MEASUREMENT OF TEMPERATURE AND PRODUCT FIELDS IN A
STABILIZED SPREADING FLAME

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Measurement of Temperature and Product Fields in a Stabilized Spreading Flame

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DEDICATION

To my parents whom provide their love, support, and sacrifice to give me an opportunity for a better life. They are role models that help me thrive to become a better human being every day.
ABSTRACT OF THE THESIS

Measurement of Temperature and Product Fields in a Stabilized Spreading Flame
by
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Master of Science in Mechanical Engineering
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This experiment seeks out to investigate the flame structure of a small scale spreading flame. At the SDSU Computational Thermodynamics Laboratory an apparatus known as the Flame Stabilizer is constructed to study the structure of a small scale downward spreading flame. The flame fields and species fields under investigation are from cellulose filter paper and thermoplastic PMMA. Flame field measurement of a spreading flame is possible by implementing a linear actuator in a control system to stabilize a flame, in other words keeping it stationary in the same relative location. The flame is tracked with a thermocouple in a linear actuator system and the motion is controlled by a PID algorithm under NI LabVIEW. The thermal flame field is measured with K-type thermocouples. The species field is measured in CO₂ with a non-dispersive infrared radiation (NDIR) sensor. A 2-D grid system is implemented in the x-y plane as a mapping field to measure the structure of the flame field. Temperature and CO₂ sensors are placed in this grid system for measurements. The motion of the grid system is controlled by motors with linear actuators in the x-y plane for precise positioning. The CO₂ fields found in this work are the first to be experimentally measured as far as moving flames are concerned. The results are useful to validate a computational model. Additionally, the fuel width, and fuel orientation to the direction of gravity are investigated to observe their effects on spread rate.
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LIST OF SYMBOLS

\( T_\infty \)  
Ambient temperature

\( T_{vap} \)  
Vaporization temperature

\( T_{ig} \)  
Ignition temperature

\( T_{sp} \)  
Set point temperature

\( T_f \)  
Flame temperature

\( T_{eq} \)  
Equilibrium flame temperature

\( CO_{2,eq} \)  
Equilibrium CO\textsubscript{2} mole fraction

\( V_f \)  
Flame spread rate, mm/s

\( V_g \)  
Oxidizer velocity

\( V_r \)  
Relative flow velocity

\( \tau \)  
Half fuel thickness, \( \mu \)m

\( K \)  
Proportional gain constant in PID control algorithm

\( T_d \)  
Derivative time constant in PID control algorithm

\( T_i \)  
Integral time constant in PID control algorithm

\( \theta \)  
Dimensionless temperature

\( \eta \)  
Dimensionless CO\textsubscript{2}

\( \phi \)  
Fuel angle with respect to vertical direction
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CHAPTER 1

INTRODUCTION

The work presented in this thesis emphasizes on the flame structure, particular the temperature and CO₂ fields, and spread rate under various ambient conditions. Refer to Appendix A for works related to residence time driven flame spread and related topics that have been published and presented at meetings of the Combustion Institute.

This chapter discusses the motivation behind this work, statement of the problem, and flame spread research that has been done in the combustion community.

1.1 PURPOSE OF STUDY

The scope of this work is to support the understanding of microgravity flame spread. The greater goal of project SoFIE is to understanding material ignitability, fire growth, and fire suppression. The understanding of spacecraft material flammability in space cabin atmospheric conditions will lead to better spacesuit and cabin material selection and design. The ability to prevent a fire and practice fire in space may avert space related disasters and casualties, such as the Challenger and Columbia disasters. There are other instances where cabin crew members have suffered fatality from a fire, such as the infamous Apollo 1 fire.

While it may seem trivial to perform an experiment on Earth to understand microgravity flame, the goal is to obtain the flame structure that could be used to validate a computational model. The model is refined with experimental data to better predict flame spread under various atmospheric conditions. The parameters that affect flame spread are many and a computational model has the ability to investigate these parameters, particularly those of a microgravity environment, to observe flame spread behavior. Some important parameters include fuel type, fuel thickness, oxidizer composition, oxidizer velocity, geometric configuration, direction of spread, ambient pressure, and gravity level are a few important factors among many. Some of these parameters can be easily changed experimentally; while some are not very feasible to achieve on Earth, such as pressure level and gravity level. In this experiment the parameters to be explored are fuel type, fuel thickness, geometric configuration, and direction of spread. The primary objective of this
thesis however, is emphasized on flame structure, particularly the thermal field and CO\textsubscript{2} species field of a stabilized downward spreading flame.

1.2 Literature Review

Fire research has been an ongoing interest for the past few decades with the goals to practice of fire safety [1-3] and the benefits fire brings to humanity. One of the primary foci of fire research in the academia world has always been on flame spread rate. There is however still lacking information on the structure of a flame, such as the temperature and flow fields, and especially the species field. While the mechanism of flame propagation has already been well established [3-6], a deeper understanding of the flame structure however, may provide useful information toward predicting quantitative flame spread rate.

Flame spread can occur in the downward direction, horizontal direction, or upward direction. Horizontal flame spread can be classified as horizontal upside or horizontal underside. The direction of the oxidizer flow can be opposed to the direction of spread, or concurrent to the direction of spread. Of these configurations the simplest case is downward flame spread with opposed oxidizer flow. The appeal of an opposed flow downward moving flame is that the flame size and structure remain very steady. While a downward moving flame isn’t the only flame spread direction, it is the easiest to study. Even though a horizontal or upward moving flame may grow in size, the spread rate remains steady. The complexity of those cases is that the flame becomes too difficult to analyze due to its changing size and structure. To further simplify the problem, a thermally thin fuel eliminates the temperature gradient across the fuel thickness.

A schematic of an opposed flow downward flame spread is shown in Figure 1.1. The solid fuel has a total thickness of 2\(\tau\). Flame spread is in the same direction as gravity, with the flame spread velocity of \(V_f\). The flame draws air from its sides which induce a buoyant flow, with a velocity of \(V_g\). The relative velocity is therefore \(V_r = V_g + V_f\), which can be approximate as \(V_g\), since \(V_f\) is likely two magnitudes lower than \(V_g\). As the flame spreads downward, heat transfer through mostly conduction and radiation raises the temperature of the virgin fuel from room temperature, \(T_\infty\) to vaporization temperature, \(T_v\). During the vaporization process, pyrolysis occurs; which can appear as charring of cellulose paper or melting of PMMA. Cellulose paper undergoes sublimation in which the solid fuel directly
changes to a fuel vapor phase. PMMA thermoplastic solid melts before it vaporizes to fuel vapor. As the flame further heats the fuel, ignition temperature $T_{ig}$ is reached, at which point the reaction occurs. A flame is formed as a result of the reaction and the process repeats as the flame moves downward. Theory of opposed flame spread is discussed in details by Wichman [1]. Diffusion flame is discussed in details by de Ris [3]. Mechanism of flame spread is explored by Williams [4], Fernandez-Pello and Hirano [7], and T’ien [5].

One of the most interest factor of a moving flame is the spread rate, the velocity which the flame consumes the virgin fuel. Starting with the widely accepted de Ris’s theory [3], which predicts quantitative spread rate for both thermally thin and thick fuels, the theory has been modified by Bhattacharjee et al. [6], Bhattacharjee, West, and Docker [8], Wichman and Williams [9], and Delichatsios [10] to find better agreement with experimental results involving different fuel thicknesses and gravitational levels. The original de Ris’s theory agrees quite well with experimental results for thermally thin fuels, and the modified theory for thermally thick fuels. Some early spread rate measurements were made by Lastrina et al. [11] on both thermally thick PMMA and thin cellulose. Tarifa et al. [12] and Sibulkin et al.
[13] performed spread rate measurements on PMMA rods. Parker [14] performed experiments to find spread rate on cellulose index cards. Frey and T’ien [15] measured spread rates of paper under different ambient conditions by varying pressure level and oxygen mole fraction. Fernandez-Pello, Ray, and Glassman [16] carried out extensive spread rate measurements with different fuels and ambient conditions. Olson et al. [17] measured spread rate of cellulose paper and PMMA under simulated microgravity environment in a narrow channel and a drop tower. Hung, Olson, and Miller performed microgravity flame spread experiments of trioxane in a narrow channel apparatus [18] and cellulose in a Couette flow apparatus [19]. Pepper, Miller, and Olson [20] measured spread rate of cellulose with various flow rates and oxygen levels under simulated microgravity environments in a narrow channel. Bornand et al. [21] performed similar studies in the same apparatus over PMMA flame spread. Zhang and Yu [22] also used a narrow channel to study opposed flow flame spread in a simulated microgravity environment by suppressing the buoyant flow. The found the narrow channel gap has a significant effect on a three dimensional flame. Papac et al. [23] simulates microbuoyancy with the help of electric fields to achieve a microgravity environment to study flame spread. They measured the flame field with \( \text{N}_2 \) CARS thermometry and \( \text{O}_2 \) LIF to examine temperature and species concentrations. Bhattacharjee and Altenkirch [24] conducted microgravity flame spread over thin cellulosic fuel experiments on a Space Shuttle flight. They concluded that spread rate is determined near the flame leading edge and gas phase radiation plays an important role in microgravity environments. Ramachandra et al. [25] also performed similar microgravity experiments on a Space Shuttle flight observing spread rate at different ambient oxygen and pressure levels. Altenkirch, Eichhorn, and Shang [26] measured the spread rate of index cards against increasing buoyant force. They correlate the dimensionless spread rate with Damköhler number. Pizzo et al. [27] studied the effect of fuel width on thermally thick PMMA for upward spreading flames. They found the heat release rate per unit width to be width-independent, and spread rate decreases as fuel width increases as a result of reduced flame height due to aerodynamics effect. Gollner et al. [28] performed experiments of upward flame spread on an inclined PMMA fuel surface. They found that the maximum spread rate was greatest near the vertical orientation, and maximum fuel mass loss rate occurred near the horizontal orientation. The method of determining spread rate in the cases discussed above is
through photography or video analysis. The spread rate is found by finding the total distance
the flame traversed over the allotted time. In doing so, the instantaneous spread rate variation
is neglected by total distance accumulation.

The structure of a flame, particularly the flow field, temperature field, and species
field are of great interest to understand flame spread. Such information would be very useful
to validate numerical models. Temperature and species are generally more feasible to
measure experimentally since they’re scalar quantities. The flow field is often more difficult
to obtain since velocity is a pressure vector, although some researchers have successfully
measured the flow field. Hirano, Noreikis, and Waterman [29] measured the temperature
field with fine wire thermocouples and the flow field by particle tracing method over
thermally thin cellulosic fuels. Hirano, Sato, and Tazawa [30] also used particle tracer and
fine wire thermocouples and found the instability of downward spreading flames in the pre-
heating zone. Juste [31] applied Moiré deflectometry to measure the temperature field of
PMMA and found good agreement with thermocouple measurements. Yamamoto, Ogata,
and Yamashita [32] measured the flame structure and spread rate of cellulose paper in
premixed atmospheres containing various mixtures of gaseous hydrocarbon fuels. They
found that spread rate increases with additional pyrolysis and flame shapes are enlarged in
gaseous fuel-rich premixed environments. Di Blasi [33] developed numerical simulations on
thermally thin and thick cellulosic fuels and found that gas phase conduction dominates in
the thermally thin limit, while solid phase conduction is more dominant in the thermally thick
limit. Fernandez-Pello and Williams [34] measured PMMA flame fields with fine wire
thermocouples, interferometry, radiometer, gas phase chromatography, and particle tracking
photography. They conclude that conduction through the solid phase is the most dominant
mode of heat transfer over thermally thick PMMA fuels. Fernandez-Pello and Santoro [35]
later conducted a similar study on PMMA rods measuring the temperature and flow fields.
They also concluded that conduction through the solid phase is the dominant mode of heat
transfer for flame spread over thick PMMA rods. Ito and Kashiwagi [36] however, also
performed experiments on thick PMMA with holographic interferometry and found that
conduction in the gas phase, as oppose to solid phase, is the more dominant mode of heat
transfer toward the fuel. Their conclusion is later supported by numerical models by
Bhattacharjee, West, and Altenkirch [37] for thermally thick fuels. Bhattacharjee, King, and
Paolini [38] also developed numerical models to investigate the temperature and velocity fields of downward spreading flames; they found reasonable agreement to experimental results.

### 1.3 Temperature Measurement

There are many methods to measure temperature. Some of the most common techniques involve mechanical effect, radiation effect, and electrical effect. One of the most common mechanical methods is an in-glass thermometer [39], which relies on fluid expansion. Another mechanical method is the bimetallic strip [39], where two strips of dissimilar metals are bonded together. Other mechanical methods involve measuring the pressure of a fluid, such as the ideal-gas thermometer [39]. Fluid expansion thermometer [39] works in the same way but involves phase change. The appeal of mechanical methods is simplicity; however, the caveat is they are generally applicable to mostly low temperature. For instance, mercury-in-glass thermometer only has a range from $-38 \, ^\circ\text{C}$ to $315 \, ^\circ\text{C}$ [39]. They are also very invasive to a small flame, which will be avoided in this experiment.

Temperature measurement by radiation method is the preferred method since it doesn’t have any direct effect on a flame. It also has very high limits of measurement, which is desirable for flame measurement. Common radiation methods are optical pyrometry and emittance determination [39]. Optical pyrometry determines temperature by identifying the color of the flame through lenses and filters utilizing Wien’s displacement law. Infrared handheld thermometer is an economical choice, however there are limitations. Some other common method includes spectrum-line reversal method [40] and sodium-line reversal method [41, 42] where fine metal particles are used to find the emissive radiation. While it would be the ideal choice of measurement, there are difficulties that come with these radiation methods. Emissivity is an important parameter for accurate radiation measurement. Unlike black and gray bodies, emissivity of an actual surface varies with wavelength; thus becomes a source of measurement error. Soot formation could affect the color of the flame. Radiation view factor of a small flame is insufficient for some optical measuring devices that require a large surface spot size.

Temperature measurements by electrical effects have become a very common approach because of its practicality and accuracy. For ultra-precise temperature
measurement, quartz-crystal thermometer based on resonant frequency, and liquid crystal thermography based on color changes of the visible spectrum provide accuracy within 0.001 °C [39]. Thermos-chromic liquid crystal (TCLC) thermometry is another variation of liquid crystal thermography with very high accuracy [43]. While these methods may be very accurate, they have a low range of measurement, ranging from −40 °C to 230 °C [39]. Electrical-resistance thermometer is also provides accurate measurement for low temperature but not as accurate for higher temperature range [39]. Temperature is measured by exposing a resistive element to the measured environment and the resistance of the element is recorded. Thermistor is a similar device to measure temperature that uses semiconductor to determine resistance value. An accuracy of 0.01 °C can be achieved if it is properly calibrated [39].

After investigating a plethora of temperature measurement method, thermocouple was chosen as the ideal device to measure temperature of a small scale flame. It was selected for cost effectiveness, accuracy, fast response time, and minimal interaction with the flame. Thermoelectric effect is the method of measurement of a thermocouple; it utilizes the Seebeck effect, Peltier effect, and Thomson effect [39]. When two dissimilar metals are joined together to form a junction, a miniscule amount of current flow is created. This phenomenon is known as the Seebeck effect. Temperature is determined by measuring the electromotive force (emf) at the hot junction of the two metals. The Peltier effect occurs when an external circuit is connected to the metals that may affect the emf measurement, therefore a potential source of error. Furthermore, if a temperature gradient exists along the length of the exposing metals, the emf may be altered, known as the Thompson effect. The main focus however remains with the Seebeck effect, since the emf is primarily dependent on the temperature at the hot junction. To correct for error and accurately measure temperature, a cold junction is used as a reference point. This often requires an additional junction exposed to a volume with a known reference temperature; an ice bath is a common example. This system is undesirable due to its up-keeping. The modern solution is a cold junction compensator, a built-in compensator in the measuring circuit that determines a known reference temperature.
1.4 Species Measurement

Species measurement isn’t as feasible as temperature measurement. The presence of byproduct species is difficult to accurately measure by mechanical or electrical methods. The most common approach to measure species is through optical devices. One of the most accurate and widely used methods is coherent anti-Stokes Raman scattering (CARS) spectroscopy. There are many variations to this method, but the concept is the same, utilizing the molecular kinetic energy of chemical bonds. The kinetic energy of chemical bonds, or molecular motion, is consisted of vibration, rotation, and translation. Most CARS spectroscopy method utilizes the molecular vibrational effect. The CARS method relies on at least three lasers, an oscillator, a spectrometer, several lenses/reflector, and a detector. Two lasers, namely pump and Stokes, are emitted through the measured medium as the beams are reflected through the lenses. The difference in frequencies of these two lasers is called the coherent anti-Stokes. The signal is amplified and received by the oscillator when it matches the resonance frequency from the vibration of the molecular bonding structure. A third laser beam, namely probe, passes through the measured medium, affected by molecular vibration before it reaches the spectrometer, and measured at the detector. Variations of the same system with additional laser beams can be implemented to measure multiple species, by exploiting the other molecular motions, rotational for instance. Such variations may include dual-pump, dual-Stokes, pure-rotational, and various combinations of additional components.

A dual-pump CARS method was used by Tedder et al. [44] at NASA Langley Research Center for temperature and species measurements in a supersonic combustor. Their results show that the CARS temperature measurements were within 26 K agreement with thermocouple measurements and species measurements were within 1.6 % of nominal value of atmospheric air. Roy et al. [45] also used a dual-pump CARS method to measure temperature and CO$_2$ of the exhaust stream of a jet fuel combustor. They found the temperature and CO$_2$ measurements to agree within 2.3 % and 6 % standard deviation of mean value, with day to day variations within 1 % and 2 %, and CO$_2$ measurement agree within 7-9 % of theoretical calculation. Hall and Stufflebeam [46] performed an experimental and theoretical investigation on CARS spectroscopy of CO$_2$ in a pressurized static heated cell and found good agreement between the two methods. Roy et al. [47] used single-beam CARS spectroscopy to measure CO$_2$ on a femtosecond scale to demonstrate the ability to use fs-
CARS in a hypersonic or detonation environment. Kalatilaka, Gord, and Roy [48] studied the effects of fs-CARS spectroscopy of O$_2$-CO$_2$ polarization and deduced that for higher concentration of CO$_2$, above 10 %, there is an effect on the coherence dephasing rate due to pulses of laser beams that would affect thermometry and species measurement.

While CARS is the more common used method, there are other techniques available, with most involves lasers. Laser-induced fluorescence (LIF) can be used for high resolution species measurement. Laser-induced incandescence (LII) and planar laser-induced fluorescence (PLIF) has the ability to measure soot formation and radical concentrations. These methods are particularly useful to measure small traces of minority species since they are difficult to detect and accurately measure. As similar to CARS, most laser systems such as LIF that can measure species also have the ability to measure temperature. Mihalcea [49] used external cavity diode lasers and high resolution spectroscopy to measure CO and CO$_2$ at different spectral bands in a combustible environment, with resulted agreed within 4 % and 2 %, respectively, to equilibrium calculation.

CARS is an effective and accurate method of species measurement. The appeal is a non-intrusive measurement process. The caveat is the experimental setup is complex and very expensive. And to measure multiple species additional laser beams are required. Like CARS, most optical measurement systems operate by sending a known electromagnetic radiation signal through a participating medium; the incoming radiation is altered, and is received at a detector to be measured. As the radiation passes through the participating media, the photons are scattered, absorbed, and may re-emit by the molecules. Under CARS spectroscopy, which utilizes Raman scattering, the collision process between a photon and a molecule is inelastic. Therefore the collision alters the kinetic energy of the photon, changing its wavelength and frequency. A very similar approach to CARS is coherent Stokes Raman scattering (CSRS), which still is inelastic collision Raman scattering. An elastic collision is Rayleigh scattering, where the photon retains its kinetic energy. Rayleigh scattering can also be utilized for temperature and species concentration measurements. These scattering methods require higher energy states. Scattering optical methods often case require extensive calibration and don’t always provide accurate result. One method that relies on lower energy state is infrared absorption, where the radiation of the photon is absorbed by the molecule.
The experimental setup for this type of system is very simple and much more economically feasible. This concept will be discussed in Chapter 2, Section 2.2.3.

1.5 EXPERIMENTAL APPROACH

This experiment begins with the construction of a frame structure to support the testing apparatus. There are three linear actuators mounted on the main frame that control a flame and its measuring instruments. The linear motion systems are driven by stepper motors. A sample holder is mounted onto one of the linear actuator on the main frame. An experimental moving flame is suspended stationary by a control system. Measuring instruments are then able to make precise location measurements on a stabilized flame field. Temperature measurement is done with fine wire K-type thermocouples fabricated by a spot welder. Species measurement is achieved by an optical CO₂ NDIR sensor. Temperature and CO₂ measurements are performed on moving flames and stabilized flames. The temperature and CO₂ profiles are compiled for comparison and to create the thermal and species fields. Fuels utilized are Whatman 1 cellulose filter paper and thermoplastic acrylic PMMA.

Additionally, an investigation on flame spread with different orientations and directions are explored, and the effect of radiation view factor has on spread rate is briefly discussed.
CHAPTER 2

EXPERIMENTAL SETUP

This chapter discusses the required experimental hardware and software. Starting with a frame structure as a foundation the remaining hardware is built upon it. Measuring probes are properly selected to acquire temperature and CO₂ data. Experimental software controls the hardware and collects measured data.

2.1 Flame Stabilizer Hardware

All flame spread experiments are performed on the flame stabilizer 2.0 apparatus. This apparatus is consisted of three separate subassemblies: a frame structure for support, a vertical linear motion system for the fuel sample holder, and a multi-axis probe positioning linear motion system in the x-y plane. The complete assembly of the flame stabilizer 2.0 apparatus is shown in Figure 2.1 in isometric view.

Figure 2.1. Complete assembly of flame stabilizer 2.0.
2.1.1 Frame Structure

The structure of the flame stabilizer is assembled by T-slot 6061 aluminum framing beams made by 80/20® Inc. Each aluminum beam has four opening slots known as T-slot for easy assembly that can build an array of versatile structures. Fasteners known as T-nuts slide along the length of any side of each beam and T-bolts connect two beams through a bracket or an anchor. The cross section area of the T-slot aluminum beam is 1.5 inches by 1.5 inches. The static torque capacity of these T-slots is rated at 250 lb-ft to 1000 lb-ft, depending on the bracket or anchor type. The structure has a base area of 3 ft by 3 ft, and a height of 6 ft. Each leg of the structure is anchored to the concrete ground with two wedge anchors. Each wedge anchor is rated at 2000 psi and 1200 lb of pullout or shear force. The CAD model of the frame structure is shown in Figure 2.2.

![Figure 2.2. CAD model of frame structure. (a) T-slot profile, (b) isometric view, and (c) front view.](image)

2.1.2 Vertical Linear Motion System

The vertical linear motion system is consisted of a stepper motor, a linear actuator, and a sample holder. The motor is connected to the linear actuator system by a shaft coupling. As the motor rotates it turns a lead screw in the linear actuator system that
translates a platform. A sample holder is connected to the platform on the linear actuator assembly. Therefore as the motor rotates it drives the sample holder in the desire direction.

The stepper motor is powered and controlled by a micro-step AX-drive indexer; both are produced by Parker Hannifin Corp., Compumotor Division. The motor is a two-phase permanent magnet hybrid stepper motor, with a resolution of 12,800 steps per revolution. The motor has the ability to rotate clockwise or counterclockwise, with equal torque and angular velocity in both directions. The motor has a maximum angular velocity of 50 rev/sec and a maximum angular acceleration of 20 rev/sec$^2$. The indexer is powered by 115 VAC and communicates with a computer via a RS-232 serial port. It converts the digital code from the computer into an analog signal to drive the motor.

The linear actuator is manufactured by PBC Linear, a Pacific Bearing Company. The apparatus is a two-piece assembly Uni-Guide linear slide system, as shown in Figure 2.3. The platform slides along the guiding rail with a self-lubricating Frelon Gold bearing in-between them. A 100 cm lead screw with a pitch diameter of 2.5 mm is equipped to drive the platform along the rail. The lead screw is threaded through a spring loaded anti-backlash journal of the platform and is attached at the bottom and top housings of the guide rail. Therefore as motor rotates the lead screw the motion translates to move the platform vertically. The entire linear actuator assembly is mounted onto the frame structure and the motor is mounted to a housing on top of the assembly.

The sample holder itself is a sub-assembly. It is attached to the platform in Figure 2.3 with aluminum T-slot beams. The backbone of the sample holder is an aluminum L-bar as shown in Figure 2.4. The aluminum L-bar is 130 cm in length and has a thickness of 1/8 inch. The L-bar is attached to the T-slot beams by two bolts. The sample holder is made of
Figure 2.4. Sample holder assembly, (a) T-slot beams, (b) L-bar, and (c) sample holder.

24-gauge 302 stainless steel. It has a fuel width of 3 cm, total width of 12 cm, and a total length of 100 cm. There is an L-bend to on the sample holder to provide structural rigidity. The sample holder is consisted of two sheets of stainless steel, namely left and right. The left one is bolted to the aluminum L-bar by machine screws. The right one is attached to hinges and the hinges are attached to the aluminum L-bar. This allows the right sample holder sheet to swing freely when fuel samples are loaded. When a fuel sample is loaded, the right sample holder sheet is secured to the left one by neodymium rare earth magnets.

The sample holder assembly has enough mass to cause a noticeable bending moment on the jaws of the Frelon bearing. There is a counter weight pulley system to offset the resulting bending moment that significantly reduces the friction on the guiding rails. The counter weight system is consisted of a rope, a 12 lb dumbbell, a supporting bar, and two ball-bearing pulleys. The two pulleys are attached at two ends of the supporting bar. The rope passes through the two pulleys with one end tied to the 12 lb dumbbell and the other end tied to the centroid of the sample holder assembly.

2.1.3 Probe Positioning System

The probe positioning system is consisted of two linear actuator systems and a platform. The two linear actuators are manufactured by Warner Electric Company. One linear actuator traverses in the vertical direction and the other in the horizontal direction. Each linear actuator is controlled by a micro-step AX-drive indexer, and a Compumotor stepper motor, both of which are manufactured by Parker Hannifin Corp. The specifications are the same as the motor-indexer combination used in the sample holder assembly, with a shaft resolution of 12,800 steps per revolution, and a maximum angular velocity of 50
The vertical linear actuator assembly consists of a lead screw with a pitch diameter of 5 mm, an anti-backlash journal attached to the lead screw, and a platform attached to the journal that slides along guide rails. The horizontal linear actuator assembly is attached to the platform on the vertical linear actuator assembly and has the same hardware specifications. The measuring probe platform is attached to the horizontal linear actuator assembly platform. The structure of the probe resting platform is consisted of two aluminum L-bars bolted to the linear actuator platform. T-slots are attached to the L-bars to form an L-structure. A 24 cm by 36 cm aluminum sheet is bolted to the L-structure as a resting platform for the measuring probes. The T-slots allow the probe position to be adjustable. Therefore a measuring probe mounted to this positioning system can be moved in the vertical and horizontal direction, independently or together, with very high precision from the motor-indexer control. Figure 2.5 is a schematic of the probe positioning system.

Figure 2.5. Probe positioning system, (a) schematic, and (b) experimental setup.

2.2 SENSOR SELECTION

Various instruments were researched for the purpose of temperature and species measurement. There are numerous methods for temperature measurement, from very simple to very complex systems. Considerations for temperature measurement include limit of measurement, resolution of accuracy, and flame interaction. Thermocouple was chosen for its cost effectiveness, accuracy, and minimal interaction with the flame. There aren’t as many options for species measurement. Most methods involve advanced optics systems. In a
hydrocarbon combustion process, the dominant species are CO₂ and H₂O, and slight traces of other byproducts. The measurement of H₂O is a challenge due to possible phase change and molecular dissociation from the heat of the exothermic reaction. CO₂ is less susceptible to phase change and therefore more ideal for measurement. Carbon emission is also a growing interest as it is a greenhouse gas. The chosen method for CO₂ measurement is an optical sensor utilizing a method known as non-dispersive infrared radiation (NDIR).

