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Microscale fire modelling at the Wildland-Urban Interface

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Abstract

The direct and indirect impacts of Wildland-Urban Interface fires on infrastructures and communities have become more severe in the last few decades, mainly due to the disproportionate growth of urban areas lacking planning and management, the abandonment of rural areas and activities, and climate changes. Many regions of the southern Mediterranean, the United States, Australia, and South America have been severely affected with catastrophic losses.

Building codes addressing the problem of WUI fires in the vicinity of the built environment are still scarce, but already with a few good examples, namely the Australian Standard AS 3959-2009, Construction of Buildings in Bushfire Prone Areas. But with the increasing risks, nowadays mainly driven by climate change, it is necessary to develop new approaches and codes for existing and new buildings effectively contributing to enhancing the resilience of the built environment and communities in the WUI. Moreover, taking advantage of new and ever-evolving computational tools, the use of a performance-based approach, replacing or complementing prescriptive codes, shows great potential to enable a deeper understanding of the complex fire spread mechanisms from forest fires to urban fires, namely radiant heat, direct flame contact and firebrands.

Physics-based modelling enables a better understanding of such phenomena, bearing in mind that up to date no accurate and reliable models for firebrands can be found. In this investigation, a performance-based approach is considered, exploring the capabilities of computational fluid dynamics and the software Fire Dynamics Simulation (FDS) to investigate and quantify WUI fire exposures. This was achieved by considering available experimental data on vegetation burning and developing and calibrating the numerical models using FDS. A Particle Method, based on Lagrangian particles was selected for this investigation since this model is particularly suitable to simulate surface and raised vegetation fire spread. With this strategy all thermo-physical properties of the fuels must be used as input, ensuring that the fire spread can be computed by the model.

Based on the calibrated models for a single tree, a new case study scenario was created (structure exposed to wildfire) and investigated aiming to assess in detail WUI fire exposures under different conditions by varying several parameters, such as wind speed and direction, distance to the structure and elevation of the terrain. Since a performance-based approach was selected and considering the basic principles associated with Fire Safety Engineering (FSE), 3 basic components must be assessed, namely the fire modelling, the thermal analysis of the structure and finally the structural analysis considering temperature increase and degradation of mechanical properties of materials. From the fire modelling investigated in this paper, some attention was devoted to assessing Adiabatic Surface Temperatures in the structure and consequently defining in a simple way to couple CFD field models to Finite Element Models (FEM) that will enable the understanding and development of ignition resistant structures in the WUI.

1. Introduction

The direct and indirect impacts of Wildland-Urban Interface (WUI) fires on infrastructures and communities have become more severe in the last few decades, mainly due to the disproportionate growth of urban areas lacking planning and management, the abandonment of rural areas and activities, and climate changes. Catastrophic loss of lives, property damage and environmental destruction have been observed on several occasions, such as the 2005 and 2017 wildfires in Portugal (Independent Technical Commission 2022; Chas-Amil et al. 2020; Independent Technical Commission 2018), the 2009 Victorian bushfires (Teague B. et al., 2009), the 2018 Camp Fire in Northern California (P. Eavis et al. 2020; Spearing et al. 2020; Ager et al. 2021), the Australian bushfires (I. Kwai 2020); Mclennan et al. 2015) or the wildfires in Eastern Attica, Greece (Efthimiou et al. 2020). The severity of the problem is relevant and may be intensified in the next few years by climate changes. In the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC

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2021), it is stated that in southern Europe, northern Asia, the USA, and Australia, the weather conditions promoting the occurrence of wildfires, are becoming more likely. The increasing frequency of such events shows the urgent need to understand these phenomena and the existing risks, aiming to predict their consequences and implement adequate mitigation measures, strengthening the resilience of communities and the built environment (Ager et al. 2021; Álvares-Miranda et al. 2018; Syphard et al. 2017). Understanding the fire spread mechanisms from wildfires to the built environment in the vicinity of forest areas is a complex task requiring extensive investigation considering not only the WUI fire exposure (radiant heat, direct flame contact and firebrands) but also the vulnerability of infrastructures (Quarles and Standohar-Alfano 2018) for the development of science-based resilient solutions/methods for retrofitting existing structures and to design new structures in the WUI, that can be incorporated in future codes.

