Second law analysis of wildfire evolution under wind and slope effect

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Elisa Guelpa[1], Vittorio Verda[2]
[1] Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy - elisa.guelpa@polito.it
[2] Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy – vittorio.verda@polito.it

Abstract

This paper aims at investigating possible relations between the fire main driving forces of forest fires, particularly wind speed and ground slope, and the corresponding entropy generated. Second law analysis is applied to an uncontrolled fire event in a grassy area (grassfire). The system is first studied through a full physical numerical model, with the aim of collecting local data in the same way that would be achieve through pervasive sensors. Simulations are conducted considering separate contributions of different wind speeds and terrain slopes. Three terms that contribute to the entropy generation are separately calculated and analyzed in the parametric simulations: mass transfer term, heat transfer term (heat losses) and transient term. The first term is globally large, especially when large wind velocities and terrain slopes are considered. This contribution is highly variable during the fire evolution, with oscillations of about ± 120% with respect to the mean value. The second term is also large and becomes dominant in the case of lower driving forces. Its behavior is more regular, with oscillations of the order of ± 40% with respect to the mean value. The third term, instead, gives an almost negligible contribution. Results also show that the total entropy generated during the fire propagation increases with increasing slope or wind speed, which also means with increasing fire propagation velocity. In the range of data considered in this analysis, entropy generated is well approximated by a logarithmic evolution as the function of propagation velocity, with a mean error of about 5%.

Keywords: Second law analysis, forest fire, wildfire modeling, entropy generation, WFDS

1. Introduction

During decades, wildfires have produced significant losses in terms of human lives and ecological and economical damages. To contrast the effects of wildfires, scientists have worked with the aim of understanding forest fire dynamics and elaborating a number of models able to predict the fire evolution. Modeling wildfires is a challenging task due to the complexity of the phenomena involved and the large areas that might be involved. The models proposed in the literature can be divided, according to Sullivan (2009), into three main groups: physical models (e.g., Sullivan 2009a, Morvan 2011), empirical models (e.g., Rothermel1972, Sullivan 2009b) and mathematical models (Sullivan 2009c,). Physics-based models, need very high computational resources. Further researches are needed in order to reduce the time and the computational resources required for the simulations (Hanson et al 2000, Morvan et al. 2009, Guelpa et al 2016) and thus to make them usable as operational tools for managing emergencies. Several reduction techniques have been proposed in literature with this goal, see for example (Schilders et al 2008, Guelpa et al 2016, Sciacovelli et al 2014). Empirical models are still affected by some limitations, such as the low precision when particular conditions occur, the incapability dealing with fire retardants effects, etc. (Morvan and Dupuy 2004; Cruz and Alexander 2013). Further analysis of fire behaviour is thus required for better knowledge of propagation and help emergency management.

The present work aims to propose the application of second law to the grassfire evolution. The ultimate goal is to obtain a rational quantification of the effects due to wind and slope when they occur separately and combined. Entropy generation is an approach that has been widely used in literature with the aims of improving energy system performances (Yilmaz et al 2001, Bejan 2001, Guelpa et al 2013). Two principles have been formulated in this framework: principle of minimum entropy generation and principle of maximum entropy generation. Even if these two principles seem to be contradictory, it has been shown that, being the difference mainly related with the conditions that are imposed (e.g. the problem boundary conditions), one it has been shown that is the direct consequence of the other (Martyushev and Seleznev 2006, Lucia 2012). The principle of minimum entropy generation has been applied to the design of energy systems involving heat transfer processes (Bejan 1996, Sciacovelli et al 2015). Maximum entropy generation has demonstrated to be the basis for some natural processes evolution (Kondepudi and Prigogine 1999). Among these phenomena, it is worth citing vegetation growth, organ size, fluid flow in ducts, animal locomotion and social organization (Paulus and Gaggioli (2004), Bejan and Lorente (2010), Bejan and Lorente (2013), Baldwin (2009)). Furthermore, radiation, turbulence and convective heat transfer, which are all involved in grassfire evolution, are known to occur in a way that minimize or maximize entropy production (Martyushev and Seleznev (2006)). This issue encourages the application of entropy generation analysis to fire propagation in vegetative fuels.

