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AN ANALYTICAL MODEL BASED ON RADIATIVE HEATING FOR THE DETERMINATION OF THE SAFETY DISTANCES FOR WIDLAND FIRES

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Abstract

The radiative heat transfer is often the main thermal impact of a wildfire on people fighting the fire or on structures. Thus, the estimation of the radiation coming from the fire font and hitting a target is of primary importance for forest and urban managers. A new flame model based on the solid flame assumption is developed by considering a finite fire front width. The realistic description of finite fire front widths allows proposing a new criterion for the estimation of the radiative impact of the fire, which is based on the ratio fire front width/ flame length, opposed to the classical approach of considering only the flame length. The new model needs to be solved numerically so an analytical approximation is proposed to obtain a simple and useful formulation of the acceptable safety distance. A sensivity analysis is conducted on the different physical and geometrical parameters used to define the flame front. This analysis shows that the flame temperature is the most sensitive parameter. The results of the analytical model are compared with the numerical solution of the flame model and previous approaches based only on flame length. The results show that the analytical model is a good approximation of the numerical approach and displays realistic estimations of the acceptable safety distance for different fire front characteristics.

Keywords: Wildfires, radiative impact, solid flame approximation, flame front length, acceptable safety distance.

1. Introduction

Wildland fires represent a growing threat on human infrastructure and activities due to climate change and the spreading of the Wildland-Urban Interface (WUI). As an example, if one considers the west coast states of the United-States during the 1990s, the WUI grew by 11% in size and the number of houses at the WUI grew by 17% [1].

Under a fire safety viewpoint, the fire has two main impacts: it can damage structures and it can affect people. The combined effects of climate change – inducing an increase in the occurrence of extreme fires – and the growing of the WUI – implying more contact between vegetation and structures – lead to a growing impact of wildfires on structures. People can be exposed to high heat fluxes coming from the fire front too. The growing of the WUI implies that firefighters have to protect more and more property and remain at a close distance form the fire front. Habitants can face the same problem as they stay to protect their homes or cannot evacuate. Unfortunately, they do not have the same level of protection and skills as firefighters to keep safe.

The involvement of the scientific community is increasing in order to address this growing problem and active research about the characterization of the fire at the WUI and the estimation of its impact is taking place. Two main approaches can be defined for the estimation of the thermal impact of the fire (we do not consider the impact of embers here, the interested reader is referred to [2]). The first one is based on an extensive description of the fire behavior at the WUI. Detailed physical fire spread models based on Computational Fluid

Dynamics can be potentially applied to the WUI problem [3]. One can note the promising development of the Wildland-urban interface Fire Dynamics Simulator (WFDS) from NIST, which is specifically designed to characterize the fire spread at the WUI and to estimate its impact [3] (see also: www2.bfrl.nist.gov/userpages/wmell/nist_wui_models.html). These models are very detailed and include many parameters for describing the combustion, the radiative heat transfer (soot in flames) and the distribution and burning of vegetation among others. Up to now, they only represent research tools and need to be fully validated at the WUI before being applied in the field [4].

A simpler approach was developed to estimate the fire impact. It is based on the observation that the main hazard for firefighters located in the vicinity of a fire front and who are not in danger of being impinged by the flames arises primarily from the radiant heat emanating from the fire [5, 6]. This approach drastically simplifies the fire front and its dynamics by assuming that the properties of the fire front are well known [5-8]. Then, it focuses only on the estimation of the radiative heat transferred from the fire front and impinging a specified target. As the fire and its dynamics are not computed, it is necessary to develop a model to represent the fire front and many flame models have been developed [7, 8].

The flame model adopted in this paper is based on the radiant surface approach [9, 10]. This approach does not account for the flow and the fire dynamics and only represents the flame as a radiant surface (solid flame assumption). The flame model is generalized to take into account the effect of the flame front width and the estimation of the flame front impact is improved by formulating a flexible location for the target. Radiative emission from the whole flame is then determined from the geometry of the flame and the properties of the fire front.

The model aims at providing an easy-to-use tool for decision-making in fire management and fire fighting. However, because of the complex formulation of the radiative transfer it has to be solved numerically. In order to provide a simpler tool, an analytical formulation of the safety distance was derived from the model. The safety distance is deduced from the flame characteristics and a threshold value for vulnerability. In this work, the threshold value has been set to the vulnerability of a standing people. The analytical formulation can provide immediate results to the end-users and can be used to support fire fighting and fire management strategies devoted to keep fire fighters and structures safe at the WUI.

The next section deals with the development of the fire front model and the establishment of the analytical expression. Then, a sensitivity analysis is conducted to study the influence of the fire front parameters on the estimation of the safety distance. Finally, the results are discussed, compared to previous models and a new criterion for the establishment of the safety distance is proposed.

