Resolving radiation in physics-based wildfire spread modelling

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Abstract: Accurate wildfire spread prediction across the landscape is essential for land management and community safety, yet most operational models in Australia are empirical and only designed for head fires where the perimeter is normal to the wind. Extending these models to two dimensions to better represent crown fire initiation and spread around the full perimeter requires quantification of rate of spread and fireline intensity, but existing elliptical growth methods do not explicitly capture the radiative–convective mechanisms that drive propagation. This study uses a three-dimensional, physics-based approach to investigate wildfire spread in grasslands without the algorithmic constraints of landscape propagation models, focusing on determining the radiation parameters needed to resolve both incident radiation and bulk fire behaviour.

Simulations were conducted using FDS v6.9.1, beginning with validation against an experimental grassfire from Mell et al. (2007). A coarse 1 m grid reproduced the observed head fire rate of spread. Ignition was then modified from a line to a 4 × 4 m point source to investigate development of more of the fire perimeter. Coarse and medium resolutions (1 m and 50cm voxels) did not produce continuous flanking spread, while a 25cm grid yielded sustained spread around the perimeter, justifying its use for further experiments.

A systematic radiation resolution study examined five parameters: solid angles, radiation iterations, grid resolution, and temporal and angular update increments. At least 400 solid angles were required to resolve radiant energy direction within 10°, with no significant rate-of-spread difference between 400 and 800 angles, and only a 4% increase at 1200. For radiation iterations, increasing from the default 1 to 2 produced a 10% increase in spread rate, with a further 7% from 2 to 4. Diminishing returns beyond 2 justified selecting 2. Grid resolution tests showed that 25cm voxels balanced adequate resolution with computational efficiency, 20cm simulations resulted in possible 'over resolving/modelling' of turbulence, while 50cm failed to resolve flanking spread.

Reducing the default temporal and angular update increments (from 15 time steps between full radiation updates) increased spread rates by 15 to 24%, with convergence achieved when the product of increments was less than the default. The effect of finer increments was consistent across tested configurations.

Combined simulations using the recommended settings, 400 or 800 solid angles, 2 radiation iterations, 2 angular increments, 2 time increments, and 25cm voxels, were compared with a near default setup. Head fire spread rates differed by only 3% between the 400 and 800 solid angle runs, but the 400 angle case developed a persistent perimeter gap on the upper flank, while the 800 angle run maintained continuity. Similar perimeter breaks occurred in other runs with certain parameter combinations, indicating that convergence in head fire rate of spread alone does not ensure realistic spread behaviour.

The study concludes that default FDS parameters underrepresent radiative transfer and fail to produce converged fire behaviour in grassland simulations. Minimum recommended settings for future work are 400 or 800 solid angles, 2 radiation iterations, reduced temporal and angular increments, and 25cm voxels. However, qualitative perimeter analysis is essential alongside quantitative metrics to capture realistic two-dimensional fire behaviour. These findings emphasise that multi-metric validation is necessary in physics-based wildfire modelling, and that adequate resolving radiation is critical to representing head fire spread and fire spread around the perimeter.

Keywords: *Wildfire, radiation, fire spread modelling, FDS*

1. INTRODUCTION & BACKGROUND

The practice of wildfire behaviour prediction dates back several decades and is vital for both land management and community safety. Rate of spread models, including those which predict the onset of crowning, have historically been developed for head fires where the fire's perimeter is normal to the wind direction which is consistent for empirical models (Cruz et al. (2013); Cruz et al. (2022)), semi-physical models (Van Wagner 1977) and physical models (Cruz et al. 2006) (which model the physical processes of fluid flow, radiation and convective heat transfer). In Australia, due to their ease of use and fast computation, empirical fire models are used most commonly in operation. In these empirical models, crown fire initiation is often predicted as a function of rate of spread and other variables like fuel moisture content (Cruz et al. 2022) or a function of fireline intensity (Byram 1959), which depends on rate of spread (Van Wagner 1977). Predicting how much of the fire perimeter is likely to crown requires extension of these models into two dimensions and the definition of quantities such as rate of spread and fireline intensity around the entire fire perimeter - not just the head fire where the fire perimeter is normal to the wind direction.

