Chapter 2
Measurement Systems

From a thermodynamic point of view, fire is an irreversible process during which vegetal cover evolves from one equilibrium state (unburned) to another (partially or totally burned). Therefore, fire deals mainly with quantities that are emitted, transported, and absorbed by material targets. The wildland fire–urban interface (WUI) (Mell et al. 2010) is concerned mainly with the heat transport from a burning forest or wildland to an urban area, including its radiation impact and firebrands (Manzello et al. 2006). Although they represent an important question of fire safety, firebrands flow as a dispersed fluid medium in which burning particulates are transported. We will see that tracking luminous particles requires special optical devices, the use of which is not trivial because flames are strongly radiative and turbulent. This is why our focus here is mainly on continuous quantities. These quantities—mass, momentum, and thermal energy—obey a conservation property. Their formal description and subsequent measurement involve two sets of thermodynamic variables. There are first so-called extensive variables, i.e. variables such as density, momentum, and heat that change in quantity with the mass or the volume of the system. They are the most important factors in fire science because they change with the size of the fire and, therefore, should be key measurements in field-scale experiments. The second type includes the 'intensive' variables that 'measure' the departure from the equilibrium state (e.g. temperature, pressure, and gas velocity). For instance, the departure from thermo-dynamical equilibrium is more intense in a Lox/H_2 laminar, diffusion flame reaching up to 3000 °C than in a candle flame, where the temperature does not exceed 850 °C. In a modern thermodynamic description of the phenomenon, the fluxes of extensive quantities can be interpreted as being dependent upon the gradients of intensive variables (Jou et al. 1996). The main example for fire is the heat flux, i.e. the amount of heat by volume unit that passes through a unit surface each second, which is related to the temperature gradient (in fact, to the gradient of the inverse squared temperature, known as the affinity). Heat flux density is the extensive variable and temperature (or affinity, in more general terms) is the intensive one.

A central question in fire science is the amount of heat that is released by the fire. In laboratory-scale conditions, equipment such as the cone calorimeter and

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the fire-propagation apparatus can offer insight. One can measure directly the total amount of heat released—the heat release rate (HRR)—by the fire as proportional to the overall oxygen consumption rate. However, such diagnostics cannot offer any information about fire in outdoor conditions where vegetal burning surfaces cover further hundreds of squared metres. Such a global quantity is less significant and hard to interpret at the field scale, whereas the local properties of the fire (local temperature and heat fluxes along the fire lines) will determine the fire hazard and guide fire-fighting processes. HRR, instead, is important for investigating the thermo-chemical properties of fuels and the fire-ignition conditions in repeatable and stable situations. At the field scale, the fire hazard is determined by the amount of heat transported towards particular targets and, therefore, fire science focuses on the heat flux. Furthermore, the fire position also is set accurately by the gas-phase temperature, which reaches up to 300 °C when gases are emitted from the thermal degradation of solid fuel and to about 800 °C in the flame. Therefore, the intensity of heat fluxes, given by temperature gradients and fire front kinematics are immediately available from multiple temperature measurement points. This is why we begin with temperature measurement systems.

2.1 Heat Measurements: The Temperature

2.1.1 Temperature Measurement

Temperature is the first quantity to measure in fire experiments at a real scale. As in radiation heat transfer, it is a dominant parameter of chemical reactions in many combustion systems, and exhibits fourth-power influence. In fire, temperature also allows the pyrolysis and flame fronts to be located; from this, the rate of fire spread can be ascertained. From the horizontal and vertical temperature distributions, the flame structure and its evolution can be observed. In addition, temperature gradients provide information about heat fluxes and temperature fluctuations reveal features of reactive flow motions (Silvani et al. 2009). In many combustion systems, measuring the temperature is a challenging problem, especially when it reaches as high as 2000 or 3000 °C. In outdoor fires, where flames are naturally ventilated by the surrounding air flow, the temperature is not expected to be greater than 1500 °C. Rather, the fire context is determined by the strong coupling of the heat radiation due to soot and/or fine-sized particles and the flow motion.

Because of the local nature of the quantity ‘temperature’, its measurement becomes subject to several errors due to local heat transfer and fine-scale phenomena that might be relevant in every case.

This local nature of the quantity ‘temperature’ has other consequences. Pointwise measurements usually are easy to perform and robust in small-scale environments. In fire scenarios, they also lead to an increase in the overall cost of the experiment because their number must increase with the fire size. Measuring a temperature field, therefore, becomes a significant issue in large-scale fire scenarios. However, this is based on modern optical diagnostics that are not really designed for use in such conditions, even if recent progress illustrates their future potential.

2.1.2 Devices for Temperature Measurement

Temperature can be measured using direct (intrusive) and optical (non-intrusive) devices.

The direct measurement devices are mainly thermocouples, i.e. electric wires of small size ranging from a few micrometres up to millimetres. Thermostats and thermometers with resistance (such as the platinum probe PT 100) are not convenient for sensing a fire at field scale.

Thermocouples are manufactured by linking two different types of metals with a joint. When the two junctions of an open circuit formed out of two different metals are at different temperatures (Fig. 2.1), a difference in potential exists between the two junctions as a linear function of the temperature difference. This is called Seebeck's effect. The coefficient S_{12}, expressing the linear dependence of voltage to temperature, is Seebeck's coefficient (Eq. 2.1).

$$S_{12} = \frac{dV_{12}}{dT_{12}} \tag{2.1}$$

where dV_{12} (resp. dT_{12}) is the voltage (resp. temperature) variation between points 1 and 2. Seebeck's coefficient is a characteristic of the coupled metal that forms the thermocouple.

The main parameters of a thermocouple are the coupled pair of chosen metals (i.e. Seebeck's coefficient and, therefore, a temperature range), the nature of the 'hot' junction between wires, and the response time. The temperature range corresponds to the category of thermocouple. Indeed, each couple of selected metals has a Seebeck coefficient. For fire of vegetal fuels, the temperature range is usually that of the K-type thermocouple (chromel–alumel), i.e. up to 1372 °C. Some

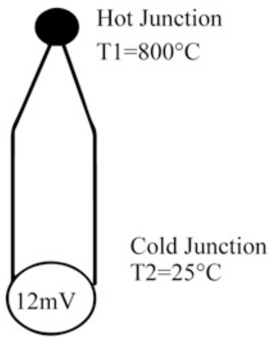


Fig. 2.1 Principle of measurement using a thermocouple

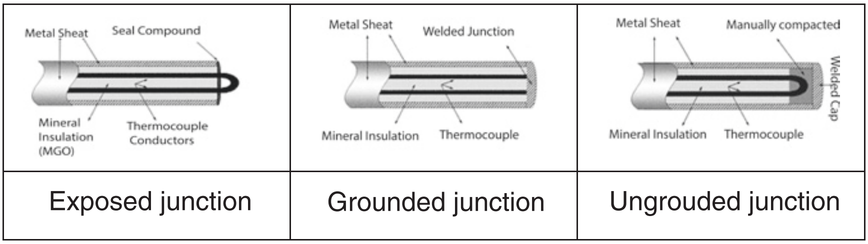


Fig. 2.2 Three different junctions for thermocouples

cautions must be taken for their use, particularly guaranteeing the control and the independent measurement of the cold wire junction if an absolute temperature is required and not just the difference between the two junctions.

