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Understanding the Dynamics of Inclined Flames in Wildland Fire

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Abstract

While it is well known that flames spread faster over an inclined surface, it has been difficult to quantify this effect as it is sensitive not only to slope, but also to the depth of the burning region, fire size, ambient wind, edge effects, etc. To simplify this process, a 61 cm x 163 cm stationary gaseous burner is used to mimic a burning region of fuel of various dimensions and fire sizes over an inclined surface. A linear array of 60 micro thermocouples were mounted close to the fuel surface downstream of the burner to characterize the time-dependent location of the flame along the surface. A critical temperature drop was used to characterize the location of the flame at each time step, allowing for a probabilistic representation of the flame location to be formed. As expected, results show that the flame location along the surface and variability of the flame location increases as both the attachment length and overall heat-release rate increases. The depth of the burning region, however, plays a larger role for small fires but is not as important for larger fire sizes. The angle at which the flame presence along the surface dramatically increases, i.e. a critical angle of flame attachment, often occurs between 12 – 15°, but depends on burner dimensions, fire size, edge effects and ambient wind.

Introduction

Wildland fires are known to spread faster when on an incline or acted upon by ambient winds. Fire spread can be understood as the process of igniting downstream fuels from an existing fire. When fires occur over an inclined surface, they tend to angle towards the downstream surface, increasing both radiative and convective heating of unignited fuels, decreasing the time to ignition. Both the magnitude of heat flux and the distance over which this heat flux is applied are therefore important parameters in determining rates of flame spread. The process by which flames angle or bend over inclined surfaces is therefore of interest.

In inclined scenarios, a threshold of attachment has often been observed where entrainment from the inclined side of the fire is effectively completely obstructed, causing the flame to lay flat on the surface, significantly enhancing convective and radiative heating. Previous studies (Drysdale & Macmillan 1992, Gollner & Singh 2017, Dold 2010, Viegas 2012), have observed this phenomenon in various geometries, sometimes terming it the 'trench' effect when entrainment from the sides is restricted, often through the use of physical sidewalls. While the flame geometry and spread has been studied in these configurations, very little is presented in terms of thermal measurements downstream of the flame, which are necessary to more quantitatively model flame spread.

In this study, high-frequency thermocouples are used to characterize downstream heating and attachment from an inclined gas burner. Because many wildland fuels are very thin, fluctuations in convective heating is the dominate mode of heat transfer and driving factor in the flame spread rate (Cohen 2015). The high frequency thermocouples provide an instantaneous temperature profile down the centerline of the flame and are useful for determining flame location. Using this method, the flame location is determined for a variety of heat release rates, burner depths, and inclines. The flame location is then plotted on a probability distribution and compared to other tests in order to determine the effect of each varied parameter. Finally, general relationships between the length of attachment, heat-release rate, angle, and geometry are formed.

Experimental Apparatus

The experiments used in this study were conducted at the U.S. Forest Service, Missoula Fire Science Laboratory on a table inclinable up to 30° from the horizontal using a 61 x 183 cm sand burner, mounted flush with a nearly-adiabatic surface, as shown in Figure 1. A 61 x 61 cm sheet of ceramic fiber insulation board was mounted in front of the flame, providing a development length for incoming flows, while two 122 x 91.5 cm pieces of insulation were mounted downstream to form a continuous 183 x 244 cm inclinable surface. Insulation board was also used to create sidewalls on both sides of the downstream flame. A metal sheet was mounted flush to the surface on the upstream side of the burner in front of the ceramic fiber board to allow a boundary layer to smoothly develop from ambient flows on the upstream side.

