WIND TUNNEL EXPERIMENTS AND NUMERICAL SIMULATIONS OF FOREST FIRE SPREADING

Antonio C. P. Brasil Junior, Antonini P. Macedo and Sidney C. Vanderlei
Universidade de Brasília. Departamento de Engenharia Mecânica.
LEA - Laboratório de Energia e Ambiente.
70910-900 Brasília. DF. Brazil.
E-mail: brasiljr@unb.br

Abstract: *In this work wind tunnel experiments are performed to evaluate fire spreading in a thin biomass layer. Those experiments are developed to validate some semi-empirical considerations of forest fires modelling used in numerical codes. The characteristics of the flame were observed, using digitized video images, and a comparison to empirical data presented in the literature is presented. The numerical simulation and the wind tunnel experiments agree very well.*

Keywords: *Forest fires. Small scale experiments. Combustion*

1. Introduction

The understanding of forest fires spreading, using small scale experiments in wind tunnel is a useful methodology to check the behavior of the mathematical models used to model it. Such models include a number of empirical considerations of the flame characteristics, that must be validated for specific situations related to the different types of fuel bed and wind velocity. These characteristics can be easier obtained in small scale experiments than in real situations. Many features of the physical parameters of the surface fires spreading, can be easily identified in wind tunnel experiments and can be transposed to real large scale situations with proper physical reasoning. On the other hand, it is important to be highlighted that the direct scale analysis and transposition from small scale experiments to large scale cannot be performed. The physical-chemical characteristics of the combustion phenomena are the same for both cases, and can not be scaled. Therefore, the modelling of combustion and heat transfer phenomena, once validated to small scale situations, would provide useful information to describe large scale ones.

Some experiments in small scale are reported in the literature. Catchpole et al.(1999), De Mestre et al.(1989) and Dupuy(1995) performed experiments using a bed of dead pine needles. Many features of the heat transfer by radiation and by convection were identified in those experiments, as well as the spreading velocity of the fire front. The works of Ventura et al.(1990) and Mendes et al.(1998) describe experiments in a bed of wood chips and pine needles. Many parameters concerning the properties of the fuel bed were analyzed in those experimental works and some of its ideas are used in the present work. Recently experiments in a Australian vertical wind tunnel have been reported (e. g. Knight(2001)). It has shown the importance of this kind of experimental approach as a complementary analysis for *in situ* observations.

The physical behavior of forest fire spreading and its relationship with the wind are reviewed in the papers of Baines(1990), Beer(1991), Beer(1995) and Viegas(1998), for instance. Several empirical equations describing the flame characteristics are presented.

The main objective of this work is to develop a small scale experiment of a bed fire spreading in a low velocity wind tunnel. The results obtained in this experiment are compared to numerical results obtained using a mathematical model for its spreading. In the second part of this paper the mathematical model is presented, as well as the empirical equations of flame behavior. The numerical techniques used to the simulation are developed in the fourth part. After, the experiments are reported and finally a discussion of the results is presented.

2. Mathematical Model

The propagation of surface forest fire is considered as a combustion reaction occurring in a part of a biomass fuel layer distributed in a 2D domain $\Omega \subset \Re^2$. If in a generic point $P(x,y) \in \Omega$ there is combustion, the mass of the fuel $m(x,y,t)$ decays as follows:

$$\frac{\partial m}{\partial t} = -K \tag{1}$$

This equation gives the kinetics of the Pyrolysis reaction and the rate of reaction, K, is given by an Arrhenius like law:

$$K = A([O_2], T) \exp(-\frac{E}{RT}) \quad (2)$$

In this equation, $[O_2]$ is the concentration of oxygen in the air layer in contact with the material in combustion. T is the gas temperature and R the gas constant. A and E are characteristic constants of forest material combustion. These constants can be evaluated from experimental exponential decay plots of Rothermel(1972) or Ventura et al.(1990).

The heat produced during the combustion process at this point is thus given by:

$$\Phi(x, y, t) = -K\Delta H_m \quad (3)$$

where ΔH_m is the heat content of the biomass fuel. This energy is released from the flame by radiation and convection. The radiation will heat the biomass layer in front of the flame line.

