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Couplage d'un écoulement simplifié à un modèle phénoménologique de propagation des feux

Coupling of a simplified flow with a phenomenological fire spread model

Albert Simeoni (1), Michel Larini (2), Paul-Antoine Santoni (1) and Jacques-Henri Balbi (1)

(1) ERT "Feux", SPE – CNRS UMR 6134, Campus Grossetti, Università di Corsica, BP 52, 20250 Corti, Corsica, France. Phone: 00 (33) 4 95 45 01 61, fax: 00 (33) 4 95 45 01 62.

Corresponding author : simeoni@univ-corse.fr

(2) ERT "Feux", IUSTI – CNRS UMR 6595, Technopôle de Château-Gombert, 5 rue Enrico Fermi, 13458 Marseille Cedex 13, France. Phone: 00 (33) 4 91 11 38 08, fax: 00 (33) 4 91 11 38 38.

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Résumé

Notre but à long terme est de proposer un simulateur de feux de forêt. Pour ce faire, nous avons développé un modèle phénoménologique de propagation. Nous l'avons ensuite fait évoluer afin de prendre en compte les transferts convectifs grâce à un écoulement simplifié. Dans ce travail, nous présentons de manière synthétique notre approche qui peut s'étendre à d'autres modèles phénoménologiques. Nous comparons enfin les prévisions du modèle à des expériences de laboratoire.

Abstract

Our long-range aim is to propose a forest fire simulator. To this end, we have developed a phenomenological model of fire spread. Then, we have improved it in order to take into account advective transfers thanks to a simplified flow. In this paper, we present in a synthetic way our modelling approach that can also be applied to other phenomenological models. Finally, we compare the model predictions to laboratory experiments.

Notre but à long terme est de proposer un simulateur de feux de forêt. Nous avons d'abord développé un modèle phénoménologique radiatif qui a été validé en laboratoire. Il s'est avéré mal représenter les propagations pour des pentes et des vents forts. Afin de l'améliorer, nous proposons de calculer un écoulement simplifié à coupler au modèle. Ce papier synthétise notre approche et présente ses améliorations. Le modèle phénoménologique de base repose sur l'équation d'énergie (1) dont les grandeurs sont moyennées sur l'épaisseur de la strate végétale [1]. Les termes du membre de droite de l'équation représentent respectivement un refroidissement du combustible dû aux transferts thermiques avec le milieu ambiant, un transfert d'énergie par diffusion, un apport d'énergie par combustion et un transfert d'énergie radiative de la flamme vers le combustible imbrûlé. Enfin, $\rho\, c$ représente la masse thermique surfacique du milieu combustible [1]. Le combustible s'enflamme à partir d'une température seuil T_{ig}, et sa masse décroît exponentiellement en suivant la loi la loi (2). t_{ig} étant l'instant où l'élément de végétal considéré s'enflamme (lorsque $T = T_{ig}$). L'apport d'énergie radiative de la flamme est supposé négligeable tant que la flamme n'est pas penchée vers le combustible imbrûlé et s'exprime par la loi (3) où le paramètre P est relié à la pente du terrain et au vent par des relations empiriques [2] (cf. équation 4). θ étant l'angle entre la normale au front de feu et la direction de propagation [1]. Nous avons supposé, pour simplifier le modèle, que le rayonnement n'agissait que sur une courte distance d devant le front de flamme. L'ensemble des paramètres du modèle est déterminé dynamiquement [1,2]. Chaque jeu de paramètres est propre à un combustible donné, pour une charge et une humidité données et reste le même pour toutes les configurations de pente et de vent [1].

