Dynamic Behavior and Structure of Wind-Blown Flames

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1 Introduction

Time-dependent movements described as pulsing, puffing or swaying are among the most visible characteristics of open flames. In the fire safety field, "puffing" of pool fires has been well studied, with scaling of the frequency of flame pulsations with the size of the burner being well correlated with the diameter of the fire size [1]. For smaller fires, a "flickering" instability at a higher frequency than "puffing" is also formed at the top of small flames [2]. Despite many years of study, the dynamics of wind-driven fires, especially those resembling a line fire configuration have not been well documented, instead focusing on their steady or averaged characteristics [3]. This configuration has recently been found to be particularly relevant when attempting to understand propagating wildland fires, prompting this more detailed study of their time-dependent behavior.

Recent studies of spreading fires in the 3×3 m wind tunnel at the Missoula Fire Science Laboratory have shown coherent structures that form in the streamwise direction of the flow as well as spanwise fluctuations that propagate to the downstream edge of the flame zone contributing to fuel heating. The highly spatially-uniform fuel beds used in these experiments allowed for the observation of these structures with more repeatable results than previous efforts [4,5]. The results suggest that flame spread in fine fuel beds is driven by non-steady convective heating and intermittent flame contact on fuel particles. These heating characteristics were measured using micro thermocouple arrays and high speed video. The travelling flaming region, however, made it difficult to carefully study these properties, such as a statistical analysis of these features which appear stochastically in the flow. A technique was therefore needed that could study these new instabilities and other general structures of propagating wildfires in a small-scale configuration that can be utilized over long times.

A stationary, non-spreading fire configuration was chosen as it allows for a thorough statistical analysis of the flame structure. Long-duration experiments allow for a large sample size and more control over variations in experimental parameters, such as decoupling the heat-release rate of the fire from flow conditions, unachievable in spreading fires. The flame zone depth in the direction of fire

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spread can also be carefully adjusted via the size of the burner. High speed video and micro thermocouples are useful on these fires to reveal and track buoyant instabilities in the fire flow which resemble those appearing in spatially-uniform fuel beds. The same intermittent heating observed in the fuel bed experiments were observed in the stationary burner, but with the ability to collect a larger data set. Other modifications to the flow field, such as the incoming boundary layer thickness is also adaptable in these small scale experiments and presented in the results.

2 Experimental Setup

Forced-flow experiments were performed on a specially-designed 30 centimeter cross section wind tunnel at the University of Maryland's Fire Phenomenon Laboratory (UMD). A laminar wind blower was designed and built for uniform forced flow combustion experiments. The wind blower was designed to pressurize a 0.75 cubic-meter plenum box with a centrifugal fan. The flow then travels through a converging section into a 30×30 cm rectangular duct into a mesh screen and honeycomb flow straightener. The flow travels another 1.35 m in the duct resulting in a fully-developed laminar boundary layer before it is exhausted at the outlet. The velocity profile of the boundary layer was measured along the centerline of the blower above the burner surface using a hot-wire anemometer. Measurements confirmed the blower is capable of repeatedly producing precise forced flow velocities between 0.6 and 4.8 ms^{-1} with turbulence intensities less than 3% at maximum velocities.

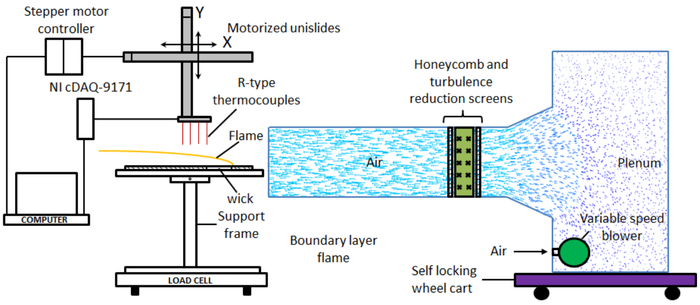

Figure 1: (A) Forced flow configuration at UMD.

High-speed videography was used to capture digital images of the flame in all configurations from both the side and top view (Figure 2). The cameras were a high-speed Casio EFX-1, recording at 120 frames per second at a 640×480 pixel resolution, mounted on a tripod mounted to the bottom of the burner surface. This allowed for observation of the flame from the upstream edge at approximately a 45 degree angle.