In homogeneous conditions, head fire rate of spread models are often extended into two dimensions using geometric templates including the commonly observed ellipses (Anderson et al. 1982). Mathematically, this is done differently in fire simulators depending on the underlying propagation model. Some models use discretised points and calculate a spread vector using Huygens' principle (such as Phoenix Rapidfire) to determine the rate of spread and the position of the fire perimeter at the next time step (green arrow in Figure 1). Others such as Spark (Miller et al. 2015) use the level set method which requires the rate of spread to be calculated in the direction normal to the fire perimeter (red arrow in Figure 1).

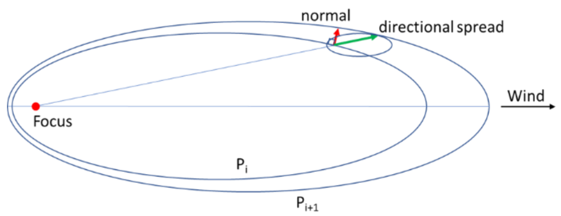

Figure 1 Elliptical wildfire growth. Vectors showing difference between normal (red) and directional (green) spread definitions.

Unfortunately, neither of these methods is based on the radiative-convective spread of the fire. Because of this, a 3D physics-based simulation study is undertaken in an attempt to quantify how a fire spreads in two dimensions without the modelling constraints of a landscape propagation algorithm. This paper presents rigorous numerical parameter checking (for which we could find no studies to date in the literature) for the physics-based simulation study, specifically, resolving the radiation processes within the simulator from a fire front in grasslands.

2. SIMULATION SET UP

2.1. Initial validation

This study was conducted using version 6.9.1 of FDS (Fire Dynamics Simulator). The simulation study was conducted in a grasslands fuel type, being one of the simpler vegetation types for fire behaviour as there are no transitions in behaviour from one strata to another (unlike forest). Firstly, the work of Mell et al. (2007) was reproduced, where a line ignition in an experimental grass fire (C064) was modelled and head fire rate of spread was used for validation. The set up for the validation is shown in Figure 2 where the red line is the ignition line, white lines represent non-combustible dirt at the vegetation boundary and brown is the burnable grass.

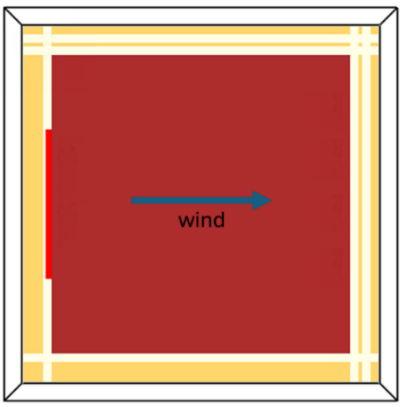

Figure 2 Grass line fire simulation set up. View from above.

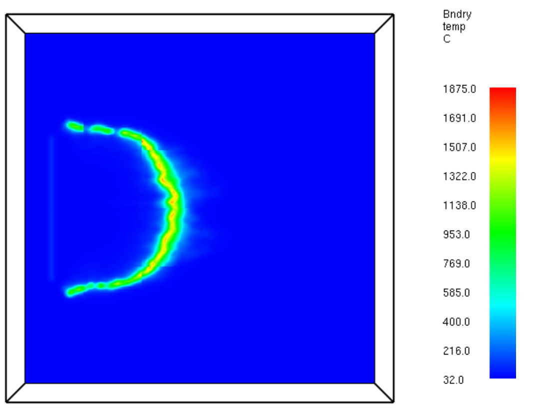

Figure 3 Fire progress 40s into simulation. Legend shows ground temperature. View from above.

All fuel parameters follow Mell et al. (2007). The 'coarse' resolution set up was used, which used a 120 by 120 by 20 mesh of 1m voxels. The ambient wind at 2 metre height was set to 4.6 m/s, and the vertical profile was modelled as a power law with 1/7 exponent. All other boundaries (other than the ground) are modelled as open (constant pressure).