The hot junction may be exposed, ungrounded, or grounded (Fig. 2.2). An exposed junction has nothing (no protective assembly or even a tube) to cover the junction. Exposed junctions have the fastest response time, the lowest radiation error, and the least conduction error (discussed below). They suffer from corrosion and fragility. There is an additional risk in using them in outdoor fire conditions. Exposed-junction thermocouples also are prone to picking up parasitic electromagnetic signals, but the risk seems low in outdoor natural conditions. However, there are solutions to guard against this.

A grounded junction is similar to an exposed junction, except that a protective metallic sheath encloses the elements and insulation. In a grounded junction, the thermocouple wires are welded directly to the surrounding sheath material. A grounded junction is more capable of tolerating physical and mechanical abuse. It is also more resistant to corrosion and oxidation. However, thermocouples with grounded junctions suffer from a slower response time and are more sensitive to errors than are exposed-junction thermocouples. Like exposed-junction thermocouples, they may pick up stray electromagnetic signals.

These considerations—wire size and junction model—directly influence measurements made using the response time. Indeed, in a measurement system where gained voltage is converted into a digital signal for recording and monitoring, the ability to capture fast phenomena depends on the cumulative response time of the data-logging system and the response time of the connected device. Standard data loggers have a measurement speed of about 200–250 μs, i.e. are able to capture rapid phenomena at 8 kHz (according to Shannon's rule).

When a thermocouple is suddenly submitted to the temperature T_1, namely a step from the temperature of the cold junction T_2, there is a delay, due to thermal inertia, in reaching up to 63.2 % of the final value according an exponential process. This delay is the response time or the time constant of the thermocouple.

Evaluating the response time of a thermocouple is possible through the derivation of the local thermal model of the thermocouple, which is subject to all of the heat transfer in a fluid medium when the temperature changes from T_2 to T_1. Current models present the constant τ depending on the junction density ρ, the volume V, the specific heat c, the convective coefficient h, and the junction area A_s, according to Eq. 2.2 (Bentley 1998).

$$\tau = \frac{\rho V c}{h A_s} \tag{2.2}$$

The air temperature was measured using a K-type sheathed thermocouple with 50 μm wire diameter. The fine wire thermocouples have low response times and allow one to follow, with good accuracy, the rapid fluctuations of the gas temperature inside the flame when signals are sampled at 1 Hz, which is the current high frequency in outdoor environmental applications, including meteorological measurements. However, this set-up is limited when investigating high-frequency temperature fluctuations (beyond 10 Hz), which are usually neglected in fire studies at real scales and may have some relevance to models (Silvani et al. 2009). The investigation of every extensive or intensive quantity in real-scale fires is related to the fluctuating features of these fires; the time constant informs the selection of a convenient measurement tool that takes into account these fluctuating aspects. In other words, using a wrong time constant –therefore, a wrong size of the thermocouple–may filter out some fluctuations, even if these are involved in the fire.

Thermocouples are, therefore, used commonly in fire research to measure gas temperatures, but often fail to measure the true gas temperature (Cox and Chitty 1985; Luo 1997; Dupuy et al. 2003; Morandini and Silvani 2010; Silvani et al. 2012). Radiation effects that depend on the measurement conditions are considered the most significant source of errors. In fire science, discrepancies between true gas and measured temperatures are acceptable because they are less than 10 % for the probes used (Silvani and Morandini 2009). The corrected temperature curves are not provided here but radiation effects on the temperature measured using thermocouples must be kept in mind. Measurement errors with thermocouples are detailed in Sect. 2.1.3.

A good example of temperature measurements during fire experiments in the open is given in Morandini and Silvani (2010). This work consists of a series of fire experiments in the field using a vegetal fuel. Two regimes of fire spread are identified. In the buoyant regime, flame fronts are quite vertical and the fire spread is governed by the thermal radiation (Fig. 2.3). In this case, three air temperature regions are measured during the fire spread (Fig. 2.4), namely the preheating, flaming, and charring regions. The measured temperatures start at the ambient temperature and increase to a maximum of about 800–900 °C, which is an usual temperature range for burning vegetal fuels. The temperature curves show a slow trend modulated by fast fluctuations. The slow trend, namely the low-frequency part of the signal, is related to the fire spreading whereas the fluctuations are due to flame pulsations and wind gusts (Morandini et al. 2006). Details about filtering are available in (Morandini and Silvani 2010) and extensively discussed in Sect. 2.3 of this brief, 'Post-processing'.

The flame-residence times measured for each experiment are defined as the time during which the temperature is greater than 500 °C, which corresponds to the visible flame temperature. The flame residence times do not show significant differences and do not account for the two fire spread behaviours—a

Fig. 2.3 Flame fronts governed by buoyancy

radiation-driven regime and a mixed-radiation convection driven regime—that also have been identified as involved in laboratory-scale experiments about slope effects on fire (Silvani et al. 2012; Dupuy and Marechal 2010).

In the radiation-driven fire-spread regime, the air temperature remains close to the ambient value before the arrival of the fire front. The air temperature increase occurs at the time of the arrival of the fire front and the rise rate is high. The corresponding flame fronts [see the buoyant fig. flame front (Morandini and Silvani 2010) were close to vertical and the smoke plume was guided upward. It should be noted that peculiar temperature behaviour could be observed (see experiment 2; the sudden temperature drop to 200 °C for about 20 s is due to the presence of discontinuities in the fuel). In the second group of experiments, in the radiative–convective regime of fire spread, the rise rate of temperature during preheating was lower.

The increase in the air temperature occurs over a longer period before flame contact (more than 100 s prior to ignition) and temperature measurements show high fluctuations.