Exploring the versatility of advanced computational tools, it is possible to adopt a Performance-Based Design (PBD) approach to investigate in detail fire spread mechanisms from forest fires to the built environment using similar strategies as the ones presented by Vacca et al. (2020) in the scope of the research project WUIVIEW - Wildland-Urban Interface VIrtual Essays Workbench ((ECHO/2018/826522), considering that serious limitations still exist mainly related to the behaviour of firebrands and their interaction with structures and how external fires impact buildings. In this investigation, physics-based models, using the software Fire Dynamics Simulator (FDS) (McGrattan et al. 2020), were developed to calibrate experimental tests on single burning trees (Douglas-fir experiments conducted at NIST) reported by Mell *et al*. (2009). Then some case study scenarios were designed, incorporating surface vegetation and trees in the vicinity of a building. Additionally, the influence of elevation and wind speed on the fire behaviour was considered to evaluate the possible fire spread mechanisms from wildfires to buildings.

2. Methodology

2.1. Modelling of single-burning trees

To conduct parametric numerical studies, it is necessary to accurately calibrate the developed models using available experimental results. In this study, the experimental tests performed by Mell *et al*. (2009) on single-burning Douglas-fir trees were reproduced using FDS 6.7.7 (McGrattan et al. 2020). The calibration was performed for 2 m and 5 m Douglas-fir trees, with a moisture content of 14% and 26%, respectively. The Particle Method was used to model the vegetation in fire. In this case, the trees are represented by a collection of Lagrangian particles that are heated up by convection and radiation, as explained by Vanella *et al*. (2021). Using the Particle Method, it is necessary to use as input all relevant thermo-physical properties of fuels, allowing the model to compute the fire spread. Physical and thermal properties/parameters used in the simulations are presented in Table 1. It is worth mentioning that different fuel chemical compositions were assumed, namely $C_{3.4}H_{6.2}O_{2.5}$ (Hostikka and McGrattan 2001), $C_6H_{10}O_5$ (Browne 1958) and $CH_{1.7}O_{0.74}N_{0.002}$ (McGrattan et al. 2021). The heat of combustion was 17500 kJ/kg.

Table 1 – Physical and Thermal Parameters used in FDS

Quantity	**Value**	**Quantity**	**Value**
Drag Coefficient [--]	2.8	Heat of Combustion [kJ/kg]	14516|17500
Moisture Vegetation [%]	14|26	Soot Yield [kg/kg]	0.02
Vegetation Density	514	Initial Temperature [° C]	28
Fuel Geometry Tree	Cone	Heat of Reaction [kJ/kg]	418
Crown Width (radius) [m]	0.85|1.45	Specific Heat Capacity [kJ/kg K]	2.0|1.5|4.184
Crown Base Height [m]	0	Thermal Conductivity [1][W/ m K]	0.11
Tree Height [m]	1.9|4.3	Density [2] [kg/m^3]	300|67
N_PARTICLES_PER_CELL	1	Reference Temperature [° C]	300 [3], 100 [4]
PACKING_RATIO (s, m, l) [5]	68, 48, 44| E-5	Shape	Cylindrical

[1] Vegetation; Char and Ash.; [2] Moisture, Char Veg and Dirt.; [3] Vegetation Grass. [4] Moisture. (small, medium, large) [5]

Mesh sensitivity tests were also performed, considering two mesh sizes, namely 10 and 25 cm. It was observed that mesh size played a very relevant role in the accuracy of the developed model. Overall, it was observed that the FDS can accurately reproduce the observed experimental behaviour in terms of Mass Loss Rate for both single Douglas-fir burning trees using a mesh size of 10 cm and a fuel chemical composition of $C_{3.4}H_{6.2}O_{2.5}$ (S. Hostikka and K. MacGrattan, 2001). As in the experimental test, a circular shape burner was prescribed with a heat release rate of 30 kW.