Considering surface forest fires, the flame front propagates through the fuel bed by the heating processes of neighbor points mainly by radiation. The combustion starts when these points reach the ignition temperature and the fuel mass decay process starts.

This heating process can be modelled by the following energy balance:

$$\overline{\rho c}\frac{\partial T}{\partial t} = q_{rad+} - q_{rad-} - q_c \quad (4)$$

$T(x, y, t)$ is the temperature, q_{rad+} is the radiative heat flux, from the flame, and q_{rad-} and q_c are the radiative and the convective loss terms.

These terms can be written as:

$$q_{rad+} = \int\int \Phi(x', y', t)\xi(x - x', y - y')dxdy \quad (5)$$

$$q_{rad-} = \alpha\sigma(T^4 - T_\infty{}^4) \quad (6)$$

$$q_c = \bar{h}(T - T_\infty) \quad (7)$$

σ is the Stefan-Boltzman constant, $\bar{h}$ is the convective heat transfer coefficient and α is the absortivity coefficient (Baines(1990), De Mestre et al.(1989)).

The term $\overline{\rho c}$ is the mean value of the product of the density and specific heat of the fuel bed. This term includes the evaporation process in a two steps model given by De Mestre et al. (1989) as:

$$\overline{\rho c} = \begin{cases} \rho_b c_f + \rho_w c_w + \frac{\rho_w \ell}{373 - T_\infty}, & T < 373 \\ \rho_b c_f, & T \geq 373 \end{cases} \quad (8)$$

In this equation c_f and c_w are the specific heat of the dry fuel and water. ρ_b, ρ_f and ρ_w are de density of bed, the dry fuel and water within the vegetation layer. ℓ is the latent heat of vaporization of water (2.254×10^6 $J/(kg.K)$).

An important point in the present modelling approach, is the use of a flame influence function given by equation (5), that simplify the radiative heat transfer process by introducing an empirical relation $\xi(x-x', y-y')$ as proposed by Dorrer(1984). This correlation function is given by (in polar coordinates):

$$\xi(x - x', y - y') = \xi(r, \theta) = a_0\delta\left(1 - \frac{\delta}{3h_f}\right)\exp\left(\frac{rcos^2\alpha_f}{r_0(1 + sin^2\alpha_f \cos\theta)}\right) \quad (9)$$

The parameters in this equation are:

a_0 : Fraction of the heat spent in the propagation of the combustion.

δ : Thickness of the fuel bed.

h_f : Flame height.

α_f : Flame tilt angle

r_0 : Effective flame effect radius

As the function $\xi(x - x', y - y')$ is in polar coordinates, r and θ are the polar coordinates with origins in the point $P(x, y)$, and x' and y' are its neighbors.

The present approach for the radiation term is different of the used in some articles, which proposes a estimative of the forth order radiation heat exchange between the flame and the ground (e. g. Baines (1991) or Simeoni et al. (2002)). The radiative term for the approach of Baines(1991) is given by:

$$q_{rad+} = \alpha\epsilon_f\sigma(T_f^4 - T_\infty^4)W(X) \quad (10)$$

Where ϵ_f is the emissivity of the flame, T_f is the flame temperature and $W(x)$ is the radiation view factor given by:

$$W(X) = \frac{2}{\pi} \arctan \frac{h_f/X}{[1+(h_f/b)^2+(X/b)^2]^{1/2}} \tag{11}$$

In this equation X is coordinate in front of the flame and b is the fuek bed half-width.

It is an exact relation for line flames, but it is a approximation for curved fronts like in real cases.

3. Flame Geometry

In the heat transfer process, expressed by the empirical equations (5) and (8), the flame height and angle are the input parameters for the flame influence function. In fact, those physical characteristics govern the spread of the fire. The geometry of the flame is controlled by the heat released during the combustion and the wind velocity. It is a consequence of the hydrodynamical conditions of the upward thermal flow. The momentum balance involving the buoyancy forces and the induced external wind, establishes the inclination angle and the length of the flame. The problem is very complex and some empirical relations are proposed in the literature. In experimental works, the flame length L_f is directly related to the the fire intensity I using:

$$L_f = aI^b \tag{12}$$

I is given, in kW/m, by Baines(1990):

