Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Investigating coherent streaks in wildfires via heated plates in crosswind

Colin Miller[a], Mark A. Finney[b], Sara McAllister[b], Evan Sluder[a], Michael J. Gollner[a,*]

[a] University of Maryland Department of Fire Protection Engineering, 4356 Stadium Dr, College Park, MD 20742, USA
[b] Missoula Fire Sciences Laboratory, US Forest Service, 5775 US Highway 10 W, Missoula, MT 59808, USA

ARTICLE INFO

Keywords:
Heat transfer
Wildfires
Flame spread
Boundary layer
Coherent structure
Streak
Infrared
Thermography

ABSTRACT

Streaklike coherent structures are consistently observed in boundary layer flames, but their role in modifying heat and mass transfer remains unknown. In the following experiment, a non-reactive thermal plume was employed to study analogous streaks in an environment where the local source of buoyancy could be directly modified. A horizontal hot plate was exposed to crossflow, and infrared thermography was successfully employed to capture thermal traces of streaks on the surface. Post-processing of surface temperature data enabled the quantification of important properties of streaks, such as location, spacing, width, and strength. The distribution of streak spacing was found to have a lognormal distribution. Mean streak spacing and width increased with downstream distance, indicating the amplification and aggregation of coherent structures. Streak spacing decreased when either the hot plate temperature increased from 150 °C to 300 °C or the wind speed increased from 0.5 to 1.2 m/s. Streaks were seen to modify the spanwise distribution of heat transfer to the surface, most notably when the hot plate temperature was increased from 150 °C to 300 °C.

1. Introduction

Although boundary layer combustion has been studied for decades by the scientific community, the aerodynamic structure of this phenomenon is largely untouched [1], especially for the low-*Re* flows characteristically encountered in fire safety. Nevertheless, recent observations of coherent structures in wildland fires have prompted new discussions on the three-dimensional nature of boundary layer combustion. In particular, flames subjected to a crosswind have exhibited streaklike structures, observed across a wide range of length scales in both flames and in smoke trails (Fig. 1). These structures are manifestations of counter-rotating streamwise vortices, which promote upwash and downwash regions in the flame sheet [2]. Given recent findings supporting convection as a dominant mechanism of preheating in wildland fire spread [2], there is reason to believe that observed coherent structures are influential in the flame spread process. Nevertheless, the physical mechanisms establishing such behavior have not been identified, and the role of local instabilities in governing the global properties of the flame is still unclear. In order to more faithfully describe and model boundary layer combustion, a deeper understanding of these structures may be necessary. Further knowledge will also be useful for the development and validation of Computational Fluid Dynamic (CFD) models of flame spread, where near-wall heating effects can play a dominant role.

Ever since Emmons [3] developed a solution for the burning rate of a liquid fuel subjected to horizontal crossflow, most studies have continued to examine boundary layer combustion from a two-dimensional perspective. Several studies [4–7] have carefully assessed the two-dimensional temperature field, but a lack of detail on the experimental configuration, particularly on the aerodynamic structure of the incoming boundary layer, can inhibit the generalization of results [1]. In reality, all boundary layers are inherently three-dimensional; coherent structures and vortices of various spatial orientation populate even the simplest non-reactive boundary layer flow [8].

In both wildland and laboratory-scale fires, streaklike structures (‘flame streaks’) are seen when the boundary layer is sufficiently developed upstream of the flame [9]. The spanwise spacing, or the wavelength λ, of streaks appears to exhibit repeatable behavior; in fact, this wavelength exhibits a lognormal distribution [9] even when flame streaks are meandering. This consistent behavior points to some sort of physical mechanism that is controlling the spacing. We currently lack an understanding of how flame streaks affect wind-blown flames such as wildland fires. Unfortunately, combustion within a boundary layer significantly complicates the problem of resolving the heat and mass transfer properties of flame streaks. For this reason, an experimental investigation of streaks in non-reactive flow presents itself as a viable first step in characterizing the fundamental mechanisms involved. In low-*Re* flames, buoyancy is expected to play a prominent role; consequently, analysis of non-reacting buoyant plumes may provide key insights into observed behavior while avoiding the complications

* Corresponding author.
E-mail address: mgollner@umd.edu (M.J. Gollner).

http://dx.doi.org/10.1016/j.firesaf.2017.03.035
Received 3 February 2017; Accepted 15 March 2017

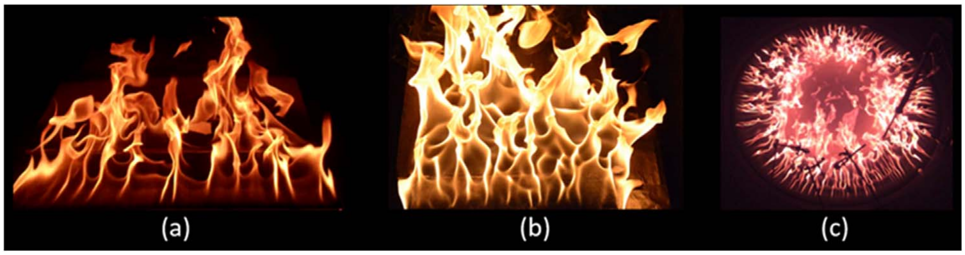

Fig. 1. Coherent streaks observed in wind-blown flames. (a) Inclined ethylene burner (b) Propane burner in crossflow (c) Ring fire at Missoula Fire Sciences Laboratory.

associated with combustion. In a flame, the internal temperature cannot be easily modified, and this limitation makes it difficult to assess and scale the role of buoyancy. However, employing a hot surface as the heat source enables the strength of buoyancy to be manipulated directly through the surface temperature. This direct scaling enables a well-characterized analog, from which the role of buoyancy in modifying flame streaks can be assessed.

