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Qualitative Flow Visualization of Flame Attachment on Slopes

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Abstract: Heating of unburned fuel by attached flames and plume of a wildfire can produce high spread rates that have resulted in firefighter fatalities worldwide. Qualitative flow fields of the plume of a gas burner embedded in a table tilted to 0°, 10°, 20°, and 30° above horizontal were imaged using the retroreflective shadowgraph technique as a means to understand plume attachment and related behavior. Tilting of the plume in the uphill direction for all non-zero slopes was explained by an imbalance in the flow of air entrained into the plume. Reversal in direction of fluid flow uphill from the flame front was shown to occur when buoyancy forces overwhelmed entrainment flow momentum. Flame and plume attachment was explained as being caused by uphill flow of hot combustion gas driven by a combination of buoyancy and an uphill pressure gradient.
Keywords: wildfire, slope, buoyancy, entrainment

1. Introduction

Wildfires propagating up a slope can, under certain circumstances, exhibit high rates of spread and expose firefighters to considerable risk. In fact, rapid upslope propagation of fire has been implicated in numerous firefighter fatalities and injuries around the world [1-3]. High rates of wildfire spread are thought to be caused by convective heat transfer to unburned fuel uphill from a fire front [4]. While radiation does have some role, convective heating of fine fuels normally dominates the heat transfer process [5]. Flame or plume attachment is the type of convective heating examined here, wherein unburned fuel uphill from a fire front is bathed in hot combustion gasses. Plume attachment is an important topic of study for improving firefighter safety, fire behavior knowledge, and predictive capability.

Fire as a physical phenomenon is often thought of only as the luminous yellow-orange flames. However, the combustion products (H_2O, CO_2, smoke, etc.) and other gases (e.g., N_2) emitted from a fire are also important for heat transfer because their temperature can be close to the flame temperature (1000-2000°C). Therefore, when concerned with heat transfer from the fire to unburned fuel, the flames and emitted gasses can be thought of as a single stream of gas: the fire plume (Fig. 1). As such, "plume attachment" and "flame attachment" are used interchangeably in this paper to refer to the same phenomenon.

Flame attachment on slopes has been a subject of research for more than fifty years, but selected references are noted here for brevity. Wu et al. [6] investigated characteristics of fires on inclined planes using a variable slope (0°-40°) table with an embedded gas-fired burner (1 to 3 kW). They reported that the critical inclination angle, that angle beyond which flame attachment length dramatically increases, is 24° and is insensitive to the burner heat release rate [6]. Dold and Zinoviev [4] highlight the importance of flame attachment on the rate of wildfire spread. The

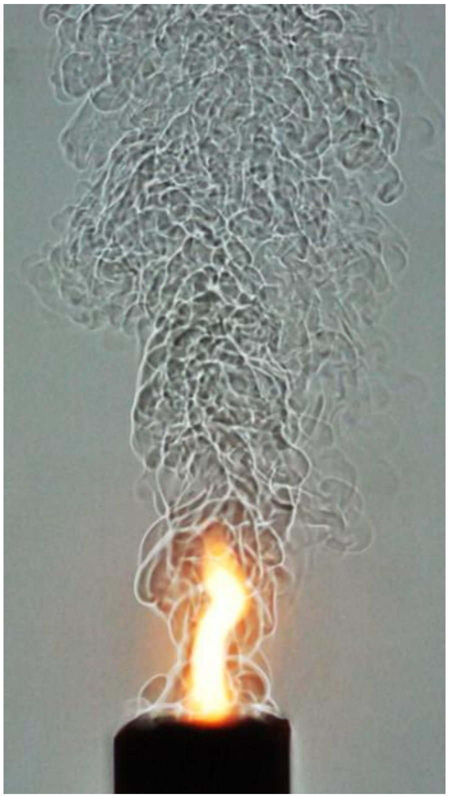

Fig. 1: Shadowgram of burner plume.