Nomenclature

AA	Acceptable accuracy (%)	*r*	Distance between the base of the fire front and the target (m)
ASD	Acceptable Separation Distance (m)	*thres*	threshold value (W.m^{-2})
ASD^{WI}	ASD distance for a large fire front (m)	T_f	Flame temperature (K)
ASD_1^{WI}	Positive ASD for a large fire front (m)	*x, y, z*	Coordinate in space (m)
ASD_2^{WI}	Negative ASD for a large fire front (m)	x_o, y_o, z_o	Coordinate in space (m)

B	Stefan-Boltzmann constant (W/m^2/K^4)	**Greek symbols**	
$F_{i\rightarrow j}$	Dimensionless view factor between surface *i* and surface *j*	ε	Dimensionless equivalent flame emissivity
$F^{WI}_{f\rightarrow M}$	Dimensionless view factor between surface *i* and surface *j* for a large fire front	γ	Flame tilt angle
g	Acceleration due to gravity (m/s^2)	τ	Dimensionless atmospheric transmissivity
h	Vertical target position above the vegetation (m)	θ_{inf}	Angle between (0_oM) and (MP_1)
(2L/lf)$_{\mathrm{lim}}$	Ratio delimiting the zones I and II (dimensionless)	θ_{sup}	Angle between (0_oM) and (MP_2)
k_{thres}	Parameter (dimensionless)	θ_{fl}	Angle ahead of the flame
L	Half width of the flame body (m)	Φ^{th}	Radiant heat flux obtained from the analytical model (W.m^{-2})
l_f	Flame length (m)		
$\vec{n}$	Unit vector, normal of the target		
$\vec{N}$	Unit vector, normal of the fire front		

2. Establishment of the analytical expression

2.1. Simplified heat flux model

In order to evaluate the thermal radiation received by an object parallel to a flame area inclined with an angle γ and located in front of its centre at a position *h* above the vegetation (Fig. 1), the solid flame model considers the visible flame to be a geometrical body that emits radiative energy uniformly throughout its surface like a grey body [11]. The medium of interest in this work is wildland vegetation and it is heterogeneous. So, the approach presented here considers an equivalent medium with average properties. Furthermore, the non-visible zones of the flame are not taken into account as non-visible radiation was found to be negligible compared with the total heat flux [12].

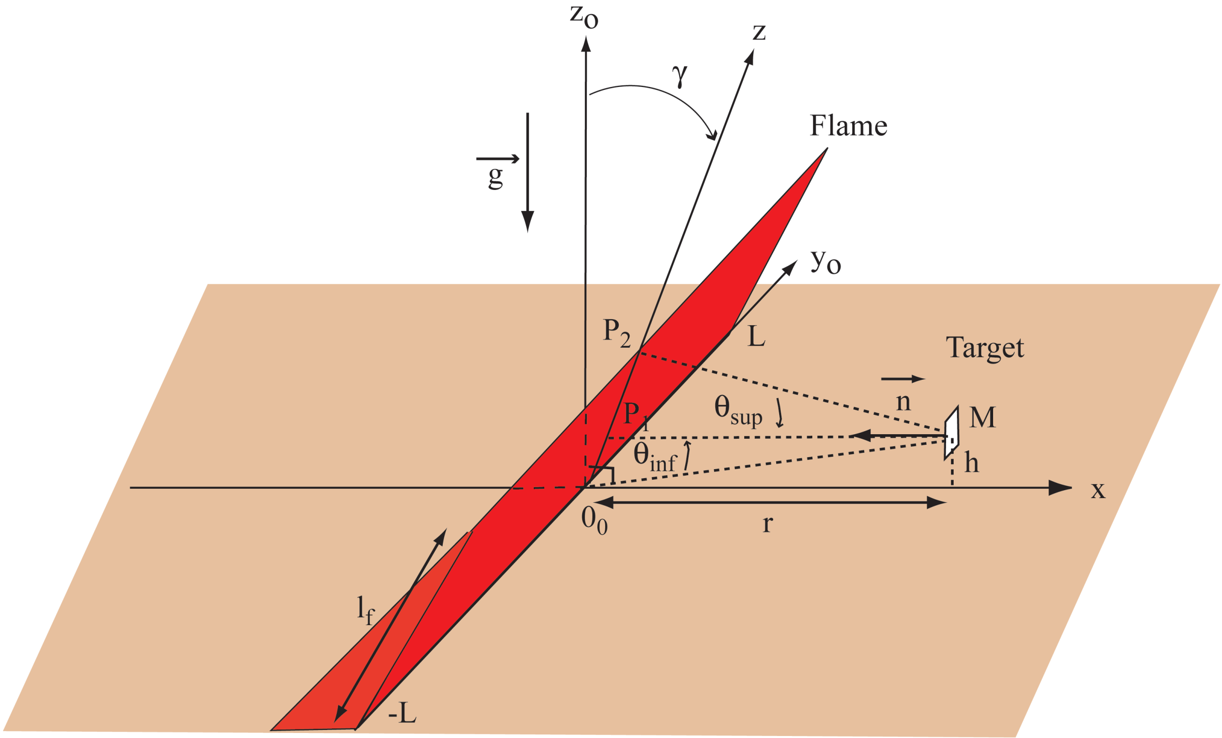

Figure 1*. Schematic geometry used to determine the heat flux at a position h above the vegetation.*

