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Experiments in Fluids
Experimental Methods and their Applications to Fluid Flow

ISSN 0723-4864

Exp Fluids
DOI 10.1007/s00348-012-1285-5

A21023 348

Research Journal

Experiments in Fluids

37

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Experimental Methods and their Applications to Fluid Flow

Springer

Volume 37 · Number 5 · November 2004

Originals

(Continuation on cover page IV)

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0723-4864(200411)37:5;1-8

Indexed in Current Contents

Springer

Exp Fluids
DOI 10.1007/s00348-012-1285-5

RESEARCH ARTICLE

Feasibility of particle image velocimetry in vegetative fire spread experiments

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Received: 9 June 2011 / Revised: 9 February 2012 / Accepted: 20 February 2012

Abstract This study is part of an ongoing effort to improve the understanding of mechanisms that control the spread of fires with a focus on the turbulent flow modified by the flame front. A large-scale PIV system was used to measure the flow field inside and in the vicinity of a flame front spreading across a bed of fuel in an open environment. The vegetative fuel consisted of a 10-m-long and 5-m-wide bed of excelsior (1 kg/m^2 fuel load) leading to a nearly 1.5-m-high flame front. The velocity field was investigated in a measurement region about 1.5 m high and 2 m long. In such a configuration, a 450-mJ laser source was used to generate the light sheet, and the flow was seeded using zirconium oxide particles (ZrO_2). The PIV measurements in the presence of flame were improved by the use of a liquid crystal shutter in front of the PIV camera, allowing very short exposure times and eliminating the flame trace in the tomographic pictures. Despite the variability of the external conditions, leading to a difficult seeding over the whole PIV area, the present study shows the feasibility of the optical method of fluid visualization in the field. The measurements of the velocity fields show some features of the dynamics of fire plumes. This preliminary study demonstrates the feasibility of the method in the open, but some strong efforts to improve the seeding of the flow must be made.

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1 Introduction

Experimental studies of free burning fires spreading across vegetative fuels usually focused on dynamics of the fire front and on thermal measurements, namely temperature and heat fluxes ahead of the flame front (Butler et al. 2004; Morandini et al. 2006; Silvani and Morandini 2009; Morandini and Silvani 2010). As far as the heat transfers activated during the fire spread are concerned, radiation emitted from the fire can be accurately measured using radiant heat flux gauges. However, due to the absence of an instrument to directly measure convection, its presence ahead of the flame front can only be qualitatively highlighted using both total and radiant heat flux gauges. In this case, the convective mechanisms exist when the radiant and total heat flux gauges exhibit signal discrepancies (Silvani and Morandini 2009). The related convective heat transfer cannot be accurately quantified while the local velocity field is unknown.

The turbulent flow surrounding a wildfire results from the competition between the inertial forces due to the wind and buoyancy forces generated by the fire. The flow in the open plays a significant role in the fire behavior. The properties of this reacting flow need more investigation to further assess the contributions of both natural and forced convection involved in fire spread. For instance, the wind is acknowledged to be one of the main factors influencing the fire spread, but its effects on the heat transfer mechanisms are less well understood due to the complex nature of the resulting flow. Numerical simulations using physics-based modeling approaches that exploit computational fluid dynamics (Porterie et al. 2005; Linn and Cunningham 2005; Mell et al. 2007; Morvan et al. 2009) can be performed as a first alternative to understand the interactions between the wind and the flame front. In these formulations, the predicted

Published online: 06 March 2012

velocity field has a leading-order impact on the fire simulation since it determines the relative contributions of radiative and convective heat transfers. Experimental studies of the velocity field in the presence of a fire are thus of great interest for validating the predictions of these CFD-based models.

In our ongoing effort to improve the understanding of the complex flow mechanisms governing the behavior of a free burning fire, an optical method of visualization of the fluid flow has been tested. Particle image velocimetry (PIV) quantifies the displacement between successive images of tracer particles following the gas flow. In the literature, previous studies applying PIV to the measurement of the velocity field were performed in the vicinity of fires at small scales, for measurement regions smaller than 0.3 m × 0.3 m (Zhou et al. 1996). The challenge of applying PIV to large-scale measurements in the open requires good seeding of the flow surrounding the fire with adequate tracer particles and the availability of a high-power laser source to produce a measurement window larger than 1 m × 1 m. Up until now, such non-intrusive optical diagnostics at that scale were exclusively used in static fire configurations, namely fires from gas burners or liquid pools (Tieszen et al. 2002) or fire-induced flow in the doorway of an enclosure (Bryant 2009). To the authors' knowledge, the present work is the first to apply PIV measurements in the vicinity of and inside a flame front spreading across vegetative fuels. The measurements provided in the following section exhibit some features of the dynamics of fire plumes.