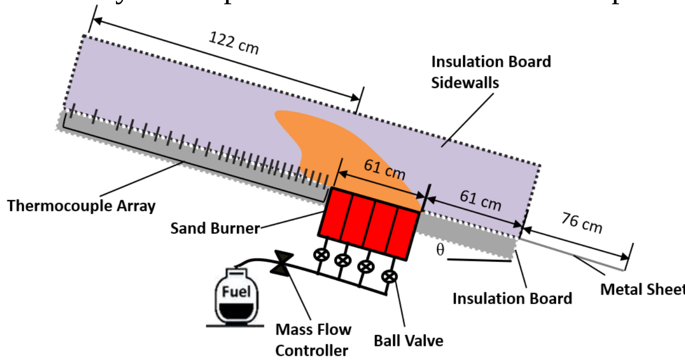

Fig 1. Schematic of the experimental apparatus mounted on a tilt table.

The sand burner used in this experiment was divided evenly, parallel to the width of the burner, into four individual regions each separated by about 15 centimeters using sheet metal spacers. These sections of the sand burner allow for four different burner depths to be studied over a wide range of heat-release rates.

A linear array of 60 K-type 50 µm diameter thermocouples were installed from below and placed 5 mm above the surface of the table. Data collected from these experiments is then used to determine how each of these factors which impact heating would be felt by fuels downstream of the burner. Temperature measurements are recorded from thermocouples using a National Instruments DAQ system at 500 samples per second per channel. Tests were performed over a range of slopes at 6° increments.

During tests, an instantaneous temperature profile down the length of the downstream surface is produced. This temperature profile provides insight into the structure of the flame, heating from the flame to a potential fuel surface, and changes in both of these quantities as a function of time. Flame attachment, which occurs during high winds or steep slopes, is a key phenomenon of interest, as movement of the flame towards the fuel surface drastically increases heating and, thus, rates of forward flame spread.

The method used in this study to define liftoff of the flame from the surface is a rate of change in temperature, measured as a function of time. It has previously been observed that cool ambient air rushes in on the back side of inclined flames after they lift off, delivering oxidizer to the flame front and potentially cooling upstream fuels (Dold 2010). This cool ambient air causes a noticeable temperature difference between adjacent thermocouples.

A MATLAB script was written to analyze the temperature data and identify the flame lift off point based on the slope of the temperature reading. An empirically-determined temperature difference threshold of 44 K/cm identified the point where the flame no longer attached, i.e. flame lift off. The distance from the edge of the downstream side of the burner and this point is considered to be the flame attachment length in this study. Figure 2 shows an instantaneous temperature curve marked with three points where the slope meets the threshold requirements. It is compared to time-averaged temperatures, shown as a dashed line.

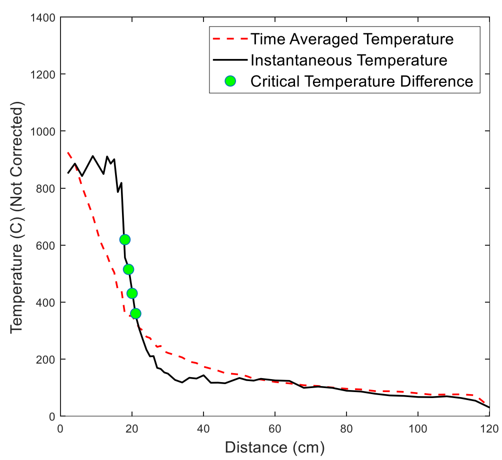

Fig 2. Instantaneous temperature profile (solid line) compared to a time-averaged profile (dashed line) downstream of the burner. Circles indicate the point where a critical temperature difference is observed, based on defined thresholds. Data comes from a 76 kW fire at an incline of 30° with a burner depth of 15 centimeters.

The recorded attachment lengths are binned a series of measurements and then applying a lognormal histogram fit. This histogram therefore shows the distribution of flame attachment lengths for each test, with the peak representing the mean flame location and its width representing the variability in flame location.

