Sub Topic: Fire

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A High Flux Forest Fire Scenario for Assessing Relative Model Accuracy for CFD Tools

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Abstract: Predicting fire ignition, propagation, and smoke/carbon transport from large-scale events like catastrophic wildfires and urban fires after nuclear detonations is challenging, but important for public safety and national security. Sandia and Los Alamos National Laboratory have developed fire simulation tools. The former institution develops and maintains SIERRA/Fuego, which is normally used to simulate transportation-scale fires, but can be extended to kilometer-scale. The latter develops and maintains HIGRAD/FIRETEC, which is developed for capturing coupled fire-atmosphere interactions, thus optimized for the larger-scale scenarios. SIERRA/Fuego benefits from validation to a variety of laboratory-scale fire tests, while HIGRAD/FIRETEC has been validated with wildland prescribed-burn tests with focus on fire behavior and spread. Little has been done previously to quantify the accuracy of the models for high radiative flux ignition events. Recent tests have provided experimental response data for trees exposed to high heat fluxes at the Solar Tower facility at Sandia. The results of these tests have been leveraged to calibrate a tree burning model in SIERRA/Fuego. A notional scenario involving a stand of trees is developed, and similar trees and flux exposures are simulated in both SIERRA/Fuego and HIGRAD/FIRETEC to help characterize the accuracy of the ignition, burn, and transport models for high flux forest ignition scenarios.
Keywords: Fire, High Radiative Flux, Ignition

1 Introduction

There is interest among multiple agencies in the US government in understanding the effects of ignition from very high heat flux. Conventional ignition flux from a fire is in the 25-200 kW/m^2 range. Higher fluxes can be obtained from metal fires, propellants, nuclear weapons, lightning, etc. The interest lies in the ability to plan and protect. Much of the existing historical information on high flux ignition dates back to the above ground nuclear test programs and spin-offs from the 1950-1960s, and many of the experimental reports involve Stan Martin and co-worker, who published extensively on this topic [1-3]. Recently, there has been some new testing at Sandia National Labs [4-7], and multiple agencies have expressed interest in computational capabilities for use in analysis of scenarios. Indications are that high flux ignitions are differentiated from conventional ignitions by a decrease in the exposure energy required to ignite. Scale, wind, and shape effects also exist, the magnitude of which may differ from those for conventional ignitions [4-6].

Sandia has developed SIERRA/Fuego for simulating low-Mach number reacting flow applications. It has been used over the past dozen or so years in support of Department of Defense

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(DOD) activities relating to fires from nuclear weapons. Additionally, Sandia has conducted nearly 200 exposure shots of various materials at the Solar Tower [4-6] and Solar Furnace [4,5,7] facilities simulating the high flux environment expected from a nuclear weapon. There have been some basic comparisons between Sandia's simulation tools and some of the datasets from the test campaign [8]. This provides benchmark evidence of accuracy of the simulation tools. Sandia's capabilities are massively parallel, but generally have not been used for problems scaled above about a square kilometer.

Los Alamos National Laboratory (LANL) has been developing HIGRAD/FIRETEC as a tool for studying wildfire behavior and coupled fire-atmosphere interactions. FIRETEC is a fire physics and turbulent mixing model on HIGRAD, which is a Computational Fluid Dynamics (CFD) framework, designed for compressible, high-gradient atmospheric flow. It is a massively parallelized code to simulate large-scale fire behavior, and is validated with prescribed fires such as International Crown Fire Modeling Experiments (ICFME) [9]. Recently, it has been expanded to study atmospheric responses to urban fire scenarios under regional nuclear exchange [10]. HIGRAD/FIRETEC is designed primarily to capture fire-atmosphere interaction to predict fire behavior and spread in a landscape scale (10,000 m^2 – 100 km^2), thus it cannot be directly validated to the Sandia Solar facility tests, which were based on a single tree per test. Although HIGRAD/FIRETEC typically uses a very fine resolution (2 meters) in terms of atmospheric dynamics modeling for wildfire simulations, this resolution still requires sub-grid modeling for combustion processes and probability density function (PDF) for fuel and flame spread characteristics, as many hydrodynamics models require sub-grid turbulence models. While this approach lacks the accuracy required for the science questions that Fuego can address, it also allows the code to resolve larger computational domains to incorporate landscape-scale atmospheric dynamics and fire-atmosphere interactions.

Reliability, robustness, and accuracy of the sub-grid combustion model is critical for the modeling approach HIGRAD/FIRETEC takes. The current FIRETEC sub-grid model showed reliable performance for some wildland fire scenarios [11-13]; however, the model has not been sufficiently tested for urban fire scenarios and ignition by unusually high heat flux. The data from Sandia's Solar tower experiments combined with higher-fidelity Fuego simulation studies are valuable for understanding physical processes under these conditions and improving sub-grid scale models.