To estimate the radiation that leaves the flame and strikes the target, the view factor between the target and the flame has to be computed. If the flame front is generalized into a finite rectangular area inclined with an angle γ and if the target is located just above vegetation, the expression of this view factor (Fig. 2) is given as [13]:

$$F_{f\to M}(r,\theta_f)=\frac{1}{2\pi}\left(\frac{2L\,arctan\left(\frac{2\,rcos\gamma\,sin\theta_f\sqrt{L^2+(rcos\gamma)^2}}{L^2\,cos(2\gamma-\theta_f)+(L^2+(rcos\gamma)^2)cos\theta_f}\right)cos\gamma}{\sqrt{L^2+(rcos\gamma)^2}}-2arctan\left(\frac{L\,cos(2\gamma-\theta_f)}{rcos\gamma}\right)sin\theta_f\right) \qquad (1)$$

where L is the half width of the fire front, θ_f is the angle ahead the flame and *r* is the distance between the base of the fire front and the receptor.

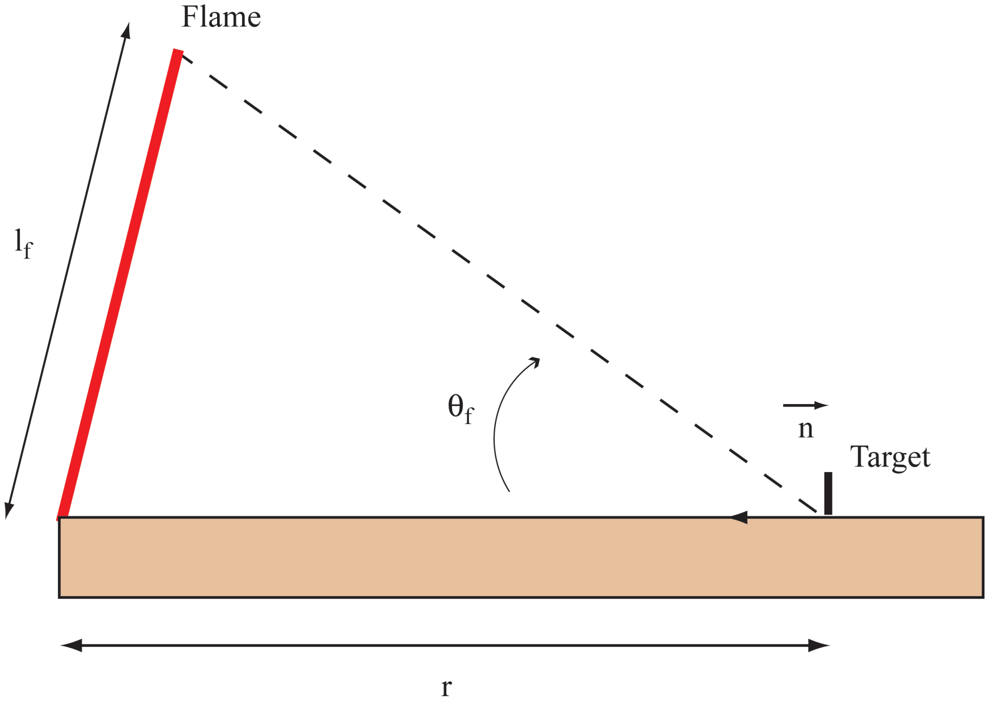

Figure 2. *Schematic geometry used to determine the view factor between the target located just above the vegetation and the flame front.*

So, using the Stefan-Boltzmann equation [11], the heat flux at the position M (Fig.1) can be given by the following expression:

$$\Phi^{th}(M) = \tau\, \varepsilon\, B\, T_f^4 \left(F_{f\to M}\left(r_{inf},\theta_{inf}\right) + F_{f\to M}\left(r_{sup},\theta_{sup}\right)\right) \tag{2}$$

where τ is the atmospheric transmissivity, ε is the equivalent flame emissivity, B is the Stephan-Boltzmann constant, T_f is the flame average temperature and $F_{f\to M}$ the view factor which is given by Eq. (1) and with:

$$\theta_{inf} = arctan\left(\frac{h}{r_{inf} - h\, tan\gamma}\right), \tag{3a}$$

$$\theta_{sup} = arctan\left(\frac{h}{r_{sup} - (\, l_f - h\, tan\gamma)}\right), \tag{3b}$$

$$r_{inf} = r, \tag{3c}$$

and

$$r_{sup} = r - h\, tan\gamma. \tag{3d}$$

2.2. Determination of the Acceptable Safety Distance

Under a safety viewpoint, one of the main concerns is the potential exposure of people to the radiant heat effects of a fire arising from large outdoor fires. These studies are based on a fixed human exposure criterion, namely, threshold heat flux level. The distance at which this level of heat flux occurs is considered to be the distance at which human beings will suffer serious skin injury. So, it is possible to determine an Acceptable Separation Distance (ASD). The ASD is the distance between the target and the fire at which the thermal radiative flux is less than a threshold heat flux level [14].

This section produces two methods for estimating the ASD: a numerical determination that is providing the exact value of the ASD and an analytical expression, which is providing an approximate value of the ASD in a useful format for end-users.