Another key feature of the measurement is the temperature fluctuations, which are related to the turbulent properties of the flame front as a reactive flow. The question of how to obtain an appropriate measurement system with a fast response

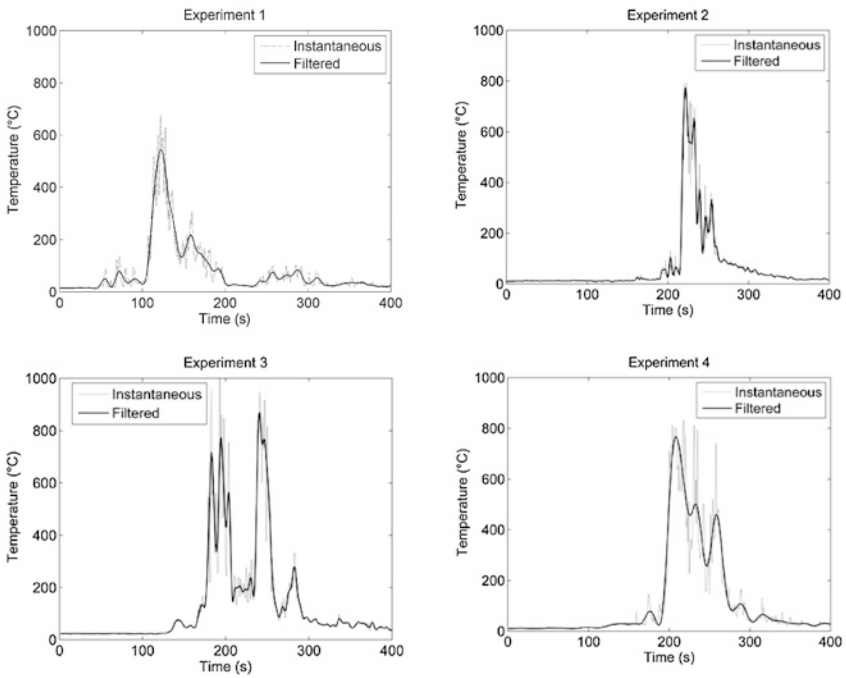


Fig. 2.4 Gas temperature in the case of previous fires (at the *top* of the vegetation)

time is addressed in the work of Frankman et al. (2010), which was pioneering research in this framework. Silvani et al. (2009) also observed that the modelling of temperature fluctuations and, therefore, their detection in fire experiments, is of primary importance for avoiding large errors in modelling the related heat flux. With regard to thermocouples, the first technological gap to discuss is reducing as much as possible the time constant to allow intrusive measurements of temperature. According to Eq. (2.2), the dependency to the ratio V/A shows that the time constant τ varies as the TC diameter. K-TCs with exposed junctions are now available with a 12 μm diameter and a time constant of about 10 μs. However, no study has reported the use of such a device in outdoor conditions. There are some applications for a protected junction in rocket engine tests, but this protection affects the thermal inertia of the tool and also degenerates the time constant.

Indirect (non-intrusive) techniques for measuring a temperature from a fire scenario in outdoor conditions are based on the optical properties of the medium. Infrared (IR) thermometry uses a map reflecting the IR emission of a hot or cold body viewed from the camera and compares this to a radiative reference of known temperature. In large-scale fires, IR digital information integrates the radiation from the entire flame volume (Fig. 2.5) and, therefore, it is hard to interpret this information as a temperature measurement. One can also cite the Rayleigh scattering thermometry, which deduces the temperature from the elastic scatter of light by molecules in a known mixture. This last method has been adapted to

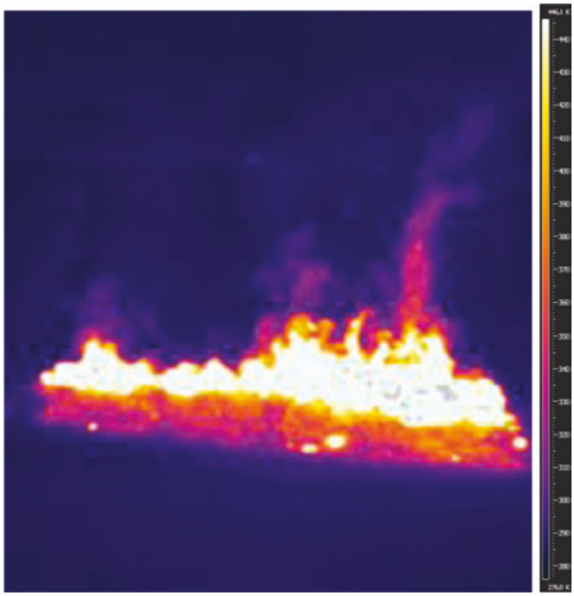


Fig. 2.5 Infrared thermometry: the plot is a 50 m² fuel bed of excelsior

clean reactive atmospheres but is not efficient for evaluating particles, as in fires. Sensors based on the use of optical fibres use the property of light reflection and measure the shift in wavelength that occurs in proportion to a temperature difference. We will not discuss these techniques, because they do not allow the capture of temperatures greater than 300 °C, which are commonly reached in fire experiments.

2.1.3 Errors in Temperature Measurements

Temperature measurements with thermocouples are widely used in fire research but the thermocouple readings are not representative of the true gas temperature (Cox and Chitty 1985; Luo 1997, Blevins and Pitts 1999; Santoni et al. 2002; Brohez et al. 2004). Radiation effects are considered the most significant source of errors and can be more or less significant according to the measurement situation. The thermocouple behaves differently ahead of or inside the flame front. When a thermocouple is located ahead of the flame front, a higher temperature than in the gas can be measured. This is due to the influence of radiation emitted from the distant fire impinging on the thermocouple junction. Conversely, in the flame, the thermocouple indicates a temperature that is lower than that of the gas because of radiative loss from the thermocouple junction to the colder surroundings. Thus, these errors are attributable to the temperature of the surroundings.

Correction methods for temperature measurements based on a double-thermocouple probe (Brohez et al. 2004) or a shielded aspiration thermocouple (Blevins and Pitts 1999) are not easy to implement in field experiments. Nevertheless, the estimated error can be derived from an energy-balance equation on the thermocouple junction (Cox and Chitty 1985; Bryant et al. 2003; Incropera and DeWit 2002). Ahead of the fire front, the difference in mean temperature between the true gas and the thermocouple junction is given, to the first order, by

$$T_g - T_{TC} = \frac{\sigma \varepsilon_{TC} \left[(1 - \varepsilon_g) T_g^4 - \varepsilon_F F_{F-TC} T_F^4 \right]}{h_{TC} + 4\sigma \varepsilon_{TC} T_g^3} \tag{2.3}$$

The two terms of the numerator represent the radiant heat emitted by the thermocouple junction and the radiation received by the thermocouple (mainly from the distant flame front).