2 Materials and methods

2.1 Experimentation area and external conditions

The experiments were designed to be representative of a fire spread across a bed of vegetative fuel under wind-blown conditions. The fuel consisted of a 10-m-long and 5-m-wide bed of excelsior (Figs. 1, 2). The fuel load was 1 kg m^{-2}, and the thickness of the bed was about 0.2 m. The experimental plot was located in an aerodrome and was oriented in a direction parallel to the landing track. In these conditions, the main wind flow blows in the longitudinal direction of the experimental plot, and the fire can propagate under wind-aided conditions. A fire line was ignited using alcohol at one edge of the fuel bed. The conditions of quasi-steady state were difficult to achieve for the fire in an open environment. Six experimental runs were performed to record the velocity field during fire spread. The first runs were used to set up the PIV system (thickness of the laser sheet, inter-image time, seeding with tracer particles), and the parameters were slightly different from one run to another due to the fluctuating nature of the natural environmental conditions. The results provided in the rest of the paper concern the experiment for which the fluid was seeded with enough tracer particles to allow computing of the velocity vectors in the flame and its surroundings.

The wind velocity and direction were recorded using a two-dimensional (2-D) ultrasonic anemometer 2.5 m above the ground surface to reflect the average horizontal wind

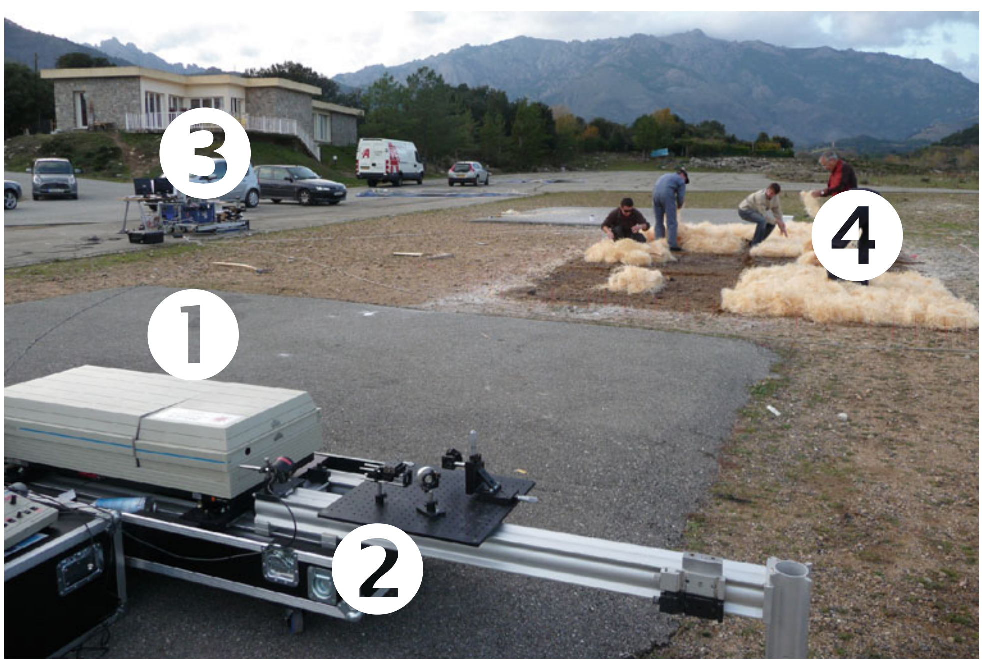


Fig. 1 *Rear view* of the experimental area: *1* the laser source, *2* lenses and mirror, *3* cameras and the image acquisition system, and *4* bed of fuel