2.2.1. Numerical determination

The equation to solve has the following form:

$$\Phi^{th}(M) = \Phi_{thres} \tag{4}$$

where Φ_{thres} is the threshold heat flux level. The software Mathematica has been used to solve Eq. (4). If only one starting value is specified, the solver searches for a solution using Newton methods and if two starting values are specified, it uses a variant of the secant method.

Fig. 3 presents results considering a vertical target located at a position h = 1.7 m above vegetation in front of a vertical flame ($\gamma = 0$). A flame temperature of 1200 K, an atmospheric transmissivity of unity, a flame emissivity of 1 and for four lengths of flame (5 m, 10 m, 15 m and 20 m) are assumed. These values are realistic values for wildfires [11]. The selected threshold value is $\Phi_{thres} = 4.7$ kW.m^{-2}. This value corresponds to the acceptable thermal radiation hazard level for public exposure set by the State of New South Wales agency, Australia [6].

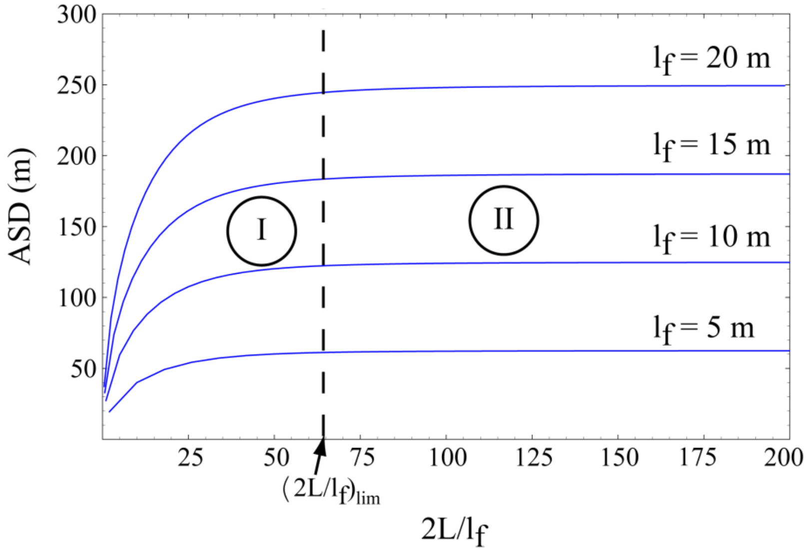

Figure 3. *Acceptable Safety Distance as a function of the ratio (flame width/flame length) considering a vertical fire front ($\gamma = 0$, $T_f = 1200$ K, $\tau = 1$ and $\varepsilon = 1$) for four lengths of flame (l_f = 5 m, 10 m, 15 m and 20 m). The threshold value is 4.7 kW.m^{-2}.*

Figure 3 shows two distinct zones: I and II. In the first zone ($2L/lf < (2L/lf)_{lim}$) the ASD is a function of the ratio 2L/lf and in the second zone ($2L/lf > (2L/lf)_{lim}$) it can be noted that this distance is a constant value.

2.2.2. Analytical expression

If one considers a large fire (infinity width), Eq. (1) becomes [16]:

$$F_{f \to M}^{WI}\left(r, \theta_f\right) = \frac{1}{2} sin\theta_f \tag{5}$$

where

$$\theta_f = arctan\left(\frac{l_f\, cos\gamma}{r - l_f\, sin\gamma}\right) \tag{6}$$

In order to obtain an analytical expression for the safety distance as a function of the flame characteristics (tilt angle, length, emissivity, transmissivity, average temperature) and threshold values for the vulnerability of people, it is necessary to get the explicit solution to the equation below:

$$\frac{\tau\, \varepsilon\, B\, T_f^4}{2} sin\left(arctan\left(\frac{l_f\, cos\gamma}{ASD^{WI} - l_f\, sin\gamma}\right)\right) = \Phi_{thres} \tag{7}$$

Using trigonometric properties detailed in appendix [17] and after some calculations the following equation is obtained:

$$\left(ASD^{WI}\right)^2 - 2\, l_f sin\gamma\, ASD^{WI} + \frac{1}{4\, \Phi_{thres}^2}\left(4\, \Phi_{thres}^2\, l_f^2\, - \left(B l_f\, T^4 \varepsilon\tau cos\gamma\right)^2\right) = 0 \tag{8}$$

Hence, it is possible to obtain explicit formulas for the two solutions of the quadratic Eq. (8) herein. These expressions are given by the relations below:

$$ASD_1^{WI} = \frac{l_f \Phi_{thres} cos\gamma \sqrt{-4 l_f \Phi_{thres} + \left(B T_f^4 \varepsilon\tau\right)^2}}{2\Phi_{thres}} + l_f sin\gamma \tag{9a}$$

$$ASD_2^{WI} = \frac{-l_f \Phi_{thres} cos\gamma \sqrt{-4 l_f \Phi_{thres} + \left(B T_f^4 \varepsilon\tau\right)^2}}{2\Phi_{thres}} + l_f sin\gamma \tag{9b}$$

The ASD must be a positive value. So in order to evaluate this distance, only ASD_1^{WI} is selected. Unfortunately, in the case of a real fire front with a finite width, no analytical solution of the Acceptable Safety Distance can be obtained because of the complexity of the problem. So, it is necessary to approximate the exact expression.

