An investigation of coherent structures in laminar boundary layer flames

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Abstract

Observations of coherent structures in boundary layer flames, particularly wildland fires, motivated an investigation on instabilities in a boundary layer flame. This experimental study examined streaklike structures in a stationary diffusion flame stabilized within a laminar boundary layer. The incoming flow was characterized with a hotwire anemometer, and locations of the flame streaks were found to align with pre-existing velocity perturbations. These upstream disturbances enabled stabilization of flame streaks, which could then be probed with point measurements. Flame streaks were seen to amplify with the stream-wise development of the fire, and this growth was quantified via thermocouple measurements. Temperature mapping of the flame streaks indicated a temperature rise in the flame streaks, while the region in between these streaks, the trough, was seen to decrease in temperature. The heat flux to the surface was measured with a total heat flux gauge. Measurements were taken below the flame streaks and below the regions between the streaks (i.e., troughs). At all measurement locations, the heat flux below the troughs was found to be higher. This was likely a function of the flame standoff distance, and indicated that the

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flame streaks were acting to modify the spanwise distribution of heat flux. The presence of instabilities had a significant effect on the spanwise distribution of heat transfer. Instantaneous properties in boundary layer combustion can vary significantly due to three-dimensional effects, and this may have significant implications for describing and modeling boundary layer combustion.

Keywords: boundary layer, instability, coherent structures, laminar, diffusion flame, streak

1. Introduction

Reactive flows within a boundary layer, representing a marriage of thermal, fluid, and combustion sciences, have been studied for decades by the scientific community. Although boundary layer combustion represents an important phenomenon in combustion, the aerodynamic structure of these boundary layers is rarely examined [1], especially for low- Re flows typifying problems in fire safety. The majority of experimental and theoretical studies on boundary layer combustion examine the problem from a two-dimensional perspective. However, a boundary layer flow field is fully three-dimensional, possessing coherent structures and vortices of various spatial orientation; this behavior is even observed in the simplest non-reacting boundary layer flows [2]. It is well-known that disturbances and instabilities in non-reacting boundary layers can produce important effects, such as transition to turbulence or variation in wall heat transfer. Yet, we still lack a fundamental understanding of how coherent structures in a boundary layer affect global and local properties of combustion, and, conversely, how combustion modifies the structure of the boundary layer.

The original motivation for this problem comes from observations in wild-land fires, which are illustrative of low- Re uncontrolled boundary layer combustion. Coherent structures have been observed across length scales in these fires, and saw-toothed flame geometry has been observed in both the laboratory and in field experiments [3]. Notably, streamwise streaks have been observed in both flames and in smoke trailing the flame (see Fig. 1), a manifestation

of counter-rotating vortices, which promote upwash and downwash regions [3]. Given recent findings that have supported convection as a dominant mechanism of preheating in wildland fire spread, there is reason to believe that the coherent structures observed in the flow field are important to the flame spread process [3]. Eddies which exist within a reactive boundary layer can control the location and development of the flame and dictate the means by which hot gases are distributed and dissipated within a boundary layer. Nevertheless, the physical mechanisms establishing these behaviors have not been satisfactorily identified, and the role of local instabilities in affecting the global properties of the flame is still unclear. The answer to this question will be relevant to types of boundary layer combustion other than wildland fires, such as that of hybrid rocket engines, process flows, building fire spread, or other wall-flame interactions. The consistent observation of streamwise streaks, in both small and large-scale fires with naturally-induced or externally-imposed winds, indicates that an account for these phenomena may be necessary for a faithful description of boundary layer combustion. Given the novelty of discussion on this phenomenon, an exploratory investigation has been undertaken to address unresolved questions, including the following: What mechanisms can produce the onset of these streaklike instabilities? What mechanisms govern their growth? Can streaks affect local gas temperatures? Do they redistribute the heat flux to the surface?

Due to the chaotic nature of turbulent flow, it is more desirable to begin by characterizing these instabilities in a laminar, well-characterized flow. In the following study, these structures were actually stabilized in a laminar boundary flame, which represents a novel and powerful approach to fundamentally characterize a streaklike instability in boundary layer combustion. A sustained streak can be carefully probed and reproduced to examine both how it responds to specific parameters and how it affects heat and mass transfer. This stabilization process enabled significant analysis of a streaklike instability in a reactive boundary layer that would not have been possible otherwise.

[Figure 1 about here.]

1.1. Similar flow structures observed in literature

Streamwise streaks are not simply a combustion phenomenon, as these aerodynamic structures are known to exist in non-reacting boundary layer flows [2]. It is understood that, in the near-wall region, streamwise counter-rotating vortices exist, and these vortices produce upwash and downwash regions. Streaks consist of the upwash regions, in which low-speed fluid from the wall is swept up into higher regions of the flow. Streaks are hypothesized to play an important role in both stability considerations and in transition to turbulence. These coherent structures consistently populate the near-wall region, with spanwise vortices being observed at the outer edge of the boundary layer [4].

In non-reactive laminar boundary layers, coherent structures have also been observed by experimentalists; in particular, streaklike instabilities are observed in the near-wall region of the boundary layer. These structures are denoted Klebanoff modes, which are often induced by low levels of freestream turbulence [5], and their breakdown promotes transition to a turbulent boundary layer [6]. These streaks produce a local thinning/thickening of the Blasius boundary layer.