2.2.1 Temperature Measurement

There are many types of thermocouple, since the number of alloy combination is endless, given if they are compatible with each other. A thermocouple is consisted of a positive lead alloy and a negative lead alloy. Each lead consists of a single metal or a mixture of various metals. The optimal alloy combinations have been investigated for their range and accuracy, and a few are widely recognized. Among the most common types of thermocouple are: J (iron-constantan), K (chromel-alumel), T (copper-constantan), E (chromel-constantan), N (nicrosil-nisil), and R, S, B, which contain various percentages of platinum-rhodium mixture, and G, C, D, which contain various percentages of tungsten-rhenium mixture. Most of these thermocouples that are manufactured by Omega Engineering Inc. have a range from below 0 ºC to over 1000 ºC, with an accuracy within 1 % of measured value. Because flames can reach very high temperature, thermocouples are properly selected for accurate measurement. Considerations for response time and emf range are also taken into account. Response time depends on the thermocouple type, thermocouple wire diameter, and data bit rate of the data acquisition system. Emf range dictates the tolerance of measurement which affects accuracy. Figure 2.6 shows temperature range and emf range for various thermocouple types [39].

Referring to Figure 2.6, type G (tungsten, rhenium) is capable of measuring temperature from 0 ºC to 2320 ºC. However, tungsten-rhenium based thermocouples are expensive, brittle, and difficult to handle. Platinum-rhodium based thermocouples, type B, R, and S are easier to handle, and are able to withstand temperature up to 1820 ºC. However, they are also expensive and have low emf range. A J-type thermocouple was tested and it was not able to withstand the flame temperature of cellulose. As the flame passed by it melted and disintegrated. The remaining thermocouples that are able to withstand high
temperature are K-type and N-type. K-type (chromel-alumel) is the preferred choice since it has a slightly higher temperature limit at 1372 °C, and a higher emf range. Chromel, the positive lead alloy consists of nickel and chromium. Alumel, the negative lead alloy consists of nickel and aluminum. The limit of error on K-type is 2.2 °C or 0.75 %. Refer to Appendix B.1 for calculation concerning thermocouple response time.

The alumel and chromel wires of a K-type thermocouple must be welded to form a hot junction. This process is often done by a spot welder and may contribute to thermocouple reading error. The workmanship of a thermocouple depends on the manufacturing process. The surface of the thermocouple may not be smooth, emissivity may vary with different coatings, composition of the metal mixture may not be uniform, and minor deformations may exist. Figure 2.7 shows a thermocouple components and the data acquisition system. Each alloy of the thermocouple is attached to the male connector by machine screws between two flanges to the corresponding lead. The connection passes to the corresponding leads of the female connector and to the extension wire. It is important that the two alloys should not make any contact at any other point except for the hot junction; otherwise another junction would be created. The extension wire connects to a National Instruments data acquisition device where the emf reading is transmitted to a computer via a universal serial port. The
National Instruments data acquisition device has a built-in cold junction compensator to determine the reference temperature. It contains 4 thermocouple channels, with 24 bits resolution, giving a maximum sampling rate of 6 Hz for each thermocouple.

### 2.2.2 Carbon Dioxide Measurement

The CO₂ sensor chosen for this experiment is manufactured by CO2Meter, Inc. The sensor is shown in Figure 2.8 (c). The dimension of the sensor including the circuit board is 5.1 cm by 5.7 cm with a height of 1.4 cm. The sampling chamber of the sensor is approximately 1 cm. The sampling chamber is covered by a tube cap as shown in Figure 2.8 (c). The circuit board supplies power to the sensor and receives measured data. The data transfers to a computer via a universal serial port. A data acquisition system (DAS) software is provided by CO2Meter, Inc. that records the data and also displays real-time measurement. The power supply to the circuit board is 6 VDC (4×AA batteries) as shown in Figure 2.9. The sensor has an operating range between −10 °C to 50 °C, and a humidity range from 0 to
Figure 2.8. (a) Iso view of air pump, (b) side view of air pump, (c) CO$_2$ sensor, and (d) schematic of sampling chamber of CO$_2$ sensor.

Figure 2.9. CO$_2$ measurement apparatus.
95 % RH, non-condensing. Water traps and particulate filters can be implemented if necessary to prevent condensation and clogging that would affect measurement.

As discussed in Section 1.4, the method of optical measurement of this CO₂ sensor is infrared absorption. A schematic of the mechanism is shown in Figure 2.8 (d). The mechanism is known as non-dispersive infrared radiation (NDIR). A gas contains CO₂ is inside the sampling chamber. An infrared lamp emits a radiation signal through the gas chamber. As the emitted radiation passes through the chamber photons collide with gas molecules, where radiation is absorbed by CO₂ molecules. It should be noted that other than absorption the radiation may get scattered and re-emitted by the gas. The particular wavelength was chosen by the manufacturer to reduce scattering and re-emission. At the other side of the sampling chamber the emitted radiation signal encounters an optical filter. This filter only permits the infrared radiation signal emitted by the lamp to pass through, where a detector measures the intensity of the signal. By knowing the intensity of the original emitted signal and the detected signal, the mole fraction of CO₂ of the gas in the sampling chamber is calculated by the sensor.

For this particular CO₂ sensor, K33-ICB, the sampling rate is 0.5 Hz, or one measurement every two second. The infrared lamp flashes “ON” for a 120 millisecond interval during the sampling period. The maximum CO₂ concentration that the sensor can accurately measure is 30 %, or 300,000 ppm (part per million). The sensor has a built-in automatic background calibration algorithm that uses air, which has 400 ppm CO₂ (0.04 %), or a zero calibration algorithm which requires pure nitrogen. The resolution of measurement is 0.001% or 10 ppm, with a repeatability of ± 0.1 % CO₂ or ± 2 % of measured value, and an accuracy of ± 0.2 % CO₂ or ± 3 % of measured value.

The sensor has two modes of operation, diffusion and force induction. Diffusion mode would be ideal as it is minimally intrusive to the flow field. Diffusion mode, however, only provide accurate measurement if the measuring volume is saturated with CO₂ or equally mixed in an enclosed chamber. The flame is not in an enclosed environment and the temperature near the flame is far beyond the sensor’s operating temperature limit. Diffusion also takes longer for the gas to reach the sampling chamber. Force induction is therefore necessary to obtain a quick and accurate measurement. An air pump is therefore equipped to draw air from the flame field.
The micro air pump shown in Figure 2.8 (a), (b) is manufactured by KNF Neuberger, Inc. The dimension of the pump is 2.5 cm by 3 cm by 1.7 cm. It is a reciprocating air pump with a cam-follower mechanism. A small DC motor drives a shaft that rotates the cam, which is connected to a crankshaft that displaces the volume in a chamber. Figure 2.8 (b) shows the inlet port where a gas is drawn into the pump and the exit port where the gas moves into the inlet of the sensor in Figure 2.8 (c). The pump has a flow capacity of 0.3 L/min with no head loss. The pump is powered by 6 VDC (4×AA batteries) as shown in Figure 2.9. Flexible plastic tubes are used to transport a sampling gas from the pump to the sensor. As shown in Figure 2.9, the pump draws a gas containing CO$_2$ from a remote source through the plastic tube to the inlet port. It pushes the gas out of the exit port into another plastic tube that connects the exit port of the pump to the inlet port of the CO$_2$ sensor. The gas travels through the sampling chamber as it gets measured before being exhaust out of the exit port of the CO$_2$ sensor into the surrounding atmosphere. The entire CO$_2$ measuring process is thus complete.

2.3 LabVIEW Software

The software program that controls the flame stabilizer hardware is NI LabVIEW, created by National Instrument Corp. It is a dataflow visual, graphic-based programming platform written in mostly G with elements of C and C++. LabVIEW programs are called “VI”, or virtual instruments. The program is written by building block diagrams, with a GUI for user control. The VIs in the following sections were originally created by Engstrand et al. [50] and later modified by Dalal [51] and Alghamdi [52]. These VIs control the indexer-motor linear actuator systems and acquire experimental data. They communicate with the indexers to control the motors via RS-232 serial ports. A digital signal is sent from a VI that gets converted to an analog signal via a D/A converter and processed by an indexer. Vice versa, a thermocouple reading is converted from an analog signal to a digital signal via an A/D converter and received through a USB port. The following VIs were created for the operation of flame stabilizer experiments.

2.3.1 Motor Control VI

This VI was solely written to move the fuel sample holder to a desired position. The GUI of the VI is shown in Figure 2.10. When activated, this VI allows the user to define a velocity and move the fuel sample in the vertical direction at will.
2.3.2 Temperature Measurement VI

The temperature measurement VI records the temperature of a moving flame. The current version measures temperature from two thermocouples with a sampling rate of 6 Hz. A total of four thermocouples can be implemented with a sampling rate of 3 Hz. Figure 2.11 shows the GUI that displays real-time measurement during an experiment. A built-in data acquisition system from LabVIEW exports the data into a text file that contains time and corresponding temperature readings.
2.3.3 Flame Stabilizer VI

The core of the flame stabilizer and temperature measurement VI is a control system that stabilizes a flame in a fixed frame of reference. As mentioned earlier, a point of reference on a moving flame isn’t fixed so it is difficult to perform measurements on a flame field. This VI has a built-in PID control algorithm that stabilizes a flame, keeping it stationary in a fixed frame reference. Figure 2.12 shows the PID control algorithm of this VI. The user defines a set point temperature ($T_{sp}$) to track a flame. As the flame approaches the thermocouple it reads a flame temperature ($T_f$). The thermocouple analog signal is converted to a digital signal and receives by the VI. The error is then calculated as $T_{sp} - T_f$ before it goes into the PID loop. The PID loop processes the error signal and sends a digital output signal. The signal is converted to analog and received by the stepper motor. The motor moves the sample, essentially the flame location, to the desired set point temperature. If the flame temperature $T_f$ is lower than the set point temperature $T_{sp}$, then the flame is too far above the thermocouple. Hence the motor moves the sample downward to move the flame closer to the thermocouple. Vice versa, if the flame temperature is higher than the set point temperature, then the flame is too far below the thermocouple. Thus the motor moves the sample upward until the set point temperature is reached. The control algorithm loop repeats itself when the thermocouple measures the following flame temperature after the motor moves the relative flame position. After a few passes through the PID control loop, steady state is reached as the error reduces and the flame is stabilized.

![Figure 2.12. Schematic of flame stabilizer PID control algorithm.](image-url)
The PID control algorithm was chosen for its effectiveness, practicality, and simplicity. PID stands for proportional, integral, and derivative. Proportional gain, $K_p$, controls how aggressive a system responds to an error signal. A low proportional gain produces a slow response when an error is detected. Therefore the system lags behind the error signal and may not reach steady state. A higher proportional gain leads to a faster response when an error is detected. However, a fast response may lead to instability as error corrections are made too rapidly. Integral time, $T_i$, eliminates the steady state error of a system. A small integral time leads to lagging as error corrections are made at small increments. A high integral time leads to instability as error corrections are made at large increments that cause fluctuations. Derivative time, $T_d$, controls the stability of a system. A small integral time improves stability of a system but decreases the rate of response. A high derivative time improves response at the cost of instability. For a control system to work effectively, the controlling parameters must be tuned. A PID control algorithm can be tuned manually by holding two parameters constant while tuning the other parameter. The tuning progression was achieved by tuning $K_p$ first, follow by $T_i$, and then $T_d$. Since the parameters are functions of one another, second-stage fine-tuning is done in the same manner after the first tuning process. After manually tuning each parameter independently, the optimal PID constants were found to be: $K_p = 0.02$, $T_i = 1.50$, and $T_d = 0.15$. Another importantly tracking parameter is the set point temperature, which also needs to be tuned with the PID constants. The optimal set point temperature to track was found to be 700 ºC.

The GUI of the flame stabilizer VI is shown in Figure 2.13. Once the VI is activated to enable the flame tracking process, real-time tracking data displays on the GUI. The upper-left graph shows the thermocouple readings in millivolt and the upper-right graph shows thermocouple temperature after a conversion from millivolt to ºC. The lower left graph displays spread rate data calculated from displacement of the fuel sample holder when the stepper motor rotates. This eliminates the laborious process of video processing to find flame spread rate. The lower right graph displays temperature measurement from the non-tracking thermocouple that measures the temperature of the thermal flame field. This VI has a built-in data acquisition (DAQ) system that exports measured data into a text file displaying time, spread rate, and temperature measurements.
2.3.4 Probe Positioning System VIs

These VIs control the position of the CO\textsubscript{2} and thermocouple probes to measure the flame field. The GUIs are shown in Figure 2.14. Velocity and acceleration of the linear actuators moving the probes are controlled variables in this VI. Limits of travel can be set and an origin can be set as a point of reference. The x-y location of a measuring probe can be changed independently or simultaneously since each axis is controlled by its own motor.

2.4 Spread Rate Processing Software

As mentioned in Section 2.3.3, spread rate of a stabilized flame is automatically calculated and recorded by the Flame Stabilizer VI. For a moving flame, spread rate is measured by video analysis, in a program called NASA Spotlight [53], an image analysis and object tracking software. Spotlight can also be used to verify the spread rate of a stabilized flame by analyzing the moving fuel sample holder. A particular spot on a flame is selected for tracking; the leading edge of the flame is a common area of interest to track. The user defines the frame step size increment to track, basically the time increment between steps. It can be as low as one frame per step size or as many as the user chooses. As each step size goes by, the flame leading edge displaces from the previous location. Automatic tracking is available and it tracks the RGB components of the leading edge of the flame. Manual
tracking is also an option however it is a laborious process. After the tracking process is complete, the frame step sizes and pixel counts data are exported into a text file. The frame step size is converted into time as the frame rate of the video is known. The pixel count is converted into distance as an object of known length and pixel count is in the video, such as a ruler. With time and distance at every step size, the instantaneous spread rate and average spread rate over an extended period can be found. Figure 2.15 shows a typical process of Spotlight tracking on a moving flame. The box with the arrow is the area of interest where the front edge of the flame is being tracked. The dotted line is to constraint the tracking direction to only the vertical direction of flame propagation. The scale on the right determines the distance from the pixel count after every tracking interval. The time step between images shown is 2 second, determined from the frame step size.
CHAPTER 3

EXPERIMENTAL METHODS

This section discusses measurement methods to obtain spread rate, temperature, and CO\textsubscript{2} data in the flame field. Tracking methods to stabilize a flame are explored and optimized. Thermocouple sizes and orientations are investigated to improve temperature measurement. Various probe sizes and flow rates are considered to achieve accurate CO\textsubscript{2} measurement. A grid structure to the flame field is implemented to achieve temperature and CO\textsubscript{2} measurements at every position in the flame field.

3.1 STABILIZED FLAME

An ideal measurement would be non-invasive to a flame. However this is not the case when measuring probes are involved. Since the flame stabilizer moves the fuel sample upward at the same velocity as spread rate, it is investigated if it has an effect on the flame. Figure 3.1 shows the spread rate comparison between a stabilized flame and a moving flame. Two separate experiments were performed back-to-back, one stabilized and one moving, with 180 μm, 88 g/m\textsuperscript{2} Whatman 1cellulose. The spread rate of the stabilized flame was determined by the flame stabilizer as 1.76 mm/s, with a standard deviation of 0.058 mm/s. The spread of the moving flame was found by Spotlight as 1.78 mm/s, with a standard deviation of 0.067 mm/s. There is also no apparent difference in flame shapes between a stabilized and a moving flame. The result is logical since the stabilizer only imposes a concurrent flow velocity of about 2 mm/s on the flame, which should hardly have any effect on the flame since the buoyancy velocity is multiple magnitude higher. A position vs. time plot would produce straight lines overlapping one another since the total distance travelled is cumulative. The slight variation in flame spread shown in Figure 3.1 is only noticeable in instantaneous spread rate.

The stabilizer was also tested for repeatability and tracking various fuel thicknesses. Three experiments were performed in the same timeframe to show the repeatability of the flame stabilizer. The instantaneous spread rates for three separate runs were found to be 1.82 mm/s, 1.81 mm/s, and 1.84 mm/s, with standard deviations of 0.050 mm/s, 0.057 mm/s, and 0.063 mm/s, respectively. The ability to track multiple thicknesses is shown in Figure 3.2.
Figure 3.1. Spread rate of a stabilized flame vs. a moving flame.

Figure 3.2. Flame stabilizer tracking multiple thicknesses in one experiment.
For this experiment a sheet of Whatman 1 cellulose was stacked on top of another to create double thickness and an additional sheet to create triple thickness. The entire sample is form as one sheet with equal length of each thickness. As the flame burns out the 180 µm thick fuel it moves onto the double thickness, 360 µm fuel and followed by the triple thickness, 540 µm fuel. The spread rates were found to be 1.81 mm/s, 1.01 mm/s, and 0.688 mm/s with standard deviations of 0.063 mm/s, 0.055 mm/s, and 0.060 mm/s, respectively. Visible images of the flames at these thicknesses are shown in Figure 3.2, starting with 180 µm on the left, 360 µm in the middle, and 540 µm on the right.

Tracking thermocouples were also taken into consideration. The ideal thermocouple would output a smooth response from the PID control system. But it should also have minimal effect on the flame shape and spread rate. It was found that any thermocouple size and orientation can be adjusted to steadily track a flame by tuning the PID control algorithm. However the effect it has on the flame front has a significant role. Figure 3.3 reveals the effects of tracking thermocouple size and orientation have on spread rate. The wire diameter of the thermocouples is 250 µm. The orientation of a thermocouple with respect to the fuel surface was explored between parallel and perpendicular. In the parallel orientation the thermocouple wires are bent in the direction parallel to the fuel surface to reduce the temperature gradient along the wires. This is known as the Thompson effect and will be explored in the next section. In the perpendicular orientation the thermocouple wires are protruding toward the fuel surface, in the direction into the fuel. This orientation reduces the contact area of the thermocouple to the flame. Two experiments were performed back-to-back with the two thermocouple orientations. It was found that the perpendicular orientation produces a spread rate of 1.89 mm/s and the parallel orientation produces a spread rate of 1.63 mm/s. The conclusion is that the absorption capacity of the parallel orientation draws a substantial amount of heat from the pre-heating regime of the fuel, thereby reducing heat transfer to the virgin fuel, hence the reduction in spread rate. All following stabilized flame experiments are therefore tracked with perpendicularly oriented thermocouples with a wire diameter of 125 µm or smaller.

Tracking points on the flame front was also investigated. Stabilized flames were tracked at the center of the fuel surface and the side edge of the fuel surface on the top plane. Figure 3.4 shows the spread rate results of two tracking points from two back-to-back
Figure 3.3. Effect of tracking thermocouple orientation on spread rate.

Figure 3.4. Tracking points on a stabilized flame front.
experiments. Tracking at the center of the fuel surface produces a spread rate of 1.81 mm/s with a standard deviation of 0.06 mm/s. The side edge of the fuel surface produces a spread rate of 1.84 mm/s with a standard deviation of 0.126 mm/s, twice higher than the center tracking point. Spread rate on the side edge has more variations due to the fingering effect on the side edges of a spreading flame. Another tracking parameter is the thermocouple distance from the surface of the fuel on the side plane. It was found the optimal tracking distance from the fuel surface is between 1 mm and 2 mm. The tracking point on the flame front is also important. It was mentioned earlier the optimal tracking height is the leading edge of the visible flame, measured as 700 °C.

3.2 Temperature Measurement

As previously discussed above, size and orientation of thermocouples not only affect the stabilized flame tracking process but it has a greater impact on accurate flame temperature measurements. An ideal thermocouple measures the flame temperature without any heat losses. This is however not the case, heat losses are present due to conduction from a temperature gradient along a thermocouple, and radiation due to emissivity of a thermocouple. The flow field is a natural phenomenon of a flame and therefore convection brings hot gases to a thermocouple. Conductive loss can be minimized by reducing the temperature gradient along the thermocouple. This is also known as the Thompson effect, reducing the temperature gradient to minimize the emf reading error of the thermocouple. Radiative loss can be reduced by minimizing the emitting surface area of the thermocouple. As far as radiative loss is concern, refer to Appendix B.2 for calculation on radiation correction factor to compensate for thermocouple temperature without radiation heat loss.

Thermocouples at two sizes and two orientations are explored to observe their effects on flame temperature measurement. Thermocouple wire sizes are 125 µm and 250 µm, with orientations of parallel and perpendicular to the fuel surface, therefore four thermocouple configurations are explored. Keep in mind that 125 µm refers to the wire diameter of a thermocouple; the bead size at the junction is usually 2.5 times larger. The flame temperature is measured with each thermocouple configuration to observe how thermocouple heat loss affects temperature measurement. Four experimental runs are performed with each configuration on a moving flame from 180 µm Whatman 1 cellulose. The junction of the
thermocouple is placed at the center and touching the fuel surface. Figure 3.5 shows one of the thermocouple configuration, 250 µm oriented perpendicular to the fuel surface. The average peak temperature from four runs is 905 ºC. The following configuration is the same thermocouple diameter, 250 µm but oriented parallel to the fuel surface. Figure 3.6 shows the temperature measurement from a 250 µm parallel orientation thermocouple. The average peak temperature from four experimental runs is 1160 ºC. Figure 3.7 shows temperature measurement from a 125 µm perpendicular orientation thermocouple. The average peak temperature from four runs is 1102 ºC. The last configuration is a 125 µm parallel orientation, with the result is shown in Figure 3.8. From four experimental runs the average peak temperature was measured as 1271 ºC.

![250 µm perpendicular thermocouple](Figure 3.5. Moving flame temperature measurement from a 250 µm perpendicular orientation thermocouple.)

The comparison of all configurations is shown in Figure 3.9. As the size of the thermocouple is increased from 125 µm to 250 µm, the peak temperature measurement is reduced by 110 ºC for the parallel orientation and 196 ºC for the perpendicular orientation. By changing the orientation from parallel to perpendicular, the peak temperature measurement is reduced by 169 ºC for the 125 µm thermocouple and 255 ºC for the 250 µm thermocouple. While significant radiative loss is observed, it can be concluded that heat loss
Figure 3.6. Moving flame temperature measurement from a 250 µm parallel orientation thermocouple.

Figure 3.7. Moving flame temperature measurement from a 125 µm perpendicular orientation thermocouple.
Figure 3.8. Moving flame temperature measurement from a 125 µm parallel orientation thermocouple.

Figure 3.9. Moving flame temperature measurement of four thermocouple configurations.
through conduction from the temperature gradient along the thermocouple is just as important if not more dominant. Further supporting evidence is the temperature measured from the 250 µm parallel thermocouple, 1160 ºC which is higher than 1102 ºC, the temperature measured from the 125 µm perpendicular thermocouple. So even though the surface area of the 250 µm thermocouple is four times greater than the 125 µm thermocouple, it still achieves a higher temperature when the temperature gradient along the thermocouple is reduced.

As indicated above, radiative loss proved to be quite significant. A smaller diameter thermocouple in theory should reduce radiative loss. For this purpose, a smaller thermocouple with a diameter of 75 µm is implemented. However, the structure of the thin thermocouple wires is compromised due to thermal stress from the flame. As the flame passes by the thermocouple, it distorts and retracts away from the flame. Hence, unless there is structural support to provide rigidity it’s not a viable option.

All thermocouples discussed thus far have a bead junction. The junction point where the chromel wire meets the alumel wire forms a bead from a weld. The diameter of the bead at the junction is usually 2.5 times greater than the wire diameter, which enhances radiative loss. There is an alternative known as butt-welded thermocouple where the junction doesn’t form a bead. The diameter at the junction is therefore the same as the wire diameter. A 125 µm parallel orientation butt-welded thermocouple is thus implemented and the result is shown in Figure 3.10. The average peak temperature from four experimental runs is 1337 ºC, which is 66 ºC higher than the 125 µm bead thermocouple shown in Figure 3.8. The radiative loss therefore appears to be reduced from the smaller junction of the butt-welded thermocouple. Likewise a 75 µm butt-welded thermocouple was also tested; however the structure is compromised due to thermal stress as discussed above. Hence, the best suited thermocouple for accurate flame temperature measurement without sacrificing structural rigidity is determined as a 125 µm parallel orientation thermocouple. Keep in mind that this is only referring to bare wire, exposed junction, unsheathed fine gage thermocouples. There are methods available to implement thermocouples as small as 25 µm or smaller if there is structural support to the thermocouple, such as micro-spring or hypodermic tubing support.

Lastly, a parameter that may affect the flame is the boundary condition of the immediate surroundings. Under a quiescent environment, there shouldn’t be any flow
disturbance to the flame. Notice the temperature measurements in Figure 3.10, after the 30 second mark, there are a lot of fluctuations downstream of the flame. This may be due to draft or entrainment of air from the HVAC system of the laboratory surroundings. To study this effect, the flame stabilizer apparatus is covered on its four sides with curtains, leaving only a small opening area on the top for air to infiltrate and escape. Temperature measurements at $y = 3$ mm of a moving flame with the enclosure and without the enclosure are shown in Figure 3.11. There isn’t much of a difference in peak temperature and variations downstream. The boundary condition is therefore very similar with or without the enclosure.

### 3.3 CO$_2$ Measurement

The CO$_2$ sensor relies on the micro air pump to transport a gas into the sampling chamber where the optical system measures CO$_2$ concentration. The introduction of force induction disrupts the natural flow field and therefore the effect it has on a flame is investigated. As indicated earlier, heat loss in the pre-heating zone plays a significant role in affecting the spread rate. To reduce heat loss, a ceramic tube and a hypodermic stainless steel tube are used as alternative probes to draw gas from the flame to the sensor. The ceramic
Figure 3.11. Temperature measurement with and without an enclosure.

tube has an inner diameter of 1.8 mm and the stainless steel tube 0.686 mm. Figure 3.12 displays the two probes in the flame field during the measurement process. While the stainless steel tube occupies fewer footprints in the flame field, however it heats up much faster than the ceramic tube. The flow rate also decreases as the flow is choked from a smaller suction area. This affects accurate CO$_2$ measurement as will be discussed in the following paragraph.

Figure 3.12. (a) Ceramic tube, and (b) hypodermic stainless steel tube.
Various flow rates are explored to observe the effect it has on CO$_2$ measurement. A PVC ball valve is installed between the air pump and the CO$_2$ sensor to regulate the flow rate. Figure 3.13 displays CO$_2$ measurements at various pumping rates from a moving flame. The ceramic tube is used in these experiments at a distance of 1 mm from the surface of the fuel. Three experiments were performed at each flow rate and the average is shown on the plot. The legend on the plot indicates the approximate orifice opening of the valve. The peak CO$_2$ mole fraction in percentage is measured as 8% when the valve is fully open and 6% when the valve is estimated to be one sixteenth open. Similarly, the same pattern is observed when the hypodermic stainless steel tube is implemented. Figure 3.14 shows CO$_2$ measurements of the hypodermic stainless steel tube compare to the ceramic tube. The measurements were performed with a stabilized flame. The probe position is 1 mm from the fuel surface and 15 mm downstream of the leading edge of the flame, similar to the position shown in Figure 3.12 (a). The average CO$_2$ mole fraction measured from the ceramic tube is 9.3% and 7.5% from the hypodermic stainless steel tube. It is therefore important that sufficient sampling gas is provided to the sensor chamber to ensure accurate measurements.

From a pump curve provided by the air pump’s OEM and the CO$_2$ sensor specifications, sufficient flow rate is estimated to be 0.2 L/min.

