Flame properties of large kerosene fires

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ABSTRACT

In order to provide experimental data to develop fire spread models, numerous tests were performed for a wide range of fire sizes and fuels. Here we focus on large scale kerosene tests (approx. 0.5 to 6 m²), with an emphasis on radiative flame properties and present a novel multispectral approach composed of an opacimetry setup and a FTIR spectrometer. This allowed to compute emittance values (based on transmittance measurements) and equivalent soot temperatures (by fitting the calculated intensities to the measured ones). These results, as well as mass loss rates and flame heights, show good repeatability and agree well with the literature, including with correlations predicting the burning rate, flame height and spectral dependence of the extinction coefficient. Generally it is shown that radiation emitted by the flame is not gray, and can only be considered black for very large flames (i.e. wider than 2.5 m for these tests). Additional data (smaller fires, other fuels, complementary parameters - e.g. flame shape) are still to be analyzed and used to model flame heat radiation.

KEYWORDS: fire tests; scaling up; radiative heat transfer; flame height; opacimetry; spectrometry
INTRODUCTION

Fire simulations require an accurate heat release rate (HRR), especially when used for fire investigation or reconstruction because results have to be reliable from the very beginning of the fire. One solution to obtain this input is to conduct full-scale tests, which provide readily usable data. However, experimental conditions may sometimes be different from the desired scenario (e.g. free burning versus under ventilated). Moreover, these tests can be costly, and are more challenging regarding repeatability, reproducibility and safety. These limitations suggest that conducting small-scale tests and then using models to scale up the results would be a convenient alternative. However, it comes with many challenges, primarily understanding the changes that occur when going from small (milli- or centimeter) to large samples (meter). The study is focussed on radiative heat transfer as it is the driving force of flame spread [1,2], and its accurate modelling is thus crucial. The starting point of this work was to gather experimental data for various fire sizes as well as several fuels (solid and liquid). In addition to the classical measurements performed in fire tests (mass loss, room temperatures, heat fluxes), a special focus was put on characterising the flames from a radiative standpoint (innovative visible and infrared opacimetry, infrared imagery and spectrometry). In this paper we will describe the large scale tests (approx. 0.5 to 6 m²) and focus on some results for kerosene.

EXPERIMENTAL SETUP

Experiments

The large scale tests were performed in a former aircraft hangar (approx. 300 × 50 × 17 m³, length × width × height), gracefully lent by Groupe ADP (Orly, France). It allowed performing well ventilated fires close to open conditions while being shielded from wind and rain. A total of nine experiments were performed with kerosene, as listed in Table 1.

| Pool dimensions [m²] | Approx. fuel mass [kg] | Approx. water mass [kg] | Number of tests |
|----------------------|------------------------|-------------------------|-----------------|
| 0.70 × 0.70          | 25                     | 50                      | 3               |
| 1.00 × 1.00          | 50                     | 100                     | 3               |
| 1.75 × 1.75          | 120                    | 200                     | 2               |
| 2.50 × 2.50          | 250                    | 300                     | 1               |

The steel pans were square shaped with a height of 20 cm and a thickness of 4 mm. The lip size (height of the pan edge above the fuel surface) was approximately 5 cm at the beginning of the tests (the fuel height was not kept constant, and the tests were conducted until flame out). The fuel was laid on water to regulate combustion. The tests were started by igniting a small layer of ethanol poured beforehand on top of the kerosene.

Measurements

Most of the tests were performed using load cells to monitor mass loss. Only the largest pool fire (approx. 6 m²) could not be weighed. Numerous cameras were used to record the tests, mainly to study the visible flame shape and the smoke spread.