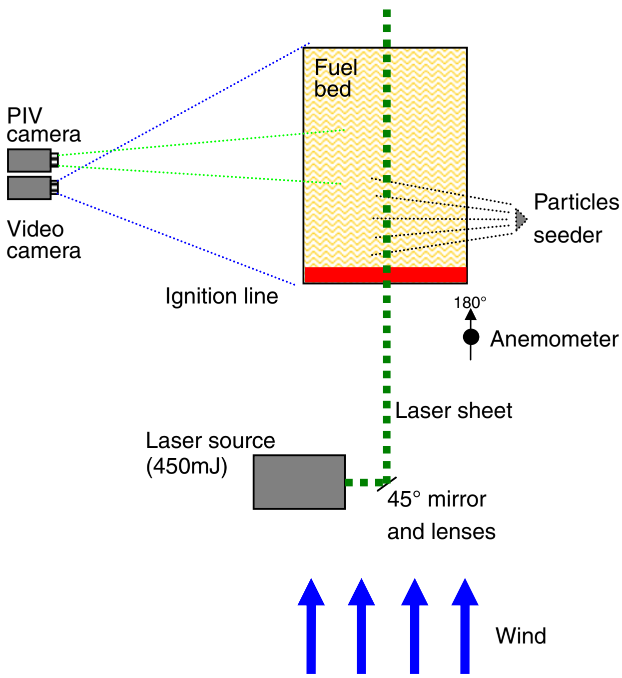


Fig. 2 Schematic of the experimental device

acting on the fire front. The 180° direction is collinear with the main plot direction. The anemometer was located at the upwind edge of the fuel bed to minimize the influence of the fire on the wind measurements. Furthermore, such a location shielded the ultrasonic transducers from smoke and large-diameter firebrands generated by the fire, which affect the sonic measurements. The wind data were recorded using another (synchronized) data logger at a sampling rate of 1 Hz.

2.2 Particle image velocimetry (PIV) measurements

The velocity field in the vicinity of the fire spreading in the open was measured using a large-scale PIV system. The illumination source used was a Nd: YAG laser. This laser source delivers two pulses (450 mJ/pulse) at a wavelength of 532 nm and a frequency of 10 Hz. The laser beam was spread into a sheet using an optical device composed of lenses and a mirror. The positioning of this laser sheet at the center of the fuel bed was performed using a 45° mirror (Fig. 2).

Two cameras were located at a distance of 10 m, perpendicular to the laser sheet. Digital images for the measurement of the displacement of the tracer particles were acquired with a high-resolution CCD camera (1,600 × 1,200 pixels – 8 bits – 15 Hz) with single pixel dimensions of 1.25 mm on a side. With such a laser sheet, the PIV camera was able to investigate the velocity field in a measurement region about 1.5 m high and 2 m long (Fig. 4). All these instruments (laser/camera) were synchronized using a delay generator.

The PIV system incorporates an optical shutter in front of the PIV camera to eliminate the flame trace in the tomographic pictures. Indeed, it is difficult to measure the velocity field in the presence of flame. Standard PIV cameras cannot obtain two consecutive images with short exposure time. The second raw image of the PIV image pair is usually contaminated by luminous flame emission. The main cause of the problem is an excess exposure time, which lets the flame emission overlap the particle image in the second frame. In the present work, the use of a liquid crystal shutter allowed very short exposure times (<100 µs). The technical features (dimension and transmission) of this shutter required the use of a special C-mount camera with high sensitivity. Another video camera, with a wider field of view, was used to record the fire spreading across the whole bed of fuel (Fig. 4).

The PIV measurements are usually performed with window sizes of about 0.5 m × 0.5 m. The aim of this study is mainly to estimate the spatial resolution attainable using just one PIV camera for quantitative measurements in large-scale fires. Future developments of this technique can incorporate the coupling of other cameras and/or laser sources for investigating larger flow fields. The large structures present in the reactive flow imply that the displacement components perpendicular to the light plane may also be important. The principle of PIV measurements consists of the conservation of flow tracers into the light sheet for two consecutive images. The displacement into the image must be sufficient to ensure a valid measurement (about 10 pixels). With the variability between the experiments of the external conditions in the open (wind properties, air temperature, and humidity), which significantly influence the fire behavior, the setup of the PIV system must be regularly adjusted. In particular, due to the three-dimensional (3-D) effects induced by the turbulent reactive flow, the probability of having a flow tracer leave the light plane can be significant. The thickness of the laser sheet can be adjusted in the range of 0.5–2 cm and has been set under preliminary fire tests to prevent particles from leaving the measurement region before completion of the measurement. It should be noted that an increase in the thickness of the laser sheet decreases the local energy density (local intensity of Mie scattering from the seed particles) and influences the texture of the PIV images. The magnitude of the displacement of the tracer particles between two PIV images is set by the inter-image time. Preliminary fire tests have also been performed in order to set the range of selectable inter-image times in these outdoor conditions. In a large-scale PIV experiment, the spatial resolution of the optical system does not allow the capture of individual particles. The specific image texture determines the nature of the post-processing algorithm to use.