Pour des propagations à plat et pour des pentes et des vents faibles on a pu observer un bon accord avec l'expérience [3,4], ce qui n'est plus le cas pour les feux soumis à des pentes et des vents plus forts. Nous avons donc fait évoluer le modèle afin qu'il prenne mieux en compte les effet du vent. Pour ce faire, nous nous sommes basés sur un travail précédent, dans lequel nous avons mené la réduction d'un modèle multiphasique [5]. Nous avons ainsi obtenu une équation de bilan d'énergie dont la forme est proche de celle du modèle radiatif. Les hypothèses de réduction les plus notables supposent l'équilibre thermique entre la phase gazeuse et les phases solides et un profil uniforme des variables d'état sur la hauteur de la strate de combustible (excepté pour la vitesse ascensionnelle des gaz). La confrontation entre l'équation obtenue et celle de notre modèle nous a conduits à proposer l'ajout d'un terme convectif dans l'équation (1) pour obtenir l'expression (5) [6]. Le terme ajouté représente l'énergie thermique transférée par la masse gazeuse traversant la couche de combustible. La vitesse horizontale du gaz varie, car d'une part le gaz se dilate dans la zone de combustion et d'autre part il y a perte de masse de végétal évacuée par le haut (cf. figure 1 en deux dimensions). L'équation modifiée contient deux nouvelles inconnues qui sont la vitesse débitante $V_{g,s}$ et la masse volumique ρ_g du gaz. L'originalité de notre approche consiste à proposer un calcul simple de l'écoulement tout en conservant les principales caractéristiques qui le pilotent. D'autres auteurs ont utilisé un terme équivalent pour traduire les transferts convectifs, mais la vitesse du gaz est soit égale au vent synoptique [7], soit donnée par une relation empirique [8]. Dans cette étude, nous nous sommes limités au cas d'un écoulement dans la direction de la pente (cf. figure 1), le cas bidimensionnel étant une généralisation de ce travail. On obtient ainsi le système (6) à (10), où δ est la hauteur de la couche de végétal, ϕ_{sl} est l'angle de pente et χ est un coefficient lié aux forces de traînée [9]. Le système est donc composé de l'équation d'énergie avec transferts convectifs (6), du bilan de masse multiphasique pour la phase gazeuse (7) et de l'équation (8), qui donne la vitesse du gaz perpendiculaire au toit de la strate combustible. Cette équation est obtenue par une résolution approchée de l'équation multiphasique de quantité de mouvement [9]. De plus, comme le vent active la combustion par apport d'oxygène, nous avons ajouté au modèle une loi empirique (11) de variation du coefficient γ en fonction de la vitesse V_{in} des gaz à l'entrée de la zone de combustion, où α et γ_0

sont des paramètres à déterminer. Pour valider notre approche, nous avons utilisé des expériences de laboratoire menées en soufflerie avec des litières d'aiguilles de *Pinus Pinaster*, sous des conditions combinées de pente et de vent [4]. Les données expérimentales sont : charge surfacique $s_k = 0{,}5\ kg.m^2$, épaisseur de la litière $\delta = 5\ cm$ et humidité des aiguilles 10 %. Les pentes varient de 0 à 15°, et les vents de 0 à 3 $m.s^{-1}$. Trois répétitions ont été réalisées pour chaque configuration de pente et de vent, fournissant trois vitesses de propagation. Pour le modèle, la distance d'action du rayonnement a été prise égale à $d = 0{,}01\ m$, la température d'ignition, $T_{ig} = 573\ K$, est issue de la littérature et les paramètres sont donnés en (12).

Les résultats du modèle sont donnés par les figures 2 à 4. La figure 2 met en exergue une amélioration très nette des prédictions par rapport au modèle radiatif. Ce qui confirme la nécessité de prendre en compte l'influence du vent de manière explicite, à la fois dans les transferts thermiques et dans l'activation de la combustion. En effet, les vitesses de propagation prédites sont en très bon accord avec l'expérience pour les vents considérés. L'apport de la prise en compte des transferts convectifs est mis en évidence par la figure 3. Nous pouvons constater que l'énergie reçue par le combustible imbrûlé devant l'interface d'ignition est bien plus importante pour le modèle amélioré que pour le modèle radiatif, ce qui explique l'augmentation des vitesses de propagation. De plus, aucun de ces deux transferts n'est négligeable devant l'autre (cf. figure 4). Cet effet a été mis en évidence dans d'autres études [10] et atteste de l'importance de la convection dans la propagation de feux soumis à des vents forts. Nous pouvons cependant remarquer que le préchauffage du combustible imbrûlé par rayonnement n'est que très peu pris en compte dans notre modèle (cf. figure 4). Ceci est dû aux hypothèses de modélisation qui font que l'énergie radiative est transférée de manière brutale, sur une courte distance ($d = 1\ cm$) devant le front de feu [1].