Streaky structures known as Görtler instabilities appear within a boundary layer forming over a concave wall and are created by counter-rotating streamwise vortices. Flow stability in these flows is known to be affected by wall temperature [7]. Görtler vortices are known to modify wall heat fluxes [8], grow in time, decay, and cause transition to turbulence [9], effects that have also been seen or hypothesized for flame streaks.

Finally, streaks have been observed in heated boundary layers, a scenario which is roughly analogous to a boundary layer diffusion flame. Experimental studies of flow over heated plates have examined thermal instability and flow regimes in the presence of longitudinal streaks [10, 11, 12, 13, 14]. Sparrow and Husar [15] studied inclined heated plates, finding that the number of streaks increases with the temperature difference between the plate and the ambient flow. Coherent structures including thermal plumes and streaks are commonly

observed in Rayleigh-Benard convection [16].

Streaks in both laminar and turbulent boundary layers have been observed to grow, often due to the non-orthogonality of Navier-Stokes operators [17, 18, 18, 19]. In the presence of a flame, temperature and density gradients will surely contribute to the development of these three-dimensional disturbances. An instability in the boundary layer could be significantly modified once it encounters a flame. A combination of buoyant forces and vorticity could lead to a dramatic acceleration in the growth of this instability.

1.2. Boundary layer combustion

In 1956, Emmons [20] examined a diffusion flame within a boundary layer, developing a solution for the burning rate of a liquid fuel subjected to horizontal crossflow. This study represents one of the first and most well cited solutions of boundary layer combustion. Since Emmons, many researchers have delved into this phenomena, and several studies have closely examined the two-dimensional temperature field [21, 22, 23, 24]. Typically, a lack of detail on experimental configurations inhibits the generalization of results; notably, the aerodynamic structure of these boundary layers is rarely delineated [1].

In both wildland fires and laboratory-scale tests, ‘flame streaks’ (Fig. 1) represent the first observed instabilities when the boundary layer is sufficiently developed upstream of the flame. Flame streaks exhibit sawtooth flame geometry indicative of counter-rotating streamwise vortices [3]. Secondary instabilities, transition to turbulence, or conglomerations of the flame sheet into macroscopic saw-toothed structures (‘flame towers’) are also observed in these flames. The spacing of flame streaks and flame towers has been briefly investigated [25], but no connection between these parameters has been confirmed. In spreading wildfires, Finney et al. [3] displayed a linear, positive relationship between the wavelength of flame towers, which were described as Görtler vortexes, and the flame length. In stationary gas-burner flames, Gorham [26] compared the flame length with the streak spacing, obtaining almost no correlation.

Flame streaks, being the first observable instability, may dictate the downstream development of other coherent structures. Understanding the mechanisms controlling downstream structures and behaviors may only be feasible if the earliest disturbances are first characterized. For this reason, our study focuses on flame streaks, which are obtained by exposing a stationary propane burner to a laminar boundary layer. Stationary burners are advantageous over spreading fires because they have known inputs, coherent structures can be visualized more clearly, and measurements of high density and accuracy can be attained. This enables a statistical viewpoint of the flame, enabling quantification of important parameters such as flame geometry or thermal characteristics of streaks.

It is currently unknown how a boundary layer flame modifies upstream coherent structures, and, conversely, how the introduction of instabilities modifies important characteristics of the flame, including heat and mass transfer. Approximating boundary layer combustion as a two-dimensional problem does not account for these phenomena. Given current boundary layer combustion literature, which “contain[s] a large number of assumptions [which] need careful experimental support” [1], it is necessary that the impact of the three-dimensionality observed in real flows be examined more closely. This study represents a fundamental investigation into the importance of flow three-dimensionality in boundary layer combustion.

2. Experimental Setup and Procedure

A laminar wind tunnel was employed in all experimental tests. The 100 x 75 x 100-cm plenum region of the wind tunnel is pressurized by an Ebm papst variable speed blower, which is controlled via a pulse-width-modulator controller. This pressurized plenum system minimizes the effects of the blower on the airflow, which passes through a 30.48-cm converging section and turbulence reduction screens. After passing through these screens, the conditioned flow moves through a 122-cm straight section with a 30.48 x 30.48-cm cross-section,

open to the ambient. Through the combination of the pulse-width-modulator and an adjustable exhaust duct in the plenum region, exit wind velocities can reach anywhere between 0.5 to 6 m/s.

In boundary layer transition studies, the turbulence level can affect the behavior of instabilities and the transition to turbulence [27]. Beyond freestream turbulence intensities of 5%, it is impossible to identify turbulent spots or flow structures [28]. For this reason, it is vital that the turbulence level be reduced to a low intensity to ensure laminarization of the flow and experimental repeatability. Therefore, a honeycomb was employed to dampen swirl and lateral velocity variations within the flow, and wire mesh screens were used to reduce turbulence by breaking up large-scale turbulent eddies [27]. Moving downstream through the wind tunnel, these screens consisted of a 0.033-mm wire mesh, a 6:1 honeycomb, another 0.033-mm wire mesh, and a 0.017-mm mesh. The maximum Reynolds number associated with the mesh screens was 105, calculated using a wire diameter and the maximum wind velocity. In order to test flow uniformity, the wind tunnel exit was fully characterized. At all blower speeds, the turbulence intensities in the bulk portions of the wind tunnel exit were on the order of 0.3-0.6%. Low levels of turbulence were observed across the vast majority of the cross-section, so the wind tunnel was determined to be adequate for the repeatable development of a laminar boundary layer.