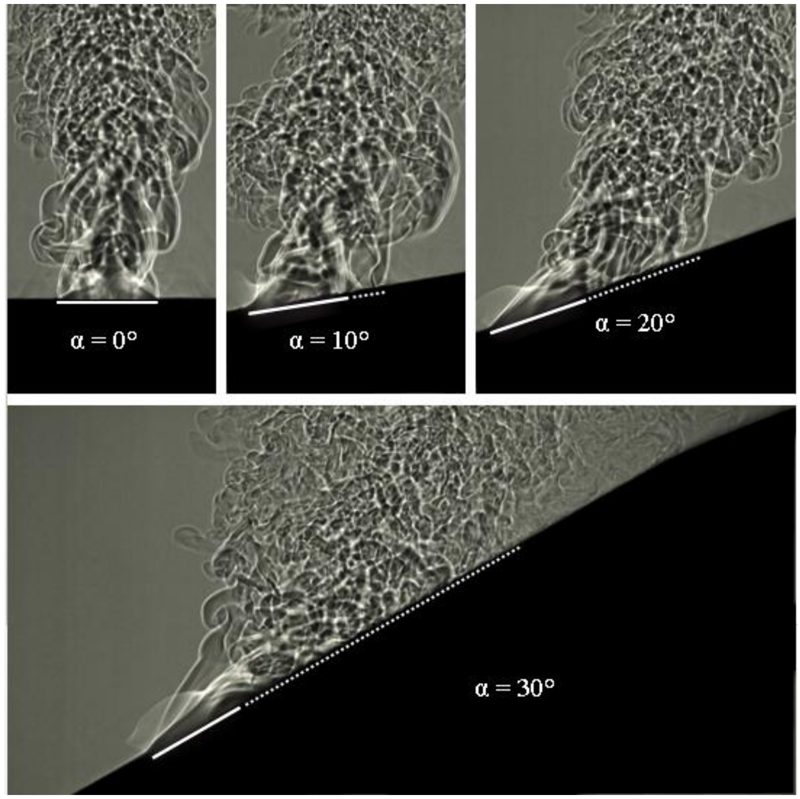

Fig. 2: Shadowgrams of plume attachment for indicated slope angles.

authors observed “separated” and “attached flow” fire behavior during propagation up trough structures of various slopes (15° to 45°) in the lab and a 0.1 hectare field burn on a 23° slope in mixed Mediterranean scrub. Morandini et al. [7] carried out simultaneous particle image velocimetry (PIV) and hydroxyl (OH*) chemiluminescence imaging of laboratory fires on flat and inclined slopes. The authors observed substantially greater spread rate in the sloped burns compared to those with a flat fuel bed. Morandini attributed the higher rate of spread to enhanced transient convective heating of unburned fuel in the region over which the plume was attached to the fuel bed. The aforementioned works report on a few of the laboratory studies that concern the effect of slope on fire behavior, with the nearly universal conclusion being that dramatically higher rates of spread are possible with a critical slope angle of 20° to 25°. We wish to build on this work by learning more about the fluid mechanics of plume attachment to sloped surfaces. It should be noted that flame attachment in wind driven flames is not unrelated to flame attachment on slopes, but is a topic which will be examined in a dedicated publication in the future.

It is imperative in laboratory-scale (0.1 to 1 meters) fire experiments to understand how observed results correspond to field-scale (10 to 1000 meters) fires, if at all. Quintiere cautions, “…[S]caling in fires is an art which requires attention to ignored phenomena and adequate proof and demonstration that the scaling technique is proper” [8]. Following Quintiere’s advice in practice amounts to understanding which parameters are important and which can be safely ignored. Perhaps most critical is understanding the implications of being forced to ignore an important parameter due to practical limitations. For example, Reynold number (Re) is usually problematic for scaled-down fire experiments in the laboratory because of the different physical scales for constant density and viscosity, and comparable velocity.