The seeding of the flow was made using a pneumatic paint sprayer. The tracer particles were injected as a fine

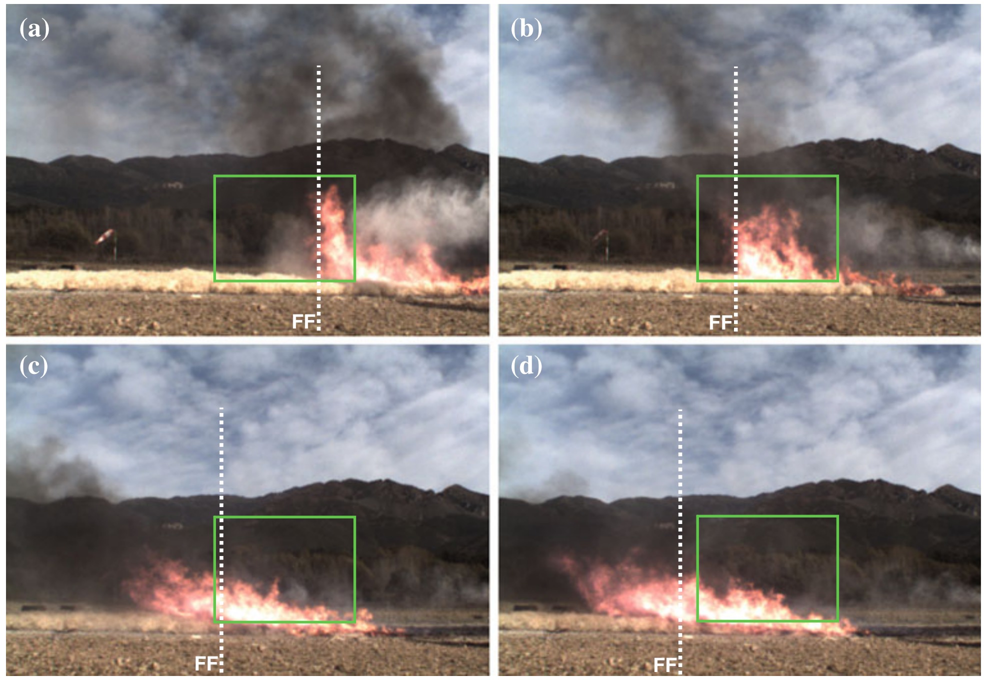


Fig. 3 *Lateral views* of the PIV experiment at time **a** 61 s, **b** 79 s, **c** 86 s, and **d** 89 s: the *green* window represents the region investigated by the PIV camera, and *dot lines* represent the locations of the FF head

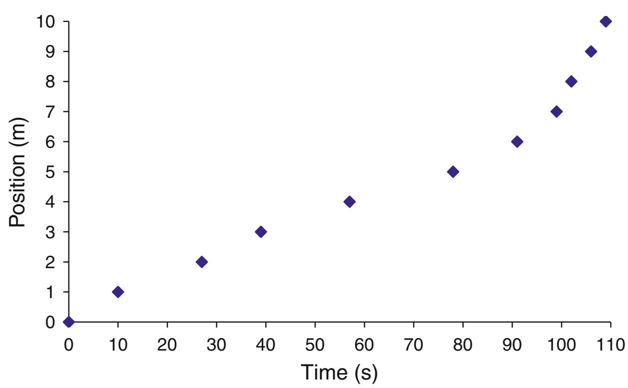


Fig. 4 FF position during time

spray perpendicularly to the direction of the flow and to the laser sheet at the upwind edge of the fire (Fig. 3). These seed particles were zirconium oxide (ZrO_2), with 1 μm of diameter, designed specifically for fire tests. They scatter enough light to be accurately visualized within the laser sheet plane and are small enough to accurately follow the flow. It is important to underscore the pioneering nature of these measurements under outdoor conditions, with large PIV windows and in the presence of reactive flow. For PIV experiments in the open, the seeding is difficult to master, and it has been adapted continuously in order to visualize a larger part of the upwind and downwind flows. Because of the size of PIV windows, a significant quantity of tracer particles has been used. In order to reduce this unavoidable bias, the seeding was switched on and off, allowing some rather short-duration puffs of tracer particles to be transported inside the reactive flow and its vicinity. The smoke released by the fire and the dust transported by the wind in the open provided further natural seeding of the flow.

The accuracy of the PIV measurements depends on several parameters: particle concentration, displacement gradients in the measurement plan, 3-D effects, and algorithm used. The velocity fields were computed using an image-processing technique. The algorithm is based on two-evaluation passes with a resizing method of the interrogation window (Susset et al. 2006). The interrogation window size was 64 pixels with 70% overlap in both directions. The PIV method assumes that the displacement of the particles in each interrogation window is deduced from the position of the cross-correlation function peak. The spatial resolution was estimated by increasing the overlap between interrogation windows to obtain close measurements. The spatial resolution was 24 pixels, which corresponds to an area of about 3 cm^2. Due to the previous parameters, some instantaneous vector fields contained regions without valid vectors and post-processing was required. The computed vector fields were post-processed using 10 passes of a 3 × 3 smoothing filter with a 75% threshold and linear interpolation to fill empty spaces.