![Graph](Moving Flame; y = 1 mm; Variable Pumping Rate)

**Figure 3.13. CO$_2$ measurements from a moving flame at various pumping rates.**
3.4 FLAME FIELD MEASUREMENTS

A grid structure as shown in Figure 3.15 is implemented as a mapping field to the visible flame structure. The flame is from the side view of Whatman Grade 1 cellulose filter paper. The size of the flame is about 8 cm wide and 13 cm tall as indicated by the grid structure. Temperature and CO$_2$ measurements are taken at every grid point to create the thermal and species fields. Each grid point where the lines intersect is 1 mm away from the next horizontal or vertical grid point. For simplicity the flame is rendered to be symmetric and two dimensional. The position of each grid point is referenced to the leading edge of the flame, indicated by the green point as (0, 0) on Figure 3.15. Since the flame is considered to be symmetric, measurements are only made on one side of the flame. The vertical direction, upstream and downstream of the flame, is called the x-axis. The horizontal direction, along the side width of the flame, is called the y-axis. The nomenclature for a grid point is then called YnumericXnumeric. For instance, the red point on Figure 3.15 is referred as y2x5 as it is 2 millimeter in the y-axis and 5 millimeter in the x-axis. Although the grid field only extends to 5 millimeter in the y-axis and 15 millimeter in the x-axis, the actual grid structure of the flame field to be measured is much larger.

Following the nomenclature discussed above, Figure 3.16 shows temperature measurement of a stabilized flame at y2x5. The green dot in the flame indicates the point of
Figure 3.15. Visible flame side view of Whatman 180 µm cellulose.

Figure 3.16. Stabilized flame temperature measurement at y2x5.
measurement. Three experimental runs are performed at this point and the temperatures are recorded as 1190 °C, 1115 °C, and 1142 °C, with standard deviations of 24 °C, 53 °C, and 36 °C. The CO₂ measurement at the same location is shown in Figure 3.17. The average CO₂ reading at this location is 14.2 %, with a standard deviation of 1.13 %. It should be noted that the average CO₂ reported is only during the interval from 50 second to 150 second. Notice that it takes a very little amount of time for the thermocouple to respond. While it takes 20 to 30 second for the CO₂ sensor to respond to the average reading during the gas induction expulsion process. This is due to the time it takes to expel the atmospheric air out of the plastic tubes and sampling chamber; and the time it takes to transport the sampling gas containing CO₂ into the chamber. The same amount of time is also necessary to expel the sampling gas out of the entire system to bring atmospheric air back into the chamber. It should be reminded that the sampling rate of the CO₂ sensor is 0.5 Hz, six times slower than the thermocouple’s sampling rate of 3 Hz. There also isn’t a transport time for thermocouple measurement.

![Graph](image)

**Figure 3.17.** Stabilized flame CO₂ measurement at y2x5.

While these experiments consisted of more than 100 second of data, it is usually more than sufficient if the measurement becomes steady. However if there is fluctuation in measurement more data points are necessary to determine an accurate average. This is
demonstrated in Figure 3.18 where the temperature is measured at \( y=5x=5 \). There are noticeable fluctuations in all three experimental runs at this particular location. The average temperatures for the three runs are 171 °C, 316 °C, and 293 °C, with standard deviations of 55 °C, 136 °C, and 85 °C. Likewise, measurements further downstream of the flame in the x-axis require more data points to acquire an accurate average. Near the surface of the fuel where the flame is very steady however, temperature becomes very steady. This is demonstrated in Figure 3.19 where temperature is measured at the front edge of the flame, \( y=1x=0 \). The temperatures of three experimental runs are 739 °C, 736 °C, and 746 °C, with standard deviations of 12 °C, 18 °C, and 18 °C. CO\(_2\) measurements also show the same trend of fluctuations and steadiness as temperature measurements. Figure 3.20 shows a CO\(_2\) signal at \( y=3x=20 \). The average mole fraction of CO\(_2\) is 2.32 %, with a standard deviation of 0.64 %.

It should be mention that measurements near the flame at \( y=0 \) mm, could not be made due to interference with the fuel surface. After burnout however, at \( x=15 \) mm, the fuel surface does not pose as problem. For the flame structure to be determined, measurements at the fuel surface, \( y=0 \) mm will not be included as it would be incomplete. The stabilized temperature and CO\(_2\) fields are therefore measured at every grid point from \( y=1 \) mm to \( y=5 \) mm, and \( x=-5 \) mm upstream to \( x=25 \) mm downstream.
Figure 3.19. Stabilized flame temperature measurement at y1x0.

Figure 3.20. Stabilized flame CO$_2$ measurement at y3x20.
CHAPTER 4

RESULTS

This chapter discusses experimental results of temperature and CO\textsubscript{2} fields. The results are shown as data points and converted to 2-D contour images. It should be noted that not all fields are comparable. Some fields have different scales and lengths. Section 4.1 to Section 4.4 discusses cellulose data and Section 4.5 discusses PMMA data. Section 4.1 contains temperature fields of stabilized flames and moving flames. Section 4.2 contains CO\textsubscript{2} fields of stabilized flames and moving flames. Section 4.3 compares the result from stabilized flame fields to moving flame fields on the same scale. Section 4.4 compares normalized temperature to CO\textsubscript{2} concentration downstream of stabilized flames.

Section 4.5 discusses temperature and CO\textsubscript{2} fields from moving PMMA flames. Additionally PMMA spread rates and images from normal gravity and microgravity are compared. Normal gravity experiments are performed on the Flame Stabilizer at SDSU. Microgravity experiments are performed in the Zero Gravity Research Facility at NASA Glenn Research Center in Cleveland, Ohio. Normal gravity experiments are performed under 21\% O\textsubscript{2} and microgravity experiments are performed under 21\% and 30\% O\textsubscript{2}. Immense gratitude is expressed to Dr Sandra Olson at NASA GRC for performing the microgravity experiments.

4.1 TEMPERATURE FIELD

Temperature measurements at every grid position from the grid structure are compiled to create a thermal temperature field. The average temperature of each grid position is shown in Figure 4.1. Three separate experiments are performed at each grid position with each experiment consists of twenty data points. Thus each data point on the graph is the average of sixty data points from three experiments. The nomenclature used here is as followed: for a downward moving flame, upstream is below the leading edge, in the direction the flame is moving toward; downstream is in the direction of the buoyant flow, toward the tail of the flame; upstream is considered negative and downstream is positive in the vertical direction; the x-axis moves along the vertical direction upstream and downstream of the
Figure 4.1. Stabilized flame temperature field #1 measurement.

flame with x = 0 mm being the leading edge; the y-axis moves along the horizontal direction with y = 0 mm being the fuel surface.

Referring to Figure 4.1, temperature in the upstream region beginning at y = −5 mm is very close to room temperature, until y = −3 mm where temperature begins to rise. Temperatures from y = 1 mm to y = 5 mm at x = 0 mm (flame leading edge) are 769 ºC, 591 ºC, 269 ºC, 103 ºC, and 57 ºC, respectively. From x = 2 mm to x = 7 mm downstream, temperature peaked at y = 1 mm and y = 2 mm in the range of 1000 ºC. Even though there’s a crossover, the difference is not exceeding 50 ºC. Going further downstream of the flame at x = 20 mm to 25 mm, temperature decreases to the range of 300 ºC to 400 ºC in the region close to the fuel surface and less than 100 ºC away from the fuel surface.

The data in Figure 4.1 is converted into contour plots as shown in Figure 4.2. The contour images are rotated by 90 degree counterclockwise. The y-axis starts at y = 1 mm since there isn’t any measurement at the fuel surface. The x-axis is reversed starting with x = −5 mm upstream on the right and moves left to x = 25 mm downstream. The temperature scale is shown on the right ranging from dark blue to maroon. The darkest blue is room temperature at 21 ºC and the darkest maroon is the highest flame temperature. Figure 4.2 (a)
Figure 4.2. Contour images of stabilized flame temperature field #1.

is a surface contour with very fine details. Figure 4.2 (b) consists of five contour lines with each representing the corresponding temperature value on the scale, maroon is 1000 °C, orange is 800 °C, and so on. Figure 4.2 (c) displays ten thermal regimes with the hottest regime starting from x = 2 mm to 7 mm at y = 1 mm and 2 mm, as correspond to data shown in Figure 4.1. A second stabilized flame temperature field is compiled to show repeatability. The temperature data is shown in Figure 4.3 and the contour plots are shown in Figure 4.4. The result from temperature field #2 is very similar to temperature field #1.

It would certainly be incomplete if a moving flame temperature field isn’t compiled for comparison. For a moving flame temperature field, the thermocouple remains stationary and it records the flame temperature as the flame passes by. The position of the thermocouple in the moving flame is determined by matching the temperature at the flame leading edge, x = 0 mm of the stabilized flame to the corresponding temperature of the moving flame as x = 0 mm. The temperature data for moving flame field #1 is shown in Figure 4.5. The contour images of moving flame field #1 are shown in Figure 4.6. A second moving flame field is compiled with the data shown in Figure 4.7 and the contour images in Figure 4.8. The contour images are rotated by 90 degree counterclockwise.
Figure 4.3. Stabilized flame temperature field #2 measurement.

Figure 4.4. Contour images of stabilized flame temperature field #2.
Figure 4.5. Moving flame temperature field #1 measurement.

Figure 4.6. Contour images of moving flame temperature field #1.
Figure 4.7. Moving flame temperature field #2 measurement.

Figure 4.8. Contour images of moving flame temperature field #2.
One apparent difference between the stabilized and moving flame temperature fields is the temperature range. The peak temperature in the moving flame is in the range of 1200 °C, a noticeable difference of 200 °C higher than the stabilized flame’s. In Figure 4.6 (b) and Figure 4.8 (b), there are six contour lines with the maroon lines correspond to 1200 °C, the red lines correspond to 1000 °C, and so on. The peak temperature occurs in the area of y = 1 mm and x = 3 to 7 mm, similar to the stabilized flame’s. Because of higher peak temperature, the thermocouple experienced thermal expansion in the hottest region of the flame. This is evidenced by the slight signal delay seen in Figure 4.5 and Figure 4.7 at y = 1 mm as the flame passes x = 0 mm. Going further downstream, there is significant turbulence as the data points cross one another. Referring to the contour images, there are minor fluctuations upstream to the middle of the flame, and going downstream there are a lot of unsteadiness. Comparing the contour images of the stabilized flame to the moving flame, there is significant improvement of the overall temperature field. The contour lines of the stabilized flame are smooth and the boundary of each temperature regime is well defined. In the moving flame contour images there are some variations from upstream to the middle of the flame, moving further downstream there are hot and cold pockets of gas throughout.

### 4.2 CO₂ Field

A stabilized CO₂ field is compiled in the same manners as the temperature field. Measurement is made at every grid position of the grid structure and the average CO₂ recorded is shown in Figure 4.9. Each CO₂ data point on the plot is the average of sixty data points from one experimental run. The upstream CO₂ readings starting at x = −5 mm are atmospheric level at 0.04 % or 400 ppm. Approaching the flame CO₂ begins to increase and at x = 0 mm (front edge of the flame) CO₂ rises to 8.29 %, 8.17 %, 6.22 %, 4.14 %, and 1.77 % at y = 1 mm to 5 mm, respectively. Between x = 0 mm to 5 mm the peak CO₂ readings are recorded, with a maximum of 17 % at y = 1 mm and x = 4 mm. CO₂ concentration remains high downstream until x = 20 mm where it begins to decrease.

The stabilized flame CO₂ field data is converted into contour images as shown in Figure 4.10. The color scale indicates CO₂ concentration from 0 to 17 %; while 15 % is shown it is not the peak of the scale. The x-axis moves from right to left starting from x = −5 mm upstream and ends at x = 25 mm downstream. The y-axis starts from 1 mm and ends at 5
Figure 4.9. Stabilized flame CO\textsubscript{2} field measurement.

Figure 4.10. Contour images of stabilized flame CO\textsubscript{2} field.
mm from fuel surface. The surface contour plot in Figure 4.10 (a) shows significant CO₂ presence not only in the region near the flame but also downstream. Figure 4.10 (b) displays five contour lines with each represents a CO₂ value, starting from the blue contour line to the red contour line, the CO₂ mole fractions are 3, 6, 9, 12, and 15 %. Figure 4.10 (c) is consisted of ten regimes with CO₂ concentration decreasing as the regimes move outward. Each regime is well defined as there is no crossover downstream. There is however some undulation at the leading edge of the flame from x = 0 mm to 3 mm. This effect is due to flow disturbance from the air pump at the leading edge of the flame that causes instability to the flame tracking process. However it only occurs at the flame leading edge near the tracking thermocouple. Away from the tracking thermocouple there seems to be no apparent effect. The CO₂ fields presented are the first to be experimentally measured as far as moving flames over solid fuels are concerned.

A moving flame CO₂ field is compiled for comparison. The CO₂ data is shown in Figure 4.11 and the contour images in Figure 4.12. One very important parameter to point out is the length of the x-axis. It starts from x = −10 mm and ends at x = 100 mm instead of x = −5 mm to 25 mm. The x-axis is elongated to compensate for the delayed time from transporting the gas to the sampling chamber, and a low sampling rate of the sensor. As previously demonstrated in Section 3.4, it takes 20 to 30 second for the air pump to transport sufficient sampling gas to the sensor chamber for an accurate measurement. This delay causes a decrease in CO₂ reading seen on Figure 4.11, where the maximum recorded CO₂ is only 8 % at y = 1 mm. It should also be noted that the color scale on the moving flame contour images only measures up to 10 %, which is not comparable to the stabilized flame contour images where the scale measures up to 17 %. The axes ratio also isn’t the same due to the elongation of the x-axis on the moving flame. The x-axis to y-axis scale ratio for the stabilized flame is 1:1 whereas on the moving flame it is 5:1. This ratio is seen in Figure 4.12 (a) where a surface contour image of CO₂ concentration is shown. Figure 4.12 (b) consists of four contour lines with CO₂ values of 2, 4, 6, and 8 correspond to blue, cyan, yellow, and orange. Figure 4.12 (c) displays ten regimes of CO₂ concentration. Despite the axis elongation and lower CO₂ concentration, the signal from the moving flame deems to be somewhat useful.
Figure 4.11. Moving flame CO\textsubscript{2} field measurement.

Figure 4.12. Contour images of stabilized flame CO\textsubscript{2} field.
4.3 Fields Comparison

The comparison of moving flame fields to stabilized flame fields are shown in this section. Figure 4.13 shows the comparison of a stabilized flame temperature field to a moving flame temperature field. The color scale is the same in both contour images. Notice the higher temperature regimes in the moving flame. Figure 4.14 compares a stabilized CO$_2$ field to a moving CO$_2$ field. The color scale is from 0 % to 17 %. Notice the elongated x-axis and lower CO$_2$ concentration in the moving flame field.

Figure 4.13. (a) Stabilized temperature field, (b) moving temperature field.

Figure 4.14. (a) Stabilized CO$_2$ field, (b) moving CO$_2$ field.

The primary interest of this thesis is shown in Figure 4.15. The images are shown in the upright position, starting with the visible flame image in (a), stabilized temperature field in (b), and stabilized CO$_2$ field in (c). The visible flame image is obtained from 180 µm cellulose from the side profile. The dimensions of the visible flame image are $y = 0$ mm to 5 mm and $x = -5$ mm to 25 mm, and the contour images are $y = 1$ mm to 5 mm and $x = -5$ mm to 30 mm.
Figure 4.15. (a) Visible flame, (b) temperature field, (c) CO$_2$ field.
While there is significant improvement in term of steadiness in the stabilized fields over the moving fields, it doesn't state whether the flame is laminar or turbulent. As briefly discussed in Section 3.4 in Figure 3.18 and Figure 3.19, some part of the flame is laminar and some part turbulent. To determine where the flame is laminar and where it is turbulent, the temperature standard deviation at every grid point is divided by the average localized temperature to yield a turbulence intensity signal. The result is shown in Figure 4.16 comparing the flame temperature field to the turbulence intensity signal. The conclusion is that the flame is laminar inside of the flame and turbulent outside of the flame. The boundary could be drawn on the 800 K contour. The underlying reason could be that the gas field inside the 800 K regime is very viscous and therefore laminar. Outside this regime the gas becomes less viscous and therefore more turbulence. The same comparison is made for the CO₂ fields shown in Figure 4.17. The same conclusion is arrived here.

Figure 4.16. (a) Temperature field, (b) temperature turbulence intensity field.

Figure 4.17. (a) CO₂ field, (b) CO₂ turbulence intensity field.
4.4 Temperature vs. CO₂ Concentration

One particular comparison worth addressing is the strength of the temperature signal and the CO₂ concentration. For a direct comparison to be made however, a baseline must be established to normalize the two signals on the same scale. The temperature signal is normalized to the adiabatic flame temperature and the CO₂ concentration is normalized to the peak CO₂ mole fraction in an equilibrium reaction. The values for adiabatic flame temperature and peak CO₂ mole fraction are obtained from TEST RIA, an online thermodynamics calculator developed by Bhattacharjee [54]. The combustion process is modeled as an equilibrium reaction with gas phase cellulose (C₆H₁₀O₅) and air. The equilibrium reaction yields an array of species that include many minor species such as OH, CO, NOₓ, CN, and etcetera. The dominant byproducts however, are CO₂ and H₂O. The equilibrium CO₂ mole fraction in this process is calculated as 16.3 % and the adiabatic flame temperature is calculated as 1943 ºC.

The temperature and CO₂ signals are converted to dimensionless quantities for a direct comparison. The dimensionless temperature conversion is \( \theta = (T - T_{\infty})/(T_{\text{eq}} - T_{\infty}) \), where \( T \) is the measured temperature, \( T_{\infty} \) is the atmospheric temperature, and \( T_{\text{eq}} \) is the equilibrium adiabatic flame temperature. The dimensionless CO₂ conversion is \( \eta = (\text{CO}_2 - \text{CO}_2,\infty)/(\text{CO}_2,\text{eq} - \text{CO}_2,\infty) \), where CO₂ is the measured mole fraction, CO₂,∞ is the atmospheric mole fraction, and CO₂,eq is the equilibrium mole fraction.

For a maximum measured temperature of 1337 ºC and a maximum measured CO₂ of 17 %, maximum \( \theta \) is 0.68 and maximum \( \eta \) is 1. The discrepancy between the two signals was briefly discussed in Section 3.2. A thermocouple emits more radiation loss at high temperature while CO₂ concentration doesn’t dissociate until very high temperature. While there is a large discrepancy near the hottest regime of the flame, it may not be so in the lower temperature regimes. To verify this hypothesis the following experiment is performed. Temperature and CO₂ measurements are made downstream at the centerline (\( y = 0 \) mm) of a stabilized flame. The two signals are normalized to dimensionless \( \theta \) and \( \eta \) for comparison. Figure 4.18 shows the temperature measurement downstream from \( x = 15 \) mm to 250 mm at \( y = 0 \) mm. Figure 4.19 shows the same measurements for CO₂ concentration. Each data point is an average of 60 seconds. The comparison is made in Figure 4.20 in dimensionless values. There appears to be considerable agreement between \( \theta \) and \( \eta \) downstream of the flame.
Figure 4.18. Downstream temperature measurements.

Figure 4.19. Downstream CO₂ measurements.
4.5 PMMA FIELD

All results discussed so far are from Whatman 1 cellulose. This section investigates preliminary data for a thermoplastic acrylic fuel called PMMA, short for poly(methyl methacrylate). Only a moving flame field and a moving CO$_2$ field will be discussed in this work. The underlying reason is there are some difficulties to stabilize a PMMA flame. PMMA acrylic fuel is prone to dripping and falling droplet which makes the thermocouple tracking process difficult. The PID control algorithm also needs to be refined to track a PMMA flame since the flame front is different than cellulose.

The average spread rate of four experiments from a moving PMMA flame at a thickness of 75 µm was determined to be 4.5 mm/s by Spotlight analysis. Visible images of PMMA flames are shown in Figure 4.21. The flame profile from the side is shown in Figure 4.21 (a). While it may appear as though the flame has significant height, the actual flame height is much shorter when viewed from the top view as seen in Figure 4.21 (b, c). The actual flame height can be deduced to only the height of the blue flame; the much larger yellow flame is the result of melting and incomplete combustion on the side edges. This phenomenon can be seen in Figure 4.21 (c), where the edges are still burning even though the
leading edge of the flame has already passed. Melting of the fuel, which is part of the pyrolysis process, is observable in all three images.

Temperature measurements are made with a K-type thermocouple that has a wire diameter of 75 µm and oriented in the parallel direction. The temperature contour images of a PMMA flame are shown in Figure 4.22. The hottest region of the flame is between $x = 4$ mm and $10$ mm, with a peak temperature of 1166 °C. The flame appears to be elongated which is probably a result of a fast spread rate and an insufficient thermocouple sampling rate. Similar to a moving cellulose flame, there are more variations downstream. CO₂ contour images of a PMMA flame are shown in Figure 4.23. Notice that the axes are not on the same scale. For the same reason as the moving cellulose flame CO₂ fields, the axes ratio is 5:1 with the x-axis starting from $x = -10$ mm and ends at $x = 100$ mm. Peak CO₂ concentration is 4.5 % which occurs at $y = 1$ mm. The contour lines are a little smoother on the CO₂ contours compare to the temperature contours.

A comparison of PMMA flames in normal gravity and microgravity is also observed. The microgravity experiments are performed at NASA Glenn Research Center 5.2 Second Drop Tower. The free fall distance is 132 m with a gravitational acceleration of less than 0.00001g. Experiments are performed inside a chamber with an ambient pressure of 14.7 psi and oxygen levels of 21 % and 30 %. Fuel thickness under consideration is 50 µm and fuel
Figure 4.22. Moving PMMA flame temperature contour images.

Figure 4.23. Moving PMMA flame CO$_2$ contour images.
width is 5 cm. Flame spreads downward in a quiescent environment during free fall. A camera captures video on the top and side view. Spread rate is found with Spotlight tracking the burnout location.

The spread rate of PMMA under a 21% O₂ environment is shown in Figure 4.24. Before the drop occurs there is a few seconds of normal gravity flame spread. The spreading process is semi-steady in both regimes up to the point of extinction. The slope of the line indicates spread rate in mm/s. For the normal gravity flame, the spread rate is 4.64 mm/s. For the microgravity flame, the spread rate is 2.51 mm/s, nearly half of the normal gravity flame. Extinction occurs before the drop ends, indicating the thermally thick regime has been reach under the specified microgravity atmospheric condition. Even though the microgravity flame is spreading, it appears to be dying during the drop before extinction.

![Figure 4.24. Spread rate of PMMA under normal gravity and microgravity.](image)

The spread rate result under a 30% O₂ environment is shown in Figure 4.25. Spread rate under the richer oxygen environment is 4.89 mm/s, nearly doubled from the 21% O₂ environment. Notice the luminance difference between the flames. Under a 21% O₂ environment, normal gravity presents a small blue steady flame, microgravity presents a very dim blue flame but much larger in size. The larger but very dim flame may signify that
radiative loss becomes significant in the microgravity regime, which may have been the driven mechanism for extinction. Under a 30 % O$_2$ environment the flame size greatly increases however there is much more soot in the flame.

Besides the apparent size difference of a microgravity flame to a normal gravity flame, the flame structure may also be quite different. To test this hypothesis, temperature profiles at y = 2 mm from the fuel surface are measured for a normal gravity and a microgravity flame. The results are shown in Figure 4.26. The x-axis refers to the downstream position of the flame, x = 0 mm being the leading edge of the flame. The temperature profile of the microgravity experiment is measured with a 50 µm bare wire K-type thermocouple, and the normal gravity experiment with a 75 µm bare wire K-type thermocouple. Referring to the normal gravity flame image in Figure 4.24, the height of the flame is approximately 7-10 mm, and the microgravity flame in Figure 4.25, the height is approximately 20-30 mm. Referring to Figure 4.26, the temperature profile of the normal gravity flame starts at room temperature and rises above 800 ºC as the flame leading edge reaches the thermocouple. From 0 to 7 mm the peak temperature is reached and flame temperature begins to decrease after 7 mm, where the thermocouple is downstream of the flame. The microgravity temperature profile however, shows a different pattern. As the flame
leading edge approaches the thermocouple, temperature rises similarly to the normal gravity flame. Moving downstream of the flame leading edge however, temperature decreases from 0 to 4 mm and increases from 4 to 8 mm before reaching steady from 8 to 22 mm. A slight drop in temperature can be observed at 23 mm before drop impact.

The temperature drop between 0 to 4 mm is hypothesized as a large standoff distance of a microgravity flame. The standoff distance is the distance from the fuel surface to the flame leading edge, where the flame is quenched and thus does not make contact with the fuel surface. This standoff distance can even be slightly observed under normal gravity in a cellulose flame as shown in Figure 4.15 (a), between 0 and 5 mm, and a PMMA flame in Figure 4.21 (a). However those standoff distances are far too small to cause a temperature drop under normal gravity. For a microgravity flame however, the standoff distance can be observed as shown in Figure 4.27 (a). The scale shown is in cm; the flame height and width are approximately 30 mm and 25 cm. As indicated by the temperature profile in Figure 4.26, temperature decreases at the leading edge standoff distance shown in Figure 4.27 (a), and temperature increases moving forward of the standoff distance. While the images shown in Figure 4.21 (a) and Figure 4.27 (a) are not so clear-cut, numerical simulations have shown similar results of the presence of a standoff distance. Patel [55] simulates flame spread over
thin PMMA in a normal gravity environment and Nagarkar [56] simulates similar PMMA flame spread studies in a microgravity environment. Their results show that a small standoff distance is noticeable in normal gravity flames and a much larger standoff distance in microgravity flames. Evidently, the simulated microgravity flames are also much larger than the normal gravity flames, as observed experimentally. The simulated flame sizes are also comparable to the experimental flames.

Figure 4.27. (a) Side view, and (b) top view of a microgravity PMMA flame.
CHAPTER 5

RADIATION EFFECT ON SPREAD RATE

While the main purpose of this thesis is the flame structure, spread rate should be taken into consideration when moving flames over solid thin fuels are concerned. There are many known factors that affect spread rate. How exactly these factors affect spread rate are still being investigated. Some important parameters include fuel type, fuel thickness, oxygen level, pressure level, and oxidizer velocity, just to name a few. These parameters will remain constant in this study. The effect of radiation on spread rate will be explored as the flame size changes. To achieve different flame sizes, the width of the fuel and the direction of flame spread with respect to gravity will be varied.

5.1 EXPERIMENTAL SETUP

Figure 5.1 shows the experimental setup of this study. The fuel being utilized is Whatman Grade 1 filter paper with an area density of 88 g/m$^2$ and a thickness of 180 µm. Three sample holders are implemented, each with a separate fuel width of 1 cm, 2 cm, and 3 cm. Each sample holder is composed of two sheets 22-gauge 302 stainless steel and a length of 45 cm. The fuel sample is inserted between the sample holders and held together by neodymium magnets. The supporting structure is a platform attached to an aluminum column and a steel bar. The sample holder is held to the steel bar by magnets and rests against the aluminum column. The sample holder has the ability to rotate as seen in Figure 5.1 (a, b). This allows the sample holder to tilt when the steel bar is translated and the aluminum column provides resting support. This setup enables the sample to fully rotate from vertical to horizontal in the x-y plane. The sample is also able to rotate in the y-z plane by 90º to create an asymmetric flame as seen in Figure 5.1 (c). The angle of the sample holder is determined by a protractor. Ignition is achieved by a butane lighter. A Nikon dSLR camera records the flame propagation video and the spread rate is found by Spotlight processing as described in Section 2.4.
5.2 EXPERIMENTAL APPROACH

The base case is a downward moving flame. This is considered to be opposed flame spread since buoyancy driven by gravity is moving in the direction opposite to flame spread. Follow the same logic, flame spread is considered to be opposed as the fuel angle changes from vertical to horizontal. As the flame spread direction goes beyond horizontal it is considered to be concurrent when the flame is spreading upward. Upward flame spread is difficult to study since the flame rapidly increases in size and becomes unsteady. Buoyancy is in the same direction as flame spread and therefore spread rate rapidly increases. Nonetheless, opposed and concurrent flame spreads are investigated in this experiment.

The first downward moving flame to be considered is in the vertical orientation. The fuel orientation is 0° with respect to the positive vertical direction. The angle of the sample holder is then rotated by an increment of 10° with each following experiment. Once the sample holder angle reaches 100° ignition starts at the lower bottom edge to initiate an upward moving flame. This rotation continues until flame spread is vertically upward. Once the process is completed for symmetrical flame spread it is repeated for asymmetrical flame spread. The data is processed in Spotlight and plotted as position vs. time. A 100°
symmetrical upward spreading flame is shown in Figure 5.2. The slope of the line indicates the spread rate, 2.30 mm/s in this case. $R^2$ is the coefficient of determination; a value close to unity indicates spread rate was very steady. An image of the flame during the spread rate process is shown in the lower right corner. The width of the fuel is 3 cm.