The rest of the experimental configuration, displayed in Fig. 2, was placed at the exit of the wind tunnel. A 0.25-inch-thick aluminum plate of length 30 cm and width of 45 cm with a super elliptical 8:1 aspect ratio leading edge was positioned nearly adjacent to the wind tunnel exit. This design was employed to minimize boundary layer separation and bluff body effects [29, 30], which could disturb the development of a laminar boundary layer, create a recirculation zone, or introduce strong disturbances into the boundary layer. For several of the flame visualization tests, this aluminum plate was replaced with 0.032-inch-thick aluminum sheets of various lengths; the thin metal lip of these sheets would minimize bluff body effects, albeit not as effectively as the machined aluminum plate. The boundary layer development length was dictated by the length of

the metal sheet or plate. Immediately following this length, a propane sand burner was placed, with its surface held flush to the lip of the aluminum. The 8-cm-deep burner was made with 3-mm-thick stainless steel with a 25 x 5-cm cross-sectional opening to the ambient. 100 % propane fuel (50.3 MJ/kg heat of combustion) entered an NPT bulkhead fitting towards the bottom, distributed within a 2-cm-tall plenum, passed through a metal honeycomb and mesh screen, and finally diffused evenly through 6 cm of multi-purpose sand (diameter of 0.1-0.5 mm). The flow rate through the sand burner was monitored by a mass flow meter connected to a propane cylinder, and care was taken to ensure gases were distributed evenly. Unless indicated, the flow rate of propane was maintained at 2.5 slpm (7.8×10^{-5} g/s). Beyond the burner, a horizontal sheet of insulation (1.27-cm-thick alkaline earth silicate wool) was used to maintain a horizontal surface over which the flame would develop. A laminar boundary layer formed over the upper surface of the apparatus, and a diffusion flame was stabilized within this boundary layer. Two 30-cm-tall sidewalls served to extend the vertical walls of the wind tunnel for 85 cm downstream; this lessened the effects of ambient mixing and eliminated disturbances due to crossflow.

[Figure 2 about here.]

Temperature measurements were made using R-type (Pt/13%Rh vs. Pt) thermocouples of 75 μm (0.003 in.) wire diameter with a bead of approximately 150 μm in diameter. The measurement range for these thermocouples extends to approximately 1900 K. The thermocouples were sheathed with a twin bore ceramic cylinder which left the bead exposed. Voltage signals from the thermocouples were acquired, conditioned, and digitized through a National Instruments 24-bit high-density 16 channel thermocouple module (NI 9214). The measurement sensitivity of this device was up to 0.2°C. LabVIEW software was employed for all data acquisition. In order to measure temperatures at precise locations in the flow, the thermocouple was mounted to a Velmex X-Y unislide, which could traverse the flame with a spatial resolution of up to 1.5 μm . This traverse mechanism enabled temperature mapping across 2-D cross-sections of the diffusion

flame. All temperature data was acquired at the rate of 100 samples/second.

Velocity measurements were made using a Dantec Dynamics MiniCTA anemometer system. This system employed a cable equipped miniature wire probe (55P16), which housed a hot wire sensor of $5\text{ }\mu\text{m}$ in diameter and 1.25 mm in length. Voltage data from the CTA was acquired using LabVIEW infrastructure at a sampling rate of 50,000 samples/second. For all velocity measurements recorded at a given spatial position, data was collected for a duration of at least 30 seconds.

Two cameras, a Nikon digital SLR camera (D7100) and a Sony digital camera (DSC-RX10M II), operating from two different vantage points were employed in order to visualize coherent structures in boundary layer flames. The Nikon was placed above the wind tunnel exit in order to photograph the flame from an overhead view. The Sony was placed downstream of the experimental apparatus, oriented into the flow and at the same level as the burner. Camera settings were adjusted in order to obtain crisp, instantaneous images of the luminous flame at intervals of approximately one second over a 30-second period. Most images clearly revealed the nature of coherent structures within the flame.

Surface heat fluxes were measured by a Vatell water-cooled total heat flux gauge (model HFM1000-0, serial number 3128) at 100 Hz. Before taking the measurement, the heat flux gauge was calibrated against a known standard incident heat flux sensor in a cone calorimeter. An amplifier was employed to make the data output readable by the data acquisition system.

3. Mechanisms driving onset of flame streaks

Streamwise streaks have been observed in both flames and in smoke from flames [3]. The observed saw-toothed structure is a manifestation of streamwise counter-rotating vortices, which promote upwash and downwash regions of the reaction zone. Dominant modes appear to govern the spanwise spacing, or the wavelenth λ , of streaks. In fact, this length scale has been shown to be lognormally distributed [26, 25] even when flame streaks are meandering. This

consistent behavior points to some sort of physical mechanism that is controlling the spacing. Although buoyancy undoubtedly plays a strong role in the late-time fluid dynamics of a wind-blown flame, it is likely that a different mechanism could govern the onset of flame streaks (at least for this particular experiment). Streaklike instabilities may actually develop due to disturbances that already exist in the incoming flow. In such a scenario, inhomogeneities associated with the incoming boundary layer would preset the spacing and onset of observed flame streaks.