En conclusion, nous pouvons affirmer que l'étude que nous avons menée montre que le couplage d'un écoulement simplifié au modèle radiatif permet de mieux représenter la

dynamique du feu ainsi que les transferts et la production d'énergie dans le végétal. De plus, comme cet écoulement ne dépend pas directement de notre modèle, on peut envisager de le coupler à d'autres modèles phénoménologiques qui fournissent des champs de température. Enfin, ce travail ouvre de nombreuses voies pour l'amélioration de notre modèle. Tout d'abord, nous devrons nous attacher à décrire l'effet à longue distance du rayonnement. Ensuite, nous devrons passer à une description bidimensionnelle de l'écoulement dans la strate combustible. Enfin, une autre étape importante consistera à diminuer le nombre de paramètres à caler pour donner au modèle une plus grande généralité.

Introduction

Our long-range aim is to propose a forest fire simulator. Thus, we have to use a model that describes in a simple way the physical phenomena while providing the main characteristics of the spreading. Firstly, we have developed a radiative phenomenological model including a single equation expressed in temperature. This model has been validated thanks to fires of pine needle litters conducted at laboratory scale. Its previsions were in agreement with experiments for low slope and wind conditions. Conversely, with higher slopes and winds there was a poorer accordance. To circumvent this weakness, we propose a simplified flow model that can be coupled to radiative models in order to allow them to take into account advection in an explicit way. Then, we apply this approach to our model. To this end, we add a supplementary term of advective transfers in the equation of energy, and the simplified flow is used to calculate the inflow velocity of the gas across the fuel layer as well as the outflow of the combustion gases through the top of the layer. Then, we set an empirical law to take into account the stimulation of combustion due to the inflow of cold gases. This paper synthesises this aerothermal approach, presents the model predictions and the improvement brought by the simplified flow in comparison with the previous radiative model.

1. The radiative model

The model we started from is non-stationnary, radiative and two-dimensional (the fire spreads on a surface with two dimensions *x* and *y*) [1]. It is based on a single equation deduced from a global energy balance set in the fuel medium:

$$\rho c \frac{\partial T}{\partial t} = -k^*(T - T_a) + K^* \Delta T - Q^* \frac{\partial s_k}{\partial t} + R, \quad \text{with} \quad T = T(x,y) \tag{1}$$

The variables are mean values along the thickness of the fuel layer. The terms on the right handside of equation (1) represent respectively a cooling of the fuel due to the whole heat transfers with the ambient medium at temperature T_a, a diffusive transfer, an energy provided by the fuel combustion and an energy transferred by radiation from the flame to the unburned fuel. Finally, ρc represents the thermal mass per unit area of the combustible medium [1].

The fuel ignites when reaching a threshold temperature T_{ig}. Above this value, the fuel mass decreases exponentially and the heat produced by chemical reactions per unit mass Q^* is assumed constant. The fuel mass variation along time is written as:

$$s_k = s_{k0}\, e^{-\gamma(t - t_{ig})} \tag{2}$$

t_{ig} being the ignition delay, that is to say when $T = T_{ig}$. The fire front is defined as the isotherm which temperature is equal to the ignition temperature of the fuel $(T = T_{ig})$.