In this paper, fire propagation has been analysed in different wind and slope conditions. It is common to consider wind speed and upslope terrain as the two main factors affecting the propagation velocity (Viegas 2004). A vector composition approach is usually adopted in combination with the 1D Rothermel model (Rothermel 1983) in order to take into account how wind and slope orientations affect fire propagation and thus obtain a 2D evolution. Such approach, as reported in Viegas 2004, is not sufficiently supported by experimental data and still requires investigation, especially in relation with flashover phenomena (Viegas and Simeoni 2011). The application of the second law to the control volumes, crossed by the fire front is here proposed as a possible alternative. In general, the approach could be used in order to overcome the limitations of the approaches based on the superimposition of the effects. Generation of entropy during a grassfire is studied. The entropy generation analysis has been performed through a lumped parameter approach on the selected control volumes. Different scenarios with parametric variation of the wind speed in no-slope terrain and others with parametric variation of the slope angles in no-wind conditions are compared. The different terms concurring to the entropy generation have been analysed in the different conditions in order to show how they are affected by the variation of the driving forces. Using this approach a relation between the entropy generation and the fire propagation velocity is obtained.

2. Methodology

2.1. System Description

The system analysed in this work is a grassland fire occurring in an herbaceous field, as represented in Fig. 1. The considered domain is 16 m long and 16 m wide. The domain includes an up-slope terrain entirely covered by fuel. A heat source is imposed in an area of 1m wide and long as the width of the simulation domain. The total ignition area is 14 m^2. In this area, a Heat Release Rate (HHR) per unit area of 1 MW/m2 is imposed, as a constraint for about 30 s. The characteristics of the fuel, referred to published work, (Mell et al 2007, Albini 1976, Scott and Burgan 2005) are reported in Tab. 1.

The second law analysis has been applied to different cases. Five different scenarios with different values of wind speed and terrain slope have been considered. In these scenarios, the direction of both the wind and the upslope terrain is E, therefore the fire front mainly propagates perpendicularly to the ignition area. The various scenarios are summarized in Tab. 2. The scenarios include the presence of wind or slope separately. This allows the analysis of the independent contributions of the two main driving forces to both the fire propagation and the entropy generation. The values of wind and slope have been selected as representative of a wide range that can be encountered in real grassfires. Referring to Tab. 2, cases from A to I are compared in order to analyze the influence of the driving forces on fire propagation trough the entropy generated.

As reported in Fig. 1 various sensors have been installed in the domain with the aims of gathering data useful for the analysis. Fire front propagation has been considered as lasting 100 s which is the time period requested to the fire front to reach al least an half of the domain in case A.

2.2. Entropy generation analysis

The second law analysis has been applied trough a lumped parameter approach to a control volume located in the centre of the fire front. The control volume has been selected as follows:

- height = fuel height
- width =1 m
- length= the space that the fire front crosses during the thermocouple measurement period.

The second law applied to an open and unsteady system (see for example Moran et al.2010) exchanging heat with the surrounding can be evaluated as reported in Eq. 1.

$$\Sigma = \frac{\Phi}{T} + \sum_J G_j\, s_j + \frac{\partial S}{\partial t} \tag{1}$$

The first term on the right-hand side (Term 1) represents the entropy generated through the heat exchanged across the external faces. In grassfire propagation, the heat flux includes both convection and radiation. Convective heat exchange (see for example Bergman et al. 2011) with the surroundings can be expressed as reported in Eq 2.

$$\Phi_{conv}(t) = \frac{h}{d}(T(t) - T_{env}) \tag{2}$$

The radiation heat exchange (see for example Bergman et al. 2011) is involved in two different steps:

1. when the fire front approaching the thermocouples and the radiative flow enters the control volume from surrounding volumes (first right-end side term of Eq. 3);
2. when the fire occurs in the control volume and the radiative flow exits towards other volumes (second right-end side term of Eq. 3).

$$\Phi_{rad}(t) = -\,\mathrm{A}_1 F\, \varepsilon\, \sigma(T_{max}(t)^4 - T_{env}{}^4) + \mathrm{A}_2\, F\, \varepsilon\, \sigma(T(t)^4 - T_{env}{}^4) \tag{3}$$

The second term on the right-hand side (TERM 2) of Eq. 1, includes the contribution of the mass flow rates which enters and exits the surfaces of the control volume. The mass flows are mainly due to the combination of the wind and slope effects. Slope in models for fire propagation is usually considered, as an equivalent wind. In this paper, the contribution of the slope module is evaluated trough the effects that wind and slope produces on the rate of spread. In particular, the equivalent wind related to a certain slope is obtained as the wind speed which produces the same rate of spread.