Using the results displayed on Fig. 3 the following correlation is assumed:

$$ASD = \; ASD_1^{WI}\left(1 - exp\left(-k_{thres}\frac{2L}{l_f}\right)\right) \tag{10}$$

where k_{thres} is an empirical parameter that must be determined for each selected threshold of the heat flux.

3. Sensitivity analysis

A sensitivity analysis is conducted to identify the model parameters that must be chosen with care because of their large impact on model predictions and the others parameters, which may have only a small impact on them. In this study, a simple univariate sensitivity analysis [18] is used to assess how the results of the model (Eq. 10) are affected by parameter uncertainty. These parameters are: the tilt angle (γ), the length of the flame (l_f), the width of the flame ($2L$), the equivalent flame emissivity (ε) and the flame temperature (T_f). The chosen values correspond to experimental fires with 0.7 m high shrubs [19]. Each input parameter is varied by ± 10 % of its default value, while all other parameters are held at their default value. Fig. 4 shows only the results for increased parameters (+ 10 %) but the conclusions are the same for decreasing them (-10 %). This analysis (see Table 1) indicates that the parameters with significant effects on ASD evaluation are the flame temperature parameter (*Tf*), the flame emissivity (ε) and the length of the flame (l_f). However, flame emissivity and length of the flame have less influence on ASD than flame temperature and variation in tilt angle (γ) and in flame width (*2L*) do not produce significant changes on the model results. If incorrect flame temperature or flame emissivity are selected, it can lead to severe error in the ASD, which imply incorrect or dangerous decisions.

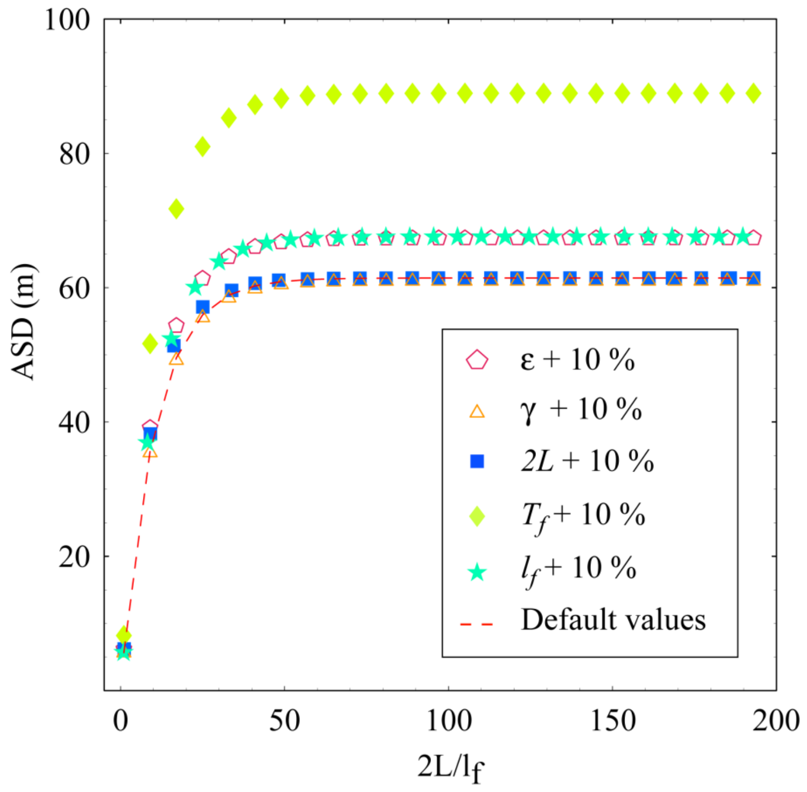

Figure 4*. Sensitivity analysis (default values: T_f = 1200 K, ε = 0.5, γ = 20°, l_f = 10 m). The fixed threshold value is 4.7 kW.m^{-2}.*

Table 1.
Sensitivity analysis results. The fixed threshold value is 4.7 kW.m^{-2}.

Parameter	*Default* value	*Value (+10%)*	*Value (-10%)*	*Mean(ASD-ASD$_{+10\%}$)* (m)	*Mean(ASD-ASD$_{-10\%}$)* (m)
T_f (K)	1200	1320	1080	- 25.66	19.23
ε	0.5	0.55	0.45	- 5.54	5.56
l_f (m)	10	11	9	- 5.38	5.45
L (m)	5 - 1000	5.5 - 1100	4.5 - 900	- 0.29	0.35
γ (°)	20	22	18	0.42	- 0.35

4. Results

4.1. Comparison between a numerical resolution and the proposed model

The proposed analytical formulation (Eq. 10) has been compared with numerical solutions (see section 2.2.1.) for different flames lengths (5, 10, 15 and 20 m). A differential receptor element at 1.7 m height, which can represent a standing person, facing a vertical fire front (γ = 0°) has been considered. A flame temperature of 1200 K and a flame emissivity of unity are assumed. The thermal radiation threshold has been set to 4.7 kW.m^{-2}. Experimental studies [20-22] suggest that these values are appropriate for large wildland fires. For outdoor exposure of persons without any special protection this limiting heat flux causes pain in 15-20 s and burns after 30 s. Figure 5 shows that the proposed analytical formulation matches the results of the numerical model.

