs at an approximately constant rate,

$$
\begin{equation*}
\overline{\mathrm{Nu}}_{x}=0.59\left(\mathrm{Gr}_{x} \mathrm{Pr}\right)^{1 / 4} \tag{5.3}
\end{equation*}
$$

where $\operatorname{Gr}_{x}=\left(g \beta\left(T_{s}-T_{\infty}\right) x^{3}\right) / \nu^{3}$ is the Grashof number, $x$ is the height of the matchstick from the base of the flame, $\operatorname{Pr}$ is the Prandtl number, $\operatorname{Pr}=\nu / \alpha_{t}$, $\beta \approx 1 / T_{g}$ is the volumetric thermal expansion coefficient and $\nu$ is the dynamic viscosity. In Equation 5.3, when calculating the heat flux from the flame to the surface, $\overline{\mathrm{Nu}}_{x}=\bar{h} x / k_{g}$ must be multiplied by 2 because the flames propagate over 2 sides of the matchsticks, contributing to heating. Equations 5.2 and 5.3 can be used to find the average heat flux to a single matchstick, $\overline{\dot{q}^{\prime \prime}}=\bar{h}\left(T_{s}-T_{\infty}\right)$, assessing correlations at the height of the matchstick. This heat flux is then used in Equation 5.1 to find an approximate pyrolysis time for each matchstick.

Figure 5.4 shows the calculated advancement of the pyrolysis front, $x_{p}$ as a function of time, compared with power-law fits to experimental data shown in Figure 5.3. The zero-spacing case (Equation 5.3) matches power-law fits to


Figure 5.4: Calculated ignition times using convective heat transfer correlations (symbols) are compared with power-law fits to experimental data (dashed lines).
experimental data well. While the slope of the fit is slightly greater than the power-law fit to experimental data, indicated by dashed lines, the calculation is well within experimental variation.

In the $S=0.6 \mathrm{~cm}$ case, the calculated ignition times closely match a power-law fit to the experimental data. The flow in this case encompasses the space between matchsticks as well as the outer surface, bathing all the outer surfaces with flame, which is why the heat transfer correlation for cross-flow over a cylinder matches well in this case. The spacing between the matchsticks results in increased exposure to flames, decreasing ignition times from the zero-spacing case. As flames reach matchsticks at greater heights, buoyancy results in hot gases flowing faster, $u_{g} \approx \sqrt{g x}$, thus leading to an acceleratory behavior that roughly matches the acceleration observed during experiments. While this increase could also be hypothesized to be caused by increased radiative heating, the successful use of convective correlations to describe the heating process points to convection and not radiation as the dominant mechanism at this small scale. Carrier et al. [6] also concluded convective heat transfer was dominant in the case of wind-aided flame spread along horizontal arrays of matchsticks. As spacings further increase the acceleration will cease once spacings are greater than the maximum flame height from a single matchstick. This limit was not reached experimentally due to limits in the experimental facility, but could conceivably found with a high enough test apparatus.

### 5.5 Burnout Times

### 5.5.1 Experimental Results

Burnout was observed using side video recordings during experiments because the side view camera was positioned closest to the matchstick array. The burnout time was defined as the time between the observation of blackening on the underside of a matchstick and the end of any yellow flames present, often coinciding with the end of "bending" of a matchstick. Average burnout times as well as the time to ignition after flames impinge on the surface of a match, $t_{f, i g}$
are provided in Table 5.2. Burnout times for matchsticks are also shown in Figure 5.5 as a function of height. The average time is found to be fairly constant in configurations with $S>0$, but significantly longer for the zero-spacing case. In the spaced cases, with $S=0.6$ to 1.4 cm , the average burnout time from Table 5.2 and Figure 5.5 is approximately 10 seconds. In the zero-spacing configuration, the time to burnout is an average of 29 seconds, almost three times the average burning time from the spaced cases. Two possible mechanisms may contribute to this effect. In the zero-spacing configuration, matchsticks are physically positioned to touch one another on the top and bottom surfaces, limiting these surfaces exposure to flames and heating, as well as limiting the out-flux of pyrolysis vapors from those sides. Looking at averaged burnout times in Table 5.2, there is also a trend of increasing burnout times with decreasing spacings. Another possibly contributing mechanism, a reduction of oxygen available during the combustion process, may explain this observation. Due to the close proximity of matchsticks to one another, it is possible that not enough oxygen is entrained into the flow field in order to sustain complete combustion of the fuel. The observed increase in burnout times, from 8.2 seconds in the $S=1.4 \mathrm{~cm}$ configuration to 12 seconds in the $S=0.6 \mathrm{~cm}$ configuration is almost within experimental uncertainty (seen as scatter in the points in Figure 5.5), however the fact that this increase is observed along all spaced tests points to reduced oxygen being at least a contributing mechanism in the process.