The entropy related to the entering and the exiting mass flow rates is evaluated by means of the measured temperature values, according to Eq. 4. Temperature evolution are obtained by numerical simulation, using the 3D model described in section 2.3. The temperature at the boundaries of each control volume are selected trough an upwind approach (Ferziger and Peric 2012).

Temperatures at the forward and backward boundaries are evaluated through a travelling wave assumption. The concept of travelling wave is based on the idea that the temperature has a 1D profile which moves in a time step at the velocity c without being modified. This means that in a time step its position is shifted from x to x-c·Δt. Following this assumption the temperature at the backward cell is evaluated considering that temperature is the same of the cell where the thermocouple is located, but shifted ahead in time of a quantity equal to the time spent by the front to travel a cell. The same is done for the forward cell, shifting the time back.

The third term on the right-hand side (TERM 3) of Eq. 1 includes the contribution of the entropy variation in time within the control volume. The term is computed as reported in Eq. 4:

$$\frac{\partial S}{\partial t} = mc\,\frac{\partial T}{\partial t} \qquad (4)$$

The entropy generation analysis has been conducted until the end of the first part of the transient, when the temperature reaches the first peak, in order to take into account for fire propagation only. The three terms on the right-hand side of Eq. 1 can be either positive and negative, while the total summation must be positive.

2.3. Model Description

Data essential for conducing the second law analysis are obtained via numerical simulations performed using the software Wildland Fire Dynamic Simulator (WFDS) developed at NIST (Mell et al 2007). WFDS is a three-dimensional simulator which solves the governing equations for buoyant flow, heat transfer, combustion and the thermal degradation of vegetative fuels. Turbulence problem in gas-phase is solved by the LES approach (large eddy simulation). WFDS provides a 3D distribution of the thermodynamic quantities and allows one to observe the evolution of the fire front in time. WFDS has been validated for both grassland fire and crown fire, as reported in Mell et al 2007 and in Mell et al 2009.

WFDS allows managing the domain conditions as follows:

1. wind velocity is set imposing a certain flow through an open face;
2. upslope terrain is set managing the gravity vector components;
3. thermo-fluid dynamic variables are monitored installing some virtual sensors in the considered domain.

The local temperature evolution is obtained through installing fictitious thermocouples all along a grid.

The considered domain and the cell dimensions are reported in Fig. 1b. The domain height selected is 12 m with the aims of taking into account also phenomena taking place in the area above. The grid dimension is 0.2 m Each entire simulation lasts about 8 hours on a single 3.3 GHz CPU.

3. Results and discussions

Fig. 2 reports the temperature evolution collected by the fictitious thermocouples in the central point of the fire front varying the terrain slope, with no wind (CASES A, B, C, D, E). In contrast, in Fig. 3

the wind speed has been varied considering a flat terrain (CASES A, F, G, H, I). The temperature evolutions present several similar aspects:

- The maximum temperature values above the fire are between 800 and 850 °C.
- The temperature during combustion varies continuously between 850 °C and a value in the range between 150°C and 500°C. These strong fluctuations are indicative of the high turbulence phenomena occurring during the propagation of the fire front (Silvani and Morandini 2009).

The temperature evolutions also differ to some extent:

- in the cases characterized by high wind speed and slope larger fluctuations occur. The mean temperature variation between consecutive times captured by the thermocouples is 18 °C in CASE A and increases until about 40 °C in case of high wind and slope values. In particular, temperature fluctuations are longer in the case of wind as the driving force than in the case of up-slope terrain (CASES B, C, D, E). In the cases affected by wind, temperatures reach quite low values, around 200°C - 300°C.
- temperature evolves differently when the propagation occurs (i.e. during the increase in temperature). The maximum before the front arrival is close to the environmental temperature for small wind and slope. This value becomes about 100°C when large wind and slope values occur. This characteristics particularly affects the entropy generated during the ignition period.
- temperature is remains high for longer periods (from 45 s in the CASE A to about 60 in the cases E and I)

