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A comparative study of wind fields generated by different inlet parameters and their effects on fire spread using Fire Dynamics Simulator

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Abstract

Wind is one of the most important environmental variables that affects the wildland fire spread and intensity. Modelling wind in physics-based models such as Fire Dynamics Simulator (FDS) has been shown to reproduce promising results. There are various methods available to generate wind field in FDS. The current paper deals with finding out a better approach to assign inlet conditions for fire simulations in FDS. Firstly, we explore some basic methods of wind field generation available in FDS. The conventional methods of wind field generation are either an unperturbed inlet profile with a roughness-trip or the by embedding artificial turbulence at the inlet. The wind fields generated by these inlet conditions are compared with each other as well as to the wind field generated using a mean-forcing method for neutral atmospheric conditions. Secondly, we use these inlet conditions to study the effects of fire spread in FDS, since simulating the fire plumes is not compatible with periodic boundary conditions. Finally, we test the effect of an underdeveloped boundary layer on fire spread.

Introduction

Wildland fires occur very frequently in Australian weather conditions, especially during late spring to mid-autumn and impacts people living in the so-called wildland-urban interface. The frequency of these fires has amplified considerably due to further climatic changes [1]. These wildland fires are a resultant of many environmental factors, among which wind speed is the predominant one [2]. Therefore, accurate prediction of wind is required for accurate fire behavior prediction. Several types of models have been developed for predicting fire behavior, among which physics-based models [3] has been shown to reproduce adequate Atmospheric boundary layer (ABL) flow over flat ground and tree canopies [4]. In the current study, we have used FDS, version 6.6.0, which is a computational fluid dynamics (CFD) model of fire-driven fluid flow and the detailed description of this model can be found in [5]-[6].

The physics-based wildland fire simulations are driven by the inlet and initial boundary conditions which models the ABL. A realistic representation of ABL is required to reproduce a correct manifestation of fire in terms of rate-of-spread, intensity and heat transfer. The inlet and initial conditions prescribed for the simulation preferably leads to a realistic flow over the fire-ground which does not nonphysically develop in space and time. For example, *Mell* [7] used a 1/7-power-law model at the inlet of their simulations. Due to initial perturbations in the simulation, a fully turbulent flow profile will develop in time and space as the simulation progresses. The spatial and temporal development of wind flow comes with the cost of computational intensiveness to reach a fully developed profile prior to the start of the fire. Development of techniques for imposing inlet and initial conditions for flow simulations has been a topic of interest in the field of fluid dynamics [8].

Wind can be generated with various initial and inlet conditions with FDS. One way to generate inlet condition is the recycling method of [9]. While this method is an effective way of generating a fully developed inlet condition on a single turbulent inlet such as that required for a channel flow, we aim to eventually develop a one-way nesting method for fire simulation in future, so that complicated wind fields which may change direction during the simulation can be used. The current study can be subdivided into two parts. In the first part, we will deal with the methods of wind generation. The wind can be developed either by introducing an unperturbed log-law or power-law inlet profile with a roughness trip or by superimposing eddies at the inlet with the log-law or power-law wind profile. Wind field can also be generated by using a 'mean-forcing' method following usual log-law profile. This study is limited to neutral atmospheric conditions only. The second part of this study will deal with the fire behavior. Fire simulations will be carried out using these inlet conditions and the rate of fire spread and heat-release-rate will be compared. We will also see the behavior of fire when the fire is set in an undeveloped and non-steady ABL condition. The primary intention of this study is to discover the fastest method for generating a stable wind profile which can give consistent fire spread results.

Methodology

We tested the effectiveness of our boundary condition implementation through simulations in channel-flow configuration. The reference simulation used in this study is the wind field generation using the 'mean-forcing' method. In this method, FDS adds a mean-forcing term to the momentum equation to 'nudge' [5] the flow in the direction of specified wind velocity. In this case we need to provide any specific inlet conditions, as log-law is used by default for wind generation. The log-law can be given by equation(1)

$$u(z) = \frac{u_*}{\kappa}[ln\frac{z}{z_0}] \qquad (1)$$

where $u(z)$ is the wind velocity at height z, u_* is the friction velocity, κ is the *Von Kármán* constant which is taken to be 0.41, z_0 is the aerodynamic roughness length and z is the distance to the bottom wall.