This activity seeks to improve the current model credibility gap by performing benchmarking simulation tests on similar simulation scenarios of interest using both LANL's HIGRAD/FIRETEC and Sandia's SIERRA/Fuego. While applying HIGRAD/FIRETEC to small wildfire scenarios is not optimal as with the spatial resolution in this study, benchmarking HIGRAD/FIRETEC simulation to the SIERRA/Fuego simulations that have tie-back to the test results provides a link to test data in this abnormal ignition regime. The primary object of this study is to identify the differences that come from the two different modeling approaches between Fuego and HIGRAD/FIRETEC, to foster future collaborations and improvement of both models.

2 Methods

2.1 SIERRA/Fuego simulations

In April of 2017, a couple of demonstration experiments were performed at the National Solar Thermal Test Facility (NSTTF) using the Solar Tower. Using concentrated solar energy, a few samples including a piñon pine tree were ignited at peak exposure fluxes in excess of 1000 kW/(m^2)[1]. The flux profile is found in Figure 1. The tree sample test results were subsequently used to develop a simulation model for a burning tree ignited by high flux conditions [14]. Because the modeling capabilities are not fully mature, free model parameters were tuned to replicate key test results from this demonstration calculation. The ignition and extinction times of the flaming were matched primarily by tuning the moisture content. A multi-step reaction model including tar, char, volatiles, and moisture evaporation was used [15], and the tree was modeled with a cone shape randomly filled with combustible particles (more details are available in [14]). Two particle size distributions were used, one for needles, and the other for the smallest branches. This constituted our model for SIERRA/Fuego.

With a tuned model for the behavior of a tree in a high flux environment, a notional demonstration scenario was developed. A 4x9 array of trees was formulated using constrained random sampling for the position of the tree, the tree height, the tree width at the base of the canopy, and the height of the base of the canopy. Exact details of the trees in the scenario are reproduced in the appendix. A parameter study was designed using the flux profile from the solar tower demonstration test (figure 1) to ignite the nine trees facing the flux directly. A constant 1.25 m/s wind flow was applied at the upwind boundary for the baseline condition, with the flow vector in the same direction as the flux vector. A broader study varying wind was part of the parametric study. As with the solar tower test, the larger forest trees ignited and sustained burning.

SIERRA/Fuego [16,17] is a low-Mach number code for simulating objects in fires and is extended to support a variety of problems of interest to Sandia and affiliates who use the code. It is massively parallel, and the resolved scale for simulations typically is in the 1-100 cm range. A variety of turbulence and reaction models exist, with this work electing to use the Eddy Dissipation Concept (EDC) model for fluid(gas)-phase reactions [18] and the Temporally Filtered Navier-Stokes (TFNS) [19] model (a hybrid LES/RANS capability) for turbulence.

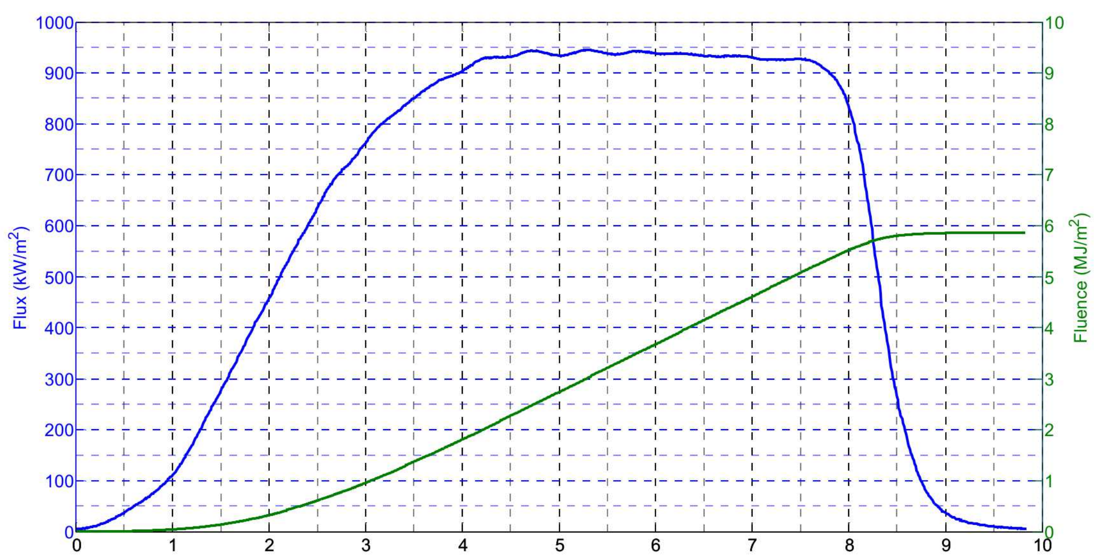


Figure 1: Heat flux and fluence for the tree exposure from Solar Tower Phase 0.