Table 5.2: Experimental results. $t_{f, i g}$ is the median time to ignition measured after the flame first impinges on the surface of the matchstick and $t_{b}$ is the average burnout time for an individual matchstick.

| $S(\mathrm{~cm})$ | $t_{f, i g}(\mathrm{~s})^{a}$ | $t_{b}(\mathrm{~s})$ | $t_{\text {spread }}(\mathrm{s})$ | $t_{\dot{m}_{\text {peak }}}(\mathrm{s})$ |
| :---: | :---: | :---: | :---: | :---: |
| 0.0 | 5.0 | 29 | 27 | 27 |
| 0.6 | 2.9 | 12 | 22 | 16 |
| 0.8 | 1.5 | 10 | 13 | 13 |
| 1.0 | 1.4 | 10 | 10 | 11 |
| 1.2 | 2.1 | 9.5 | 11 | 10 |
| 1.4 | 2.1 | 8.2 | 10 | 11 |

The time to ignition after flame impingement, $t_{f, i g}$ was also found to remain nearly constant throughout all spaced configurations, within experimental uncertainty, shown in Table 5.2. A possibly significant increase in the time to ignition after flaming in the zero-spacing case, which was nearly double the time to ignition in the spaced cases is explained due to the physical configuration present in the zero-spacing case, where less surface area is exposed to heating from flames. The time for the ignition front to spread to the top of the array, $t_{\text {spread }}$ was extracted from data in Figure 5.3 and is also shown in Table 5.2. Because $t_{\text {spread }}$ is not very different than $t_{b}$ in most cases, burnout is not observed during the majority of the spread process and therefore a steady state spread rate is not achieved during the experiments. Matchsticks in the $S=0.6 \mathrm{~cm}$ case, however start to burnout after reaching about halfway through the array. The time for experiments to reach the peak mass-loss rate, $t_{\dot{m}_{\text {peak }}}$ is also provided based on mass-loss rate measurements in Figures 5.7 and 5.8, described in Section 5.6.1. For all except the $S=0.6 \mathrm{~cm}$ case, the peak mass-loss rate occurs at nearly the same time all matchsticks have ignited. This peak mass-loss rate is achieved where the most matchsticks are still burning, so for the $S=0.6 \mathrm{~cm}$ case this occurs at a time between the first burnout of a matchstick and the time to spread to the top of the array.

### 5.5.2 Analysis

The burnout times in Figure 5.5 are similar among all spaced cases and considerably longer for the zero-spacing case, regardless of height. The burnout time, therefore, might be adequately considered in two limiting cases. First, where the spacing is zero and second where the spacing is large enough so that each matchstick burns as an individual element $(S \rightarrow \infty)$.

The case of zero spacing is nearly similar to combustion over two sides of a vertical wall, so that heating from the flame to the solid occurs by conduction from the flame to the fuel surface, $\overline{\dot{q}^{\prime \prime}} \approx k_{g}\left(T_{f}-T_{s}\right) / y_{f}$, where $k_{g}$ is the average thermal conductivity of the gas between the flame $\left(T_{f}\right)$ and fuel surface $\left(T_{s}\right)$ and $y_{f}$ is the flame standoff distance. If the half-thickness of the fuel, $d / 2$ remains small enough to assure thermally-thin behavior and if it is assumed that the standoff distance of


Figure 5.5: Burnout times, $t_{b}$ as a function of the height of the matchstick from the base of the setup, $x$. Experimental measurements are indicated by symbols and predicted burnout times for the $S \approx 0$ and $S \approx \infty$ cases are shown as dashed lines.
the flame is fairly uniform along the length of the surface, then a balanced equation of energy is

$$
\begin{equation*}
2 \int_{0}^{t_{b}} k_{g} \frac{T_{f}-T_{s}}{y_{f}} d t=\rho_{s} c_{p, s}\left(T_{s}-T_{\infty}\right) d-\Delta H_{p} \rho_{s} d \tag{5.4}
\end{equation*}
$$

where $\rho_{s}$ and $c_{p, s}$ are the density and thermal conductivity of the solid, respectively, $d$ is the thickness of the fuel in meters and $\Delta H_{p}$ is the heat of pyrolysis of the solid. Integrating and solving for the burnout time, $t_{b}$ then yields

$$
\begin{equation*}
t_{b}=\frac{y_{f} \rho_{s} d\left[c_{p, s}\left(T_{s}-T_{\infty}\right)-\Delta H_{p}\right]}{2 k_{g}\left(T_{f}-T_{s}\right)} \tag{5.5}
\end{equation*}
$$

for $S \approx 0$.
For the case of infinite spacing, the burning rate theory for combustion of a single spherical fuel droplet can be extended to a cylindrical geometry, similar to the analysis of Lee [17]. To solve for the mass-loss rate of a horizontal fuel cylinder a Schvab-Zeldovich formulation with a flame-sheet model and a correlation for flame standoff distance is employed following Lee [17]. Assuming the matchstick is nearly cylindrical with initial radius $r_{i}=d / 2$, the mass-loss rate per unit length for the cylinder becomes

$$
\begin{equation*}
\dot{m}^{\prime}=-\frac{d}{d t}\left(\rho_{s} \pi r_{s}^{2}\right)=2 \pi r_{s} \rho_{s} \frac{d r_{s}}{d t}=\dot{m}^{\prime}\left(r_{s}\right), \tag{5.6}
\end{equation*}
$$

where $\dot{m}^{\prime}$ is the mass-loss rate per unit length of the cylinder and $r_{s}$ is the radius of the cylinder at time $t$.