The results of the validation simulation are shown in Figure 3 as a snapshot of ground temperature (from the fire) at the 40s mark. This was in strong agreement with the work in Mell et al. (2007).

2.2. Point ignition

Once the line ignition work of Mell et al. (2007) was reproduced, the modelling set up was modified such that the initial ignition was no longer a line fire, but a 'point' ignition of dimensions 4m by 4m. Using the coarse mesh from the validation work produced results with no apparent flanking spread. Similarly, using a medium resolution (50cm) grid for the same domain did not lead to flanking spread (Figure 4), although the head of the fire did broaden throughout the simulation.

Using a 25cm grid for the burnable domain (as per Moinuddin et al. (2018) and Sutherland et al. (2020)), continuous flanking spread was able to be achieved. Figure 5 shows a continuous perimeter of active fire from the head all the way around the flank until the unburnable section of the simulation domain. Backing spread was out of scope for this study, partly due to limitations in the combustion process of the software used, and partly due to dynamic and transitional fire behaviour being much less likely to occur in the back half of a fire compared to the front half.

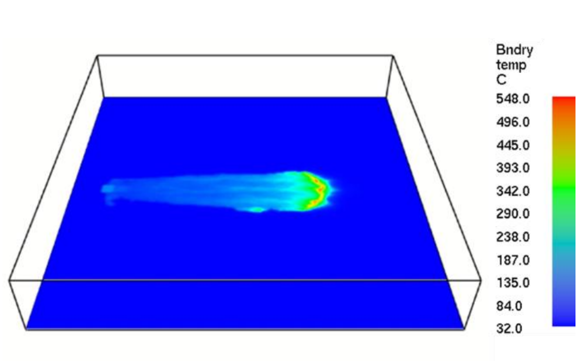

Figure 4 Fire progress 100s into simulation. Legend shows ground temperature. 50cm resolution used.

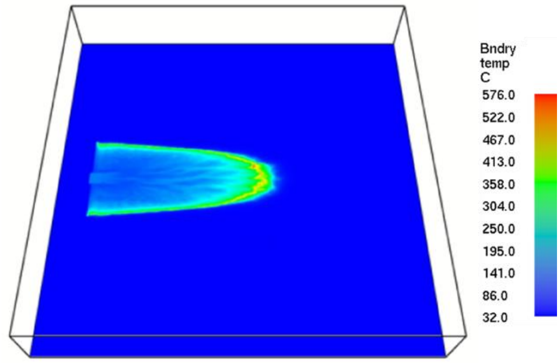

Figure 5 Fire progress 91s into simulation. Legend shows ground temperature. 25cm resolution used.

3. RADIATION RESOLUTION STUDY

The aim of this study was to identify the minimum radiation 'resolution' parameters required to accurately model radiance from a fire front in grasslands. The common parameters which can be used to control the spatial and temporal radiation resolution in physics-based simulators include:

- The number of radiation angles (or solid angles) at which radiation is emitted and absorbed,
- An angle increment, which determines how often radiation angles are updated (a value above 1 will save computation time),
- A time increment, which sets the frequency of calls to the radiation solver (a value above 1 will save computation time),
- The number of radiation iterations, which allows radiation to cross over N-1 mesh boundaries when this value is set to N, and
- Grid resolution, which sets the size of the voxels used in the simulation.

To test whether various combinations of radiation parameters were sufficient for the bulk of the fire behaviour to converge, simulations were conducted and the head fire rate of spread from the simulations was compared. We estimated the head fire position as the windward distance with maximum temperature (within 1m of the centre line). The head fire rate of spread was estimated using least squares linear regression, assuming a constant spread rate once the fire had developed to a reasonable size (which is a reasonable approximation based on the subsequent figures). Based on observations of the development of the fires, the fitted rate of spread between 25 and 110 seconds was used and compared.