Since lab-scale fires exhibit a lower Re than field-scale fires, one must take care in interpreting physical phenomena in which Re is important. For example, lower Re means the turbulence intensity of fluid flow in these lab-scale experiments will be corresponding lower. Since turbulence strongly influences convection, one should not expect heat transfer between the hot combustion plume and the tabletop (and/or some scaled vegetation analog) to correspond to analogous heat transfer in the field. (It is for this reason we made no attempt to measure heat transfer to the tabletop.) A further example of the need for caution is the attachment length of the plume. Reynolds number is an important parameter in the development of natural convection boundary layers [9] such as those visualized in these experiments. The mismatch in Re means one should likewise not expect the attachment length of the plume to scale to that observed in the field. Nonetheless, the lab experiments remain useful because they are governed by the same physical processes (buoyancy and entrainment) as the field-scale fires. There is much that can be learned if care is taken when interpreting the results.

2. Methods / Experimental

Fire plume attachment was explored using a 9.2 x 50.2 cm propane-fueled flat flame burner mounted flush in a 122 x 122 cm table that tilted to arbitrary angles (α=0°-45°). The burner and table combination was meant to be analogous to a wildfire propagating up a hill. Gas temperature of the attached plume was recorded by a linear array of twenty-one thermocouples (type K, 50 μm) mounted approximately 5 mm above the table surface. Images of the hot fire plume were captured with a retroreflective shadowgraph system [10] that imaged changes in gas temperature (more precisely, the Laplacian of the index of refraction: $\nabla^2 n$) [11]. The burner was fueled partially premixed with 6.6 slpm propane and 57 slpm air (equivalence ratio ϕ=2.2) to avoid an overly luminous sooting flame that over-ranged the shadowgraph camera. A propane flowrate of 6.6 slpm corresponds to a burner heat release rate of 6.1 kW and a heat flux of 133 kW m^{-2}, assuming complete combustion. The experiments were carried out at the Missoula Fire Sciences Lab (975 m altitude) in an enclosed room (~13℃) where the ambient was made as quiescent as practical. Thus, apart from the small initial velocity of unburned mixture leaving the burner surface and unavoidable minor room currents, all fluid flow was largely buoyancy driven.

3. Results and Discussion

Fig. 2 illustrates attachment of plumes at selected slope angles in a series of shadowgraph "images" (shadowgrams). The dark structure at the bottom of all four photos is the tilting table. The solid white line indicates the 9.2 cm width of the burner and the region over which the plume is attached to the table is marked by the dotted line. The complex turbulent structure of the hot gaseous plume is evident above the surface of the burner and table. The features and textures of the shadowgrams seen in Fig. 2 result from turbulent structures throughout the 50.2 cm width of the burner because shadowgraphy is integrative in nature along the optical axis [11]. In other words, shadowgrams do not show a two-dimensional slice of the plume, but rather a composite average through its total width. Therefore, one must keep in mind that all the shadowgrams presented here will include contributions from parts of the plume exhibiting edge effects. Nonetheless, the 50.2 cm width of the burner ensures that much of the structure seen in the shadowgrams will arise from the central region of the plume where edge effects are minimal.

For α=0° in Fig. 2, the plume rises more or less vertically above the burner and makes no contact with the table surface. For the 10° slope, the plume begins to exhibit a slight lean to the right and is attached to the table for ~3 cm uphill of the burner. The plume has a more pronounced lean for the 20° slope angle and is attached for approximately 10cm. Even more striking is the 30° case where the plume is strongly tilted and the attachment length extends to several tens of centimeters. Also noteworthy in this latter case is the lack of a distinct point of separation of the plume from the table. In contrast, consider the 10° and 20° cases where the extent of the attachment zone is clear because the plume boundary is very distinct (explained below).

The tilting behavior of the plume with slope can be explained by varying rates of entrainment from uphill and downhill sides of the plume. In the α=0° case, the flow of entrainment air from the left and right is roughly equal [7], therefore a vertically oriented plume is reasonable. This explanation implies that for non-zero slope angles there exists an asymmetry in the rate of entrainment from the left and right, and this is borne out by experiments [4, 7]. Specifically, an entrainment deficit from the right (in Fig. 2) causes the plume to tilt in that same direction due to momentum imparted by the greater entrainment from the left. Historically, this reduction in entrainment has been explained by flow resistance on the uphill side caused by the proximity of the ground to the tilted plume (see e.g., [12]). This explanation makes a certain intuitive sense, but fails to satisfactorily explain why for sufficiently steep slopes, entrainment from the uphill side will cease when the plume tilts completely over and the flow of gas changes to an uphill direction. Instead, consider the following argument based on the interaction of buoyancy force with entrainment flows.