Mass loss was a primary metric of comparison for the tests. A larger parameter study was performed with SIERRA/Fuego, primarily focused on the presence of ground litter and wind

[1] https://www.youtube.com/watch?v=P4So-SwuqA0

magnitude, which is not addressed in this paper. Figure 2 illustrates the simulated 30 m x 20 m domain (12 meters high). The Eulerian fluid meshes consisted of either 426,000 nodes (coarse) or 839,000 nodes (medium), and the domain utilized a slight growth bias approaching open (top, sides, and down-wind) and inflow (up-wind) boundaries. A nominal constant wind of 1.25 m/s was imposed on the domain with vectors in the same direction as the flux exposure. Wind variants illustrated here include -1.25 m/s, 1.5 m/s, 2.0 m/s, and 2.5 m/s wind magnitude.

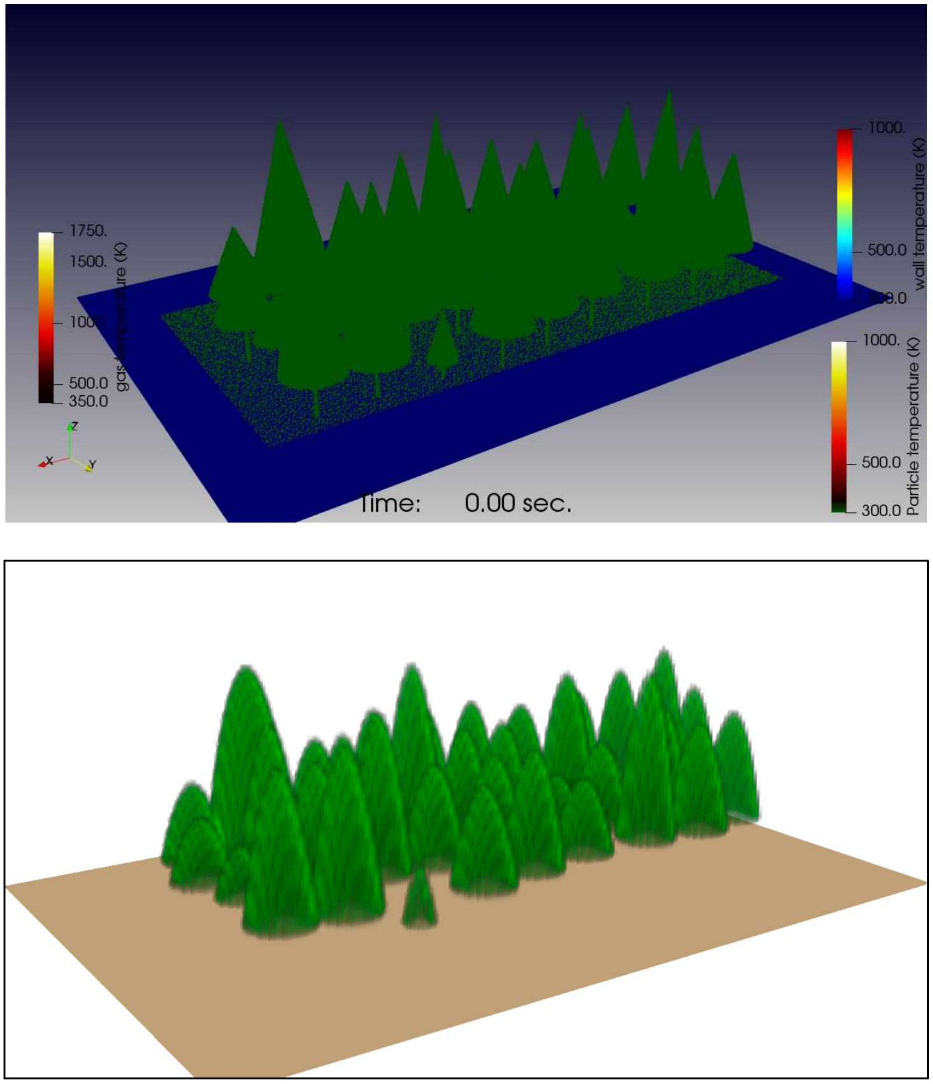


Figure 2: An illustration of the wildland fire simulation domain and trees: (*top*) SIERRA/Fuego and (*bottom*) HIGRAD/FIRETEC