The second wind field generation approach deals with the most commonly used method of wind generation; namely allowing the wind to develop naturally with the application of a roughness trip over the surface with a power-law profile enforced at the inlet. In this case, the wind develops over time and space and acquires turbulence eventually and finally reaches to a fully-developed flow condition. It takes a reasonable amount of time for the flow to develop a constant and steady ABL. To speed up the process, the Synthetic Eddy Method (SEM), which was originally developed by Jarrin et. al.[8], can be used in FDS, which accelerates the development of a uniform boundary faster than other methods such as physical trip. This comprises our third method of wind field generation. In this method *eddies* are injected into the inlet at random positions and advect with the inlet log-law velocity inflow which subsequently gets rescaled to match the desired turbulent characteristics. FDS uses the log-law as presented by [10]. The length, velocity scales and number of eddies are the parameters that the user supplies. Typically the velocity and the length scales of the eddies should be chosen in a way so that some turbulent statistics, usually Reynolds stresses, are reproduced. [11] says that the total number of eddies can be calculated using Equation(2).

$$N = max(\frac{V_B}{\sigma^3}) \tag{2}$$

where (σ) is the size of eddies, V_B is the box volume of the inlet where the eddies are embedded. As discussed in [12], the number of eddies N should be large enough to ensure the Gaussian behaviour of the fluctuating component in each direction. In this study, N is set to 200.

FDS simulates the fire by solving a system of equations including the Navier-Stokes equations for fluid momentum, Mixing-controlled chemistry for combustion and heat transfer by conduction, convection and radiation. To save the computational cost Large Eddy Simulation (LES) is used in which the filtered Navier-Stokes equations are solved and the effect of the cut-off scales are modelled. FDS uses the Deardorff model of turbulent viscosity by default. A detailed discussion about turbulent models and LES has been given by [10]. For combustion, FDS uses a Mixing-controlled combustion model which involves one gaseous fuel where transport equations for only the lumped species, i.e. fuel and products (such as O_2, CO_2, H_2O, N_2, CO and soot), are solved (the lumped species air is the default background). In the mixture-controlled method, single fuel species that are composed primarily of C, H, O, and N reacts with oxygen in one mixing controlled step to form H_2O, CO_2, soot, and CO. The reaction of fuel and oxygen is considered infinitely fast. Further details about this model can be found in [5]. Thermal degradation of solid fuel to gaseous fuel is modeled with a linear model following [13]. Radiation is accounted for by solving the radiation transfer equation with a discrete ordinates method. Convective heat transfer is modelled using a series of empirical correlations. Conduction is negligible for grassland fuels. References [6] and [5] gives further details about these models. At some critical points in calculations, like the moment of ignition, the limitations in the models or long time steps can lead to large local reaction rates, which can lead to numerical instabilities. An upper bound on the local heat release rate per unit volume needs to be maintained in order to prevent this. Following the scaling analysis of pool fires by [14], FDS 6.2.0 uses an upper bound following Equation(3):

$$q'''_{upper} = 200/\delta x + 2500 kW/m^3 \tag{3}$$

FDS 6.6.0 does not use a reaction rate threshold, instead expecting the computation to be sufficiently resolved to avoid such numerical instabilities. The resolution requirement is prohibitive for large-scale wildfire simulations. However, we introduce the threshold Equation(3) to be consistent with previous fire simulations [15] and to avoid restrictive grid resolution requirements. The fire simulations for the current paper has been conducted using this current edited version of FDS 6.6.0. There are two cases of fire simulations that have been performed for the current study. In the first case, the most widely used log-law inlet condition has been used, which is similar to the first wind simulation, and the fire is started after the upstream of the fire reaches a steady-state wind profile obtained from the wind simulations. The second fire simulation uses SEM introduced at the inlet, with conditions similar to the SEM wind simulation mentioned previously.

Simulation Domain

The size of the external domain is chosen such that it ensures to capture the largest relevant structures. The overall domain size for all the simulations is taken to be 130m X 40m X 80m. Inlet velocity of 4.7 m/s is given at a height of 10 m. The mean velocity of $\sim 5.5 m/s$ at fully developed state is maintained at 2m for all the simulations. 40 m from the inlet in the longitudinal direction, the burnable grass plot (40mX40m) was placed so that there was another 50 m subdomain downstream of the non-burnable grass plot before reaching an open outlet. The spanwise of the flow stream is set to periodic boundary conditions. In case of the fire simulations, a line fire is ignited which covers the width of the domain (along y) as used by [16]. The simulation domain has been divided into multiple meshes with different grid sizes. To avoid any numerical instabilities, the aspect ratio is maintained not more than 2 for any grid cell. The sub-domain with burnable grass plot has 0.25 m grid resolution in all direction throughout the height of the domain. The fuel parameters used in the simulations were replicated as done by Moinuddin et.al.[15]. Figure(1) represents a generalized domain used for all the simulations.