Assessment of our experimental setup in light of existing literature indicates that streamwise streaks known as Klebanoff modes may appear, which are commonly observed in laminar boundary layers with low levels of free stream turbulence. The theory proposed by Goldstein et al. [28] describes how distortions in flow upstream of the leading edge can promote Klebanoff modes. Mechanisms in this paper apply for turbulence intensities of less than 5%, implying that the relevant theory is quite applicable to our experimental setup. The boundary layer on the surface of our plate likely acts as a filter for free-stream turbulence, amplifying low frequency structures to initiate Klebanoff modes. Perturbations originating from the free stream turbulence would then be passed into the boundary layer by vortex stretching at the leading edge [28, 31, 32].

We experimentally investigated whether disturbances analogous to Klebanoff modes existed in our velocity boundary layer. Hotwire anemometer measurements were taken while the burner was inactive because the maximum operating temperature of the hotwire was only 150°C . Furthermore, cold flow measurements were necessary to confirm that velocity perturbations were not induced by the flame. The spanwise distribution of streamwise velocity within the boundary layer was measured 27 cm downstream of the leading edge (3 cm ahead of the burner). Klebanoff modes have been reported to have a peak value at a Blasius η value ($\eta = y\sqrt{\frac{U}{2\nu x}}$) of about 2.3 [28]. This results in a value of $y \approx 2$ mm for $U = 2.2$ m/s, so we decided to traverse our probe 3 mm above the surface. The wind tunnel free stream velocity was 2.2 m/s and the boundary layer development length was 30-cm. Measurements were taken in the spanwise

direction every 5 mm, with a sampling period of at least 30 seconds. Results are displayed as the black line in Fig. 3, and it is immediately clear that inhomogeneities exist within the boundary layer flow. Regular velocity fluctuations of ± 0.15 m/s exist at intervals of approximately 2.6 cm.

Subsequently, the propane burner was turned on and top-view pictures of flame streaks were taken. Images were processed in MATLAB. Examining a spanwise subset of the flame streaks, the luminous intensity was obtained as a function of spanwise distance. Because the bright flame streaks are expected to appear in regions of low velocity, the luminous intensity was inverted and plotted on top of the previous velocity measurements. In this way, the peaks in velocity should correlate with the high levels of darkness between the streaks, and results are plotted in Fig. 3. Looking at this plot, we see a clear correlation between the location of the flame streaks and the velocity perturbations in the cold flow. Not only do the locations of the perturbations align well, but the amplitude of the perturbations correlates as well. When the velocity perturbation is large, the associated perturbation in luminosity is also large. This result effectively confirms the hypothesis that the flame streaks in our specific experiment are controlled by pre-existing structures in the flow.

[Figure 3 about here.]

4. Coherent structures in flame visualizations

It is common practice to employ tracers in wind tunnels to obtain greater insight into the nature of the flow field around obstructions. In boundary layer diffusion flames, the flame itself can function as a tracer, revealing coherent structures within the flame sheet. Examining these coherent structures in detail can give valuable insight into the mechanisms controlling both heat and mass transfer.

Digital SLR cameras were employed to photograph coherent structures, which were observed to change with the parameter space of the experiment

(i.e., as the wind speed and the boundary layer development was varied). Perhaps the most notable observation was due to the change in the boundary layer development length, which is depicted in Fig. 4. When the boundary layer development length was only 10-cm in length, the flame resembled a lattice, within which spanwise waves and streamwise streaks would appear, meander, and disintegrate. This behavior was reproducible at all wind velocities above 1 m/s. As the wind speed was lowered, spanwise waves propagating through the flame would become wider and more pronounced.

Markedly different behavior was observed when the boundary layer development length was extended to 30-cm in length. This experimental observation is shown in the bottom row of pictures in Fig. 4. For all wind speeds above 1 m/s, steady, streamwise streaks were observed. These streaks would not meander across the width of the burner, but would remain locked in place with only slight sinuous movements. Visible streaks would remain distinct and avoid merging with neighbors. We witnessed the transformation from a meandering, unsteady lattice to ordered, stationary streaks as the boundary layer was extended. The streak spacing is approximately 2.6 cm, which matches the wavelength of velocity perturbations from Fig. 3.

Fig. 5 displays the aforementioned observations from a surface-level viewpoint, obtained downstream of the burner. In this way, the vertical growth and development of the coherent structures is visualized. For the 10-cm boundary layer development length, structures are seen to rapidly meander across the spanwise width, exhibiting short, volatile lifespans. For the 30-cm development length, steady flame streaks exhibiting minimal fluctuations are observed across the entire width of the burner.

[Figure 4 about here.]

[Figure 5 about here.]

Examination of multiple images for different configurations enabled quantification of the spanwise spacing between streaks. In tests where the boundary

layer development length is 30 cm, image analysis reveals spacing that is on the order of 2.6 cm. As this development length is *decreased* to 10 cm, the spacing also decreases, falling to roughly 1.9 cm at the onset of the burner.