Fig. 4 reports the evolution in time of the three terms on the right hand side of Eq.1. Term 1 increases with increasing temperature. This is due to the convective losses, which are the highest fraction of the losses (Guelpa and Verda 2017). The maximum value in the evolution of Term 1 is quite similar in all the considered cases, except for CASE A. An important point is that the most up-sloped terrains lead to an increase of Term 1 in the period immediately before the front arrival. In addition, the ramp tends to begin before as the slope increases. Similar anticipation in the ramp occurs with increasing wind speed values. This is due to temperatures over 100°C occurring in the period before the front arrival; such period is wider and characterized by higher temperatures, with high wind speed and slope values.

Entropy generation due to mass flow rates (Term 2) is always zero when no wind and no slope occur. This is because the equivalent wind (i.e. the sum of wind and the equivalent wind due to slope) is zero and thus the contribution of natural convection. In all the other cases (B to I), the evolution is fuzzy, with continuous temperature changes in the various boundaries of the control volume. Term 2 assumes the highest values in case of terrain slope 30 to 40° (D and E), which are among the cases with highest equivalent wind velocities. In particular, CASE D presents the highest peak (about 600 W/K) while CASE E has various high peaks between 300 W/K and 500 W/K. The evolution of the Term 2 in case of wind does not reach very high values and the contribution has often the same sign.

The Term 3 mainly depends on the temperature variations within the cell; the larger the temperature variation between two time instants, the largest the term is. Due to the discretization scheme selected, the evolution of the Term 2 can be in some cases similar to the one of the Term 3, in particular when the contribution of the lateral mass exchange is low.

The curves reported in Fig. 4 have been integrated in time with the aim of evaluating the overall contribution of each term during the entire propagation. Results are shown in Fig. 5 for both wind and slope variation.

Fig. 5 shows that the less significant term is the one related to the entropy variation in time (Term 3).

The other two terms are of the same magnitude. Term 1 is quite similar in all the considered cases, with both the driving forces (wind and slope). The mean value is about 172 J/K and variations are about ± 40% with respect to the mean value. Term 2 instead, considerably varies with the variation of the equivalent wind, because of the increasing mass flow rates crossing the volume boundaries (the mean value 255 J/K and variations of the values are in a range of ± 120% of the mean value). The values characterized by the Term 2 are higher in case of up-slope terrain, for equal equivalent wind velocity. This means that the temperature evolution occurring in the various boundaries causes a higher entropy generation due to mass exchange with up-slope terrains.

The three terms that form part of the total entropy generated are summed and compared. Results are reported in Fig 6, for the different cases considering separately slope and wind speed variation. The entropy generation is minimum in no-wind and no-slope conditions. Both the presence of wind and slope terrain produce an increase in the entropy generated. The larger the wind or slope angle, the larger the entropy generated during the propagation process (red arrows in the figure indicate the increasing wind velocity and slope angle).

In order to better highlight the relation between the entropy generated and the fire propagation velocity, the results of the test performed in this work are plotted in Fig. 7 in terms of such quantities. In particular, the entropy generated of all the considered cases (CASE A to I) is reported together with the propagation velocity. A comparison between the entropy generated and the propagation velocity of all the considered cases (both the light and the dark points) shows that entropy generation is higher when the propagation velocity is higher and vice versa. Even considering separately the data obtained when wind and slope occur (the light and the dark points), the evolution of entropy generation as the function of the propagation velocity appears as logarithmic in both cases. The evolution in this range of propagation velocity is very similar and the main error obtained considering a logarithmic evolution is about 5% using both the correlation obtained with slope and wind variation. The similar evolution of wind-driven and slope-driven cases suggests that not only the entropy generation is related to the propagation velocity but also that it is similarly related to the forces driving the propagation. The entropy generation, can thus be considered able of optimally take into account the contribution of both the main driving forces affecting the wildfire evolution, which are the up-slope terrain and the wind speed. All these results are obtained through the separate analysis of wind and slope effects; for analysis of the combined contribution of wind and slope in the fire propagation refers to Guelpa and Verda 2017.

