Measurement device for data collection during fire spread experiments in the field

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Abstract

Wildfires are increasingly damaging forests and threatening homes. Experimental data on fire spread at large scale are rare but such data are needed in order to improve the knowledge of the fire spread mechanisms or to validate and improve fire spread models across vegetative fuels. These considerations have provided the main motivation for the present work to collect data during a series of fire spread experiments conducted in the field across scrublands. To this end, a fast and easy to place measurement device dedicated to the measurements of temperature and heat fluxes was developed. This device consist in K-type thermocouple and heat flux gauges (radiant and total) located at the top of the vegetation and plugged on a datalogger buried under the ground surface. The measurements were done both inside and ahead of the vegetation plots. The whole sensors were fixed on an insulated support which inside was filled with a layer of ceramic felt to prevent from high temperature during fire travel. A two-dimensional ultra-sonic anemometer was located near the measuring device, downwind from the vegetation plot in order to reduce to its minimum the influence of the fire front on the wind measurements. Furthermore, digital video cameras recorded images of the fire from the side and front views to determine the fire behaviour and the flame geometry during spread. The measurement of radiation and convection are of great interest for a better understanding of heat transfers involved in wind-aided fire spread. For the range of experiments considered, radiation was the dominant heat transfer process in the preheating region and represent up to 90 % of the energy transferred ahead of the flame front. The set of data collected provide useful information for fire-fighters safety distance or wildland/urban interface dimensioning.

Introduction

In forest fire research, the experimental studies of the fire spread across vegetal fuels are of great interest for understanding and modelling the fire behaviour. The fire spread experiments across beds of fuel at laboratory scale have generated an abundant and miscellaneous literature from the last fifty years. Theses works provide some information for understanding and predicting the fire spread. At present time, there is a need of valuable data on fire spread at a scale larger than the laboratory one to improve the knowledge of the behaviour and properties of wildfires or to improve and validate physics-based modelling approaches at that scale (Morvan and Dupuy 2004; Linn and Cunningham 2005; Mell and others 2006).

Few experimental studies of fire spread across vegetative fuels were conducted in the field up to now (Cheney and Gould 1995; Carrega 2002; Viegas and others 2002; Butler and others 2004; Morandini and others 2006). The major part of these works only provides observations or measurements of the macroscopic characteristics

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of the flame front (rate of spread, flame length, flame tilt angle, residence time...) and temperature or even heat fluxes were rarely measured because instrumentation in the field is difficult.

This paper reports a preliminary analysis of heat fluxes emitted from fire fronts. To this end, a fast and easy to place measurement device dedicated to data collection in the field, was developed. It consists in a K-type thermocouple and two heat flux sensors (radiant and total) fixed on an insulated support and plugged on a local datalogger. The data were collected in the field during a series of four fire spread experiments conducted across various vegetative fuels ranging from pine needle bed to shrub. The device was intrusive and the measurements were made during fire spread in the preheating, flaming and charring regions. In order to assess the characteristics of the wind and its effects on fire, an anemometer was placed near the plot. Digital video cameras recorded images of the fire from the side and front views to determine the flame geometry. The fire grows and spreads by direct burning, which results from impingement of the flame on combustible materials, and from heat transfer to the unburned fuel by means of convection, or radiation. The aim of this work is, first, to identify and analyse the relative amplitude of these heat transfer processes associated to different fire spread configurations and, second, to provide information for the assessment of the potential fire hazards.

Experimental Procedure

Fire spread experiments in the field

Four fire spread experiments were conducted in the field in spring 2006. The vegetation plots were located in the Mediterranean region (south France) and the areas ranged from 25 to 1500 m². The fire spread experiments were conducted across various vegetal fuels for average wind speed and slope ranging from 0.1 to 4 m/s and from -5 to 35°, respectively (*table 1*). The plot orientation was chosen according to the main wind direction. The first three fire experiments were conducted across fuel beds (pine needles or cut tree branches with leaves). The last experiment was conducted through living shrubs (wild broom). A line ignition was performed along the windward plot edge thanks to a petrol-torch. The main objective of these experiments was to measure the gas temperature and the heat fluxes at the centre of the vegetation plot, during the fire spread.