3.1. Solid angles

A desired outcome from these simulations is to distinguish where the maximum radiant energy is coming from to propagate the fire to within 10 degrees. Running simulations with the default value of 100 solid angles was insufficient for this purpose as it was found that observations 10 degrees apart had the same incident radiant heat flux for the entire simulation. The same observation was found for simulations with 200 solid angles, indicating that radiation angles were again not yet resolved sufficiently. It was found that 400 solid angles were sufficient to at least resolve between observations 10 degrees apart. This was not an unexpected result since it was shown by Hilton et al. (2020) that ~200 solid angles were insufficient to resolve radiation tens of metres from a target, but ~1000 solid angles were sufficient.

To test whether 400 solid angles was sufficient for the bulk of the fire behaviour to converge, simulations with 400, 800 and 1200 solid angles were conducted and the head fire rate of spread from the simulations was compared. The head fire position and associated rates of spread are shown in Figure 6 which shows that for all simulations the fire has established itself by 25 seconds post ignition. There is also no significant difference between simulations with 400 and 800 solid angles, and only a 4% increase in rate of spread when the number of solid angles was increased to 1200. This was considered to be within the expected difference between simulations due to turbulence, so 400 solid angles were deemed as likely appropriate for resolving radiation in future simulations, and was used in the simulations in following sections.

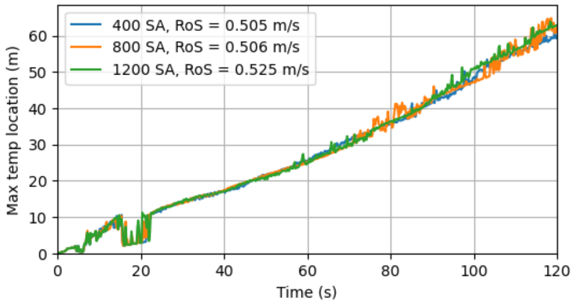

Figure 6 Head fire position and associated rates of spread for simulations with different radiation solid angles.

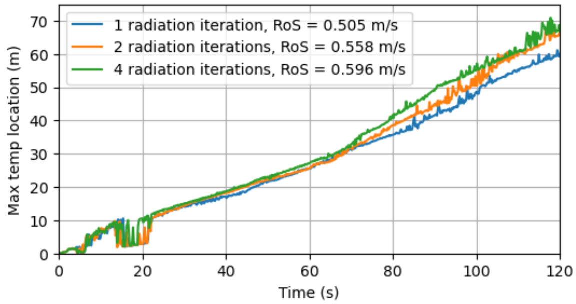

Figure 7 Head fire position and associated rates of spread for simulations with different radiation iterations.

3.2. Radiation iterations

This parameter sets the number of iterations the radiation model can undergo in each time step. In this physics-based solver, radiant energy is normally stopped at a mesh boundary (a certain number of voxels defined upon setup, 20m by 20m by 20m in these simulations) when the default number of radiation iterations (1) is used, however increasing this parameter to N allows radiant energy to be transmitted across N-1 mesh boundaries.

To test whether more than 1 radiation iteration was required for the bulk of the fire behaviour to converge, simulations with 1, 2 and 4 radiation iterations were conducted and the head fire rate of spread from the simulations was compared. The head fire position and associated rates of spread are shown in Figure 7 which again shows that for all simulations the fire has established itself by 25 seconds. There is no significant difference between simulations up until the 70 seconds mark, after which the simulations with more radiation iterations spread at a faster rate. Overall, this was 10% faster spread rate for 2 iterations compared to 1, and a further 7% faster when the number of iterations was increased to 4. A small increase in spread rate was expected with more than 1 radiation iteration, as it allows fuels to be preheated by the fire for a longer period of time. Given the smaller increase in spread rate as the number of radiations increased, 2 radiation iterations were deemed as likely being appropriate for resolving radiation in future simulations.

3.3. Grid resolution

The grid resolution of the solver was also investigated. The grid resolution determines the scale at which all fluid mechanics and radiation are calculated at within the software. To test whether 25cm voxels were sufficient for the bulk of the fire behaviour to converge, simulations with 20, 25 and 50cm voxels were conducted and the head fire rate of spread from the simulations was compared. The head fire position and associated rates of spread are shown in Figure 8. Given the much larger difference between the 20 and 25cm simulations compared to the 25 and 50cm simulations, it is likely that the software was 'over resolving/modelling' the turbulence within the large eddy simulation in the 20cm simulation. Thus, a 25cm resolution will be used within the remainder of this study.