Results and Discussion

Three different fuel flowrates and four different burner sizes were used to create a total of 12 different heat-release rates per unit area. Figure 3 shows mean attachment lengths from two of the three different fuel flow rates with the heat release per unit area displayed. The mean attachment lengths were determined from the peak of the lognormal fits mentioned previously. Altering the burner depth also changes the aspect ratio of the burning region, which is another factor that could impact the downstream heating experienced by fuels in a wildland fire scenario. As the number of burners decreases, as shown in Figure 1, the aspect ratio increases, calculated by dividing the streamwise length of the burner by the width of the burner. The aspect ratio varies between 3-12 in these experiments, with the smallest values approaching a linear flame front.

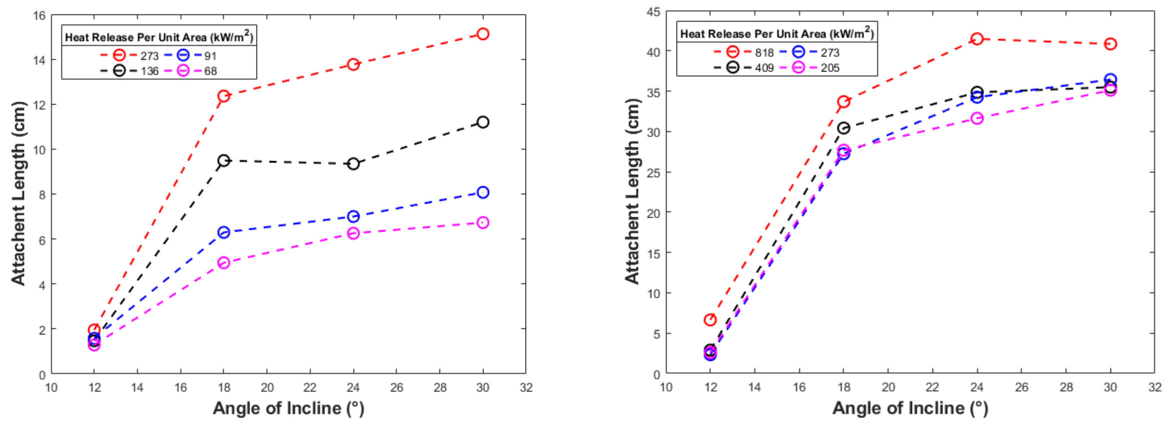

Fig 3. Plots of flame attachment length as a function of the angle of incline for different burner geometries and heat-release rates.

As expected, the overall length of the flame increases as the heat-release rate per unit area increases. However, it is shown in Figure 3 that as the overall flowrate is increased, the influence of the aspect ratio and burner area decreases. In other words, as the burning region becomes more linear and less spread out, the heat-release rate plays less of a role in influencing the downstream attachment length. This is apparent as the variation in attachment length shrinks as the flowrate is increased.

Figure 3 also shows that a sharp increase in attachment length occurs from 12° to 18°. After this transition point, the increase in attachment length is less significant with increasing inclinations. The transition to an "attached" flame from 12° to 18° has been observed before, representing the moment when a buoyant plume 'blocks' entrainment to the fire from the uphill side, causing the fire to stick to the downstream surface. A transition between 12° and 18° is consistent for all tests conducted using sidewalls with no ambient wind and agrees with previous work regarding flame attachment in inclined trenches (Wu 2000, Orloff 1975, Drysdale 1992).

Distributions of flame location can also be investigated, using lognormal fits, but under different burner depths, angles, and heat-release rates. Figure 4 shows an example of these trends for a 30° angle of incline and a fuel flow rate of 50 SLPM. The burner size is varied, increasing the total heat-release rate per unit area and aspect ratio.