The burnout time, defined as the amount of time necessary to deplete all available fuel in the cylinder can be found from

$$
\begin{equation*}
t_{b}=\int_{0}^{r_{i}} \frac{2 \pi r_{s} \rho_{s}}{\dot{m}^{\prime}\left(r_{s}\right)} d r_{s} \tag{5.7}
\end{equation*}
$$

Replacing $\dot{m}^{\prime}\left(r_{s}\right)$ with the solution for the mass-loss rate of a cylindrical fuel surface [17],

$$
\begin{equation*}
\dot{m}^{\prime}\left(r_{s}\right)=\frac{2 \pi k_{g}}{c_{p, g} \ln \left(r_{f} / r_{s}\right)} \ln (1+B) \tag{5.8}
\end{equation*}
$$

where $B$ is the mass transfer number of the fuel, $B \approx\left[Y_{O_{2}, \infty} \Delta H_{c}-c_{p, \infty}\left(T_{p}-\right.\right.$ $\left.\left.T_{\infty}\right)\right] / \Delta H_{p}$ and integrating Equation 5.7, the burnout time for a fuel cylinder ( $S \approx$ $\infty)$ is

$$
\begin{equation*}
t_{b}=\frac{\rho_{s} c_{p, g} r_{i}^{2}\left[2 \ln \left(r_{f} / r_{i}\right)+1\right]}{4 k_{g} \ln (1+B)} \tag{5.9}
\end{equation*}
$$

The ratio of flame standoff distance to initial radius in Equation 5.9, $\ln \left(r_{f} / r_{i}\right)$ is estimated from a correlation, $\ln \left(r_{f} / r_{s}\right)=0.2(d / 2)^{-0.75}$, with $d$ in cm , determined from experimental measurements on polymethyl methacrylate cylinders by Lee [17]. The flame standoff distance found in the vertical wall case, Equation 5.5, however was estimated from video footage to be approximately $y_{f}=5 \mathrm{~mm}$. The rest of the parameters used to estimate $t_{b}$ from Equations 5.5 and 5.9 are presented in Table 5.3. Using these values, the burnout times for zero and infinite spacing were calculated to be 27.4 seconds and 9.3 seconds, respectively. These predictions are shown as dashed lines in Figure 5.5 and are well within experimental uncertainty for both cases.

Table 5.3: Properties used in burnout time and mass-loss rate calculations.

|  | Property | Quantity | Citation |
| :---: | :---: | :---: | :---: |
| $B$ | Mass transfer number | 1.75 | $[18]^{a}$ |
| $c_{p, g}$ | Specific heat of the gas | $1000 \mathrm{~J} / \mathrm{kg} \cdot \mathrm{K}$ | $[19]$ |
| $c_{p, s}$ | Specific heat of the fuel | $2400 \mathrm{~J} / \mathrm{kg} \cdot \mathrm{K}$ | $[20]^{b}$ |
| $d$ | Diameter | $2.5 \times 10^{-3} \mathrm{~m}$ |  |
| $\Delta H_{p}$ | Heat of pyrolysis including losses | $2.43 \mathrm{~J} / \mathrm{kg}$ | $[18]^{a}$ |
| $k_{g}$ | Thermal conductivity of gas | $0.06 \mathrm{~W} / \mathrm{m} \cdot \mathrm{K}$ | $[19]$ |
| $L$ | Length of matchstick | $1.91 \times 10^{-2} \mathrm{~m}$ |  |
| $\ln \left(r_{f} / r_{s}\right)$ | Flame to surface radius | 0.9 | $[17]$ |
| $T_{f}$ | Flame temperature | 2270 K |  |
| $T_{s}$ | Surface temperature | 650 K | $[20]^{b}$ |
| $T_{\infty}$ | Ambient temperature | 300 K |  |
| $y_{f}$ | Flame standoff distance | $5 \times 10^{-3} \mathrm{~m}$ | From video |
| $Y_{O_{2}, \infty}$ | Ambient O $\mathrm{O}_{2}$ mass fraction | 0.23 | $[18]$ |
| $\rho_{s}$ | Density of solid | $500 \mathrm{~kg} / \mathrm{m}^{3}$ | $[20]^{b}$ |

${ }^{a}$ Fir Wood
${ }^{b}$ Colombian Pine

Both the theoretical and experimental results in this study compare fa-
vorably with previous experimental data. Clements and Alkidas [21] performed experiments on wood (birch) cylinders and square segments in methanol flames. Their experimental data of burnout times for different wood diameters was curve fit to find a relationship between burnout time and initial diameter, $t_{b} \approx 81(d)^{1.6}$, where $t_{b}$ is in seconds and $d$ in cm . Using this correlation, for birch rods or square segments the burnout time is estimated to be 8.8 seconds. This value is remarkably close to the average measured for square pine matchsticks measured in this study, which will undoubtedly have some different properties due to the difference in species of wood. Steward and Tennankore [22] also measured the mass-loss rate and burnout time of an individual dowel in a uniform fuel matrix, under steady and forced convection conditions, similar to the experiments conducted here. Their test surface, however was oriented horizontally. The average burnout time for the 0.25 cm diameter birch dowel in their experiments was found to be approximately 9.3 seconds, very close to the experimental and theoretical values determined for pine matchsticks above. It is important to note that Steward and Tennankore measured mass-loss rates and burnout times while varying the flow velocities around the dowels and found little or no change with a variance in wind velocity. This agrees with the experimental observations of a constant burnout time with increasing height in these experiments, in which increasing height also constitutes increasing flow velocities due to the naturally buoyant flow surrounding matchsticks.

Charring is not specifically addressed in the analysis of the burnout time, because matchsticks are thin enough that the charring has little effect on the massloss rate. Burnout times possibly would lengthen a little as charring would slow the burnout process, but this is a small effect, and the mass remaining in the char is small compared with the initial mass.

