ISSN: 2634 - 8853

Journal of Engineering and Applied Sciences Technology

SCIENTIFIC Research and Community

Research Article

Open Access

Critical Behavior of an Extreme Fire "Fire Junction"

Khelloufi K[1,2]*, Baara Y[1], Raposo J[3,4] and Viegas XD[3,4]

[1]Professor, Superior School in Electrical Engineering and Energy ORAN ESG2E BP 64 ch2 Achaba Hanifi-USTO- Oran, Algeria

[2]University of Sciences and Technology Oran Mohamed Boudiaf, Physics Department, LEPM, BP 1505 El Mnaouer, Oran, Algeria

[3]Associated Researcher, Forest Fire Research Centre (CEIF / ADAI), University of Coimbra, Rua Pedro Hispano, 12, 3031-601 Coimbra, Portugal

[4]Professor, Department of Mechanical Engineering, University of Coimbra, Pinhal de Marrocos 3030-788, Coimbra, Portugal

ABSTRACT

In this paper the concept of extreme forest fire behavior denominated as Junction Fire is analyzed, this phenomenon consists of the interaction between two linear fire fronts which in their propagation intersect at a single point making a small angle between them. In their process of fusion, the phenomena of heat transfer by radiation and convection are extremely amplified due to the concentration of energy at the point of intersection. The concentration of energy and therefore the development of the powerful heat transfer mechanism induces an extremely high and sudden increase in the rate of spread until it reaches a maximum value after which begins to decrease. This behavior of the order parameter exhibits a non-universal phase transition. The analysis carried out in the ADIA-LEIF laboratories show that fires junction are a source of instability which leads to serious safety and management problems for those who are confronted with this type of forest fire. The results show that the fire junction spread exposed two main regimes; an initial acceleration phase characterized by a high rate of spread depends essentially on the initial angle between the fire fronts θ_0, which shifts during the evolution of the fire until the limit of creation of a single front of fire in a straight line explaining a decreasing phase. Nevertheless, the front fire dynamics depends both on the initial angle between the fire fronts θ_0 and on the slope ground αJ exhibiting a non-universal phase transition known in the literature.

***Corresponding author**

Khelloufi K, Professor, Superior School in Electrical Engineering and Energy ORAN ESG2E BP 64 ch2 Achaba Hanifi-USTO- Oran, Algeria. Tel No: +213 657644843.

Received: April 16, 2024; **Accepted:** April 18, 2024; **Published:** April 29, 2024

Keywords: Extreme Fire Behavior, Forest Fire Junction, Merging Fires, Dynamic Effects, Non-Equilibrium Phase Transition (Theory), Critical Exponents and Amplitudes (Theory)

Acronyms and Nomenclature

ADAI	Association for Development of Industrial Aerodynamics	-
LEIF	Forest Fire Research Laboratory	-
ROS	Rate of spread	[ms^{-1}]
D	Intersection point	-
θ_0	Initial angel between fire lines	[°]
α_J	Slopes Ground	[°]
(OX)	Reference axis	-
mc	Masse load	[$Kg.m^{-2}$]
W(L,t)	Fire interface width	[m]
Ly	Lateral system size	[m]
$X_i(t)$	The maximum fire position	[m]
B	the growth exponent	-
α	the roughness exponent (also called Hurst exponent)	-
z	dynamic exponent	-
t	Propagation time	[s]
τ	correlation time	[s]
$d_i(t)$	Average spreading distance	[m]
$\mathcal{R}^2$	mean square of the spreading distance	[m^2]

Introduction

Forest fires are phenomenon that occurs frequently in many regions of the world because the climatic conditions such as fuel drought and low soil water and often because humans activities as urban and electrical witch Importunely cause a huge damage on the environmental and socio-economical life.

In the last decade the occurrence of many large fires with massive and destructive area has increased due sometimes to the climate changes but often to the improper fire management and firefighting [1]. These events known as extreme fires are the worst scenario to fire fighter and socio-economic environment because it behaves in a surprising way from a moderated propagation with relatively low rate of spread to an explosive propagation with an unstable rate and heat release for a large time causing many losses of assets and humans live [2-4].