![Graph showing spread rate and flame image](image)

**Figure 5.2. Spread rate and image of a 100° symmetrical upward spreading flame.**

One hypothesis investigated in this work is the radiation effect on flame spread rate. A larger flame increases the radiation view factor to the virgin fuel, which may increase the heat transfer to the pre-heating zone. Hence the reaction rate may increase which could lead to a faster spread rate. While the change of angle may provide a glimpse of the effect of radiation on spread rate, it is not clear-cut since there are other factors affecting the spread rate. Although the width of the fuel remains the same, the flow field is altered as the angle changes. The flame may grow in size and spread rate may increase, however that may be the result of heat transfer enhanced by convection. To truly observe the effect of radiation on spread rate, the flow field should remain the same. To test this hypothesis, three different fuel widths of 1 cm, 2 cm, and 3 cm are implemented, and three different flame spread orientations are observed: symmetrical vertically downward, symmetrical horizontally, and
asymmetrical horizontally. The wider fuels should produce larger flames and therefore theoretically should produce higher spread rates.

5.3 Experimental Result

The spread rates of symmetrical and asymmetrical flame from vertically downward to upward are shown in Figure 5.3. The fuel width is 3 cm for all experiments. Spread rate remains relatively similar from 0° to 80° downward flames spread. From 90° to upward flame spread however, a small difference is noticeable and the difference grows as the angle increases. The gap closes at vertically upward flame spread, which is fundamentally sound since the two cases are the same. Higher asymmetrical flame spread rates in the upward flame spread regime can be deduced to two factors, higher radiation view factors and enhanced convection. Flame shapes at various fuel angles for symmetric and asymmetric flames are shown in Figure 5.4. Notice larger flames in the upward asymmetric configurations between 90° and 180°, which may contribute to higher radiation view factors. However, it is difficult to pinpoint as radiation effect since the buoyant flow is directly projected onto the bottom fuel surface on the asymmetric configurations. For a symmetric configuration the flow direction is parallel to the fuel surface on both sides but not so for an asymmetric configuration.

![Symmetric and Asymmetric Flame Spread; 3 cm fuel width](image)

**Figure 5.3.** Symmetrical and asymmetrical flame spread comparison.
Figure 5.4. Flame shapes vs. fuel angles, (a) symmetrical, (b) asymmetrical.
Spread rate of different fuel width of 1 cm, 2 cm and 3 cm for vertically downward moving flames are shown in Figure 5.5. Consider the 0° case where the flame size remains relatively small, spread rate slightly increases as the fuel width increases from 1 cm to 2 cm. Moving on to 90° symmetrical flame where flame size is slightly larger, spread rate gradually increases as fuel width increases. Further on to the 90° asymmetrical orientation, spread rate significantly increases as flame size grows rapidly when the fuel width increases from 1 cm to 2 cm and 3 cm. Notice the change in spread rate at the same fuel width as the fuel orientation changes. To further validate the radiation view factor effect on spread rate, the addition of a curvature to a fuel is implemented without changing the width of the sample holder. Refer to Figure 5.6 for the demonstration of this method. The width of the sample holder remains as 3 cm in all three cases. In Figure 5.6 (b) and (c) however, there is 4 cm and 5 cm width of fuel, respectively. These configurations increase the view factor as more fuel is added. The spread rates were found to be 1.70 mm/s, 1.93 mm/s, and 2.10 mm/s at total fuel widths of 3 cm, 4 cm, and 5 cm, respectively.

![Figure 5.5. Spread rate with different fuel widths.](image)

Further supporting evidence comes from PMMA, where soot and PAH are more dominant in PMMA combustion than cellulose combustion. The results show similar
patterns, spread rate increases as fuel width increases. For 50 µm PMMA with fuel widths of 2 cm, 3 cm, and 5 cm, spread rates were measured as 4.29 mm/s, 5.16 mm/s and 6.03 mm/s, respectively. For 75 µm PMMA with fuel widths of 2 cm, 3 cm, and 5 cm, spread rates were measured as 3.11 mm/s, 3.83 mm/s, and 4.78 mm/s, respectively. It becomes conclusive at this point to state that as fuel width increases, radiation view factor increases, and spread rate therefore increases.
CHAPTER 6

CONCLUSIONS

An experimental apparatus named the Flame Stabilizer has been built to study small scale flame structures. The solid fuels under investigation in this experiment are Whatman 1 cellulose filter paper and thermoplastic acrylic PMMA. A PID control algorithm is implemented to stabilize a flame via a motor and a linear actuator system. The flame structural fields found in this experiment are temperature and CO\textsubscript{2}. A J-type thermocouple was tested however it melted under high heat. Temperature measurement is made with K-type thermocouples. Various thermocouple wire diameter and configuration are explored to optimize the temperature measurement process. CO\textsubscript{2} measurement is made with a non-dispersive infrared radiation (NDIR) sensor with force induction. Measurements are performed on moving flames and stabilized flames. There is considerable improvement in the stabilized flame fields compare to the moving flame fields.

Experimenting with thermocouple configurations unveiled that heat loss in various forms that affect accurate temperature measurement. Heat loss to convection is omnipresent where there is a flow field. Heat loss through conduction can be reduced if the gradient along the thermocouple wire is minimized. Heat loss through radiation could also be reduced if the surface area of a thermocouple is reduced. The latter two factors are implemented to achieve a peak temperature of 1337 °C. At this temperature the upper threshold of K-type thermocouple is reached, however it is still significantly below the calculated adiabatic flame temperature. It is recommended to implement platinum (S-type or R-type) or tungsten based thermocouples. A future investigation on the flow field would be very useful on top of the temperature and CO\textsubscript{2} fields. While non-intrusive optical methods are ideal, precise position measurements on a small flame is a challenge. Optical instruments measure an entire path length through a volume, whereas a small probe has the ability to pinpoint an exact location.

An investigation on spread rate was also explored. It was found that radiation view factor has a considerable impact on spread rate. This hypothesis was tested by changing the fuel width to create a larger flame while maintaining the same spread direction.
REFERENCES


APPENDIX A

JOURNAL AND CONFERENCE PAPERS
A Novel Apparatus for Flame Spread Study

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Abstract

One of the challenges in the experimental study of flame spread is that, even if the flame spreads at a steady rate, the propagating flame creates an unsteady phenomenon with respect to the laboratory frame of reference. As a result, only a few studies have been done where the detailed flame structure has been experimentally measured along with the spread rates. In this work, we demonstrate the feasibility of a new flame spread apparatus that moves the fuel in the opposite direction of the flame so as to keep the leading edge of the flame stationary with respect to the laboratory. A thermocouple, fixed to the laboratory frame of reference, in front of the leading edge of the flame, senses the presence of the flame and a PID controller keeps the set point temperature constant by moving the sample holder, driven by a stepper motor, in the opposite direction at the velocity of the spread. Unlike conventional studies, this apparatus, called the flame stabilizer, produces real time spread rate with a time resolution of 0.3 s. In this paper, instantaneous flame spread rate and the visible flame structure are compared between a downward spreading flame and the corresponding stabilized flame for spread over ashless filter paper. The results indicate that the difference between the two configurations are within experimental uncertainties and the stabilized flame can represent a spreading flame adequately, including variability of flame spread rate and the flame geometry, for further observations.

Keywords: flame-spread, flame spread rate measurements, PID control, flame shape, downward flame spread, thermally thin fuel, stabilized flame
Nomenclature

**K**  Proportional gain coefficient

**k**  Loop index

**L**  Travel length by the sample, m

**P**  Number of pixels per mm

**T**  Temperature, K

**t**  Time, s

**t_d**  Derivative time coefficient, s

**t_i**  Integral time coefficient

**T_v**  Constant vaporization temperature, K

**T_a**  Ambient temperature, K

**V_g**  Velocity of the oxidizer, m/s

**V_f**  Absolute spread rate, m/s

**V_{ref}**  Reference voltage

**V_M**  Output signal

**V_e**  Error in signal, V

**W**  Width of the fuel in \( z \)-direction, m

**Subscripts**

**M**  stepper motor

\( \varepsilon \)  error
1. Introduction

Flame spread over solid fuels in an opposed-flow configuration is a fundamental combustion problem that has attracted continued research over last five decades [1]. Not only is the topic important from a practical standpoint of fire safety, it constitutes one of the central problems related to our understanding of fire spread. While the overall mechanisms of flame spread is relatively well understood [2] [3] [4], quantitative predictions of flame spread rates and well established data on flame spread rate and flame shapes are still relatively rare.

One of the most sought after variables of interest in a flame spread study is flame spread rate, the speed with which a flame creeps forward towards the virgin fuel. Beginning with de Ris’s theory [5], many theoretical studies have been devoted in predicting this spread rate while most experimental studies report the measured spread rate under various conditions. The flame spread rate is a scalar that is a function of fuel and oxidizer properties, and physical parameters such as geometric configuration, fuel thickness, oxidizer composition, oxidizer velocity, ambient pressure, and gravity level, to name a few. Flame spread rate is such an important global variable that understanding and predicting this quantity is often one of the major goals of fire research. However, given the complexity of the problem, analytical solutions are available only in simplified regimes. The de Ris solution [5] is probably the most well-known solution for flame spread over thin and thick fuels in the thermal regimes, which have been modified or improved in subsequent theoretical studies [6] [7] [4]. A number of studies have established qualitative agreement between experimental results and prediction from flame spread formulas; however, relatively few studies have been dedicated to a comprehensive comparison of prediction of flame structure and spread rates between theory and experiments.

There is a clear need for accurate measurement of flame spread rate and flame structure because these quantities provide the most effective measurement of flame behavior. From one of the earliest studies on flame spread rate measurement [8], flame spread rate has played a central role in most experimental studies. Perhaps the most extensive spread rate measurements were carried out by Fernandez-Pello et al. [9] who reported the dependence of flame spread rate on ambient and fuel conditions. In all these studies, the spread rate was obtained by analyzing flame images from photography or video by tracking the position of the visible leading edge or, in the case of charring fuel, tracking the pyrolysis front. Because the flame is assumed to be steady, the variation of the spread rate was not reported in most of these studies. In more recent experiments [10] [11] [12], tracking of the flame leading edge
was done with the use of digital video analysis; however, the variability in spread rate is still neglected by curve-fitting a straight line to position vs. time data.

A spreading flame also poses a considerable challenge for obtaining detailed information on its structure. Measurement of the temperature and velocity field, for example, could be of great value for evaluating modeling results. Hirano et al. [13] measured the velocity field by particle tracing methods and used fine wire thermocouples to obtain temperature data for flame spread over thin cellulosic fuels. Fernandez-Pello [14] used thermocouple probes, interferometry, radiometer measurements, gas-phase chromatography, and particle-tracking photography to conclude that the dominant mode of heat transfer in flame spread over thermally thick PMMA is conduction through the solid phase. Fernandez-Pello et al. [15] also performed downward flame spread experiments on thick PMMA rods to measure temperature and velocity fields, reaching the same conclusion that conduction through the solid phase is the dominant mechanism of flame spread. However, Ito et al. [16] used holographic interferometry to conclude just the opposite, that is, that gas phase conduction is more dominant for forward heat transfer, a conclusion that has been supported by later numerical models [17].

The challenging experimental environment posed by a spreading flame is perhaps at the root of some of the inconclusive data on flame spread. In this work, we report the design, construction, and testing of a new flame spread apparatus, which we call a Flame Stabilizer, that immobilizes a spreading flame, creating a stable, stationary flame for experimentation. By controlling the motion of a fuel sample in the opposite direction of flame spread, a flame is rendered stationary for the duration of flame spread. There are several potential benefits of this configuration. Firstly, a stabilized flame allows easier access to probes for the measurement of field variables. Optical diagnostics are especially facilitated by a standing flame. Secondly, fluctuation in flame structure can be studied and the source of any instability can be more easily identified. Thirdly, flames that are very dim can also be photographed by increasing the exposure time. Fourthly, the apparatus records instantaneous spread rate without the need for any post processing, which can be time consuming, depending on the resolution of the video. Finally, the real time monitoring of flame spread rate can be used to determine effects of flame retardants on the flame spread rate and flame shape, both of which are considered important fire hazard indicators. Conversely, effects from external radiation can be studied in this apparatus in a more consistent manner because the view factor of the radiation source and the unburned fuel remain constant in a stabilized flame.

2. Flame Stabilizer Mechanism
2.1 Overview The purpose of the stabilizer mechanism is to perform a coordinate transformation in real time for a downward spreading flame. A flame spreading in an opposed-flow environment is an unsteady phenomenon from a laboratory reference even if the spread rate is steady. Steady-state analytical models of the spread are based on flame fixed coordinates in which the fuel approaches the flame at a relative velocity $V_f$, the spread rate, and the oxidizer approaches the flame at a relative velocity $V_g + V_f$, where $V_g$ is the opposing flow velocity. For downward flame spread in a quiescent environment, $V_g = 0$ at a sufficiently large distance upstream of the flame leading edge. The flame stabilizer mimics this modeling approach by moving the fuel upward at $V_f$, thereby making the flame stationary. However, the boundary conditions are slightly altered because the oxidizer still moves towards the flame at $V_g$ and not $V_g + V_f$. The hypothesis to be tested is that this slight alteration in the flow boundary condition has negligible effect on the flame spread rate and flame structure because $V_f$ is small compared to the characteristic buoyancy induced opposing flow velocity.

2.2 Experimental Hardware A schematic of the experimental hardware is shown in Fig. 1. The apparatus relies on vertical velocity control of the fuel sample. A linear motion assembly was chosen [19] consisting of a motor, indexer, lead screw and nut, carriage, and a pair of guide rail and pillow blocks. The motor selected is a Compumotor AX83-135 two-phase permanent magnet hybrid step motor. The Compumotor is controlled by an indexer that processes commands sent from a serial port of the controlling computer and produces an analog voltage signal for moving the motor. This motion controller produces an angular velocity range of 0.01 rev/sec to 50.00 rev/sec with a resolution of 12800 steps per revolution. A steel lead screw was chosen with a pitch of 2 mm and a diameter of 10 mm, creating a linear velocity range of 0.02 mm/s to 100 mm/s for the motion system. An Acetal-Teflon and Silicone anti-backlash nut was selected to transfer the load from the screw to the carriage. This nut was designed for a maximum preload of 5.2 kg and a maximum torque of 0.28 Nm. The Precision Industrial Components Corporation manufactured both the lead screw and the nut. Thompson Industries manufactured the guide rails and pillow blocks. Two kill switches, connected to the AX indexer, were used at the top and bottom of the ball screw to prevent the nut from accidentally hitting the end support bearings.

The sample holder was made of two thin aluminum (or steel) plates 45 cm long hinged at one end with a rectangular slot of width 3 cm (equal to the sample width) cut through both plates. A thin fuel sample (ashless filter paper or thin PMMA film) is placed
between the two plates, which are pressed against each other using magnets (for the steel sample holder) or clips (for the aluminum). The sample holder is then secured on the carriage with wing nuts. The length of the fuel sample, which controls the duration of the experiment, \( L/V_f \), is limited by the length of the lead screw. In our current set up, a burn time of more than 150 s is typical for flame spread over 0.16 mm thick filter paper. Ignition is performed with a butane lighter or a heating wire. An EICO 1078 AC variable current power supply was used to produce 2.5 amps at 10 V across a 0.009” diameter nichrome wire touching the top front surface of the fuel. We found this method of ignition to have no effect on the spreading behavior of a flame.

We selected a 0.01” diameter K type thermocouple, attached to the test stand (fixed relative to the laboratory coordinates), as the sensor to locate the leading edge of a flame. A K type thermocouple has a temperature range of 0 to 1370 °C. Selection of such a small diameter thermocouple reduces any heat-sink effect on the flame front and provides a fast response time, a necessity for the stability of the control system. A National Instruments USB-9211A device with built-in sensors for cold-junction compensation is used for reading the thermocouple signal with a 24 bit resolution.

2.3 PID Control Algorithm A closed loop feedback control algorithm was implemented using LabVIEW to stabilize a spreading flame. A block diagram for the digital control system is shown in Fig. 2. In this control loop, \( V_t \) is the voltage signal from the thermocouple that is fixed in the laboratory coordinates. As the flame approaches the thermocouple, \( V_t \) increases. The digital reading of this voltage is represented by \( V_{kt} \), where \( k \) is an integer value representing the number of passes through the control loop. The goal of the control algorithm is to keep \( V_{kt} \) as close as possible to the reference voltage \( V_{ref} \); that is, to minimize the error function \( V_e_{kt} = V_{ref} - V_{kt} \). After trying several different control algorithms, we decided that PID (proportional gain, integral time, and derivative time) control was the best choice. In this algorithm, the output signal \( V_{M_{kt}} \) is determined using proportional, integral, and derivative information determined from the error signal. The discretized velocity algorithm for a PID controller is:

\[
V_{M_{k}} = V_{M_{k-1}} + K \left[ V_{e_{k}} - V_{e_{k-1}} \right] + \frac{\Delta t}{t_i} V_{e_{k}} + \frac{t_d}{\Delta t} V_{e_{k}} - 2V_{e_{k-1}} - V_{e_{k-2}} \tag{1}
\]
In this equation, $K$, $t_i$, and $t_d$ are the proportional gain coefficient, the integral time, and the derivative time, respectively. The proportional gain coefficient affects the responsiveness of the feedback control and introduces a steady-state error. With the addition of integral control, the steady-state error can be eliminated at the expense of some instability. The derivative time constant is analogous to a damping coefficient that can be increased to mitigate the instability introduced by the integral control. Optimization of the flame stabilizer reduces to finding an optimal set of values for $K$, $t_i$, and $t_d$. These coefficients were found experimentally by first using only proportional control, and then successively introducing integral and differential controls. For our particular set up, the values found were 7.05, 0.2 s and 1.5 s respectively.

2.4 Imaging Hardware and Software For video capturing, a Logitech Webcam Pro9000 webcam was used. This webcam has a Carl Zeiss optical lens with autofocus. The video capture resolutions are up to 1600 x 1200 pixels with a frame rate of up to 30fps. With the set up optimized for the best close up image, the pixel resolution was determined to be about 5 pixel/mm by placing a scale alongside the fuel sample. A Nikon 5000 digital SLR was used for long exposure photographs and for short videos with higher resolution (13.5 pixel/mm).

To track the visible leading edge of the flame, we used the Spotlight tracking software developed by NASA [18]. This application allows the user to track an image using one or more “areas of interest”, or “AOIs”. An AOI is a small rectangular region selected around the flame leading edge at a suitable starting point in the video. The software records the pixel displacement of this region, frame by frame, by tracking a threshold. A guideline is used to ensure that the rectangular spot moves vertically down the sample. Threshold tracking proves to be the simplest fully automatic tracking method. After the tracking process is completed, the track data is generated and imported into a spreadsheet for further analysis.

3. Experimental Results and Discussion

3.1 Spread Rate Unless otherwise mentioned, most of the experimental results presented in this section are for flame spread over ashless filter paper (density 518.7 kg/m$^3$) of thickness 0.165 mm. A sample that is 3 cm wide and about 20 cm long is held vertically in a quiescent atmospheric condition (100 kPa, 25°C). To create a baseline condition, downward flame spread experiments were conducted and spread rates were calculated by the Spotlight tracking software. Instantaneous spread rates obtained from three different runs by tracking a
spot at the charring edge near the centerline of the fuel sample are shown in Fig. 3. To obtain
sufficient pixel resolution, the webcam is placed very close to the sample, capturing the
spread video over a 10 cm length along the sample. Over that distance, the average spread
rates were calculated as 1.93 mm/s, 2.01 mm/s, and 2.00 mm/s, respectively. Although
spread rate can be seen to vary, a linear curve fit of the position vs. time data would produce
a very high degree of correlation of about 0.999 [19], masking the inherent instantaneous
fluctuation in spread rate.

The time resolution of the fluctuations captured is not necessarily the inverse of the
imaging frame rate, but is a function of the resolution \( p \) (pixels per mm) of the imaging
system and the flame spread rate \( V_f \). In time \( \Delta t \), the expected number of pixels traversed by
the spot is \( pV_f\Delta t \). Since the Spotlight software can count pixels at an increment of one, the
condition for a less than 5\% error in calculated spread rate can be written as

\[
\frac{1}{pV_f\Delta t} < 0.05; \quad \Rightarrow \Delta t > \frac{20}{pV_f}
\]  

With a spread rate of about 2 mm/s, and a \( p \) of 5 pixel/mm (for the camera set up used), the
minimum time resolution can be calculated from this equation as only about 2 sec. This
means the leading edge must cross \( pV_f\Delta t = 5 \times 2 \times 2 = 20 \) pixels between consecutive spot
locations. The variation in spread rate, as quantified by the standard deviation, is also found
to depend on this pixel separation between consecutive readings. For example the standard
deviation in spread rate is about 0.2 mm/s for a pixel separation of 10 (time resolution 1 s)
and 0.1 mm/s for 40 (time resolution 4 s). Therefore, it is quite difficult to isolate the natural
variability of flame spread rate from the numerical error introduced by the conventional Spot
tracking method.

In the stabilizer, step motor angular position was recorded by the flame stabilizer at 6
Hz, producing a time resolution of 0.17 s. Velocity recorded by the flame stabilizer for three
consecutive runs are plotted in Fig. 4. Although the flame is rendered stationary by the
apparatus for the entire duration of the experiment, about 300 s, data from the beginning and
dead of the experiments are truncated to eliminate transient behavior during ignition and
extinction of the flame. For the three runs, the average spread rates recorded were 1.99 mm/s,
1.99 mm/s, and 1.96 mm/s with the corresponding standard deviation of .08 mm/s, 0.06
mm/s, and 0.07 mm/s respectively. The stabilized flame clearly reproduces, within
experimental variability, the same spread rate as a downward spreading flame. Moreover, a
visual examination of the spread video during tracking suggests that the low standard
deviation and the fine time resolution produced by the stabilizer are not artifacts of the
control system and truly reflects flame behavior. To obtain equivalent information from the video analysis, the camera resolution should be at least ten times, about 50 pixel per mm or 5000 pixels over a 10 cm spread distance.

The error in the recorded spread rate possibly stems from three sources: the control algorithm, thermocouple characteristics (its size and location), and inertia of the mechanism. The control parameters, $K$, $T_i$, and $T_d$, which can have a significant effect on the fluctuations were optimized to minimize the fluctuations. An increase in thermocouple bead diameter reduces the fluctuations due to thermal inertia; however, the bead diameter can affect the shape of the flame front by acting as a radiative heat sink, especially if the sample width is less than 20 mm. The 0.01 inch K type thermocouple was found to be a robust solution for all types of samples studied in our laboratory, which included PMMA sheets and cellulosic fuels of different thicknesses and width. To improve the inertial response time of the mechanism, a counter weight was added using two fixed pulleys to balance the weight of the carriage (on which the sample holder is attached). Because of this retrofit, the average spread rate and the fluctuation (measured by the standard deviation over the duration of spread) showed even better agreement between stabilized and downward configurations. Moreover, sample holder of much larger length can be used, allowing a residence time of up to 300 s.

To determine how spread rates obtained from the stabilizer compare with downward spread rates, two successive experiments were performed, one with the stabilizer turned off and one with the stabilizer turned on. Spread rates obtained from the stabilizer and from the video analysis of the downward spreading flame are compared in Fig. 5. The average spread rates are 1.972 mm/s from the stabilizer and 1.973 mm/s from the Spotlight analysis of the downward spreading flame. The results clearly establish that the flame stabilizer produces a spread rate that is within the experimental uncertainty of video analysis of spread rate of a downward spreading flame. It should be stressed that, while the video analysis tracks a spot on the pyrolysis front, the thermocouple stabilizer sensor is located in the gas phase. The variability in spread rate (as measured by the standard deviation) produced by the stabilizer was found to be about the same, around 0.1 mm/s, when the experiments were repeated with different thermocouple locations across the width and at different distances away from the fuel surface.

One of the primary reasons for the variability of spread rate is the non-uniformity of the fuel sample and heat loss from the side. The charring front sometimes creates a wavy edge, which keeps on changing its shape with one part catching up with another as the flame
spreads at a variable rate at different distances from the centerline. This probably explains the low frequency fluctuation of spread rate, as can be seen in Fig. 3-5. This type of fluctuation can be reduced in a stabilized flame by introducing multiple sensors across the width of the sample. To test this possibility, the centerline gas-phase thermocouple was replaced by a pair of thermocouples placed 2 mm away from the fuel surface and 10 mm away from each other and spaced symmetrically on two sides of the centerline. The average value of the signals produced by these thermocouples was used as $V_t$ in the control algorithm (see Fig. 2). Use of two thermocouples produced a smoother spread rate (1.97 mm/s with a standard deviation of 0.1 mm/s, as opposed to 1.97 mm/s with a standard deviation of 0.05 mm/s). Use of multiple sensors will allow stabilizing flames whose leading edge is irregular, say, V shaped due to heat loss from the sides. Using the setup for studying horizontal or even vertical fire spread will require multiple sensors.

3.2 Stationary Flame Having established that the flame spread rate is not altered by the stabilizing mechanism, it remains to be seen how the flame shape or size is affected by this apparatus when compared with data from an actual downward spreading flame. Time averaged side views of the stabilized flame with exposure times of 1 s, 10 s, 20 s, and 30 s are shown in Fig. 6. The images look remarkably similar, except for the eruptions occasionally caused by pyrolyzing chars. The black bar is actually the edge view of the sample holder. The contrast between the sample holder frame and the flame increases as the flame brightness is increased by the higher exposure time. A comparison is made between the side view of a spreading flame and a stabilized flame in Fig. 7 (each with an exposure time of 1 s). In both cases, the visible flames have similar shape: 15 mm long with a maximum height of about 7 mm.

The success of the conversion of a spreading flame into a pseudo-stationary flame can be demonstrated by measuring the temperature at any given point in the stabilized flame. Using a K-type thermocouple (0.01” diameter), the gas temperature is recorded at the tip of the flame (15 mm above the leading edge and 1 mm away from the surface). Results from two different experiments are compared in Fig. 8, which show remarkable agreement and steady temperature for the duration of the experiment. The difference between the two traces can be seen to be within the experimental uncertainty. By freezing a spreading flame in this manner, the stabilizer offers a new experimental platform for exploring the flame structure in flame spread research.

4. Numerical Simulation:
Although the stabilizer adequately seems to represent a spreading flame, it can be argued that the moving sample introduces slightly different boundary conditions for the stabilized flame. While a spreading flame sees the far field environment and fuel approaching the flame leading edge at the flame spread rate, the stabilized flame only sees only the fuel moving towards it at the spread rate, while the far field environment remains stationary.

A numerical model for downward flame spread over a thick fuel bed [20] was developed and tested for PMMA. The model consists of the two-dimensional, steady, elliptic, partial differential equations describing conservation of energy, species, mass, and momentum in the gas phase and ordinary differential equations for conservation of mass and energy in the solid phase. A single-step, second order, overall reaction with finite rate Arrhenius kinetics is used for the gas phase reaction and single-step first order Arrhenius kinetics is used for the pyrolysis reaction. The gas and solid phases are solved sequentially and are coupled by the interface conditions. Replacing the PMMA properties with those of cellulose resulted in a spread rate of 3.7 mm/s, which is almost twice as high as the experimentally measured spread rate of 2.0 mm/s. However, the prediction of the flame shape agrees reasonably well with flame images.