4.1. Discussion

The recognition that pre-existing structures control flame streak spacing in our configuration provides several insights into the nature of these instabilities. As a first point, this finding helps to explain the divergent behavior observed in different boundary layers: a short boundary layer development length (10 cm) produces varied, meandering structures, including spanwise waves, while consistent flame streaks will not form unless the development length is longer (30 cm). The flame appears to be taking on the coherent structures already present in the velocity boundary layer. Observed structures appear analogous to coherent structures in nonreactive boundary layers, in which streamwise vortices inhabit the near-wall region, spanwise vortices are observed in the outer region, and a mix of spanwise and streamwise vortices populate the intermediate region [4]. This behavior also mirrors observations from Rayleigh-Benard convection (natural convection phenomenon between a hot lower surface and a cold upper surface). Haramina [33] describes coherent structures, visualized with dye, moving along the hot lower surface of his water-filled apparatus. Spanwise waves are seen when the layer of dye is thicker than the velocity boundary layer; streamwise streaks are seen when the layer of dye is thinner than the velocity boundary layer. These findings are in agreement with an earlier study [16], where waves were described atop the velocity boundary layer in Rayleigh-Benard convection. Our experiments coincide with these observations. The height of the incoming boundary layer determines whether streamwise streaks, spanwise waves, or a combination of the two will inhabit the flame sheet. For this experimental configuration, the incoming velocity field, and not just the buoyant force of the flame, clearly plays a role in governing coherent structures.

Fig. 6 provides a schematic to describe the processes believed to be responsible for the onset and development of streaks in our experiment. The leftmost di-

agram depicts a flame sheet that is initially unperturbed. However, pre-existing disturbances, likely in the form of counter-rotating streamwise vortices, lie directly above the diffusion flame. These vortices create the initial perturbations associated with the flame streaks, lifting the flame in upwash regions and suppressing the flame in downwash regions. It should be noted that the upwash regions in non-reactive flow consist of fluid that has been lifted up from the near wall region; consequently, it has a low streamwise velocity [2].

[Figure 6 about here.]

5. Streak characterization

An investigation of the thermal and spatial properties of stabilized flame structures was undertaken in order to examine how local instabilities affect the macroscopic properties of the flow. The following sections detail experimental measurements undertaken in the previously described laminar wind tunnel. In all experiments characterizing the streaks, the boundary layer developed ahead of the burner over an inert distance of 30 cm. Two wind speeds (1.1 m/s and 2.2 m/s) were employed during experiments. The Froude number ($Fr = \frac{U}{\sqrt{gL}}$), is commonly employed to describe the ratio of inertia to buoyancy in wind-blown flames. In wildland fires, a flame length is often employed as the buoyant length scale L while U is taken as the free stream velocity. Using measured flame lengths for wind speeds of 1.1 and 2.2 m/s, our experimental flames possess Froude numbers of 0.7 and 1.3, respectively. Comparing these numbers with the results plotted in Finney et al. [3], our results lie in the realm of inertia-dominated boundary layer flames including wildland fires.

5.1. Flow characterization

The velocity profiles and turbulence intensities of the incoming flow were measured for both velocities, and results are displayed in Figs. 7 and 8. Measurements were obtained at three streamwise positions: the wind tunnel exit ($x = -1$ cm), near the middle of the plate ($x = 10$ cm), and just before the

burner ($x = 27$ cm). The maximum Reynold's number Re measured at the burner onset is 44000, obtained using the boundary layer development length of 0.3 m and a wind speed of 2.2 m/s. This places the incoming flow well below the transitional regime for boundary layer flow over a flat plate. Stretching of the flow around the leading edge, which acts as an airfoil, was seen to slightly increase the bulk velocity. Nevertheless, the flow remained laminar. The boundary layer thickness deviated slightly from the Blasius profile, but this was not unexpected because we already knew that inhomogeneities in the form of streamwise streaks existed in the flow. These streaks, likely analagous to Klebanoff modes, produce a local thinning/thickening of the Blasius boundary layer.

[Figure 7 about here.]

[Figure 8 about here.]

The measured velocity profiles confirm that the flame lies well within the velocity boundary layer at the burner onset; however, buoyant forces can push a flame outside the boundary layer farther downstream. Although our flame detached from the wall at the lower wind speed (1.1 m/s), the flame remained within the boundary layer.

In this laminar boundary layer, streaks remain at a fixed location; however, they will not remain stationary within a turbulent boundary layer. Turbulence will induce flame streaks to meander in spanwise directions, occasionally merging and aggregating. This behavior was accidentally witnessed in our own experimental configuration, when blockage of the screens promoted high values of turbulence. While this chaotic behavior is more representative of certain real-world flows, including wildland fires, a study of stationary flame streaks provides a novel opportunity to characterize a streaklike instability in a reactive boundary layer that would not have been possible otherwise.

At larger scales, such as a wildland fire, upstream vegetation or atmospheric instabilities could govern the disturbances which are passed into the flow. In turbulent boundary layers, streamwise streaks commonly occurring in the near-wall

region are known to have a spanwise wavelength of approximately 100 viscous wall units [34, 35, 36], a unit of measurement given by $\lambda^+ = \frac{\lambda u_\tau}{\nu} = \frac{\lambda \sqrt{(du/dy)}}{\sqrt{\nu}}$ with λ being the wavelength, u_τ the shear velocity, and ν the kinematic viscosity. Utilizing the velocity gradient (du/dy) from Figs. 7a and 8a, it can be shown that the reported streak wavelength (2.6 cm) is approximately 82 or 117 wall units for wind speeds of 1.1 and 2.2 m/s, respectively. The similarity in non-dimensional spacing between instabilities in our experiment and turbulent scenarios supports the possibility that boundary layer characteristics may provide a framework for future scaling arguments.

