Calibration of the propagation models of forest fires by adapted thermal sensors

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ABSTRACT: In order to simulate forest fires, there are three-dimensional models of combustion and models of propagation. The latter are approximations of the former. They are simpler and faster to simulate. An input of these models of propagation is the radiative flux emitted by the flame. Its measurement allows the calibration of the models of propagation and a partial validation of the models of combustion. The present study concerns the calibration and the validation of the propagation models of forest fires by an assimilation of parameters using a specific sensor. This sensor measures the heat flux in four directions of space and in order to separate these flux in radiative flux and convective flux, we manufactured an adapted differential sensor. Experiences of propagation in a fire tunnel on "Kermes oak" allows to characterise the propagation by a velocity measurement. They also permit the identification of the flame height and the emitted power.

1 VARIOUS MODELS OF PROPAGATION

Several types of propagation models have been derived these last years, classified by order of complexity:

1. Statistical models
2. Empirical models
3. Physical models

The "validation" of the models of type 1 or 2 relies only on the identification of the propagation velocity of the fire front which is the only output of these models.
The models of the type 3, in addition to the propagation velocity, require for their calibration the measurement of radiative flux, convective flux, the power emitted by the flame and its height. This work treats the calibration of these models by a simple thermal sensor, Chetehouna & al. (2000) and another differential are described in paragraph 2.
An experiment of fire without wind is presented in order to measure and identify the parameters of propagation such as the propagation velocity, the emitted power, the height of flame, convective flux and radiative flux. Two series of experiments, one with wind variable and another with load variable will make it possible to carry out a parametric study of the propagation mechanism of fire according to the wind velocity and the vegetation load.
2 DESCRIPTION OF THE DIFFERENTIAL SENSOR

To instrument real fires, this sensor (Fig. 1) should satisfy the following conditions:

- It must be simple and convenient of installation and employment.
- It must be as cheap as possible.
- It should not be destroyed by the passage of the flames.
- Its scale is adapted to the one used in physical models of propagation.
- It can allow an average evaluation of radiative flux, convective flux, temperature of gases and their velocity.

Figure 1. Photographs of the differential sensor

2.1 Technical presentation

The differential sensor (Fig. 2) is made of a steel frame, with a coat of thermal insulating for high temperature, of glue coats, of 8 molybdenum small plates and of 13 thermocouples of K type, with a diameter 0.5 mm. The plates 1, 2, 3, 4 are painted black and the plates 5, 6, 7, 8 are painted in gray in order to distinguish their flux. This sensor is fixed on a removable metal support and its height varies from 60 cm to 85 cm.

Figure 2. Horizontal section of the differential sensor
We have represented the thermal behavior of this apparatus by a capacitive-resistive model with 5 physical parameters. These parameters represent the heat transfers between the various elements of the differential sensor (Fig. 3).

\[ \Phi_{mo}, \theta_{mo}, \Phi_{st}, \text{and } \theta_{st} \text{ are the Laplace transformed of the flux and the temperature, measured respectively, by each plate of molybdenum and the steel frame. } T_{ref} \text{ is the temperature measured by thermocouple N° 13.} \]

The heat flux absorbed by the black plate, \( \varphi_n(t) \), and the gray plate, \( \varphi_b(t) \), of each face of the sensor can be written:

\[
\begin{align*}
\varphi_n(t) &= \varphi_c(t) + \varphi_r(t) \\
\varphi_b(t) &= \varphi_c(t) + \varepsilon \varphi_r(t)
\end{align*}
\]

where:

\[
\begin{align*}
\varphi_n(t) &= \left( C_{mo} \frac{d}{dt} + \left( \frac{1}{R} + \frac{1}{R_{c1}} \right) \right) \theta_n(t) - \frac{1}{R} \theta_{ac}(t) \\
\varphi_b(t) &= \left( C_{mo} \frac{d}{dt} + \left( \frac{1}{R} + \frac{1}{R_{c1}} \right) \right) \theta_b(t) - \frac{1}{R} \theta_{ac}(t)
\end{align*}
\]

\( \varphi_c(t), \varphi_r(t) \) are the convective flux and the radiative flux measured on each face of the differential sensor. \( \theta_n(t), \theta_b(t) \) are the measured temperatures by the black plate and the brilliant plate. \( \varepsilon = 0.60 \) is the radiative emissivity of the brilliant plate.
The solution of the system of equations (1) and (2) are expressed as follow:

\[
\varphi_r(t) = \frac{1}{1 - \varepsilon} \left( \frac{C_m^0}{d^2} \frac{d}{dt} + \left( \frac{1}{R} + \frac{1}{R_{v1}} \right) \frac{\theta_a(t) - \theta_b(t)}{R} \right)
\]