The radiative properties of the flames were characterized by infrared emission spectrometry and by opacimetry: a Fourier-transform infrared (FTIR) spectrometer (Matrix spectrometer by Bruker) allowed to record spectral radiation intensities during the tests (from 1000 cm⁻¹ to 6000 cm⁻¹) and opacimetry measurements were made at different wavelengths. Regarding opacimetry, the light coming from laser diodes was modulated thanks to a chopper, and demodulated with a lock-in amplifier, to retrieve the transmitted intensity without the contribution from the flame emission. Four wavelengths were used simultaneously: 785, 1650, 2300 and 3800 nm for large scale tests, and 410, 520, 785 and 1650 nm for tests at smaller scale. We note that all these wavelengths are located outside the absorption bands of major combustion gases (CO₂ and H₂O) in order that only soot absorption was studied here. A 200 mm off-axis parabolic mirror was used to collect the four parallel light beams toward an integrating sphere. This allows to overcome the beam deviation due to the refractive index variations inside and around the flame. Bandpass optical filters were used to retrieve the signal corresponding to each wavelength. The measurements with the spectrometer and the opacimetry measurements were made along the same horizontal optical path (approx. 20 cm above the pan), to provide comparable data. Heat fluxes were also measured to study their vertical and horizontal distributions depending on the fire size and fuel. The results are presented elsewhere [2] and will be further discussed in...
later communications, along with comparisons with numerical model for example. Here we will focus on mass loss rate, flame height and soot radiative properties (emittance and equivalent temperature).

RESULTS AND DISCUSSION

Mass loss rates and flame heights

Mass loss rates (MLRs) for the 0.5 m² and 1.0 m² fires (repeated three times) are presented in Fig. 1.

These results show high repeatability for the growth and steady phases. The increase in MLR at the end of each test is due to water boiling and projecting fuel outside the pans. This behaviour is not an issue for the present study as we focus on the steady phase, which happens much earlier during the tests (approx. 5 min to 10 min after ignition) and is sufficiently long to gather representative time-averaged values.

Cameras were used to extract the visible flame shape and to evaluate its changes when scaling up. These visible flame shapes will later be used for radiation models. Images were processed to extract the flame contour and compute the flame height. The evolution of median mass flux and flame height with the pan diameter is shown in Fig. 2, and compared to the literature.

The agreement is good with experimental data from other sources, as well as common correlations to predict burning rate and flame height.

![Fig. 1. Mass loss rates over time for two pan sizes.](image1)

![Fig. 2. Median mass loss rates per unit area (MLRPUA) and dimensionless flame heights (flame height divided by pan diameter), see ▲, compared to other kerosene tests (+ [4]; × [5]; □ [6]) and correlations from Babrauskas [4] (solid line), Heskestad [7] (dashed line) and Zukoski [8] (dotted line).](image2)
Flame radiative properties

In addition to flame shape, which is also a key factor of flame heat radiation, two other flame properties were determined, namely emittance and equivalent soot temperature. The first quantity was computed from the opacimetry measurements, which allowed to determine transmittance $\tau$ across the flame at several wavelengths $\lambda$, as illustrated in Fig. 3.

\[ \tau = \frac{1}{e^{\beta \lambda}} \]

where $e$ is the length of the optical path ($\beta \lambda$ is the optical thickness of the flame). The dependence of $\beta$ on the wavelength is illustrated in Fig 4.

\[ \beta_{\lambda} = \frac{C_1}{\lambda^{C_2}} \]

The fit with the model [9] shows good agreement with the data. Here, constants $C_1$ and $C_2$ were estimated to be 15337 and 1.163 respectively, which is in the range of reported values ($0.7 < C_2 < 2.0$ [9]). Equation 2 will later allow to easily take into account the spectral dependence of the flame radiative properties.

As the final objective of this work is to model flame heat radiation, predicting the flame emittance would be more appropriate. This can be done by considering that the particles in the flame are small in relation to the studied wavelengths (infrared), which implies that extinction is mainly due to absorption (i.e. negligible scattering), thus giving
with $\kappa$ the absorption coefficient. Moreover, according to Kirchhoff’s radiation law, for a given wavelength $\lambda$ and direction $\Omega$,

$$
\epsilon_{\lambda,\Omega} = a_{\lambda,\Omega}
$$

where $\epsilon$ is the emittance and $a$ the absorptance. Consequently, with the hypothesis of a homogenous equivalent medium, we get the flame spectral emittance as a function of the extinction coefficient

$$
\epsilon_{\lambda} = a_{\lambda} = 1 - \exp(-\kappa_{\lambda} e) \approx 1 - \exp(-\beta_{\lambda} e).
$$