5.2. Temperature map

As described earlier, the flame streaks, which are preset by inhomogeneities in the upstream flow, remained stationary when the boundary layer development length was 30 cm. This behavior, attained after significant experimental refinement, presents a unique opportunity to carefully characterize important properties associated with a flame streak. In fact, we were able to use a thermocouple to obtain detailed temperature maps of a pair of adjacent streaks under two wind velocities (1.1 and 2.2 m/s) and at two streamwise locations ($x = 5$ and $x = 10$ cm). These temperature maps can be seen in Figs. 9 and 10. The reported temperatures in this experiment have not been corrected for radiative losses. An upper bound on the radiation correction was obtained using the methodology of Singh [37], a cylindrical Nusselt number correlation from Collis and Williams [38], and a platinum emissivity correlation from Jakob [39]. The correction was found to be at most +127K, obtained at the peak flame temperature. As applying this correction would only serve to increase the contrast between the flame and the surrounding gases, the current thermocouple maps provide adequate detail on the spatial variation of gas temperatures.

The temperature maps display flame streaks that amplify significantly with streamwise distance. At the first streamwise measurement location, $x = 5$ cm, the flame streaks are visible only as small perturbations. Moving downstream to $x = 10$ cm, the flame streaks grow significantly, becoming larger and more

distinct. This trend is observed at both wind speeds. The dramatic growth in the size of the flame streaks over such a short distance indicates that the buoyancy is playing an important role in the growth, which far outpaces the growth of a non-reactive boundary layer.

[Figure 9 about here.]

[Figure 10 about here.]

Additionally, the wind plays a significant role in suppressing the growth of the flame streaks. As the wind speed is increased from 1.1 to 2.2 m/s, the flame streaks at the same streamwise location are much less pronounced. The spatial growth of the flame streaks is strongly tied to the wind velocity.

This result is expected, as an increased velocity means that the flame has less *time* to develop before it reaches a designated location. The decreased *spatial* growth could simply be a consequence of a decreased amount of *time* to grow. However, it is possible that the shear from the velocity is also suppressing the growth of the streaks [40, 41]. Alternatively, the increased wind speed may even accelerate the temporal growth of the streaks by augmenting the strength of pre-existing vortices. Unfortunately, the temporal growth of the streaks cannot be known without accurate velocity measurements in the flaming region.

The overall temperature distribution at $x = 5$ cm, displayed in Figs. 9(a) and 10(a) is relatively consistent. The temperature throughout the flame sheet is fairly uniform, with no perceivable difference between the flame streaks and the trough in between. However, this uniform distribution changes considerably at $x = 10$ cm (Figs. 9(b) and 10(b)), where the temperature within the flame streaks is significantly higher than the temperature in the flame trough. For both wind speeds, the measured temperature within the flame streaks reaches more than 1300 K, but the temperature in the trough region changes significantly with wind. Under a wind of 2.2 m/s (Fig. 10(b)), the temperature of the flame trough is only about 1050 K, while the temperature declines to value of 850 K for a wind speed of 1.1 m/s (Fig. 9(b)). This represents a significant change in the spanwise

distribution of gas-phase temperatures, revealing the three-dimensional effects of the flow.

There are several explanations for this redistribution of heat. It is possible that unburnt fuel is being forced out of the troughs by the counter-rotating vortices, leaving behind a mixture that is too lean to burn. Alternatively, the low temperature in the trough could be a function of strain-induced extinction of the flame. The counter-rotating vortices, which control the onset and assist the growth of the flame streaks, may have gained enough strength to stretch the flame sheet nearer to its extinction limit. The flame sheet in our experiment resembles a counterflow diffusion flame at early stages, until it is acted upon by a counter-rotating vortex pair on the oxidizer side to induce flame streaks. Local extinction due to vortices injected from the oxidized side in a counterflow burner has previously been observed numerically and experimentally [42, 43, 44]; Thevenin et al. [42] even witnessed intensified combustion adjacent to the area of quenching. This parallels the temperature map in Fig. 9(b), which portrays local extinction at the region of vortex penetration buttressed by heightened temperatures in the adjacent flame streaks.

The variation of temperature was also processed, and the largest fluctuations were seen at the interface between the flame sheet and the air on either side of the flame streaks. This indicates a slight meandering of the streaks from side-to-side, revealing a possible sinuous nature of these instabilities. This movement mimics the behavior of Görtler vortices, a possible analog for flame streaks which has been previously discussed [3]. Similar to the flame streaks in this experiment, Görtler instabilities do not have a natural mechanism of wavelength selection, but they amplify the instabilities imposed by the experimental facilities on the incoming flow [45]. Görtler vortices are known to modify wall heat fluxes [8], grow in time, decay, and cause transition to turbulence [46], effects that have also been seen or hypothesized for flame streaks.

