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NUMERICAL MODELLING OF FIRES ON FOREST FLOOR AND CANOPY FIRES

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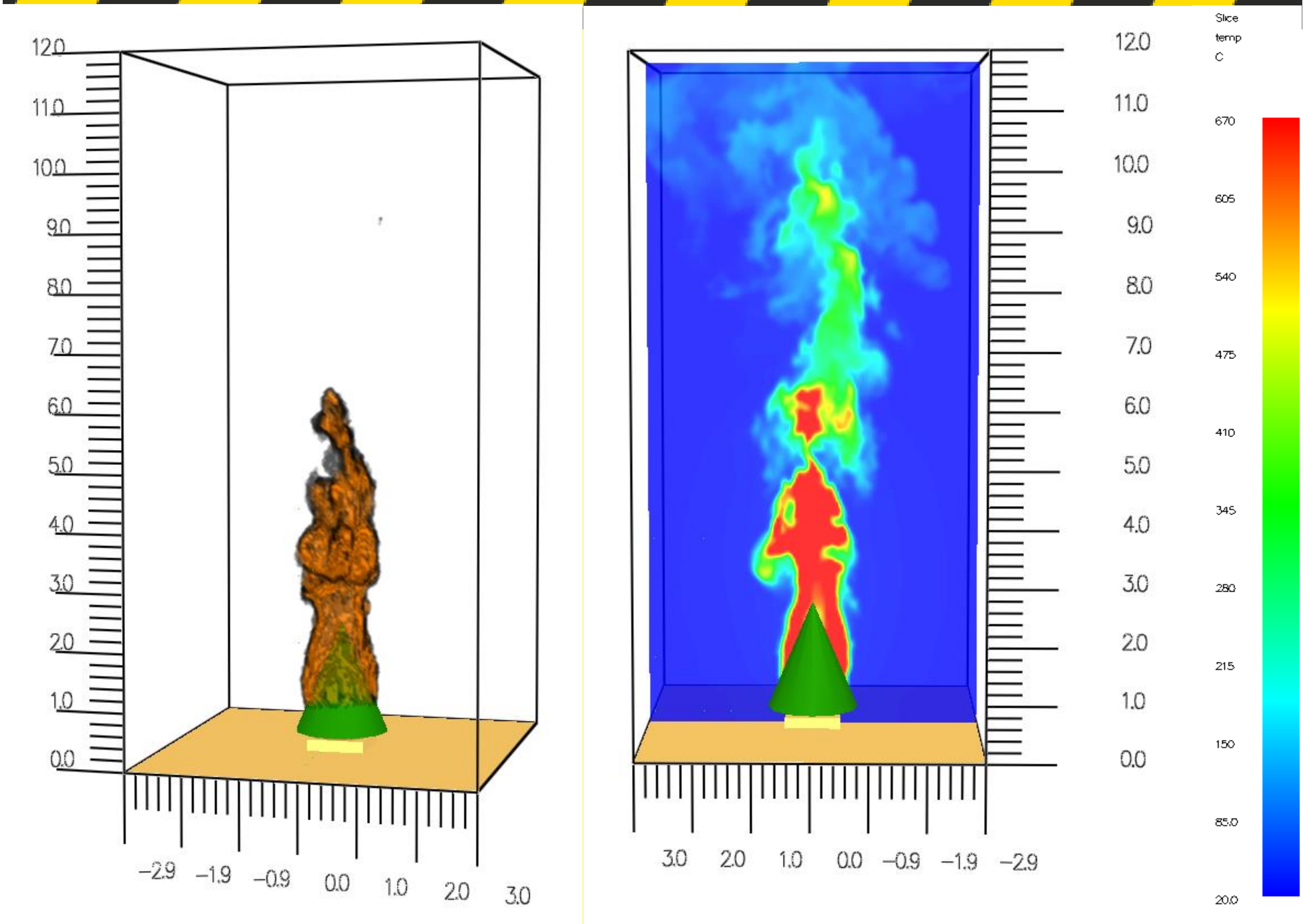

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Cover: Graphical representation of Douglas fir tree burns simulation using WFDS.

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ABSTRACT

The Wildland Urban Interface Fire Dynamics Simulator (WFDS) is a physics-based fire model developed by the US Forest Department and to simulate fire spread in landscapes. It is an extension of National Institute of Standards and Technology (NIST) building fire model Fire Dynamics Simulator (FDS). Currently both models have the capability to model surface fire as well as crown fire. Both quantitative and qualitative analyses are important for further advancement. This study shows that for quantitative analysis, grid convergence is not elusive and the grid converged solution agrees well with the experimental result involving ignition of a Douglas fir tree. The WFDS model is also capable of qualitatively predicting propagation of surface fire to the forest canopy.

KEYWORDS: Wildland fire, WFDS, physics-based modelling, canopy, grassfire

INTRODUCTION

Wildland fires/bushfires are the uncontrolled spread of fires that could occur in areas of the countryside or wilderness. In recent events, bushfires have encroached on the built environment causing injuries, fatalities and loss of property. The fires caused in these areas can also impact on the viability of the surrounding areas. This includes disruption in water supplies due to erosion and contaminants caused by the fires. The incidence of fires attracts much public concern and fires are given considerable attention by the media due to their devastating effects. This is exemplified by the cases of Black Saturday (2009) and Ash Wednesday (1983) in Australia and the 2009 bushfires in Athens and Los Angeles. Therefore it is important to conduct studies on the behaviour of fire spread, although this would prove extremely difficult since the sizes and rate of spread depends on numerous factors.

Wildland fires/bushfires can be surface fire such as grassfire or crown fire. Usually crown fires are originated from surface fires spreading either along the barks of the tree trunks or direct flame contact to low branches with leaves and needles. In the previous study [1], grassfire spread simulation was successfully conducted using physics based model, Wildland Urban Interface Fire Dynamics Simulator (WFDS). It is important that its capabilities of tree and forest canopy fire are explored. In this part of the project, we have first studied a single tree burning quantitatively and then qualitatively studied forest floor fire leading to a crown fire.