### 5.6 Mass-Loss Rates

### 5.6.1 Experimental Results

Mass-loss histories were recorded for all spacings, averaged together and polynomial, least-squares fits applied of order 6. All fits applied had an $R^{2}$ value
of at least 0.99 , indicating a good degree of fit. The choice of a 6 th order polynomial fit was best in this case because it captured the behavior of the burning process while smoothing over fluctuations on the order of 0.03 g that are not representative of the general behavior, and probably are caused by air currents as noted by Gollner et al. [23]. Derivatives of the fits were taken, resulting in mass-loss-rate profiles shown in Figures 5.7 to 5.9. Alternative methods to polynomial fits, such as a finite-difference scheme coupled with smoothing and a smoothing spline were also used to test the accuracy of this method, and were found to follow the same curve, reach the same peaks and troughs, but included a more "jagged" behavior due to these small air currents or deviations that hide the behavior of the burning process.

The mass-loss rates shown in Figures 5.7 to 5.9 increase over time in the region of upward spread and begins to decrease as matchsticks burn out. Spaced tests have a similar mass-loss rate over time, however, the single-column test with zero spacing increases its mass-loss rate much slower. This is due to only half the matchstick area being exposed to flames compared to other tests in which all sides are exposed to flames. The initial peak in the mass-loss rate for the zero spacing test shown in Figures 5.6 and 5.7 is due to a post-ignition transient.

The mass-loss rate per unit area for single-column tests, shown in Figure 5.6 was calculated by dividing the mass-loss rate profiles in Figures 5.7 and 5.8 by the area burning, estimated by observing blackening of material in consecutive frames of video footage. Because the area burning could not be observed in the array tests, the mass-loss rate per unit area is only shown for single column tests. For spaced tests, once approximately the same number of matchsticks are burning the mass-loss rate per unit area reaches a steady value, between 2 to $2.7 \mathrm{~g} / \mathrm{cm}^{2} \cdot \mathrm{~s}$. The mass-loss rate per unit area for the zero-spacing case again is much lower than spaced tests because the "exposed" area more appropriately is only the two sides of the matchsticks, half the area exposed in spaced tests. It is therefore sensible to understand that the mass-loss rate per unit area for the zero-spacing test is about half the average of the spaced tests.


Figure 5.6: Mass-loss rate per unit area of single-column tests, found by dividing the mass-loss rate by the area burning. Symbols represent experimental data and only regions of upward spread are shown for clarity.

### 5.6.2 Analysis

In order to predict the mass-loss rate of single rows and arrays, the massloss rate of a single matchstick must first be estimated. As a first approximation, a single matchstick may be assumed to burn at a constant rate, $\bar{m}$ from the time it ignites until it burns out. This average mass-loss rate can be estimated by multiplying Equation 5.8 by $L$, where relevant parameters such as the mass transfer number of the fuel, $B$ have already been provided in Table 5.3. Equation 5.8 assumes that the fuel's surface is cylindrical, with an area equal to $2 \pi r L$. In reality, the matchstick's surface is planar with a surface area of $2 \times(4 r L)$. A correction for the surface area can be used multiplying $\overline{\dot{m}}$ by $8 / 2 \pi$. Using Equation 5.8 and the surface area correction, the average mass-loss rate is estimated to be $3.8 \mathrm{mg} / \mathrm{s}$.

The average mass-loss rate of a single matchstick was also measured experimentally. The several arrays were weighed before and after combustion, as well as each individual matchstick being weighed before and after combustion. Dividing the weight loss by the time burning provides a reasonable approximation of the average mass-loss rate, which was found to be between 3 to $5 \mathrm{mg} / \mathrm{s}$, within the accuracy of experiments. The high degree of variability occurs because matchsticks do not all burn evenly, the accuracy of the scale was just enough to detect the mass loss changes of an individual matchstick, and char tends to fall off during combustion. The theoretical value lies within the experimental data and will therefore be used in subsequent analysis.

The mass-loss rate of a row or array is determined by assuming that once ignited, matchsticks burn at a constant rate, $\overline{\dot{m}}$ until they burnout. Predictions for the time to ignition and burnout time depending on spacing have already been presented (Figures 5.3 and 5.5). The total mass-loss rate of an array of matchsticks is determined by summing the number of burning matchsticks at each time step and multiplying this by $\overline{\dot{m}}$. The result of this procedure is displayed in Figures 5.7 and 5.8. The same concept can also be applied to arrays with multiple columns, multiplying the mass-loss rate times the number of columns, the result of which is shown in Figure 5.9.

Figures 5.7-5.9 display mass-loss rate measurements as symbols and theo-


Figure 5.7: Mass-loss rates of single-column tests ( $S=0.6$ to 0.8 cm ) determined by differentiating polynomial fits to mass lost data over time. Symbols represent experimental data while solid lines represent theoretical predictions.


Figure 5.8: Mass-loss rates of single-column tests ( $S=1.0$ to 1.4 cm ) determined by differentiating polynomial fits to mass lost data over time. Symbols represent experimental data while solid lines represent theoretical predictions.


Figure 5.9: Mass-loss rates of array tests determined by differentiating polynomial fits to mass lost data over time. Symbols represent experimental data while solid lines represent theoretical predictions.
retical predictions for mass-loss rates as solid curves which were formed by taking a Gaussian fit through the predicted values. The predicted mass-loss rate in single columns reaches a similar maximum value to experimental observations, however the initial rise in mass-loss rate is somewhat slower than observations and the burnout time is somewhat over predicted. It seems clear, therefore that the predicted burnout time used in the mass-loss rate prediction, 12.2 seconds is longer than the actual value, and in fact it is larger than the test average in Table 5.2 ( $\sim 10$ seconds). Despite the rough first-order estimation used, the predictions do seem to roughly capture observed phenomena in single-column tests. In array tests, the shift in time is more pronounced, and the peak mass-loss rate for the $S=0.8 \mathrm{~cm}$ test is over predicted. This may be due to the close spacing, limiting the entrainment of oxygen and therefore slowing the rate of burning for individual matchsticks, especially as the number of matchsticks involved increases.

