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LUÍS MÁRIO RIBEIRO

Application of the Computational Fluid Dynamics in Forest Fires Investigations for Mitigation of the Wildland-Urban Interface Fires' Risks

MohammadReza Modarres; Miguel Almeida*

[1] *Department of Mechanical Engineering, University of Coimbra, ADAI, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal, {mohammad, miguelalmeida}@adai.pt*

**Corresponding author*

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Abstract

Realistic modeling of the vegetation fires based on reliable data from laboratory experiments is a key factor in the prediction of the fire dynamics behavior and its spread rate in wildlands. A robust understating of the fire behavior in different species can provide a pragmatic insight to take precautionary steps to mitigate the fire risks in Wildland-urban interfaces. Computational Fluid Dynamics (CFD) modeling of wildland fires offers a considerably high load of information needed for engineers and policymakers. This paper addresses the numerical modeling of the Ivy (Hedera helix) and grapevine (Vitis) plants using the fire dynamics simulation for the fire behavior analysis. Other species which authors have conducted experiments are Acacia, Apple tree, Arizona cypress, Bay laurel (Laurus nobilis), Blueberry tree (Prunus Spinosa), Cherry Tree, Fig tree, Gum rockrose (Cistus ladanifer), Hydrangea, Kiwi tree, Leyland cypress, Lindens (Tilia), Loquat (Eriobotrya japonica), Nerium oleander, Olive tree, Pacific madrone (Arbutus menziesii), Rhus typhina (Anacardiaceae), The Holly (Ilex Aquifolium), Thuja occidentalis (white cedar), and Wild Blackberry (Rubus Ulmifolius) shrub, in alphabetical order. The corresponding mathematical modelings of these experiments are being carried out by the authors.

The current numerical study was performed using the NIST open-source FDS code, developed by the National Institute of Standards and Technology with specific emphasis on the heat release rate from fires in different types of indigenous plants common in the Mediterranean climate, especially in Portugal. The validations of the numerical results are realized based on the observations from the experiments conducted at the Laboratório de Estudos Sobre Incêndios Florestais (LEIF) by the authors. The large-eddy simulation (LES) is used in these sets of simulations to close the turbulence equations in the low-Mach regime. The 2nd order accurate finite difference approximation scheme is used to discretize the governing equations on uniformly spaced three-dimensional staggered grids. The flow obstructions are treated using the simple immersed boundary method. Comparing the results of the FDS with those from the practical experiments, it is concluded that mathematical modeling of the vegetation fires can provide reasonably accurate results based on the fuel's physical and chemical characteristics along with operating boundary conditions.

1. Introduction

Forest fires as uncontrolled and non-prescribed combustion or burning of plants are considered a serious threat not only to the forests by jeopardizing the fauna and flora, mistuning the biodiversity in forest ecosystems but also in severe cases of extended fires, the residential areas. During drought seasons, especially in summers, with escalating effects imposed by global warming, the forests become more vulnerable caused by scattered litters of dry senescent leaves, twinges, and twigs as potent fuel types to make forests susceptible to lethal fires with colossal loss of the vegetation cover. Wildfires can become more intensified based on the environmental conditions (e.g., meteorological conditions, and terrain topography) which in turn can lead to irreparable casualties for the residential sites nearby or even farther. A forest fire may exist as surface, underground, ground, crown fires, and in severe cases as firestorms with natural or man-made causes. According to the European Commission report on forest fires, in 2020, southern European countries, e.g., Spain, France, Portugal, Italy, and Greece were the most affected regions losing thousands of acres of forest lands, including Romania, which is an expanding threat to the central and northern Europe. Based on the recent forest fires in Portugal, especially in 2017, the concept of WUI fires becomes more important than ever, which necessitates more laboratory experiments as the basic requirement for theoretical investigations. Since performing tests on different vegetation fuels is limited due to the dimensions of the species with complex arrangements and diversities in nature, FDS can be an efficient tool to simulate the fire behavior based on the data gathered from laboratory-sized burnings. The FDS results can be subsequently applied to the diverse species in size and arrangements to have a realistic vision to define precautionary measures and policies. This paper intends to address the computational fluid dynamics modeling (CFD) of the fire behavior in Ivy and grapevine plants, using the FDS based on the experimental data conducted by the authors at LEIF located in Lousã, Coimbra (Portugal). This methodology is an efficient way to broaden the vision of engineers and down the road the policymakers in urban planning sectors.