3 Results and discussion

3.1 Fire behavior

Lateral views of the experiments recorded during the fire spread are displayed in Fig. 3. The position of the head of the fire front (FF) is indicated with a vertical dot line on

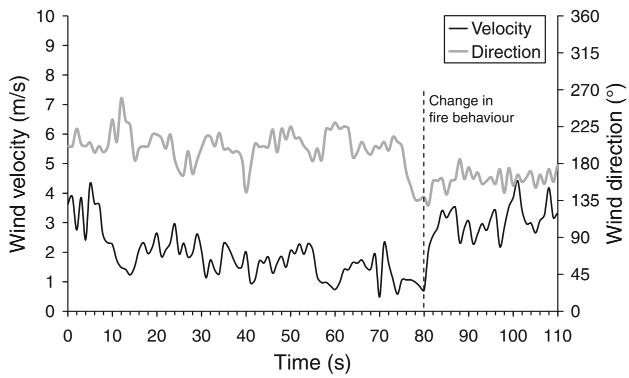


Fig. 5 Wind properties measured during fire spread

each image. These images show the presence of two considerably different behaviors of the fire. Indeed, the FF initially exhibits 1.5-m-high vertical flames (Fig. 3a, b) and a slow rate of spread (<0.07 m/s) for the propagation over the first 5 m. However, 80 s after ignition, a significant change in the fire behavior is observed. The flame front is then tilted forward, and the fire spreads faster (0.3 m/s) by direct contact with unburned fuel. In the literature, the first regime is referred to as "plume-dominated" and the second one as "wind-driven" (Pagni and Peterson 1973; Morvan et al. 2009; Morandini and Silvani 2010; Sullivan 2010). The modification of the flame dynamics induced by the wind is visible in Fig. 3c, d. It should be noticed that the rate of spread increases by a factor of more than four during the experiment. The plot of the position of the FF versus time clearly shows this acceleration (Fig. 4). These two different regimes of fire spread are correlated with a change in wind properties about 80 s after the ignition (Fig. 5). Indeed, the average wind speed increased from 1.4 to 3.0 m s^{-1}, and its direction becomes collinear to the main plot direction (180°). The sudden increase in the rate of spread of wildfires is very dangerous and has caused many casualties among fire fighters. This acceleration of the fire is associated with eruptive fire behavior (Dold and Zinoviev 2009; Viegas et al. 2011). It should also be noted that the depth of the FF greatly increases with increasing wind (Fig. 3). Indeed, the unburned vegetation located ahead of the flame front lights up very fast due to the contact of the flames. The effects of the change in wind properties on the velocity field in the neighborhood of the flame are detailed in the following section.

3.2 Flow properties in the neighborhood of the flame

The PIV allowed the measurement of the instantaneous 2-D velocity fields across the centerline of the bed of fuel during the propagation. The velocity vectors and the contour of velocity magnitude at different times are displayed in Fig. 6. The position of the head of the FF is indicated with a vertical dot line in the first two velocity fields (time 61 and 79 s). The region investigated by the PIV camera is located near the middle of the bed of fuel and is represented by a green window in Fig. 3. The velocity fields exhibit regions where velocity vectors could not be acquired due to the absence of tracer particles (blue isocontours). Nevertheless, these data show some interesting features of flow dynamics, which can provide a comparison basis for the validation of physical models of fire spread (Porterie et al. 2005; Linn and Cunningham 2005; Mell et al. 2007; Morvan et al. 2009). The flow in the vicinity of the flame drastically changes depending on the regime of fire spread. In the first regime of fire spread (Fig. 6a, b), the wind flow strongly responds to the great buoyancy forces generated by the fire. The flames act like a barrier to the wind (1.4 m s^{-1}), and the flow is guided upward with the plume. In these conditions, radiation from the flame is invoked as the dominant heat transfer mechanism (Morandini and Silvani 2010). The buoyancy also induces an influx of fresh air on the downwind side of the fire. The seed particles (ZrO_2) survived in the fire plume, which allowed performing PIV measurements inside the flame. Horizontal and vertical profiles of the velocity components (P1–P4) are plotted in Fig. 7 during both regimes (time 79 and 89 s) for selected locations. These locations are indicated with dash-dot lines in Fig. 6b, c. The profiles P1–P3 (Fig. 7 a–c) measured at time 79 s, which are representative of the buoyancy-driven regime, demonstrate the significant variation in the vertical component of velocity (VY) according to the elevation, induced by the fire. The VY profiles exhibit an average velocity magnitude of about 5 m s^{-1} within the flame region. In the second fire spread regime (Fig. 6c, d), the flow seems governed by wind. The horizontal profile of the velocity components P4 (Fig 7c) measured at time 89 s is characteristic of a fire spreading process driven by inertial forces. Indeed, this profile demonstrates that the flow is mainly horizontal. The horizontal component of velocity VX is about 2 m s^{-1} and that of velocity VY is almost nil. A slight acceleration of the flow occurs close to the flame region. It should be noted that even if the majority of the vectors are horizontal, their magnitude is not as large as the vector measured in the first regime because the flame region investigated is different. It is apparent that the head of the flame front has already passed through the PIV area. Therefore, these measurements are relative to the region located at the end of the FF, which generates lower buoyancy forces than the head of the fire. The velocity fields indicate the development of an attachment of the air flow through the flames. The flow seems to cross the fire and pushes the hot gaseous products of combustion toward the unburned fuel. Considering the unsteady behavior of fires in an open environment, the increase in number of the measuring areas should be