2.2 HIGRAD/FIRETEC simulations

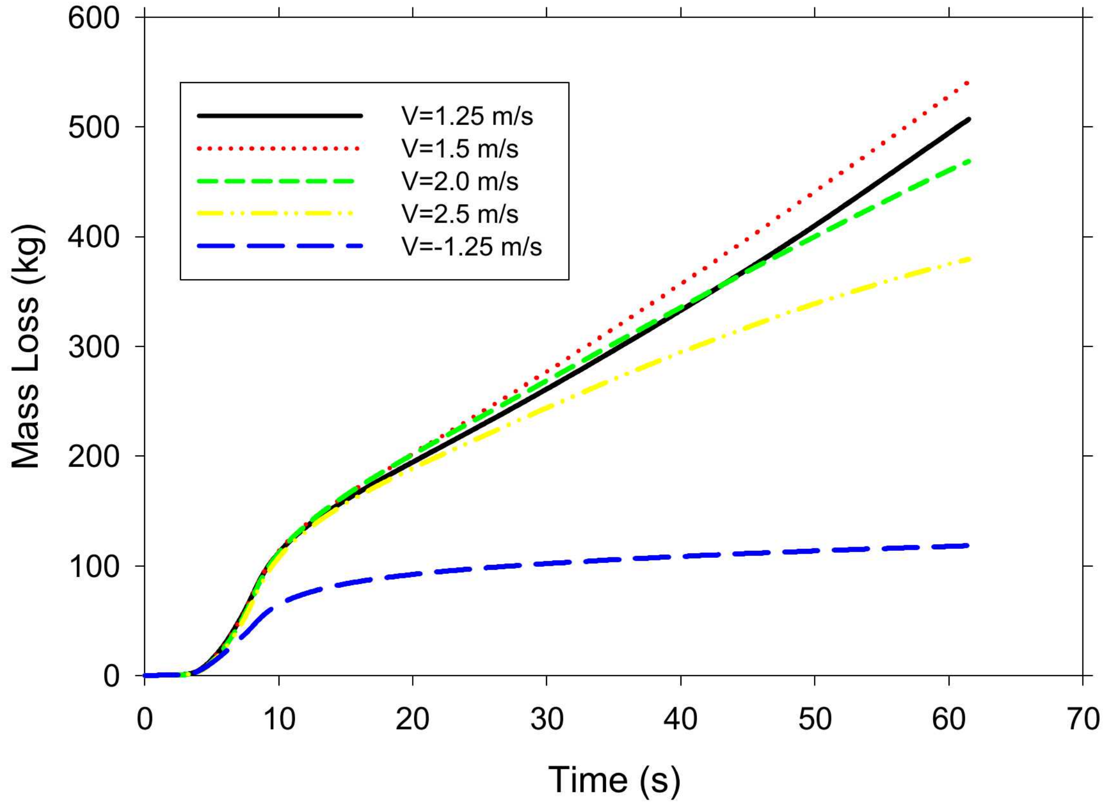
A series of simulations of ignition and fire spread through the same 36 trees (Figure 2) described by Table 1 in the Appendix were performed using HIGRAD/FIRETEC, with the same 5 wind conditions varying from -1.25 m/s to 2.5 m/s. While trees were modeled as cones with the tree trunks for Fuego simulations, they were modeled as a parabolic shape with the same crown base heights and the same crown radii. Since the mass consumption over time would be the primary results to be compared, tree density was adjusted to have the same total mass of trees as the Fuego simulations, to compensate for the slight difference in total volume of a tree caused by the slight shape difference. The main difference in modeling trees comes from how fuel elements were modeled: they are modeled as Lagrangian particles with spherical shape in Fuego and as porous media in an Eulerian grid in HIGRAD/FIRETEC. Drag formulations of the canopy in HIGRAD/ FIRETEC assumed porous media consist of cylinders of certain length scale (diameter), aimed to model pine needles. The length scale of the porous media in HIGRAD/FIRETEC was set as the same as the length scale of Fuego fuel elements.

Two different size domains were used for HIGRAD/FIRETEC simulations: one with a 30 m x 20 m area, which has the same horizontal extent as Fuego simulations, and the other with a 30 m x 200 m area, which extended the domain by a factor of 10 in the wind direction. The longer domain simulations were performed with the 2.0 m/s and 2.5 m/s wind condition, in addition to 5 wind condition simulations with 30 m x 20 m size domain, to see the impact of a different outflow boundary condition of HIGRAD/FIRETEC from Fuego: HIGRAD/FIRETEC typically uses relaxed outflow boundary conditions to match inflow boundary condition. The purpose of this boundary condition is to have wind conditions as 'ambient wind' or 'environmental wind' at the boundary. This boundary condition could underestimate portions of the effect of the wind field generated by the fire plume, such as entrainment, when fire is too close to the boundary. The longer domain simulations were performed for stronger wind cases to see the impact of the distance between the outflow boundary and the fire. For the same reason, the top boundary is set at 60 m for HIGRAD/FIRETEC with 20 m of the damping layer, instead of the 12 m of Fuego domain with the open top boundary.