2. Solution Methodology in FDS

The current FDS formulation applies the low Mach number assumption which yields in filtering out the acoustics from the equations and allowing the variations both in temperature and density, Rehm and Baum (1978). This approximation converts the governing equations into the elliptic format in the LES turbulence model. The FDS code utilizes Deardorff's turbulent eddy viscosity sub-grid closure model by default, Deardorff (1980). Turbulent Schmidt and Prandtl numbers are set to the constant values. The fast chemistry eddy dissipation concept by Magnussen and Hjertager (1977) is used for the formulations of the turbulence-chemistry interaction with the single-step reaction for the fuel and oxidizer combustion using the lumped species method, Fox (2003), discussed in McGrattan et al. (2013).

The Runge-Kutta discretization with high stability-preserving (SSP) is used over time for flow variables. This scheme is second order in both space and time. The Poisson equation is solved using the direct fast Fourier transform (FFT) solver. The mesh is uniform and staggered. The immersed boundary method is applied to treat the flow obstructions in the computational domain.

3. Experimental Tests

Five samples of each type of vegetation fuel were used for the experiments. Tables 1 and 2 contain the characteristics of the samples of the Ivy and the Grapevine in detail:

Table 1 – Details of case studies for the Ivy.

Case Nº	Initial Mass (kg)	Final Mass (kg)	FMC_w (%)	Length (cm)	Height (cm)	Depth (cm)
1	13.73	11.35	49.00	70	80	25
2	5.40	4.30	47.00	65	70	20
3	8.40	7.20	46.30	75	80	25
4	13.26	12.00	36.70	80	80	25
5	17.96	16.70	52.40	75	80	28

Table 2 – Details of the samples of the Grapevine.

Case Nº	Initial Mass (kg)	Final Mass (kg)	FMC_w (%)	Length (cm)	Width (cm)	Depth (cm)
1	1.12	0.14	60.40	124	68	14
2	1.12	0.05	61.20	130	67	16
3	1.10	0.08	51.50	130	68	14
4	1.16	0.12	56.67	133	69	15
5	1.18	0.12	59.21	127	67	13

In Tables 1 and2, the initial and final masses refer to the mass of the plants before and after the burning process in kilograms measured by the instantaneous mass acquisition system. The wet basis moisture content of the species is measured using the digital moisture analyzer.

The first experimental case, the Ivy plant, fixed to a massive vertical plate to mimic the common ivy-green-wall, in which the length in Table 1 refers to the horizontal distance from the point A to B, and the height refers to the distance from B to C, as pointed out in Figure 1. In the case of the Grapevine, the sample has a horizontal configuration on a metal grid, in order to create the scenario of a pergola of vines that is so often seen next to houses. The length in Table 2 is the distance from the point D to E, and width refers to the EF length as illustrated in Figure 2. Depth (cm) in both cases defines the distance between the opposite sides of each sample. The experiments have been carried out in the environmental conditions with a mean temperature of 26.7 ºC, 23.6 ºC, and relative humidity of 42.4%, and 58.2% for the Ivy and the Grapevine, respectively.

Figure 1. Laboratory tests, Ivy.

Figure 2. Laboratory tests, Grapevine.