Fig. 3 shows buoyancy force F_{buoy} decomposed into a component normal to the slope $F_{\mathrm{buoy,n}}$ and one parallel to the slope $F_{\mathrm{buoy,p}}$. Notice that uphill entrainment from the left will be enhanced because $F_{\mathrm{buoy,p}}$ acts in the same direction of the flow, while downhill entrainment from the right will be suppressed because $F_{\mathrm{buoy,p}}$ acts opposite to the direction of flow. Therefore, the degree to which a plume tilts will increase with increasing slope angle as uphill entrainment increases and downhill entrainment decreases. Moreover, when $F_{\mathrm{buoy,p}}$ becomes sufficiently large at some critical angle α_c, downhill entrainment flow will (theoretically) stop altogether. Angle α_c represents a transition point because for $\alpha > \alpha_c$, the flow of fluid on the right side of the fire will reverse and travel uphill. Notice that for α = 10° and 20° in Fig. 2 ($0<\alpha<\alpha_c$,), the downhill flow of entrainment air from the right is apparent because there is a distinct plume boundary on the uphill side where entrainment air meets and is entrained into the plume. Contrast this scenario with α = 30° in Fig. 2 ($\alpha > \alpha_c$), where there is no distinct uphill plume boundary because the downhill entrainment flow of air has ceased and instead combustion products are flowing uphill. Far from the burner, the plume appears to dissipate as it entrains air and approaches thermal homogeneity (and therefore becomes invisible to the shadowgraph technique). The above argument seeks to explain fire plume tilting behavior through asymmetry in the momentum imparted on the plume by uphill and downhill entrainment flows. Understanding the origin of plume tilting is important because it dictates the extent of plume attachment to the ground and the associated degree of convective heat transfer to unburned fuel.

An explanation follows of how and why plumes appear to attach to an uphill slope for α>0. Generally speaking, the attached region of a plume is a flow of hot combustion gas moving uphill along the ground. This flow is created by the combination of two forces: the component of the buoyancy force parallel to the slope, $F_{\mathrm{buoy,p}}$; and a pressure gradient force caused by the tilted plume. The latter results from hot, low-density gas in a plume creating a hydrostatic pressure deficit (relative to the ambient) on the surface of the table (ground) according to the following formula (see section 12.6 of [13]):

$$p(x, y=0) = -g\cos(\alpha)\int_0^\infty (\rho_\infty - \rho)dy, \qquad (1)$$

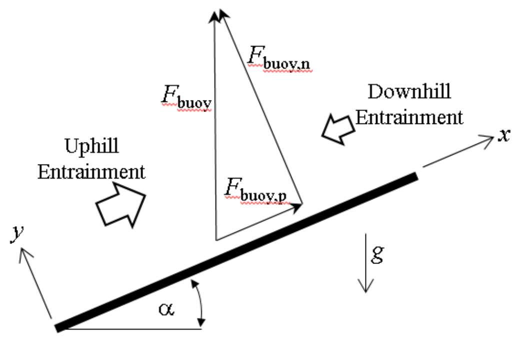

Fig. 1: Decomposition of the buoyancy force into components parallel and normal to the slope.