One of these scenarios was occurred in the vicinity of Canberra on 18 January 2003, where two fire fronts – MacIntyre Hut Fire and Bendora Fire – are merging and creating a massive tongue between them with extreme high rate of spread who destroy a part of the city of Canberra and several hectares of burned land. As documented in Doogan (2006) the merging of that fire fronts creates extraordinary junction fire phenomenon. The flanks of Bendora and McIntyre Hut's large fires merged on the undulating ground covered by grass, shrubs and groups of trees under a strong wind of the order of 25m.s^{-1} witch developed very rapidly (27km.h^{-1}) towards Canberra and even produced a tornado near one of its flanks (see Figure 1).

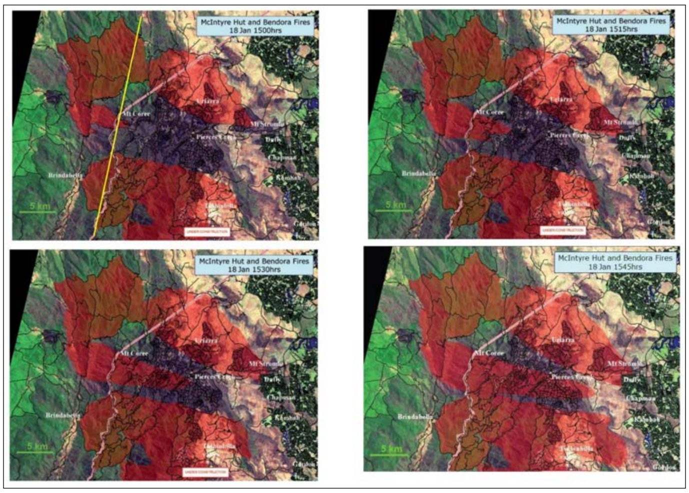

Figure 1: Evolution of McIntyres Hut and Bendora fires on the 18th January between 15.00h and 15.45h. Plates from Cheney report

In fact, the interaction between fires or parts of fires has been observed and studied in the past. The increase in intensity at junction zones have been documented empirically (McRae et al. 2005; Brown and Davis 1973) when dealing with prescribed burning refer to interactions of fire fronts and mention that large areas or even small areas of high energy fuels near edges are unsafe, because dangerous runs against one side may develop. In Johansen (1984) is observed that in prescribed burns with spot fires in pine stands in the Georgia coastal plain, early flank merger caused a rapid increase in width of the flame zone at the moving fire front and an attendant to increase in flame height. Although this description does not correspond strictly to our definition of 'Junction Fire', it is very likely that the situations observed by Johansen (1987) were similar to the ones described in the Junction Fires.

Whereas, Pyne (1984) say that in large fires are normal to have a proliferation of heads or columns but against this process of divergence, there is also a process of convergence: large fires absorb small fires; large columns incorporate small columns; multiple heads burn out intervening fuels and merge. Morvan et al (2011) studied the interaction between two parallel fire fronts and concluded that their interaction is felt only at a relatively short distance.

In a very detailed and exhaustive work about the interaction of fires Finney and McAllister (2011), it is noted that despite the relevance of the topic, there is no unified theory to explain fire interactions and spread dynamics and much of the research on fire interactions comes from laboratory experiments with artificial fuel sources.

However, the Canberra fire (2003) brought the motivation to better understand the problem of the interaction of fires and make rise for a set of studies and investigations of the spread dynamics of fire junction [5].

One of those studies was carried out by D. Viegas, J.Raposo at the forest fire center Portugal, where they investigate the rate of spread in such situation in laboratory and field scales, the investigation shows a transition of rate of spread ROS profile from an accelerated regime with extreme high values to a decelerated one [5]. Almost, this transition is strongly affected by the terrain slopes and the angel between fire lines. However, the investigation of fire fronts dynamics and growth interface morphology wasn't elaborate.

In order to identify the different crucial phenomenon appears on the spread dynamics during the junction, we focus our studies on the investigation of the growth morphology of fire interface within the same terrain parameters employed in D. Viegas, J.Raposo [5].

The classification of this crucial phenomenon with a known universality classes allows the modeling of the spread and reduce the numbers of factors influencing the fire by introducing a set of basic laws describing the microscopic reality of the growth. Which lead to a good management of firefighting and forest preservation in a minimum time [6,7].

As a fire is a movement that evolves in time and space, it was basically modeled by a simple percolation network with a deterministic long range interaction between burning and non-burning cells, beyond the nearest neighbors.