$$I = 0.42\Delta H_m W V_f \tag{13}$$

where W is the fuel weight (in tonnes/hectare) and V_f the speed of the fire given in the same work as:

$$V_f = 0.436 W f(\phi) \exp\left(\frac{U}{V_0}\right) \tag{14}$$

In those equations U is the characteristic wind speed (measured at a 10 m above the ground for real scale forest fires), V_0 is a constant equal to 6.9 and $f(\phi)$ is a function of the fuel moisture content in percent if oven-dry weight, ϕ, given by:

$$f(\phi) = \begin{cases} \exp(-0.0897\phi), & \text{if } \phi < 18.8 \\ 0.127(30-\phi), & \text{if } 18.8 < \phi < 30 \\ 0, & \text{if } \phi > 30 \end{cases} \tag{15}$$

In the review presented by *Beer* (1991) the constants a and b of the equation (12) are given as 0.05771 and 0.5 respectively, for surface forest fires. In the paper of Ventura et al., for a small scale experiment, the values are quite different (0.0775 and 0.46).

For the mathematical model, the fire intensity is replaced by the amount of heat released during the combustion. Then, the equation (9) can be written as:

$$L_f = a\Phi^b \tag{16}$$

The flame angle is always estimated as a empirical function of the Froude number as:

$$\tan \alpha_f = cFr^d \tag{17}$$

where

$$Fr = \frac{U^2}{gh_f} \tag{18}$$

In the experiments of Ventura et al. the values of the constants c and d are given as 0.999 and 0.296. Nelson & Adkins(1986) had obtained the values 0.89 and 0.29 which are quite the same of the last ones.

An important point in the determination of the physical parameters of the flames in small scales end real situations, is the error associated to their measurements. The turbulence flow near the flame produces a fluctuation of the flame geometry and many measurements uncertainties are observed in experimental analysis. The results obtained here will also have the same characteristic of uncertainties, and the errors associated to those measurements will be shown. In a statistical point of view, the variation of the flame parameters is negligible in face of the inhomogeneities of the physical-chemical characteristics of the fuel bed, in real situations.

4. Numerical Methods

The numerical solution of the integro-differential model described by equations (1)-(7) is performed using the Euler method coupled to Monte-Carlo integration techniques. This method is described in previous papers of Macedo & Brasil Junior(1994) (1995). In this method the domain Ω is discretized in a structured mesh where the evolution of temperature and mass fields at each node are computed. Equations (1)-(4) are discretized on time using a first order explicit Euler method. At each time step one has:

$$T_{ij}^{t+\Delta t} = T_{ij}^{t} + \frac{\Delta t}{\overline{\rho c}} \left(q_{rad+}^{t} - q_{rad-}^{t} - q_{c}^{t} \right) \tag{19}$$

$$m_{ij}^{t+\Delta t} = T_{ij}^{t} - K^{t} \Delta t \tag{20}$$

$$\Phi_{ij}^{t+\Delta t} = -K^{t} \Delta H_m \tag{21}$$

Before the computation of the temperature in equation (17), it is necessary to compute the radiative heat transfer function q_{rad+}^{t} which is given by a convolution integral (5) and (9). The computation of this integral is performed using a Monte-Carlo method, which considers a random distribution of 300 points near to the node ij. The result of each time step is the distribution of the fuel mass m_{ij} and temperature T_{ij} over the entire domain Ω. The flame front is defined by the region where the temperature is greater than the ignition temperature of the fuel. The reactive combustion process is extinguished in a point if the mass decay to a minimum value related to the unburned material content.

5. Experimental Setup

The experiments of the spreading in a ground fire are performed using a thin layer of wood chips placed on the floor of a low speed wind tunnel. The layer of the biomass fuel was 1 cm thick with dimensions of 1.0 $\times$ 0.5 m. Three different kinds of Brazilian woods had composed the biomass layer: *Angelim*, *Ipê* and *Castanheira*. The water content of the wood was controlled to be fixed in $7-9\%$. The mass of the fuel are measured before and after the fire in order to determine the combustion efficiency.

A turbulent boundary layer was produced in the wind tunnel using turbulence inducers, placed on the flor, in order to obtain a boundary layer thickness of 20 cm. The free wind velocities used in the experiments were from 0 to 0.6 m/s. The velocity measurements were performed using a hot wire sensor at the top of the boundary layer and at 5 cm from the ground (plane of the flame).