Assuming an isothermal equivalent medium, this allows the calculation of the spectral intensity emitted by soot according to

$$
I_{\lambda} = \epsilon_{\lambda} I_{\lambda}^0(T) \approx [1 - \exp(-\beta_{\lambda} e)] I_{\lambda}^0(T),
$$

$I_{\lambda}^0(T)$ being the blackbody spectral intensity at temperature $T$. This model is valid for every wavelength if the emittance is known. Here measurements were done for wavelengths where soot is the primary emitter, i.e. outside the combustion gases wavelengths, consequently results are valid only for emission of soot. The spectral intensity being evaluated independently from the opacimetry measurement (i.e. with the infrared spectrometer), temperature is the only parameter to be determined. This is an advantage compared to classical emission measurements, for which two parameters (spectral emittance and temperature) are to be calculated from only one measurement, which is impossible (an infinite number of couples $(\epsilon_{\lambda}, T)$ can fit the measured intensity). The use of Eq. 5 to fit the intensities measured by the infrared spectrometer to obtain the soot equivalent temperature is illustrated in Fig. 5 with a test for each pan size.

![Fig. 5. Measured (solid) and modelled spectral intensities (dotted for blackbody, dashed for Eq. 5). From left to right, top to bottom: pan width of 0.70 m, 1.00 m, 1.75 m and 2.50 m (one test for each).](image)

The large absorption bands seen in the experimental spectra (solid line) are due to cold atmospheric $\text{H}_2\text{O}$ and $\text{CO}_2$ found between the pool and the spectrometer. In the tests performed during this campaign, the distance between the pool and the spectrometer was 23 m, which explains why the spectra are so much hollowed. Calculated spectra (dotted and dashed lines) do not take this absorption into account. Outside atmospheric absorption bands, there is a good agreement between measured and calculated spectra (solid vs. dashed line). Moreover, the fits give similar equivalent soot temperatures, namely 1230 K for the 0.70 m and 1.00 m pans and 1250 K for the 1.75 m and 2.50 m pans. We can also see that in the general case the radiation emitted by the flame is not gray, as stated by Eq. 2. It is also shown that the flame becomes black (i.e. dashed and dotted lines overlap) only for large flames, that is for a flame thickness $e$ greater than 2.5 m. The authors emphasize that the present model gives an equivalent emittance and an equivalent temperature, not a mean emittance and a mean temperature, of an equivalent homogenous isothermal medium that emits a radiation similar to the mean radiation emitted by the flame in the direction of measurement. Our measurements conducted on a large range of flame thicknesses have shown that the extinction coefficient is weakly dependent on the flame thickness (results not shown here). Some additional measurements have to be performed at different heights in the flame. The goal is to see if a fully homogenous (i.e. same absorption coefficient and same temperature
everywhere in the flame) volumetric flame model, can yield a good enough prediction of the radiative heat flux received either by the combustible or by any target around the flame.

CONCLUSION

The tests presented here are the first part of a larger experimental campaign aiming at investigating the changes in burning behaviour when scaling up. They are the biggest fires planned for this study and provide original data regarding some key flame properties, namely emittance and equivalent soot temperature. The results prove that spectrally resolved measurements are a valuable investment when studying flames and that further work is needed to accurately model them. Another key aspect that could not be addressed so far is flame inhomogeneity: complementary tests could be performed to produce "radiative maps" of flames, as done before [10–12] but with the multispectral approach presented here.

More generally, all results show high repeatability, and correlate well with common models (for MLR, flame height and extinction coefficient). In addition to these experiments, smaller fire sizes (down to 0.05 m²) and other fuels (heptane, diesel, polyurethane foam) are being investigated. Further work is planned to study the evolution of other parameters (e.g. flame shape, flame spread over solids) when scaling up, and the differences from one fuel to another. These results will be used to assess various assumptions used when modelling radiative heat transfer (black or gray body, equivalent flame shape or temperature...) by comparing numerical results to the measured heat fluxes. This work will also provide valuable input data to develop fire spread models meant to predict full-scale burning behaviour based on small-scale tests.

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