2.2. WUI case study

The selected case study comprised a small industrial warehouse (15 × 10 m^2) facing a set of trees. The maximum height of the building is 12 m. Two doors (3.5 x 8 m^2) are located on the eastern and western sides. Two square gates (8 × 8 m^2) are placed on the northern and southern wall perimeters. The trees are on a slope, as depicted in Figure 1. The dimensions of the computational domain are the following: X = 57 m, Y = 36 m and Z = 40 m. Four meshes were created to optimize the computation time. Three meshes, with a cubic cell of 25 cm were created (Z direction ranging from 0 to 24 m). The fourth mesh with cubic cells of 50 cm was created in the Z direction from 24 to 40 m. A total of 3.414.528 cells are generated. The cladding of the walls is made of a concrete panel with a thickness of 25 cm. The glass surfaces are 15 mm thick. The terrain has two flat planes with an 8 m difference in altitude. The warehouse is located on the higher ground (west side), where there is no vegetation. The flat ground has an extension of 37 x 36 m^2 and an elevation of 8 m above the bottom level (east side). The ground area covered with grass is 20 x 36 m^2. A slope of 46 º (*i.e.*, 80 %) is considered. Grass and nine trees, having a height of 15 m and a girth of 1.5 m, are positioned on the slope. The wind is a critical parameter and was considered in the model, using different wind speeds aiming to assess its influence on the fire behaviour. The wind was modelled using the Monin-Obukhov (Vanella et al. 2021) similarity theory, considering neutral stability with an Obukhov length of 1000000 m and a Davenport-Wieringa roughness length classification of 0.03 (classification: open; grass prairie, farm fields, tundra, airports, heather) (McGrattan et al. 2021). For the detailed case study, the following wind speeds were assessed: 4.15 m/s, 5.80 m/s and 6.7 m/s.

To assess the impact of the forest fire in the structure, aiming to easily transfer data from the fire model to the heat transfer model and mechanical model and understand heat transfer to solids, several Adiabatic Surface Temperature (AST) devices were used. The AST concept is useful to calculate temperatures in fire-exposed structures (expressing the thermal exposure of a surface).

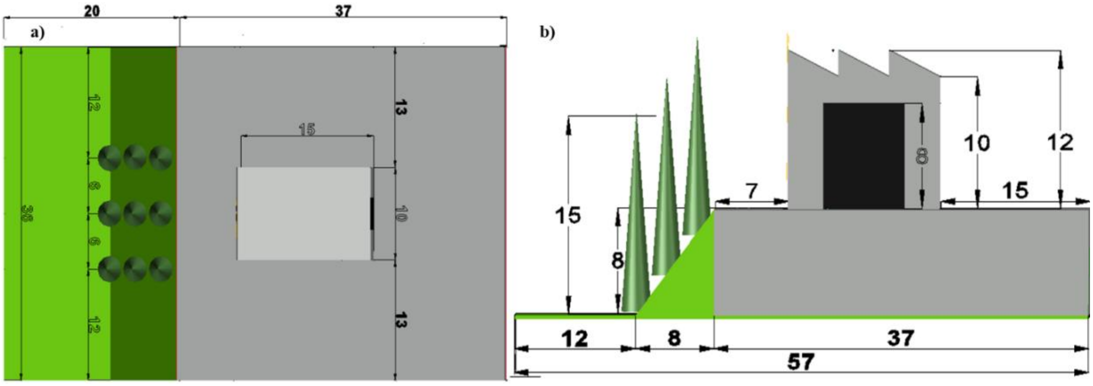

Figure 1 – Schematic representation of the selected case study. a) Top view. b) Lateral view.

3. Results

3.1. Calibration of single-burning trees

The previously described modelling strategies and assumptions provided accurate estimations using a more refined mesh size of 10 cm, but with significantly higher needs in terms of computational resources. The comparison between experimental and numerical results is depicted in Figure 2. The peak mass loss monitored in the experimental test of the Douglas-fir tree with 2 m (moisture of 14%) was 0.417 kg/s, whereas the numerical model provided an estimation of 0.409 kg/s. The results show an excellent agreement, hence enabling additional parametric studies. Regarding the case of a tree with 5 m (moisture of 26%), as depicted in Figure 2b), the peak mass loss rate was 1.90 kg/s in the experimental test and 2.03 kg/s in the numerical simulation considering a mesh size of 10 cm (showing a difference of less than 7%).