Table 1— *Characteristics of the four fire spread experiments.*

	Fire spread experiment 1	Fire spread experiment 2	Fire spread experiment 3	Fire spread experiment 4
Vegetation type	Pine needles	Oak branches	Oak and arbutus branches	Broom
Fuel load	0.5 kg/m²	~15 kg/m²	~30 kg/m²	10 kg/m²
Vegetation height	0.03 m	0.5 m	1.4 m	0.8 m
Plot dimensions	5 × 5 m²	5 × 12 m²	8 × 18 m²	30 × 50 m²
Slope	-5°	0°	25°	20°
Wind speed	0.1 m/s	1.5 m/s	2.2 m/s	3.3 m/s
Rate of fire spread	0.003 m/s	0.015 m/s	0.020 m/s	0.180 m/s

Measurement and observation devices

The measurement device (*fig. 1*) consists in two heat flux sensors and a thermocouple fixed on a steel support facing the approaching fire front. This device was developed in order to be fast and easy to place with the future aim to collect data during forest fires. The support inside was filled with a layer of ceramic felt. A photograph of this device was provided in.

The air temperature was measured using K-type thermocouple with 50 µm wire diameter. The temperature measurements provide information on the flame residence time and peak temperature. The total and radiant heat fluxes emitted from the flame front during fire spread were measured using Gardon gauges. A Sapphire window attachment was added on the radiant heat flux transducer for elimination of convective heat transfers. The sensors were horizontally oriented and the view angle was 150°. The transducers were factory calibrated by submitting them to reference heat fluxes and were designed for measuring total and radiant heat fluxes up to 200 kW/m². The sensors were water-cooled. The instruments were plugged on a power-supplied data logger buried 0.3 m under the ground surface to prevent from high temperature during fire spread. This configuration allows the use of short extension cables (1.5 m) which reduces measurement errors.

Wind can be highly variable and was probably the most important environmental factor affecting the fire spread. A two-dimensional ultra-sonic anemometer was located near the measuring device, downwind from the vegetation plot in order to reduce to its minimum the influence of the fire front on the wind measurements. The anemometer has a low response time and allowed to record the rapid fluctuations of the wind (speed and direction). The measurements were made at a height of 2.5 m above the ground surface with a sampling rate of 1 measurement per second. Considering the range of flame heights encountered for the experiments, these measurements were assumed to be representative of the open wind influencing the flame properties.

Figure 1— Photograph of the measurement device

Figure 2. — Photograph of the fire experiment 3

In order to help to obtain accurate observations of the fire spread, three digital video cameras recorded images (25 images/s) of the fire from the side, front and rear views (*fig. 2*). The video recordings provide information on the rate of fire spread and on the flame geometric properties, namely the flame length and tilt angle.

Results and discussion

Gas temperature

The temperature-time curves for the four experiments were filtered with a low-pass filter designed to filter out the highest fluctuations (*fig. 3*). The air temperature measured at the centre of the vegetation plot during the fire spread shows the presence of three regions, namely the preheating, flaming and charring regions. These data indicate that air temperature remained near the ambient value before the arrival of the fire front. The data, collected wind-aided fire spread during experiments 1, 2 and 4, suggest that convective heat transfer do not played a significant role in the preheating processes; with the exception of masses of hot gases, which frequently separated from the main flame front, when fire front is close to the sensors. Some intermittent convective heating occurred over a very short range and is due to direct flame contact or hot gases from combustion. Conversely, for the fire experiment 3 the temperature rise was slower. In this case, the fire plume was highly tilted forwards which suggest convective heating ahead of the fire front.

When the measurement device was in the flaming region, high temperature fluctuations were observed in the data. The average temperature measured was in the range of 600-800°C. The temperature increase is due to the flame presence but the distinction of the different scales on these temperature curves is problematical.