5.3. Streak amplification

Linear temperature profiles, measured at the centerline of either a prominent streak or trough, were obtained for both wind speeds. Measurements were made every 5 cm in the streamwise direction, and all profiles were obtained along a designated streak and a designated trough. These profiles were used to create a spatial map of the flame streaks and flame troughs. Establishing 1000 K as the outer edge of the flame sheet enabled a spatial mapping that agreed with visual observations. Both the upper and lower extents of the flame streaks and troughs were established and plotted in Figs. 11 and 12. Fig. 11 displays the shape of the flame streaks at two wind speeds. At 1.1 m/s, the streak extends to twice the height of the streak exposed to a crosswind of 2.2 m/s. The growth of the flame streak appears to be accelerating at this low wind speed, indicated by the concave upper surface. Additionally, this streak is seen to flare out downstream, extending upward and downward so as to occupy a significant depth before burning out. Meanwhile, the streak at 2.2 m/s remains narrower, and a deceleration of growth is indicated by the convex shape of the upper surface. The wind clearly plays a strong role in determining the shape of the flame streak; however, varying the wind speed minimally affects the shape of the troughs. At both wind speeds, the trough remains attached to the surface, exhibiting negligible growth at $x = 10$ cm. Both troughs also burn out quickly, exhibiting a streamwise length that is only half that observed by the adjacent flame streaks.

[Figure 11 about here.]

[Figure 12 about here.]

The growth of the flame streaks and the suppression of the flame troughs is a consequence of the counter-rotating streamwise vortices and the natural buoyancy of the flame (see schematic in Fig. 6). The accelerated growth of the streaks strongly points to the role of buoyancy, indicating that the amplification of these instabilities may be similar to the growth of a Rayleigh-Taylor Instability (RTI), which is controlled by the density difference between a suspended

heavy fluid and a lower lighter fluid. Scaling laws to describe the growth and mixing of RTI's have been established; consequently, it was desirable to investigate whether this scaling could also describe the amplification of a flame streak. The growth of an RTI is typically characterized by the height or amplitude of the perturbations, often measured by the peak-to-trough difference in height. In our measurements, this distance is the difference between the upper extent of the flame streak and the upper extent of an adjacent trough, as the top of the flame sheet represents the rational choice for a density interface. This perturbation amplitude has been plotted vs. the streamwise distance in Fig. 13. At both wind speeds, this perturbation height appears to grow exponentially. Additionally, the growth appears to be doubled when the wind speed is halved.

[Figure 13 about here.]

This buoyant amplification could potentially be described by scaling laws for a Rayleigh-Taylor Instability (RTI). Early-time RTI growth is described by linear stability theory, but the early-time resolution of our measurements is inadequate for comparison. After the earliest stage of growth, nonlinear terms begin to play a role in the amplification of RTI's. At sufficiently late times, the development of the mixing height has been assumed to scale with αAgt^2 [47, 48], where α is a dimensionless coefficient characterizing the growth, A is the Atwood number, g the gravitational constant, and t is time. The Atwood number, A , is determined from a density difference such that $A = (\rho_1 - \rho_2)/(\rho_1 + \rho_2)$ where ρ_1 is the density of the heavier fluid. The growth of our flame streaks does not quite reach the regime where α asymptotes to a constant value, instead residing somewhere between the extensively-studied linear and quadratic growth. Fortunately, two numerical studies in particular have tabulated growth covering this transition regime for flows with Atwood numbers similar to our experiment ($A = 0.5$). Both Burton [49] and Cook et al. [50] have performed numerical simulations and tabulated instantaneous values of α as a function of a dimensionless time parameter, t/τ , where τ , a dimensionless progress variable, is defined as $\tau = \sqrt{\lambda/(Ag)}$. In order to examine

the scaling of α vs. these parameters, the following equation describing the late-time perturbation height [51] was fit to the downstream perturbation heights measured in our experiment:

$$H(t) = \alpha A g t^2 + 2(\alpha A g h_0)^{1/2} t + h_0 \quad (1)$$

Here, h_0 is a virtual starting thickness established by the perturbation height at the beginning of the curve fit and the time at this point is $t = 0$. It is standard practice to measure α by fitting Eq. 1 to data on the perturbation amplitude, but typical values, even in the asymptotic range, often vary between experiments [49, 51]. Applying Eq. 1 to our data, we obtain Fig. 14 using $\alpha = 0.14$ for the wind speed of 1.1 m/s and $\alpha = 0.17$ for the wind speed of 2.2 m/s. The quadratic fit aligns well with our downstream data points, and we can now compare our measurements for α vs. values in the literature. This comparison can be seen in Fig. 15. The data from Cabot et al. [51] fails to fully extend to the regime of our data, but the α values obtained from Burton’s simulations [49] match remarkably well with our data.

[Figure 14 about here.]

[Figure 15 about here.]

Overall, Rayleigh-Taylor scaling seems to present a viable option for describing the growth of a flame streak in a laminar boundary layer. Behavior during the transition to nonlinear growth appears to be within reasonable agreement with existing literature. However, the growth of the flame streaks may not be governed entirely by buoyancy. Pre-existing vorticity in the flow, while it may not be a dominant mechanism of instability amplification, likely contributes to the growth as well. The narrowing of the trough region may also play a role, as this will confine the vortices and intensify their strength. A full decomposition of streak growth into its constituent mechanisms is beyond the scope of this paper. Regardless, buoyancy, induced and proliferated by the combustion reaction, still asserts itself as the most likely driver of streak amplification.

Additionally, the detailed experimental data we have provided may serve to validate future numerical simulations, which are likely needed to further probe these instabilities.