The same spatial resolution of 0.2 m was used in HIGRAD/FIRETEC as in the Fuego simulations. Thus, 4.5 million grid points (150 x 100 x 300) or 45 million grid points (150 x 1,000 x 300) were used for HIGRAD/ FIRETEC simulations. This resolution was an order of magnitude finer than what FIRETEC is designed for with its sub-grid turbulence mixing model and PDF of fuel characteristics, which basically describes statistical variability of parameters that go into the reaction model. Thus, the fuel temperature PDF and turbulent mixing parameter in the reaction model are modified accordingly with the increased resolution. The other model implemented in HIGRAD/FIRETEC for this study was the ignition model by high radiative flux. This is in addition to other different options for initiation of fires designed to replicate techniques such as drip torch or aerial ignitions, which are often used in prescribed fires. Taking advantage of a Monte Carlo radiation model which solves radiative heat transfer in HIGRAD/FIRETEC, the new radiative ignition routine was added simply by modeling a virtual blackbody wall at the boundary (12-m height as Fuego boundary) with temperature change over time that will emit the same radiative heat flux as describe in Figure 1.

3 Results and Discussion

Figure 3 shows Fuego and FIRETEC predicted mass loss as a function of time for five wind velocity assumptions. The mass loss for both codes is a summation of the mass change in the particles in the domain. Mechanisms for mass loss include pyrolysis (defined as dry fuel consumption in FIRETEC), evaporation, and transport of the burnt particle out of the domain. Pyrolysis is thought to be the dominant mechanism for mass loss, however this was not specifically quantified.



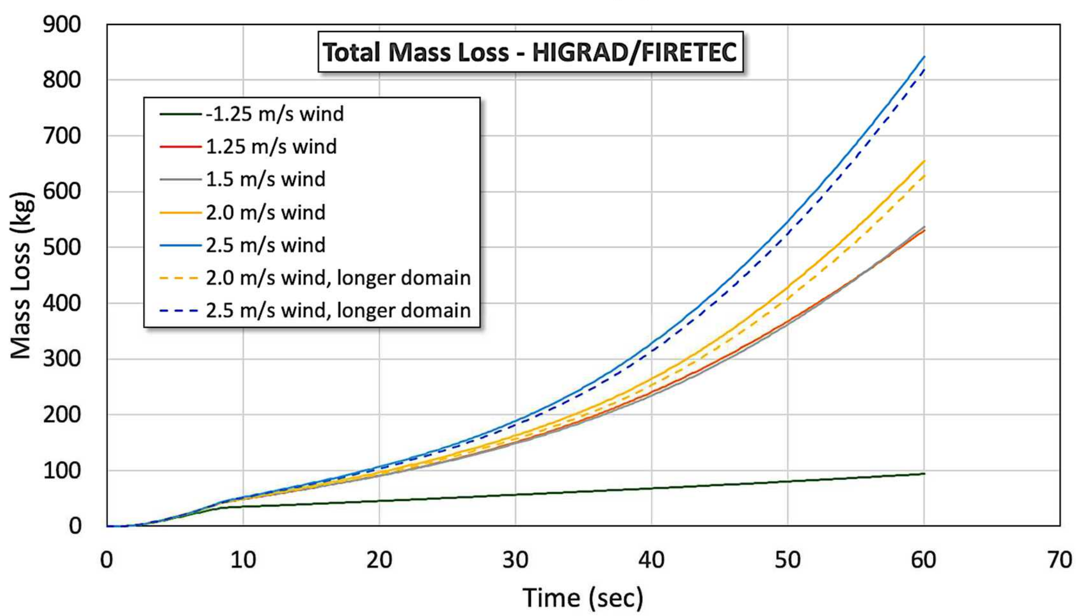


Figure 3. Temporal variation in mass loss depending on the wind velocity: (*top*) SIERRA/Fuego and (*bottom*) HIGRAD/FIRETEC

The results were surprisingly similar in the 1.25 m/s mass loss. Both exhibit similar trending through the first 10 seconds of the exposure. Both also predict about 500 kg mass loss by 60 seconds. The transient behavior differs, with Fuego predicting a near linear trend, and FIRETEC predicting a slower start and an accelerating burn. Both codes predict significantly lower mass loss for the -1.25 m/s case and are relatively consistent with about 100 kg mass loss at 60 seconds. The codes differ in the trend as velocity increases. FIRETEC simulations predict increasing mass loss with increasing velocity to 2.5 m/s, while Fuego simulations predict an increase to 1.5 m/s, then a decrease. It is well known that wind can augment the burn rate and spread of wildland fires. However, there is a limit to this behavior, a wind speed above which the fire is retarded. The Fuego predicted point of decrease of 1.5 m/s is lower than what is commonly observed, not a particularly strong wind condition.