(3)

\[
\varphi_c(t) = \frac{1}{1 - \varepsilon} \left( \frac{C_m^0}{d^2} \frac{d}{dt} + \left( \frac{1}{R} + \frac{1}{R_{v1}} \right) \frac{\theta_b(t) - \frac{\varepsilon}{\theta_a(t)} - \frac{1}{R} \theta_a(t)}{R} \right)
\]

(4)

The physical parameters of the differential sensor model (identified by laboratory experiments) are given in Table 1 below.

Table 1. Parameters of differential sensor

<table>
<thead>
<tr>
<th>Parameters values</th>
<th>1013.5</th>
<th>46.7</th>
<th>2.9</th>
<th>66.4</th>
<th>26.4</th>
</tr>
</thead>
</table>

3 FIRE EXPERIMENT WITHOUT WIND AND PARAMETERS OF PROPAGATION

In order to characterise the propagation, we carried out in a fire tunnel (Fig. 4) an experiment of fire propagation without wind on “Kermes oak”, dominant vegetation in the Mediterranean region, where its surface density is equal to 3 kg/m². The average height of the Kermes oak is equal to 90 cm. A layer of wood chips of thickness 10 cm and surface density of 1.5 kg/m² was used as vegetable litter. A fluxmeter, three simple sensors and a differential sensor were placed in the fire tunnel in order to measure the radiative flux and the convective flux (Fig. 5 & Fig. 6).

Figure 4. Fire tunnel
3.1 Propagation velocity

The propagation velocity was measured using six thermocouples of K type, placed all along the vat of combustion. The distance between two thermocouples is 40 cm. The expression of velocity is written in the following form:

\[ V = \frac{40}{\Delta t_{TC}} \]  \hspace{1cm} (5)

\( \Delta t_{TC} \) is the difference of time between two consecutive peaks of temperatures.

The propagation velocity is the average of the local velocities obtained after the initial phase of acceleration (thermocouple 1) and before the final phase of deceleration (thermocouple 6) and its value is equal to \( V=1.5 \text{ cm/s} \).

Figure 5. Experimental set up and propagation

Figure 6. Positions of the instruments in the fire tunnel
In figure 6 above:

1. The simple sensor N° 1 is placed at the point C1 (3 m, 1 m) and its height is equal to 1 m.
2. The simple sensor N° 2 is placed at the point C2 (3 m, 1.5 m) and its height is equal to 0.8 m.
3. The simple sensor N° 3 is placed at the point C3 (2.75 m, 1 m) and its height is equal to 0.5 m.
4. The differential sensor is placed at the point D (3 m, 0.8 m).
5. The fluxmeter is placed at the point F (3 m, 1.3 m) and its height varies from 0.6 m to 1 m.

3.2 Heat flux of the simple sensor

The heat flux \( \varphi_r \), measured by face N° 1 of the simple sensor N° 1, at a fixed point \( M_0(x_0, y_0, z_0) \) was modelled by regarding the flame as a plane surface, characterised by a height, \( h_f \), an emitted power, \( \varphi_0 \), and moving with a constant velocity, \( V \). This flux can be written:

\[
\varphi_r(t, h_f, \varphi_0) = f_r(t, V, h_f)\varphi_0 - B \left[ 1 - f_r(t, V, h_f) \right] T_r^4
\]

where:

\[
f_r(t, h_f) = \frac{1}{\pi} \int_{-L}^{L} \int_{0}^{h_f} \frac{(x_0 - Vt)^2}{(x_0 - Vt)^2 + (y - y_0)^2 + (z - z_0)^2} dy dz
\]

with:

- \( B \) is the Stefan-Boltzman coefficient
- \( T_r \) is the temperature of face measuring the flux \( \varphi_r \)
- \( 2L \) is the width of the vat of combustion.

The characterisation of the flame requires the identification of emitted flux \( \varphi_0 \) and the height \( h_f \)

3.3 Height of the flame and its emitted power

3.3.1 Optimisation function

In order to identify the height of flame, \( h_f \), and the flux emitted, we chose the following objective function:

\[
Obj(h_f, \varphi_0) = \int_{t_i}^{t_f} \left( \varphi_r(t, h_f, \varphi_0) - \varphi_r^{exp}(t) \right)^2 dt
\]

\( \varphi_r^{exp}(t) \) is the radiative flux measured by face N° 1 of the simple sensor N° 1 at the point \( M_0 \) during the time interval \([t_i, t_f]\).