Inside the fire front, this error (Luo 1997) is estimated by

$$T_g - T_{TC} = \frac{\sigma \varepsilon_{TC} (1 - \varepsilon_g) T_g^4}{h_{TC} + 4\sigma \varepsilon_{TC} T_g^3} \tag{2.4}$$

The convective heat transfer coefficient, $h_{T,}$ for a thermocouple junction assumed as a cylinder can be obtained from a Nusselt number correlation (Luo 1997), and is given by

$$h_{TC} = \frac{k_g}{d_{TC}} (0.43 + 0.53 \mathrm{Re}^{0.5} \mathrm{Pr}^{0.31}) \tag{2.5}$$

These corrections show that the uncertainties can also be reduced by the use of fine wire-diameter thermocouples. The finer the wires in the junction, the lower the amount of radiant heat received and released by the thermocouple, and the closer the temperature of the thermocouple will be to the gas temperature. The downside is the lower tolerance to physical and mechanical abuse, which must be considered in fire experiments at the field scale.

2.2 Heat Measurements: The Heat Flux

The main objective of experimental fire studies is to better understand the heat transport and transfer towards targets, either material or living, to preserve the integrity of the targets to thermal degradation. With the overall heat release, heat transport is central to every discussion related to fire, for scientific and engineering considerations. For the latter, the extinction of fire by water provides a framework for active research and development. In the fuel-storage industry, where fire safety is related to heat flux attenuation, how one monitors the fire scenario and manages the related extinction strategy is determined by the heat flux; this monitoring is one of the most challenging aspects in fire technology. The measurement of the heat flux of a real-scale fire remains, therefore, a central question in fire metrology.

2.2.1 Heat Flux Measurement

The heat flux measurement is generally based on the properties of solid metallic bodies that intrude into the medium where the fire occurs. These bodies, called heat fluxmeters, are the location of heat conduction from a face exposed to the fire to another face in cooled conditions. Temperatures are measured on both faces with thermoelectric sensors serving as thermocouples. The temperature gradient arising between the face heated by the fire and the cold one leads to the flux impacting the sensor; an inverse-method model for relating the outer flux to the inner one allows the measurement of the temperature gradient. This principle is theoretical and the set-up of such gauges requires an experimental procedure in which the flux measured by the sensor is compared to a calibrated one. This question is central because one generally considers as a good skill the ability of a new sensor when it returns a voltage response that is linearly dependent upon the reference heat flux. The central purpose of the calibration procedure is related to the nature of the outer flux, which the sensor is designed to measure.

Fluxmeters usually are sensitive to the total heat flux, i.e. the addition of convective, radiative, and conductive heat flux impacting the sensing face. Where fire is concerned, conduction is generally neglected if the fluxmeters observe transport only in the gas phase or in the vegetal fuel, which is a weak heat conductor. In fire experiments at the field scale, it therefore is necessary to calibrate heat fluxmeters exposed to radiative and convective heat fluxes that range over a 100 kW/m^2 scale; for comparison, a domestic oven has a maximal heat flux of about 5 kW/m^2. At that point, the question of calibration is split into two parts.

- The first concerns radiation: large-scale sources for generating an intense thermal radiation exist all over the world in laboratory or industrial environments. These sources produce a calibrated heat flux according spectral properties close to the black-body emission. This points out a condition for using radiant-heat fluxmeters in fire studies: the spectral properties of the flame emitting thermal radiation must be known or, at least, considered to be close to those of a black-body emitter. At the laboratory scale, that might not be the case for vegetation fires (Boulet et al. 2011).
- The second issue concerns heat convection. As described by Pitts et al. (2006), a group of researchers observed the response of two types of commonly used heat fluxmeters (the Gardon and Schmidt–Boelter total heat flux gauges) to pure irradiation. This was performed during an international campaign with several laboratories (a round robin). They concluded that sensitivity to heat convection must be investigated through dedicated methods. Measuring total heat flux with the Gardon gauge, using radiation-based calibration, may not

be possible in a mixed environment, such as fire. Thus, facilities are necessary to calibrate the convective contribution of the heat flux when total heat flux gauges are employed. Such facilities currently are being developed, but they are restricted to low convective heat flux levels, up to 5 kW/m² (Holmberg et al. 1999). Beyond this limitation, a central issue is the current absence of a widely used experimental set-up to calibrate the heat fluxmeter for pure convective heat flux from a turbulent flame. This is due to the large degree of freedom in a hydrodynamic transport process that occurs in complex media, such as those used for fire studies and under turbulent flow conditions. Defining the calibration conditions that are able to reproduce the fine structure of a turbulent hot flow in which the thermal convective transfer to a reference target is well-known, remains an open, and challenging, issue.

2.2.2 Devices

The thermal radiation can be measured using total or radiant heat fluxmeters (HFMs). Radiant HFMs differ from total heat fluxmeters in that they have a window fixed upon the thermosensitive electrical part of the HFM. This window stops all contact heat transfer—namely, convection and conduction—between the surrounding medium and the thermoelectrical part. This window allows only the passage of thermal radiation, and, in particular, a selected wavelength bandwidth that is composed of IR radiation. Wildfire science often employs radiant HFMs with a sapphire window, which usually allows the passage of wavelengths ranging from 0.3 to 5.5 μm. This is due to the following consideration: if the flame emits as a black body, for a flame temperature of about 800–900 °C, a significant part of the thermal radiation (more than 90 %) is emitted in the 0.3–5.5 μm range. This argument completely avoids the question of temperature fluctuations. In (Silvani et al. 2009), authors reveal the extent of fluctuations: in fire experiments at the field scale, the root mean square of a single point measurement in temperature may reach about 40 % of the average temperature value. The consequence is that the radiative properties of the flame as an emitter can cover an interval larger than 0.3–5.5 μm. The spectral properties of flame radiation in the IR raise questions related to the hydrodynamic nature of the flow. One can cite the pioneering work performed at the LEMTA (France) on such properties (Parent et al. 2010; Boulet et al. 2009).

Despite this complex environment and the large amount of technical skill required by the metrology, one can use a single measurement system to obtain robust experimental data from fire experiments in the open. The measurement of the heat flux must discriminate the nature of the flux—that is, either radiative or convective—as it must be as accurate as possible to obtain a good determination of the order of magnitude and the time scale. In the absence of a relevant tool for directly measuring the heat convection, the fire community associates the radiant HFM with the total HFM by considering that the heat conduction occurs on time scales longer than those for radiant and convective transfer (Silvani et al. 2012). In the absence of significant heat conduction (in the gas phase as well as in the solid one, if the fuel is a low heat conductor such as a vegetal fuel), the total heat flux is the sum of the radiant heat flux and the convective heat flux. As we have explained already, HFMs, both total and radiative, suffer from the lack of calibration versus a reference convective flux (more than 5 kW/m²). They are mainly calibrated facing pure irradiation. Therefore, if the two sensors are installed at the same point facing a large-scale fire and are under a pure radiant heat flux (as in the case of the buoyant driven regime in Fig. 2.6), they must measure the same signals. In this case, quantitative measurement of the heat flux is guaranteed by the limited pure irradiance calibration. The correspondence of the two signals, radiative and total, leads to a relevant measurement of the heat flux emitted by the flame—which is assumed to behave as a black body—in the irradiance condition close to the conditions at which the heat fluxmeters were calibrated.