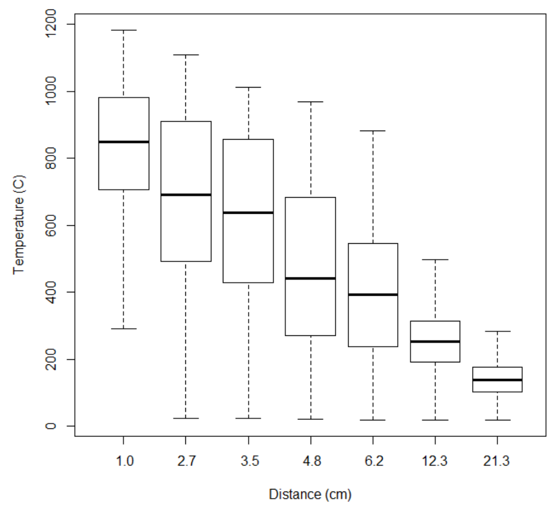

Fig. 2: Box plots of temperature at α=30° for selected thermocouples at the indicated distance

where g, ρ_∞, ρ are gravity, fluid density in the far field, and local fluid density, respectively. Eqn. (1) indicates that pressure at x decreases for decreasing density (increasing temperature) and increasing extent of hot gas above x. (The latter can be thought of as the thickness of the thermal boundary layer [14].) In the case of a tilted plume for, say, $\alpha = 20°$ in Fig. 2, the thermal boundary layer can be defined as extending from the surface of the table to the upper boundary of the plume. Along the width of the burner and attachment regions (solid and dotted lines) it is apparent that the thermal boundary layer thickness is increasing. Moreover, gas density is quite low in this region due to the proximity of the hot flame zone and limited entrainment. As such, there exists a decreasing (favorable) pressure gradient along the leading edge of the burner to the trailing edge of the attachment zone that induces a flow of hot combustion gas along the wall in the uphill direction. A region of low pressure as described here has been detected in laboratory burns [15] and field measurements are planned. The combination of this pressure-gradient induced flow and the influence of $F_{buoy,p}$ is responsible for the uphill flow of hot combustion gas [14] that comprises the plume attachment zone.

Plume tilt is important in plume attachment because it dictates the shape of the thermal boundary layer and, therefore, the extent of the attachment zone. The minor tilt observed in Fig. 2, $\alpha = 10°$ creates a relatively narrow thermal boundary layer that results in a correspondingly small attachment region. The more pronounced tilt of the plume in Fig. 2, $\alpha = 20°$ causes a proportionally larger attachment region. Fig. 2, $\alpha = 30°$ is strongly tilted and therefore creates a particularly large attachment region. Similar behavior is seen in the field where flow of hot gas in the attachment region will heat fuel in a wildfire propagating uphill. Heating unburned through convective heat transfer reduces the sensible heat required by the flame to raise the fuel to pyrolysis temperature. This lower heating requirement permits higher flame temperature, which increases combustion rate (perhaps dramatically due to Arrhenius temperature-dependence of chemistry) and therefore spread rate.

Wildfires are an extremely complex, highly nonlinear physical phenomenon, so the onset of plume attachment cannot be predicted as a function of α alone. Moreover, plume attachment is a highly dynamic process like all turbulent flows. For example, significant variability of gas temperature near the table surface was observed, as demonstrated by the box plot in Fig. 4. Each column shows median temperature (heavy line) and the extent of the ±25 percentile (box) for select thermocouples at the indicated distance from the burner. Significant variability in temperature is evident (tall boxes) especially at 3.5 and 4.8 cm. All of these factors are among the reasons that predicting onset of significant flame attachment and rapid fire spread is very difficult. Therefore, further work is planned to continue to improve knowledge of this interesting and sometimes dangerous phenomenon. Ultimately, we hope to understand the physics of the problem sufficiently well so that we can improve firefighter training and safety, and predictive capability of computer models.

4. Conclusions

Under certain circumstances, wildfires propagating up slopes can exhibit surprisingly fast propagation rates caused by heating of unburned fuel ahead of the fire. The heating occurs when the plume of the fire appears to attach to the slope surface, bathing unburned fuel with hot combustion gas. It is important to understand this phenomenon to improve firefighter safety, fire behavior knowledge, and predictive capability of models. A laboratory facility analogous to a wildfire was constructed to create qualitative shadowgraph images of the plume of a burner embedded in a tilting table. The resulting shadowgrams revealed plume tilting and plume attachment for all non-zero slope angles. The tilting and attachment phenomena were explained by a complex interaction among buoyancy forces and entrainment of air by the plume.

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