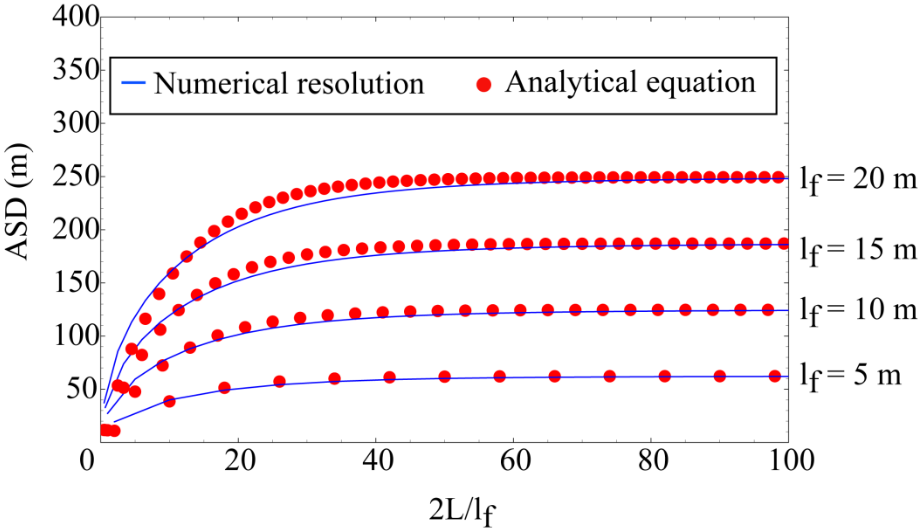

Figure 5. *Agreement of the analytical formulation with the numerical model under no-wind condition (γ = 0). Acceptable Safety Distance as a function of the ratio (flame width/flame length). The threshold value is 4.7 kW.m*$^{-2}$.

4.2. Comparison between two previous models and the proposed model

Fire behavior modeling systems, like BehavePlus [23], are a collection of many fire behavior and fire effect models. Fire spread models (surface and crown) are linked to several other models such as those used to estimate firefighter minimum safety zone size [5]. Butler and Cohen [5] assumed a vertical fire front, a flame temperature of 1200 K, flame emissivity of unity and 20 m wide flame. They selected a threshold of 7 kW/m^2 for the incident heat flux. This threshold is considered as the maximum level tolerable by firefighters wearing protective equipment. They have been derived from experimental results an empirical law: the safety zone size should be at least 4 times the maximum flame height. Zàrate *et al.* [9] have used the solid flame model to estimate radiation emitted by a vertical and infinite flame front of a wildland fire and they have established safety zones after determining flame heights yielded by several fuel models and the 'worst case' assumption. In the aforementioned 'worst case' assumption the receptor is always located at a height equivalent to 50 % the flame height and the flame remains vertical position.

Table 2 shows the agreement, for two scenarios, between the safety distances calculated using the proposed model and the two aforementioned models (the law derived in [5] and the "worst-case" model proposed in [9]). The first scenario considers a vertical fire front 20 m wide and 5 m high and the second a 20 m and 15 m rectangular vertical flame. The receptor is located at 2 m height above the ground parallel to the fire front. In these cases, the results lend credibility to the proposed model. The differences between [5] and the two other models can certainly due to the fact that this empirical model was obtained in real fires conditions with uncertainly in the determination of the fire front geometry. This empirical law relies on the experimental conditions of testing. So, the use of this relationship to calculate the Acceptable Safety Distance for fuel beds, which have very different flame characteristics, cannot be estimated properly. Indeed, a tough calibration process is necessary before any operational use.

Table 2.
Comparison between the analytical model and two previous models for two fires configurations under no wind condition: (a) 20 m wide and 5 m high and (b) 20 m and 10 m. The threshold value is 7 kW.m^{-2}.

Model	*ASD (m)* Scenario (a)	*ASD (m)* Scenario (b)
Proposed model	21.58	31.13
Butler and Cohen	20	40
Zàrate et al.	21.60	31.41

The common assumption depicted above approximates the flame as a flat vertical sheet of given height located at the base of the flame front [24]. By making the box vertical, the effect of the inclination of the flames is ignored. However, this assumption can be inadequate in some cases. To illustrate this, ASD is predicted using the proposed model and the 'worst-case' configuration for various flame tilt angle values (γ = 0° to 40°). A large wildland fire is assumed (infinite width) and the values of the model parameters are: $h = 2$ m, $l_f = 10$ m, $T_f = 1200$ K, $\tau = 1$ and $\varepsilon = 1$. Figure 6 depicts that the two approaches have the same results for a vertical fire front but one can noticed that the 'worst-case' under-predicted the ASD for high values of the flame tilt angle. These results show the necessity to take into account the wind and/or slope contributions that is one of the most important environmental variables that affect wildland fire behavior and therefore a key factor for the accurate prediction of models and simulators.