In the simulation of downward flame spread in a quiescent environment, the flame is regarded as stationary and the ambient atmosphere far upstream is assumed to approach the flame at the velocity of the flame. In the flame stabilizer apparatus the flame is also stationary; however, while the fuel approaches the flame at the spread rate, the ambient far upstream remains quiescent. This slight difference in fuel and oxidizer boundary conditions is incorporated in the code. The temperature profile and upward velocity profile in the gas phase at the flame leading edge (about 2 mm upstream of where the pyrolysis front is) for the two simulations are compared in Fig.8. The temperature profile as well as species profiles (not shown) are almost identical for the two configurations. The temperature can be seen to increase rapidly from a surface temperature of about 327 K to a peak temperature of 411 K over a short distance of 1 mm and then gradually decrease back to the ambient temperature at a distance of about 6 mm. The stabilizer seems to have no impact on the temperature profile. The velocity profile starts from 3.87 mm/s at the surface for both the stabilized flame (fuel moving) and downward spread in a flame-fixed coordinates system. The velocity can be seen to increase as one moves away from the fuel surface, reaching a peak of 64 mm/s at about 1.3 mm distance and then gradually decreasing to the far field conditions - zero for the stabilized flame and the spread rate for the downward moving flame. However, close to the fuel surface, the velocity profile seems to be mostly controlled by the buoyancy effect and the
slight difference in the velocity boundary condition does not seem to have much impact. This is true for all locations in the vicinity and above the leading edge. Only far upstream, where the induced flow strength is low, do we observe any appreciable difference between the two profiles. Even in a kinetically controlled flame, the motion of the fuel is not likely to alter the oxygen entrainment near the flame leading edge.

The heat transfer into the fuel surface (not shown) are found to be identical as are the calculated flame spread rates for the two configurations. The flame shape as indicated by the reaction rate contours are also found to be identical. The visible image of the stabilized flame is compared with the computed fields for fuel, temperature, and reaction rates in Fig. 9. The flame image seems to be smaller in size than the extent of the temperature or the reaction rate contours, but is comparable to the fuel field size. Given that the visible emission from the flame is mostly due to soot radiation and soot is present mostly in the fuel side of the diffusion flame, the flame image can be expected to be enveloped within the reaction rate contours. Also, the buoyancy induced flow elongates the thermal field much beyond the reaction zone in the downstream direction. Therefore, the temperature field can be expected to be much longer than the visible flame.

Just like the visible flame images compare well (Fig. 7) for the spreading and stabilized flame, computed reaction rate contours for the two configurations are found almost identical (figure not shown). It is therefore reasonable to conclude that the flame stabilizer does not alter the flame shape or size, field variables, and spread rate in any significant way.

5. Conclusion

A novel experimental apparatus for the study of flame spread over solid fuel in an opposed flow configuration is proposed. The purpose of this setup is to arrest the propagation of the flame by moving the fuel mounted on a linear motion system at the propagation speed in the opposite direction of the flame spread. A gas phase thermocouple attached to the test stand serves as a sensor for the approaching flame. A PID control algorithm was developed with the objective of keeping the thermocouple temperature constant, thereby arresting the propagation of the flame, by controlling the motion of the step motor that drives the linear motion system. Instantaneous spread rate recorded by this apparatus is shown to compare well with the instantaneous spread rate of a downward propagating flame, obtained by analyzing a digital video. The flame shape and size also compare well between the two configurations. The PID control parameters developed for a particular case are found to work
well for different fuel thicknesses, fuel width, and fuel type. The boundary layer created by the motion of the fuel in this apparatus, which is absent in a downward spreading flame, does not seem to create any significant difference. This is confirmed by numerical simulation using an existing model in which the velocity boundary conditions are altered at the upstream boundary of the computational domain to account for the moving fuel.

A stabilized pseudo-stationary flame provides a much larger residence time for experimental measurements. The time resolution of the instantaneous spread rate is much superior to the conventional digital video analysis methods. In addition, because the apparatus records and displays in real time the instantaneous flame spread rate, the stabilizer apparatus has the potential to serve as a simple platform to study the effect of flame-retardants or other external factors such as irradiation on a spreading flame.

Acknowledgment

The research at SDSU is supported by a grant from NASA with Dr. David Urban serving as the contract monitor.
References


http://microgravity.grc.nasa.gov/spotlight/


Fig. 1 The flame stabilizer apparatus. The stabilizing thermocouple is attached to the test stand while the sample is mounted on a carriage moved by the PID control algorithm in the opposite direction of the spread to maintain a constant thermocouple signal, thereby arresting the flame motion and anchoring the leading edge just above the thermocouple.

Fig. 2. Control loop block diagram for the PID control algorithm with the goal of minimizing the error function \( V_E \) .
Fig. 3 Results from three consecutive runs obtained by video analysis using spot at the centerline shows inherent variability of instantaneous spread rate.

Fig. 4 Spread rate measured by the stabilizer for a stationary flame. Results from different runs show the same variability as in downward spreading flames.
Fig. 5 Comparison of flame spread rates between downward spreading flame and flame rendered stationary by the flame stabilizer.

Fig. 6 Stabilized flame images for different exposure time show a relatively stationary shape. Exposure time from left to right: 1 s; 10 s; 20 s; 30 s.
Fig. 7 Comparison of visible flame shape, obtained experimentally, between a spreading flame (left) and a stationary flame created by the stabilizer (right). A mm grid is superposed.

Fig. 8 Comparison of upward velocity profile relative to the flame computed at the flame leading edge for (a) downward spreading flame and (b) stabilized flame (blue).
Fig. 9 Images of the stabilized flame: (a) computed fuel mass fraction field, (b) side-view photograph, (c) computed temperature field, (d) computed reaction rate.
Flame Tower: A Novel Apparatus to Study Flame Spread at Low Concurrent or Opposed Flow Velocity

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Opposed flow flame spread over solid fuels has been an ongoing research interest with the goal of developing a fundamental understanding of fire spread. In an opposed flow configuration, flame spread rate remains steady, even if the flame increases in size. While concurrent flow is more relevant in understanding spread rate for fire safety, an understanding of the physics that governs the transition between the two regimes has not been well established. Most of the flame spread research has been carried out in wind tunnels, where it is difficult to create a uniform flow at low velocities, typically in the range of 10-100 cm/s. To develop a better understanding of the effect of flow velocity, an eight-meter enclosed steel vertical Flame Tower has been built at San Diego State University that facilitates the study of opposed and concurrent flame spread. A translating carriage within the tower holds a fuel sample and is accelerated to a constant velocity, either downwards or upwards, to impart an opposed or concurrent flow condition, respectively, with a desired oxidizer velocity. While the velocity of the carriage can be accurately controlled, the velocity seen by the fuel sample will depend on the blockage created by the sample holder, igniter, cameras, and the carriage box that holds the onboard computer. To verify the oxidizer velocity relative to the sample holder, a MEMS airflow rate sensor was used to measure oxidizer velocity at various locations around the sample holder, while the carriage was moved both upwards and downwards. The result shows a reasonably uniform flow augmented by a factor that approximately scales with the inverse of one minus the blockage percentage, the area ratio of the tower cross-section with and without the carriage. A commercial CFD package was used to model the cold flow as seen by the carriage in the presence and absence of the enclosing wall. The results agree reasonably well with the experimental observations and establishes the inverse of one minus the blockage percentage
as a correction factor for the velocity seen by the fuel sample. Additionally, the simulation results show that, for the given tunnel dimensions, the boundary layers and the wakes created by various surfaces and carriage structure do not substantially affect the flow field in the immediate vicinity of the fuel leading edge.

**Introduction**

Due to its relevance in fire safety applications, opposed-flow flame spread has been investigated for over four decades [1, 2]. Papers detailing techniques for measuring real-time flame velocity are few, even though extensive research in this field has demonstrated the mechanism of opposed-flow flame spread in a downward configuration fairly well [3, 4, 5, 2, 6, 7]. Of foremost importance was de Ris’ 1969 paper wherein he presented a theory describing the physics of a laminar diffusion flame spreading against an air stream over solid and liquid-fuel beds [8]. It was de Ris’ who, in this paper, established that flame spread is a process wherein the leading edge of a flame heats unburned solid fuel in front of its path, causing the solid fuel to vaporize. The fuel vapor then reacts with ambient oxygen gas present in the opposed flow which releases heat and product species back to the environment. Heat generated by the exothermic combustion reaction facilitates the spreading process by heating remaining unburned fuel ahead of the flame’s leading edge, which generates additional vapor to maintain a combustion reaction. Rates of flame spread over thermally thick and thin fuels are well predicted by de Ris’ model and reveal that spread rate is steady in an opposed flow configuration, even if flame size increases. Over the last four decades, many researchers have extended de Ris’ model by developing analytical equations for predicting spread rate for flames in other regimes, under different fuel and oxidizer mixtures, oxidizer velocities $V_g$, ambient pressures, and gravitational conditions [3, 5, 2]. Development of closed-form expressions for spread rate under different values of $V_g$ are of special interest and are typically created by matching data collected from experiments involving the burning of materials subjected to an opposed flow established within a wind tunnel. Unfortunately, generating uniform, low-velocity flows in the 10-100 cm/s range is difficult within a wind tunnel, and limited studies have been performed to comprehend the effect of forced, opposed flows over flames within confined tunnels. To develop a better understanding, an eight-meter enclosed steel vertical tower has been constructed at San Diego State University (SDSU) to facilitate the study of opposed and concurrent flame spread over cellulosic and thermoplastic materials of different thickness. Figure 1 shows a frontal view of the tower with gas and instrumentation ports at the top. The tower is constructed from 1020 carbon steel and reinforced with steel joists to withstand a 0.5atm vacuum pressure. The tower spans two
floors in the SDSU College of Engineering building and was constructed through an abandoned access way to a basement from the building first floor.

The “flame tower” provides an ability to accelerate a translational carriage to a desired velocity, up or down along a vertical rail, to impose a constant oxidizer velocity, \( V_g \), on a flame propagating along a sample of fuel within a sample holder attached to the carriage. The carriage trajectory (position, velocity, and acceleration) is controlled by a Parker COMPUMOTOR AX indexer that drives a Parker COMPUMOTOR Model M106-178 DC motor mounted at the top of the tower. The AX indexer is controlled by the PC shown mounted behind the tower in Figure 1. The carriage lifts and descends via a cable on a pulley system with the assistance of a counterbalance that is enclosed within a 4” diameter tube that spans the length of the tower, shown in Figure 2. The COMPUMOTOR M106-178 DC motor produces 700 inch-ounces of torque on the pulley shaft. A compression spring is fixed underneath the rail guide in case the cable breaks. The PC executes a LabView application we developed to control carriage trajectory along the rail. Two moving carriages have been built since the tower’s inception. Both carriages feature an aluminum frame that holds a Toshiba ToughBook tablet, fuel sample holder, supporting electronics, and one or more cameras. The first carriage we built, named *FlameTracker 1* [9], features a 12V Mercury stepper motor attached to a lead screw and controlled by an Arduino microcontroller (MCU). The tablet PC executes a 32-bit Windows application that controls various functions on the MCU, such as sampling and recording flame temperature and driving a 7-segment LCD display used to synchronize time and video. The MCU executes an embedded PID algorithm we developed that matches the speed of a translating arm to the speed of a flame moving along the fuel sample. A K-type thermocouple is used to track the flame's leading edge at an adjustable set point temperature using PID control. The second carriage we built, *FlameTracker 2*, features a larger aluminum case and a more rigid, cylindrical fuel sample holder. Shown in Figure 3 and Figure 4 the second generation carriage was constructed because the first carriage had difficulty tracking slow flame spread under 0.5mm/s using PID control. The second carriage measures spread rate by measuring flame position vs. time with four in-line thermocouples. The upper ring assembly has four magnets that grasp a fuel sample holder. A camera shown on the right, mounted in a black plastic arm, records flame spread and produces a video that can be analyzed using the NASA SpotLight video analysis software.

The principle motivation behind constructing the flame tower and multiple carriage assemblies is to allow us to determine the environmental conditions under which an opposed-flow flame may auto-extinguish if the fuel thickness is more than a critical value.
The developed apparatus will allow us to determine how oxidizer flow, oxygen concentration, and fuel thickness affect material flammability by allowing oxidizer residence time to be user controlled to permit a transition from a wind-opposed to a wind-aided regime.

While the velocity of the carriage can be accurately controlled, the velocity seen by the fuel sample will depend on the blockage created by the sample holder, igniter, cameras, and the carriage box that holds the onboard computer. To determine the oxidizer velocity relative to the sample holder at a given carriage velocity, a MEMS airflow rate sensor was used to measure oxidizer velocity at various locations around the sample holder, while the carriage was moved both upwards and downwards. The particular sensor used is an Omron D6F-W01A1 MEMS Flow Rate Sensor, which supports a range of 0 to 1 m/s. Further operating characteristics of the D6f-W01A1 are given in Table 1 and a picture of the sensor is shown in Figure 5. An Arduino UNO microcontroller is used to sample air velocity and record to an EEPROM on the white prototyping board shown in Figure 4. A real-time clock is also present on the prototyping board and used to log accurate time along with each sampled velocity measurement.

Methods

The mass flow sensor was placed at eight locations of FlameTracker 2’s fuel sample older, as shown in Figure 6, and measured twice for \( V_g \pm 40 \text{ cm/s} \), in a wind opposed (+) and wind aided (-) configuration. In addition, the tower and carriage geometry were modeled in SolidWorks and imported into ANSYS Fluent where a 3D flow simulation was performed to compare computational results against experimental. Four measurement locations were designated at different offsets within the channel region of the fuel sample holder where a 10cm fuel sample resides. The offset positions are with respect to the bottom of the channel. Positions 5-8 reside 1cm below the slot between each of the four posts on the bottom ring of the fuel sample holder. Experimental measurements were performed twice and the results averaged. All CFD simulations were performed with second-order accurate models for pressure and momentum, an upwind discretization scheme, and the SIMPLE algorithm for pressure-velocity coupling.

Results and Discussion

A comparison of experimentally and computationally measured velocity in the y-axial direction where the carriage translates along the tower rail, for sensor locations 1-4 and a
configured cart velocity of $V_g + 40 \text{ cm/s}$, is shown in Figure 9. Both experimental and computational results reveal the flow is accelerated in the channel where the fuel sample lies. From the results shown, the velocity the fuel sample “experiences” is approximately 1.05 times the user configured cart velocity. Accelerated flow can clearly be seen from a 3D isosurface plot of y-velocity behind a clipping plane through the fuel sample holder channel (Figure 8). A contributing factor to the accelerated flow is the blocked area created by the carriage, rail, and counterweight conduit. From the cross-sectional area of the tower with the carriage, the area of the significant blocked area is $0.0379 \text{m}^2$, within an internal area of $45.1 \text{ cm}^2 = 0.02033 \text{m}^2$. Thus 18.64% of the internal area is blocked for airflow, due to the carriage, rail, and counterweight tube. We see that the inverse of one minus the blockage percentage is approximately a correction factor for the velocity seen by the fuel sample, as $1/(1-18.64\%) = 1.23$. As the carriage translates up and down in the tower, air flow around the bluff bodies that comprise the carriage and fuel sample holder cause flow separation and increased velocity in the fuel sample holder channel, as shown in Figure 9. Thus, the velocity imposed on the fuel is somewhat greater than the velocity of the carriage. Voltage data acquired from the 40cm/s downward carriage configuration is given in Figure 10. Channel offset position for $x=0 \text{cm}$ corresponds to the leading edge of the fuel sample. Table 2 lists the velocity at the leading edge for two other user configured carriage velocities, 20 and 50 cm/s. For the 20 cm/s case, flow at the leading edge is roughly equivalent to the free-stream velocity, but at a carriage velocity of 50 cm/s, velocity is shown to be higher at the leading edge as in the 40 cm/s case. Similar results were observed for upward carriage translation, which corresponds to a concurrent-flow orientation. Table 3 lists the sensor measured velocity at the top of the channel where fuel ignition commences. At an upward carriage velocity of 20 cm/s, the sensor reported velocity was approximately 17 cm/s, somewhat less than free-stream. However, for 40 and 50 cm/s, air flow velocity was seen to increase at the ignition edge.

**Conclusions**

An eight-meter enclosed steel vertical Flame Tower has been constructed at San Diego State University to enable the study of opposed and concurrent flame spread by controlling the velocity of a downward and upward translating carriage within the tower, respectively, to impart a desired oxidizer velocity on a moving flame. The carriage consists of an aluminum chamber to hold a laptop computer, microcontroller, associated electronics, and a fuel sample holder which secures a sheet of cellulosic or thermoplastic fuel. The velocity of the carriage
can be accurately controlled by a user through a LabView application that controls a stepper motor that winds and unwinds a cable attached to the carriage which translates along a rail. To measure the oxidizer velocity relative to the sample holder, a MEMS airflow rate sensor was used to measure oxidizer velocity at various locations around the sample holder, while the carriage was moved both upwards and downwards. A commercial CFD package was used to model the cold flow as seen by the carriage in the presence of the enclosing wall. The result shows a reasonably uniform flow augmented by a factor that approximately scales with the inverse of one minus the blockage percentage, the area ratio of the tower cross-section with and without the carriage. The velocity “seen” by the fuel sample is altered by the blockage created by the sample holder, igniter, cameras, and the carriage box that holds the onboard computer. The simulation results agree reasonably well with experimental observations and establishes the inverse of one minus the blockage percentage as a correction factor for the velocity seen by the fuel sample. As air flow is accelerated over these bluff bodies, the oxidizer velocity in the fuel sample holder channel can become greater than the user defined free stream velocity. This condition can be seen in Figure 11 from a CFD simulation of internal air flow within the tower over the carriage. The inner tower wall can also interact with the oxidizer flow to increase velocity, as show in Figure 12. Implications of this finding are that consideration must be given to account for bluff body interaction and tunnel blockage for experimenters who measure flame spread rate in drop towers, as is typically done.

**Acknowledgements**

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References


Figure 1. View of the SDSU flame tower showing gas and instrumentation ports. A controller PC is shown mounted behind the tower.

Figure 2. FlameTracker 1 carriage mounted on the tower guide rail. The left arm translates along a fuel sample held in place by the right arm, using a bearing driven by a lead screw and stepper motor. The 4” diameter tube shown on the left encloses a counterweight that assists in carriage translation.
Figure 3. CAD solid model of FlameTracker 2. The aluminum frame is 43cm tall.

Figure 4. FlameTracker 2 carriage with an Omron MEMS flow rate sensor that was placed at different locations in the vicinity of the fuel sample holder.

Table 1. Omron D6F-W01A1 operating characteristics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Flow range</td>
<td>0 to 1 m/s</td>
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<tr>
<td>Operating output voltage (VDC)</td>
<td>1 to 5 VDC</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 5% F.S. max. of detected characteristics at 25°C</td>
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<tr>
<td>Repeatability</td>
<td>± 0.4% F.S</td>
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<tr>
<td>Compact size</td>
<td>39 (L) x 20 (W) x 9 (H) mm</td>
</tr>
<tr>
<td>Weight</td>
<td>6.3 g</td>
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Figure 5. Omron D6F-W01A1 air flow sensor.
Figure 6. The mass flow sensor was placed at the eight locations shown in red and air velocity was measured and recorded for $V_g \pm 40$ cm/s, in a wind opposed (+) and wind aided (-) configuration.

Figure 7. Tower cross-sectional flow area. Significant blocked regions are identified in red.

Figure 8. Isosurfaces of $y$-velocity behind a clipping plane through the fuel sample holder channel. Flow is shown to moderately accelerate within the channel.
Figure 9. Comparison of experimentally and computationally measured velocity in the y-axial direction where the carriage translates along the tower rail, for a configured cart velocity of $V_g + 40$ cm/s. In the left figure for locations 1-4, flow sensor sampled data values are shown in red, while CFD simulation values are shown in black. In the right figure for locations 5-8, sensor values are shown in black, while CFD velocity values can be deduced from the legend.
Figure 10. Acquired sensor data from a 40cm/s downward carriage configuration to generate opposed air flow over a sample of fuel positioned.

<table>
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<tr>
<th>Location</th>
<th>x</th>
<th>y</th>
<th>z</th>
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<td>1.55</td>
<td>47.04</td>
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Figure 11. Opposed-flow, steady-state Fluent simulation of FlameTracker 2 in the flame tower. The left image shows isosurfaces of velocity > $V_\infty$ in the vicinity of the carriage for a freestream velocity of $V_\infty = 0.4$m/s. The right image shows a model of the carriage in the tower at the same scale. Simulation was performed using an upwind scheme with SIMPLE pressure-velocity coupling. Flow around the bluff carriage is accelerated and results in a moderately increased oxidizer velocity in the channel where a fuel sample resides.
Table 2. Downward configuration (opposed-flow) sensor velocity measurements at channel offset position 0cm where the fuel sample leading edge resides.

<table>
<thead>
<tr>
<th>Carriage Velocity</th>
<th>Velocity at Fuel Sample Leading Edge</th>
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<tr>
<td>20 cm/s</td>
<td>18.69 cm/s</td>
</tr>
<tr>
<td>40 cm/s</td>
<td>44.86 cm/s</td>
</tr>
<tr>
<td>50 cm/s</td>
<td>57.12 cm/s</td>
</tr>
</tbody>
</table>

Table 3. Upward configuration (concurrent-flow) sensor velocity measurements at the top of the channel where ignition begins.

<table>
<thead>
<tr>
<th>Carriage Velocity</th>
<th>Velocity at Fuel Sample Ignition Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 cm/s</td>
<td>16.61 cm/s</td>
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<tr>
<td>40 cm/s</td>
<td>45.99 cm/s</td>
</tr>
<tr>
<td>50 cm/s</td>
<td>60.17 cm/s</td>
</tr>
</tbody>
</table>

Figure 12. Opposed-flow, steady-state Fluent simulation of FlameTracker 2 in the flame tower. Image shows contours of velocity on ZY-slice in the tower for $V_x = 0.4\text{m/s}$. The tower inner wall interacts with the flow around the bluff carriage and contributes to an increased oxidizer velocity in the fuel sample channel.
Boundary Layer Effect on the Correlation of Spread Rate Data in Opposed Flow Flame Spread

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Abstract

In opposed-flow flame spread over solid fuels, an indefinite increase in flow velocity eventually leads to flame extinguishment. While the chemical time is independent of the flow velocity, the residence time of the oxidizer at the flame leading edge is inversely proportional to the flow velocity, and, therefore, a competition between the two leads to a situation where finite-rate kinetics dominates the flame spread behavior, leading to blow-off extinguishment. The ratio of the two competing times (residence time to chemical time), known as the Damkohler number, captures this finite-rate effect and has been used to correlate the non-dimensional spread rate with opposing flow velocity and ambient oxygen level. Although these correlations explain the behavior observed in the experiments, there is considerable spread in the correlations found in literature despite the use of several variations of the definition of the Damkohler number. With all the progress made in this area, it is still not possible to predict the blow-off extinction velocity for a given fuel at any given oxidizer condition.

In this work we present new flame spread data over ashless filter paper acquired in an eight meter tall vertical steel chamber in which the sample is moved at a command velocity to create a desired opposing flow. The developing boundary layer over the fuel sample and the relative humidity in the chamber are shown to have a significant effect on the measured spread rate and it does not correlate at all with opposing flow. Once the data is adjusted for humidity, and an effective flow velocity that incorporates the developing boundary layer is substituted for opposing velocity, the correlation is shown to improve drastically. Given the importance of the boundary layer development, much of the data in literature that does not mention the development length must be cautiously used.
Keywords: flame-spread, blow-off extinction, Damkohler number, boundary layer, thermally thin fuel.

1. Introduction

Flame spread over solid fuels in an opposed-flow environment has been investigated for over four decades [1] [2] [3] for understanding the fundamental nature of hazardous fire spread. The appeal for this configuration stems from the fact that flame spread rate remains steady even if the flame itself may grow in size. The configuration can be further simplified by restricting fuel thickness to the thermally thin limit whereby the entire thickness of the fuel can be assumed to be uniformly heated by the spreading flame.

The simplified problem still retains the richness of exhibiting characteristics of a full range of flame spread regimes. In the thermal regime, the spread rate is characterized by a balance between conduction from the gas phase and the energy required to heat up the virgin fuel from the ambient to the vaporization temperature. The well-known de Ris-Delichatsios formula [4] [5] expresses the flame spread rate in terms of fuel thickness, thermodynamic properties, and a non-dimensional temperature coefficient that depends on the flame temperature and the vaporization temperature. A very interesting feature of the thermal regime is that the flame spread rate is independent of the opposing flow velocity.

If the opposing flow velocity is reduced, buoyancy creates a permanent opposing flow for a downward spreading flame. However, in the microgravity environment, the opposing flow can be very small or even completely absent. It has been shown that in addition to gas phase conduction, the radiative effects become important [6] [7] [8] and flame spread rate actually depends on the flow velocity. A closed-form expression for flame spread rate has been proposed by Bhattacharjee et al. [9] in this radiative regime that predicts flame extinguishment for fuels exceeding a certain critical thickness.

An implicit assumption in the thermal regime is that the flow velocity is low enough to allow sufficient time for combustion to be complete. That is, combustion and pyrolysis can be assumed to be infinitely fast compared to other processes. However, when the opposed flow is indefinitely increased, the residence time at the flame leading edge can become too small for this assumption to hold and the effect of finite-rate kinetics can become significant. Flame spread rate begins to decrease in this kinetic regime and the flame eventually extinguishes at a sufficiently high velocity. Use of phenomenological arguments led Frey and Tien [10], Altenkirch et al. [11], Fernandez-Pello et al. [12] and Wichman [13] to correlate
the spread rate, non-dimensionalized using its thermal limit, with the Damkohler number, the ratio of the residence time and chemical time at the flame leading edge.

Although successful in correlating a given set of data, such correlations are far from universal due to several complicating reasons: First, the flame temperature appears both in the spread rate expression in the thermal regime and in defining a chemical time, the denominator of the Damkohler number. While de Ris' solution [4] requires the use of a linearized flame temperature (which is considerably higher than the adiabatic flame temperature for complete combustion), adiabatic flame temperature or even the equilibrium flame temperature has been used in the expression for chemical time. Second, for flame spread in a quiescent environment in a normal or partial gravity environment, the opposing flow velocity is not known and must be scaled by balancing the inertia term with buoyancy in the momentum equation[14] [11]. In a forced convective situation, the free stream velocity may be known, but the velocity gradient encountered by the flame will depend on the boundary layer development upstream of the flame. For flame spread over thick fuels in the thermal regime, Wichman [15] explored the effect of the velocity gradient at the flame leading edge while West et al. [16] proposed the concept of an effective velocity seen by the flame based on the velocity profile encountered by the flame.

For thin fuels, spread rate being independent of flow velocity in the thermal limit, the developing boundary layer needs to be incorporated only in the Damkohler number. Eto et al. [17] used an unsteady numerical simulation to show that flame spread can be considered pseudo-steady, despite the fact that the flame encounters a developing boundary layer with a varying effective flow velocity. They defined an effective velocity as the local velocity where the peak flame temperature occurs and showed that the spread rate for different development lengths and flow velocity correlate well with the numerically obtained effective velocity. Bhattacharjee et al. [18] used a scaling approach to define an effective velocity as the velocity seen by the flame one length scale above the fuel surface. Using data from a steady-state numerical model, they proposed a formula for this velocity in terms of the development length of the boundary layer development length, free-stream velocity, and fluid properties.

In this work we present newly acquired data from the flame tower at SDSU. The data provides strong indication that the boundary layer development length must be considered in correlating spread rate with opposed-flow velocity.
2. Effective Velocity

In order to obtain an expression for the effective velocity seen by a flame, consider the leading edge of the spreading flame shown in Fig 1. At a distance $x$ from the leading edge of the fuel sample, the flame is shown to be embedded inside the boundary layer of thickness $\delta$. Based on numerical evidence [16] [17] that the diffusion length scale $L_g$ at the flame leading edge plays a critical role in defining flow experienced by the flame, we define velocity at a distance $L_g$ from the fuel surface at the leading edge as the effective velocity (see Fig. 1).