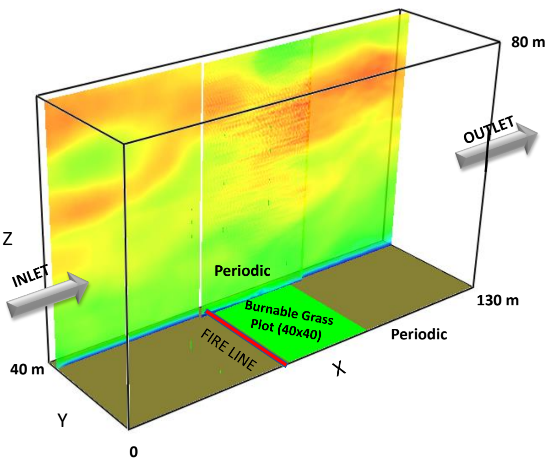


Figure 1: *Domain of simulation showing the dimensions, fire plot, fire line and establishment of ABL.*

All other relevant information regarding the wind simulations are given in *Table 1* and that for fire simulations are given in *Table 2*. The simulations will be depicted using the case names given in the table hereafter.

Table 1: *Wind Simulations*

Case name	Generation method	Mean profile	Turbulent profile
wind0	mean-forcing	Log-law	–
wind1	Roughness change-trip	1/7 Power law	–
wind2	Explicit log-law	Log-law	SEM

Table 2: *Fire Simulations*

Case name	Generation method	Mean profile	Turbulent profile
fire0	Underdeveloped ABL	1/7 Power law	–
fire1	Roughness change-trip	1/7 Power law	–
fire2	Explicit log-law	Log-law	SEM

Results and Discussions

Several numerical parameters like inlet conditions, domain size, grid resolution and boundary layer development time are considered for a systematic approach. In our study, we are considering a small domain, and our results are strictly according to the parameters that we have used. The results may vary with different domain size, grid size, inlet conditions or wind velocities. The wind simulations *wind0*, *wind1* and *wind2* are run for

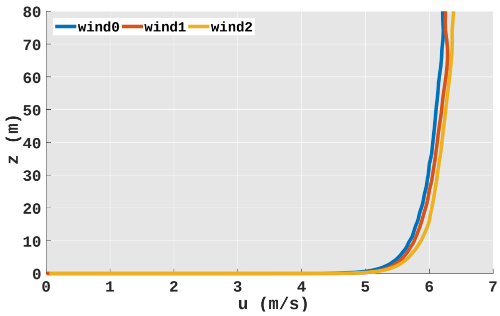
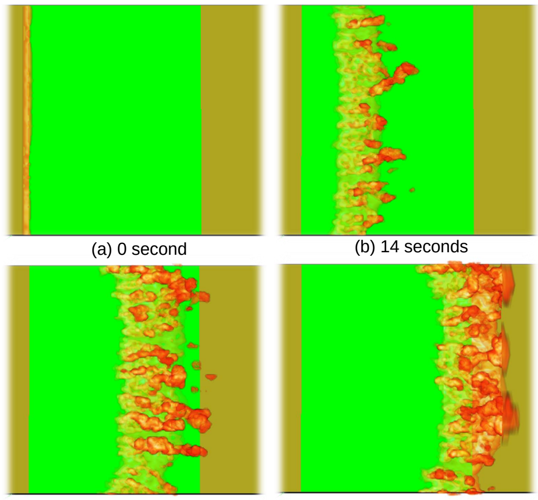


Figure 2: *The mean velocity profile comparison for 3 wind cases over the fire ground.*

5000 seconds of simulation time to find out time for a stable ABL to get established. We observe that *wind0* acquires a stable ABL in less than 100 seconds. In case of *wind1*, the ABL is established in approximately 1000-1200 seconds, whereas for *wind2*, it takes less than 1000 seconds. Figure(2) depicts the mean wind velocity profile on the fire-plot before the start of the fire. Figure(2) depicts that the three wind simulation cases produces similar mean velocity profiles. In fire simulations the mean u-velocity profile as a function of height is more informative than examining other quantities in wall units. We examined the TKE(Turbulent Kinetic Energy) and confirmed that the flow was well developed for each cases when the TKE was oscillating around a constant value. In case of *wind1*, the flow trips and become turbulent leading to a developing boundary layer. This results in more computational time for wind to get stabilized. On the other hand for *wind2*, since the turbulence is embedded in the form of synthetic eddies along with the inlet log-law profile, the flow develops faster. We observe that the mean profile pattern for *wind0* agrees well with *wind1* and *wind2*.

We have used the stabilized wind-field generated in *wind0* simulation as the initial condition for the fire simulations *fire0*, *fire1* and *fire2* to reduce the time to reach the steady-state ABL over the fire ground and start the fire. We have started the fire for *fire1* and *fire2* after 300 seconds in order to allow a steady-state ABL to develop prior starting the fire. For *fire0* case, we have located the burnable-grass plot near the inlet with minimum upstream of the fire, so that the wind is not allowed to get stabilized over space and started the fire after 100 seconds. The intention here is to not allow the steady-state ABL establishment prior to the start of the fire. We have done some adjustments over the axes so that *fire0* can be plotted against *fire1* and *fire2* for comparison. The fire ignitor was put off after 11 seconds [7]. The fire took about ~ 25 seconds to burn the burnable grass plot completely for all the three cases. The fire propagated in a straight



(a) 0 second (b) 14 seconds

(c) 20 seconds (d) 24 seconds

Figure 3: *Fire propagation contour for fire1.*

line across the domain as shown in Figure(3). Figure(4) depicts the percentage change of wind speeds during the burn at 2.04m over the fire plot. This depicts the percentage change in wind speed varies in a similar pattern for all the three cases.

