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Fire spread across a sloping fuel bed: Flame dynamics and heat transfers

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ABSTRACT

The complex interactions between the inclined terrain and the flow generated by the fire make the slope one of the most influencing factors on fire spread. In order to gain a deeper understanding of the mechanisms involved in wildfires spreading upslope, the investigation of flow dynamics and heat transfers is fundamental. This paper reports a series of fire spread experiments conducted across a porous bed of excelsior in a large-scale facility, under both no-slope and 30° up-slope conditions. The coupling of particle image velocimetry and video imaging allowed characterizing the flow pattern with respect to the fire front. Simultaneous heat flux measurements with high scan rate were also performed at the edge of the fuel bed. From the collected data, the increase of the rate of spread with increasing slope is attributed to a major change in fluid dynamics surrounding the flame. For horizontal fire spread, flame fronts exhibit quasi-vertical plume resulting from the buoyancy forces generated by the fire. These buoyancy effects induce an inward flow of ambient air that is entrained laterally into the fire from both sides. Flame radiation is the dominant fuel preheating mechanism. Under upslope conditions, the fire plume is tilted toward the unburnt vegetation, increasing radiation levels. The air entrainment at the burnt side of the fire strongly influences the downstream flow, which becomes attached to the surface over a characteristic length scale. Ahead of the flame front, the induced wind blows away from the fire rather than toward it, enhancing convective heating. Periodical forward bursts of flame combined with distant fuel ignitions were also observed. The heat flux measurements confirmed the existence of such convective mechanisms.

1. Introduction

Wildfires spreading uphill burn more intensively than on flat ground. The slope affects the characteristics of the flames as well as the resulting heat transfers impinging on the unburnt fuel [1–6]. The increase of the rate of spread is often attributed to the flames being closer or in direct contact with the vegetation, but in fact the overall flame dynamics and induced flow are subject to far more radical changes [7–9]. As a consequence, very dangerous conditions are more likely to occur on inclined terrain and some extreme fire behaviour in the field has already been reported [10]. Unfortunately, such scenarios were responsible for numerous on-duty firefighter injuries or fatalities [11–13].

The heat transfer processes that govern the spread of wildland fires deserve attention, most particularly convection that has received less attention than radiation [14,15]. Nevertheless, flame radiation alone cannot fully explain the fire spread across vegetative fuels, which should rather be driven by a mixed radiative–convective heat transfer [3,15–21]. Although most authors agree that the fire spread regime is peculiar for slope angles above a threshold value close to 25°, some studies led to contradictory conclusions on the effects of convection on the unburnt fuel. On the one hand, experimental studies [3,4,7,22–25] supported by CFD simulations [26–28] concluded that it plays a crucial role in the pre-heating and ignition of the vegetation over long spatial range. While on the other hand, measurements ahead linear fire fronts indicated that it has a remarkable effect of cooling [29,30]. The previous considerations indicate the necessity to study the flow to improve the knowledge of the intricate convective mechanisms that arise under upslope conditions. Furthermore, because of the fine size of the particles that compose most of the vegetation species [31–34], these porous fuels are very sensitive to convection since the heat transfer coefficient is directly proportional to the inverse of this characteristic length scale.

During fire in the open, some properties of the flow can be derived from global observations of the smoke movements [22]. The

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main features are usually an updraft column of smoke and the rear and lateral inflow to the fire that influence its behaviour on both short and long time scales [35]. Over sloping terrain, the regime of fire spread is intimately related to the fire-induced flow and the released smokes were observed to be attached along ground the rather than rising vertically above the flame front [18,36,37]. Digital image processing [16,38] enable some qualitative information on the flow. However, a more reliable quantification of the convective mechanisms is not obvious. Among the existing optical diagnostic methods, two-dimensional particle image velocimetry (2D PIV) has become one of the most versatile whole-field techniques to measure velocity in a cross-section of a flow. This technique has already been applied for fire spread tests in the laboratory [39,40]. Its application to large-scale reactive flows is difficult, due to the need of suitable tracer particles and high-energy light sheet in a large measurement section, but still possible [8,39,41].

This work is devoted to the experimental characterization of the processes involved in upslope fire spread. A series of 10 fire tests was carried out over large beds of excelsior (21 m^2) under horizontal and 30° upslope conditions. The flow and associated heat transfers were investigated. To this end, PIV measurements are performed with an improved setup compared to a previous work [8] where a single laser source was located backwards from the fire front. An attenuation of the laser energy by the fire at the unburnt side of the fire was observed and the lower Mie scattering signal captured by the PIV camera did not allow computing velocities in the whole measurement region. In the present study, two aligned and synchronized lasers located at both ends of the bench, facing one another, were used to generate the light sheet. The 2D (vertical) velocity field at the centerline of the fuel bed was measured during fire spread. The PIV system was synchronized with video imaging. Heat flux measurements with high scan rate were also performed close to the bed edge.