4. Conclusions

The application of the second law to grassland fire events is performed through a lumped parameters approach. The fire front evolution has been first simulated using a physical full 3D model (WFDS). The software allows one collecting the evolution of the quantities in different points in the domain in the same way a pervasive experimental campaign would.
The influence of wind speed and up-slope terrain have been studied in terms of entropy generation variation. The evolution of the terms that form part of the entropy generated has been analysed: heat transfer, mass transfer and transient term. The first term related to heat transfer towards the ambient (heat losses) is quite constant in all cases, with deviations of about ± 40% with respect the mean value. The term associated with mass flow rates crossing the control volume significantly varies with the considered cases; variations are of the order of ± 120% respect the mean value. In particular, this term is small in the case of low wind velocity and small slopes, where the heat transfer term is instead large. In contrast, when wind velocity and slope increase, this term becomes the largest.

The contribution of the entropy variation in time it is quite similar in all the considered cases and it is almost negligible in all the considered cases, especially with high wind and slope.
The total entropy generated during the fire propagation is minimal (220 J/K) when no wind and slope occur and increases when the slope or the wind speed increase. A maximum value of 690 J/K is reached in the considered ranges.
The entropy generated within the process presents a logarithmic evolution as the function of the propagation velocity. The main error performed considering a logarithmic evolution is about 5%. Furthermore, the entropy generation seems to be able to excellently taking into account the contribution of both the presence of up-slope terrain and the wind speed which are the main driving forces affecting the wildfire evolution.

Nomenclature

c	:specific heat (J.kg-1.K-1)
F	:view factor
G	:mass flow rate (kg.s-1)
d	:fuel height (m)
h	:convective transfer coefficient, (W.m-2.K-1)
m	:mass, (kg)
t	:time, (s)
T	:temperature, (°C)
s	:specific entropy (J.kg-1.K-1)
S	:entropy, (W.K-1)
V	:propagation velocity (m s-1)
Greek letters:	
ε	:emissivity
σ	:Stefan-Boltzmann (W.m-2.K-4)
Σ	:entropy generation (W.K-1)
Φ	:heat exchanged (W)
Subscripts:	
max	:maximum
env	:environmental
rad:	: radiative
conv	: convective

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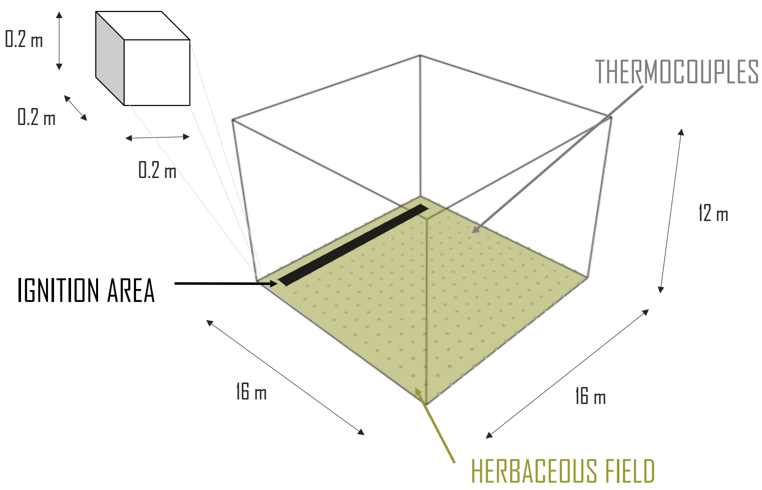


Fig. 1 System analysed decription with computational domain and discretization

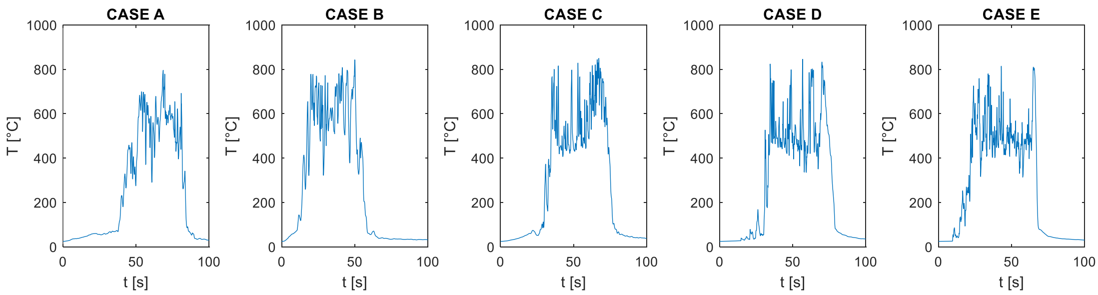


Fig. 2 Temperature evolution for no-wind condition, with increasing slope (from 0 to 40°)