Assuming a linear velocity profile, we can express $V_{\text{eff}}$ in terms of $L_g$ and $\delta$ as:

$$V_{\text{eff}} = \frac{L_g}{\delta} V_g$$

(3)

A balance between the forward conduction and the advection term of the energy equation establishes the diffusion length scale

$$\frac{\partial}{\partial x} \rho c_p u \frac{\partial T}{\partial x} \left( \lambda_g \frac{\partial T}{\partial x} \right); \quad \Rightarrow \frac{\rho V_g c_p \Delta T}{L_g} = \frac{\lambda_x \Delta T}{L_x}; \quad \Rightarrow L_g = \frac{\alpha_x}{V_g}$$

(4)

The boundary layer thickness can be scaled by balancing the inertial term with the friction term of the momentum equation.

$$\frac{\partial}{\partial x} \rho u^2 \left( \frac{\partial u}{\partial y} \right) \left( \mu_g \frac{\partial u}{\partial y} \right); \quad \Rightarrow \frac{\rho V_g^2}{x_d} = \frac{\mu_g V_g}{\delta^2}; \quad \Rightarrow \delta = \frac{x_d}{\sqrt{\text{Re}_x}}$$

(5)
Substituting expressions (4) and (5) in Eq. (3) and introducing Prandtl number, \( Pr = \nu / \alpha \), we obtain

\[
V_{\text{eff}} = \frac{V_g}{Pr \sqrt{Re_x}} \tag{6}
\]

To improve the correlation, we notice that the diffusion length scale is also affected by the developing boundary layer. If the correct velocity scale is \( V_{\text{eff}} \), it should be used in Eq. (4) as well in place of \( V_g \). That is,

\[
L_{g,\text{eff}} = \frac{\alpha_g}{V_{\text{eff}}} \tag{7}
\]

Substituting this expression in Eq. (3) and a little manipulation leads to a different power law.

\[
V_{\text{eff}} = \frac{V_g}{Pr Re_x^{1/4}} \tag{8}
\]

![Graph showing the effective velocity as a function of opposed-flow velocity and boundary layer development length.](image)

**Fig. 2** The effective velocity as a function of opposed-flow velocity and boundary layer development length \( x_d \) as predicted by Eq. (9)

Comparison with several sets of numerical data led [18] to an empirical expression using a one-third power,

\[
V_{\text{eff}} = \frac{V_g}{Pr Re_x^{1/3}} \tag{9}
\]
This final expression, Eq. (9), seems to work satisfactorily as can be seen from the collapse of the numerical spread rate data in Fig. 2 for flame spread over PMMA sheets in a 50% oxygen and 50% nitrogen environment at 100 kPa for different development lengths, which can be seen to play a very significant role in determining the blow-off velocity. When the development length is 30 mm as opposed to 60 mm, the spread rate is consistently depressed as the effective velocity is much higher, as shown in Fig. 7(c). Except for the very last near-limit computation, which carries more numerical uncertainties than other stable spreads, all data points fall on one universal line. The formula seems to work well in the microgravity regime too, as can be seen from the nice collapse of the numerical data for low effective velocities.

Fig. 3 Computed [18] spread rate over PMMA films at a 50-50 oxygen nitrogen environment for two different development lengths collapse into a single graph when plotted against the equivalent flow velocity.
3. The SDSU Flame Tower

Most opposed-flow flame experiments have been performed in wind tunnels. However, creating a low velocity field with a known profile is a challenging task. At SDSU we built a 8 m tall vertical steel chamber with a 45 cm x 45 cm square cross-section, which we call the flame tower [19] (see Fig. 4), inside which a fuel sample mounted on a cart can be traversed up or down with a prescribed velocity. The cart carrying the experimental package is connected by a string going over a pulley at the top of the tower to a counter weight that moves up and down through a vertical tube in opposite direction of the cart. A stepper motor (step angle 0.028125 degree, 12800 steps per shaft revolution, 120 VAC, 5.0 A, max holding torque 5.4 N-m) housed at the top of the tower creates the desired motion by winding or unwinding a separate string connected to the cart. The power supply and the connection to the serial port of the indexer of the motor is run through an electrical seal.

![Fig. 4 The 8 m tall flame tower at SDSU where a fuel sample can be ignited and moved up or down with a desired velocity.](image)

The velocity of the cart was measured by analyzing a digital high-speed video of a measuring tape attached to the rail from a camera mounted on the cart. The acceleration,
velocity and deceleration profiles matched the command profiles almost exactly. A hot wire anemometer was connected to the cart and placed at several locations to ascertain the flow velocity, which was tested to be reasonably uniform [20] over a 10 cm by 10 cm area upstream of the fuel sample.

The cart, shown in Fig. 4, carries an assembly of fuel sample, igniter, diagnostic system, and an on-board computer, all powered by a battery and remotely accessed from outside through a wireless network. The fuel sample, 2 cm wide and 10 cm long, is sandwiched between two thin aluminum plates with rectangular cut outs held by an arm attached to the cart. A Kanthal (iron-chromium-aluminum, FeCrAl) alloy igniter wire at the top of the sample holder is connected to the ignition circuit controlled by a micro-controller through the same arm. A web camera captures a high resolution video of the flame spread. Using the NASA spotlight video analysis software [21], a centerline spot is tracked as the flame passes over a predetermined location (with the desired length of boundary layer development length upstream). The pixel location vs. time data generated by the software is converted into a location vs. time plot and a linear curve fit produces the average spread rate. Typically, a distance of 15 mm is found to be sufficiently long to produce an average spread rate.

Fig. 5 As the sample holder travels down the rail inside the flame tower at a prescribed speed, the spread rate is measured when the flame crosses the 11 cm and the 2 cm marks. As the flame passes over the 2 cm mark over a distance of 14 mm, the average spread rate is measured as 1.35 mm/s. The spot at the centerline tracks the leading edge of the flame.

rate at a given location.
4. Flame Tower Data and Discussion

The data reported in this work is for flame spread over ashless filter paper (Whaman grade 1) of thickness 180 \( \mu m \) with atmospheric air at ambient pressure as the oxidizer. A typical video analysis of the flame spread using the Spotlight imaging software is shown in Fig. 5. As can be seen from the figure, tracking a spot at the centerline over 10 s of spread (over a distance of 13.6 mm) produces a linear fit with a high degree of correlation.

Downward flame spread in a quiescent environment is characterized by buoyancy generated opposing flow and the spread rate or the flame structure is found to be independent of the flame front location [22] with respect to the leading edge of the fuel sample. Even if a forced flow is present, buoyancy effects can still be dominant. In the flame tower, when a sample is moved down with a speed below 20 cm/s, there is no discernible change in flame spread rate. The same behavior can also be observed in the data of Fernandez-Pello et al. [12].

To experimentally investigate the effect of the boundary layer development, the relative flow velocity must be sufficiently large to dominate over the buoyancy induced opposing flow. In the flame tower, when the sample is moved at a speed over 25 cm/s, the spread rate starts decreasing leading to blow-off extinction at about 50 cm/s. Based on this observation, we select 30 cm/s and 40 cm/s as the cart velocities to study the effect of the boundary layer development on the spread rate and flame structure.

Top view of the flame for a downward spread experiment in a quiescent environment (zero cart velocity) for three different runs are compared with the corresponding flame images for a cart velocity of 40 cm/s at two different development lengths (2 cm and 11 cm) in Fig. 6. Flame images for pure downward spread look remarkably similar for the cart velocity of 40 cm/s when the development length, \( x_d \), is 11 cm. However, the flame size significantly decreases at a lower development length of \( x_d = 2 \) cm as can be seen from Fig. 6. In fact, the flame size continues to shrink as \( x_d \) decreases until a critical size is reached at about \( x_d = 1 \) cm when the flame extinguishes.

The flame position along the centerline of the sample, tracked with the Spotlight software [21], is shown in Fig. 7 along with the instantaneous spread rate obtained by differentiating the data and smoothing it using a moving average over 4 data points. For pure downward spread during the first 35 seconds, the spread rate can be seen to be relatively steady around an average spread rate of 1.92 mm/s.
When the cart starts its downward motion and accelerates to 40 cm/s, the flame undergoes transition adjusting to the relative opposing flow created by the motion of the cart. However, even after the transition period, the spread rate can be seen to continuously decrease. This trend has been verified to be repeatable in multiple runs of the same experiment. It supports the result of the scale analysis where the effective velocity seen by the flame can be seen to continuously increase (see Fig. 2) as the boundary layer.

Fig. 6 Flame shape (top view) for three different experiments with a cart velocity of 40 cm/s and two different development lengths compared with a pure downward spreading flame.
development length decreases during the spread. The flame finally extinguishes before the cart reaches the bottom of the tower. As far as we know this is the first experimental evidence of flame extinguishment caused by variation in boundary layer thickness.

To quantitatively demonstrate that the boundary layer development length is indeed the reason behind the drop in flame spread rate in Fig. 7, spread rate measured for two different development lengths at two cart velocities are plotted in Fig. 8 with each data point being the average of 3 different runs. For the larger development length of 11 cm, the standard deviation in the spread rate is less than 0.03 mm/s; however, for the shorter development length of 2 cm, the standard deviation increases to about 0.19 mm/s. Because of the flow constriction caused by the cart, the cart velocity is not the same as the free-stream.

**Fig. 7** Flame position vs. time plot obtained from digital video analysis is differentiated to obtain transient spread rate. Notice how the spread rate progressively decreases until extinguishment.
velocity seen by the leading edge of the sample. Using a velocity probe and Fluent simulation [20], the flow velocity has been shown to be about 1.05 times that of the cart velocity. This constriction factor is incorporated in the data of Fig. 8.

The dimensional plot of Fig. 8(a) shows that depending on the development length $x_d$ the spread rate behaves differently as the opposing flow velocity is increased from 30 cm/s to 40 cm/s. With $x_d = 11$ cm the spread rate goes from 1.66 to 1.67 mm/s. On the other
hand, for $x_d = 2$ cm the spread rate goes from 1.50 to 1.31 mm/s. Because of the finite-rate kinetics effect, one would expect the higher opposing flow to cause a decrease in the spread rate. But, ignoring the role played by the development length, what we see is quite the opposite with the spread rate increasing from 1.5 mm/s to 1.67 mm/s as the opposing flow velocity increases from 30 cm/s ($x_d = 2$ cm) to 40 cm/s ($x_d = 11$ cm). The apparent contradiction can be explained when the effective velocities are calculated as 4.2 cm/s and 2.9 cm/s. That is, even though the opposing flow velocity increases, the effective flow velocity actually decreases in this case. In fact, the apparent lack of correlation between the spread rate and opposing flow velocity in the dimensional plot of Fig. 8(a) disappears when the spread rate, non-dimensionalized, by the pure downward spread rate is plotted against the effective flow velocity as given by Eq. (9).

Given the importance of the role of the developing boundary layer, established in this work, the Damkohler number correlations found in literature where the development length is completely ignored brings into question the validity of such results. Re-plotting the existing data with the effective velocity in place of the opposing flow velocity is not possible because the development length of the boundary layer when the flame spread rate is measured is not reported in most published work.

5. Conclusion

The effect of a developing boundary layer on spread rate is experimentally established by conducting opposed flow experiments in an eight meter tall closed chamber. The novelty of the experimental set up allows the sample to be moved at a desired speed creating a relative opposed flow velocity. Results from two different development lengths, 2 cm and 11 cm, of the boundary layer, and two different opposing flow velocities, 30 cm/s and 40 cm/s, are reported. When the spread rate is plotted against the opposing flow velocity, the result shows non-physical behavior with the spread rate sometime increasing with opposing flow velocity in the kinetic regime where just the opposite is expected. A closed form formula for the effective flow velocity seen by the flame that takes into account the boundary layer development length is used to explain the apparent contradiction. The Damkohler number correlations found in literature for the kinetic regime of opposed-flow flame spread have to be revisited to incorporate this important boundary layer effect before they can be used for quantitative purposes.
6. Acknowledgement

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7. Nomenclature

- $c_g$: Specific heat of gas, kJ/kg·K
- $c_s$: Specific heat of solid, kJ/kg·K
- $F$: Flame constant, Eq. (5)
- $f$: Radiation view factor for the gas to the solid preheat region
- $L_g$: Gas-phase diffusion length scale, m
- $T_{\infty}$: Ambient temperature, K
- $V_g$: Velocity of the oxidizer, m/s
- $V_f$: Absolute spread rate, m/s
- $V_r$: Velocity relative to the flame, $V_r = V_g + V_f$

Greek Symbols

- $\alpha_g$: Thermal diffusivity of gas, evaluated at $T_v$, m$^2$/s
- $\varepsilon$: Surface emissivity
- $\lambda_g$: Gas-phase conductivity evaluated at $T_v$, kW/m·K
- $\eta_g$: Non-dimensional flow velocity, Eq. (10)
- $\rho_g$: Gas density evaluated at $T_v$, kg/m$^3$
- $\rho_s$: Solid density, kg/m$^3$
- $\tau$: Fuel half-thickness, m
- $\sigma$: Stefan-Boltzmann constant, kW/ m$^2$·K$^4$

Subscripts

- $comb$: Combustion
- $eff$: Effective
- $g$: Gas phase
- $rad$: Radiation
- $res$: Residence
- $s$: Solid phase
- $th$: Thermal
- $vap$: Vaporization
Works Cited


Measurement of Temperature Field in a Stabilized Downward Spreading Flame

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Abstract

Although a downward spreading flame exhibits steady-state behavior in flame fixed coordinates, the propagating flame creates an unsteady phenomenon with respect to the laboratory frame of reference, making it difficult for field measurement. In this study, a spreading flame is stabilized by moving a sample holder upward at the rate of spread. This is accomplished by a PID controller that moves the sample holder through a stepper motor in order to maintain a constant temperature (voltage) reported by a gas phase thermocouple at the flame leading edge that is fixed to the laboratory frame. For flame spread over thin ashless filter paper, the stabilizer produced a stationary flame for a 120s duration. A thermocouple mounted on a dual-axis probe is used to map the flame temperature. Different thermocouple sizes and orientations are tested to reduce the heat loss due to radiation and conduction through the thermocouple wire. The temperature field is reconstructed from multiple experiments and compared with results of a numerical simulation.

Keywords: flame-spread, flame spread rate measurements, PID control, flame shape, downward flame spread, thermally thin fuel, stabilized flame
1. Introduction:

Flame spread over solid fuels in an opposed-flow configuration is a fundamental combustion problem that has attracted continued research over the last five decades [1] [2]. Not only is the topic important from a practical standpoint of fire safety, it constitutes one of the central problems related to our understanding of fire spread. While the overall mechanisms of flame spread is relatively well understood [3] [4] [5], quantitative predictions of flame spread rate and field variables, and comparison with experiments are relatively rare.

One of the most sought after variables of interest in a flame spread study is flame spread rate, the speed with which a flame creeps forward towards the virgin fuel. Beginning with de Ris’s theory [6] many theoretical studies have been devoted in predicting this spread rate while most experimental studies report the measured spread rate under various conditions. The flame spread rate is a scalar that is a function of fuel and oxidizer properties, and physical parameters such as geometric configuration, fuel thickness, oxidizer composition, oxidizer velocity, ambient pressure, and gravity level. Flame spread rate is such an important global variable that understanding and predicting this quantity is often one of the major goals of spread rate research. However, given the complexity of the problem, analytical solutions are available only on simplified regimes. The de Ris solution [6] is probably the most well-known solution for flame spread over thin and thick fuels in the thermal regimes, which have been modified or improved in subsequent theoretical studies [7] [8] [5]. A number of studies have established qualitative agreement between experimental results and prediction from flame spread formulas; however, relatively few studies have been dedicated to a comprehensive comparison of prediction of flame structure and spread rates between theory and experiments.

A spreading flame poses considerable challenges for obtaining detailed information on its structure. Measurement of the temperature and velocity field, for example, could be of great value for evaluating modeling results. Hirano et al. [9] measured the velocity field by particle tracing methods and used fine wire thermocouples to obtain temperature data for flame spread over thin cellulosic fuels. Fernandez-Pello [10] used thermocouple probes, interferometry, radiometer measurements, gas-phase chromatography, and particle-tracking photography to conclude that the dominant mode of heat transfer in flame spread over thermally thick PMMA is conduction through the solid phase. Fernandez-Pello et al. [11] also performed downward flame spread experiments on thick PMMA rods to measure temperature and velocity fields, reaching the same conclusion that conduction through the
solid phase was the dominant mechanism of flame spread. However, Ito et al. [12] used holographic interferometry to conclude just the opposite, that is, that gas phase conduction is more dominant for forward heat transfer, a conclusion that has been supported by later numerical models [13].

A number of recent experimental studies have been published on spread rates. Olson and Miller [14] experimentally studied flame spread over thin fuels in actual and simulated microgravity conditions. These experiments were conducted by using a Narrow Channel Apparatus (NCA) in normal gravity and actual microgravity. Yamamoto et al. [15] investigated downward flame spread over a thin solid fuel in a partially premixed environment. Yamamoto included hydrogen, methane, or propane in the gaseous product of the pyrolysis reaction and showed that both blue flame and luminous flame regions are enlarged, and the flame spread rate is increased. Zhang and Yu [16] performed experiments to determine the three-dimensional effects of opposed flow flame spread over thin solid materials in a natural-convection-suppressing horizontal narrow-channel. They concluded that the extent of three-dimensional effects was inversely proportional to the gas flow speed or its square. They found that the effects were significant near quenching extinction limits. However, far away from the quenching extinction limits, the effects were weak.

To mitigate the challenging experimental environment posed by a spreading flame, we proposed a new flame spread setup [17], which arrests the motion of a spreading flame to create a stable, frozen flame for experimentation. This is done by controlling the motion of the fuel sample in the opposite direction of the flame spread whereby the flame remains stationary for the spread duration. There are several potential benefits to such a configuration, the most important of which is a stabilized configuration allows a large enough residence time for field variables to be measured.

In this work we present thermocouple measurements of the temperature field of a stabilized flame. Individual measurements are then compiled to produce a two dimensional thermal image of a flame. Experimental results are compared with predicted results from a two dimensional numerical model.

2. The Flame Stabilizer:

A schematic of the experimental hardware is shown in Fig. 1. The apparatus relies on vertical velocity control of the fuel sample. A linear motion assembly was chosen [18] consisting of a
step motor, indexer, lead screw and nut, carriage, and a pair of guide rail and pillow blocks. The motor is controlled by an indexer that processes digital commands sent from the serial port of a controlling computer and produces the analog voltage signal for moving the motor. Two kill switches, connected to the AX indexer, were used at the top and bottom of the ball screw to prevent the nut from accidentally hitting the end support bearings.

The sample holder was made of two thin aluminum (or stainless steel) plates 45 cm long hinged at one end with a rectangular slot of width 3 cm (equal to the sample width) cut through both plates. A thin fuel sample (ashless filter paper) is placed between the two plates which are pressed against each using magnets or clips. The sample holder is then secured on the carriage with wing nuts. The length of the fuel sample, which controls the duration of the experiment, $L/V_f$, is limited by the length of a lead screw. In our current configuration, a burn time of more than 150s is typical for flame spread over 0.16 mm thick filter paper. Ignition is performed with either a butane lighter or using a heating wire.

A 0.01” diameter K-type thermocouple, attached to the test stand (fixed relative to the laboratory coordinates) was selected as the sensor to locate the leading edge of the flame (see Fig. 2). A National Instruments USB-9211A device with built-in sensors for cold-junction compensation is used for reading the thermocouple signal with a 24-bit resolution.

A closed loop feedback control algorithm was implemented using LabVIEW to stabilize a spreading flame. A block diagram for the digital control system is shown in Fig. 3. In this control loop, $V_t$ is the voltage signal from the thermocouple that is fixed in laboratory coordinates. As the flame approaches the thermocouple, $V_t$ increases. The digital reading of this voltage is represented by $V_{kt}$, where $k$ is an integer value representing the number of passes through the control loop. The goal of the control algorithm is to keep $V_{kt}$ as close as possible to the reference voltage $V_{ref}$; that is, to minimize the error function $V_{ek} = V_{ref} - V_{kt}$. After trying several different control algorithms, we decided that PID (proportional gain, integral time, and derivative time) control was the best choice. In this algorithm, the output signal $V_{u} = V_{kt}$ is determined using proportional, integral, and derivative information determined from the error signal. The discretized velocity algorithm for a PID controller is:

$$V_{M}^k = V_{M}^{k-1} + K \left[ V_{e}^{k} - \frac{\Delta t}{t_i} V_{e}^{k-1} + \frac{\Delta t}{t_d} V_{e}^{k-1} - 2V_{e}^{k-1} + V_{e}^{k-2} \right]$$

(10)
In this equation, $K$, $t_i$, and $t_d$ are the proportional gain coefficient, the integral time, and the derivative time, respectively. The proportional gain coefficient affects the responsiveness of feedback control and introduces a steady-state error. With the addition of integral control, the steady-state error can be eliminated at the expense of some instability. The derivative time constant is analogous to a damping coefficient that can be increased to mitigate the instability introduced by the integral control. Optimization of the Flame Stabilizer reduces to finding an optimal set of values for $K$, $t_i$, and $t_d$. These coefficients were found experimentally by first using only proportional control, and then successively introducing integral and differential controls. For our particular configuration, the values found were 7.05, 0.2 s and 1.5 s respectively.

Spread rates obtained from the stabilizer and from the video analysis of the downward spreading flame are compared in Fig. 4. The average spread rates are 1.76 mm/s from the stabilizer and 1.72 mm/s from Spotlight [19] analysis of the downward spreading flame. The difference in spread rate between the two configurations have been found [17] to be within the inherent variability in spread rate over solid fuels. For the particular hardware, a stationary flame can be observed for about 150s.

3. Flame Probe and Linear Motion Control:

With the flame turned stationary, an external probe can be used for the duration of the spread. A two-axis probe motion system is designed to position the probe accurately. The flame probe assembly consists of two linear motion controls, which give exact positioning in both the vertical and horizontal directions. The two linear motion control assemblies are similar to the one described in Sec. 2. The horizontal motion assembly is attached to the carriage of the vertical motion assembly, as shown in Fig. 5. A LabView program was developed to move the probe to any desired $x$–$y$ location.

K-type thermocouples, manufactured by Omega, are used for stabilizing the flame and flame temperature measurements. The current LabView data acquisition system limits the sampling rate to 3 Hz. These thermocouples have a temperature range from -200°C to 1250°C [20]. To obtain the smallest response time, exposed junction thermocouples and small diameter wires have been selected. A thermocouple with the diameter of 0.01” is used for stabilizing the flame. Different diameter thermocouples, 0.0015”, 0.004”, and 0.01”, are compared for the measurement of flame temperature. Because of their fragility, the 0.0015” and 0.004” probes
were installed inside ceramic tubes that were inside stainless tubes to provide protection and minimize the heat loss as shown in Fig. 6.

The thermocouple probe arm is mounted on the horizontal motion assembly. This probe arm is designed to be rigid to minimize vibration. The design allows the arms to move in a two-dimensional direction which also allows access to the testing area to load a new fuel sample after each experiment. After positioning the thermocouple close to the fuel surface, the fuel is moved up and down to ensure that the sample is vertically mounted. To calibrate the \( y = 0 \) (fuel surface) location, the probe is moved incrementally close to the surface with a bright light casting its shadow on the fuel sample. As the probe is brought closer, the shadow of the probe tip approaches the surface. We are confident this method results in an accuracy of 0.5 mm or better in positioning the thermocouple.

Unless otherwise mentioned, most of the experimental results presented in this work are for flame spread over ashless filter paper (density 518.7 kg/m\(^3\)) of thickness 0.165 mm. The sample is 3 cm wide and about 20 cm long and is held vertically in quiescent atmospheric conditions (100 kPa, 25°C, R. H. 60%).

4. Experimental Results and Discussion:

4.1 Spreading Flame:

Temperature recorded by a gas phase thermocouple located 3 mm away from the surface is recorded by a thermocouple of bead diameter 0.01" for five different runs of downward flame spread to test repeatability. The results plotted in the temperature vs. time coordinates of Fig. 7 shows significant fluctuations in temperature, especially in the trailing end of the flame. The peak temperature recorded for the runs are 1042, 990, 1023, 1083, and 1048 °C respectively. These variations are probably attributable to differences in flame shape and geometry over different runs as a flame passes a particular thermocouple. Averages over five runs show a more consistent pattern, which is adopted as our preferred way of data presentation.

To assess the sensitivity of measured flame temperature with respect to thermocouple size, two different bead diameters, 0.004" and 0.0015", are used to record the temperature at a distance 1 mm from the fuel surface. Averaged over five runs for each thermocouple, the results are presented for the first 60s (the visible flame takes only about 9s to move through
In Fig. 8, a larger bead diameter can cause significant under-prediction of flame temperature. For the 0.0015" diameter bead, the highest temperature (at a 1 mm stand-off distance) is recorded as 1041 °C while the 0.004" diameter bead produces only 832 °C, a significantly lower peak temperature.

An energy analysis of a thermocouple is complicated by the fact that, in addition to convection and radiation, there is conductive heat transfer through the thermocouple leads. In the hottest zone of a flame, a thermocouple underestimates flame temperature due to radiative losses [21], while in the cooler region radiative gain may elevate the bead temperature beyond the surrounding temperature it is meant to measure. While eliminating radiative effects on thermocouples is difficult, energy loss through conduction can be reduced if the thermocouple bead is placed parallel to a fuel surface along the width of a flame. The temperature gradient in such a direction is much lower than in a direction normal to the fuel surface. Through butt-welding, we constructed such a thermocouple hung on a bifurcated probe. Because of thermal expansion and contraction, it was easier to use a larger bead diameter in this orientation. Temperature measured using a 0.01" diameter bead in the parallel orientation is compared with the 0.0015" thermocouple in normal orientation in Fig. 9. The peak temperature recorded by the 0.01" thermocouple is in remarkable agreement with the finer thermocouple in normal orientation. The result validates the hypothesis that end loss from the thermocouple is one of the major sources of temperature measurement error.

Given the robustness of the probe in a normal orientation, all further measurements are done with the 0.0015" thermocouple. Temperature, averaged over five runs, was recorded by the thermocouple at different distances from the fuel and plotted in Fig. 10. From the knowledge of the spread rate, the temperature vs. time plots are converted to temperature vs. distance using the transformation $x = V_f t$, where $V_f$ is the measured flame spread rate. However, aligning the origin of the $x$ coordinate at different distances from the surface requires matching the time at which the flame hits the thermocouple with the rapid rise of temperature in the temperature vs. time profile. The peak temperature recorded by this thermocouple is 1040 °C at a distance of 1 mm from the flame, which is significantly below the equilibrium temperature of 1916 °C, obtained from the publicly available rich internet application for computing equilibrium solutions [22].

The temperature profiles of Fig. 10 are converted to a contour image and plotted along with a visible side view of the spreading flame in Fig. 11. Although the temperature image can use some refinement, it reproduces the visible flame shape quite well.
4.2 Stabilized Flame:

For the stationary flame produced by the Flame Stabilizer, the probe is used in two different ways. To evaluate the steadiness of the flame, the probe is stationed at different locations and the temperature is recorded for the duration of the experiment. A couple of typical runs are shown in Fig. 12, obtained at the coordinates $x = 15$ mm, $y = 1$ mm. The location of the control thermocouple (see Fig. 2) is assigned as the origin of the x-coordinate in the vertical direction. Once a flame is stabilized, the probe is moved to the desired location and then the data acquisition system is turned on, explaining the sudden rise in the recorded temperature. In this configuration, temperature remains remarkably constant. Moreover, variability between the two runs, about 27°C, is well within the standard deviation of a single run, about 30°C. However, away from the surface, the standard deviation, as well as run to run variation, increases.

In order to capture a thermal image of a flame, the thermocouple is traversed in the x-direction at a predetermined speed at a fixed distance from the surface, producing a temperature vs. distance signal. Fig. 13 shows the result of such thermocouple traces averaged over five runs (five different stabilized flames) at five different distances from the surface, giving a total of 25 experiments. Due to the stationary nature of the flame, the uncertainty with respect to the location of the thermocouple relative to the flame, as encountered in the data presented in Fig. 10, is now completely removed. The thermal image is reconstructed from this data in Fig. 14 and compared with the side view of the stabilized flame. A comparison with the corresponding thermal image, Fig. 10, of the spreading flame shows that the temperature field of a stabilized flame is almost identical to a spreading flame. Given the advantages a stabilized flame offers, any flame spread related field measurement can therefore be performed using the Flame Stabilizer.