On the contrary, if the total heat flux and radiant heat flux signals differ and the total heat flux is larger than the radiant heat flux, a convective contribution exists, as is the case when sensors are embedded into the flame. However, because of the lack of sensitivity studies of pure convection, the corresponding convective heat flux cannot be considered to be the difference between the total and radiant fluxes (Pitts et al. 2006).

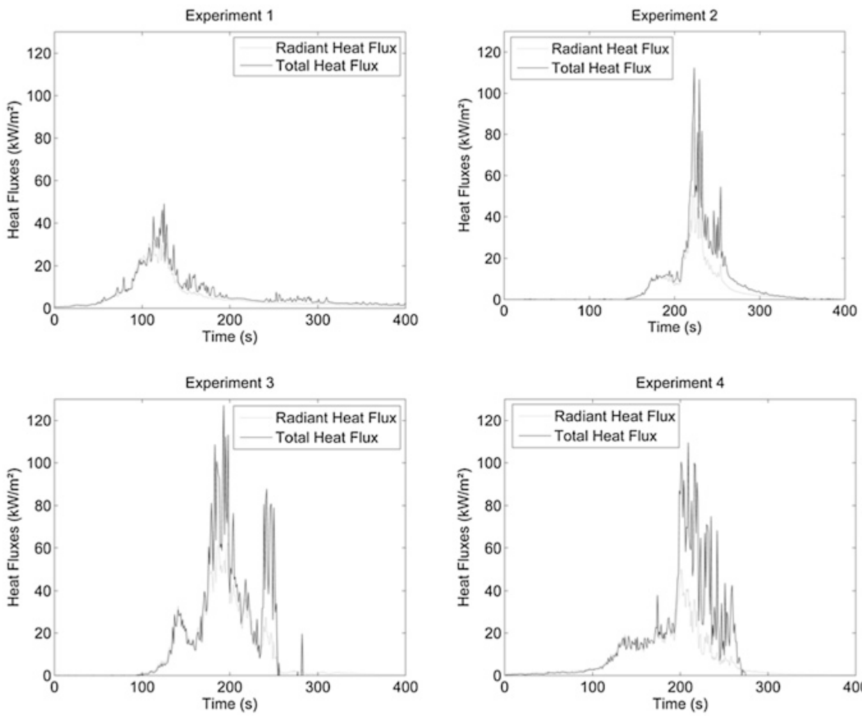


Fig. 2.6 Time evolution of heat flux densities at the *top* of the vegetation

The response of the total heat flux to strong convection, as in the case of large-scale fires, is unknown, regardless of the brand of fluxmeters that is used. A situation in which the total heat flux is lower than the radiant one signals a cooling phenomenon due to convection of the total HFM. No quantification of this cooling can be performed because of the unknown sensitivity of HFMs to convection.

If HFMs are calibrated only under pure irradiance, differential measurements of the total and radiant HFM can qualitatively detect the presence of a convective flux but they cannot quantify this characteristic.

2.2.3 Measurement Errors

The measurement uncertainties of radiant heat flux gauges with window attachments are given by the manufacturer (3 % for Medtherm Gardon gauges) when they are calibrated facing pure black-body irradiance. However, caution should be exercised when interpreting the measurement of total heat flux in a mixed radiant–convective environment obtained from the output of Gardon gauges using radiation-based calibration, because measurement uncertainties occur. In their pioneering study, Kuo and Kulkarni (Kuo and Kulkarni 1991) quantified this error, which leads to heat flux underestimation, and proposed a correction when calibration is based only on radiative heat flux. The correction to be applied is obtained from the thermal diffusion equation for the foil and can be expressed in terms of the modified Bessel's function of the first kind. This correction depends on the magnitude of the convective heat transfer coefficient. The ratio of the incident heat flux in a mixed environment and the heat flux indicated by the gauge is given by (Kuo and Kulkarni 1991)

$$\frac{q_{mix}}{q_{rad}} = \frac{(\frac{mr}{2})^2 I_0 mr}{I_0 mr - 1} \tag{2.7}$$

where m stands for the squared root of the Nusselt number, Nu; r is the radius of the gauge; and I_0 is the modified Bessel's function of the first kind,

$$m = \sqrt{\frac{h}{\delta\kappa}} = \sqrt{Nu} \tag{2.8}$$

This means that the ratio of the total and pure radiant heat flux measured by total and radiative HFMs is a non-linear function of the heat transfer coefficient. In the absence of any calibration in the convective conditions, this non-linear dependence is unknown.

The use of two different gauge types (total and radiant) allows for a quantitative determination of the radiant heat flux when convective heat transfers are negligible. In this case, the heat fluxes measured with total and radiant gauges are equal and no correction to the total heat flux is necessary, because the gauges are used in a thermal environment that is similar to the one in which they were calibrated. Conversely, when the heat fluxes exhibit significant discrepancies, the role of convective heat transfer cannot be neglected and the uncertainties need to be evaluated. This coefficient for a gauge foil assumed as a flat plate can be obtained from the Nusselt number ($Nu = m^2$) correlations (Drysdale 1985; Incropera and DeWit 2002). It should be recalled that the Nusselt number, Nu, is the non-dimensional form of the convective heat transfer coefficient, h. This coefficient depends on the flow properties around the gauge and on its geometry. If gas-transport properties can be evaluated from the measurement of the temperature (Bird et al. 2006), the regime and the nature of the convective flow viewed from the sensor are unknown ahead of and into the flame front. Identifying these features is not straightforward when the flame front spreads under wind-blown conditions and direct information about the velocity field is unavailable, because the gas velocity was not measured in the present study.

Several Nusselt number correlations were, therefore, tested in (Silvani and Morandini 2009) assuming a natural or forced convection regime around the HFM (Drysdale 1985; Incropera and DeWit 2002; Baukal and Gebhart 1996). From the range of Reynolds and Grashof numbers estimated using the gauge diameter, the flow can be considered to be laminar at the gauge surface, even if the flames are strongly turbulent. From the set of experiments in (Silvani and Morandini 2009), the error for evaluating the thermal radiation associated with the use of a total Gardon gauge in a mixed radiative convective environment may exceed 50 %. In conclusion, the total HFM cannot be considered to be reliable for measuring the heat flux due to both radiation and convection without a strong effort in calibrating this versus a convective heat flux.