For tree burning simulations, experiments conducted at National Institute of Standard and Technology (NIST) in which Douglas fir was the selected tree species are considered [2]. During the NIST experiments, 2m high trees were mounted on custom stands and allowed to dry. Based on the moisture content in each sample, the 2m trees were grouped into two (moisture content averages of 14% and 49%). Trees were ignited using a custom igniter (circular natural gas burners with a specific heat release rate of 30 kW). The mass was measured and the mass loss rate calculated taking into consideration the moisture content in the samples. We have used two thermal degradation sub-models to simulate tree burning – WFDS (Linear) [2-3] and FDS (simplified Arrhenius) [4]. Both models have the same fluid flow, turbulence, continuity, pressure, energy, radiative heat transfer and combustion models. They also use fuel description model in the similar way. The main difference is in thermal degradation sub-model which will be discussed in the next section.

FIGURE 1: BURNING OF 2.4M TALL
DOUGLAS FIR

Figure 1 shows the experimental snapshots of the above mentioned experiments.

MODEL OVERVIEW AND INPUT PARAMETERS

WFDS and FDS use a Computational Fluid Dynamics (CFD) methodology to solve the governing equations for buoyant flow, heat transfer, combustion, and the thermal degradation of vegetative fuels and Large Eddy Simulation (LES) techniques are used to account for turbulence [4]. The model aims to include fire spread through vegetative fuels. Vegetative fuels can include those characteristic of bushlands i.e. trees, grasses, understory growth, and ground litter as well as those purchased at nurseries for home or community landscaping purposes such as trees, mulch, grasses, and decorative plants.

FUEL (VEGETATION) MODELS

The models have two ways of modelling vegetative fuels, namely (i) the fuel element (FE) model for vegetation that occupies a specified volume such as trees (for example, Douglas fir trees are modelled as cones [2]) and (ii) the boundary fuel (BF) model for surface fuels such as grasslands [1].

With the FE model, trees can be modelled with various shapes: cone, frustum, cylinder and rectangle. Example of cone, cylinder and frustum shaped trees is shown in Figure 2 If we select any of these shapes we need to specify their dimensions as given in Table 1. This table also gives other physical parameters needed for the tree fire simulation. In the FE model, there is no distinction between solid phase and gas phase grid. Resolutions are the same for both phases. The fuel distribution within the tree (ie the leaves and twigs) is modelled as a cloud of burnable particles with specified properties.

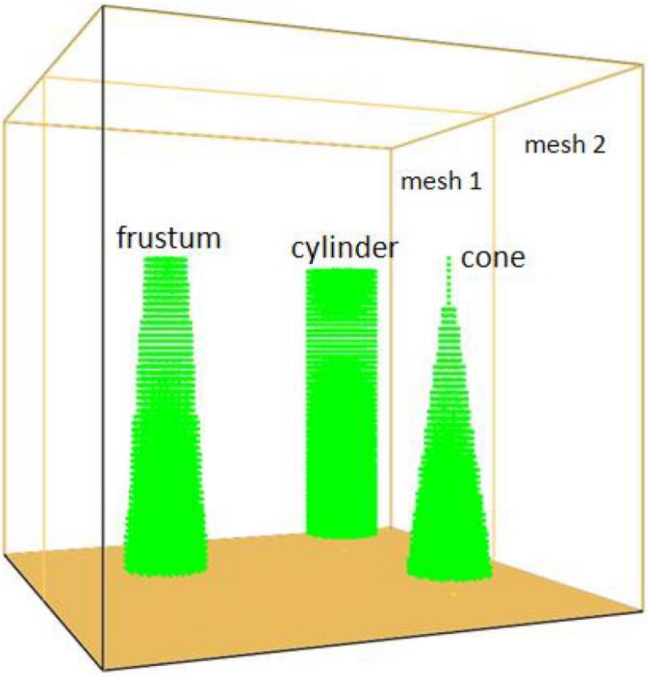


FIGURE 2: EXAMPLE OF CONE, CYLINDER AND FRUSTUM SHAPED TREES AS REPRESENTED BY THE FE MODEL (COURTESY DR WILLIAM MELL, US FOREST DEPARTMENT

The BF model treats fuel as a flat bed and above this the domain is used for gas phase. Within the fuel bed a sufficiently high spatial resolution is used to capture the vertical radiant heat transfer. However, the horizontal grid is the same as the gas phase and the accuracy of convective heat transfer will be heavily influenced by the gas phase grid resolution. The assumptions leading to the BF model are most consistent with large fires for which the majority of the heat release (and, therefore, radiant emission) occurs above the fuel bed (resulting in predominantly vertical radiant heat transfer in the thermally degrading fuel bed).

While BF model is the same in WFDS and FDS- the FE model is a bit different in the FDS. In this study, Douglas Fir tree crown is approximated as being cone shaped with four different sizes of particles in both models. In WFDS needles, 0-3mm branch, 3-6 mm branch and 6-10 mm branch are used and their properties are given in Table 1. They are differed by surface to volume ratio and vegetation bulk density. On the other hand, in FDS we used: foliage (length 0.05m and thickness 0.0005 m), small roundwood (length 0.1m and thickness 0.001 m), medium roundwood (length 0.1m and thickness 0.002 m) and large roundwood (length 0.1m and thickness 0.003 m) and all with cylindrical shapes. There are 100,000 particles of each type per unit volume and bulk densities are 2.0, 0.4, 0.3 and 0.5 kg/m^3, respectively.