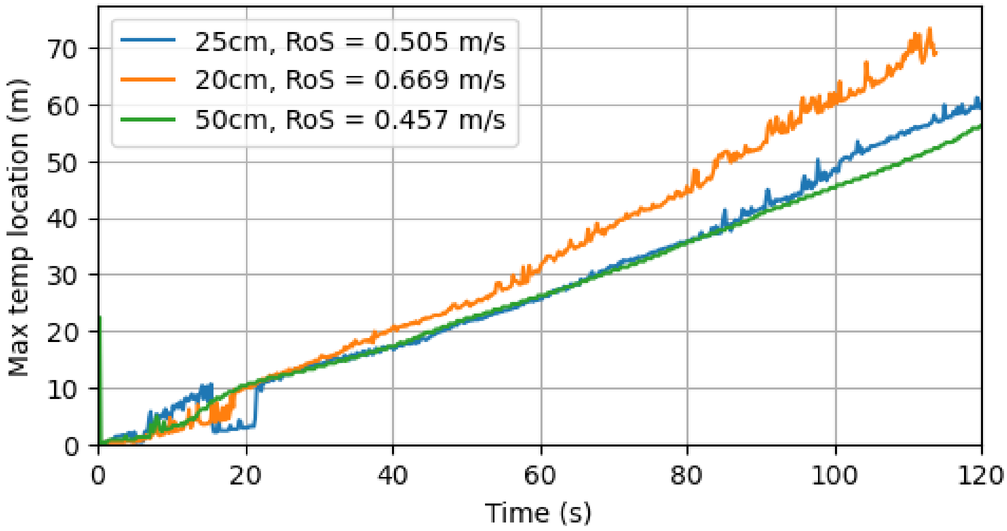

Figure 8 Head fire position and associated rates of spread for simulations with different simulation resolutions.

3.4. Angle and time step increments

The frequency of calls to the radiation solver can be changed from every 3 time steps (the solver default) with the time step increment parameter. The increment over which the angles are updated can be changed from 5 steps (the solver default) with the angle increment parameter. If both parameters are set to 1, the radiation field is completely updated in a single time step, but the run time of the simulation increases significantly. By default, the radiation transport equation is fully updated every 15 time steps (McGrattan et al. 2023).

To test whether the default time step and angle increments were sufficient for the bulk of the fire behaviour to converge, simulations with various increment combinations were conducted and the head fire rate of spread from the simulations was compared. The head fire position and associated rates of spread are shown in Figure 9. Figure 9 shows that all fires were developed by the 25 second mark. It also shows that all configurations with smaller increments than the default led to similar head fire behaviour, with spread rates 15% to 24% larger than when using the default increment parameters. Some increase in spread rate was expected with decreasing increments, as the radiation is being calculated closer to the active edge of the fire rather than lagging several time steps behind. The small spread in the simulations with finer increments than the default values show that it isn't that significant which increment parameters are reduced below the default values, but it is important that the product of the increment parameters is less than the default in order to resolve head fire behaviour.