3 Reacting Flow Instabilities

In both spreading, forced flow (wind-driven) fires and stationary forced flow experiments two dominant instabilities have been observed. The first consisted of streamwise streaks, appearing as flame peaks and troughs when observed parallel to the direction of external flow (Figure 2). These structures resemble counter-rotating vortex pairs (Taylor-Görtler vortices) which form over concave surfaces [6]. The significance of these structures is that they splay flames downward into the fuel-bed, adding heating to the fuel surface that increases rates of flame spread. Similar structures have been observed in experiments on inclined heated surfaces with correspondingly increased rates of heat transfer noted [7]. In stationary burner experiments, flame attachment was seen to occur downstream of the burner in both forced flow and inclined experiments, facilitating heating of "unburnt" fuel and thus simulating flame spread. Within this attachment region the flame front was also observed to pulse or burst further downstream, extending the direct flame contact zone with the unburnt fuel surface far beyond the mean flame front. The frequency of these observed pulsations were then extracted from oscillations of the flame location within this attachment region. This behavior is important as it could be similar to heating of fuel particles by direct flame contact which may be responsible for flame spread, as observed in larger scale experiments [5].

In order to investigate the mechanisms responsible for these instabilities, experiments were conducted on UMD's forced flow burner apparatus to see what flow configurations were necessary for the formation of streamwise streaks. After a series of experiments, it was found that the length of the flat, inert surface leading into the flame significantly modified observed structures in the flow. A 30 cm wide, 12 cm deep porous ceramic wick was soaked with heptane and ignited in a 1.3 ms^{-1} flow with two different leading edge conditions. First, the wick was placed directly in the free stream flow, allowing for negligible boundary layer development. Second, the wick was placed parallel to the surface of the wind tunnel, providing an 8 cm boundary layer development length. Figure 2 illustrates this effect with two different configurations. The difference in the flames is striking, the uniform flow generated flame with no boundary layer development has almost no observable streaks, with a flatter, more laminar appearance (left-hand side of Figure 2). The flame with the boundary layer, however, forms strikingly coherent streaks which periodically force the flames closer to the fuel surface (troughs) or further into the air (peaks) along the width of the burner. Analysis of the two configurations utilizing methods described in the proceeding sections also showed that the boundary-layer configuration results in higher burning rates (0.8 g/s vs. 0.3 g/s), measured by a load cell and higher flame fluctuation frequencies than the uniform-flow configuration (7.3 Hz vs. 3.5 Hz). Therefore, the formation of streaks appears to be important in understanding downstream heating and thus fire spread.

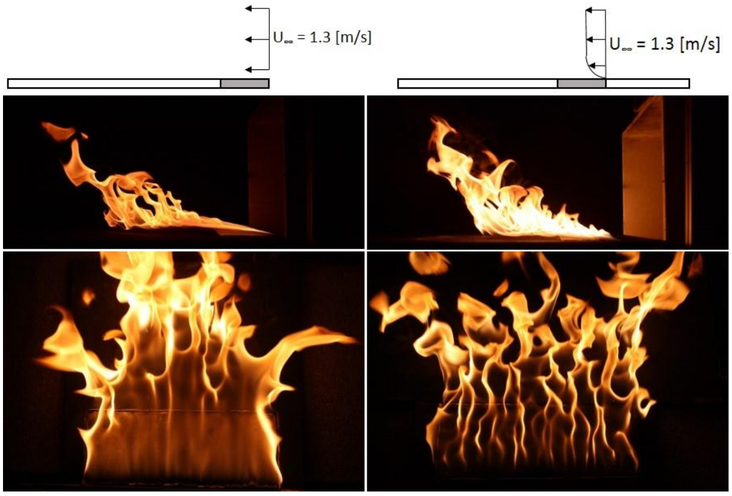

Figure 2: Boundary layer effects on a stationary wind-blown fire. (Left) No boundary layer development surface, i.e. placed directly in the free-stream flow. (Right) 25 cm boundary layer development surface (boundary layer thickness ≈ 2 cm). The fuel source was a heptane-soaked wick and an inert surface was placed downstream for all experiments to observe attachment of the flame.

4 Time-Dependent Flame Extension Analysis

Pulsations, or bursts of the flame beyond the mean flame front location were observed in spreading fire experiments as well as in stationary burners (Figure 3). The flame location in stationary experiments was determined using side-view high-speed video and an array of thermocouples ahead of the burner. A region starting at the downstream edge of the burner and extending fully downstream, 1 cm above the surface was determined as a region of interest where extension of the flame would relate to flame attachment and fuel particle heating. The flame location was then determined in this region-of-interest by tracking the furthest-most downstream tip of the flame. This location fluctuated in time and it was observed that the flame would pulse downstream, "bursting" into what would be the unburned fuel region in a spreading fire experiment.