The later interaction introduces an interaction domain for each burning cell characterized by two joined half-ellipses, one in the main propagation direction, and the other in the opposite direction defining a characteristic length for ignition lc.

Each non burning cell located at a distance from the flame receives an amount of heat by radiation and convection process -the conduction process is being neglected- of:

$$Q_T = Q_R + Q_l + Q_c \qquad (01)$$

Where Q_R and Q_1 are respectively the radiation flow and loss, Q_c is the convection flow

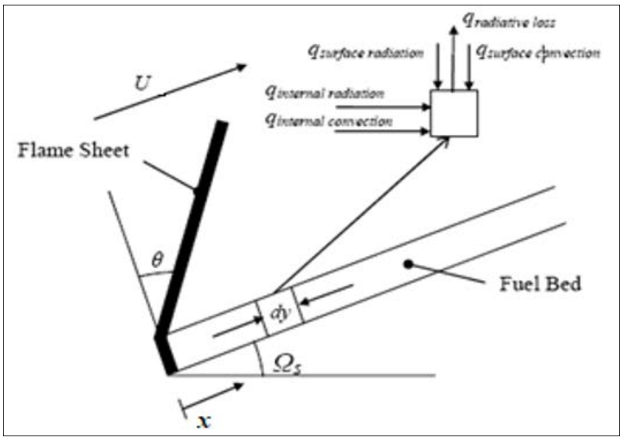

Figure 2: Representative Scheme of the Diffusion of the Flame

Model Description
Experimental Study
The idealization of the Canberra problem in a general and simple form, which can be studied, consists of a formulation in which two linear fire fronts which intersect at point D and make an angle θ_0=30° between them spreading over a bed of uniform fuel making an angle αJ (0°, 20° and 30º) with the horizontal, spread out so that the area between them burns completely [8].

The axis (OX) is supposed to be a line of symmetry of the fire and the intersection point D is the reference for the arrangement of the new fire front.

The initial fire fronts are made along the two large sides of the triangle (indicated as Flame 1 and Flame 2 in Figure 2)

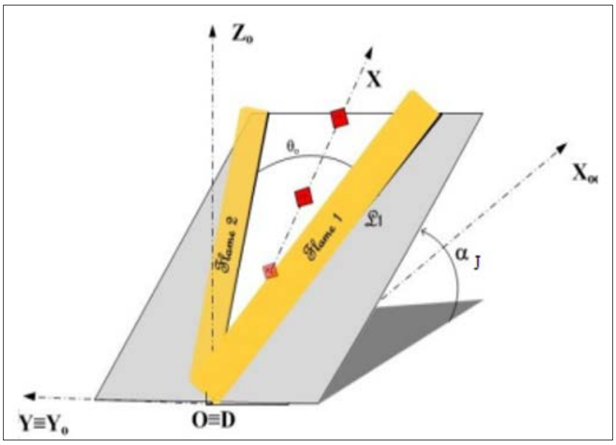

Figure 3: Schematic representation of the tests performed with the basic parameters

The measurement of the temperature was made with a multi-point system of 25 K type thermocouples, connected to a NI cDAQ-9174 that allows a synchronous data-logging. These 25 thermocouples (TC) were placed in a beam coincident with the (OX) axis with a constant gap of 20 Cm between them and a rate of acquisition of 1Hz. When the fire front arrives near the thermocouples the temperature suffers a gradual increase then when it reaches the thermocouple the temperature increases sharply and after the passage of the fire front it decreases. The time and the place of measurement is fixed when the temperature remains above a certain threshold (of 350ºC according to Xie et al. (2014)).

Infrared images were adapted to fellow the evolution of the position of the point D and the ROS because it allows a better temporal and spatial resolution of the processes. The IR images were recorded using an infra-red camera FLIR ThermaCam SC640. The acquisition rate was also 1Hz.