TABLE 1: PHYSICAL PARAMETERS USED IN WFDS

Namelist	**Variable**	**Values**				**Units**	**Description**
		Needles	**0-3mm**	**3-6mm**	**6-10mm**		
		63%	13%	10%	14%		
PART	TREE	Text					.TRUE. or .FALSE.; whether the particle is vegetation.
	VEG_SV	3940	2667	889	500	m^{-1}	Surface to volume ratio of the vegetation element
	VEG_MOISTURE	0.14					Moisture fraction (mass of moisture in vegetation/dry mass of vegetation)
	VEG_CHAR_FRACTION	0.25					Fraction of char that develops from virgin dry virgin vegetation
	VEG_DRAG_COEFFICIENT	0.375					Non-dimensional multiplicative factor used to model drag
	VEG_DENSITY	514				kg/m^3	Vegetative fuel's density
	VEG_BULK_DENSITY	1.66	0.34	0.26	0.37	kg/m^3	Density of the bulk vegetation; mass of dry vegetation divided by the bulk volume that is containing the vegetation
	VEG_REMOVED_CHAR	Text					.TRUE. or .FALSE.; whether the fuel element is removed or kept once the thermal degradation has converted the vegetation to pure char
TREE	FUEL_GEOM	Cone					Shape of bulk volume that contains vegetation: RECTANGULAR, CYLINDER, CONE, FRUSTUM
	CROWN_WIDTH	1.65				m	Diameter, measured in meters relative to XYZ of the top of the bulk vegetation if the shape is cone, cylinder or frustum.
	CROWN_BASE_HEIGHT	2.25				m	Height, measured in meters relative to XYZ of the base or bottom of the bulk vegetation if the shape is cone, cylinder or frustum.
	CROWN_WIDTH_BOTTOM						Diameter, measured in meters relative to XYZ of the bottom of the bulk vegetation if the shape is frustum.
	CROWN_ WIDTH_TOP						Diameter, measured in meters relative to XYZ of the top of the bulk vegetation if the shape is frustum.
	TREE_HEIGHT	0.3				m	Height, measured in meters relative to XYZ of the top of the bulk vegetation if the shape is cone, cylinder or frustum

THERMAL DEGRADATION MODELS

There are two models for thermal degradation: ‘Linear’ and ‘Arrhenius’. Both are based on empirical studies. However, in this study only the linear degradation model is used which assumes a two-stage endothermic thermal decomposition (water evaporation and then solid fuel pyrolysis). For water evaporation, Eq 1 is used:

$$\text{If } T_s\text{=373 } K,\ \dot{m_{vap}} = \frac{\dot{Q_{net}}}{\Delta h_{vap}} \ \ldots\ldots\ldots(1)$$

where, T_s is the vegetation surface temperature, $\dot{m_{vap}}$ is the evaporation rate, Q_{net} is the net energy (convection plus radiation) on the fuel surface and Δh_{vap} is the latent heat of evaporation. It uses the temperature-dependent mass loss rate expression of Morvan and

Dupuy [5] (presented as Eq 2) to model the solid fuel degradation and assumes that pyrolysis begins at 400 K.

$$\text{If } 400\ K \le T_s \le 500\ K,\ \dot{m_{pyr}} = \frac{\dot{Q_{net}}}{\Delta h_{pyr}} \text{ x } \frac{\dot{T_s}-400}{500-400} \ \ldots\ldots\ldots(2)$$

where, $\dot{m_{pyr}}$ is the pyrolysis rate and Δh_{pyr} is the heat of pyrolysis (also known as the heat of reaction). Char oxidation is neglected in this model. With the Linear model, ignition and sustained burning occurs more ‘easily’ (i.e., at lower gas phase temperatures) because pyrolysis occurs over a lower temperature range. Because of this, coarser gas phase grid resolutions may be sufficient but requires that the user to supply a bound on the maximum mass loss rate per unit area or volume in the form of `FIRELINE_MLR_MAX` (kg/s/m^2), `VEGETATION_BURNING_RATE_MAX` (kg/s/m^3) or `VEGETATION_DEHYDRATION_RATE_MAX` (kg/s/m^3).

TABLE 2: THERMAL PARAMETERS USED IN WFDS

Variable	Values	Units
HEAT_OF_COMBUSTION	17,770	kJ/kg
SOOT_YIELD	0.015	kg/kg
VEG_INITIAL_TEMPERATURE	20	°C
HEAT_OF_VAPORIZATION	2259	kJ/kg
HEAT_OF_PYROLYSIS	416	kJ/kg
SPECIFIC_HEAT_CAPACITY	1.11 + 0.0037 Ts	kJ/kg/C
VEGETATION_BURNING_RATE_MAX	0.4	
VEGETATION_BURNING_RATE_MAX	0.4	

The ‘Arrhenius’ model used in WFDS/ FDS is described in [1] which employs a kinetic triplet to model thermal degradation. However FDS also has a simplified Arrhenius model which uses alternative parameters REFERENCE_TEMPERATURE, REFERENCE_RATE and HEATING_RATE [3]. We have termed this here as “simplified Arrhenius” model and used for simulation using FDS version 6.2.0.

HEAT TRANSFER MODELS

To calculate T_s for Eq 2, Eq 3 is solved:

$$\bar{\rho}_s C_s \frac{dT_s}{\mathrm{dt}} = D\frac{\partial^2 T_s}{\partial x^2} + h\left(T - T_s\right) + \phi_{Fl\rightarrow s} \qquad \text{.................(3)}$$

where, ρs^bar is the vegetation bulk density, Cs is the specific heat capacity, h is the convective heat transfer coefficient, Q_(Fl→s) is the radiant heat energy on the fuel surface and D is the thermal diffusivity of the vegetation. An empirical correlation (involving surface to volume ratio, □s, vegetation packing ratio known as leaf area density or fuel volume fraction, □s, conductivity of air, an empirical correlation obtained for laminar or empirical flow around a cylinder) is used to work out h to estimate convective heating of twig/grass/stuff materials, which are modelled as a collection of cylinders. Q_(Fl→s) is calculated using a ray-tracing method from advancing flame temperature.

$$Q_{Fl\rightarrow s} = \frac{\alpha_s\sigma_s}{4}\left(J - 4\sigma {T_s}^4\right) \;\text{......(4)}$$

J is the total irradiance calculated from ray-tracing method and σ is the Stefan-Boltzman constant.