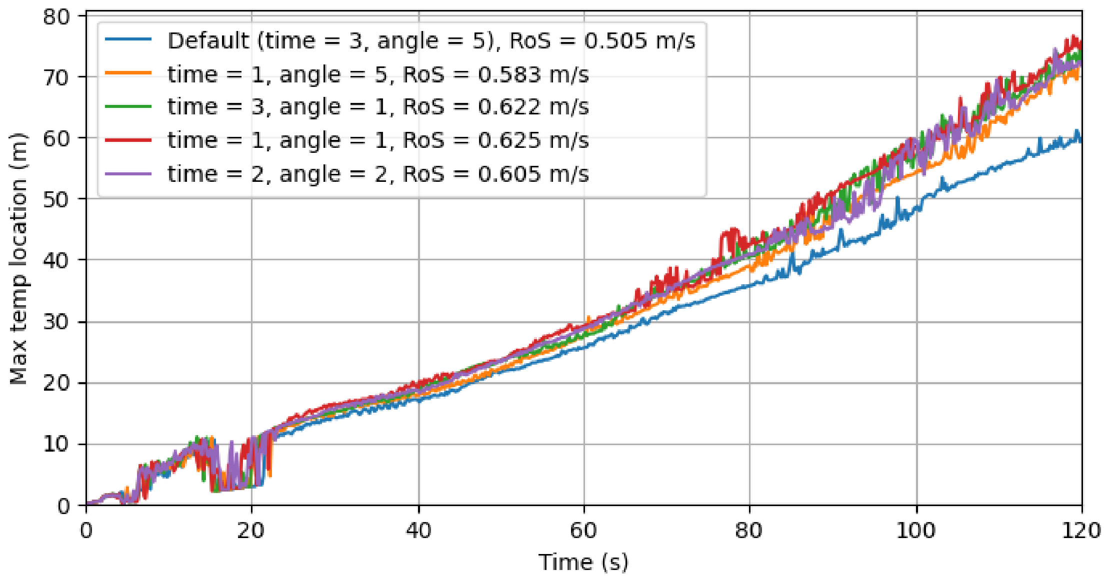

Figure 9 Head fire position and associated rates of spread for simulations with different angle and time step increments

3.5. Combined simulations

Simulations were then conducted with the parameters deemed to be suitable from the previous sections. Specifically, the parameters used were 2 radiation iterations, 2 angle increments, 2 time step increments, 25 cm voxels and 400 or 800 solid angles. The head fire position and associated rates of spread are shown in Figure 10. The results from a near default set of parameters (400 solid angles, 25cm voxels, 1 radiation iteration) are also shown as a comparison.

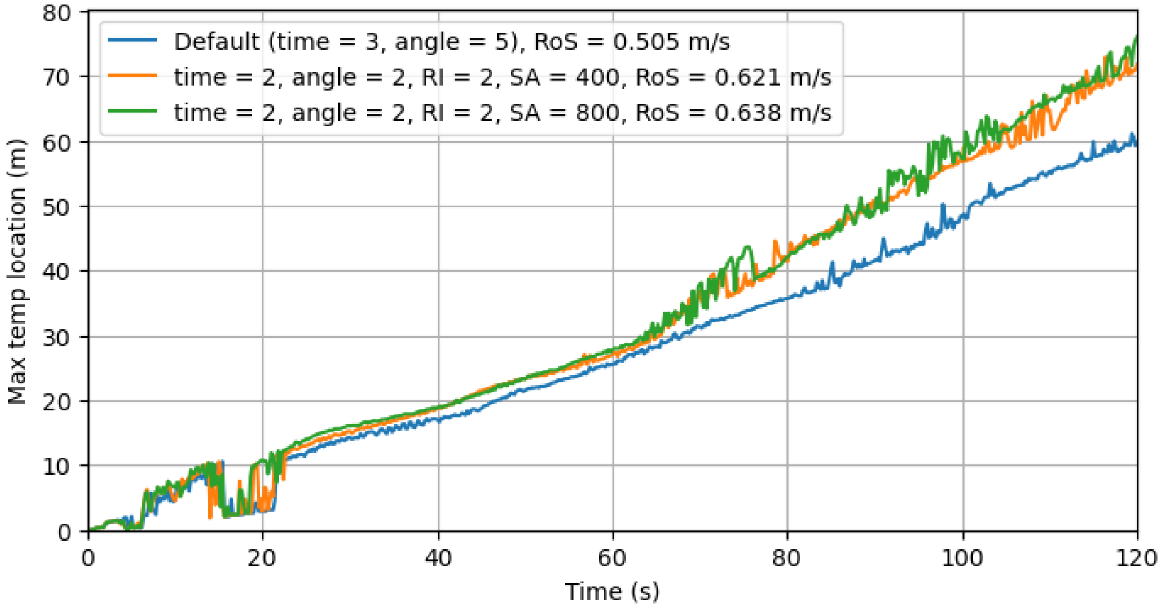

Figure 10 Head fire position and associated rates of spread for combined simulations with different solid angles