Using IR methodology, the position of the fire perimeter at given time frames was assessed and from these images the fire width interface at various times and positions were estimated

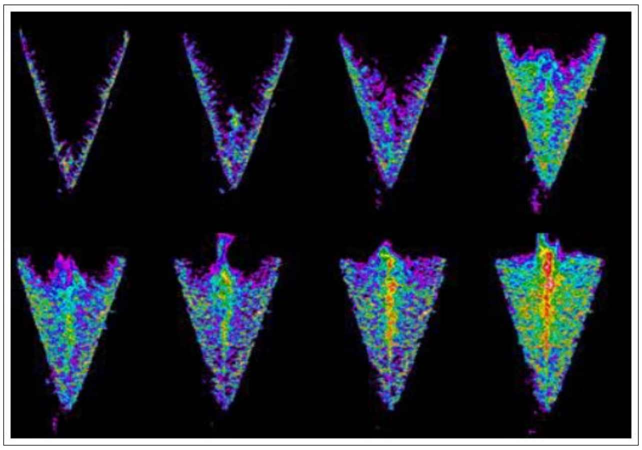

Figure 4: Infrared Frames from a Junction Fire Test. CF (30º, 30º). The Time between Frames is of 4s.

Front Dynamics
The front dynamics is characterized by a set of non-equilibrium critical exponents found by analyzing the behavior of the average width of the main fire interface built by the merging of two linear fronts giving by:

$$W(t, L_y) = \frac{1}{L_y}\left[\sum_i x_i^2(t) - \left(\sum_i x_i(t)\right)^2\right]$$

Where Xi (t) , is the maximum fire (burning cells) position in the (OX) axe obtained by fire perimeter given from the IR photos, L_y is the lateral system size, and denotes averaging over realizations (fire perimeter detection).

The front width is expected to behave as $W(t, L_y) \propto t^\beta$ being the growth exponent. For , the front width is expected to saturate and to scale as $W(t > \tau, L_y) \propto L_y^\alpha$, α being the roughness exponent (also called Hurst exponent) [9]. The system size L_y is increased until it reaches saturation. The correlation time also scales as $\tau \propto L_y^z$ (z is called dynamic exponent). These exponents are thus not independent (β = α/z) . This scaling picture is known as Family-Vicsek Scaling Ansatz [9,10].

Another way to determine the dynamic exponent z is the mean square of the spreading distance $\mathfrak{D}_i(t)$ from the initially ignited cell (intersect point D). It scales as [9]

$$\mathcal{R}^2 = \frac{1}{N(t)}\sum_i \mathfrak{D}_i^2(t) \propto t^z$$

Where N(t) is the number of burning cells at time t, and the dynamic exponent is z = 2/Z.

Results and Discussion
Fire front evolution was recorded with an infrared camera FLIR SC 660 camera over different condition and realisation. Focusing our attention on the advancement of fire fronts, a very slow lateral development can be observed by comparison with the areas close to the intersection zone. It is observed tha the major area between the fire lines is burned by the advance of the fire front near the intersection point of the two lines D. The overall spread of the fire lines consists of a rotation of each line so that the angle θ_0 between them increases until they become a straight line (θ_0 =180º).

The general development of the fire line(s) was analyzed by images (containing information about the whole movement of the fire line) taken during the experiments

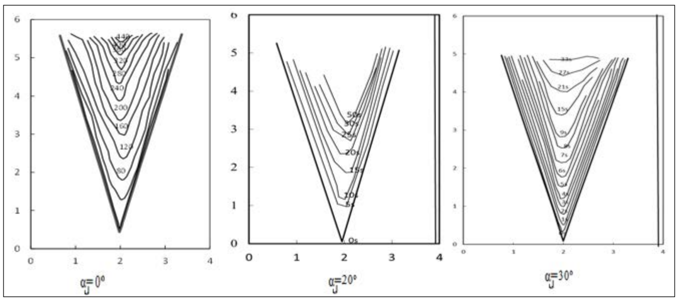

Figure 5: Evolution of the Fire Perimeter according to Data obtained with IR Images α_J=0º; α_J=20º and α_J=30º with θo=30º.

At the start of the merging process, the rate of spread of the intersection point D increases very rapidly, given the very high values of rate of spread that it can reach, in which is considered the acceleration phase. Even on a horizontal fuel bed, the displacement velocity can reach very high values. The behavior of the fire can be linked to a quick jump of the intersection point that is followed by a gradual decrease of its displacement velocity in the course of time that is denominated as deceleration phase [5].