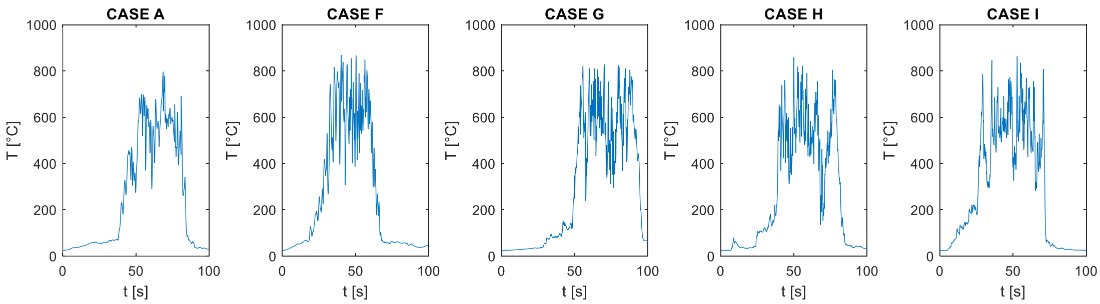


Fig. 3 Temperature evolution for flat terrain, varying wind (from 0 to 4 m/s)

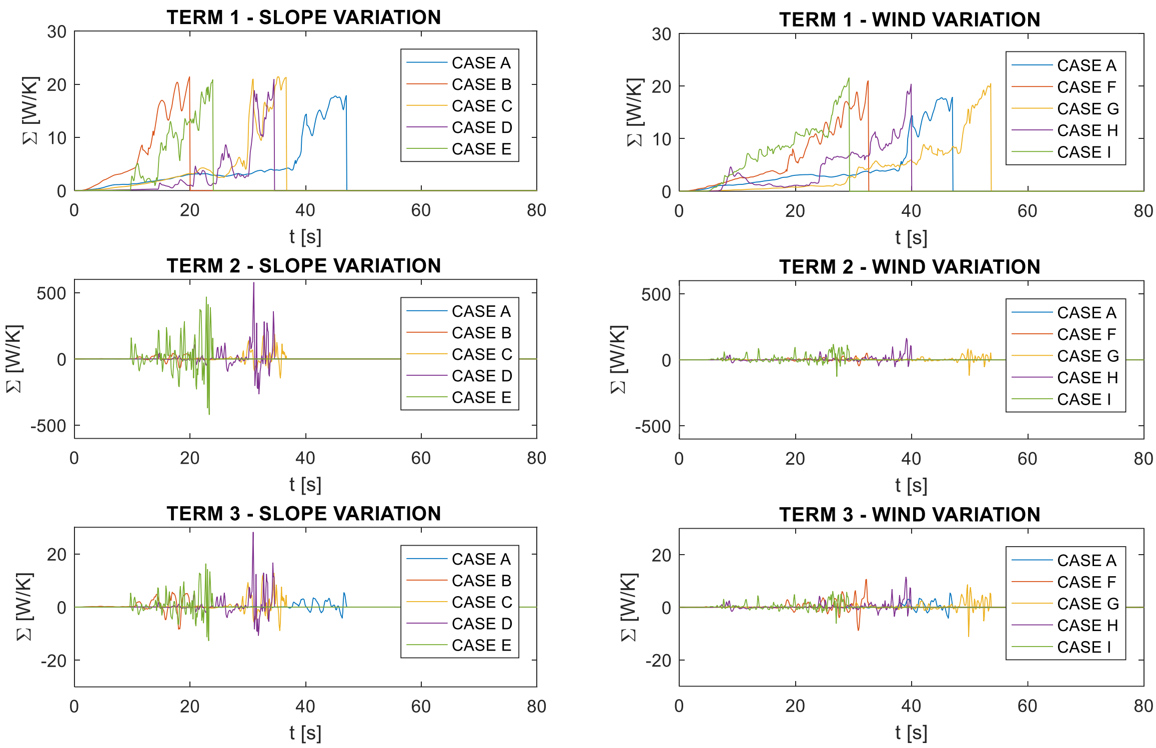
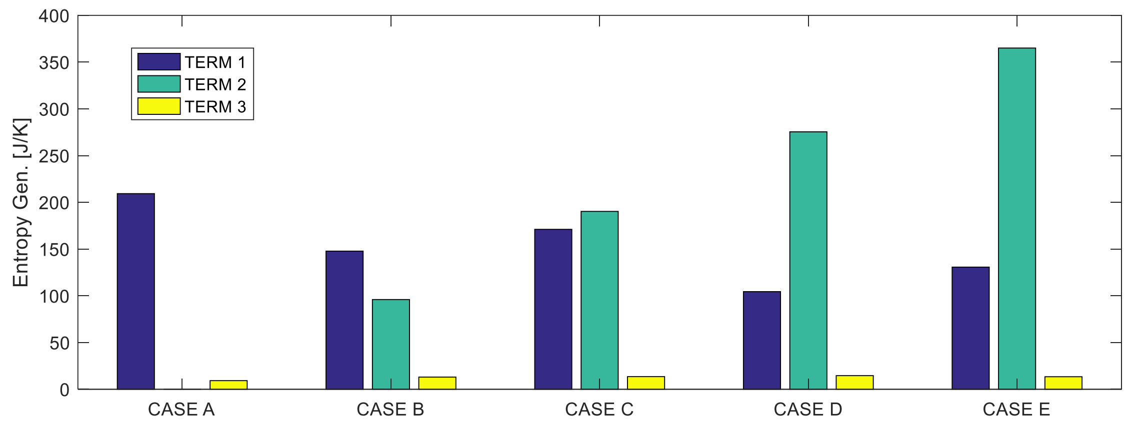