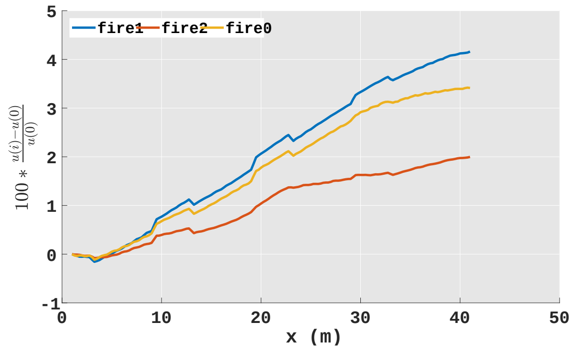


Figure 4: *Wind speed variation over the burnable-grass plot at 2.04 m height.*

There are various parameters for comparing the simulated fire. In the current study, we have compared the Heat Release Rate (HRR) and the Rate of Spread (ROS) to predict the nature of fire propagation. HRR represents the height or intensity of fire whereas ROS depicts fire spread with respect to time.

Figure(5) depicts the HRR for all the three fire simulations to be similar. we observe that the HRR reaches maximum when the fire has consumed the whole burnable fuel over the fire plot (at about 25 seconds) and then drops down to zero as the plume exists the domain. For the fire simulations, the ROS has been calculated at the maximum value of the fire-front on the boundary where the temperature of the vegetation is above $400K$-$500K$ (the pyrolysis temperature). From Figure(6), we observe that towards the start of the fire, the ROS is maximum, then it reaches a quasi-steady of about $2m/s$ state while burning down the whole fire plot and the reaches zero when whole of the burnable fuel has been consumed.

The fire propagation and its characteristics agree good in both *fire1* and *fire2*. As discussed previously that *fire0* simulation was carried out in an underdeveloped boundary which means that the fire was started in an unsteady ABL condition. However, the fire propagation is not much affected by this. It can be argued that the domain considered in this study is comparatively smaller, and so the steady-state ABL is getting established in as

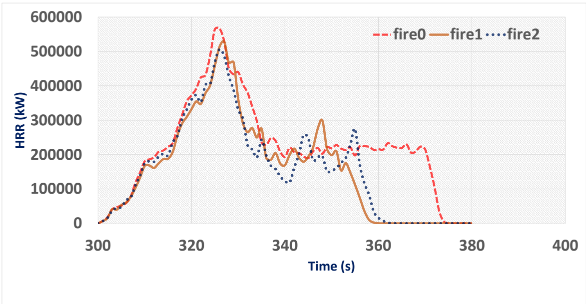


Figure 5: *Heat Release Rate (HRR) as functions of time*

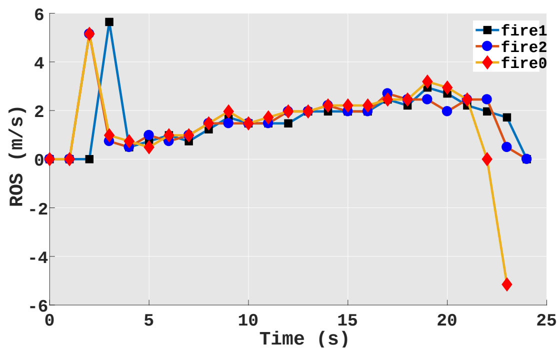


Figure 6: *ROS vs Time comparison over fire plot.*

short as $\sim 20m$ in fire upstream. So we see a fire propagation pattern similar to the other cases. The simulation results may vary considerably for larger burnable grass domain.

Conclusion

The wind simulations performed in this study shows that the SEM and the roughness trip method for wind simulation produce similar steady-state wind profiles to that generated by the mean-forcing method. The mean-forcing method generates achieves a steady-state profile faster than the SEM and roughness trip method and hence uses lesser computational time. The mean-forcing method and roughness-trip method also require fewer input parameters than the SEM. The HRR and ROS profiles shows very little difference between the three fire cases. Therefore, simplicity suggests just taking a 1/7th power-law and a very short upstream distance and spin up time is a simple approach which still recovers the RoS results of more complicated methods. We look forward to developing a method in the future where we can use real-time terrain modified wind data to perform more realistic fire simulations. This method will lead to reduced simulation initialisation time.

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