Experimental videos were loaded into a MATLAB script for analysis. The previously described region of interest was defined from the downstream edge of the burner surface to the end of the image in the downstream direction, with a height above the surface of 1 cm (see the dashed rectangle in Figure 3). Each image in the video was cropped to this same region-of-interest and then converted to a black and white image using the same average threshold value from the streak analysis. The attached flame location (x_a) was determined as the furthest downstream pixel in the region-of-interest that satisfied the flame threshold level (Figure 3).

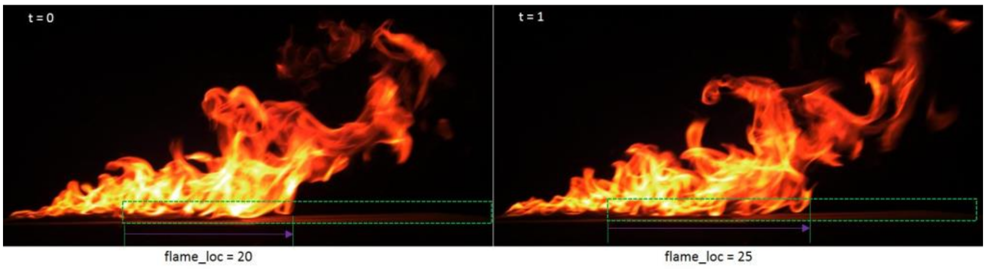

Figure 3: Flame location between two time steps in a forced flow experiment. The flame attachment location (x_a) is measured from the downstream edge of the burner to edge of the flame within the attachment region.

The flame extension downstream within the attachment region fluctuated in time, causing intermittent flame contact with the simulated unburnt fuel region (Figure 4). The frequency of the flame pulsations was determined at locations on the downstream end of the burner using a thresholding technique [4] similar to the variable interval time average (VITA) method used in analysis of turbulent boundary layers [8]. The levels were determined at a range of locations downstream of the burner, starting at the burner edge and increasing in 1 cm increments (Figure 4). The flame position in time was compared to each of these locations and the number of occurrences was tallied. A level-crossing in the VITA technique was only considered for one direction; therefore only when the flame was previously not at a location and then at it in the next time step was it considered a crossing. The frequency for each location was then determined by dividing the number of crossings by the total number of frames analyzed, and multiplying by the frame rate of the video.

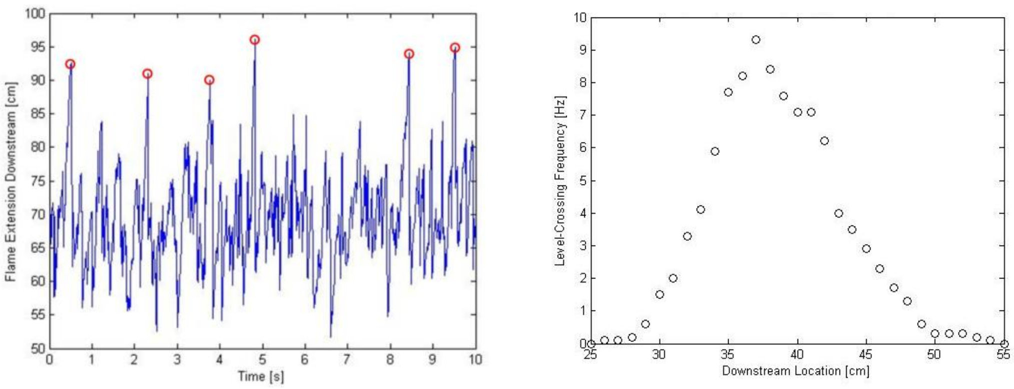

Figure 4: (Left) Flame location over time *from* high-speed videography and (right) VITA frequency at advancing downstream locations. Flame location fluctuates around the maximum frequency pulsation distance, but occasionally "bursts" further downstream (noted by red circles on the left).

In analysis of the trend of the frequency with different configurations, an analogy with pulsating pool fires was applied in the form of a Strouhal-Froude relationship. The Strouhal number,

$$\mathrm{St} = fL / U$$

where f is the VITA frequency, L is a characteristic length scale and U is the free-stream velocity, was used to non-dimensionally relate oscillating flow mechanics to a balance of momentum and buoyancy forces. For this, the Froude number was used,

$$Fr = U / (gL)^{1/2}$$

where g is the acceleration due to gravity. Following the analysis of spreading fires [5], the flame length L_f was first chosen as a characteristic length scale for the system, which represents the magnitude of the buoyant force. Further analysis showed that a more suitable parameter,