Ten termocouples were placed in different positions into the fuel bed. They were located at an upwind distance of 5 cm one of each other and the temperatures were recorded during the fire spreading. Using those temperature plots, the difference in time of the peaks of the temperature at each termocouple gives the spreading velocity of the fire.

The fire were ignited in the upwind border of the fuel bed and its evolution was recorded by a VHS video camera. The images were digitized by a TARGA frame grabber. In a first experiment, the position of the camera was chosen in order to evaluate the evolution of the front of the fire and the velocity of the fire front could be determined by a visualization. A second experiment was performed placing the camera in the same plane of the fire. In this last position, the physical parameters of the flame could be observed.

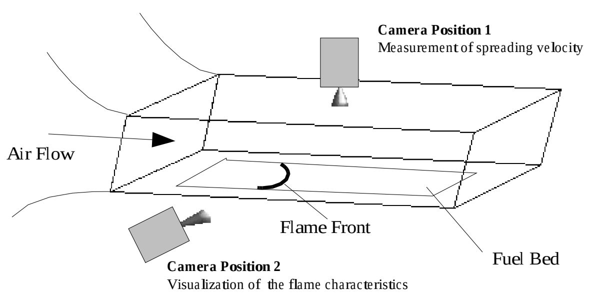


Figure 1: Experimental Setup

6. Results and Discussions

The results were obtained for wind velocities from 0 to $0.58 m/s$. For those conditions, visualizations and temperature measurements were performed. The velocity of the flame spreading and the geometrical parameters of the flame were determined for those situations. For the same conditions, numerical simulations were performed using the physical parameters of the wind tunnel experiments (fuel bed parameters and wind velocity).

In Figure 2 a lateral visualization of the flame is illustrated for two different wind velocities. The images are treated in order to determine the contour of the flame. Using those images the length and the inclination angle could be measured.

The results of flame angle and length for different values of wind speed is summarized in tables 1 and 2. The results of spreading velocity are also reported in tables 1 and 3. The results are compared to those ones obtained by the empirical equation (17) and also to the numerical simulations. The results agree well, taking into account an uncertainty band for the measured values for the present experiment. The use of those empirical relations is then validate by experimental data.

Table 1: Experimental characteristics of the flame

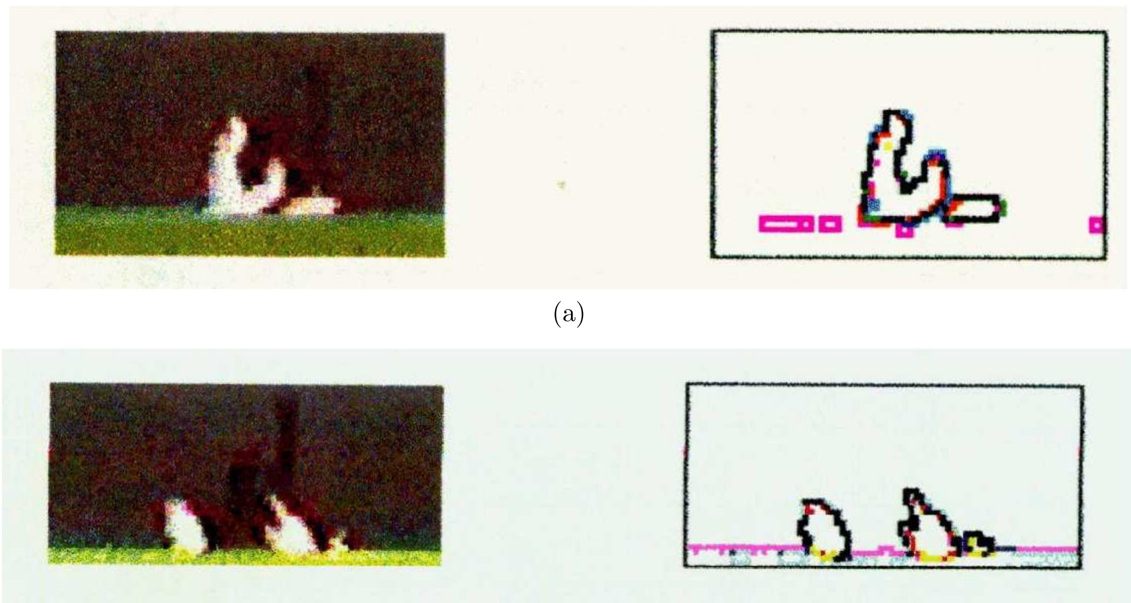
Wind Velocity (m/s)	Flame Length (cm)	Flame Angle (Degrees)	Spreading Velocity (m/s)
0.0	$4-6$	$0-10$	2.3×10^{-3}
0.46	$4-5$	$35-45$	3.1×10^{-3}
0.58	$4-5$	$40-55$	3.7×10^{-3}