Figure 4 shows graphical representation of the Fuego results at 60 seconds using a volume rendering scheme for the temperature of the gas, with particles also colored by temperature as indicated by the color bars. The ground is also colored by temperature, which simulates heating using a 1D solid approximation model based on radiation and convection exchange with the environment. At 60 seconds, there is an obvious difference in the magnitude of the active burn for each wind condition. The negative wind condition exhibits no significant burning. The 1.25 m/s wind condition exhibits profuse burning in the exposed trees. As velocity increases, the scale of the burning diminishes.

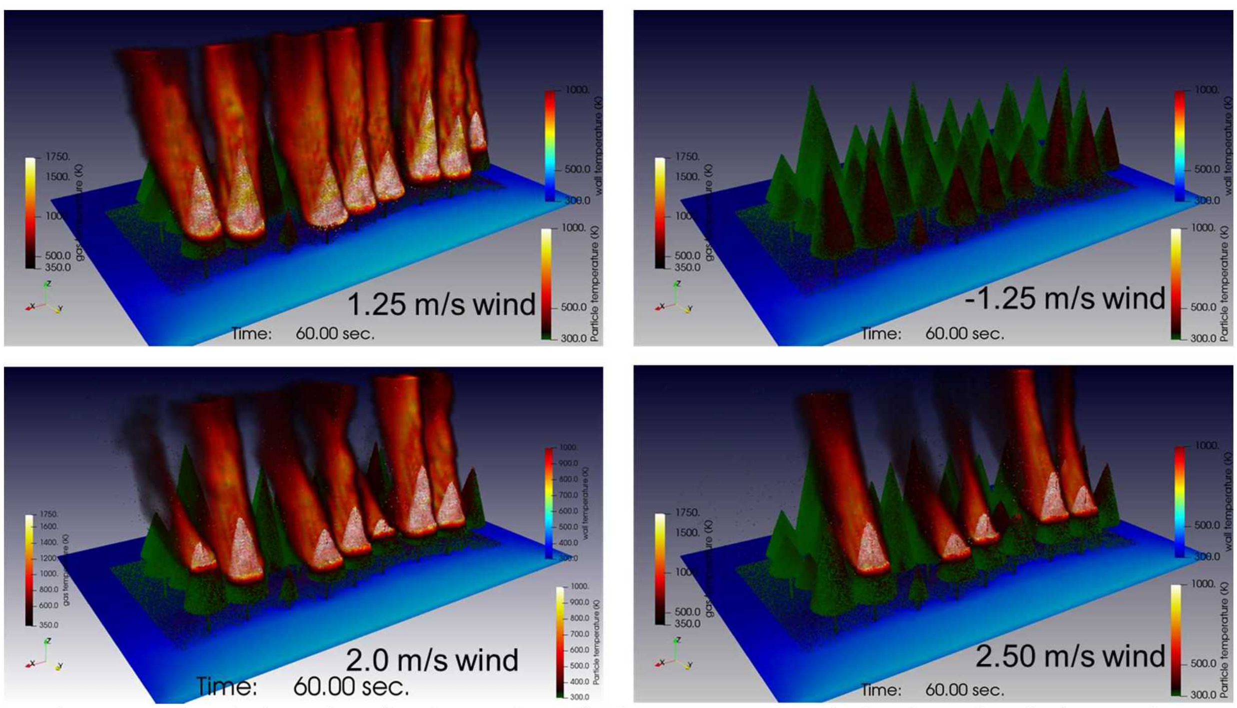


Figure 4. Simulation visualizations of predictions at 60 seconds for four simulation variants: SIERRA/Fuego.

Figure 5 shows similar HIGRAD/FIRETEC simulation results. The burn rate is not obviously different by examining these images between the range of positive wind conditions. The negative wind condition still shows burning, but only in portions of the front row of trees. Three main differences between Fuego and HIGRAD/FIRETEC are observed. First, the angle of the fire and plume is shallower in the FIRETEC simulations. Second, the angle of the fire potentially lends to the increased burning because the flames from the front trees impinge on the back ones more.