Perhaps the most important reason for the deviation between observed and predicted phenomena is that in reality matchsticks do not burn at a constant rate. Steward and Tennankore [22] measured the mass-loss rate and burnout time of an individual dowel in a uniform fuel matrix, under steady and forced convection conditions, similar to the experiments conducted here, however horizontal. The mass-loss rate curve that was measured for a 0.25 cm diameter dowel was found to be approximately Gaussian. The peak mass-loss rate was between 4 to $5 \mathrm{mg} / \mathrm{s}$, but varied between $2 \mathrm{mg} / \mathrm{s}$ and the peak value between ignition and burnout. At ignition, matchsticks increase in mass-loss rate while the entire surface is igniting, but very quickly start to decrease in mass-loss rate because of charring and a reduction in surface area that is not accounted for in the average value used in this prediction. Incorporating these effects would ultimately increase the accuracy of such predictions.

### 5.7 Flame Heights

Flame heights were determined by importing videos into a Matlab program written to analyze flame heights similar to one used previously by [24]. The front
view was used to measure flame heights because it offered a wider field of view to capture the entire length of the flame than the side view, which was positioned close to the matchsticks to observe burnout. Images were extracted from the video, cropped, and an image of the background was subtracted from the current video frame. This method highlighted only changes in the video over time, i.e. the presence of a flame. All videos were calibrated with an object of known dimension at 3 separate locations on the screen, and analysis was run every 5 frames, resulting in 6 frames per second of image analysis. Images were then converted into grayscale, normalized to a scale where 0 is black and 1 white, and a threshold of $0.5-0.6$ was applied to the image, distinguishing all intensities greater than this threshold to be white or "flame". This threshold was chosen for each test depending on the average background lighting, which varied depending on the time of day of experiment and intensity of flames produced. Flame heights were shown to fluctuate frequently, but between the threshold and removal of any disturbances that were 3 mm or less in diameter, a very accurate and repeatable value was taken, and confirmed with visual measurements of the flame front for all tests. The result of this method is shown in Figure 5.10 with each point averaged between three frames.

Following a trend similar to mass-loss rates, flame heights are generally greater over time for tests in which matchsticks are spaced further apart, on exception of the $S=1.4 \mathrm{~cm}$ test. Flame heights progress faster for the $S=1.0$ and $S=1.2 \mathrm{~cm}$ cases, while the $S=1.4$ and $S=0.8 \mathrm{~cm}$ cases have similar but lower flame heights. This again is due to a slower rate of progression of the pyrolysis front, caused from a matchstick spacing that is farther than the initial flame length above an ignited match in the 1.4 cm spaced case. Because they are spaced further than this length, it takes an additional amount of time for flames to reach matchsticks above, and this subsequently reduces the flame height over time.

Power-law fits to flame heights reveal that most spaced fits, $S=1.0$ to 1.4 follow a trend of $x_{f} \sim t^{1.6}$ with $R^{2}$ values of 0.98 or higher. These agree with fits of pyrolysis height data of the same spacings, where $x_{p} \sim t^{1.6-1.7}$, indicating flame and pyrolysis heights follow a linear trend with one another. Fits of the $S=0.0$ to 0.8 cm tests follow a trend of $x_{f} \sim t$ with $R^{2}$ values of 0.97 or higher, which is


Figure 5.10: Flame heights recorded from front video footage (for single column tests) are shown only during regions of upward spread. Symbols indicate experimental measurements and dashed lines indicate power-law fits to these measurements.


Figure 5.11: Flame height, $x_{f}$ versus mass-loss rate, $\dot{m}$ where the mass-loss rate is proportional to the heat-release rate shown only during regions of upward spread. The dashed line represents a linear fit to spaced tests.
expected for the zero-spacing case but rather unexpected for the $S=0.6$ and 0.8 cm cases. A non-linear relationship between the flame and pyrolysis height may occur here.

### 5.8 Relationship Between Flame Height and MassLoss Rates

Because flames reside mostly away from the wall supporting them, entrainment of air is not restricted due to geometry and should mostly resemble that of a typical jet-diffusion flame as described by [25]. Without a limitation on air entrainment into the combusting plume, flame heights should therefore be found to scale linearly with fuel mass-loss rates, shown to agree in Figure 10. A linear
relationship of nearly the same slope is observed for most tests within the accuracy of the data. Fitting a line through all spaced test data provides the relationship $x_{f} \sim 265(\dot{m})$, shown as a dashed line in Figure 5.11. The zero-spacing test, however has a greater dependence of flame height on mass-loss rate compared with other tests. This may be due to some degree of limited entrainment because no airflow is capable of crossing through the column, which may increase flame lengths. Within the degrees of accuracy of the measurements, however, a nearly linear profile is observed. Slight deviations from linear behavior toward higher mass-loss rates may also be caused by the onset of matchstick burnout toward the end of tests.