The Flame Stabilizer currently produces only about 150s of observation time. By increasing the length of the lead screw of the motion controller, the observation time can be doubled. In addition, use of a thermocouple array can produce a much smoother thermal image.

5. Conclusion:

A novel experimental apparatus called the Flame Stabilizer has been recently proposed for the experimental study of flame spread over solid fuel in an opposed flow configuration. The stabilizer arrests the propagation of a flame by moving fuel mounted on a linear motion
system at the propagation speed in the opposite direction of the flame spread. In this work, we have compared the temperature field of a spreading flame with that of a stabilized flame using thermocouples. The size of the thermocouple is shown to significantly affect the peak temperature measurement. By changing the orientation of the thermocouple, it is established that the conduction loss through thermocouple leads is largely responsible for this temperature measurement error. While positioning the thermocouple bead parallel to the fuel surface along the width of the flame minimizes this loss, thermal expansion leads to inaccurate positioning and leads to frequent thermocouple breakage. The temperature trace at a given location produced by a stabilized flame is found to be quite steady, especially at locations close to the fuel surface. Thermal images reconstructed from the ensemble averaged thermocouple traces are remarkably similar to the visible side view for both the downward spreading and stabilized configurations.

Acknowledgment

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References:


http://microgravity.grc.nasa.gov/spotlight/


www.thermofluids.net
Fig. 1. The *Flame Stabilizer* apparatus. The stabilizing thermocouple is attached to the test stand while the sample is mounted on a carriage moved by the PID control algorithm in the opposite direction of the spread to maintain a constant thermocouple signal, thereby arresting the flame motion and anchoring the leading edge just above the thermocouple (see Fig. 3).

Fig. 2. Front and side view of a stabilized flame with the fuel moving up at the spread rate of the flame to keep the control thermocouple, fixed in the laboratory coordinates, at a constant (control) temperature.
Fig. 3. Control loop block diagram for the PID control algorithm with the goal of minimizing the error function $L_{sg}$. 

Fig. 4. Comparison of flame spread rates between downward spreading flame and flame rendered stationary by the flame stabilizer.
Fig. 5. Schematic of the probe motion system, a two-axis step motor driven linear motion system.

Fig. 6. Tubular sheathed thermocouple probe with the exposed bead of diameter 0.0015".
Fig. 7. Temperature recorded by 0.01" diameter K type thermocouples 3 mm away from the fuel surface for five different runs of downward spread over ashless filter paper.

Fig. 8. Temperature recorded by two thermocouples of different bead diameters 1 mm away from the fuel surface in downward spread of the flame.
Fig. 9. Temperature recorded by two thermocouples 1 mm away from the surface, one oriented normal to the surface and one parallel to the surface.

Fig. 10. Temperature, averaged over five runs, recorded by a 0.0015" thermocouple located at different distances from the fuel surface.
Fig. 11. A thermal image of the spreading flame reconstructed from the temperature records of Fig. 10 is compared with the visible side image of the downward spreading flame.

Fig. 12. Temperature recorded by a 0.0015" thermocouple 1 mm away from the surface and 15 mm downstream from the leading edge show a remarkable degree of steadiness and repeatability for a stabilized flame.
Fig. 13. Temperature, averaged over five runs, recorded by a 0.0015” thermocouple traversed at a constant speed at different distances from the fuel surface.

Fig. 14. A thermal image of the *stabilized* flame reconstructed from the temperature records of Fig. 13 is compared with the visible side image of the spreading flame turned stationary by the stabilizer.
Abstract

One of the challenges in the experimental study of flame spread is that, even if the flame spreads at a steady rate, the propagating flame creates an unsteady phenomenon with respect to laboratory frame of reference. As a result, only a few studies have been done where the detailed flame structure has been experimentally measured along with the spread rates. In this work, we demonstrate the feasibility of a new flame spread apparatus that moves the fuel in the opposite direction of the flame spread so as to keep the leading edge of the flame stationary with respect to the laboratory. A thermocouple, fixed to the laboratory frame of reference, in front of the leading edge of the flame senses the presence of the flame and a PID controller keeps its temperature constant by moving the sample holder, driven by a stepper motor, in the opposite direction at the velocity of the spread. Instantaneous flame spread rate and the visible flame structure are compared for a downward spreading flame over ashless filter paper with the corresponding stationary flame. The results indicate that the difference between the two configurations are within experimental uncertainties and the stabilized flame can represent a spreading flame adequately, including variability of flame spread rate and the flame geometry, for further observations.

Keywords: flame-spread, flame spread rate measurements, PID control, flame shape, downward flame spread, thermally thin fuel, stabilized flame
1. Introduction:

Flame spread over solid fuels in an opposed-flow configuration is a fundamental combustion problem that has attracted continued research over last five decades [1] [2]. Not only the topic is important from a practical standpoint of fire safety, it constitutes one of the central problems related to our understanding of fire spread. While the overall mechanisms of flame spread is relatively well understood [3] [4] [5] quantitative predictions of flame spread rates and well established data on flame spread rate and flame shapes are still relatively rare.

One of the most sought after variables of interest in a flame spread study is flame spread rate, the speed with which a flame creeps forward towards the virgin fuel. Beginning with de Ris’s theory [6] many theoretical studies have been devoted in predicting this spread rate while most experimental studies report the measured spread rate under various conditions. The flame spread rate is a scalar that is a function of fuel and oxidizer properties, and physical parameters such as geometric configuration, fuel thickness, oxidizer composition, oxidizer velocity, ambient pressure, gravity level, to name a few. It is such an important global variable that understanding and predicting the spread rate is often one of the major goals of spread rate research. However, given the complexity of the problem, analytical solutions are available only on simplified regimes. The de Ris solution [6] is probably the most well-known solution for flame spread over thin and thick fuels in the thermal regimes, which have been modified or improved in subsequent theoretical studies [7] [8] [5]. A number of studies have established qualitative agreement between experimental results and prediction from flame spread formulas; however, relatively few studies have been dedicated to comprehensive comparison of prediction of flame structure and spread rates between theory and experiments.

There is a clear need for accurate measurement of flame spread rate and flame structure because they provide the most effective measurement of a flame behavior. One of the earliest studies on flame spread rate measurement is by McAlevy and Magee in 1967 [9] who correlated flame spread rate over thick fuel bed with ambient pressure and oxygen level. Lastrina et. al [10] used both PMMA and cellulose to obtain the thick and thin limits. Parker et al [11] measured flame spread rate over index cards while Tarifa et. al [12] and Sibulkin et. al [13] measured spread rates over PMMA rods. Frey and Tien [14] measured flame spread rates at low pressures and oxygen mole fractions. But perhaps, the most extensive spread rate measurements were carried out by Fernandez-Pello et al [15] who reported the dependence of flame spread rate on ambient and fuel conditions. In all these studies, the spread rate was obtained by analyzing flame images from photography or video by tracking
the position of either the visible leading edge or, in the case of charring fuel, tracking the pyrolysis front. Because the flame is assumed to be steady, the variation of the spread rate was not reported in most of these studies. In more recent experiments [16] [17] [18] flame tracking of the flame leading edge was done with the use of digital video analysis; however, the variability in spread rate is still neglected by curve-fitting a straight line in the position vs. time data.

A spreading flame also poses considerable challenge for obtaining detailed information on its structure. Measurement of temperature and velocity field, for example, could be of great value for evaluating modeling results. Hirano et al. [19] measured the velocity field by particle tracing methods and used fine wire thermocouples to obtain temperature data for flame spread over thin cellulosic fuels. Fernandez-Pello [20] used thermocouple probes, interferometry, radiometer measurements, gas-phase chromatography, and particle-tracking photography to conclude that dominant mode of heat transfer in flame spread over thermally thick PMMA is conduction through the solid phase. Fernandez-Pello et al. [21] also performed downward flame spread experiments on thick PMMA rods to measure temperature and velocity fields, reaching the same conclusion that the conduction through solid was the dominant mechanism of flame spread. However, Ito et al. [22] used holographic interferometry to conclude just the opposite, that is, the gas phase conduction is more dominant for forward heat transfer, a conclusion that has been supported by later numerical models [23].

The challenging experimental environment posed by a spreading flame is perhaps at the root of some of the inconclusive data on flame spread. In this work, we report the design, construction, and testing of a new flame spread apparatus, which we will call the Flame Stabilizer, that freezes the spreading flame creating a stable, frozen flame for experimentation. By controlling the motion of the fuel sample in the opposite direction of the flame spread, the flame is turned stationary for the duration of flame spread. There are several potential benefits in such a configuration. Firstly, a stabilized flame allows easier access to probes for the measurement of field variables. Optical diagnostic is especially facilitated by a standing flame. Secondly, fluctuation in the flame structure can be studied and the source of any instability can be more easily identified. Thirdly, flames that are very dim can also be photographed by increasing the exposure time. Fourthly, the apparatus records instantaneous spread rate without the need for any post processing, which can be time consuming depending on the resolution of the video. Finally, the real time monitoring of flame spread rate can be used to determine effects of flame retardants on the flame spread
rate and flame shape, both of which are considered important fire hazard indicators. Conversely, effect of external radiation can be studied in this apparatus in a more consistent manner because the view factor of the radiation source and the unburned fuel remain constant in a stabilized flame.

2. Flame Stabilizer Mechanism:

2.1 Overview The purpose of the stabilizer mechanism is to perform a coordinate transformation in real time for a downward spreading flame. A flame spreading in an opposed-flow environment is an unsteady phenomenon from a laboratory reference even if the spread rate is steady. Steady-state analytical models of the spread are based on flame fixed coordinates in which the fuel approaches the flame at a relative velocity $V_f$, the spread rate, and the oxidizer approaches the flame at a relative velocity $V_g + V_f$, where $V_g$ is the opposing flow velocity. For downward flame spread in a quiescent environment, $V_g = 0$ at a sufficiently large distance upstream of the flame leading edge. The flame stabilizer mimics this modeling approach, by moving the fuel upward at $V_f$, thereby making the flame stationary. However, the boundary conditions are slightly altered because the oxidizer still moves towards the flame at $V_g$ and not $V_g + V_f$. The hypothesis to be tested is that this slight alteration in the flow boundary condition has negligible effect on the flame spread rate and flame structure because $V_f$ is small compared to the characteristic buoyancy induced opposing flow velocity.

2.2 Experimental Hardware A schematic of the experimental hardware is shown in Fig. 1. The apparatus relies on vertical velocity control of the fuel sample. A linear motion assembly was chosen [24] [19, 20] consisting of a motor, indexer, lead screw and nut, carriage, and a pair of guide rail and pillow blocks. The motor selected was a Compumotor AX83-135 two phase permanent magnet hybrid step motor. It was controlled by an indexer that processed digital commands sent from the serial port of the controlling computer and produced the analog voltage signal for moving the motor. This motion controller produced an angular velocity range of 0.01 rev/sec to 50.00 rev/sec with a resolution of 12800 steps per revolution. A steel lead screw was chosen with a pitch of 2 mm and a diameter of 10 mm, creating a range of 0.02 mm/s to 100 mm/s for the motion system. An Acetal-Teflon and Silicone anti-backlash nut was selected to transfer the load from the screw to the carriage. This nut was designed for a maximum preload of 5.2 kg and a maximum torque of 0.28 N.m. Both the lead screw and the nut were manufactured by the Precision Industrial Components Corporation. The guide rails and pillow blocks were manufactured by Thompson Industries.
Two kill switches, connected to the AX indexer, were used at the top and bottom of the ball screw to prevent the nut from accidentally hitting the end support bearings.

The sample holder was made of two thin aluminum (or steel) plates 45 cm long hinged at one end with a rectangular slot of width 3 cm (equal to the sample width) cut through both plates. A thin fuel sample (ashless filter paper or thin PMMA film) is placed between the two plates which are pressed against each other using magnets (for steel sample holder) or clips (for aluminum). The sample holder is then secured on the carriage with wing nuts. The length of the fuel sample, which controls the duration of the experiment, \( L/V_f \), is limited by the length of lead screw. In our current set up, burn time of more than 150 s is typical for flame spread over 0.16 mm thick filter paper. Ignition is performed with either a butane lighter or using heating wire. An EICO 1078 AC variable current power supply was used to produce 2.5 amps at 10 V across a 0.009” diameter nichrome wire touching the top front surface of the fuel. Method of ignition was found to have no effect on the spreading behavior of the flames.

A 0.01” diameter K type thermocouple, attached to the test stand (fixed relative to the laboratory coordinates) was selected as the sensor to locate the leading edge of the flame. It has a temperature range of 0 to 1370 °C. Selection of such a small diameter thermocouple reduces any heat-sink effect on the flame front and provides a fast response time, necessary for the stability of the control system. A National Instruments USB-9211A device with built-in sensors for cold-junction compensation is used for reading the thermocouple signal with a 24 bit resolution.

### 2.3 PID Control Algorithm

A closed loop feedback control algorithm was implemented using LabVIEW to stabilize the spreading flame. A block diagram for the digital control system is shown in Fig. 2. In this control loop, \( V_t \) is the voltage signal from the thermocouple which is fixed in the laboratory coordinates. As the flame approaches the thermocouple, \( V_t \) increases. The digital reading of this voltage is represented by \( V_{kt} \), where \( k \) is an integer value representing the number of passes through the control loop. The goal of the control algorithm is to keep \( V_{kt} \) as close to the reference voltage \( V_{ref} \); that is, to minimize the error function \( V_{error,kt} = V_{ref} - V_{kt} \). After trying several different transfer functions, it was decided that the PID (proportional gain, integral time, and derivative time) control is the best choice. In this algorithm, the output signal \( V_{out,kt} \) is determined using proportional, integral, and derivative information determined from the error signal. The discretized transfer function used is as follows:
\[ V_{m_k} = V_{m,k-1} + K \left[ V_{e,k} - V_{e,k-1} + \frac{\Delta t}{T_i} V_{e,k} + \frac{T_d}{\Delta t} V_{e,k} - 2V_{e,k-1} + V_{e,k+1} \right] \] (11)

In this equation, \( K \), \( T_i \), and \( T_d \) are the proportional gain coefficient, the integral time, and the derivative time respectively. The proportional gain coefficient affects the responsiveness of the feedback control and also introduces a steady-state error. With the addition of integral control, the steady-state error can be eliminated at the expense of some instability. The derivative time constant is analogous to a damping coefficient which can be increased to mitigate the instability introduced by the integral control. Optimization of the flame stabilizer reduces to finding an optimal set of values for \( K \), \( T_i \), and \( T_d \). These coefficients were found by experimentally by first using only proportional control, and then successively introducing integral and differential controls. For our particular set up, the values found were 7.05, 0.2 s and 1.5 s respectively. Figure 3 shows typical top and side views of a stabilized flame with the thermocouple on one side. The asymmetry of the flame is due to fluctuations, typical at the trailing edge of the flame, and should not be attributed to heat loss through the thermocouple.

2.3 Imaging Hardware and Software

For video capturing, a Logitech Webcam Pro9000 webcam was used. The webcam used a Carl Zeiss optical lenses with autofocus. The video capture resolutions are up to 1600 X 1200 with a frame rate of up to 30fps. With the set up optimized for the best close up image, the pixel resolution was determined to be about 5 pixel/mm by placing a scale alongside the fuel sample. The GOM Media Player [25] software is used to play all the recorded videos of the flame spread rate by the Logitech webcam. The player puts a time stamp on each frame, which was tested by playing the recording of a clock. It supports various different media files including AVI, MP4, FLV, WMV and more. The GOM player allows capturing a screenshot directly from the video and is also checked out for real time recording. The software itself has its timer. However, to validate the time stamp, we recorded a digital clock with the webcam and played it through the GOM player to make sure that the time stamp elapsed on the video clock matches with the actual clock indicating an accurate count of the frame rate.

To track the visible leading edge of the flame, we used the Spotlight tracking software developed in NASA [26]. This application allows the user to track an image using one or more “areas of interest”, or “AOIs”. An AOI is essentially a small rectangular region selected around the flame leading edge at a suitable starting point in the video. The software
records the pixel displacement of this region frame by frame by tracking a threshold. A guide line is used to ensure that the rectangular spot moves vertically down the sample. Threshold tracking proves to be the simplest fully automatic tracking method. After the tracking process is completed, the track data is generated and imported into a spreadsheet for further analysis.

3. Experimental Results and Discussion:

3.1 Spread Rate Unless otherwise mentioned, most of the experimental results presented in this section are for flame spread over ashless filter paper (density 518.7 kg/m$^3$) of thickness 0.165 mm. The sample which is 3 cm wide and about 20 cm long, is held vertically in a quiescent atmospheric conditions (100 kPa, 25 deg-C). To create a baseline condition, downward flame spread experiments are conducted and spread rates are calculated by the Spotlight tracking software. Instantaneous spread rates obtained from three different runs by tracking a spot at the charring edge near the centerline of the fuel sample are shown in Fig. 4. To obtain sufficient pixel resolution, the webcam is placed very close to the sample, capturing the spread video over only about 10 cm length along the sample. Over that distance, the average spread rates are calculated as 1.66 mm/s, 1.64 mm/s, and 1.65 mm/s respectively with a standard deviation of approximately 0.11 mm/s. Although spread rate can be seen to vary, a linear curve fit of the position vs. time data would produce a very high degree of correlation [27], masking the fluctuation in spread rate.

The time resolution of the fluctuations captured is not necessarily the inverse of the imaging frame rate, but is a function of the resolution $p$ (pixels per mm) of the imaging system and the flame spread rate $V_f$. In time $\Delta t$, the expected number of pixels traversed by the spot is $pV_f\Delta t$. Since the Spotlight software can count pixels at an increment of one, the condition for a less than 10% error in calculated spread rate can be written as

$$\frac{1}{pV_f\Delta t} < 0.1; \quad \Rightarrow \Delta t > \frac{10}{pV_f}$$

(12)

With a spread rate of about 2 mm/s, and a $p$ of 5 pixel/mm, the time resolution is only about 1 sec. In the results presented, spread rates were calculated using moving average over 20 frames, producing a time resolution of 0.66 s.

Step motor angular position was recorded by the flame stabilizer at 6 Hz, producing a time resolution of 0.17 s. However, the calculated velocity was averaged over four samples to match the time resolution, 0.66 s, of the Spotlight data. Velocity recorded by the flame stabilizer for three consecutive runs are plotted in Fig. 5. Although the flame is rendered
stationary by the apparatus for the entire duration of the experiment, about 170 s, data from the beginning and end of the experiments are truncated to eliminate transient behavior during ignition and extinction of the flame. For the three runs, the average spread rates recorded are 1.77 mm/s, 1.79 mm/s, and 1.82 mm/s with the corresponding standard deviation of .068 mm/s, 0.061 mm/s, and 0.068 mm/s respectively. The plot clearly establishes repeatability of the results. The high frequency fluctuations are possibly due to the control algorithm, but the low frequency variations capture the actual changes in spread rate, visible with naked eyes. To verify that, the recorded spread rates for a particular run is compared in Fig. 6 with the velocity of the sample holder by tracking a spot on the sample holder with the help of the Spotlight application. Use of a high resolution Nikon 5000 digital SLR camera produced a high resolution video (13.5 pixels/mm) at a frame rate of 24 Hz. The remarkable agreement in the velocity measured by the two methods establishes the accuracy of the PID controller in recording the instantaneous spread rates.

The success of the flame stabilizer is further demonstrated by conducting an experiment over a longer duration in which a flame is allowed to spread downward for about 30 s at which point the flame leading edge comes in contact with the gas-phase thermocouple, triggering the stabilizer mechanism. The flame is frozen at that location by the stabilizer and after about 100 s, the stabilizer is turned off at which point the flame resumes its downward spread over the remaining length of the fuel. Spread rate obtained by tracking a spot with Spotlight application at the pyrolysis front is plotted in Fig. 7 along with the spread rate recorded by the stabilizer. The average spread rates in the three segments (blue line) produced by Spotlight analysis are 1.60 mm/s, -0.05 mm/s, and 1.84 mm/s respectively with a standard deviation of about 0.15 mm/s. A perfect stabilizer would produce a zero velocity of the flame leading edge; however, the inherent unsteadiness of the flame coupled with the error in the control system produces slight variations; however, the very small value of average spread rate for a stabilized flame (-0.05 mm/s) indicates that the stabilizer performs in an excellent manner for the overall duration of the control. During the time the flame is stabilized, the spread rate recorded by the apparatus is shown by the red line in Fig. 7. The average spread rate recorded is 1.81 mm/s with a standard deviation of 0.12 mm/s. The stabilizer measurements sit right in between the Spotlight measurement of the spread rate of the spreading flame.

To determine how spread rates obtained from the stabilize compares with downward spread, two successive experiments are performed, one with the stabilizer turned off and one with the stabilizer turned on. Spread rates obtained from the stabilizer and from the video
analysis of the downward spreading flame are compared in Fig. 8. The average spread rates are 1.76 mm/s from the stabilizer and 1.72 mm/s from the Spotlight analysis of the downward spreading flame. The results clearly establish that the flame stabilizer produces a spread rate that is within the experimental uncertainty of video analysis of spread rate of a downward spreading flame. It should be stressed that while the video analysis tracks a spot at the pyrolysis front, the stabilizer sensor is located in the gas phase. The variability in spread rate (as measured by the standard deviation) produced by the stabilizer was found to be of about the same, around 0.1 mm/s, when the experiments were repeated with different thermocouple locations across the width and at different distances away from the fuel surface.

One of the primary reasons for the variability of spread rate is the non-uniformity of the leading edge, which is not always a straight line as photographed in Fig. 3. The charring front sometimes creates a wavy edge, which keeps on changing its shape with one part catching up with another as the flame spreads at a variable rate at different distances from the centerline. This probably explains the low frequency fluctuation of spread rate as can be seen in Fig. 8. If this is indeed true, the fluctuation can be reduced in a stabilized flame by introducing multiple sensors across the width of the sample. To test this hypothesis, the centerline gas-phase thermocouple is replaced by a pair of thermocouples, which are placed 2 mm away from the fuel surface and 10 mm away from each other spaced symmetrically on two sides of the centerline. The average value of the signals produced by these thermocouples is used as $V_t$ in the control algorithm (see Fig. 2). As can be seen from Fig. 9, use of two thermocouples produces a smoother spread rate (1.77 mm/s with a standard deviation of 0.04 mm/s as opposed to 1.77 mm/s with a standard deviation of 0.05 mm/s).

### 3.2 Flame Shape

Having established that the flame spread rate is not altered by the stabilizing mechanism, it remains to be seen how the flame shape or size is affected by this apparatus when compared with data from an actual downward spreading flame. Time averaged side view of the stabilized flame with exposure time of 1 s, 10 s, 20 s, and 30 s are shown in Fig. 10. The images look remarkably similar, except for the eruptions occasionally caused by the pyrolyzing chars. A more detailed comparison is made between the side view of a spreading flame and a stabilized flame in Fig. 11. In both cases the visible flames have similar shape, 15 mm long with a maximum height of about 5 mm.
4. Numerical Simulation:

A numerical model for downward flame spread over thick fuel bed [28] was developed and tested for PMMA. The model consists of the two-dimensional, steady, elliptic, partial differential equations describing conservation of energy, species, mass, and momentum in the gas phase and ordinary differential equations for conservation of mass and energy in the solid. A single-step, second order, overall reaction with finite rate Arrhenius kinetics is used for the gas phase reaction and a single-step first order Arrhenius kinetics is used for the pyrolysis reaction. The gas and solid phases are solved sequentially and are coupled by the interface conditions. Replacing the PMMA properties with those of cellulose resulted in a spread rate of 3.7 mm/s, which is comparable to the measured spread rate of 1.8 mm/s. Prediction of the flame shape also agrees reasonably well with flame images.

In the simulation of downward flame spread in a quiescent environment, the flame is regarded as stationary and the ambient atmosphere far upstream is assumed to approach the flame at the velocity of the flame. In the flame stabilizer apparatus also the flame is stationary; however, while the fuel approaches the flame at the spread rate, the ambient far upstream remains quiescent. This slight difference in fuel and oxidizer boundary condition is incorporated in the codes. The resulting simulation did not produce any appreciable difference in the spread rate. The fuel mass fraction image for the downward spreading and stabilized flame simulations are compared with the corresponding flame images in Fig. 12. The visible flame images are slightly larger than the fuel concentration images, which is reasonable to expect. What is striking however is that the images for the stabilized flame (both experiment and simulation) are almost identical to those of the spreading flame. It is therefore reasonable to conclude that the flame stabilizer do not alter the flame shape, size, or spread rate in any significant way.

5. Conclusion:

A novel experimental apparatus for the study of flame spread over solid fuel in an opposed flow configuration is proposed. The purpose of this setup is to arrest the propagation of the flame by moving the fuel mounted on a linear motion system at the propagation speed in the opposite direction of the flame spread. A gas phase thermocouple attached to the test stand serves as the sensor for the approaching flame. A PID control algorithm is developed with the objective of keeping the thermocouple temperature constant, thereby arresting the propagation of the flame, by controlling the motion of the step motor that drives the linear motion system. Instantaneous spread rate recorded by this apparatus is shown to compare
well with instantaneous spread rate of a downward propagating flame, obtained by analyzing a digital video. The flame shape and size also compare well between the two configurations. The PID control parameters developed for a particular case are found to work well for different fuel thicknesses, fuel width, and fuel type. The boundary layer created by the motion of the fuel in this apparatus, which is absent in a downward spreading flame, does not seem to create any significant difference. This is confirmed by numerical simulation using an existing model in which the velocity boundary conditions are altered at the upstream boundary of the computational domain to account for the moving fuel.

A stabilized pseudo-stationary flame provides a much larger residence time for experimental measurements. Also, because the apparatus records and displays in real time the instantaneous flame spread rate, it has the potential to serve as a simple platform to study the effect of flame retardants or other external factors such as irradiation on a spreading flame.

Acknowledgment

The research at SDSU is supported by a grant from NASA with Dr. David Urban serving as the contract monitor.
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http://www.gomlab.com/eng/GMP_download.html

http://microgravity.grc.nasa.gov/spotlight/


Fig. 1 The flame stabilizer apparatus. The stabilizing thermocouple is attached to the test stand while the sample is mounted on a carriage moved by the PID control algorithm in the opposite direction of the spread to maintain a constant thermocouple signal, thereby arresting the flame motion and anchoring the leading edge just above the thermocouple (see Fig. 3).

Fig 2. Control loop block diagram for the PID control algorithm with the goal of minimizing the error function.
Fig. 3 Front and side view of a stabilized flame with the fuel moving up at the spread rate of the flame to keep the thermocouple at the same temperature.

Fig. 4 Results from three consecutive runs obtained by video analysis using spot at the centerline shows inherent variability of instantaneous spread rate.
Fig. 5 Spread rate measured by the stabilizer for a stationary flame. Results from different runs show the same variability as in downward spreading flames.

Fig. 6 Spread rate recorded by the stabilizer is compared with the upward velocity of the sample holder obtained by tracking a mark on the sample holder using the Spotlight application.
Fig. 7 Velocity of a spot at the leading edge of the flame front obtained from video analysis. The flame stabilizer is turned on at 40 s and then turned off after 140 s.

Fig. 8 Comparison of flame spread rates between downward spreading flame and flame rendered stationary by the flame stabilizer.
Fig. 9 Comparison of flame spread rates produced by the stabilizer using different number of sensors across the width. With two thermocouples the variation in spread rate is reduced.

Fig. 10 Comparison of flame spread rates between downward spreading flame and flame rendered stationary by the flame stabilizer using the same method.
Fig. 11 Comparison of visible flame shape, obtained experimentally, between a spreading flame and a stationary flame created by the stabilizer.