Concerning the radiative heat provided by the flame, we supposed that it is negligible as long as the flame is not titled in the direction of the unburned part of the fuel (for fire spreads under no slope and no wind, downslope or back-wind conditions), thus we have $R = 0$. For upslope and/or upwind conditions, this term is expressed by a Stefan-Boltzman law:

$$R = P \sigma T^4 (x - d, t) \tag{3}$$

The flame temperature is supposed equal to that provided by the model [1]. Parameter *P* is a function of the tilt angle between the flame and the surface of fire spread, which is provided by empirical relations expressed in terms of slope and wind [2]. So, we have:

$$P = P^* \cos\theta \, f(\text{slope}, \text{wind}) \tag{4}$$

θ being the angle between the normal of the fire front and the direction of spreading. It allows the model to represent the bidimensional fire front distortion [1]. We further assumed, for the sake of simplicity, that radiation acts on a short distance *d* ahead of the fire front.

The model contains five parameters to set (k^*, K^*, Q^*, γ and P^*). We dynamically identify the first four parameters thanks to laboratory experiments conducted for a fire spreading under slopeless and windeless conditions. To proceed, we use an experimental temperature curve versus time [1]. Each set of parameters corresponds to one given fuel with one load and one moisture content. This set remains constant for all the other slope and wind configurations. Parameter P^* is determined in a different way. It has been fitted thanks to different slopes under windless conditions. As we have established that it has a weak variation for the range of studied slopes, we used a mean constant value for the combined slope and wind conditions [2].

The results provided by the model were compared to experimental fire spreads [3,4] conducted through pine needles litters at laboratory scale. For slopeless and windless spreads, the model previsions match well the experiments (concerning the temperatures shapes versus time and the rates of spread), as the parameters were fitted for this case. For low slopes and low winds we also observed a good agreement with experimental results (for the experiments considered, up to 5° slopes and $2\, m s^{-1}$ winds). Finally, for fire spreads under higher slopes and winds the model proved to represent poorly the increase in the rates of spread.

2. The improved model

To circumvent the weaknesses previously mentioned, we improved the model to take into account explicitly the wind effects. In this section, we introduce an advective term in the energy equation of the model and we propose to calculate the inflow velocity of the gas due to the aerothermal effects in the fuel layer.

2.1. Improvement of the energy equation of the radiative model

In a previous work, we conducted a reduction of a multiphase model [5,6], and particularly of its energy equations in the gaseous and solid media. This reduction allowed us to set an energy balance with an expression near to that of the radiative model. To proceed, we set reduction assumptions. Among them the more relevant assume thermal equilibrium between the gaseous and solid phases, a constant specific heat of the gas at constant pressure and an uniform profile along the vertical in the fuel layer for the state variables of the system (excepted for the horizontal component of the gaz velocity). This led us, by comparison between the energy equations of the radiative model and the reduced multiphase one, to propose to add the advective transfers in equation (1). This procedure, which is detailed in [6], led to the following expression of the energy equation:

$$\rho c \frac{\partial T}{\partial t} + \delta \rho_g C_{p,g} \vec{V}_{g,S} . \vec{\nabla} T = -k^* (T - T_a) + K^* \Delta T - Q^* \frac{\partial s_k}{\partial t} + R \tag{5}$$

with: ρ_g, mean gas density value along the height δ of the fuel layer, $C_{p,g}$, specific heat of the gas at constant pressure and $\vec{V}_{g,S}$, inflow velocity component through the fuel layer.

The added advective term represents the heat transferred by the mass of gaseous products throwing the fuel layer. In this case, the horizontal gas velocity varies. Indeed, the gas expands in the burning zone and there is a mass loss of fuel through the top of the fuel layer (cf. figure 1 for the two-dimensional case). The modified equation contains two supplementary unknown variables which are the inflow velocity of the gas $\vec{V}_{g,S}$ and the gas density ρ_g. The original feature of our approach consists in proposing a simple procedure to calculate the gas flow while keeping the principal physical features involved in the gas phase. Indeed, other authors have also taken into consideration advective terms, but the gas velocity $\vec{V}_g$ considered in these works was equal to the synoptic wind velocity [7] or was provided by an empirical law [8].