3.3.2 Sensitivity analysis

Identifiability of the parameters \( h_f \) and \( \varphi_0 \) must be studied before estimating them. The reduced sensitivity is defined by:
where $\mathbf{\xi} = \begin{pmatrix} h_f \\ \varphi_0 \end{pmatrix}$ is the parameters vector which has to be estimated.

By using relations (6) and (9), the two coefficients of reduced sensitivities $X_1^*$ and $X_2^*$ can be expressed by:

$$X_1^* = \xi_1 \frac{\partial f_r(t, \xi)}{\partial \xi_1} \left( \xi_2 + BT_f^4 \right)$$  \hspace{1cm} (10)

$$X_2^* = \xi_2 f_r(t, \xi_1)$$  \hspace{1cm} (11)

These reduced sensitivities are plotted in Figure 7 below.

![Figure 7. Reduced sensitivities of the parameters](image)

It is clear from this figure that the parameters are not correlated so that they can be estimated.

3.3.3 Method of optimisation and results

We used an algorithm based on the method of Newton. Each iteration involves the approximate solution of a large linear system using the method of preconditioned conjugate gradients (PCG). The initial parameters that we took into account are: $h_f = 2 \text{ m}$ and $\varphi_0 = \varepsilon_f BT_f^4$ where $\varepsilon_f = 0.28$ (emissivity of flame proposed by Weber in 1989) and $T_f = 812 \degree C$ (value measured by thermocouples). After a certain number of iterations, the algorithm converges and gives the following results:
Table 2. Physical parameters of propagation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$h_f$ (m)</th>
<th>$\varphi_0$ (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>1.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

3.4 Radiative flux and convective flux of the differential sensor

The measurement of temperatures of the brilliant plates and the black plates, using relations (3) and (4), gives the following results:

Figure 8. Different temperatures measured by the differential sensor

Figure 9. Radiative flux and convective flux measured by the differential sensor
From figure 9, one notices that radiative flux is clearly distinct from convective flux only on face N° 1 and face N° 4 of the differential sensor. The maximum values of radiative flux and convective flux on the four faces of the differential sensor are presented in table 3 below.

Table 3. The maximum values of heat flux

<table>
<thead>
<tr>
<th>Face N°</th>
<th>Radiative flux $\varphi_r^{\text{max}}$ (kW/m²)</th>
<th>Convective flux $\varphi_c^{\text{max}}$ (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° 1</td>
<td>3.57</td>
<td>1.25</td>
</tr>
<tr>
<td>N° 2</td>
<td>0.32</td>
<td>0.63</td>
</tr>
<tr>
<td>N° 3</td>
<td>0.51</td>
<td>0.31</td>
</tr>
<tr>
<td>N° 4</td>
<td>1.12</td>
<td>0.29</td>
</tr>
</tbody>
</table>

The results of this table show that radiative flux and convective flux represent, respectively, approximately 75 % and 25 % of the total heat flux.

4 DETERMINATION OF DIFFERENT REYNOLDS NUMBERS

Before determining the Reynolds number on each face of the differential sensor, we present the correlations of the Nusselt number by the Reynolds number obtained by Igarachi in 1986, concerning the fluid flow and the local heat transfer from a square prism:

on the front:  \( Nu_f = 0.64 \text{Re}^{0.5} \)  \( (12) \)

on the side faces:  \( Nu_s = 0.131 \text{Re}^{2/3} \)  \( (13) \)

on the back face:  \( Nu_b = 0.173 \text{Re}^{2/3} \)  \( (14) \)

The values of the Nusselt number on the four faces of the differential sensor are calculated from the values of the convective flux, given in table 3, and the maximum temperatures of the brilliant plates and the black plates.

Using expressions (12) to (14) and the values of Nusselt number, we obtain the following results:

Table 4. Values of Nusselt numbers and Reynolds numbers

<table>
<thead>
<tr>
<th>Face N°</th>
<th>Nusselt numbers $Nu$</th>
<th>Reynolds numbers $Re$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° 1</td>
<td>48.3</td>
<td>$5.7 \times 10^3$</td>
</tr>
<tr>
<td>N° 2</td>
<td>113.5</td>
<td>$2.5 \times 10^4$</td>
</tr>
<tr>
<td>N° 3</td>
<td>751.5</td>
<td>$2.8 \times 10^5$</td>
</tr>
<tr>
<td>N° 4</td>
<td>73.6</td>
<td>$1.3 \times 10^4$</td>
</tr>
</tbody>
</table>

Face N° 1 is considered as a front face, faces N° 2 and N° 4 are the side faces and face N° 3 is considered as a back face.