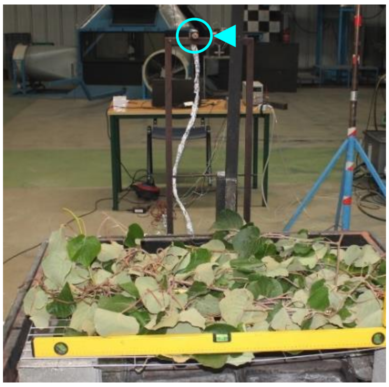

Figure 3. The location of the heat flux sensor.

Figure 4. S-type pitot tube in the experiments.

Fire evolution was recorded by three RGB and two IR cameras. Having the calibration rod at the RHS of Figure 3 (distance between red/white tapes is 20 cm), one can determine the flame dimensions. The thermal behavior of the fire was captured by installing the sets of thermocouples to measure temperatures at different points and the heat release rate was measured using the heat flux sensor installed at a 1.0 m height. The S-type pitot tube is used to detect the uprising convective gas flow velocity from fire installed at a 3.5 m height, as illustrated in Figure 4. The mass-loss rate is measured continuously using the load cells installed at 3 points beneath the test stand with a precision of 10 gr, connected to the summing junction, before connection to the digital indicator.Two trays of denatured alcohol (96% v/v) each containing 200 ml and four trays each containing 250 ml, were used to ignite the Ivy and the Grapevine plants, respectively. The reason for utilizing the trays of alcohol is to imitate the fire in the understory in wildfires and use a sustainable energy source to keep the fire lit in the primitive stages of the experiments.

The dry basis moisture content of each species was measured based on the mass difference between the wet and oven-dry conditions for both pre and post-burn cases as reported in Tables 3 and4**,** as follows

Table 3 – Details of the samples of the Ivy.

	Pre-burn			**Post-burn**		
Plant segment	m_0 (g)	m_f (g)	FMC_d (%)	m_0 (g)	m_f (g)	FMC (%)
Foliage	177.10	63.23	1.80	98.79	54.86	80
0 < Ø < 3 mm	517.60	299.57	0.73	197.84	129.13	53
3 < Ø < 6 mm	300.33	122.44	1.45	281.86	150.64	87
6 < Ø < 10 mm	365.00	166.60	1.19	208.22	93.60	122
Ø > 10 mm	2350.00	973.70	1.41	3202.75	1461.60	119

Table 4 – Details of the samples of the Grapevine.

	Pre-burn			**Post-burn**		
Plant segment	m_0 (g)	m_f (g)	FMC_d (%)	m_0 (g)	m_f (g)	FMC (%)
Foliage	368.99	137.29	1.69	52.14	31.38	66
0 < Ø < 3 mm	62.32	22.89	1.72	13.22	8.08	64
3 < Ø < 6 mm	147.33	60.82	1.42	93.46	51.90	80
6 < Ø < 10 mm	33.68	17.52	0.92	18.18	13.86	31

In Tables 3 and 4, m_0 is the initial mass, m_f is the final oven-dry mass in grams, and FMC_d is the dry basis moisture content. Different classes of species' segments are divided into 5 categories: i) foliages; ii) parts with a diameter/thickness (Ø) less than 3 mm; iii) from 3 to 6 mm; iv) 6 to 10 mm; and v) larger than 10 mm for both pre and post-burn cases.

4. FDS Modeling

4.1. The Computational Domain

To study the fire behavior and specifically the heat release rate, as an important factor from each species, the structured, staggered grid is generated for two computational domains. For the Ivy case study, the 3D sketch corresponds to Figure 1, and the domain has a dimension of 0.9 m × 1.0 m × 3.7 m in the x, y, and z directions, and contains 3,971,968 grid cells as illustrated in Figure 5, with two trays of alcohol (colored in red). The computational domain for the Grapevine corresponds to Figure 2 and has a dimension of 6.0 m × 6.0 m × 6.0 m in the x, y, and z directions, containing 2,979,200 mesh cells, as depicted in Figure 6. In this case, four trays of alcohol were used to ignite the plant. The details of the samples correspond to the Case Nº 2 of the laboratory tests reported in Tables 1 and 2.