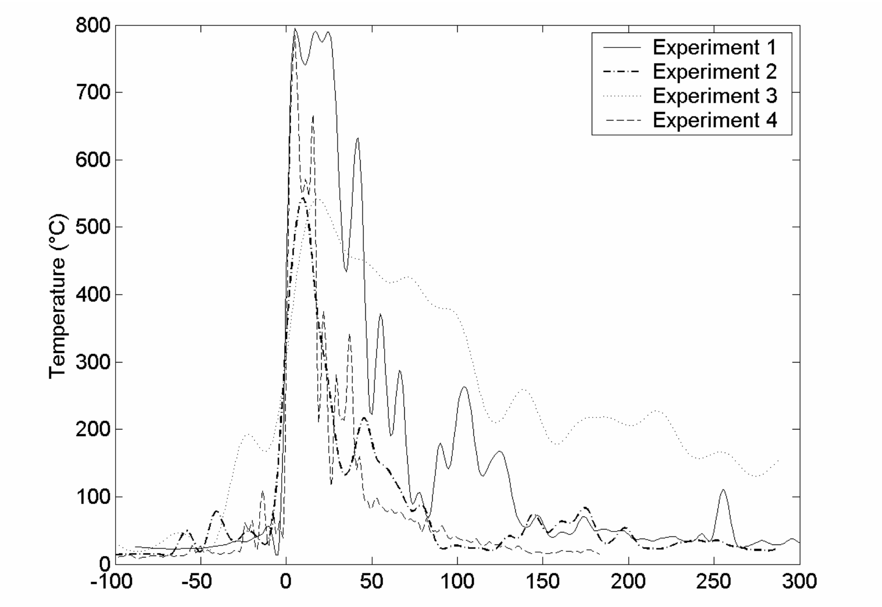

Figure 3–Temperature-time measurement for the four fire spread experiments

The residence time of the flames was obtained from the time that temperature remained above 300°C, which corresponds to the minimum temperature for piloted ignition of vegetative fuels. The flame residence times were in the range of 24-110 s and were mainly related to the fire dynamics and vegetative fuel properties. The longer residence time was observed for the fire experiment 3 where the temperature remained fairly high due to the greater fuel load. Furthermore, the greater diameter material also led to strong char combustion processes.

Heat fluxes

The total heat flux curves (*fig. 4*) were also filtered with a low-pass filter designed to filter out the highest fluctuations. The measurements remained inside the calibration range. The heat fluxes also show the presence of the three previous regions identified on temperature measurements. In the preheating region, the heat fluxes increase progressively while the fire front approached the measurement device, whereas the temperature suddenly increased with direct flame contact. Inside the flaming region, the peak heat fluxes measured during the four experiments increased with flame front size and were in the range of 39-112 kW/m². While the temperature measurements did not, the heat fluxes exhibit significant differences which account for the fire dimension, dynamics and intensity.