The required parameters to solve equations (1-4) in WFDS are presented in Tables 1 and 2. Thermo-physical parameters used in FDS simulation is presented in Table 3. Heat of combustion and soot yield used are as given in Table 2. It is to be noted that in FDS, a different convection heat transfer equation is used.

TABLE 3: THERMO-PHYSICAL PARAMETERS USED IN FDS

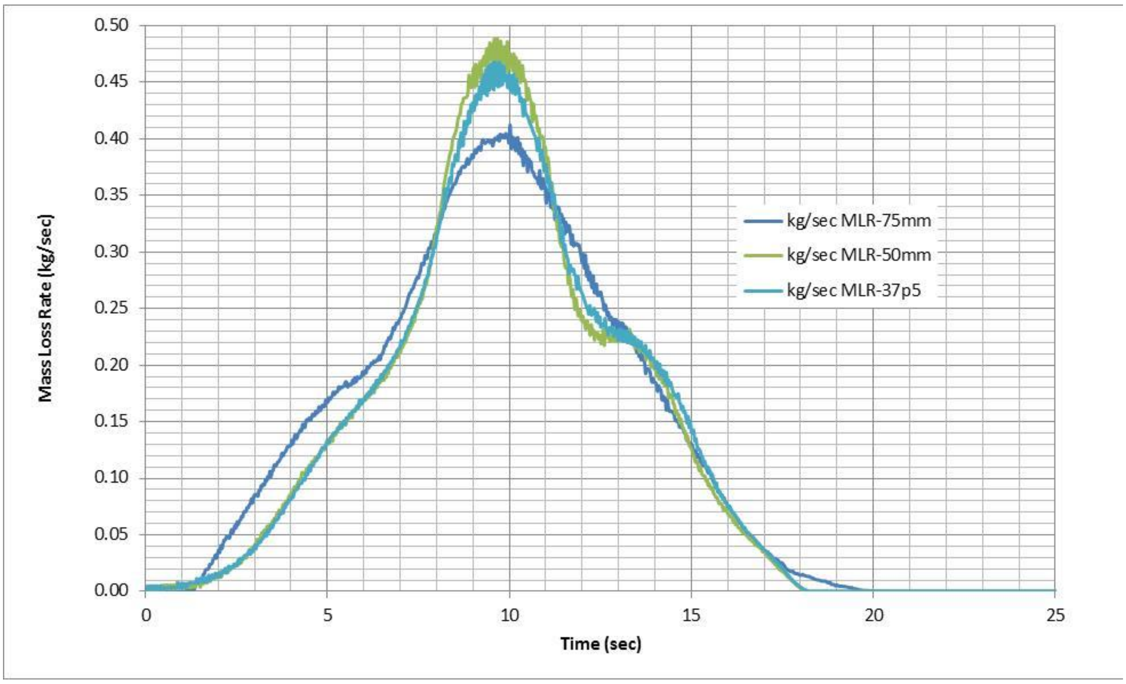
Parameters	Moisture	Vegetation	Char
Thermal conductivity (W/m.K)	2.0	2.0	2.0
Specific heat (kJ/kg.K)	4.184	1.2	1.2
Density (kg/m^3)	1000	514	300
REFERENCE_TEMPERATURE (oC)	100	200	350
REFERENCE_RATE	0.002	.0005	0.0002
HEATING_RATE (oC/min)	1.6	1.6	1.6
HEAT OF PYROLYSIS (kJ/kg)	2500	418	418
MASS FRACTION	0.123	0.649	0.228

RESULTS AND DISCUSSION

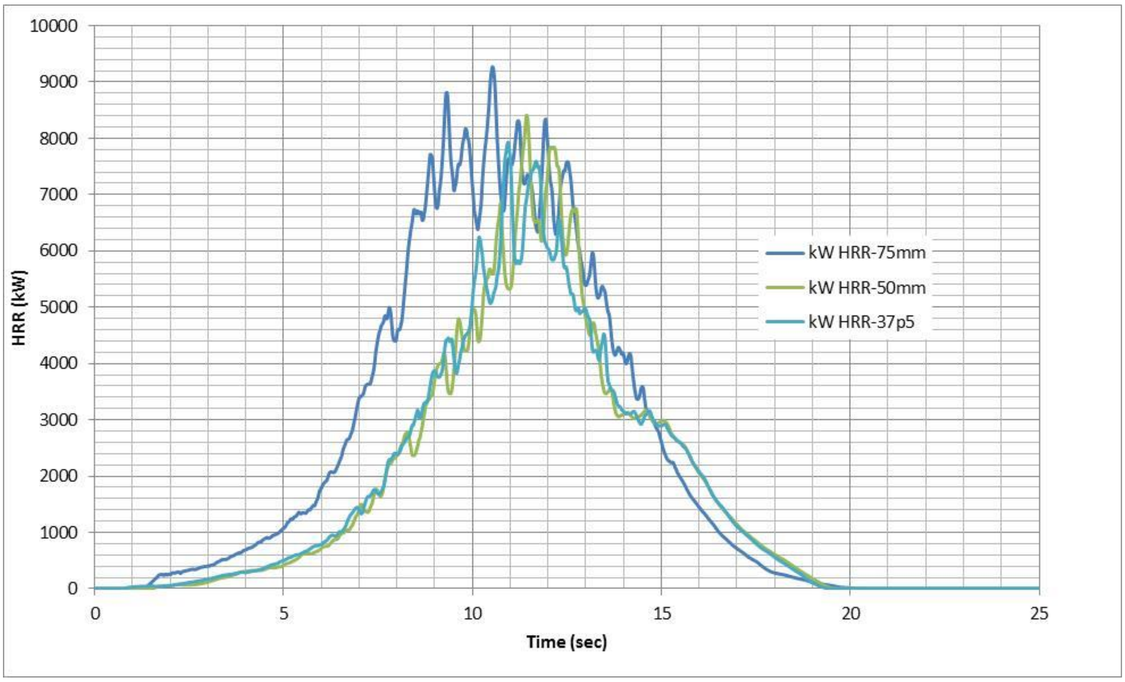
DOUGLAS FIR TREE FIRE – QUANTITATIVE ANALYSIS

The choice of the size of the grid (cell) in a mesh is one of the first and most important decisions one must make when conducting a quantitative simulation. The choice of grid size can affect the results. In conducting physics-based analysis it is essential to undertake a grid refinement process by gradually reducing the grid spacing (cell size) used in the simulation to examine the effect on the predicted outcome. It is usual to find that as the cell size is reduced the results converge to the solution of the spatially and temporal continuous governing equations on which the analysis is formulated. Further reducing the cell size has virtually no effect on the results produced and this result is known as a grid-independent result.