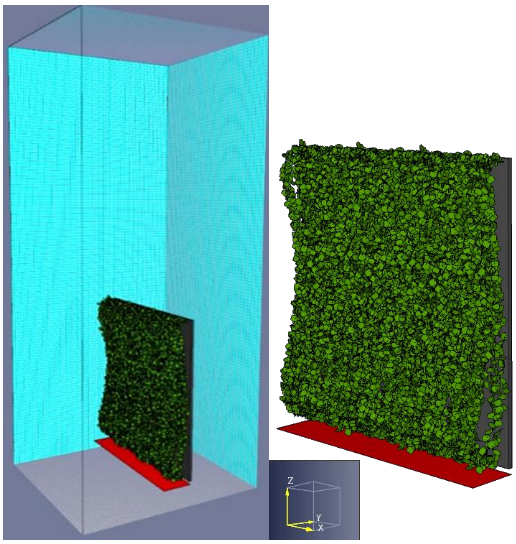

Figure 5. 3D Computational Model, Ivy.

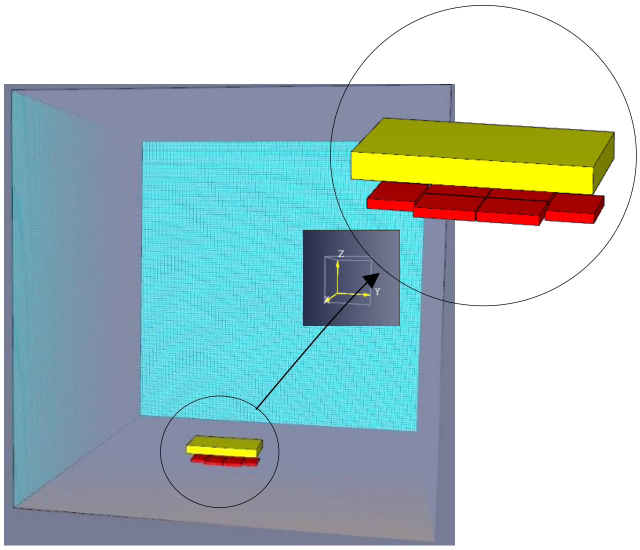

Figure 6. 3D Computational Model, Grapevine.

The boundaries of the CFD of fire in both plants correspond to the details mentioned in Tables 1 to 4. The 3D model for the Ivy is sketched in 3D-CAD SOLIDWORKS software. In the second stage, the geometry is translated into the parallelepiped volume using MATLAB code. In the Grapevine test case, the Lagrangian particle cloud approach is used to model the presence of leaves and twigs along with a possibility for the flow penetration through the cuboid. In both cases, the XY planes beneath the sample are set to be solid and adiabatic, while other boundaries are set as air vents to allow the passage of flows from either side corresponding to the test conditions.

5. Results and Discussion

The FDS simulations of both plants were performed using the equivalent hydrocarbons with CHON contents of 1.0, 1.7, 0.72, 1.0E-3, and 2.0, 3.7, 0.72, 1.0E-3, for the Ivy and the Grapevine, respectively. The Ivy plant is simulated as a porous obstruction with a 3D configuration inspired by the factual test sample. The Grapevine is modeled using the Lagrangian particle cloud method. The plant is simulated as an ensemble of 4 different classes mentioned inTable 4. The results of the transient LES simulations for both cases are demonstrated in Figures 7 and 8 for the corresponding time-lapse of 0, 5, 15, 20, and 40 seconds in both real-time laboratory experiments and CFD simulations. The heat release rate from FDS for each case study is compared with the corresponding HRR from the laboratory tests conducted at LEIF, in Figures Figure and Figure .