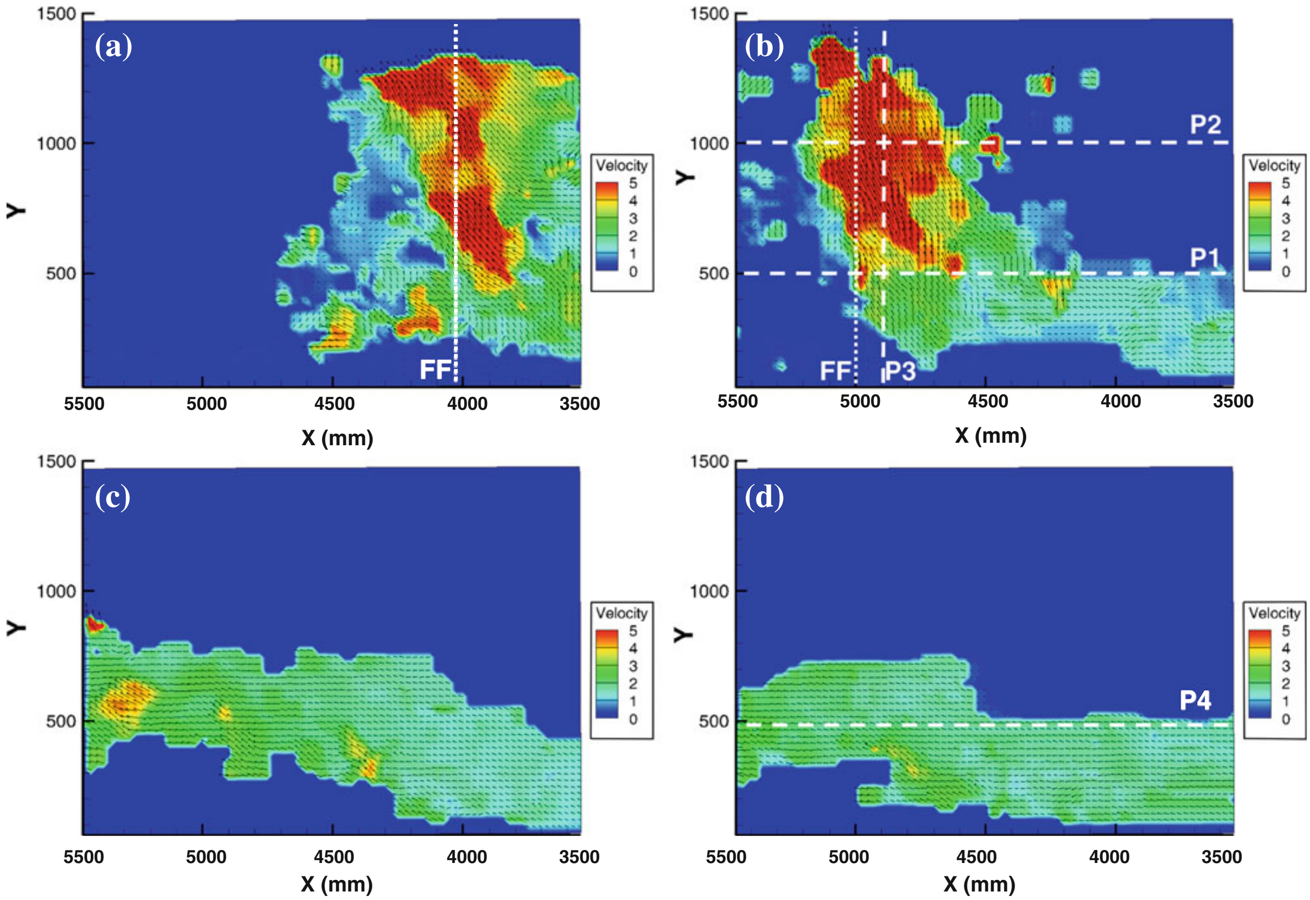
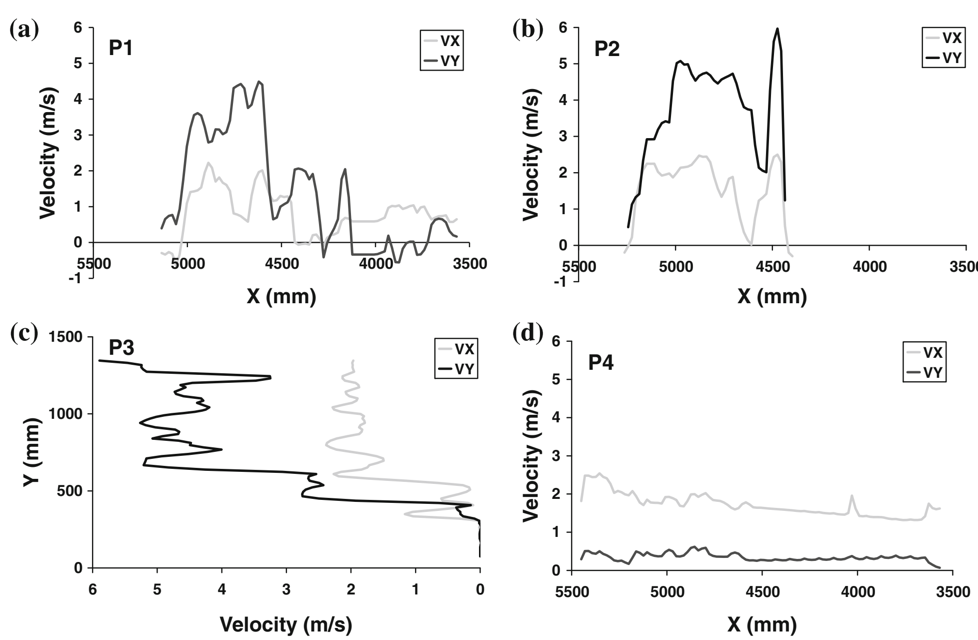