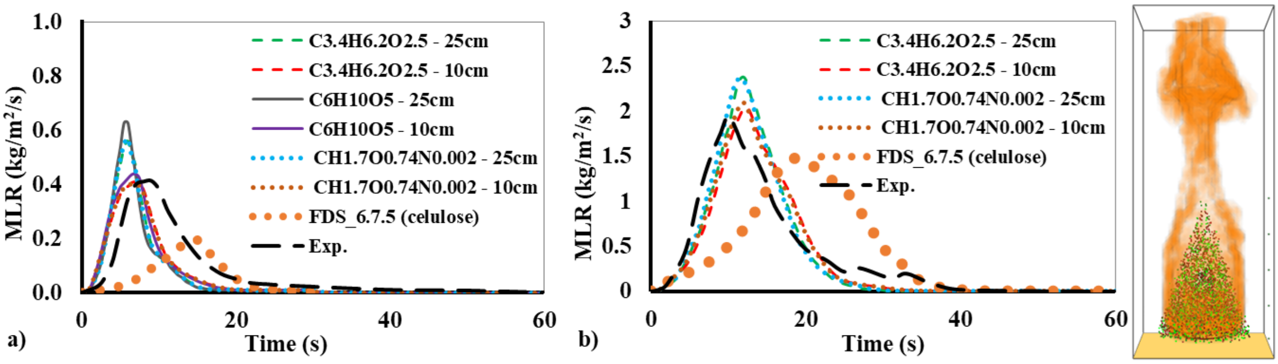

Figure 2 - Calibration of the numerical models against single burning Douglas-fir trees. Mass loss rate comparison. a) Tree with 2 m with a moisture content of 14%. b) Tree with 5 m with a moisture content of 26%.

3.2. Case study

Figure 3 shows values referring to Radiative Heat Flux obtained in the investigated scenario. Two quantities are displayed, F and R, respectively from the façade and the roof, considering three different wind speeds expressed in m/s (4.15, 5.85 and 6.70). Figure 4 depicts the obtained Adiabatic Surface Temperatures (AST) at different locations.

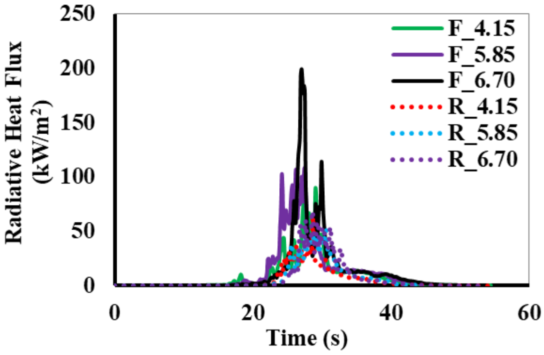

Figure 3 – Radiative Heat Flux as a function of the adopted wind speed.

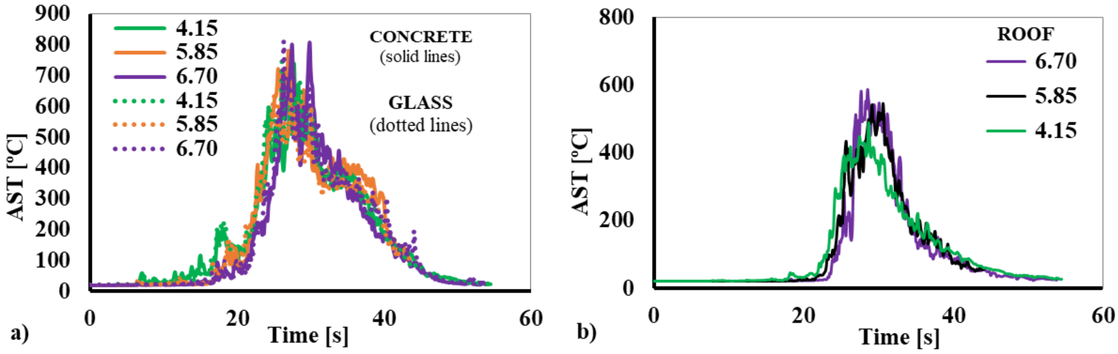

Figure 4 – Adiabatic Surface Temperatures at different locations of the building as a function of wind speed. a) AST in concrete and glass. b) AST in the roof.