One can note that equation (5) does not contain neither term representing the mass flow of gas through the top of the fuel layer nor term expressing the energy variation due to the gas composition variation. This lack of representation is confirmed by the multiphase model reduction for the which we obtain, by setting the hypotheses cited here before, a single equation of energy with a form equivalent to expression (5) [6]. Furthermore, an advantage of this approach consists in not introducing a supplementary parameter to set, if we calculate the inflow velocity $\vec{V}_{g,S}$ of the gas. Moreover, the reduced multiphase procedure can allow us to avoid the dynamical fitting of the model parameters by determining them from the fuel physico-chemical properties. This is one of our aims for the future model improvement, but we limit the present study to the development of a simplified flow and we will keep in the model the current set of parameters. So, we have to calculate now the inflow gas velocity present in the term of advection.

2.2. The simplified flow

As a first step, we limited our approach by considering a flow in the direction of the slope (no *y*-component for the flow, as shown in figure 1). Indeed, this configuration corresponds to that of the experiments considered for the testing of our approach [4]. The two-dimensional flow represents an extension of this study. We obtain the following system:

$$\rho c \frac{\partial T}{\partial t} + \delta \rho_g C_{p,g} V_{g,x} \frac{\partial T}{\partial x} = -k^*(T - T_a) + K^* \frac{\partial^2 T}{\partial x^2} - Q^* \frac{\partial s_k}{\partial t} + R \tag{6}$$

$$\frac{\partial \rho_g V_{g,x}}{\partial x} + \frac{\rho_g V_{g,z}(\delta)}{\delta} = -\frac{1}{\delta}\frac{\partial s_k}{\partial t} \tag{7}$$

$$V_{g,z}(\delta) = \chi \sqrt{2\delta \left(\frac{T}{T_a} - 1\right) g \cos\phi_{sl}} \tag{8}$$

$$\rho_g T = \rho_a T_a \tag{9}$$

$R = 0, s_k = s_{k0}\, e^{-\gamma(t - t_{ig})}$ for a burning cell
$R = P\sigma T^4(x - d, t), s_k = s_{k0}$ for an inert cell ahead of the fire front
$R = 0, s_k = s_{k0}$ for an unburned cell elsewhere

With the following initial and boundary conditions:

$$\begin{array}{ll} T = T_a & \text{at the boundaries far from the fire} \\ V_{g,x} = V_\infty & \text{at the inflow of the domain} \\ T(x,t=0) = T_a & \text{for an unignited cell at time 0} \\ T(x,t=0) = T_{ig} & \text{for an ignited cell at time 0} \end{array} \qquad (10)$$

were δ is the height of the fuel layer, ϕ_{sl} is the slope angle and χ is a coefficient representing the drag forces [9]. These parameters are known, and the adding of a simplified flow coupled with the model does not cause the introduction of new parameters to set. The system is now constituted by the equation of energy including advective transfers (6), the multiphase mass balance for the gas phase (equation 7) and equation (8) which allows to determine the component of the gas velocity perpendicular to the top of the fuel layer. This form of the upward velocity is obtained thanks to an approached resolution of the multiphase momentum equation for the gas phase in this direction, considering the drag forces [9]. If the drag forces are neglected, χ parameter is equal to unity. So, to keep a simple expression for the model, we used an aerothermal approach which takes into account solely the influence on the flow of the hot gases elevation in the flame.

Furthermore, the increase in the thermal transfers does not represent the only influence of wind. So, we set an empirical law for the γ variation, in order to take into account the stimulation of combustion by the wind (which brings oxygen in the combustion area). So, the γ parameter does not keep a constant value as it did in previous works [9], and we have:

$$\gamma = \alpha V_{in}^2 + \gamma_0 \qquad (11)$$

where V_{in} represents the inflow velocity of the gas in the combustion zone and α is an empirical coefficient.