The first step in a grid convergence study is to compare the Mass Loss Rate (MLR) and Heat Release Rate (HRR) results of the same simulation but with finer grid sizes. We conducted similar study with WFDS's version 4 [6] in terms of HRR and we found that grid convergence was elusive. However, the developers of FDS/ WFDS claim that the current version (version 6) is less grid sensitive due to use of alternative LES model, new near-wall model, new combustion model and some bug-fixing. We have selected 75 mm, 50 mm and 37.5 mm grid cells for WFDS_9977 version and 100 mm, 50 mm and 37.5 mm grid cells for FDS 6.2.0 version.



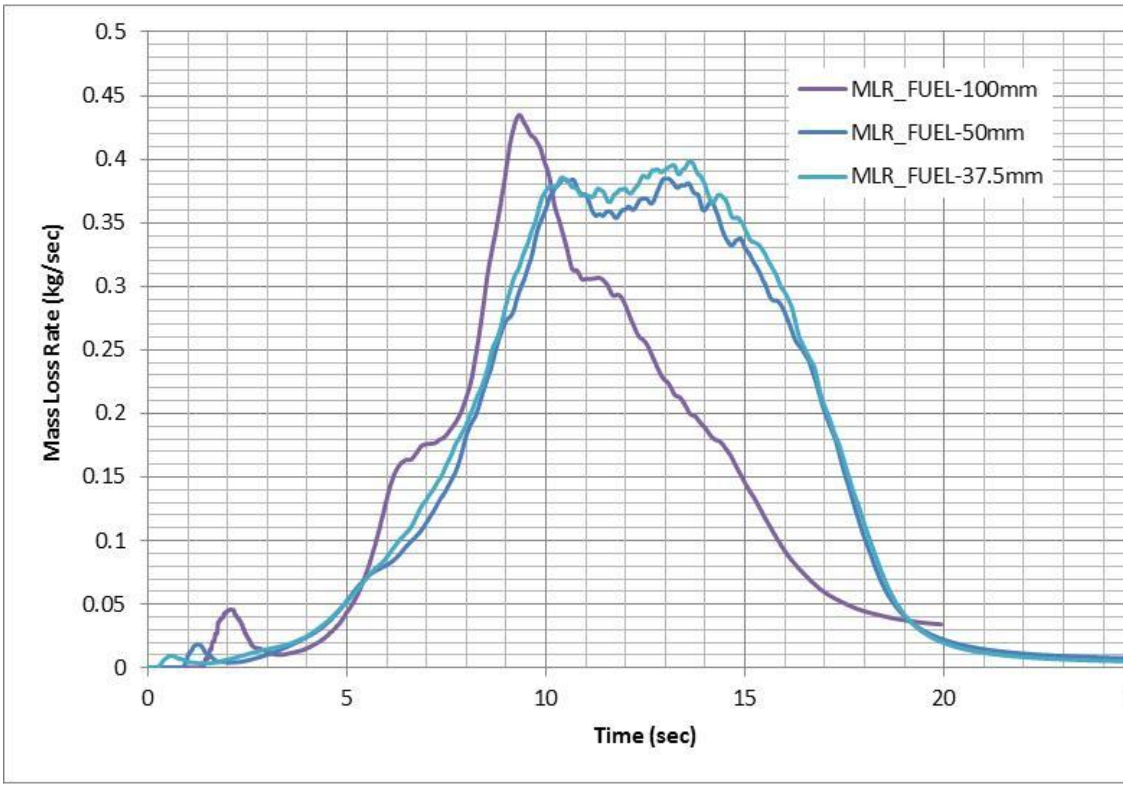
(a)MLR result



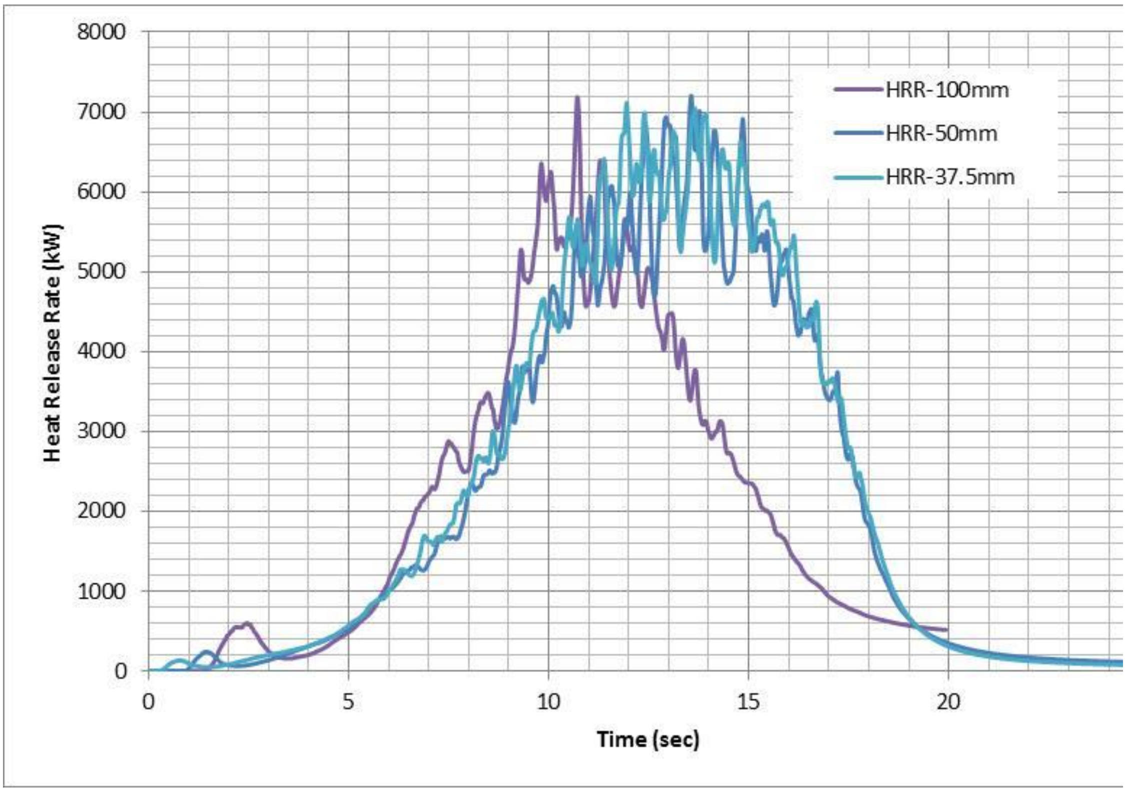
(b) HRR results

FIGURE 3: COMPARISON OF RESULTS FOR 2.25M DOUGLAS FIRE TREE SIMULATIONS FOR GRID SIZES: 75MM, 50MM AND 37.5MM - SIMULATION WITH WFDS_9977

The MLR and HRR results are compared for the three simulations of the 2m Douglas fir tree with WFDS_9977 in Figure 3. It can be observed that for both parameters the results from 50mm grid and 37.5 mm converges. Similarly these parameters obtained using FDS 6.2.0 are presented in Figure 4. Once again convergence is deemed to obtained with 50 mm grid.



(a) MLR result



(b) HRR results

FIGURE 4: COMPARISON OF RESULTS FOR 2.25 M DOUGLAS FIR TREE SIMULATIONS FOR GRID SIZES: 100 MM, 50 MM AND 37.5MM – SIMULATION WITH FDS 6.2.0

The MLR results from grid converged simulations (where 50 mm grid cells are used) of the 2.25m Douglas fir tree with the experimental data in Figure 5. The simulation results are shifted towards the left by 1.5 sec to roughly match the peak. It can be observed that the area under the curve is roughly the same. The averaged total mass loss from nine experiments was 3.62 kg. It is exactly the same for FDS 6.2.0 simulation. However it is roughly 12% less while the simulation is conducted with WFDS_9977. It may be due to the fact that lower bulk densities are used for WFDS simulation.