Figure 10 shows an insignificant 3% difference in heat fire spread rate between the combined simulations with 400 and 800 solid angles. Further investigation into the two dimensional spread of the fire does show a difference, in the simulation with 400 solid angles obtains a gap in the fire perimeter of the topmost flank near the 100s mark which persists until the end of the simulation (Figure 11). This also happened with several other simulations within this radiation resolution study. The simulation with 800 solid angles did not yield any gaps or breaks in the fire perimeter (Figure 12).

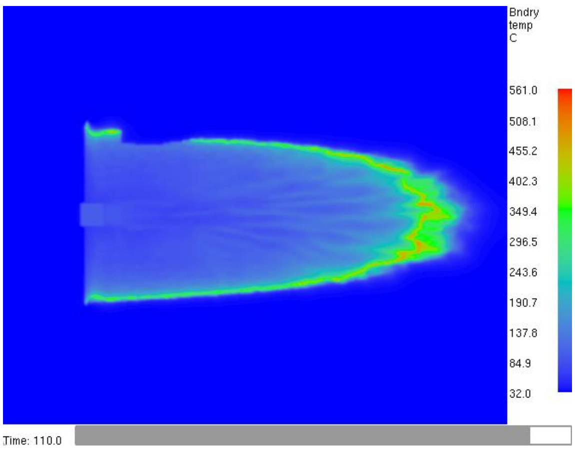

Figure 11 Combined simulation with 400 solid angles. Legend shows fuel temperature. Gap in fire perimeter at upper flank observed near end of simulation.

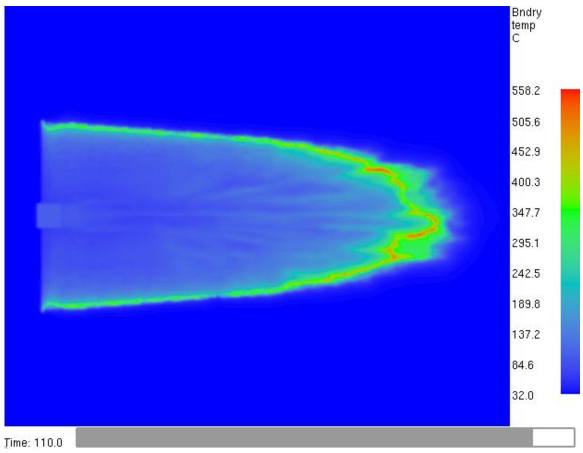

Figure 12 Combined simulation with 800 solid angles. Legend shows fuel temperature. No gap in fire perimeter observed throughout simulation.

4. DISCUSSION AND CONCLUSION

This study set out to determine the radiation parameters required to both resolve incident radiation to within 10 degrees, and for the bulk of the fire behaviour to converge. The simulations conducted showed that the default parameter values in FDS v6.9.1 were insufficient for radiation or bulk fire behaviour to converge to less than a 5% error. It was determined that the number of solid angles required was at least 400, and at least 2 radiation iterations were required to allow radiation energy to cross mesh boundaries. Time step and angle increments were also required to be reduced for head fire rate of spread to converge. A voxel size of 25cm was also found to be appropriate for this study.

Interestingly, meeting the radiation parameter requirements for head fire rate of spread to converge did not necessarily mean that the simulated fire was realistic. There was only a small (~10%) difference between head fire rate of spread between simulations with 25 and 50cm resolutions, however the difference in fire behaviour was stark, with the 50cm simulation not resolving any flanking fire spread. Similarly, comparing the combined simulations in Figure 11 and Figure 12 showed that small differences in radiation parameters could cause holes in the fires perimeter which open up during the simulation. This raises the importance of not just using one or two metrics to determine convergence in physics-based fire models, but also to understand the fire as a whole, especially taking note of the specific fire behaviour important to each particular study.

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