5 PARAMETRIC STUDY OF PROPAGATION

5.1 Influence of the wind

To study the influence of the wind velocity on the characteristics of propagation, we carried out a series of experiments by imposing three values of wind velocity $w_1=1.5$ m/s, $w_2=2$ m/s and $w_3=2.5$ m/s. The differential sensor is placed in the vegetation in order to measure the radiative flux and the
convective flux. The load of Kermes oak is taken equal to 3 kg/m². The results are illustrated in table 5 below.

Table 5. Propagation velocity for different values of wind

<table>
<thead>
<tr>
<th>Winds (m/s)</th>
<th>$w_0 = 0$</th>
<th>$w_1 = 1.5$</th>
<th>$w_2 = 2$</th>
<th>$w_3 = 2.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation velocity (cm/s)</td>
<td>1.63</td>
<td>2.06</td>
<td>4.00</td>
<td>5.71</td>
</tr>
</tbody>
</table>

5.2 Influence of the load

In order to study the effect of the load of the Kermes oak on the mechanism of propagation and the absorption of the vegetation, we carried out, for a density varied between 1.5 kg/m² and 6 kg/m², four experiments of fire without wind. The results are illustrated in the table below.

Table 6. Propagation velocity for different values of load

<table>
<thead>
<tr>
<th>Loads (kg/m²)</th>
<th>$P_0 = 1.5$</th>
<th>$P_1 = 3$</th>
<th>$P_2 = 4.5$</th>
<th>$P_3 = 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation velocity (cm/s)</td>
<td>2.23</td>
<td>1.78</td>
<td>1.68</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Table 6 above, shows a decrease of the propagation velocity for a variation of the load of fuel between 1.5 kg/m² and 4.5 kg/m².

The propagation velocity, for a load of 6 kg/m², has a larger value compared to that obtained for a load of 4.5 kg/m². We interpret this by the existence of a wind of 4 km/h velocity, within the propagation direction.

Absorption coefficient of the vegetation

The radiative flux received at a point $M(x, y, z)$ in the vegetation, by applying the "Beer’s law", can be written in the following form:

$$\Phi(x, y, z) = \Phi(x, y) e^{-a(\delta-z)}$$  \hspace{1cm} (15)

where $a$ is the absorption coefficient of the vegetation, $\Phi(x, y)$ is the radiative flux per unit of area coming from the flame on the surface of fuel and $\delta$ is the average height of the vegetation. Its value is equal to 90 cm.

By taking the flux $\Phi(x, y, z)$ equal to the $\phi_{i}^{sensor\ 3}$, flux measured by the face N° 1 of the sensor N° 3, and the flux $\Phi(x, y)$ equal to the $\phi_{i}^{sensor\ 1}$, flux measured by the face N° 1 of the sensor N° 1, the absorption coefficient of the vegetation $a$ can be written as:

$$a = -\log \left( \frac{\phi_{i}^{sensor\ 3}}{\phi_{i}^{sensor\ 1}} \right) \frac{\delta - z}{\delta}$$  \hspace{1cm} (16)

where $z = 60$ cm is the height of the sensor N° 3.
The evolution of the absorption coefficient of the Kermes oak according to its load is illustrated in the table 7 below.

Table 7. Absorption coefficient for different values of load

<table>
<thead>
<tr>
<th>Loads (kg/m²)</th>
<th>$P_0 = 1.5$</th>
<th>$P_1 = 3$</th>
<th>$P_2 = 4.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption coefficient (m⁻¹)</td>
<td>0.33</td>
<td>2.27</td>
<td>3.38</td>
</tr>
</tbody>
</table>

6 CONCLUSION

We presented, during this work, a differential thermal sensor intended to measure the radiative flux and the convective flux in four directions of space. The technical description and the specifications of this apparatus were presented.

An experiment of fire without wind and an assimilation of physical parameters made it possible to identify the characteristics of flame.

The measurement of temperatures and convective flux permit the identification of the Nusselt number on each face of the differential sensor. From the correlations of Reynolds number by Nusselt number, existing in the literature, we could determine the Reynolds number on the four faces of this sensor.

Two series of experiments, one with wind variable and another with load variable, were presented in order to study the influence of different parameters: the wind velocity and the fuel load on the propagation mechanism.
REFERENCES