Fig. 12 Comparison of flame shape between a spreading flame and a stabilized flame. (a) Experimental image of the flame; (b) Fuel mass fraction field from numerical simulation.
A Remote Controlled Automated Experimental Apparatus for Real-Time Flame Spread Measurement

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Abstract

In the experimental study of flame spread, accurate measurement of the spread rate is paramount as variability in the spread rate becomes important under different fuel-oxidizer configurations. For example, opposed-flow flame spread over solid fuels has been a research interest for several decades, with the goal of developing a fundamental understanding of the physics of fire spread. It is well known that in an opposed-flow configuration, flame spread rate remains steady even if the flame increases in size. While concurrent or wind-assisted flow is of a more practical importance in understanding spread rate for fire safety concerns, in this work we present a portable, remotely operational device that uses embedded PID control to measure the real-time spread rate of an opposed-flow flame. The apparatus is remotely controlled, using a standard 802.11 WLAN, and features two robotic arms: one translates up and down via a lead screw and holds a K-type beaded thermocouple that tracks the leading edge of a flame at a user-defined setpoint temperature (200°C is used in this research) while the second arm remains stationary and holds a thin strip of fuel (paper in this study). A Kanthal heating wire ignites the paper on the top edge via remote control and an onboard digital camcorder records flame spread. A microcontroller is used to perform real-time PID computation and stepper motor control. Flame velocity is then determined by recording the velocity of the translating arm and confirmed through video analysis using NASA’s Spotlight image analysis software. Several case studies are presented along with a discussion of the control system and supporting electronics. Velocity data recorded by the controller and separately computed by Spotlight show that real-time variations in flame velocity occur and hence flame spread rate is not a constant that can accurately be approximated through least-squares linear regression of time-position coordinates. Furthermore, we demonstrate that PID control of a translating thermocouple is an effective mechanism for measuring flame velocity, without requiring any post-processing.
effort, and that such a mechanism can be portable and controlled remotely which allows the apparatus to be used in closed systems such as a pressurized drop tower for investigating the effect of acceleration on flame velocity. Results of testing our apparatus are presented and show that real-time flame velocity is seen to vary slightly about an average velocity.

1 Introduction

Opposed-flow flame spread has been investigated for over 30 years [1,2] due to the relevance in fire safety applications. While previous research in this field has shown the mechanism of opposed-flow flame spread in a downward configuration is a well understood process [3,4,5,2,6,7], studies using experimental devices for measuring real-time flame velocity are sparse. In 1969 de Ris presented a theory describing the physics of a laminar diffusion flame spreading against an air stream over solid and liquid-fuel beds [8]. In his paper, de Ris defined the mechanism of flame spread as a process by which a flame heats unburned solid fuel, ahead of its leading edge, which then vaporizes. The resulting gaseous fuel vapor then interacts with oxygen gas present in the opposed flow of air which generates product species and heat from an exothermic combustion reaction. The heat evolved from combustion then maintains the spreading process by supplying the energy needed to vaporize proceeding sections of solid fuel. While the de Ris model is predictive of spread rate for thermally thick and thin fuels in the thermal regime, many theoretical studies have extended de Ris’ theory for various scenarios involving different fuel thicknesses and gravitational conditions [3,5,2]. These works aim to establish mathematical models that predict spread rate under different physical conditions while other studies focus exclusively on reporting spread rate. Developed analytical equations for calculating spread rate are functions governed by fuel and oxidizer mixture properties, oxidizer velocity $V_g$, ambient pressure, and gravity. Unfortunately, relatively few papers have been published that provide a comprehensive treatment of flame spread prediction with corresponding experimental results that show strong correlation between theory and experiment [4]. Early investigations by McAlevy et al. in 1967 [9] showed how flame velocity over thermally thick fuels is correlated with pressure and $O_2$ concentration. Further studies by Lastrina et al. [10] showed how flame velocity approaches different limiting velocities over thermally thick and thin samples of PMMA and cellulose fuels. Flame velocity of over index cards was investigated in 1972 by Parker et al. [11] and in 1982 measurements over solid cylindrical rods of PMMA were investigated by Sibulkin [12]. The effect of low atmospheric pressure and low $O_2$ concentration on flame velocity was reported by Frey et al. and in 1976 [13] Fernandez-Pello et al. [14] conducted extensive studies on measuring flame velocity over fuels with different
fuel-oxidizer configurations. Spread rate measurements in these studies were performed exclusively by image analysis where software [15] was used to locate either the leading edge of a flame's reaction zone or the pyrolysis front in each frame of a recorded video. At a constant frame rate, the change in position of the leading edge or pyrolysis front between successive frames is then taken to be the flame velocity. People have long assumed that flames spreading in an opposed-flow configuration propagate at a constant velocity and therefore report an overall average velocity calculated through image analysis. As shown in Figure 1, it is customary to use an image analysis package to identify the leading edge position at discrete times and then determine flame velocity by fitting a linear function through time-position coordinates and accepting the constant slope of the fitted line as the flame velocity. Researchers using this approach will claim the slope to be a good representation of velocity by showing a coefficient of determination near 1. Although a number of experimental studies have been done to measure the average spread rate of opposed flow flames in a laboratory setting, few studies have focused on investigating the inherent unsteadiness of spread. Even in very recent studies within the last two years, authors have performed object recognition and tracking on digital video and fit a linear function to the resulting position vs. time output to report an average constant spread rate [16,17,18]. Such an approach is not without limitation as instantaneous variations in velocity will not be accounted for by approximating flame velocity as a constant value obtained through least-squares linear regression. In this work we show that instantaneous variations in velocity do, in fact, occur. From a fire safety viewpoint, the average spread rate is all that is needed. However, to gain a more complete understanding of the physics of flame spread at the flame scale, it is important to be able to measure real-time variations in velocity because many situations exist in which the spread rate can rapidly fluctuate due to unsteady environmental conditions.

In this paper we present the design and use of a remote controlled device for measuring instantaneous flame velocity that uses PID control to move a translational arm, with an attached K-type beaded thermocouple, to track the location of a setpoint temperature of a downward spreading flame over ashless filter paper. We assume that the location of constant temperature upstream of a downward spreading flame represents the instantaneous position of a flame at a given time. The control system dynamically adjusts the translational velocity of the moving arm so as to maintain a position of constant temperature ahead of a flame’s leading edge. If our assumption is correct that temperature is invariant within a small (1-2mm) distance ahead of a flame’s leading edge, then the real-time velocity of the moving arm will be equal to the real-time velocity of the moving flame.
2 Measurement Apparatus

In order to develop a device for accurate instantaneous flame velocity measurement under different species, pressure, and gravitational conditions, we have constructed a portable caddy designed to fit within a long pressurized vessel that is controlled remotely. Shown in Figure 2, the apparatus consists of a 10 x 13 x 2 3/8 inch aluminum box designed to hold a Sony Vaio laptop. On each side of the box, a lead screw (1/20.8 TPI) assembly is connected to two stepper motors (step angle 1.8°, 200 steps per shaft revolution, 12VDC, 0.33A, maximum holding torque 2.3 kg-force cm). The left arm is positioned to a desired location and remains stationary during a measurement while the right arm translates in a downward direction. The left arm holds a plate shown in subfigure (c). This plate holds a Kanthal (iron-chromium-aluminum, FeCrAl) alloy igniter wire and a magnetized frame with a rectangular cutout. The frame secures an 11x3 cm strip of ashless filter paper against the plate. The right arm shown in subfigure (c) holds a 0.005in wire diameter beaded K-type thermocouple. During an experiment, the igniter wire is enabled remotely and ignites the top edge of the paper sample. The right arm then positions itself at an assumedly constant distance away from the downward propagating flame's leading edge by maintaining a constant setpoint temperature over the burn duration. The caddy includes three digital cameras: one on the top of the box facing toward the rear shown in subfigure (a), one on the left arm shown in subfigures (a) and (c) focused on the fuel plate, and a Sony Bloggie Touch camera mounted inside the main chassis and focused on the side view of the fuel sample holder. The red vertical PCB mounted to the stationary (left) arm shown in subfigure (c) is a serial 7-segment LED display that operates as a stopwatch. When the operator remotely ignites a given fuel sample, the control system will move the translational (right) arm upward to position the thermocouple bead at a location where $T_{TC} = T_{SP}$, where $T_{TC}$ is the temperature reported by the thermocouple and $T_{SP}$ is a user defined setpoint temperature. Once the control system finds $T_{TC} = T_{SP}$, the control system switches to downward translational motion and dynamically adjusts the thermocouple velocity ($V_{TC}$) to maintain the setpoint condition $T_{TC} = T_{SP}$. In this mode of operation, the user begins an experiment with the thermocouple slightly offset from the top edge of the fuel sample so the control system has an opportunity to locate the setpoint temperature while moving toward the flame's leading edge. The stopwatch is initially set to 00:00 (seconds:centiseconds) and begins incrementing time once the control system detects $T_{TC} = T_{SP}$. The time displayed on the LED display is recorded by the Bloggie camera through a hole in the box front panel, as shown in subfigure (c). This allows us to synchronize the position of the flame in the video with the position of the thermocouple. Shown in Figure 3, the ignition, control system, and
Bloggie are all controlled through a 32-bit Windows application that runs on the Vaio laptop and communicates with a USB connected microcontroller. The user begins an experiment by holding down the Ignite Fuel button until a steady flame forms on the top edge of the ashless paper sample. The 12V LiPo battery, shown in the upper right corner of the caddy rear in Figure 2(d), supplies 2A to the Kanthal heading element while the Ignite Fuel button is depressed. The camera mounted on the stationary arm is connected via USB to the Sony Vaio and displays a live image of the fuel sample so the user knows when the fuel sample has been ignited. The user then clicks the Control Mode button which activates a control system embedded in a microcontroller. Once activated, the control system will advance the translational arm upward until the setpoint condition $T_{TC} = T_{SP}$ is reached and then downward at a velocity that maintains the setpoint condition. The control system will stop tracking a propagating flame whenever the translational arm has advanced to its maximum lower position or when the control system detects the flame has extinguished. The former condition is detected through the use of a Hamlin reed switch placed at the base of the translational arm’s lead screw assembly. The reed switch is normally open and closes in the presence of a magnetic field. Each arm is affixed to an aluminum block with two linear bearings and a lead screw nut. The side of the block facing the chassis side panel contains a 0.25 in$^3$ rare earth magnet that provides a magnetic field sufficient to close the reed switch when the arm has reached its maximum bottom position. The latter condition is detected when the microcontroller finds $T_{TC} < 40^\circ C$ for at least 2s after prior establishment of the setpoint condition. A second reed switch is mounted at the top of the lead screw assembly to allow the microcontroller to detect when the arm has advanced to its maximum top position. These two reed switches protect the stepper motor from trying to advance the arm beyond its maximal upper and lower positions. The thermocouple is attached via chromel-alumel wire to an Analog Devices AD595-AQ thermocouple type-K amplifier. This amplifier provides a 10mV/°C output with ±3°C accuracy from a 5V supply and provides voltage values to a 10-bit ADC provided by a microcontroller. The Sony Bloggie is controlled through the GUI by clicking on the green round button labeled Record. This button toggles the recording/stop recording facility on the camera. After the remote viewer activates control mode by clicking the Control Mode button, the user will click the Record button to begin saving video. Once the flame has extinguished or the translational arm has reached its maximal lower position, the user can click the round button again to stop recording video. Once the control system has stopped tracking a propagating flame, the user can save stored position vs. time data to a file on the Sony Vaio by clicking the Save EEPROM Data button on the GUI. This will open a file selection dialog and allow the user to specify a filename to store saved position vs. time
data. Data is logged by the microcontroller using a Microchip 256K \textsuperscript{1} \textsuperscript{C} CMOS Serial EEPROM (model 24LC256). The format of a data file is four integer columns of ASCII text with the column assignment given in Table 1.

The output field in column 4 is a value $O$ in the range [0..100] that a linear delay function $D$ uses to adjust the time the motor waits between steps,

$$D = mO + D_{\text{max}}$$

where $D_{\text{max}} = 16385$ ms. The variable $m$ in equation (13) is the slope defined as

$$m = \frac{D_{\text{min}} - D_{\text{max}}}{100}$$

where $D_{\text{min}} = 1225$ ms. Both $D_{\text{min}}$ and $D_{\text{max}}$ were found to be the absolute shortest and longest inter-step delay times, respectively, under which the Mercury SM-42BYG011-25 stepper motor can operate. From (13) and (14) it is clear that when $O=100$, $D=D_{\text{min}}$ and the motor shaft will revolve with maximum angular velocity and when $O=0$, $D=D_{\text{max}}$ and the motor shaft will revolve with minimum angular velocity. Thus the output variable adjusts the angular velocity of the motor shaft and consequently the linear velocity of the translational arm.

Table 1. Four column format of the data logged by the microcontroller and stored on a Microchip 256K \textsuperscript{1} \textsuperscript{C} CMOS Serial EEPROM

<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in milliseconds</td>
<td>Number of stepper motor steps taken since the previous time step</td>
<td>Thermocouple temperature in °C</td>
<td>PID control output as a percentage</td>
</tr>
</tbody>
</table>

The output variable is dynamically computed by an embedded proportional–integral–derivative (PID) controller implemented on an Arduino Duemilanove microcontroller. The Arduino has an Atmel ATmega328 IC which is an 8-bit AVR RISC-based microcontroller. The microcontroller board, placed in the upper left corner of the caddy rear, is visible in Figure 2(d) and has 14 digital I/O pins, 6 analog inputs, a 6-channel 10-bit A/D converter, and a 16 MHz crystal oscillator. The Arduino connects to the caddy Vaio workstation through a USB connection. The AVR architecture implemented by the ATmega328 is
a modified Harvard architecture and uses on-chip memory for program storage. The board is powered by 5VDC supplied by the Vaio through a USB connection. We have used the Arduino PID library [19] to implement embedded PID control. This closed loop feedback mechanism uses a variation of the dependent, ideal form of the PID equation given by (15),

\[
O(t) = K_p e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau - T_i \frac{d}{dt} e(t)
\]

where
- \( O(t) \) is the controller output at time \( t \), scaled to fall in the range [0..100]
- \( K_p \) is the controller proportional gain parameter
- \( e(t) \) is the current error at time \( t \) which is equal to the difference \( T_{SP} - T_{TC} \)
- \( T_i \) is the reset time (>0)
- \( T_d \) is the derivative time (>0)

The \( K_p \) parameter defines how forceful the controller will adjust the output variable in response to the error difference \( T_{SP} - T_{TC} \). For smaller values of \( K_p \), the output value will be small and will result in a lethargic controller response. Conversely, large values of \( K_p \) will cause the control system to respond quicker to correct an error. The \( T_i \) parameter operates as a weight on the integral term to modify the effect of integral action on the output value. The integral term accumulates the total sum of the controller error over time. Since the \( T_i \) parameter falls in the denominator of the weighting factor, increasing the value of \( T_i \) dampens the effect of integral action on the output. The \( T_d \) parameter weights the derivative term to modify the influence of derivative action on the output value. The derivative term measures the rate at which the instantaneous error is changing. When the error rate of change is large and positive, the derivative term with the negative coefficient will act to decrease the output value. Similarly, when the error rate of change is large and negative, the derivative term will act to increase the output value. For example, suppose the thermocouple reports a temperature of 250\(^\circ\)C and the setpoint temperature is 200\(^\circ\)C. The instantaneous error \( e(t) \) is \( T_{SP} - T_{TC} = 200\(^\circ\)C - 250\(^\circ\)C = -50\(^\circ\)C \). In this case the thermocouple is too close to the flame front and needs to move faster in the downward direction away from the flame. The overall influence on the controller output in this case would be a positive quantity weighted by the always positive \( T_d \) gain. A board level schematic of the control system including sensors and other electronic components is shown in Figure 4. We conducted several experiments to determine optimal values of \( SP, K_p, T_i, \) and \( T_d \). These parameters were found to be 200\(^\circ\)C, 4.0, 0.0, and 0.6, respectively. When \( T_i \) is set to 0 the microcontroller disables inclusion of the integral term in computing the output variable. We found that disabling the integral term
results in better tracking about a temperature higher (effective setpoint) than the user defined setpoint, but still reasonably close to this higher temperature since the overall error accumulation will not influence the controller to maintain the exact setpoint. This behavior was found to be acceptable since the only effect was to reduce the distance between the thermocouple and the leading edge of the flame. Results for tuning the controller with different values of $T_d$ are shown in Figure 5. The optimal $T_d$ value will be that value which yields the smallest overshoot of an effective setpoint. We selected a $T_d$ value of 0.6 (black line in Figure 5) because this particular value showed the smallest standard deviation from the effective setpoint as shown in Figure 6.

3 Measurement Results

Many experiments were conducted to evaluate the performance of our flame tracking apparatus. All experimental results are based on flame spread over 11x3 cm segments of ashless filter paper with a density of 518.7 kg/m$^3$ and a thickness of 0.165 mm. These paper segments are held vertically in the fuel sample holder and ignited under standard conditions (1 bar, 25°C). To evaluate the accuracy of the control system in determining spread rate, we compared instantaneous velocity data logged by the controller with velocity calculations obtained using NASA Spotlight [15] to process the Bloggie captured video and an additional video captured using a Nikon SLR camera. The vertical resolution of the Bloggie video is 720 pixels yielding a 5.5 pixel/mm resolution in Spotlight while the Nikon video vertical resolution is 1280 pixels yielding an 11 pixel/mm Spotlight resolution. To measure the instantaneous spread rate of a flame using Spotlight, three different square areas of interest (AOI) are defined that center the leading edge of a flame against the paper background and provide a region where a sharp luminance gradient exists. Spotlight records the displacement of the high luminance pixels with respect to the lower luminance pixels and computes velocity using this displacement and time difference between successive frames. Instantaneous flame spread velocity data generated by the control system and Spotlight from performing several experiments of burning filter paper in a quiescent environment were recorded and plotted using MATLAB. Results of two selected experiments are shown in Figure 7 – Figure 10. As these four figures reveal, instantaneous velocity variations in the leading edge, as defined by a luminance gradient, are shown to exist. Figure 7 and Figure 8 show object tracking results for selected experiment 1 and Figure 9 and Figure 10 show results for experiment 2. In each experiment, object tracking was performed by analyzing
three distinct AOIs in both a frontal view video and a side view video. Figure 11 shows the pair of three AOIs used for front and side video processing.

While Spotlight determines flame velocity by tracking a luminance field, the control system determines velocity by tracking a thermal field. Figure 12 shows a close up view of the embedded PID control system tracking a flame's leading edge at a setpoint of 200°C. Results from two additional experiments measuring instantaneous spread rate using data collected by the embedded PID control system are shown in Figure 13 and Figure 14. In these two figures, flame velocity computed by the controller is compared against Spotlight calculated velocity using two separate video recordings: one from the Sony Bloggie camera and one from the Nikon SLR camera. Judging the two figures, one can see that all three sources record small variations in instantaneous velocity. One can also observe how the control system records the same trends in flame velocity as reported by Spotlight. In Figure 13, the blue line indicates the velocity at which the control system is moving the thermocouple. The Spotlight reported initial rise and fall trend from 0s to approximately 7s, the slow ramp up from 7s to 20s, the small rise and fall from 22s to 40s, and the final rise, peak, and fall from 42s to 50s is mirrored by the controller reported velocity. Similarly, in Figure 14, for the most part, the blue line is seen to fall within the same velocity range as that reported by Spotlight.

4 Conclusion

A remote controlled experimental apparatus for the measurement of real-time flame velocity over solid fuel in an opposed flow configuration has been presented. The purpose of this device is to use PID control to measure the velocity of a propagating flame by moving a translational arm with a beaded thermocouple at the same velocity as the flame by forcing the thermocouple to maintain a setpoint temperature upstream of the flame’s downward propagating leading edge. We have assumed that a thermal field of constant temperature remains at a constant distance in front of a flame’s leading edge. Real-time spread rate is recorded by a microcontroller with an EEPROM for logging real-time data. Many experiments were performed by igniting segments of ashless filter paper and the controller recorded real-time flame velocity was compared against flame velocity determined through video analysis using NASA’s Spotlight object tracking software. The control system was tuned by disabling the integral term and choosing a derivative time gain which minimized the deviation about an effective setpoint temperature. Velocity vs. time plots from several experiments were generated and these results showed the controller determined velocity.
tended to lie within the same velocity range, at any given time, as that reported by Spotlight. All the velocity vs. time results showed that variations in flame velocity occur and hence flame spread rate is not a constant that can accurately be approximated through least-squares linear regression of time-position coordinates. Furthermore, we have shown that PID control of a translating thermocouple is an effective mechanism for measuring flame velocity and that such a mechanism can be made portable and controlled remotely which allows the apparatus to be used in closed systems such as a pressurized drop tower for investigating the effect of acceleration on flame velocity. Obtaining transient information about flame behavior as the flame responds to a changing environment gives a more complete understanding of the physics of flame spread at the flame scale. Finally, measuring spread rate using a control system has an advantage over using object tracking software in that the control system outputs flame velocity in real-time. Measuring flame velocity using software is an additional post-processing task that requires an investigator to record a propagating flame using a high resolution camera and then separately process the video.
References


![Graph](image)

**Figure 1.** Distance vs. time plot produced by tracking a centerline area of interest using image analysis produces a constant spread rate of 1.64 mm/s with a high degree of correlation.
Figure 2. The SDSU drop tower caddy is designed to measure instantaneous flame velocity in opposed- or concurrent- flow conditions while being accelerated in a drop tower.

Figure 3. Windows 32-bit GUI application that runs on the caddy enclosed Sony Vaio laptop and controls the caddy microcontroller over a USB connection.
Figure 4. Board level schematic of the SDSU μFlameTracker microcontroller and connected components.
Figure 5. Effect of different derivative time parameter $T_d$ values on controller output. A $T_d$ value of 0.6 (black line) resulted in acceptable thermocouple tracking of a constant setpoint temperature.

Figure 6. The optimal derivative time parameter will be that value of $T_d$ which yields the minimum $\sigma$. 
Figure 7. Instantaneous flame spread rate computed using NASA Spotlight at three distinct AOIs labeled A, B, and C on the front view of selected experiment 1 video recorded by the Nikon SLR camera. The legend shows average spread rate at each of the three AOIs.

Figure 8. Instantaneous flame spread rate computed using NASA Spotlight at three distinct AOIs labeled A’, B’, and C’ on the side view of selected experiment 1 video recorded by the Nikon SLR camera. The legend shows average spread rate at each of the three AOIs.
Figure 9. Instantaneous flame spread rate computed using NASA Spotlight at three distinct AOIs labeled A, B, and C on the front view of selected experiment 2 video recorded by the Nikon SLR camera. The legend shows average spread rate at each of the three AOIs.

Figure 10. Instantaneous flame spread rate computed using NASA Spotlight at three distinct AOIs labeled A’, B’, and C’ on the side view of selected experiment 2 video recorded by the Nikon SLR camera. The legend shows average spread rate at each of the three AOIs.
Figure 11. Areas of interest (AOIs) defined for flame velocity measurement using NASA Spotlight. In the left subfigure, the selected AOIs labeled A, B, and C are used for velocity measurement when processing a video recording of the front view of the paper segment. In the right subfigure, selected AOIs labeled A', B', and C' are used when processing a video recording of the side view. Note that locations A, B, and C are not equal to locations A', B', and C' (i.e. location B $\neq$ B').

Figure 12. A close up view of the embedded PID control system tracking the leading edge at a setpoint of 200°C. While Spotlight determines flame velocity by tracking a luminance field, the control system determines velocity by tracking a thermal field.
Figure 13. Results of selected experiment 3: measuring instantaneous spread rate using data collected simultaneously from the embedded PID control system, video recorded by a Sony Bloggie camera, and video recorded by a Nikon SLR camera.

Figure 14. Results of selected experiment 4: measuring instantaneous spread rate using data collected simultaneously from the embedded PID control system, video recorded by a Sony Bloggie camera, and video recorded by a Nikon SLR camera.
APPENDIX B

CALCULATIONS
B.1 THERMOCOUPLE RESPONSE TIME

Thermocouple response is a transient process as the thermocouple is exposed to a flame, the energy balance according to Holman\(^1\) is written as,

\[
hA \left( T_\infty - T \right) = mc \frac{dT}{d\tau}
\]  

(1)

and the temperature of the thermocouple as a function of time can be written as,

\[
\frac{T-T_\infty}{T_0-T_\infty} = e^{-\frac{hA}{mc} \tau}
\]  

(2)

Since non-dimensional temperature is \( \theta \), Eq. (2) above could also be written as,

\[
\theta = e^{-\frac{t}{\tau}}
\]  

(3)

where \( \tau \) is the response time and is given by Holman\(^1\) as,

\[
\tau = \frac{mc}{hA}
\]  

(4)

where \( m, c, \) and \( A \) are the mass, specific heat, and area of the thermocouple, \( h \) is convection heat transfer coefficient, which can be expressed in term of Nusselt number. According to Bejan\(^2\), Nusselt = 2 for a sphere in a quiescent, no flow environment.

\[
Nu = \frac{hD}{k} = 2 \Rightarrow h = \frac{2k}{D}
\]  

(5)

where \( k \) is the thermal conductivity of the surrounding gas.

Combining Eq. (4) and Eq. (5), the time constant can therefore be expressed as,

\[
\tau = \frac{mcD}{2kA}
\]  

(6)

For a K-type thermocouple with a wire diameter of 125 μm, area can be found, and mass can be found with a known density and volume, specific heat and thermal conductivity are also known. The material properties of a K-type thermocouple are approximate as nickel since it is composed of almost entirely nickel. Density of nickel is 8900 kg/m\(^3\) and specific heat is estimate as 562 J/kg-K at 1000 K. Bead diameter of thermocouple is 2.5 times larger than wire diameter. Thermal conductively of surrounding gas is estimate to be 0.515 W/m-K. The time constant for a 125 μm wire diameter thermocouple is then therefore,


Based on Eq. (6) above, if specific heat and thermal conductivity remain constant, response time is proportional to diameter squared. Therefore for a thermocouple with a wire diameter of 250 µm, twice that of 125 µm, the response time increases fourfold, to 0.315 s.

The calculation above does not account for radiation heat transfer, as it is assume to be negligible for simplicity.

\[
\tau = \frac{(1.42 \times 10^{-7} \text{kg})(562 \text{ J/kgK})(3.125 \times 10^{-4} \text{m})}{2(0.515 \text{ W/mK})(3.07 \times 10^{-7} \text{m}^2)} = 0.0789 \text{ s}
\]
B.2 RADIATION CORRECTION FACTOR

The calculation below only accounts for the emissive losses and does not take into consideration of the incoming radiation incident on the thermocouple surface.

For a thermocouple in flame at steady state, the energy balance according to Holman\textsuperscript{1} can be written as,

\[ hA \ (T_g - T_t) = \sigma A \epsilon (T_t^4 - T_s^4) \]  

Eq. (7) above balances convection heat transfer to radiation heat loss to the surroundings. \( T_g \) is true gas temperature, \( T_t \) is thermocouple temperature, \( T_s \) is surrounding temperature, \( \sigma \) is Stefan-Boltzmann constant and \( \epsilon \) is emissivity of thermocouple surface. As discussed above in A.1, \( h \) can be expressed in term of Nusselt number, area cancels on both sides, and hence Eq. (7) becomes,

\[ \frac{2k}{D} (T_g - T_t) = \sigma \epsilon (T_t^4 - T_s^4) \]  

Solving for \( T_g \) to obtain true gas temperature yields,

\[ T_g = T_t + \frac{D}{2k} \sigma \epsilon (T_t^4 - T_s^4) \]  

The correction is applied and shown in Figure B.1 for a moving flame. The results are consisted of two thermocouple sizes, 125 µm and 250 µm wire diameter. The thermocouple orientation is parallel to reduce heat loss to conduction. Emissivity of the thermocouple surface is set conservatively at 0.5. Refer to the legend to determine the increase in temperature with radiation correction. \( T_t \) refers to thermocouple measurement and \( T_g \) refers to gas temperature after radiation correction. A noticeable but not significant temperature increase is observed after radiation correction is applied. At peak temperature an increase of 73 °C is observed for the 250 µm thermocouple and 56 °C for the 125 µm thermocouple. The corrected temperature of the 125 µm thermocouple is 1382 °C, still significantly below the calculated equilibrium temperature discussed in Section 4.4.
Figure B.1. Temperature correction from radiative loss.