Fig. 6 Velocity field measured in the surrounding of the flame front at time **a** 61 s, **b** 79 s, **c** 86 s, and **d** 89 s (*dot* and *dash-dot lines* represent the position of the FF head and the locations of the profiles of the velocity components, respectively)

Fig. 7 Measured profiles of the velocity components: **a** *horizontal* profile *P1* at $Y = 500$ mm ($t = 79$ s), **b** *horizontal* profile *P2* at $Y = 1{,}000$ mm ($t = 79$ s), **c** *vertical* profile *P3* at $X = 4{,}900$ mm ($t = 79$ s), and **d** *horizontal* profile *P4* at $Y = 500$ mm ($t = 89$ s)



considered in future experiments. This should be done either with the displacement of a single PIV camera (when the fire has passed through the measurement area) or by the use of several cameras. Thus, the data collected in several PIV areas during a single experiment will allow to gain a deeper understanding of the convective mechanisms occurring during fire spread and more especially during the wind-driven regime.

3.3 Reliability of PIV measurements in the open

The optical method used in the present study yielded to capture some features in the dynamic field of a flame spreading in the open across a vegetative fuel bed. But the measurement method applied to reactive flows in the open suffers from some technical limitations and strains, which have to be discussed for guiding future developments of the technique. As observed in the previous section, the flow in the presence of a spreading flame front is strongly influenced by the incoming air, and many precautions must be taken in order to perform PIV measurements at a large scale under wind-blown conditions. The quality of PIV images required for an accurate computation of the velocity fields depends on key parameters such as the setup of the PIV system (thickness of the light sheet, inter-image time) and above all the seeding of the area of measurements.