The highest values are obtained on the façade (around 200, 108, and 90 kW/m^2 respectively, for 6.70, 5.85 and 4.15 m/s). The higher values were obtained when the higher wind speeds were considered, which caused a greater deflection of the flames. The average maximum value of the radiative flux measured on the roof was about 60 kW/m^2.

AST temperatures on concrete and glass (placed on the façade) and on the roof are depicted in Figure 4 a) and b), respectively. All the curves in Figure 4 a) are very close. For concrete, the peak value was 806ºC, and for glass, it was 813ºC. Both values were reached for a wind velocity equal to 6.70 m/s. Figure 4 b) shows that the difference between the maximum peak values is 100ºC, with the highest value of 587ºC with the wind blowing at 6.70m/s. The obtained information allows coupling CFD results with finite element software, enabling the mechanical analysis of buildings in the WUI and consequently the analysis and design of fire-resistant and resilient buildings.

4. Conclusions

Fire spread mechanisms from wildfires to the built environment are complex phenomena that still require extensive research, especially when related to the behaviour of firebrands and their interaction with structures (different levels of vulnerability of structures may lead to new secondary fires). However, existing tools already show the potential for further developments for a better understanding and more accurate quantification of fire exposures in the WUI. This will lead to relevant developments in terms of new design methodologies for buildings in the vicinity of forest areas incorporating Performance-based principles.

In this study, numerical models were developed and calibrated against experimental results, enabling new parametric studies focusing on the relevant heat transfer phenomena from wildfires to the built environment. Wind speed was one of the key parameters investigated. Its impact on the radiative heat flux and AST was assessed and reported. For the selected case study, the higher the wind speed the higher the incident radiative heat flux and AST in the structure.

Further studies on firebrands and new mathematical models must be developed to better simulate their behaviour and interaction with surrounding infrastructures.

5. Acknowledgements

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6. References

Ager, A. Alan, Michelle A. Day, Fermin J. Alcasena, Evers, Cody R., Karen C Short, Isaac Grenfell, (2021), Science of the Total Environment, 784, 147057. https://doi.org/10.1016/j.scitotenv.2021.147057

Álvarez-Miranda, Eduardo, et al., (2018) A multicriteria optimization model for sustainable forest management under climate change uncertainty: An application in Portugal, European Journal of Operational Research, 269, pp. 79-98. https://doi.org/10.1016/j.ejor.2017.04.052

Chas-Amil, María-Luisa, García-Martínez, Eduardo, Touza, Julia, (2020). Iberian Peninsula October 2017 wildfires: Burned area and population exposure in Galicia (NW of Spain), International Journal of Disaster Risk Reduction, vol. 48, 101623. https://doi.org/10.1016/j.ijdrr.2020.101623

Efthimiou, N., Psomiadis, E., Panagos, Panos, (2020). Fire severity and soil erosion susceptibility mapping using multi-temporal Earth Observation data: The case of Mati fatal wildfire in Eastern Attica, Greece, Catena, vol. 187, 104320. https://doi.org/10.1016/j.catena.2019.104320

F.L. Browne (1958), Theories of the combustion of wood and its control: A survey of the literature, Report 2136, Forest Products Laboratory, US, Department of Agriculture, 1958.

I. Kwai, (2020) What to read on Australia's bushfire crisis. New York Times. Retrieved February. https://www.nytimes.com/2020/01/10/world/australia/bushfire.html (2020), 17-2020.