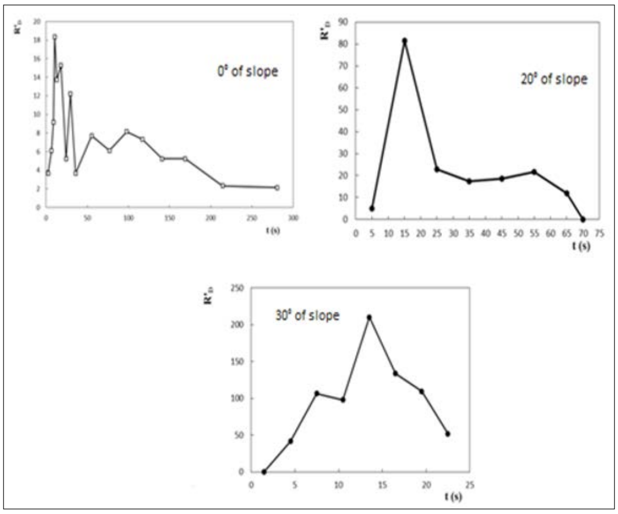

Figure 6: Characteristic Curves of the Non-Dimensional Rate of Spread of Junction Fire for Three different Fuel Bed Slopes, 0º, 20º and 30º With θo= 30º

The accelerated phase is attributed to the development of convective flows generated by the fire itself, leading to a high concentration of energy near the intersection point of the fire lines.

The interference of the interaction domains of the burning cells creates a supper roughness tongue with a huge convective flow intensity that heats rapidly the area between the two oblique fronts. So that the combustible layer located at the front of the junction receives a quantity of heat corresponds to:

$$Q_c = \frac{0.565\ k_f\ Re_y^{\frac{1}{2}}\ Pr^{\frac{1}{2}}\left(T_f - T_y\right)e^{-0.3y\,L_f}}{y\,l_c} \qquad (02)$$

Where: L_f is the flame length, K_f is the thermal conductivity and L_c the characteristic ignition length of flame

The Reynolds number Re_y , and the Prandtl number are related to the fuel parameters and their sition, they are respectively deduced by:

$$R_{ey} = \frac{U_H y}{\vartheta_g} \quad , \quad P_r = \frac{\vartheta_g}{\alpha_g} \qquad (03)$$

Where: ϑ_g and α_g are respectively the kinematic viscosity and thermal diffusivity of the gas. U_H and y are the average humidity factor and the distance to the flame.

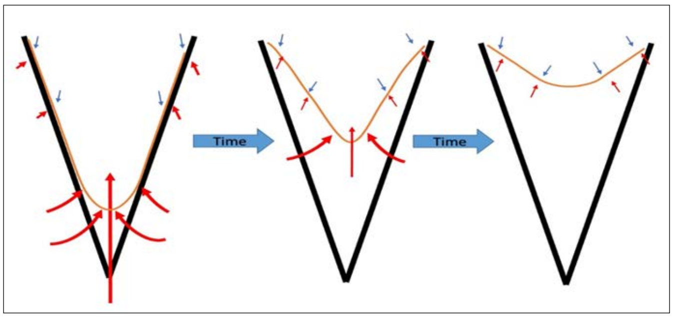

Figure 7: Distribution of the Convection Flow during the Spreading Period of Fire Junction

With the increase of the slope angle α_J the trend of the curve of ROS are slightly modified; the maximum relative flow velocity which is essentially positive occurs gradually earlier. However, the growth interface morphology is being different. Where it is delicately modified between the case of (α_J =0º, 20°), contrary to the case of (α_J =30°).

Actually, the ground slope dependence is essentially due to the value of the rotation velocity of the initial fire lines, where the achievement of a linear fire front, is more evident and faster for (α_J=0º) than for (α_J=30º).

As a consequence, a huge amount of energy will be available in the upper part of the junction and will be directed towards the converging point.

At the case of (α_J =30°), The combustion reaction will be more intense due to the high flame length which leads to a higher angular velocity and to a random deposition universality class (see table 1), because of the rapid advance of the fire perimeter.

These configurations are comparable to there of an eruptive fire which is the most dangerous fire to control and manage to firefighters because of the major's quantity of harmful gases emitted by both fronts and their centralization, and because of the deviation of the propagation direction from the predicted direction from the ignited lines.

This phenomenon has been observed in fire experiments on toilet papers where the fire front propagates across the machine direction despite the fact that the ignition has been carried out on the main direction of the paper machine, this defines an anomalous roughness in the growth of fire interface, explaining the destabilization of the main fire front caused by the interference created by the merging of the two fire lines.