3. Results and discussion

To test the new model in the case of spreads under wind conditions, we used the experiments carried out at the IST of Lisbon [4]. They were conducted through pine needle beds of *Pinus Pinaster* in a wind tunnel and under combined slope and wind conditions. The experimental conditions are: fuel load $s_k = 0{,}5\, kg\, m^{-2}$, depth of the needle bed $\delta = 5\, cm$ and needles moisture content 10 %. The slope can vary from 0 to 15° and the wind from 0 to $3\, m s^{-1}$. Three repetition were conducted for each slope and wind configurations, providing three values of the fire rate of spread. Concerning the model, the prevalence distance of radiation is taken equal to $d = 0{,}01\, m$ and the ignition temperature is given in the literature equal to $T_{ig} = 573\ K$ for pine needles. We used the following set of parameters [9]:

$$k^* = 560\, J\, m^{-2}\, K^{-1}\, s^{-1},\ K^* = 83.7\times 10^{-3}\ J\, K^{-2}\, s^{-1},\ Q^* = 21.2\times 10^{6}\ J\, kg^{-1},$$

$$\alpha = 0{,}0275\, s\, m^{-2},\ \gamma_0 = 0.19\, s^{-1},\ P^* = 51.9\times 10^{-6}\ J\, m^{-2}\, K^{-4}\, s^{-1} \text{ and } \chi = 0.25 \qquad (12)$$

Figure 2 represents the experimental and simulated rates of spread (radiative model and improved model), for different winds and for a 5° slope. One can notice that considering a simplified flow brings to a valuable improvement of the model predictions in comparison with the radiative model. Indeed, the predicted rates of spread are in good agreement with experiments for the considered wind velocities, when the radiative model underpredicts them. Furthermore, considering that the combustion is stimulated by the entrance of fresh gases in the combustion zone allows the model to predict better the increase of the rates of spread with the increasing wind (in comparison with [9] that assumed that γ remained constant).

The improvement due to the modelling of advective transfers is brought to the fore by figure 3 which represents the spatial distribution of the energy exchanged in the fuel layer, at a given time for a $3\, m s^{-1}$ wind. Indeed, one can notice that the energy received by the unburned fuel ahead of the ignition interface is more important for the improved model than for the radiative one. It explains the increase in the rates of spread. Furthermore, as shown in figure 4, which represents the advective and radiative transfers contribution in the fuel layer for the improved model under no-slope and $3\, m s^{-1}$ wind conditions, none of them is negligible in comparison with the other. This effect has been observed in other studies [10] and it confirms the necessity of modelling explicitly advective to represent well the fire dynamics under strong wind conditions. Nevertheless, it should be noticed that the long-range preheating due to radiation is not provided by our model (cf. figure 4). This is a consequence of the modelling assumptions that involve radiation to be transferred in an abrupt manner, on a short distance $\left(d = 1\,cm\right)$ ahead of the fire front [1].

Conclusions

The present study has shown that the modelling of a simplified flow allows our model to represent better both the dynamic of the fire spread and the heat transfers in the fuel layer. Furthermore, as the simplified flow does not depend directly on our model, one can contemplate to couple it with other phenomenological models which provide a temperature field. On the other hand, the stimulation of combustion induced by the wind has been taken into account and permits to represent better the combined high slopes and winds effects on fire spread.

This work also permitted us to determine in which direction our future efforts in improving our model have to be conducted. Firstly, we will have to describe the long-range effect of radiation that must have an important influence on the spreading. Then, we will have to describe the flow in the fuel layer in a two-dimensional way. Finally, an other important step in the improvement of the model will consist in determining its parameters from the fuel physico-chemical properties, which will bring it more general.