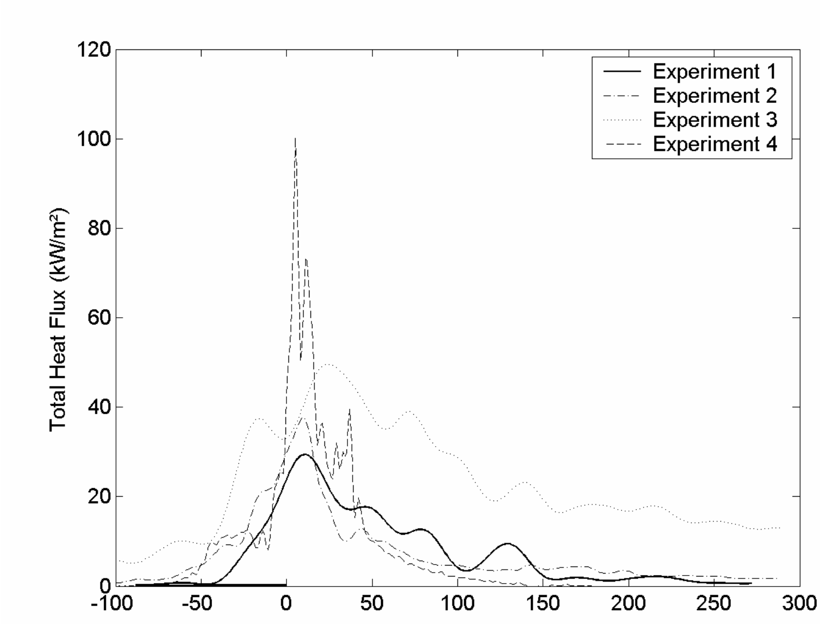

Figure 4–Flux-time measurement for the four fire spread experiments

Nevertheless, caution should be exercised interpreting the measurements of total heat fluxes in a mixed radiative-convective environment obtained from gauges output using radiation based calibration, since measurement errors occurs (Kuo and Kulkarni 1991). Nevertheless, total heat flux measurements ahead of the fire front, are expected to be more representative of the heat transfers thanks to the low value of h in this region. The radiant and convective heat fluxes prior ignition are compared (*fig. 5*) for the higher intensity fires (experiments 3 and 4). The convective heat transfer was deduced from the difference between total and radiant heat fluxes assuming that conduction is negligible in the air. These data exhibit that radiation was the dominant heat transfer process ahead of the fire front for the range of experiments considered. Radiation had effect a long time before ignition which confirms a long range preheating process above the vegetation top. Radiative heating represented about 65 and 90 % of the energy transferred ahead of the flame front for experiments 3 and 4, respectively. For experiment 4, convection became significant only a short time prior ignition and convective heating occurred within the immediate surroundings of the flame front. Conversely the data from experiment 3 suggest convective heating by hot gases from combustion or direct contact of the flame slightly farer from the fire front. These results on heat transfers processes confirm the hypotheses brought up during the previous analysis of the temperature measurements. The highly turbulent flow, caused by the interaction between wind and fire, induced flickering of flames which frequently leant towards the unburned fuel. The high fluctuations in heat flux measurements account for this flame behaviour during experiment 3. The Froude number, relating the relative importance of inertia and buoyancy forces inside the reacting fluid flow, was often invoked as being representative of the fraction of the energy exchanged by radiation and convection (Pagni and Peterson 1973; Morvan and Dupuy 2004). Furthermore, the predictions of a multiphase formulation1 highlighted the existence of two different regimes of fire spread dominated either by radiative or convective heat transfer according to wind velocity. The model predictions exhibited an increasing convective heating with increasing Froude number becoming the dominant heat transfer process. For the two greater fire intensity experiments, the Froude numbers based on average wind velocity and flame height were in the range of 0.2-0.3 and heat transfers in the preheating zone ahead of the flame front were mainly dominated by the radiant heating. The range of experimental configurations considered here makes difficult to confirm this change in the dominant heat transfer mechanism.

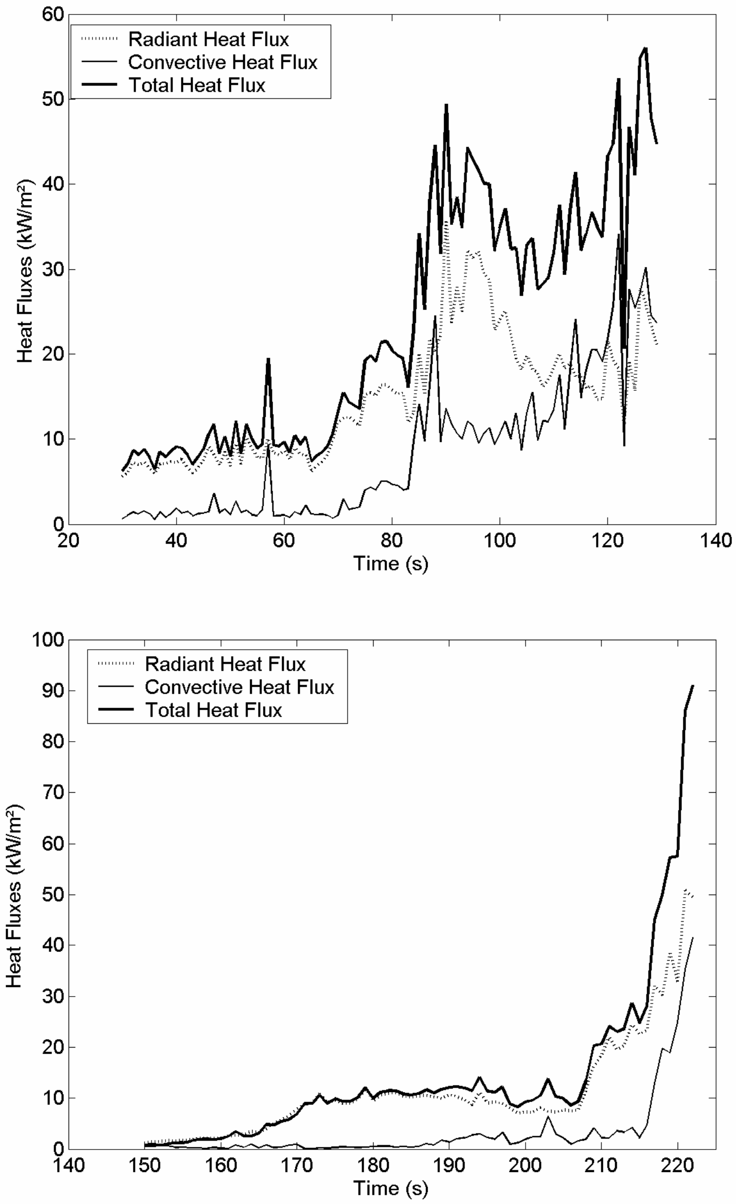

Figure 5–Flux Comparison of the radiative and convective heat fluxes as fire approaches for experiment 3 and 4