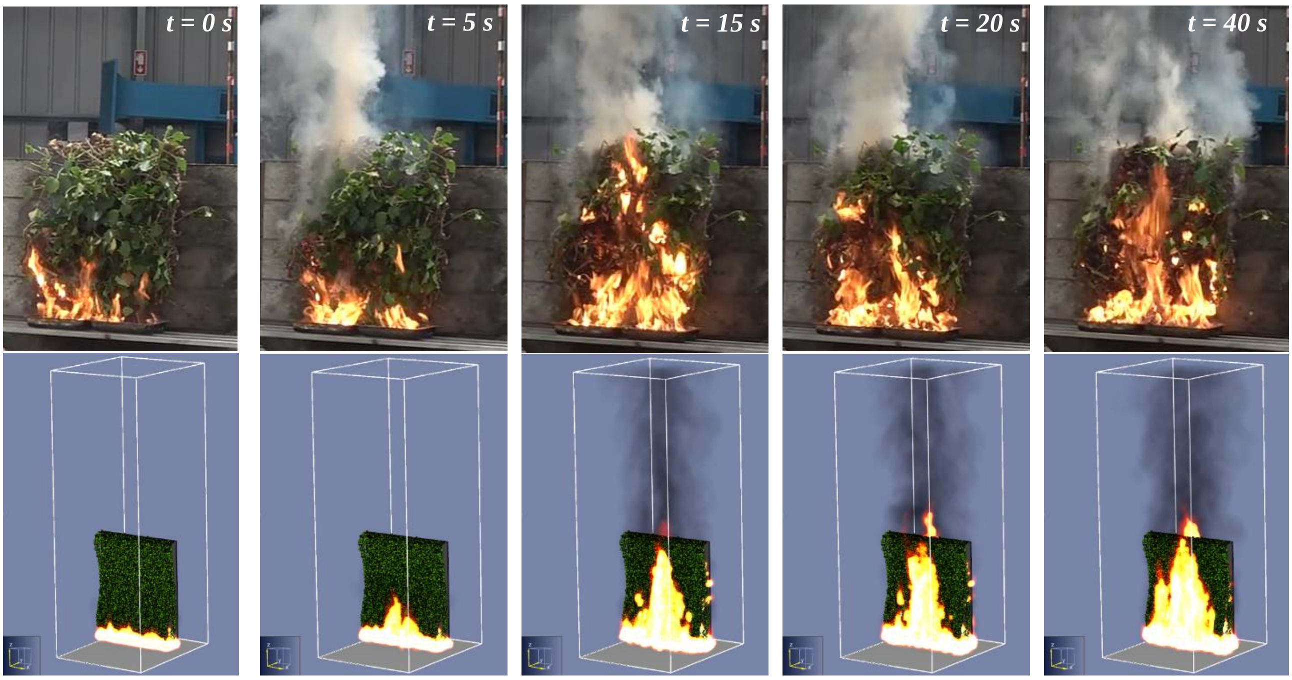

Figure 7. Comparison of the real-time lab experiments with numerical modeling from FDS for the Ivy plant at 0; 5; 15; 20; and 40 s.