Third, the fire is lower in the trees in the FIRETEC simulations, with this feature augmented for higher wind speeds. The Fuego simulations have a known issue that is probably the culprit for much of the discrepancy. The particles all exhibit drag as if they are isolated spheres in a computational cell. In reality, most cells with particles have relatively large particle volume fractions and number counts. Fuego is therefore likely severely over-predicting the effects of drag, and this could result in differences as noted between FIRETEC and Fuego predictions.

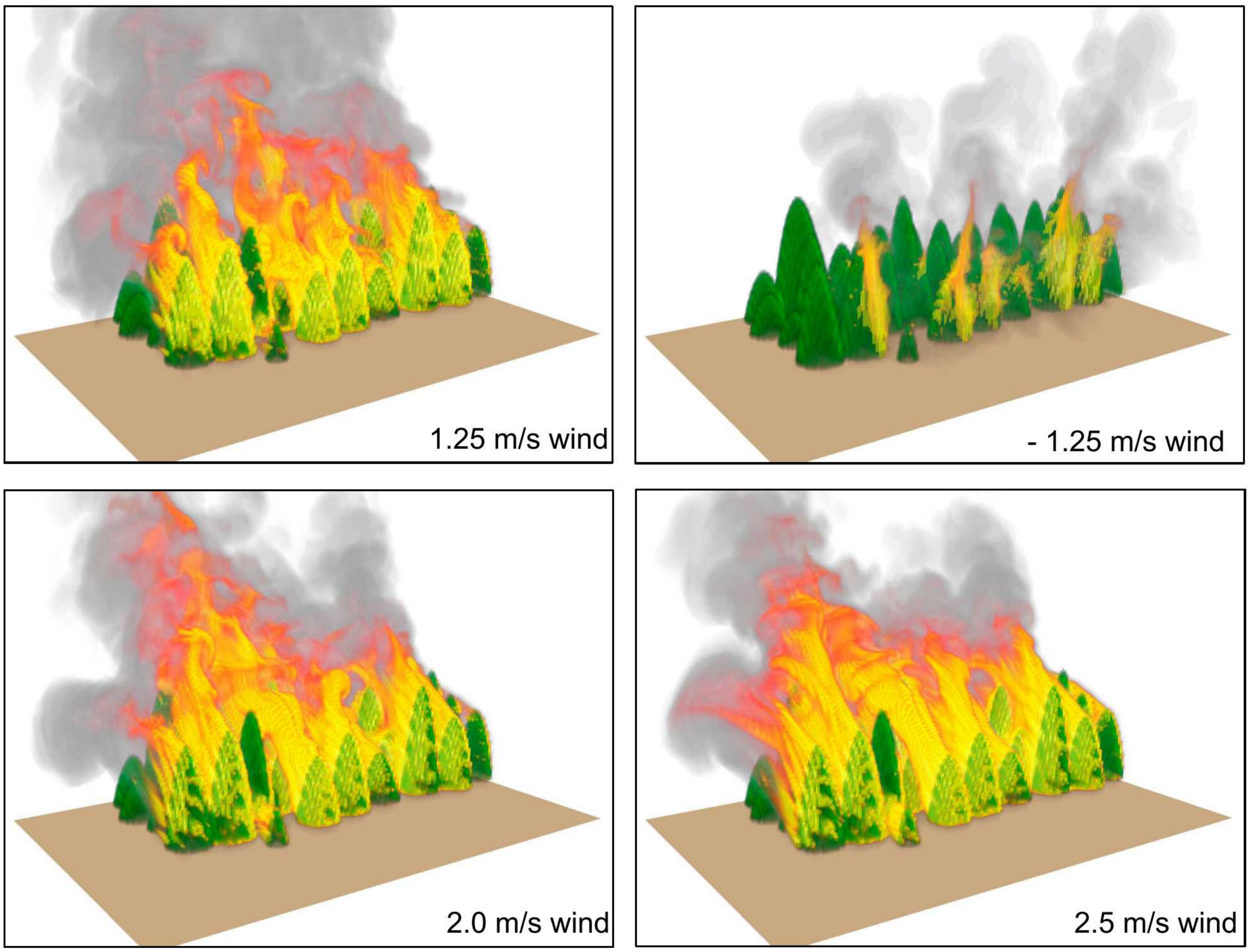


Figure 5. Simulation visualizations of predictions at 60 seconds for four simulation variants: HIGRAD/FIRETEC

The motivating objective of this comparison was to evaluate whether ignition at a very high heat flux can be credibly predicted by the simulation tools. A secondary objective was to assess the models' relative agreement. The models both showed excellent agreement in mass loss and mass loss response to the imposed flux condition during the first 10 seconds of the simulations. The imposed flux condition is expected to ignite a tree because such a test was performed and exhibited flaming and the same tree modeling techniques were employed to describe the notional forest. The test scenario was in an optimal scale for Fuego comparisons to the data, however the typical scale of FIRETEC predictions is too large to sensibly attempt to validate to the tree ignition data. This notional scenario was devised to accommodate the differences and allow assessment of FIRETEC ignition capabilities with a reach-back to the test data. The codes performed well and consistently through the first 10 seconds of the ignition. After the high flux exposure, the domain behaves much more similar to a traditional forest fire, and the historical validation work for FIRETEC provides confidence in the longer-term predictive capability. Fuego has not been previously optimized or characterized for accuracy for forest fire scenarios of this nature.