### 5.9 Summary

Investigation of vertical arrays of horizontally protruding matchsticks have revealed the influence spacing has on the advancement of the flame and pyrolysis front, mass-loss rates, and correlations often used in flame spread modeling. The fluid dynamics of the flow field surrounding matchsticks is believed to significantly influence the heat transfer downstream, thereby influencing heating rates and spread times. Standard heat transfer correlations for observed flow scenarios were adapted to predict ignition times for matchsticks, which in turn revealed the controlling mechanism of convective heat transfer being responsible for ignition at this small scale. Burnout rates were predicted using a burning rate theory for a cylindrical geometry and for combustion of a vertical wall. Mass-loss rates for spaced arrays were also predicted using spread rates and an estimation of the steady mass-loss rate for a single matchstick. Results from arrays of matchsticks that were multiple columns across were difficult to assess, however single column results may be useful in designing multiple-column tests in the future that could be used to distinguish these limits in larger arrays, possibly incorporating scale modeling in the future. Future experiments may benefit from improved methods of detecting the ignition front through arrays, use of a more standardized fuel that does not char and variation of the geometry with a range of known heat transfer correlations.

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## Chapter 6

## Conclusion

Despite many years of research, including the development of analytical and numerical models and extensive experimentation, the complexity of the process of upward flame spread continues to deserve attention in the fire-research community. Much of fire science revolves around the ability to extract trends out of complicated data sets. The trends that we extract from these observations form the basis for correlations and theories that help us to understand the underlying mechanisms governing fire phenomena.

Experiments performed in this study focused first on the most commonly used packaging material in warehouses, corrugated cardboard, which was found to affect predictions of upward flame spread by current descriptions. Physical disruptions in the boundary layer, produced by delamination of the top layer of corrugated cardboard, affects the heat flux ahead of $x_{p}$, for example by increasing the average flame standoff distance. Many current flame-spread models employ a constant heat flux from the flame to unburnt surface, which may be inappropriate for the description of many different fuels at varying scales and which does not fit with a simplified description of the present observations. Instead, the spatial variation of the heat flux from the flame to the surface deserves further study for improved predictions in the future.

Next, an experiment was designed to test the effects of surface orientation on burning rates and spread rates. It was concluded that spread rates are greatest in near-vertical orientations while burning rates are maximized in near-horizontal
orientations. The experimental design attempted to approach as closely as possible conditions that may be expected to be encountered in practice. In so doing, a number of three-dimensional effects were identified in the experiment. Nevertheless, it was reasoned that the qualitative trends observed, including the spread-rate maximum at angles slightly less than vertical, are general and would also apply in strictly two-dimensional configurations in the size range studied or larger, for both polymeric (and, in some respects, cellulosics, not discussed here) solid fuels like PMMA.

Finally, investigation of vertical arrays of horizontally protruding matchsticks have revealed the influence spacing has on the advancement of the flame and pyrolysis front, mass-loss rates, and correlations often used in flame spread modeling. The fluid dynamics of the flow field surrounding matchsticks is believed to significantly influence the heat transfer downstream, thereby influencing heating rates and spread times. Standard heat transfer correlations for observed flow scenarios were adapted to predict ignition times for matchsticks, which in turn revealed the controlling mechanism of convective heat transfer being responsible for ignition at this small scale. Burnout rates were predicted using a burning rate theory for a cylindrical geometry and for combustion of a vertical wall. Mass-loss rates for spaced arrays were also predicted using spread rates and an estimation of the steady mass-loss rate for a single matchstick. Results from arrays of matchsticks that were multiple columns across were difficult to assess, however single column results may be useful in designing multiple-column tests in the future that could be used to distinguish these limits in larger arrays, possibly incorporating scale modeling in the future. Future experiments may benefit from improved methods of detecting the ignition front through arrays, use of a more standardized fuel that does not char and variation of the geometry with a range of known heat transfer correlations.

## Appendix A

## Supplementary Inclined Flame Spread Data

## A.0.1 Calculation of the Spread Rate

The spread rate is calculated based upon measurements of the pyrolysis height with thermocouples melted onto the surface of the solid fuel surface. A pyrolysis temperature of $300^{\circ} \mathrm{C}$ was chosen to distinguish the pyrolysis front reaching the thermocouple location. Figures A. 1 to A. 3 show readings from thermocouples melted onto the surface of PMMA during representative tests of $-60^{\circ}, 0^{\circ}$ and $60^{\circ}$. Polynomial fits to raw thermocouple data are used to smooth brief fluctuations in the data. The chosen pyrolysis temperature as well as times that the pyrolysis front reaches thermocouples are indicated. The height of thermocouples $1-7$ is indicated in Figure 4.1. Figures A. 4 and A. 5 show the calculated pyrolysis height as a function of time, after averaging the results of 4-9 tests at each inclination, the deviation of these results shown as horizontal error bars. Figure A. 5 has been extended onto a longer timescale in order to display the entire $60^{\circ}$ test.