In the present study, the energy delivered from the laser source was sufficient for the illumination of a wide PIV area for large-scale applications. Only the seeding of the flow appears as the main limitation of the overall technique for flow measurements in an outdoor fire. For steady upwind conditions like the one encountered in wind tunnels or in pool fires in an enclosure, it is quite easy to set the injection of tracer particles, in order to obtain a convenient seeding of the region crossed by the light sheet. The usual seeding employs atomized liquids, which are commonly used in low-temperature aerodynamic applications, is not possible in high-temperature reacting flows due to the evaporation or combustion of the droplet. In the present study, the seeding used, based on solid particles (powder of ZrO_2), was well suited since these tracers survived in the flame front. For low wind velocity, the particles were introduced at the base of the fire and entrained successfully inside the FF. The velocity field could be measured inside the flame and in its immediate surroundings, but only during the buoyancy-driven regime. The seeding of the flow with the system commonly used in confined environments was reasonably relevant during the buoyant regime of fire spread. Nevertheless, in outdoor experiments, the stable seeding injection is hard to set and the fire experiment would benefit from the injection of tracer particles at both upwind and downwind edges of the fire. This will allow measurement of the velocity field in the preheating region and will put to the fore some eventual convective mechanisms in heat transport toward the unburned fuel. Furthermore, the seeding procedure must therefore be fully improved for the investigation of the wind-driven regime of fire spread. Indeed, when wind velocity increases (3 m/s), many zones with null velocity vectors appeared. These are not regions where the fluid is at rest, but the concentration of tracer particles was too low to compute the velocity field. Indeed, a good seeding over the entire measurement region, with injection perpendicular to the laser sheet at the upwind edge of the fire, was difficult to achieve under these wind-blown conditions. Therefore, the one-point seeding device must be more adapted to the filling of a wide measurement region. To this end, a large seeding system with a distribution of injection nozzles along the vertical should be developed to ensure higher density of tracer particle in the PIV images.

As a consequence of the seeding difficulties, the thickness of the light sheet and inter-image time were fitted from an experiment to another in order to obtain good density images. It should be noted that the out-of-plane motion of the particle through the laser sheet thickness is unavoidable. At such a scale, in the open, the fire is a reactive turbulent flow generating 3-D local flow motions. Particles entrained in the flow have a 3rd velocity component in the transverse direction. In experiments under controllable environment, the seeding can be fitted to ensure the number of particles conserved into the laser sheet from a pulse to another is sufficient for directly measuring 2-D velocity fields. But the wind flow in the open is turbulent, and furthermore, the fire is a reactive flow generating 3-D effects that cannot be compensated. Thus, choosing the appropriate laser sheet thickness and inter-image time for minimizing the effects of out-of-plane motions is difficult in outdoor experiments. Indeed, the external conditions cannot be replicated from one experiment to another, and overall, they suffer from a strong variability during the experiment: the wind fluctuates in both velocity and direction. Considering the large size of the PIV area and the flow fluctuations, the thickness of the laser sheet cannot be reduced too much without many particles being lost between the first and the second frame of the pair of images and particle displacements becoming too small in comparison with the resolution of the PIV measurements. For this experiment, the laser sheet thickness and the inter-image time were set to 8 mm and 4 ms, respectively, and this setting yielded satisfactory results for the main duration of the experiment. In this preliminary study, our ambition was to illustrate that the optical technique of flow visualization can be used at a large scale for reactive flow. Methods are available to extract the third component of the flow velocity. Stereo-PIV using two cameras with different view angles can be used for this purpose. The stereo technique will allow correcting the 2-D measurements for quantitative analysis of the flow and related structures.

4 Conclusion and future improvements

A large-scale PIV system has been used in the open to measure the velocity flow field in the vicinity of a flame front spreading across a bed of vegetative fuel. This dynamic fire configuration presented a great challenge compared with compartment fires or static pool fire tests. Nevertheless, this preliminary study demonstrates the feasibility of PIV measurements in the open. The data collected showed some modifications of the flame dynamics induced by the variation of the wind properties. The velocity fields show that the flow is governed by buoyancy generated by the fire and by inertial forces due to the wind in the "plume-dominated" and "wind-driven" regimes, respectively. A change in the nature of the flow field around the fire engendered a change from one regime of fire spread to another with a significant increase in the fire rate of spread. In this large-scale PIV configuration in the open, many problems arise due to the variability of the external conditions. The main problems to overcome were the setting of the inter-image time, the thickness of the laser sheet, and a good seeding over the entire measurement region. Despite these difficulties, the present study exhibits the feasibility of the optical method of fluid visualization for dynamic fire tests in the field. The PIV measurements in the presence of flame were improved by the use of a liquid crystal shutter in front of the PIV camera, allowing very short exposure times and eliminating the flame trace in the tomographic pictures. Nevertheless, the properties of the flow field in the vicinity of the fire deserve further investigation. In particular, some strong efforts to improve the seeding of the flow must be made in order to allow the computation of valid vectors in the whole PIV area. The seeding will benefit from the injection of tracer particles at both the upwind and downwind edges of the spreading fire to reduce the regions where velocity vectors cannot be acquired. A powerful seeding generator able to produce a high concentration of tracer particles in the measurement area in the flow, even at high flow velocity, is needed for this purpose. In future studies, such a seeding system with multiple injection nozzles along the vertical will be developed. The injection of tracer particles from the bed of fuel should also be tested.

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