With the evolution of the fire front, the geometry that causes this rapid acceleration will change where the two initial lines of the fire move considerably away from each other forming a homogeneous support between them ($\theta_0 \rightarrow 180^o$).

At this level, the mechanisms inherent to the spread of fire change gradually, where the convection activity still to affect, due to a gradual change of the flame configuration that allows the entrance of a contrary flow that decreases the rate of spread of these fires however the radiation take places as the main mechanism of heat transfer.

The radiation flow received by the adjacent cells to the fire front is given by:

$$Q_r = \frac{a_{fb}\ \sigma\ \varepsilon_f T_f^4}{l_c} F \qquad (04)$$

Where a_{fb} is the absorption coefficient of the combustible layer, ε_f and T_f are respectively the emissivity and temperature of the flame.

σ is the Stephan Bolzmann constant and F is the view factor given by:

$$F_{12} = \frac{dA_2}{A_1} \int_{A_1} \frac{\cos(\gamma_1).\cos(\gamma_2)}{\pi.r^2} dA_1$$

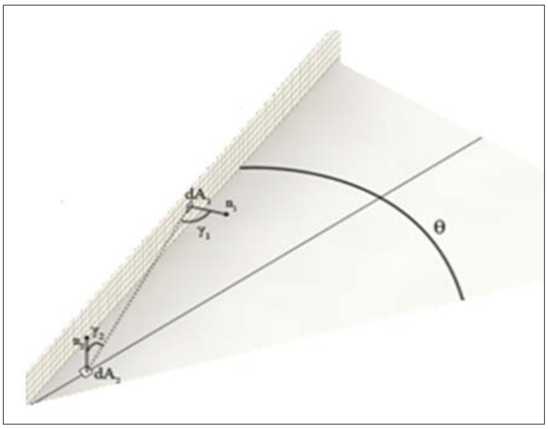

Figure 8: Schematic Representation of the Calculus of the Radiative Heat Flux

During this regime, the rate of spread decrease considerably with the front spreading line, and the propagation direction will be homogenized. That reduces the risk of explosion and danger and facilitates the fight against.

This homogenization of fire fronts leads to an ordinary percolation growth dynamic for a flat ground ($\alpha_J = 0°$), the fire spread is within the interaction domain beyond nearest neighbors defined by the radiation effect [11].

However, for ($\alpha_J = 20°$), the growth dynamics change to be directed due to the medium amount of the energy produced inside the junction and which is distributed uniformly over the fire front line leading to a slight change in the initial angle between the fire lines in respect to the propagated distance and time. While for ($\alpha_J = 30°$), a depinning propagation with moving interface is defined because of the destabilization and quick change of the amount of the energy released by the main fire front and their position. The high flame length and the sharp angel to the ground active the ignition process and minimize the residence time.

Table 1: Summary of Critical Exponent Values for different Fuels Bed Slops and ROS Regimes [9]

Case / dynamical exponents	Regime	β	α	z	Universality classes
$\alpha_J = 30°$	Accelered	0.52(1)	1.46(1)	1.73(4)	Super roghness random deposition
	Deccelered	0.72(1)	1.78(4)		Depining propagation with moving interface
$\alpha_J = 20°$	Accelered	1.03(4)	2.65(3)	0.66(2)	KPZ with super roghness
	Deccelered	0.74(1)	1.41(2)		Directed percolation d=1
$\alpha_J = 0°$	Accelered	1.0(1)	1.26(4)	0.48(3)	KPZ with super roghness
	Deccelered	0.41(1)	1.26(4)	0.48(3)	Ordinary percolation

Furthermore, the dynamical exponent z, was found unique regardless the ROS regime, it increase proportionally to the ground slope α_J from 0,48 to 1,73 (see table 1). That's confirm that the spread profile change from a ballistic propagation at 0° to a diffusive one at 30° with an intermediary domain at 20°. It is a phase transition from a normal diffusion to anomalous one.

Conclusion

In this study a particular form of extreme fire behavior that consists in the merging of two fire lines that intersect making a small angle between them, and that is characterized by an initial phase of acceleration in which very high values of ROS are reached followed by a deceleration phase was analyzed.

The main parameters that govern the development of junction fire were described and the dynamic behavior of the fire front growth was put in evidence.