Fig. 4 Evolution of the terms that provide the entropy generation

a)



b)

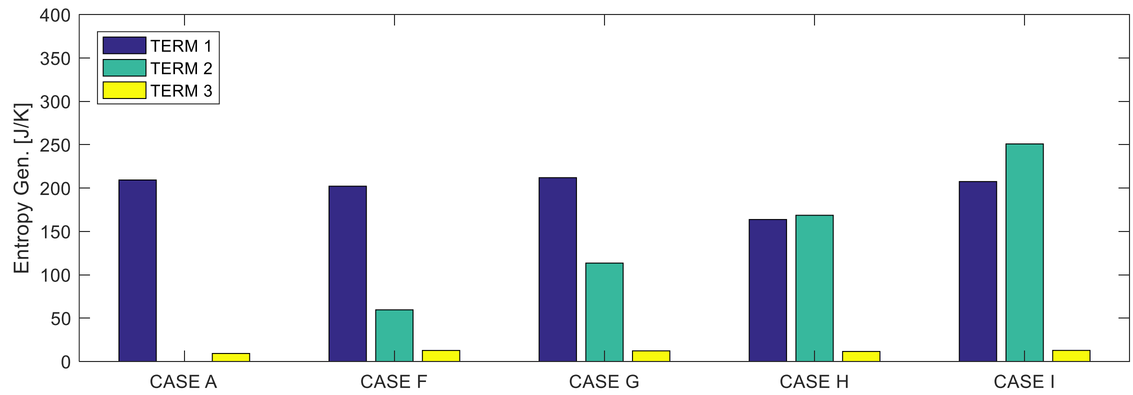


Fig. 5 Entropy generated trhough different processes. a) Slope variation b) Wind variation