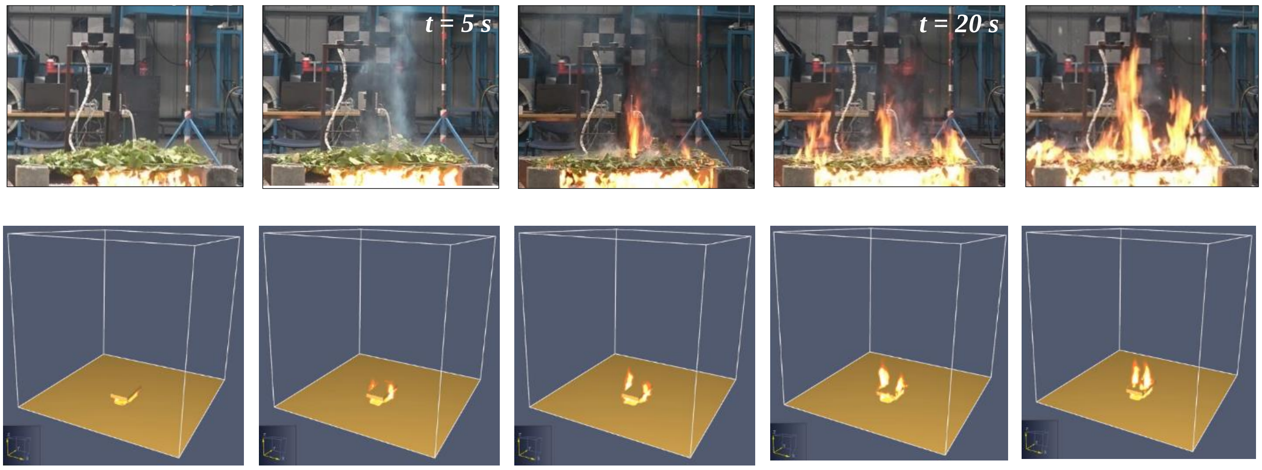

Figure 8. Comparison of the real-time lab experiments with numerical modeling from FDS for the Grapevine plant at 0; 5; 15; 20; and 40 s.

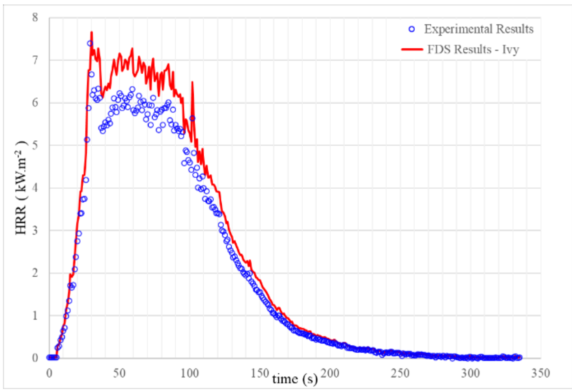

Figure 9. Comparison of HRR for experimental and numerical cases, Ivy.

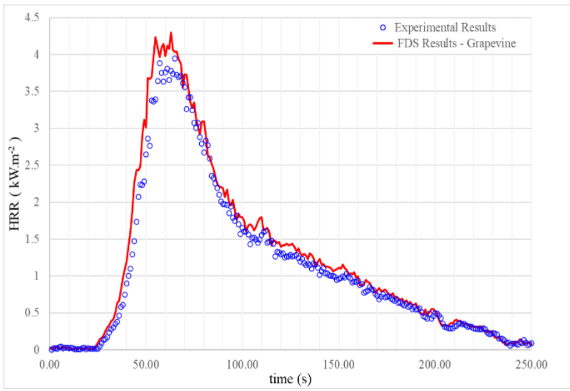

Figure 10. Comparison of HRR for experimental and numerical cases, Grapevine.

6. Conclusion

In this paper, both experimental and numerical modeling of the fire behavior for the Ivy and the Grapevine plants are addressed. Utilizing the capability of FDS in the simulation of fires can be very helpful for fire researchers and experts. The heat release rate from each vegetation species is an important factor that needs to be analyzed for further fire risk analysis and management. Since FDS solely cannot materialize this goal, experimental observations for reliable fire calculations are mandatory. Modeling the fire behavior using the FDS, developed by NIST, the authors could simulate the fire behavior in two forest species with a promising agreement with the experimental data. Moreover, the authors have carried out multiple experiments using different types of plants indigenous to the Mediterranean climate, especially in Portugal. For future work, it is intended to perform FDS modelings based on the available laboratory data to have a complete database for thermal characteristics of the vegetation fuels, their interactions with the surrounding environment, and their contribution to the wildfires. Last but not the least, the final purpose of the ongoing reach is to categorize the forest species as less vulnerable to the hazardous types which can jeopardize lives and residential sites, especially in WUI regions.

7. References

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