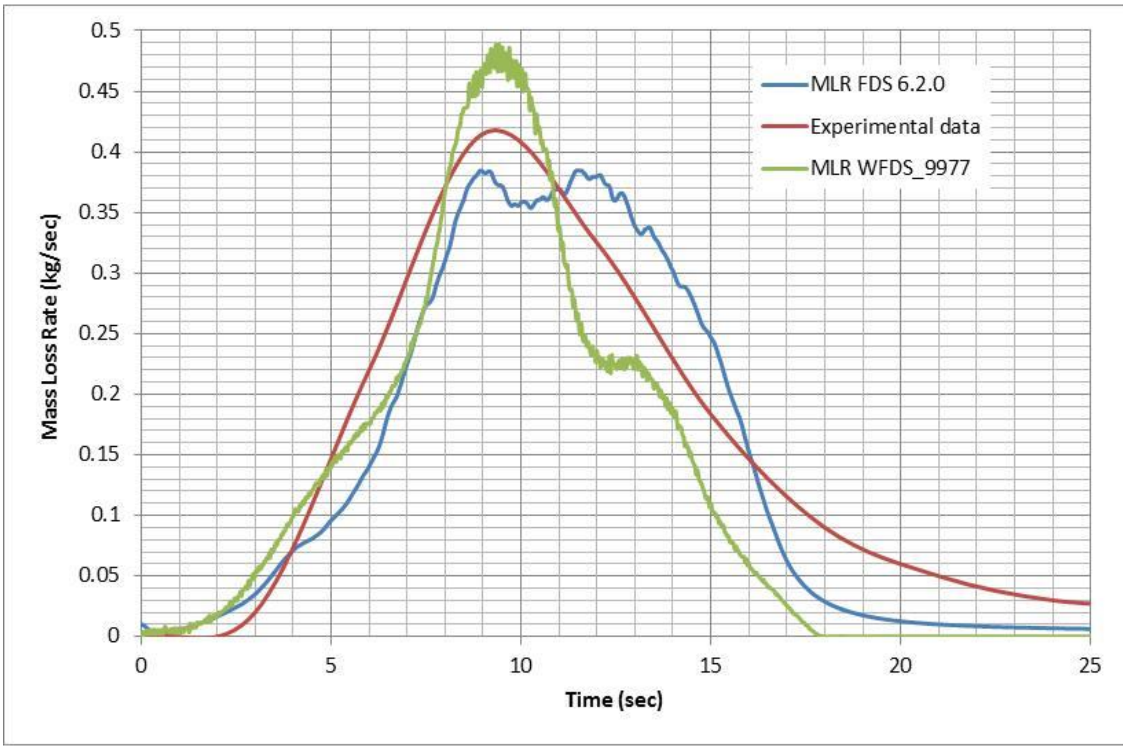


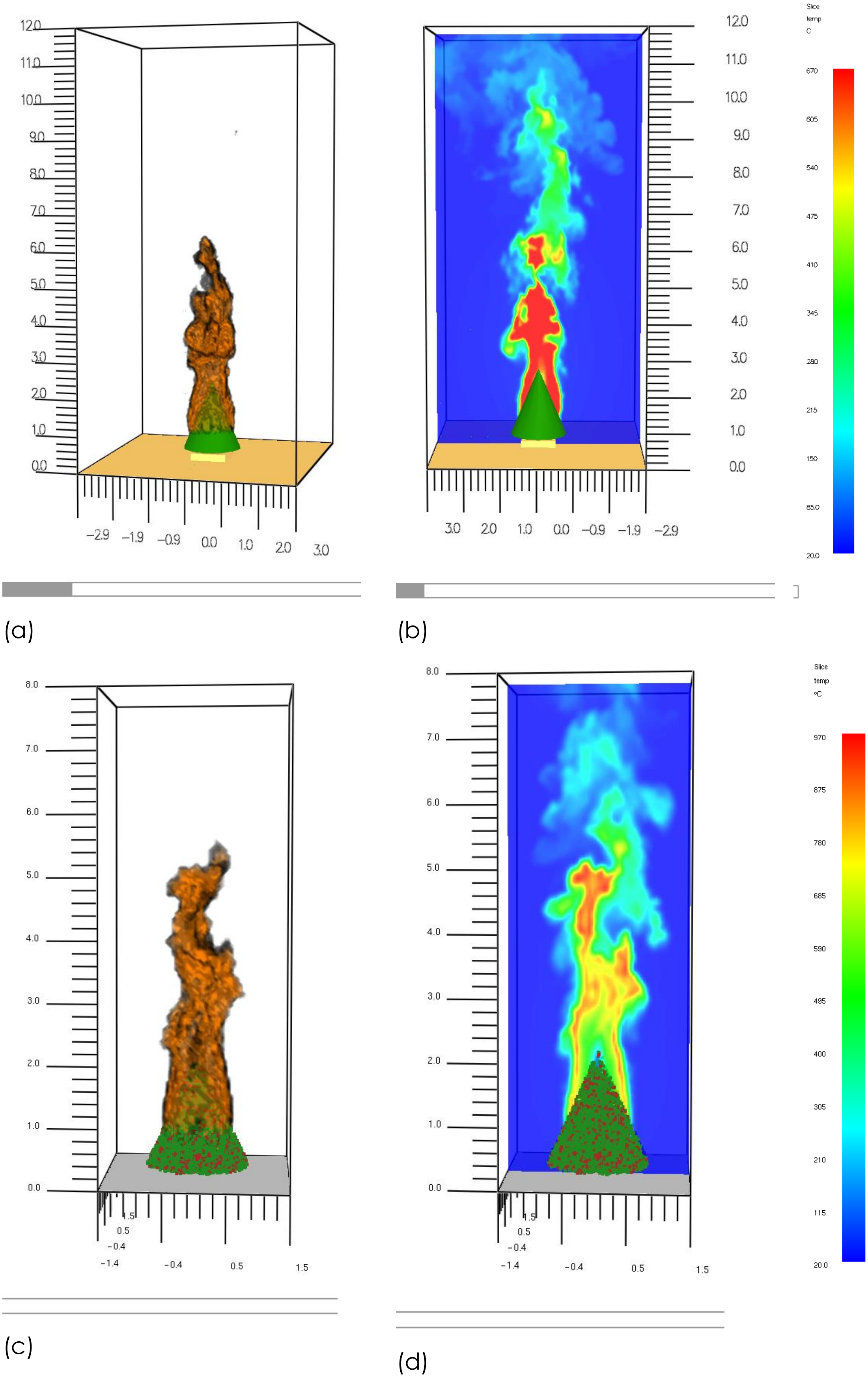
FIGURE 5: MLR RESULTS COMPARISON WITH EXPERIMENTAL DATA [2] - BOTH NUMERICAL RESULTS ARE SHIFTED BY 1.5 SEC

Figure 6 shows snapshots of simulations of a 2.25 m tall tree using WFDS' companion graphical output software Smokeview [7]. The left column is an isosurface representation of HRR and the right column are temperature slices to show the gas-phase temperature. The results are pretty similar (flame height etc) and it is unlikely that both models would give identical flame contour results.

FOREST FLOOR AND CANOPY FIRE – QUALITATIVE ANALYSIS

With successful quantitative simulation of 2.25m Douglas Fir tree along with achieving numerical convergence, we now attempt to model a scenario where forest floor fire interacts with tree canopy. We have used WFDS due its lesser computational resource requirement. As FDS needs 100,000 particles of each type of vegetation parts per unit volume, it needs enormous computational resources to model a number of trees.

We have modelled a forest of Douglas Fir trees sitting on a grassland. This is absolutely a hypothetical scenario (may not be practical, though possibly it can be a model of a plantation) to assess whether fire can progress from the surface to the crown. The simulation domain is 96 m long, 8 m wide and 10 m high as shown in Figure 7. The inlet is prescribed as power law (1/7) ABL with a wind speed of 3 m/s at 2 m. Two lateral edges are modelled as periodic.



(a)

(b)

(c)

(d)

FIGURE 6: GRAPHICAL REPRESENTATION OF DOUGLAS FIR TREE BURNS SIMULATION. THE RESULTS FROM THE WFDS SIMULATION IS DEPICTED IN (A) AND (B) AND FROM FDS IS DEPICTED IN (C) AND (D).