5.4. *Surface heat fluxes*

Although the streaks had been mapped with a thermocouple, it was still unclear what role they played in the overall heat transfer of the flame. In particular, it was unknown how the wavelike pattern of streaks and troughs affected the heat flux distribution to the surface, a controlling parameter in processes such as wildland fire spread. Consequently, a Vatell water-cooled heat flux gauge was employed to measure the total heat flux, and this device was mounted flush with the surface downstream of the burner. All measurements were taken under a flame streak or below a trough region in order to quantify the difference in heat flux between these structures. Four positions downstream of the burner were examined, $x = 10, 15, 20$, and 25 cm under two wind velocities, 1.1 and 2.2 m/s. Results are displayed in Figs. 16 and 17. The heat flux below the troughs, displayed as a dashed line, is greater than the heat flux below the streaks at all measurement locations. This indicates that the flame streaks are playing a significant role in modifying the spanwise distribution of the heat flux. This finding corresponds with the temperature profiles measured earlier, which indicated higher near-surface temperatures below the troughs.

[Figure 16 about here.]

[Figure 17 about here.]

The increased heat flux below the trough regions is likely a function of the flame standoff distance. Although we saw earlier that the flame streak can be significantly hotter than the trough, the flame sheet at the streaks is forced up and away from the surface by the upwash from counter-rotating streamwise vortices. Meanwhile, the trough is being pressed towards the ground by the downwash of the vortex pairs, decreasing the standoff distance from the surface and increasing the heat flux delivered.

5.5. Discussion

This study has identified two distinct regimes of the flame, streaks and troughs, which are differentiated not only by their visual appearance, but also by markedly different thermal properties. The flame streaks exhibit increased gas temperatures in a region that is lifted away from the surface. Meanwhile, troughs consist of a flame sheet which is forced downward, delivering a higher heat flux to the surface. Clearly, instabilities in boundary layer combustion can have an effect on the spanwise distribution of heat transfer. This finding has significant implications for boundary layer combustion, indicating that instantaneous properties can vary significantly in a three-dimensional flow field. While factors which increase the meandering of instabilities, such as turbulence, will serve to wash out *spatial* variation in the spanwise direction, there is still reason to expect that the mere presence of these instabilities could significantly alter time-averaged properties. In the first place, it is well-known that scalar dissipation affects flames, even influencing their stability and extinction [52]. The combined effect of powerful streamwise vortices, which would alter scalar dissipation, could serve to modify the large-scale behavior of a wind-blown flame. Secondly, the time-averaged properties of the flame can be considered to be the summation of intermittent fluctuations. As of yet, the role of intermittency in heating due to flames is still an area of active research. Finally, real-world situations exist where dominant instabilities will remain relatively stationary in boundary layer flames. For instance, upstream obstacles can introduce instabilities through vortex shedding. Downstream of this shedding process, dominant instabilities will be introduced to flames, potentially modifying important properties such as heat transfer. Results from this study have highlighted the ability for local instabilities to affect macroscopic properties of the flame. More research is necessary to investigate different regimes of instabilities in boundary layer combustion, but this study provides an experimental framework for future investigations.

6. Conclusion

This study examined the impact of streaks on a small-scale stationary flame in a laminar boundary layer. Initial observations revealed a strong dependence of the behavior of flame streaks on the development of the velocity boundary layer. Pre-existing velocity perturbations within the upstream boundary layer were employed to control the location of flame streaks. The temperature field was mapped by a thermocouple, and significant amplification of flame streaks was seen over the duration of the flame. The accelerated growth of streaks within the flame pointed to the influence of buoyancy, and results were determined to be compatible with Rayleigh-Taylor scaling. Gas-phase temperature redistribution, in the form of a higher temperature at flame streaks, highlights the variability of local properties due to the three-dimensional nature of the flow. Lower temperatures were observed in trough regions, but the decreased flame standoff distance enabled a higher heat flux below the troughs.

Two distinct regions of the flame, streaks and troughs, have been identified and shown to possess markedly different thermal properties. These instabilities clearly modify both the spanwise distribution of heat flux to the surface and the internal temperatures at the flame sheet. This finding has significant implications for boundary layer combustion, indicating that instantaneous properties can vary significantly due to a three-dimensional flow field. Scenarios may certainly exist where the typical two-dimensional assumption fails to capture controlling mechanisms of heat and mass transfer. We have seen that an understanding of pre-existing sources of instability may be essential in describing coherent structures in a laminar boundary layer flame. Results from this study have highlighted the ability for local instabilities to affect macroscopic properties of the flame. More research at different scales is necessary to extrapolate these results to different regimes of instabilities in boundary layer combustion, but this study provides an experimental framework for future investigations.

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(a) 1.1 m/s, velocity profile

(b) 1.1 m/s, turbulence intensity profile

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(a) 2.2 m/s, velocity profile

(b) 2.2 m/s, turbulence intensity profile

Figure 8: Vertical velocity and turbulence intensity profiles taken at a freestream wind velocity of 2.2 m/s.

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Figure 15: Examining the estimated value for α based on the best quadratic fits to our data. The two points display the calculated values while the lines represent values from existing literature [51, 49]. Plots are made vs. dimensionless time.

Figure 16: Measured heat fluxes vs. streamwise distance at a wind speed of 1.1 m/s. The solid black line indicates the heat flux measured below a streak while the dashed red line indicates the heat flux measured below a trough.

Figure 17: Measured heat fluxes vs. streamwise distance at a wind speed of 2.2 m/s. The solid black line indicates the heat flux measured below a streak while the dashed red line indicates the heat flux measured below a trough.