Longer-term objectives are to continue to assess accuracy of the simulation tools in large-scale urban and rural fire scenarios. FIRETEC is intended to be predictive for the very large-scale fire scenarios, and will take a different development path as a consequence of its objective and target scenarios. Some targeted development in Fuego appears to be warranted, with the objective to enable higher accuracy in predictions of this nature.

The fact that the codes performed as similarly as they did was of moderate surprise. The models are sufficiently different that there was anticipation of greater disagreement between the predictions. Points of concern include:

- The different morphology of the fuel including the drag behavior of the fundamental elements (cylinders versus spheres)
- Variable heat of combustion between the tools
- Turbulence model variations (LES versus TFNS)
- Outflow boundary condition differences (open versus wind)
- Models for compressibility of the gases

While the simulation campaign made efforts to eliminate or remove differences between the codes (mesh, geometry, flux, and wind boundary conditions), the models are sufficiently different that the expectation of uniformity of answers was not high.

Urban scenarios represent an additional complication, and future work may focus on these for improving model accuracy. A challenge here for both codes would be defining an appropriate scenario and obtaining high flux ignition data in that regime.

4 Conclusions

A notional forest fire scenario has been developed that provides a consistent scenario to compare HIGRAD/FIRETEC and SIERRA/Fuego simulations for ignition resulting from high heat flux. The simulations are closely related to a concentrated solar exposure of a tree to $\approx 10^6$ W/m^2. The comparison was good, with similar mass loss trending to the flux exposure in the first 10 seconds, and similar total mass loss at 60 seconds. Some details differed, including the linearity of the trend between ignition and 60 seconds as well as the mass loss trend for increasing velocities beyond 1.5 m/s. This exercise helps identify and motivate future development activities, and it provides confidence in the predictive capabilities in lieu of a more traditional approach of using direct validation, a possibility inhibited by lack of relevant datasets.

5. Acknowledgements

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7. Appendix

Table 1. Tree details

Tree	*x (m)*	*y (m)*	*Tree Height (m)*	*Crown Base Height (m)*	*Crown Radius (m)*
1	0.319	0.112	6.3	1.74	1.1
2	2.73	0.5	5.4	1.72	1.13
3	5.21	0.2	3	0.8	0.5
4	7.9	0	7.4	1.7	1.17
5	-2.3	-0.3	4.7	1.8	1.11
6	0	-2.8	5.4	1.7	1.13
7	2.8	-2.6	5.5	1.7	1.12
8	-2.9	-2.7	4.2	1.9	1.06
9	2.4	-4.7	8.8	1.7	1.14
10	-0.3	-5.3	5.9	1.8	1.07
11	-5.5	-0.4	8.3	1.7	1.1
12	-2.1	-5.2	5.9	1.7	1.15
13	5.1	-2.6	7.7	1.7	1.07
14	-5.1	-2.7	5.2	1.7	1.15
15	5	-5.4	6.3	1.8	1.12
16	-5.4	-5.3	7.5	1.8	1.15
17	-0.1	-7.8	6.2	1.8	1.09
18	-7.9	-0.1	6.1	1.75	1.16
19	7.5	-2.8	6.2	1.9	1.13
20	2.4	-7.7	6.5	1.7	1.09
21	-7.8	-2.1	6.4	1.8	1.1
22	-2.5	-8	6.2	1.7	1.11
23	5	-7.6	5.7	1.8	1.17
24	-4.9	-7.8	5.8	1.8	1.18
25	-7.7	-5.5	4	1.8	1.02
26	8.1	-5.1	7.2	1.8	1.06
27	-10.1	-0.5	6.2	1.8	1.14
28	-9.9	-2.6	6.9	1.8	1.08
29	10.3	0	7	1.8	1.15
30	-7.7	-7.5	6.1	1.9	1.13
31	10.3	-3	3.7	1.8	0.84
32	7.7	-7.7	8.8	1.9	1.6
33	-10.3	-4.9	8.1	1.9	1.06
34	10.8	-5.1	4.2	1.9	1.06
35	10	-7.7	4.7	1.8	1.13
36	-10.4	-7.8	6.7	1.8	1.08