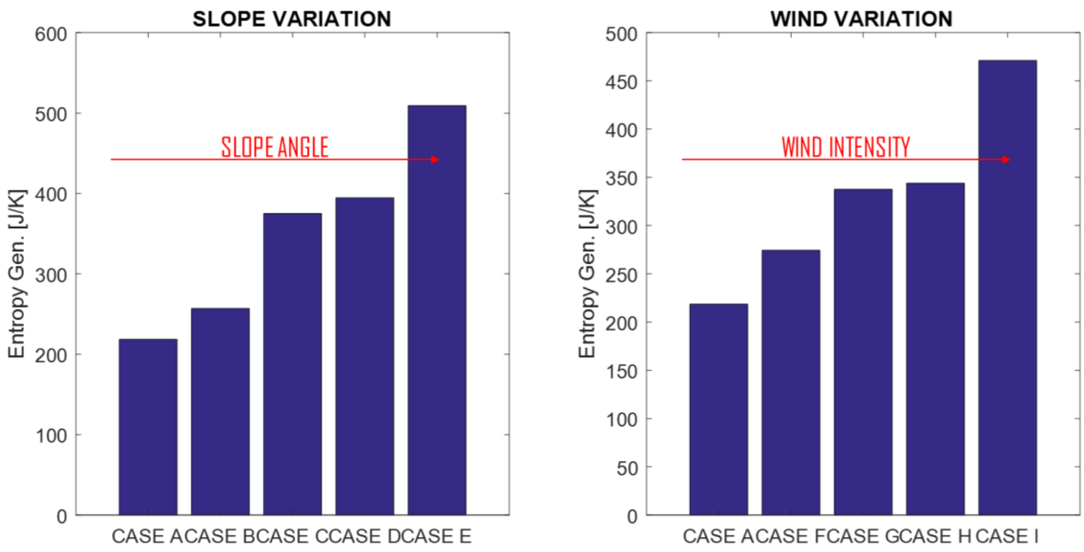


Fig. 6 Total entropy generated during the propagation process and propagation velocity

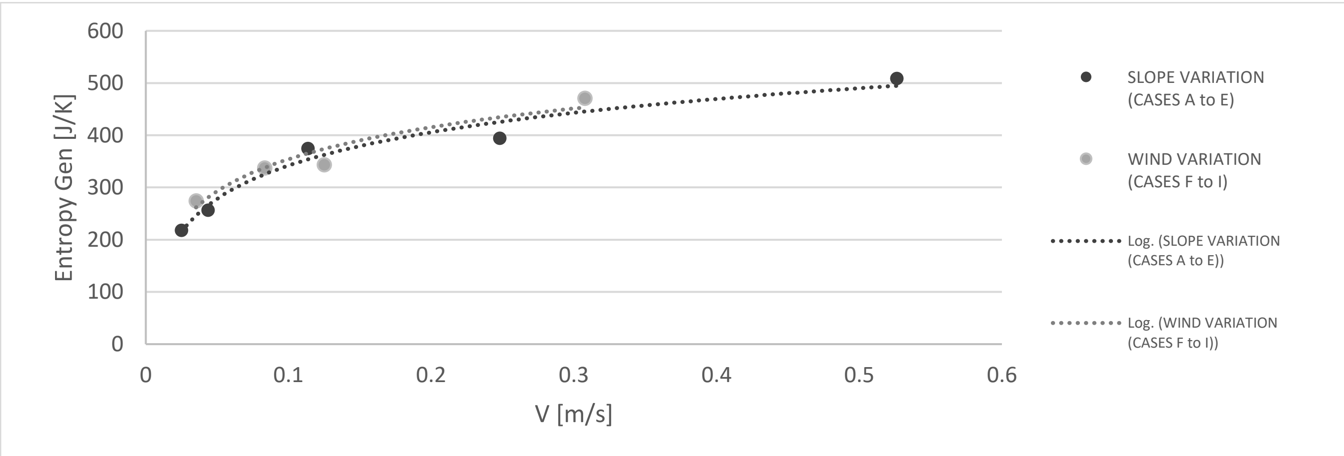


Fig. 7 Total entropy generated during the propagation for different propagation velocity V (CASES A to I)

Tab. 1: Vegetative fuel properties

parameter	***symbol***	***value***	***unit***
height	*h*	*0,2*	*m*
heat of combustion	*H*	*18500*	*kJ/kg*
moisture content	*x*	*0,04*	*-*
fuel load	*m*	*0,5*	*kg/m2*
char fraction	*c*	*0,1*	*-*
density	*ρ*	*512*	*kg/m3*
surface over volume ratio	*σ*	*4950*	*m-1*

Tab. 2: Vegetative fuel properties

CASE	**Wind speed [m/s]**	**Slope Angle [°]**
A	0	0
B	0	10
C	0	20
D	0	30
E	0	40
F	1	0
G	2	0
H	3	0
I	4	0