Table 2: Comparisons for the flame angle

Wind Velocity (m/s)	Experimental Data	Equation (17)
0.46	$35-45$	40.2
0.58	$40-55$	46.8

Table 3: Comparisons for the Spreading Velocity (in m/s)

Wind Velocity (m/s)	Experimental Data	Numerical simulations
0.0	2.3×10^{-3}	2.0×10^{-3}
0.46	3.1×10^{-3}	3.5×10^{-3}
0.58	3.7×10^{-3}	4.1×10^{-3}



(a)

(b)

Figure 2: Actual and processed images: (a) $U = 0$ (b) $U = 0.58 m/s$

Figure 3 shows the visualization of the fire spreading for experiments and numerical simulations. For the experimental results the temperature levels in the fuel bed are plotted in order to determine the flame position (green levels are at ignition temperature). The wind velocity in the plane of the flame is 0.58 m/s. The flame in all experiments propagates much faster in the center of the biomass layer than in the lateral borders. This geometric form of the fire front is due to the heat transfer by radiation. The central region has greater view factors from the lateral portion of the line flame than the regions placed on the side, and the fire front do not spreads in a equal velocity. For big line fronts this phenomena is not significant. It is also clear from graphs in Figure 3 that the prosed mathematical model reproduces well the behavior of the fire fronts. Certainly, the considerations of straight line fronts (1D spreading) would not work well as the consideration of a curved line-front do not consider the same radiation view factor proposed in equation (11) . A 1D approach would also underestimate the spreading velocity. The use of the present empirical model, based in a 2D correlation function given by equation (9), if calibrated as proposed in the present paper, can describe realistically the spreading of real ground or surface fires.

The experimental temperature in the termocouples in front of the flame is presented in figure 4. The experimental results are compared to the numerical simulations and the agreement between the results is very good. The formulation presented here can describe with a good level of description the temperature in the fuel bed, consequently validating the estimative of heat transfer terms.