$$D^* = \left(\frac{\dot{Q}}{\rho c_p T_\infty \sqrt{g}} \right)^{2/5}$$

could be used as a characteristic length scale with $\dot{Q}$ representing the heat-release rate of the fire and $\rho c_p T_\infty$ the ambient density, specific heat and temperature, respectively. Figure 5 shows this scaling, St = 1.06 $\mathrm{Fr}^{-0.5}$ which is resolved from forced-flow gas burner experiments. The value of this exponent is below the value of -0.43 found in scaling for larger-scale fire spread experiments with L_f as the characteristic length scale [5] and the -0.5 for diameter scaling of puffing in circular pool fires [9,10]. The exponent here with D^* is almost identical to the correlation of puffing of pool fires, except the constant in front is double, compared to the correlation coefficient of 0.52 for pool fires [10]. It is important to note the St-Fr relationship for pool fires uses the fuel flow velocity instead of the ambient wind velocity (perpendicular to fuel flow direction) used for wind-blown flames.

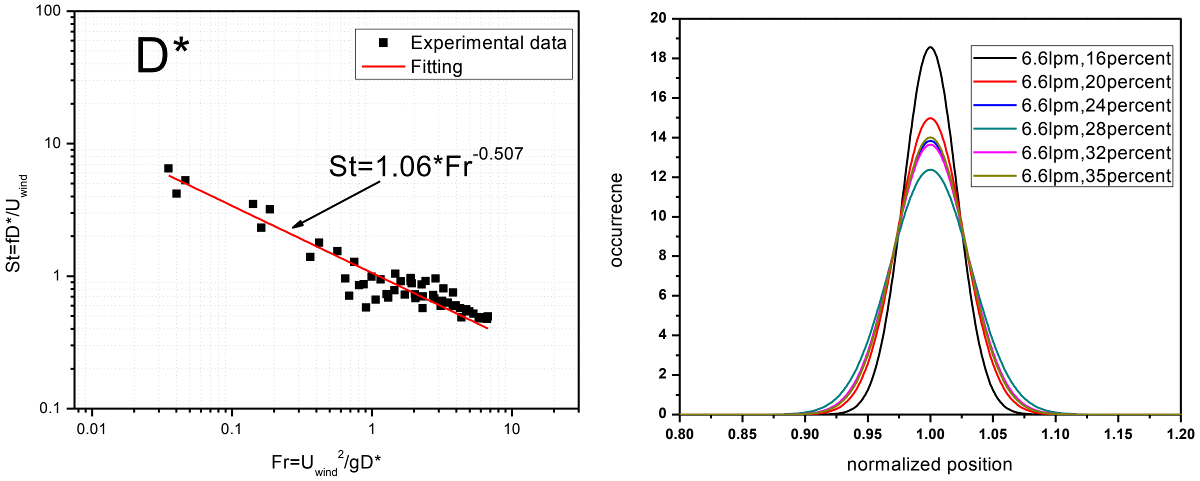

Figure 5: (*Left*) Strouhal-Froude scaling for stationary burners in a forced-flow environment and (*right*) occurrence (probability density function) of mean flame position where lpm represents the flow rate of gas and the percentage indicates % free-stream velocity from maximum (~6 m/s).

Statistical analysis of the flame position over time was also performed by producing a probability density function of the normalized flame attachment length (x_a) for different flow rates (lpm) with different free stream velocities (% of maximum) on the forced-flow gas burner. A histogram of the flame attachment length consistently shows a normal distribution of the downstream flame extension along the surface for each experiment. To compare the distribution for experiments, the attachment length was normalized with the average of the flame attachment distance in the attachment region (nominally an average flame extension along the free surface). The mean and standard deviation of the normalized flame location was then used to produce normal probability density functions, several of which are shown in Figure 5.

The representative tests shown in Figure 5 indicate increasing heat-release rates with increasing fuel-flow rate (lpm). As the heat-release rate of the fire is increased, it is clear that the peak downstream extension of the flame resides further away from its mean position and extends further downstream more often. The implications of this finding are that, despite varying flow conditions and relative fire sizes (L_f), it is the overall heat-release rate of the fire that represents increasing extension of flames beyond the mean flame length into unburnt fuels. This perhaps suggests a means for correlation or future study.

5 Conclusions

This initial study sheds some light on the buoyant dynamics of wind-driven line fires. The use of stationary gas burners has proven to be a repeatable method to generate stable flames over long timescales, whose time-dependent statistical behavior can be well characterized. The scaling analysis initially reveals that buoyant dynamics are central to the processes observed, however more work must be done to fully understand the processes contributing to the phenomenon.

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