2. Materials and methods

2.1. Experimental facility

A series of ten fire spread experiments was carried out, in June 2014, on the DESIRE bench located inside the INRA facility. Horizontal and 30° upslope fires were compared. The full experimental setup is shown schematically in Fig. 1. This large-scale bench is 10 m long, 4 m wide, and its plate, made of insulated material (aerated concrete, Siporex), is inclinable. The edges of the combustion plate are surrounded by four rulers with 0.25 m graduations for more accurate characterization of the fire front spread. The bench is located in a large experimental hall (20 m long, 12 m wide and 12 m high) with passive smoke and heat exhaust system (large opening roof vents).

The fuel consisted of a 7 m long and 3 m wide bed of excelsior. Three fuel loads were studied: 0.2, 0.4 and 0.6 kg/m^2. The depth of the porous fuel bed was measured at five random locations and average values for each configuration are provided in Table 1. The surface-to-volume ratio and density of the fuel were 4730 m^{-1} and 780 kg/m^3, respectively. The fuel was not conditioned before the fire tests, and moisture content was about 10%. A fire line was ignited at one end of the bench using 20 mL of alcohol. Excelsior was first of all chosen for the experimental campaign for its ease of implementation, allowing homogeneous bed properties on wide area. Furthermore, this fuel, composed of fine sized elements, has very high consumption ratio (>90%) and very few materials remained after fire spread.

2.2. Particle image velocimetry and color imaging

The velocity fields in the vicinity and inside the spreading flame were measured over time using a PIV system that consisted of the following synchronized devices: two laser sources for light sheet generation and two computer-controlled cameras (PIV and video) for image acquisition. Time synchronization between all the devices was performed using a multi-pulses generator from R&D Vision. The location of the different cameras and lasers used is provided in Fig. 1. The illumination of the particles in a very large field require light sheet with a high energy density. Therefore, two lasers were used, instead of only one, in order to generate a 2D vertical sheet of double-pulsed light. The two lasers, rigorously aligned, were located at both end of the bench, facing one another. The beam from each laser source was spread into a vertical sheet (perpendicular to the bench surface) using an optical device composed of a set of cylindrical divergent and spherical convergent lenses. This dual laser configuration allowed a good illumination at both unburnt and burnt sides of the fire. Figure 2 shows the resulting laser sheet at the centerline of the bed of fuel during upslope fire test. Each illumination source used was a double cavity Nd:YAG laser delivering couples of pulses (2×200 mJ/pulse, 7 ns/pulse) at a wavelength of 532 nm and a frequency of 4 Hz. The timing interval between the couple of pulse is 4 or 3 ms under no-slope and upslope conditions, respectively. The Q-switch was set for the laser to deliver the larger energy per pulse in order to maximize light scattering by particles (Mie scattering). The light sheet at the measurement area is about 2 m high, 5 mm thick.

A very high definition PIV CCD camera (Vieworks, 6576×4384 pixels resolution, 8-bit dynamic range), located perpendicularly to the laser sheet, recorded the light scattered by illuminated seed particles in the vertical plane. The use of a 29 million pixels camera allows to increase the dynamic range of the velocity field measurement improving the ratio between the maximum and minimum resolvable displacements of the particles for a given pulse separation time. The camera, mounted in landscape mode, was equipped with a passband filter 532 nm ± 1.5 nm centered on laser wavelength. The field of view provided by an 85 mm lens allowed PIV measurements in a 2.6 m long by 1.7 m high area, located near the end of the bench (from 4.3 to 6.8 m in the *x*-direction and 0 to 1.6 m in the *y*-direction according the coordinate system displayed in Fig. 1b). The resulting magnification was 2.47 and 2.55 px/mm for horizontal and sloping configurations, respectively. The velocity vectors cannot be computed inside the fuel layer but only above its top. The measurement of the velocity field in presence of luminous flame is difficult since PIV CCD cameras are not able to capture two consecutive images with the same short exposure times. The storage time of the first frame is not fast enough for the camera to be ready for a second exposure with the same characteristics (camera's second frame integration period longer than 200 ms). As a result, the second frame has usually an exposure time longer than the first one, which is a real problem for velocity measurements in fire environment, causing over-exposition and blurring of the flame region. To circumvent this issue, the PIV camera was equipped with fast-acting electromechanical shutters (7 ms) located in between the lens and the CCD sensor of the camera, to shorten the duration of the second frame exposure. It is worth noting that ferroelectric liquid crystal shutter, with faster switching speed (<100 μs) should be preferred [39], but its modulation transfer function cuts-off high spatial frequencies (low-pass filter). This shutter was thus not suited to cameras' high-resolution sensor with small size pixels such as the one used in the present study. The PIV images acquisition rate was 4 fps. Each experiment represents about 500–800 successive frame pairs for no-slope experiments and about 40–100 frame pairs for 30° slope experiments according to the fuel load and fire rate of spread. A digital video camera (Ueye Color, 1280×1024 pixels resolution, 8-bit dynamic range), mounted in landscape mode, was also used to record color images. This camera equipped with a 16 mm wide-angle lens and provided a field of view of