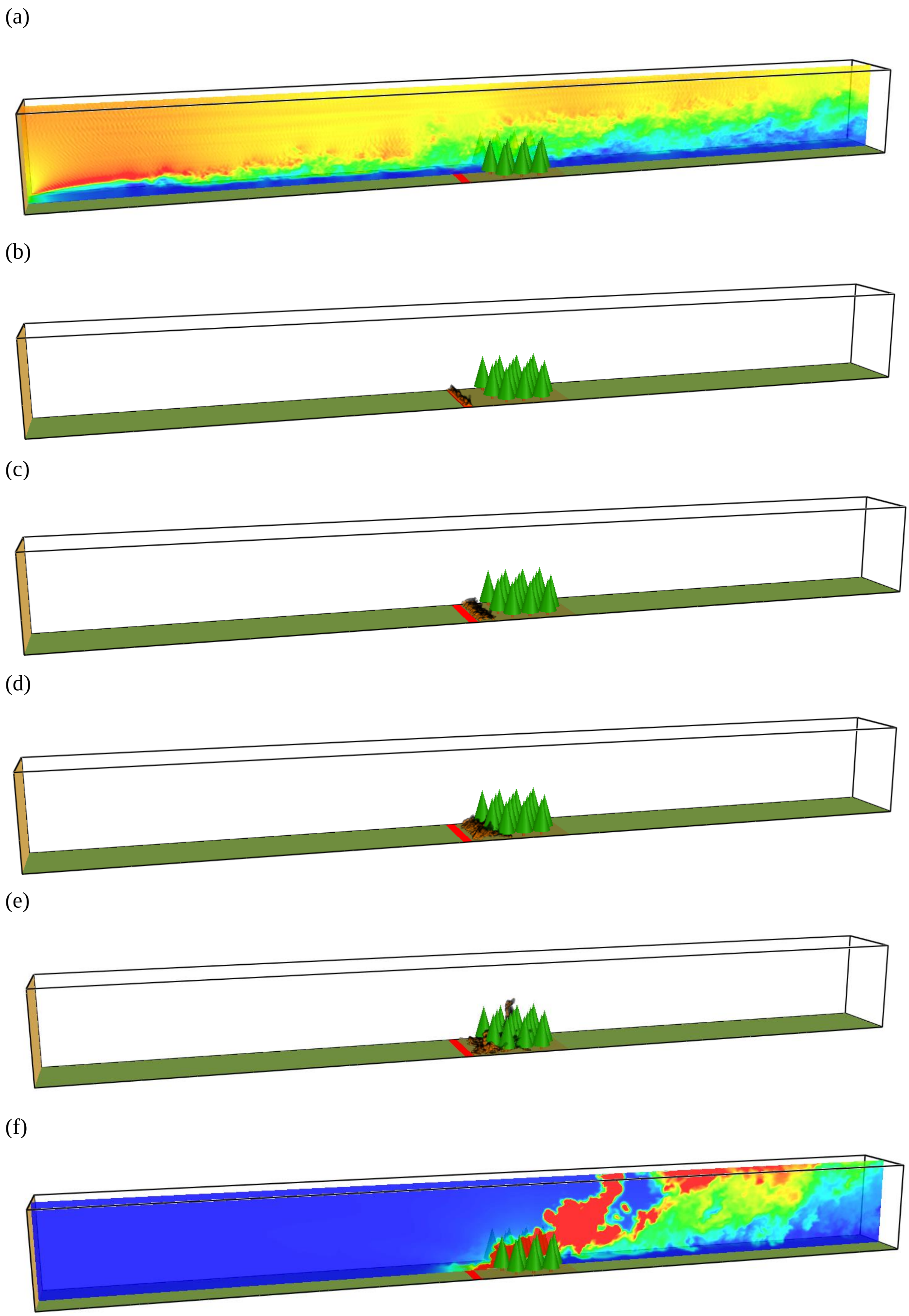


FIGURE 7: GRAPHICAL REPRESENTATION OF SURFACE FIRE-CROWN INTERACTION SIMULATION. (A) ESTABLISHMENT OF ABL, (B) IGNITION OF THE SURFACE FIRE (C) STEADY STATE SURFACE FIRE (D) SURFACE FIRE APPROACHING CANOPY FIRE (E) CANOPY FIRE IS ESTABLISHED (F) REPRESENTATION O

The outlet and top of the domain are modelled as open. 44 m from the inlet in the longitudinal direction, the burnable grass plot (12 m long) is placed so that there as another ~40m subdomain downstream of the plot before reaching an open outlet. 100 mm x 100 mm x 100 mm grids are used throughout.

Four longitudinal columns of Douglas Fir trees were modelled. The crown was approximated as cones and the trunk as cylinders. For simplicity the crowns are modelled only as needles with 2.2 kg/m^3 bulk density. Alternately columns had three and four trees in staggered fashion. The columns are 2m apart and within the column, the trees are also 2m apart. Prior to actual simulation of fire line spread, a precursor simulation was carried out to map atmospheric boundary layer (ABL) above the grassland within the simulation domain. An established ABL can be observed in Fig 7(a) (before it impacts on the canopy). Upon establishment of ABL, the surface fire is ignited along lateral line of 1m width with 500 kW/m^2 heat release rate per unit area (Fig 7b). Fig 7(c) shows steady state surface fire, whilst surface fire approaching canopy fire is depicted in Fig 7(d). Established canopy fire is shown in Fig 7(e) and gas-phase temperature at that instance is represented in Fig 7(f).

FURTHER WORK

A wild fire can be quantitatively simulated using a mixture of fuels and the rise in temperature due to radiation at various distances from the fire front can be predicted. By changing the properties of fuels, simulation of native Australian vegetation can be attempted. These can be used to test the accuracy of the model in predicting scenarios similar to events such as those on Black Saturday, where entire houses began to burn simply from radiation effects. However, these simulations can be computationally very expensive.

CONCLUSIONS

This study is a first step into understanding the capabilities of physics-based models FDS and WFDS establishing its capability of producing grid-converged results for fuel element models. A 2.25 m Douglas fir tree burning experiment conducted at NIST has been used to benchmark models' capability. Both models produced grid converged results of both mass loss rate and heat release rate which is a large step forward from its version 4. In the second step of the study a scenario where forest floor fire interacts with tree canopy is modelled using WFDS where forest floor fire was modelled using boundary fuel model whilst the forest is modelled as fuel element. The simulation shows that WFDS can qualitatively predict propagation of surface fire to the forest canopy.

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