Citations for the pyrolysis temperature of PMMA vary widely in literature [1], therefore different values could have been chosen when calculating the pyrolysis heights and eventual spread rates. Figure A. 6 shows the result of calculating pyrolysis heights and then their derivatives (spread rates) at different pyrolysis temperatures. Based on available literature, the pyrolysis temperature of PMMA


Figure A.1: Readings from thermocouples melted onto the surface of PMMA during a representative test at an inclination of $-60^{\circ}$. Polynomial fits to raw thermocouple data (solid lines) are used to smooth brief fluctuations in the data. The chosen pyrolysis temperature $\left(300^{\circ}\right)$ as well as times that the pyrolysis front reaches thermocouples are indicated by dashed lines.
lies somewhere between $300^{\circ} \mathrm{C}-380^{\circ} \mathrm{C}$, so temperatures in this range as well as lower were tried. Figure A. 6 shows that temperatures lower than $300^{\circ} \mathrm{C}$ display higher spread rates and a steeper curve. At a temperature of $327^{\circ} \mathrm{C}, V_{p}$ still retains a somewhat curved shape, but the flame spread rate no longer lies on as smooth of a curve, as thermocouples have more variations in the reading of the time the pyrolysis front passes. At temperatures beyond $327^{\circ} \mathrm{C}$, shown at the bottom of the plot, spread rates are no longer distinguished because the surface does not consistently reach this temperature when the pyrolysis front spreads over. The temperature of $300^{\circ} \mathrm{C}$ was chosen as $T_{p}$ because it is the most reliable and reproducible while lying within the range of accepted pyrolysis temperatures in


Figure A.2: Readings from thermocouples melted onto the surface of PMMA during a representative test at an inclination of $0^{\circ}$. Polynomial fits to raw thermocouple data (solid lines) are used to smooth brief fluctuations in the data. The chosen pyrolysis temperature $\left(300^{\circ}\right)$ as well as times that the pyrolysis front reaches thermocouples are indicated by dashed lines.
literature. Even if a lower temperature was chosen, the trend remains the same.

## A.0. 2 Flame Heights

Flame heights were calculated from the inclined PMMA experiments using two methods, first using a threshold heat flux value from sensors above the fuel and second using visual data from front video. The first method utilizes a threshold heat flux value from Consvali et al. [2] of $10 \mathrm{~kW} / \mathrm{m}^{2}$. The flame was defined as reaching the height of a heat flux sensor if the heat flux of that sensor reached above the threshold value. The result is shown in Figure A. 7 where horizontal error bars represent variability between tests, which was greatest at longer times.

This heat-flux threshold methodology was defined only for vertical flame spread, so while it may have some credence for defining the $0^{\circ}$ inclination, it


Figure A.3: Readings from thermocouples melted onto the surface of PMMA during a representative test at an inclination of $60^{\circ}$. Polynomial fits to raw thermocouple data (solid lines) are used to smooth brief fluctuations in the data. The chosen pyrolysis temperature $\left(300^{\circ}\right)$ as well as times that the pyrolysis front reaches thermocouples are indicated by dashed lines.
may not accurately represent other angles. A general and expected trend that is observable is the fastest increases with flame height occurs for the $-45^{\circ},-30^{\circ}$ and $0^{\circ}$ inclinations, however the highest spread rate is recorded for $-30^{\circ}$. This is consistent with measurements of the flame-spread rate from surface-thermocouple measurements in Figure 4.2. In Figure A. 7 the increase in the $0^{\circ}$ flame height around 250 seconds, which outpaces other tests, is not measured with enough accuracy (note the large error bars) to determine if this phenomena actually occurs. Most likely it is an experimental error. Similar reasoning goes for the backward jump on the $45^{\circ}$ test near 350 seconds. The rate of increase in the flame height for lower inclinations continues to follow the trend for $V_{p}$ found in Figure 4.2.

The flame height for $60^{\circ}$ is not shown because only one sensor reaches over the $10 \mathrm{~kW} / \mathrm{m}^{2}$ required to define the flame height using this method. Because


Figure A.4: Pyrolysis heights measured by surface thermocouples with $T_{p}=300$ ${ }^{\circ} \mathrm{C}$.
of the effects of "liftoff" and "necking" of the flame, the flame-standoff distance dramatically increase along the centerline of the surface downstream of the burning fuel for upward-facing orientations. Eventually, during spreading tests the threshold heat fluxes are only reached close to the fuel surface.

The second methodology for determining flame heights involves extracting the flame height from front video footage, following a methodology provided by Audouin et al. [3]. The video is converted into a series of grayscale images which then have a threshold applied, separating luminous regions of the flame from the background. These are then interpreted into contours of the flame. These contours are averaged to determine the average flame height for each frame, shown in Figure A.8.

The flame heights shown in Figure A. 8 follow a similar trend to Figure A.7.


Figure A.5: Pyrolysis heights measured by surface thermocouples with $T_{p}=300$ ${ }^{\circ} \mathrm{C}$.

They are compared to those in Figure A. 7 in Figure A.9. The time is shifted to represent the presence of the flame, because observation of the luminous flame does not seem to directly correspond to observed heat fluxes of $10 \mathrm{~kW} / \mathrm{m}^{2}$. Other general trends are similar.

Many descriptions of upward flame spread utilize a correlation of the flame to pyrolysis height, $x_{p} \sim x_{f}^{a}$ which is given in Figure A. 10 using flame heights measured from heat flux sensors.

## A.0. 3 Heat Fluxes

Average heat fluxes in the combusting plume (formed by averaging all 11 sensors along the centerline shown in Figure 4.1) at different times during flame spread are shown in Figure A.11. The bottom curve represents the moment where


Figure A.6: Dependence of the average rate of flame spread $V_{p}$ on the inclination angle $\theta$ of the fuel surface. Here $V_{p}$ is calculated from thermocouple measurements of $x_{p}$ the pyrolysis-front position using different values of the pyrolysis temperature $T_{p}$.
the pyrolysis front reaches the top of the fuel surface ( $x_{p}=20 \mathrm{~cm}$ ), as measured by thermocouples on the fuel surface. Later lines indicate measurements 100 and 200 seconds past this moment. The highest measurement is an average during steady tests, where the entire surface of the fuel burned for the entire duration of the test and the heat flux averages are taken over the entire steady region.