The work was essentially based in experimental laboratory tests of the ADAI team of LEIF, in which the initial angle between the fire fronts were constant and the ground slopes were varied in an indicated range.

The acceleration phase of the junction fire was associated to the high concentration of energy of the convective flow near the intersection point leading to a supper roughness fire front growth. It was shown that in this acceleration phase the fire develops like an eruptive fire with the particularity that the rate of spread did not increase indefinitely [12-16].

The deceleration is associated to convection and principally radiation effects. The tendency to achieve a linear fire front, is more evident and faster for α_J=0º than for α_J=30º. it exhibit a phase transition from ordinary percolation class to a depinnig percolation with moving interface trough a directed percolation class at 20°.

As future work more research has to be carried out, Experimental tests at laboratory scale to better understand the physical processes involved in (wind effect, non-symmetric ground and climate conditions, radiation flow modeling).

Finally, field scale experiments and real fire analysis should be performed in order to extend the range of data points and compared with real situations.

Acknowledgements

The first author would like to thank the Erasmus Modulus Group—Al idrisi II—for the opportunity to improve my studies, Prof. Domingos Xavier Viegas for invitation and for the supervising during this scholarship.

The first author also wants to thank Dr. Jorge Raposo for his support, guide and suggests, to all the personal and teams of ADAI and LEIF for their help, guide and their advises.

References

1. Schemel CF, Simeoni A, Biteau H, Rivera JD, Torero JL (2008) A calorimetric study of wildland fuels. Exp Therm Flu SCI 32: 1381-1489.
2. Chandler MO, Nagy AF, Fontheim EG, Behnke RA, Richards PG, et al. (1993) Comparison of measured and calculated low-latitude ionospheric properties. Journal of Geophysical Research 88: P09187.
3. Brown AA, Davis KP (1973) Forest Fire: Control and use. McGraw-Hill series in forest resources 2nd Edition https://books.google.co.in/books/about/Forest_Fire_Control_and_Use.html?id=tXqe-eKM6hEC&redir_esc=y.
4. Pyne SJ (1984) Introduction to wildland fire. Fire management in the United States. John Wiley & Sons https://www.cabdirect.org/cabdirect/search/?q=pb%3a%22John+Wiley+%26+Sons%22.
5. Viegas D, Raposo J, Davim D, Rossa C (2012) Study of the Jump Fire Produced by the Interaction of Two Oblique Fire Fronts. Part 2: Analytical Extended Model and Validation with Slope Laboratory Experiments. International Journal of Wildland Fire 21: 843-856.
6. Plishke M, Bergersen B (1994) Equilibrium Statistical Physics. World Scientific, Singapore.
7. Balescu R (1997) Statistical Physics Out of Equilibrium. Imperial College Press, London.
8. Viegas D, Raposo J, Figueiredo A (2013) Preliminary analysis of slope and fuel bed effect on jump behavior in forest fires. Procedia Engineering 62: 1032-1039.
9. Barabasi AL, Stanly HE (1995) Fractal Concepts in Surface Growth. Cambridge University Press https://www.cambridge.org/core/books/fractal-concepts-in-surface-growth/0D9076FC287B60B2B1126BB165112F13.
10. Family F, Viscek T (1991) Dynamics of Fractal Surfaces. World Scientific, Singapore https://www.worldscientific.com/worldscibooks/10.1142/1452.
11. Odor G (2004) Universality classes in non-equilibrium lattice systems. Rev Mod Phys 76: 663.
12. Stauffer D, Aharony A (1992) Introduction to Percolation Theory. Taylor and Francis, London.
13. Sander LM, Warren CP, Sokolov IM, Simon C, Koopman J (2002) Percolation on Heterogeneous Networks as a Model for Epidemics. Math Biosci 180: 293.
14. Khelloufi K, Baara Y, Clerc JP, Porterie B, Zekri N, et al. (2013) Forest fire spread with non-universal critical behavior. Journal of Statistical Mechanics 2013: P10027.
15. Rodrigues A, Ribeiro C, Raposo J, Viegas D, André J (2019) Effect of Canyons on a Fire Propagating Laterally Over Slopes. Frontiers in Mechanical Engineering 5: 1-9.
16. Porterie B, Kaiss A, Clerc JP, Zekri L, Zekri N (2008) universal scaling in wildfire fractal propagation. Appl. Phys. Lett 93: 204101.