Other researchers have also investigated streaks in heated boundary layers, studying the onset of thermal instability and identifying flow regimes [10–14]. These streaks have been shown to modify heat transfer, which deviated from values predicted by two-dimensional theory [10]. Sparrow and Husar [15] studied natural convection on inclined heated plates and found that the number of streaks is positively correlated with the temperature difference between the plate and the ambient flow. Coherent structures including thermal plumes and streaks are also regularly observed in Rayleigh-Benard convection [16], which refers to the natural convective circulation occurring between a hot lower surface and a cold upper surface. In this phenomenon, streamwise streaks are observed within the boundary layer while spanwise waves are seen atop the velocity boundary layer [16,17].

Streaks are routinely observed in boundary layer flames, including both wildland fires and laboratory-scale tests. These flame streaks are the first observed instabilities, at least when the boundary layer is sufficiently developed upstream of the flame. In these flames, luminous streaks meandering across the flame sheet can be readily identified with the naked eye. However, streaks are not visible in heated air flow over a hot plate. Point measurements, such as thermocouples, could be employed to track these streaks, but an inordinately large number of these invasive devices would be necessary to track streaks, which meander rapidly across the width of the hot plate. As these structures appear very close to the wall, reflections complicate the use of laser-diagnostic techniques for flow observation. A non-invasive method with high spatial resolution would be ideal; for this reason, infrared thermography was chosen as the best candidate for tracking streaks. Streaks can be detected by examining the temperature fluctuations on the surface of the hot plate. This is possible because streaks are controlled by counter-rotating streamwise vortices, in which upwash regions force warmer near-wall fluid upward while downwash regions push cooler ambient fluid towards the surface (see Fig. 2). This produces an alternating heating/cooling effect on the surface, and these temperature fluctuations will be directly correlated with the location of a nearby streak.

In the following, we propose a technique for detection and tracking of streaks over an isothermal hot plate. This methodology enables the quantification of several important streak parameters, including location and spacing. Because this detection strategy is inherently associated with the magnitude of surface temperature fluctuations, it also provides information associated with the heat transfer properties of these coherent structures. The macroscopic behavior of both non-reacting thermal plumes and boundary layer flames is governed by a competition between momentum and buoyancy. By manipulating either the ambient wind velocity or the surface temperature, the behavior of these streaks can be scaled directly with these important mechanisms. The following experimental study investigates this relationship.

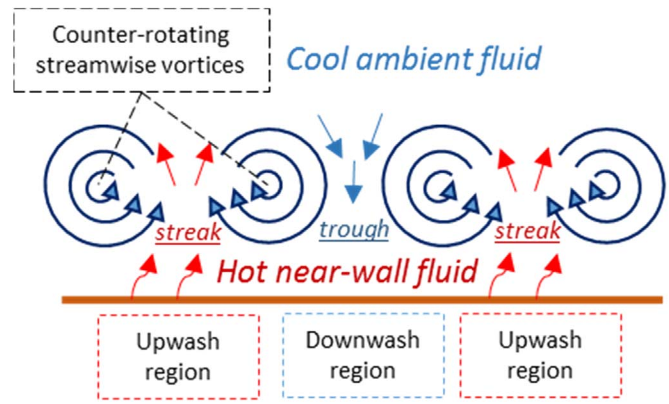

Fig. 2. Schematic of counter-rotating vortices, in which alternating upwash and downwash regions produce streaks. Viewpoint is looking into the flow above the hot plate.

2. Experimental design

All experiments took place in the wind tunnel facility at the Missoula Fire Sciences Laboratory. This facility has a 3×3 m cross-section recirculating wind tunnel, and experimental wind speeds were varied from 0.5 to 1.2 m/s. A large horizontal apparatus was placed in the center of the wind tunnel, and its surface was 1.2 m in width and 2.5 m in streamwise length. A flat copper plate was installed flush with this surface 1.63 m downstream of the leading edge. This plate was 0.91 m in width, 0.21 m in streamwise length, 0.025 m thick, and placed on the centerline of the platform surrounded by insulation board (see Fig. 3). The bottom surface of the copper plate rested upon three electric strip heaters (1500 W, 240 V) that provided uniform heating. A K-type thermocouple was wedged securely between the copper plate and the surrounding insulation board to record the temperature of the plate via a temperature controller, which would regulate the plate temperature via on/off control. Finally, a thin metal sheet was placed at the upstream end of this surface to minimize bluff body effects, and this sheet protruded 0.2 m beyond the edge of the apparatus. A schematic of this setup is shown in Fig. 3.

The macroscopic properties of both non-reacting thermal plumes and boundary layer flames is generally understood to be governed by a competition between momentum and buoyancy. Consequently, the parameter space of this experiment consists in varying the strength of momentum through the ambient wind velocity or in controlling the power of buoyancy through the surface temperature of the hot plate. For the following experiments, the bulk wind speed was held at either 0.5 or 1.2 m/s (+/−0.04 m/s), while the surface temperature of the hot plate was either 150 or 300 °C. It should be noted that the local wind speed near the surface of the hot plate is less than the bulk flow velocity due to the development of a boundary layer. The convective Froude numbers of this parameter space range from 0.36 to 1.29, placing this experiment in a regime where both inertia and buoyancy are expected to govern the global flow structure, nearly equal to values reported for simulated wildfires in Clark et al. [18].

A FLIR SC6811 infrared camera was placed above the hot plate in order to measure surface temperatures. The wavelength range detected