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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 streamwise 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 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.

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 wildland 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

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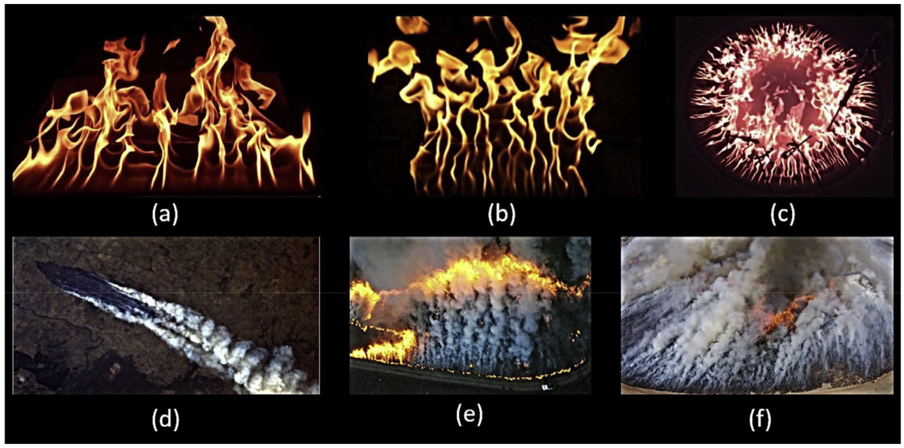

Fig. 1. Coherent structures in the form of streaks observed in wind-blown flames. Clearly visible streaky structures can be seen emanating from the leading edge of all these wind-blown flames. (a) Top view of flames from an inclined ethylene burner (b) Top view of propane burner in crossflow (c) Ring fire at Missoula Fire Sciences Laboratory (d) View of Australian brush fire from International Space Station (Credit: NASA/ Chris Hadfield) (e) Aerial view of flames and smoke from prescribed burn (NPS/ John Nobles) (f) Closing the circle on a prescribed burn, Deerhead, KS (https://youtu.be/lcLnhs4FXvI).

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.

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 [10–14]. 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 [17–19]. 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 [21–24]. 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].