Average heat fluxes in the combusting plume are also shown as a function of time in Figure A.12, where the average heat flux from sensors is taken at different times, to show the difference between different tests.

The average heat fluxes for steady tests, where the entire fuel surface burned for the test duration are shown in Figure A.13. These steady heat fluxes do not correspond exactly with spreading heat fluxes, possibly because heating of the sensors


Figure A.7: Flame heights calculated from a threshold heat flux of $10 \mathrm{~kW} / \mathrm{m}^{2}$.
for long duration causes additional heat transfer effects that area not accounted for.

Spatial measurements of the heat flux in the combusting plume were also taken from an array of heat flux sensors adjacent to the centerline, plotted in Figure A.14. Heat fluxes are represented by colors, where dark red indicateds higher heat fluxes ( $\sim 20 \mathrm{~kW} / \mathrm{m}^{2}$ ) and dark blue low heat fluxes. Three-dimensional effects such as "necking" described in Chapter 4 are visible through these plots. The heat fluxes are very uniform in the underside-spread cases, however as the fuel is oriented upwards entrainment of air from the sides changes the heat flux contours to be more triangular, with higher heat fluxes along the centerline and lower on the edges. The liftoff of the flame from the fuel surface also reduces heat fluxes further downstream as the orientation angle approaches $90^{\circ}$.


Figure A.8: Flame heights measured from front video footage.

## A.0.4 Mass-Loss Rates

Figure A. 15 shows all previous steady mass-loss rate per unit area experimental results for inclined fuel samples, including gaseous fuels by de Ris and Orloff [4], PMMA by Ohtani et al. [5] and data from the present study.

## A.0.5 Laminar to Turbulent Transition

Previous experimental work on heat transfer of inclined surfaces has produced some data on the transition from laminar to turbulent flow behavior which was applied to this experiment to try to determine what the relative influence of this transition would be. It is shown in Figure A.16. Based on these correlations from Al Arabi [6], it appears the effect of transition to turbulence may not be significant in these experiments.


Figure A.9: Comparison of flame heights measured by thresholds of heat fluxes (symbols) and videos (lines).

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Figure A.10: Flame heights versus pyrolysis heights, where flame heights were determined using a threshold heat flux.
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Figure A.11: Average heat fluxes in the combusting plume over time, averaged from 11 heat flux sensors downstream of the fuel sample.


Figure A.12: Heat fluxes in the combusting plume for each angle averaged at the moment when $x_{p}$ reaches the height indicated on the $x$-axis..


Figure A.13: Heat fluxes during steady tests.


Figure A.14: Spatial profiles of heat fluxes in the combusting plume. Heat fluxes are represented by colors, where dark red indicates higher heat fluxes ( $\sim 20$ $\mathrm{kW} / \mathrm{m}^{2}$ ) and dark blue low heat fluxes.


[^2]

Figure A.16: Laminar to turbulent transition of the present set of experiments, using two correlations from [6]

## Appendix B

## PMMA Matchstick Data

Vertical arrays of horizontally-protruding PMMA rods, 0.25 cm in diameter and 1.91 cm long, arranged 3 to 5 matchsticks across were used to investigate the influence of spacing on discrete fuel elements on rates of upward flame spread similar to experiments in Chapter 5. These experiments, however did not form conclusive spread results because the rods were clear and therefore it was not possible to distinguish which were burning and not. Additionally, melting and dripping of PMMA rods affected results in later stages of the experiments. Massloss rate data was still extracted from these experiments and is presented in Figure B.1. The data follow a similar trend to that presented for wooden matchsticks in Figures 5.7 to 5.9 , where an initial increase in mass-loss rate with time occurs, slowly decaying thereafter. The peak mass-loss rates for the closer-spaced arrays, $S=0.8$ and 1.0 cm are the same, just as in the wooden arrays shown in Figure 5.9 , with a lower peak mass-loss rate for the 1.2 cm spacing.


Figure B.1: Mass-loss rates of array tests of PMMA determined by differentiating polynomial fits to mass lost data over time. Symbols represent experimental data.


[^0]:    ${ }^{1} \mathrm{~A}$ factor neglected here is the difference between the plume and ambient densities, divided by the ambient density, because this ratio is close enough to unity [19].

[^1]:    ${ }^{1}$ Total heat fluxes over the fuel surface are estimated via an energy balance, $\dot{q}_{p}^{\prime \prime}=\dot{q}_{r r}^{\prime \prime}+\dot{m}^{\prime \prime} \Delta H_{p}$, where $\dot{q}_{r r}^{\prime \prime} \approx \sigma T_{p}^{4}=6.1 \mathrm{~kW} / \mathrm{m}^{2}$ is the re-radiation to the fuel surface, assuming the surface temperature to be equal to $T_{p}$ and the surface emissivity equal to $1, \dot{m}^{\prime \prime}$ is the steady massloss rate per unit area measured in Figure 4.3 and $\Delta H_{p}=1,620 \mathrm{~kJ} / \mathrm{kg}$ the effective heat of gasification [18, 19]

[^2]:    Figure A.15: Previous steady mass-loss rate per unit area experimental results for inclined fuel samples, including gaseous
    fuels by de Ris and Orloff [4], PMMA by Ohtani et al. [5] and data from the present study.