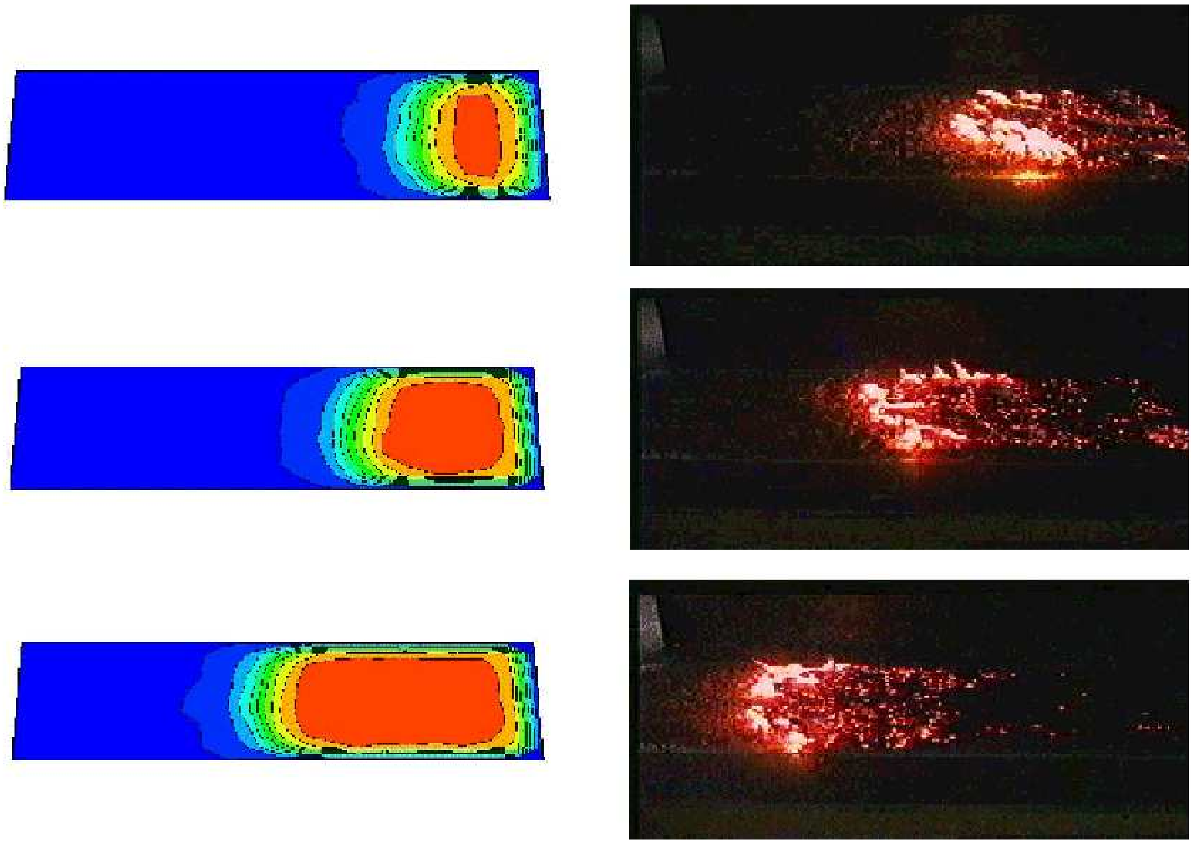


Figure 3: Flame Spreading - Visualization of Numerical and Experimental Results

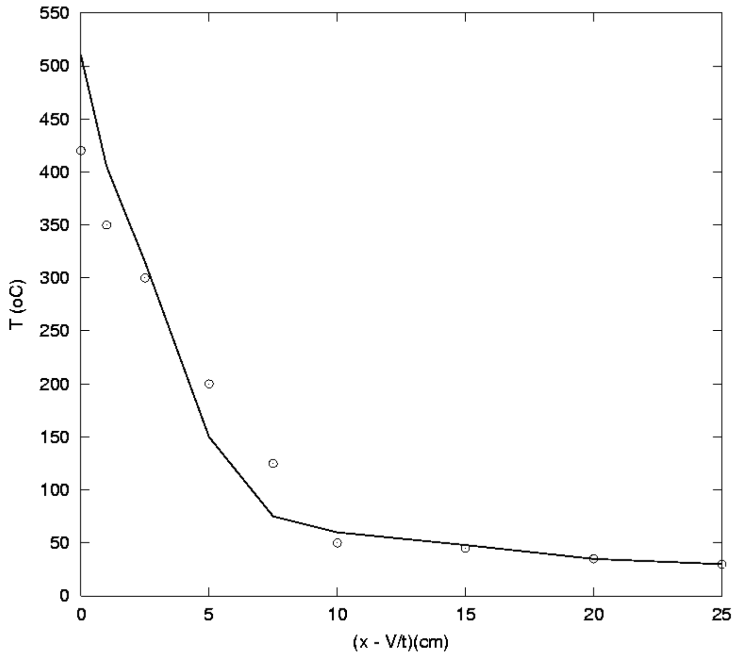


Figure 4: Temperature in the front of the flame (Points are experimental data and line the Numerical simulations)

7. Conclusions

The experimental results obtained during the present experiments shown the possibility of the validation some empirical correlations used in forest fire simulation. The model proposed in the present paper could reproduce with good agreement the experimental results, all flame characteristics and the physical behavior of the flame spreading. The wind tunnel experiments has proved to be an interesting tool for understanding the ground fire behavior and check the calibration of some empirical constants. The transposition of the results from a small scale to the large real situations have to be performed by the use of the modelling strategy as in the present paper. Future works will be performed to reproduce the fire fronts behavior for different kinds of fuel bed.

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