Independent Technical Comission, Guerreiro J. et al. (2018) Avaliação dos incêndios ocorridos entre 14 e 16 de outubro de 2017 em Portugal Continental, Relatório final. Comissão Técnica Independente. Assemnly of the Portuguese Republic, Lisboa, 2018, p. 274.

Independent Technical Commission, Coord. Guerreiro, J., et al (2022), Análise e apuramento dos factos relativos aos incêndios que ocorreram em Pedrogão Grande, Castanheira de Pera, Ansião, Alvaiázere, Figueiró dos Vinhos, Arganil, Góis, Penela, Pampilhosa da Serra, Oleiros e Sertã, entre 17 e 24 de Junho de 2017, Final Report, Assembly of the Portuguese Republic, Portugal.

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, et al.]. Cambridge University Press. In Press.

M. Vanella, K. McGrattan, R. McDermott, G. Forney, W. Mell, E. Gissi and P. Fiorucci (2021), A Multi-Fidelity - Framework for Wildland Fire Behavior Simulations over Complex Terrain, Atmosphere, vol. 12, no. 273, pp. 1-16. https://doi.org/10.3390/atmos12020273

McGrattan K., Hostikka S., Floyd J., McDermott R., Vanella M. (2020), Fire Dynamics Simulator Technical Reference Guide, Volume 3: Validation- NIST Special Publication 1018-3 6th ed., pp. 27–29, 896, 897. http://dx.doi.org/10.6028/NIST.SP.1018

McGrattan K., Hostikka S., Floyd J., McDermott R., Vanella M. (2021), Fire Dynamics Simulator, User's Guide, NIST Special Publication 1019 6th ed., http://dx.doi.org/10.6028/NIST.SP.1019

Mclennan, Jim, Paton, Douglas, Wright, Lyndsey, (2015). At-risk householders' responses to potential and actual bushfire threat: An analysis of findings from seven Australian post-bushfire interview studies 2009-2014, International Journal of Disaster Risk Reduction, vol. 12, 319-327.

Mell W., Maranghides A., McDermott R, Manzello S.L. (2009), Numerical simulation and experiments of burning douglas fir trees, 641 Combustion and Flame, Volume 156, Issue 10, pp. 2023-2041. https://doi.org/10.1016/j.combustflame.2009.06.015

P. Eavis, I. Penn. (2020) California says PG&E power lines caused camp fire that killed 85, New York Times (2019, May 15). https://www.nytimes.com/2019/05/15/business/pge-fire.html, Accessed 20th sept. 2020.

Quarles, S. L.; Standohar-Alfano C. D. (2018), Ignition Potential of Decks Subjected to an Ember Exposure - Wildfire Research, Technical Report, pp. 2,3,5,7,17. https://ibhs.org/wp-content/uploads/Ignition-Potential-of-Decks-Subjected-to-an-Ember-Expo- 603sure.pdf

Simo Hostikka, K.B. McGrattan (2001), Large-eddy simulation of wood combustion, Interfalm'2001, International Interflam Conference, 9th Proceedings. Volume 1. September 17-19, Edinburgh, Scotland, Interscience Communications LTD, London, England, 755-762, 2001.

Spearing, Lauryin A., Faust, Kasey M. (2020). Cascading system impacts of the 2018 Camp Fire in California: The interdependent provision of infrastructure services to displaced populations, International Journal of Disaster Risk Reduction, Vol. 50, November 2020, 101822. https://doi.org/10.1016/j.ijdrr.2020.101822

Syphard, A. D., Brennan T.J., Keeley J. E. (2017), The importance of building construction materials relative to other factors affecting structure survival during wildfire, International Journal of Disaster Risk Reduction, Volume 21, Pages 140-147. https://doi.org/10.1016/j.ijdrr.2016.11.011

Teague B., McLeod R., Pascoe S., (2009), Victorian Bushfires Royal Commission, Final Report, Parliament of Victoria, Melbourne, Australia.

Vacca P., Caballero D, Pastor E., Planas E. (2020) WUI fire risk mitigation in Europe: A performance-based design approach 2020, Journal of Safety Science and Resilience 1 97–105.