This analysis exhibits the challenging problems that may be resolved by experimental fire science. One can summarise previous considerations by observing that two main unknowns remain for upgrading the measurement of heat transfer using fluxes: the velocity field, which can set the value of Nusselt numbers, and the gas density. The latter is a very important quantity; its behaviour signals the nature of fire in a combustion systems. In a fire, flammable gas result from the pyrolysis of solid materials (vegetal or not) and a mass flow from the solid to gaseous phases where the flame exists is set up at each instant by the ‘fire system’. Contrary to burners, engines, and other ‘human-designed combustion systems’, in a fire at the field scale, this mass flow rate is not a steady quantity causing the fire to be a strongly turbulent flow. The mass transfer is usually called the ‘source term’ in fire modelling. Its rate corresponds to the kinetic of solid material degradation and involves some considerations in thermochemistry and analytical chemistry. However, neither heat fluxes nor the vegetal samples involved in these laboratory-scale analyses can be compared to those encountered in real conditions. The results they provide are limited to academic considerations.

Measuring these quantities in outdoor conditions—the velocity field in the gaseous phase and the mass transfer between solid to gas—is the greatest challenge in experimental fire sciences. Such questions relate to the ability to investigate the mass and the momentum budgets of a fire at a local scale to improve the understanding of the heat (energy) transfer.

2.3 Measuring Heat Convection and Source Term: Outlooks and Prospects

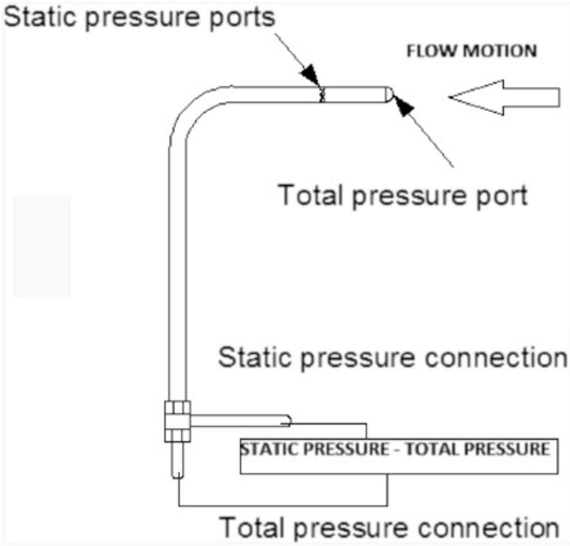
The measurement of the momentum requires measuring both the velocity and gas density in the gas phase. This measurement, if locally performed, allows for a direct measurement of the convective heat flux. Indeed, the local density of momentum is an extensive quantity defined by $\rho\, \boldsymbol{u}$, where ρ stands for the gas density and u the 3D velocity vector at the measurement point. By assuming that the heat density per mass unit is given by the product c_pT, i.e. the specific heat c_p at constant pressure and the gas temperature T, the convective heat flux is the vector field $\rho\, c_pT\, \boldsymbol{u}$. The measurement of the convection involves, therefore, the measurement of the velocity field, which is one of the most challenging questions in experimental fire science and involves the heat transported by convection. Determining the heat transfer toward a solid or a liquid fuel requires information about the contact between the flow and the fuel. It is important to distinguish between transport and transfer.

2.3.1 Measuring the Velocity Field

Fire is a scale-dependant process (Pitts 1991), with the range of the length and time scale from a chimney to a forest fire increasing by several orders of magnitude. This means that the experimental tools designed to measure thermodynamic quantities related to fire must be fire-resistant and able to capture these increasing scale ranges. In terms of the velocity field, another difficulty arises as one scales from a candle to a forest fire, because flow regime changes from laminar to turbulent both because of the extension of the scale range and the stochastic nature of the data. The velocity field shaping a flame in a real-scale fire is turbulent. Its measurement requires fast-response tools and, when possible, the ability to be non-intrusive, so that the local flow perturbation caused by contact with a solid instrument can be limited.

Pressure probes seem to be a robust measurement technique for investigating the velocity in a fire, although only a few fire studies have examined these instruments. These probes include the Pitot tube (Fig. 2.7). The velocity measurement principle proceeds from Bernouilli's theorem applied to the tube: the Pitot tube measures a velocity difference between a null velocity point (static pressure point) and a non-null velocity point (dynamic pressure point). First, however, the density must be constant over the entire tube, or corrected as a temperature function. This once again illustrates the strong coupling of gas density and velocity fields in a variable-density flow and the strong need to measure gas density. Performing the latter measurement in a fire is not a trivial issue. Second, the streamlined flow that is stopped on the static pressure point must be aligned with the tube; if this is not the case, angle error is generated

Fig. 2.7 Pitot tube



that is quite impossible to correct. Finally, there is strong inertia in the pressure measurement because it requires time to transport the pressure difference that is observed all along the tube to an analogue–digital converter that provides numerical data, without leading to pressure loss along the line. Finally, the response time of the Pitot tube is linearly dependent on the dynamic viscosity and the square of tube length from the pressure point to the data logger. In a fire, the dynamic viscosity increases with the 3/2-power of temperature and, at the field scale, the hydraulic line from the Pitot tube to the data converter can be long. In practical experiments, we have measured response time to be about 0.1 s, i.e. close to that of the 250 μm TC and the radiant heat fluxmeter that we used. However, the metrology quickly becomes intrusive and the one-point unidirectional measurement that can be obtained with this technique is subject to caution. One can also find double pressure probes, such as those used by Bryant in the full-scale fire enclosure (Bryant 2009). These probes work on the same principle as a Pitot tube but, when the probe is attached to a bi-directional pressure transducer, the flow can be sensed in either direction.