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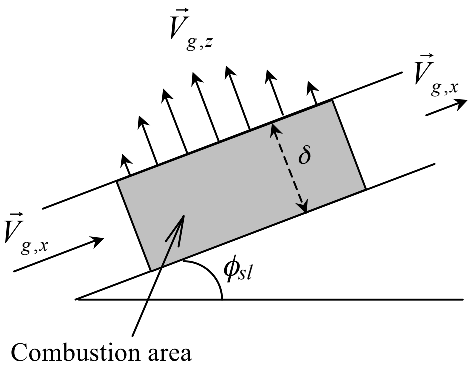
Figures



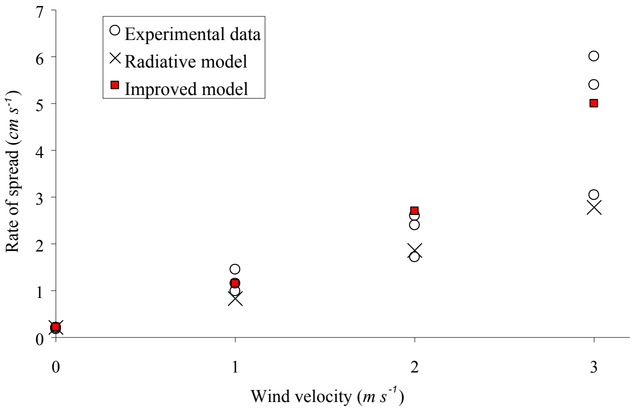
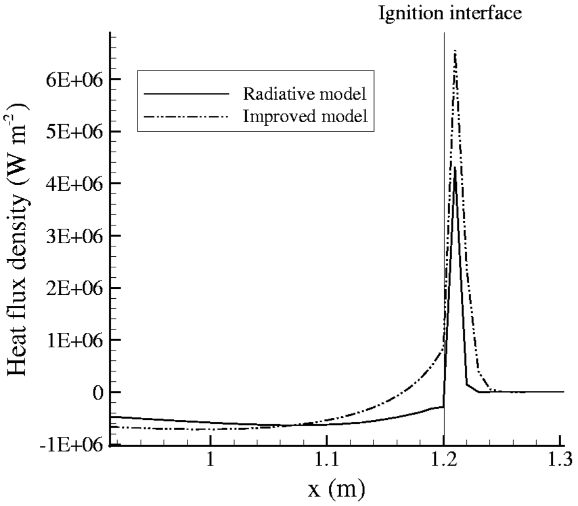


Figure 1: Schéma de l'écoulement dans la couche de combustible

Figure 1: Schema of the flow in the fuel layer

Figure 2: Vitesses de propagation expérimentales (3 répétitions) et simulées pour une pente de 5° et différents vents

Figure 2: Experimental (3 repetitions) and predicted rates of spread for a 5° slope and different winds



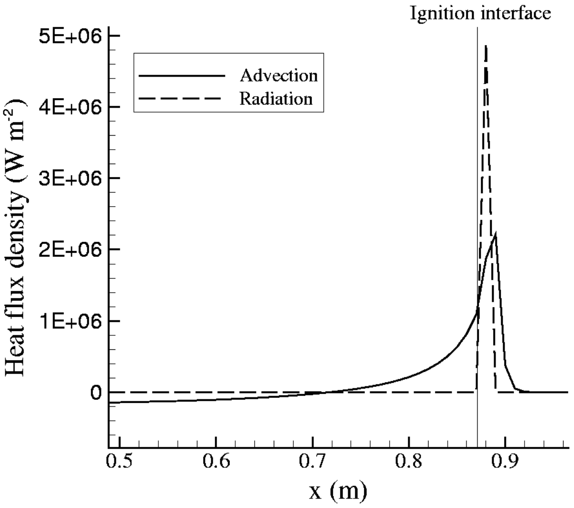


Figure 3. Somme des transferts thermiques dans le combustible, donnés par le modèle radiatif et le modèle amélioré, pour une pente nulle et un vent de 3 $m.s^{-1}$

Figure 3. Sum of heat transfers in the fuel layer for both the radiative and the improved models, under no-slope and 3 $m\ s^{-1}$ wind conditions

Figure 4. Transferts thermiques dans le combustible par convection et rayonnement, prédits par le modèle amélioré pour une pente nulle et un vent de 3 $m.s^{-1}$

Figure 4. Advective and radiative transfers in the fuel layer, provided by the improved model under no-slope and 3 $m\ s^{-1}$ wind conditions