The incident radiation (*fig. 6*) strongly depends on flame height and decreases with distance to flame front. Theses curves exhibit an increasing span preheating with increasing fire intensity and confirm the necessity to study the large-scale behaviour of the fire. For the fire spread experiment 4 which was the most representative of a wildfire, the radiant heating was significant far from the flame front (over 10 m). Some critical heat fluxes for skin exposure are displayed in order to provide useful information for fire-fighters safety distance. Assuming a heat flux tolerability of 7 kW/m² for a fire-fighter, the distance to the flame front which corresponds to this burn injury threshold was located at 12 m. The rule-of-thumb used by forest fire managers, approximating a safety distance of at least four times the flame height, is in reasonably good agreement with the measurements. The radiant heat fluxes ahead of the fire front are also compared to critical heat fluxes for piloted wood ignition (25 kW/m²) or auto ignition (50 kW/m²) in order to estimate hazards for the flammable parts of a home. Concerning the wildland/urban interfaces, clear zones around homes are made in order to keep distant the radiant heat source and to reduce intensity of fire spreading from wildland towards homes. For instance, based on expert's opinion and limited data available 50 m wide fuel breaks are imposed in France to avoid underestimating fire hazards. This size should be adapted to the most severe fire, but estimation of ignition occurrence based on radiant heating data, such as the ones collected in the present study, will be more efficient.

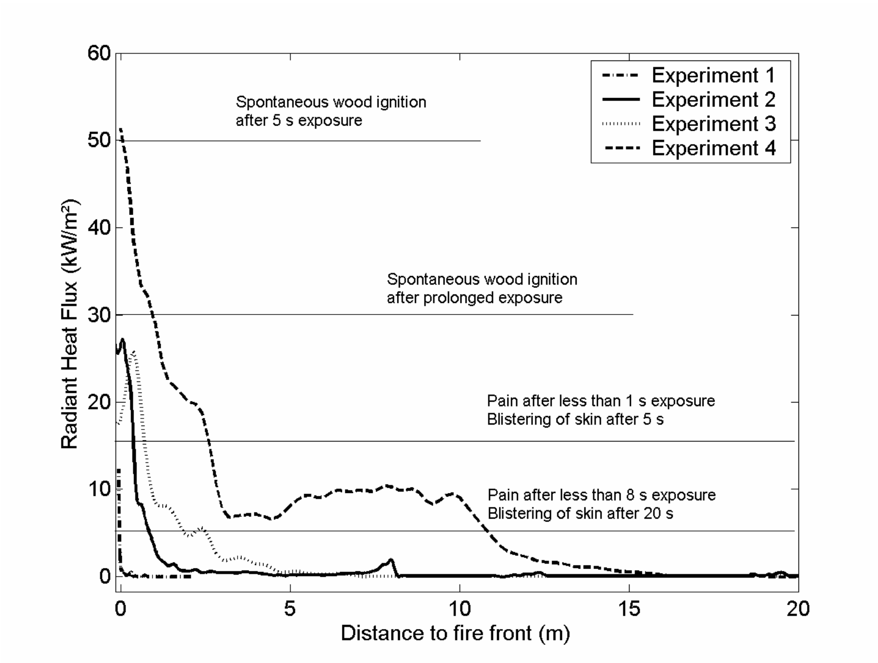

Figure 6–Distribution of the incident radiation ahead of the fire front

Conclusion

Some data on fire spread across vegetative fuels collected at different scales were presented in the present paper. The device used was demonstrated to be a robust instrument for the measurements in large-scale fire tests since it withstood, for flame residence time lower than one minute, heat fluxes and temperature over 100 kW/m² and 800 °C, respectively.

The main results emerging from this preliminary work exhibit that the experimental studies of wildland fires should be preferably conducted measuring scale dependant quantities, namely the heat fluxes, rather than temperature or rate of spread. The collected data showed that variations of the peak temperature inside the flaming region were not significant with increasing fire scale in comparison to the variations of the peak heat fluxes. Furthermore, the air temperature measurements are of interest only in the flaming region, whereas heat flux measurements are relevant in both preheating and flaming regions. For the range of experimental configurations considered, radiation was the dominant heat transfer mechanism ahead of the fire front. The distribution of the incident heat fluxes in this region deserves further investigations and several measurement devices located at various distances from the fire front will be used in future works. To this end a series of higher intensity fire experiments under high wind velocity conditions will be conducted to further assess the convective heat transfers which are often supposed to play a non-negligible role in the thermal transfers ahead of the flame front.

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