New optical diagnostics such as particle-image velocimetry (PIV) now can be adapted to fire experiments. In its standard configuration, PIV involves lighting a flow containing particles to produce two sets of images separated by an inter-image interval of two laser pulses. By computing the most probable displacement of particles from one image to the next using an intercorrelation procedure, one can measure the 2D velocity field in the light plane (Fig. 2.8). In fire experiments at the laboratory scale, one can cite the pioneering contribution of Lozano et al. (2010), who found that, by seeding a fire spreading over a horizontal bed of excelsior with alumina oxide particles (which are fire resistant), strongly resolved velocity fields could be produced to investigate the vertical structure of

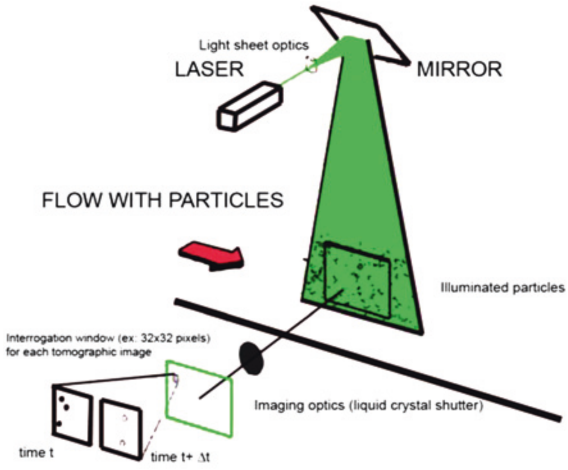


Fig. 2.8 Principle of particle-image velocimetry PIV measurement

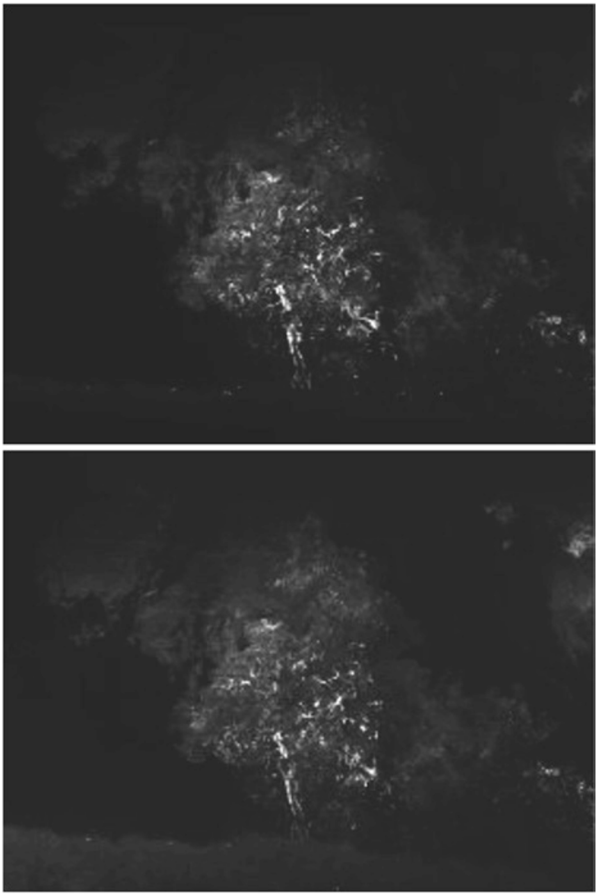
the corresponding flame. Such a technique also is feasible in outdoor conditions if special precautions are made (Fig. 2.8) (Morandini et al. 2012b).

Whatever the size of the experiment, some attention must be made to the following points. First, one has to control the flame illumination in the second PIV image (as represented on Fig. 2.9). Indeed, soot in the flame causes excessive illumination of the second PIV image, which is usually produced over a longer aperture time than the first (for reasons related to the CMOS flash). We previously proposed the use of a crystal liquid shutter with a C mount to reduce the long aperture time of the PIV camera during the capture of the second image. The quality of the second image obtained using such a technique can be observed in Fig. 2.10.

Second, to use PIV in fire experiments at the field scale, a technical solution must be found when seeding in outdoor conditions, to avoid the natural dispersion of the seeds by wind, which takes them far from the light plane. Figure 2.11

Fig. 2.9 Large-scale particle-image velocimetry of a fire spreading over a vegetal fuel bed in outdoor conditions

Fig. 2.10 Tomographic images from pulsed-laser lightning of a spreading flame front



shows the displacement of the intercorrelation peak computed with the two previous images. This causes the velocity field to be measured in pixels. Scaling using the delay between two images produces a velocity field in dimensional units. Despite its promising features, PIV for fire experiments has some limitations. The main limitation relates to the resolution of PIV cameras. Indeed, when all technical problems are solved (i.e. the set-up of the light plane and related optics and the seeding system), one can produce a pair of PIV images. However, the ability to use PIV to capture the whole range of flow scales is limited by the resolution of the smaller flow scales possible with its cameras. Usually, for combustion, PIV cameras have resolutions of about 2–4 Mp in each direction. However, the flow field is not resolved at the pixel size. About 32 or 64 pixels are needed to form the interrogation window in which the group velocity of particles is computed as the flow velocity. In large-scale PIV, the ratio between the larger and the smaller resolved scales is given by the ratio between the PIV window dimension and the interrogation window dimension (Fig. 2.8). This approaches 2000/64–30 if the

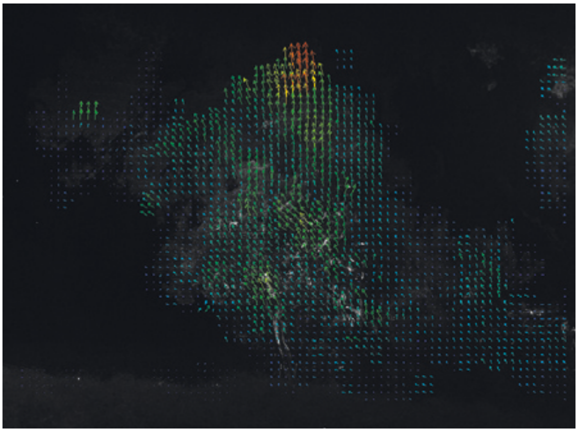


Fig. 2. 11 Velocity field resulting from intercorrelation between previous tomographic images (vectors are in displacement units)

camera has a resolution of about 2 Mp per direction and if it requires a standard window size of 64 pixels. If the PIV window is 2 m large, the flow velocity field is resolved at 6 cm, i.e. far above the size of smaller vortices.

2.3.2 Measuring Scalars: Mass Loss Rate, Density Field, and Reaction Rate

The mass loss rate is a key parameter of fire sciences: in modelling approaches based on empirical models, the heat release is proportional to the mass loss rate, considering the reaction enthalpy for a mass unit of fuel. In physics-based models, this quantity expresses the mass flux between the fuel and the gas phase. It is usually set by the temperature of the fuel under thermal degradation. At the laboratory scale, many results are available for this measurement for fire materials, vegetal or otherwise, using a cone calorimeter or thermogravimetric analysis (TGA). This measurement also may be possible at the field scale using load cells that are protected from the fire using thermal insulation, although the technology is still under development. The correlation of the measurement usually is set with the temperature, but for large-scale fire experiments, it would be more convenient if it were correlated with the incident heat flux. The heat flux is a strongly scale-dependant quantity whereas the temperature is not.