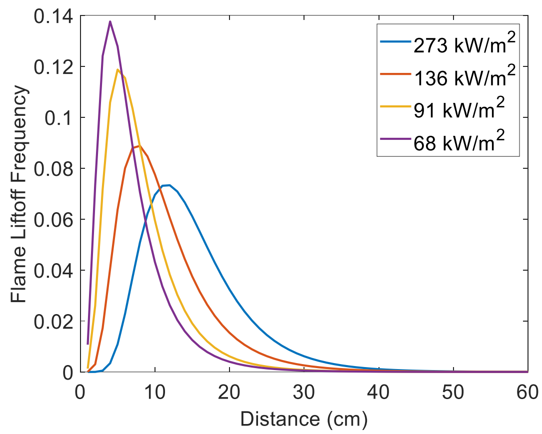

Fig 4. Histograms of flame liftoff length from four different overall heat release rates compared. Data comes from a 76 kW fire at an incline of 30° with four different burner depths.

Figure 4 shows that, as the overall heat-release rate increases, the attachment length also increases. Although more intermittent, this could have a significant effect on fine fuel heating and ignition (Cohen, 2015).

A relationship between the attachment length and all varied parameters was also explored. Figure 5 shows flame attachment lengths versus a parameter summarizing the influence of the heat-release rate, angle, and aspect ratio, shown in Figure 5. This relationship is not nondimensional or universal but helps to show the trend that exists between the attachment length, heat release and burning rate. Further work will clarify this relationship into a more universal form, connecting non-wind sloped and wind-driven fires.

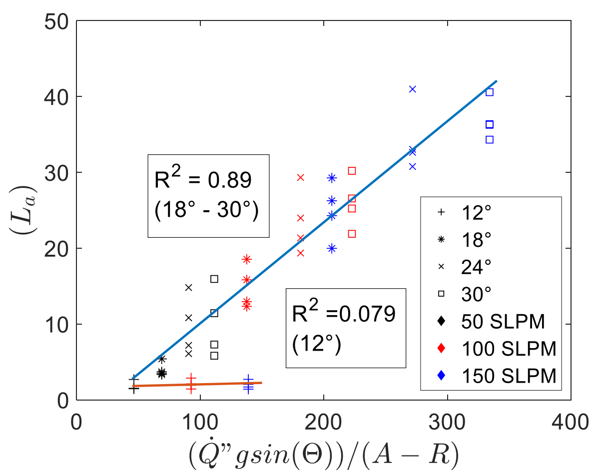

Fig 6. Attachment length vs. key parameters for tests inclined from 12° -30°. The heat-release rate was varied between 76 – 228 kW for fires with 4 different burner depths.

There is an obvious linear relationship shown in Figure 5 from the previously discussed variables within two apparent regimes. For the majority of tests, the flame is attached to the surface. This is fit with a linear function and a 0.89 R^2 value is obtained. The angle of incline is seen to be the most important parameter when considering attachment length. The heat-release rate then is the second-most important parameter, causing small changes in the attachment length seen by the vertical spread of points in Figure 5, with the colors indicating this fuel flow or overall heat-release rate

Conclusions

This work takes a new approach to capturing downstream heating from inclined fires both with and without an associated forced flow. Instantaneous temperature measurements are used to capture the location of a flame over time, which provides both time-averaged attachment lengths as well as a probabilistic representation of the flame location over sloped surfaces. The intermittent heating observed may have an impact on ignition times and therefore spread rates, especially in fine fuels commonly seen in wildland fire.

This study shows that, for fully-attached flames, there is a clear linear relationship between the attachment length of the flame and the angle, heat-release rate, and the aspect ratio. More angles need to be considered to investigate the impact of transition from attached to non-attached flames. The physics that control the transition between the attached and unattached flame must be more closely considered so that this phenomena can be better predicted. A more universal, nondimensional approach must also be developed so that these results can be scaled to larger fires in the future.

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Presenter's bio:

Evan Sluder is a Masters of Science candidate in the Department of Fire Protection Engineering at the University of Maryland, College Park. He previously earned a Bachelors of Science in the same program and is working with the USFS Missoula Fire Sciences Laboratory on research related to fire spread. His previous research has included investigation of fire whirls and the effects of intermittent heating on flame sprea