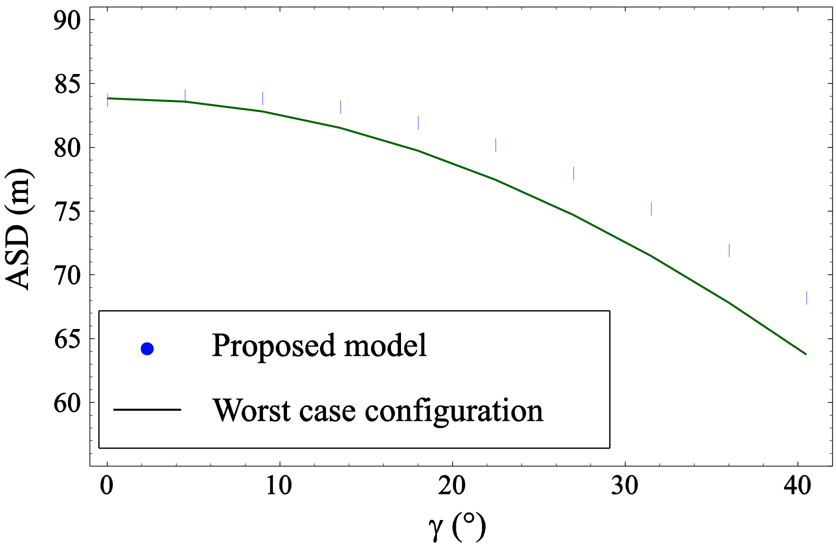

Figure 6. *Comparison between the proposed model and the worst case configuration proposed by Zarate et al. [9] for various flame tilt angle values and a wildland fire (infinite width,* $\gamma = 0°$ *to* $40°$*,* $h = 2$ *m,* $l_f = 10$ *m,* $T_f = 1200$ *K,* $\tau = 1$ *and* $\varepsilon = 1$*). The threshold value is 7* $kW.m^{-2}$.

4.3. Determination of a new criterion

Usually predictions of separation distances are given as a function of flame height [5, 9]. To test this criterion ASD calculations have been conducted using four flames heights: 5, 10, 15 and 20 m. A vertical flame front, a flame temperature of 1200 K, an emissivity and a transmissivity of unities, a threshold value of 4.7 kW/m^2, and a receptor at 1.7 m height above the vegetation are assumed. Figure 3 shows two distinct zones: I and II. The values of the ratio $(2L/lf)_{lim}$ delimiting these zones are calculated using the equation below:

$$\frac{1}{ASD}\left(ASD - ASD_2^{WI}\right) = AA \tag{11}$$

where *AA* is an acceptable accuracy.

Table 3 displays results of the calculated ratio for three *AA* values: 2, 5 and 10 %. They show that the ratio delimiting the zones I and II is a constant for a selected threshold of the incident heat flux. So, the criterion to calculate the safety distance must be this ratio and not the height of flame usually used in the previous models [5, 9].

Table 3.

Determination of the ratio $(2L/l_f)_{lim}$ *for four flames heights: 5, 10, 15 and 20 m and three selected precisions (AA = 2, 5 and 10 %). The fixed threshold value is 4.7* $kW.m^{-2}$.

$l_{f\,(m)}$	$(2L/l_f)_{lim}$ with AA = 2 %	$(2L/l_f)_{lim}$ with AA = 5%	$(2L/l_f)_{lim}$ with AA = 10%
5	62	44	32
10	63	44	31
15	63 .3	43.3	30.7
20	63.5	43.5	31

Zarate et al. [9] make the following statement: 'In practice, wider values of the flame front width do not increase significantly the thermal radiation at the distances of interest'. So, they have calculated the ASD for various scenarios with a fire front width of 20 m. Table 4 shows the ASD for the same type of fuel bed *as used in [9]* ($l_f = 5$ m, $T_f = 1200$ K, $\tau = 1$ and $\varepsilon = 1$) under no-wind condition (($\gamma = 0°$) and for three fire front widths: 20 m, 50 m and infinity. The fixed threshold value is 4.7 kW.m^{-2} and the target is considered at a 1.7 m height above the combustible medium. Table 4 shows the necessity to take into account the fire front width for estimating the ASD with such models using the radiant surface with constant properties assumption for the flame.

Table 4.
Determination of ASD for the same type of fuel bed as used in [9] ($l_f = 5$ m, $T_f = 1200$ K, $\tau = 1$ and $\varepsilon = 1$) under no-wind condition (($\gamma = 0°$). The fixed threshold value is 4.7 kW.m^{-2}.