The measurements of scalar quantities related to the reactive mixing—that is density, mass or mixture fraction, and reaction rate—are not trivial to perform in the framework of turbulent combustion, for internal and enclosed geometries (engines, burners). Some modern optical diagnostics exist, even for scenarios with large-scale radiative flames (Nathan et al. 2012). However, as of the end of 2012, there is no evidence in the related literature that such diagnostics are likely to be available for fire experiments in the open. The question of the density is central: how can the gas mixture—specifically, the composition and density—be measured in a fire? This is important for many reasons, including the ability to understand the gas-mixture dynamics and measuring the convective heat flux. The Fourier transform IR (FTIR) spectrometer can be used for fire scenarios; indeed, continuous emission monitoring (CEM) based on the FTIR spectrometer exists for combustion systems and provides continuous information about carbon monoxide, oxygen, and carbon dioxide in flue gases of engines and industrial burners. Because these species are expected to play a significant role in fire chemistry, CEM may be performed in fire sciences, even at the field scale, for tracking H_2O, CO_2, CO, N_2O, NO, NO_2, SO_2, HCl, NH_3, CH_4, C_2H_6, C_3H_8 and C_2H_4, C_5H_{12}, and C_6H_{14}, which have been identified as being generated by the thermal degradation of vegetal fuels. Progress currently is being made in this direction.

One can also expect the development of optical diagnostics for investigating the scalar field of a large-scale reacting flame. However, obtaining results from large-scale fire experimental scenarios is not trivial. In (Schulz and Sick 2005), light-induced fluorescence (LIF) is presented as the most robust technique for quantitative measurements of scalars including temperature in flames. First, however, because of the principle of LIF—which involves tracking by imaging the natural relaxation of molecules excited by a strong laser light—the technique requires powerful lasers that are not easy to display in outdoor conditions. Furthermore, the investigation windows, which cannot exceed tens of centimetres in size, are rather hard to select in a flame front that is several metres high. Furthermore, with this lighting technique it is rather difficult to eliminate interference from particles larger than molecules.

Despite these difficulties, determining the fraction of given reactive species in the turbulent motion of the flame remains a good tracer of the mixing dynamics. In this framework, we recently performed small-scale experiments of a fire spreading over a fuel bed of excelsior to test the coupling of optical diagnostics (Morandini et al. 2012a). At the time of the writing of this brief, there was no reference in English. In (Morandini et al. 2012a), using an optical diagnostic to investigate the chemical field of a spreading fire was a new technique; despite its limitation to a laboratory scale, we present the main results here because of its promise.

The technique, called chemiluminescence OH*, consists of capturing the natural emission of the OH* radical during the combustion process using an intensified digital camera (ICCD) with filters. Because of the intense radiation of a fire flame over a large wavelength band (mainly in the IR), the spectroscopy of a fine ray in the UV range is technically hard to obtain. However, this technique, when coupled with an optical diagnostic for flow measurement such as PIV, may produce precious information about the mixing process during combustion and the influence of external parameters such as slope and wind flow. Figure 2.12 shows why the UV radiation of OH* radical is a good tracer of the reaction zone.

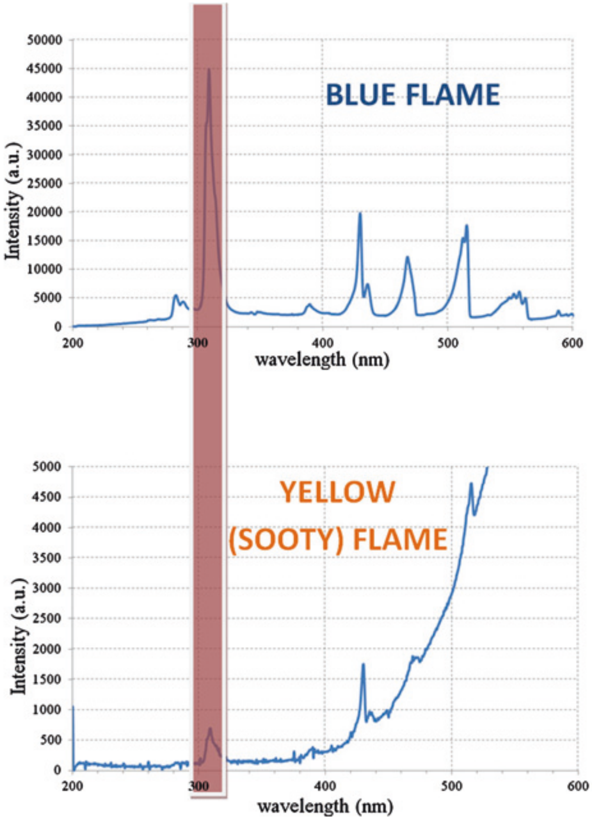


Fig. 2.12 Spectral properties of radiation for flame spectroscopy of a fire spreading over 1 m² excelsior

The emission occurs in the UV range, which means that it is sufficiently far away from the contribution of the thermal radiation in sooty flames. The modified camera is protected with a bandwidth filter centred on the UV peak of OH* emission.

In the field of turbulent combustion, some geometric configurations indicate that the reaction rate is linearly dependant on the OH* intensity. This is the case when the flame is stabilised in a conical shape over a constant mass flow rate, as with a burner. However, this can no longer be assumed in an extended fire front because the ICCD diagnostic for OH* chemiluminescence is an integrated diagnostic. From this point of view, the technique suffers from the same limitations as IR imagery for temperature measurement. In this sense, it is important to recall that the OH* field represented on Fig. 2.13 is integrated in the flame volume and not captured the intercept with a light plane.

Despite the difficulties inherent in using these optical diagnostic techniques to study fire, they may represent the future in fire science, allowing us to explore the internal dynamics of the mixing and combustion processes in the gas phase.

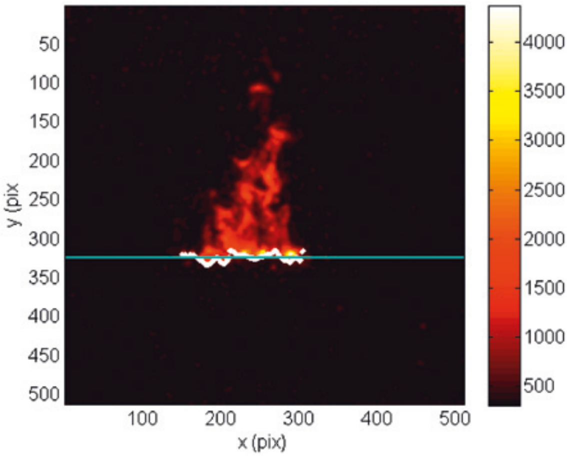


Fig. 2.13 Intensity of OH* emission captured by chemiluminescence

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