2L *(m)*	*ASD* *(m)*
20	21
50	31
Infinity	42

4.4. Determination of the ASD

4.4.1. Determination of the parameter of the analytical correlation

The proposed model provides an analytical expression to evaluate the ASD for a fixed threshold of the radiative heat flux hitting the target and given flame geometry and flame properties. In order to evaluate this ASD, fuel models [25] or vision metrology [26] can be used to determine the geometrical inputs: flame length, title angle and fire font width. For large wildland fires, a radiative temperature of 1200 K and an emissivity of unity are usually assumed to characterize the flame [5]. To use the analytical correlation instead of the numerical model, it is necessary to determine the parameter k_{thres} for some selected threshold heat flux values. In this study, four thresholds are considered: 5, 7, 12 and 37.5 kW.m^{-2} [6, 9]. Several countries in Europe have adopted the heat flux level of 5 kW/m^2 as the criterion for determining the hazard distance to people exposure from large fires [6]. The level 7 kW/m^2 is the maximum tolerable value for fire fighters completely covered by special equipment. 12 kW/m^2 is the unpiloted ignition of wood exposed to thermal radiation. 37.5 kW.m^{-2} is the level that causes the instantaneous death. In order to calculate the model parameter k_{thres}, *Mathematica Packages* [15] have been used to interpolate the numerical results of the ASD determined using Eq. 4 and the methodology described in section 2.2.1. These Packages provide a numerical solution to the mathematical problem of minimizing a sum of squares of one or several, nonlinear functions that depend on a common set of parameters. Table 5 displays the parameter k_{thres} for the four selected threshold heat flux values. So, it is possible to evaluate the ASD considering a finite width (zone I) or an infinite width (zone II) for the fire front (see Figure 3 and 5).

Table 5.
Determination of the model parameter k_{thres} for 4 thresholds of heat flux: 5, 7, 12 and 37.5 $kW.m^{-2}$.

Heat flux threshold (kW/m^2)	*Criterion*	k_{thres}
5	Maximum tolerable value for people	0.1
7	Maximum tolerable value for firefighters	0.14
12	Unpiloted ignition of wood	0.25
37.5	Instantaneous death	0.48

4.4.2. Determination of the ASD for large wildland fires

The analytical expression for ASD (Eq. 10) provides a simplified way of looking at systems that are complex and that vary a lot with the external conditions. When using this kind of expression, it is important to fully understand their sensitivity to a given set of inputs and it is necessary to apply extreme caution when choosing them. So, the variability of some given parameters must be considered. The sensibility analysis (section 3) shows that selecting unadequate flame temperature and flame emissivity could severely underpredict or overestimate the ASD.

Table 6 provides the ASD calculated for large wildland fires (infinity width) by using the analytical model and 13 fuel models under a wind condition of 8 m/s. According to [22], the emissivity of large wildland fires (fire front depth greater than 3.2 m) can be considered to be close to the emissivity of a blackbody (ε =0.9). Usually, a flame radiative temperature of 1200 K is considered appropriate for large wildland fires. But, changes over time in this temperature have been reported by several studies [20-22]. Two values have been selected: 873 and 1353 K. Table 6 displays the results for these different scenarios. These results show that it is very important to know the range of values of the model parameters that will correspond to fire behavior during periods of high fire potential. To ensure firefighter safety, a general rule-of-thumb could be to always select the scenario with the higher value of the radiative flame temperature. However, a systematic overestimation of the ASD would lead to a unjustified conservative and paralyzing approach.

Table 6.

ASD determination for 13 fuel models under a wind condition of 8 m/s (ε =0.9). The fixed threshold value is 7 kW.m^{-2}.

Type of fuel used by Rothermel's model	l_f (m)	γ (°)	ASD (m) with T_f= 873 K	ASD (m) with T_f= 1353 K
Short grass (1ft)	4.6	18	10.7	44.9
Timber (grass and understory)	5.6	23	13.2	53.3
Tall grass (2.5 ft)	6.2	26.5	14.6	57.8
Chaparral	8.7	40	19.8	71.8
Brush	5.9	25.4	13.9	55.5
Dormant brush, hardwood slash	5.6	23.2	13.2	53.3
Soutern rough	5.6	24	13.2	53.1
Closed timber litter	0.5	2.3	1.1	5
Hardwood (long-needle pine) litter	5.4	22.2	12.7	51.7
Timber (litter and understory)	7.0	31	16.4	63.2
Light slash	6.1	27	14.3	56.8
Medium slash	8.4	38.6	19.2	70.5
Heavy slash	9.6	43.8	21.4	75.5

5. Conclusion

This study proposed an improved solid flame model. The fire front was idealized as a solid flame front emitting thermal radiation from its side. The new formulation led to the establishment of a new criterion for estimating the ASD based on the fire font width. A simplified analytical expression was derived from the model, which allows determining the ASD for people as well as for houses or facilities from a simple-to-use formula. Only one parameter needs to be fitted to the solid flame model. A sensitivity analysis indicated that the parameters with a significant effect on the estimation of the ASD are the flame temperature (*Tf*) and the flame emissivity (ε). If the end-users select a flame temperature or a flame emissivity that are not representative of the actual fire front, the model could provide a bad estimation of the ASD, which would lead to incorrect and dangerous decisions.

In future works the challenge will be to study the range of validity of the assumptions used to derivate the model. Convective heat transfer and spotting have not been considered yet and their inclusion in the model would represent a very interesting challenge. Considering the considerable progress in heat flux measurement, a validation of this model with experimental data from outdoor fires would be quite desirable. This would allow developing a set of parameters to apply to different fire conditions.

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Appendix

Trigonometric properties

$$sin\theta = \frac{tan\theta}{\sqrt{1+tan\theta^2}}$$

If $\theta = arctanx$, the expression herein becomes:

$$\sin(\arctan x) = \frac{x}{\sqrt{1+x^2}}$$

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