Numerical Modeling of Grassland Fires: Investigating the Role of Wind Speed and Slope Angle

Ankit Patil[a], Kirti Bhushan Mishra[b]

[a] *Technological risk and analysis group (TRAG), Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee- 247667, Uttarakhand, India*

[b] *Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee- 247667, Uttarakhand, India*

Abstract

This study aimed to investigate the effects of fuel bed slope and wind speed on the head spread rate and Heat Release Rate (HRR) of grassland fires. Numerical investigations were conducted across three different terrains with varying wind speeds. The WFDS results from the C064 grassland fire experiment were utilized for validation purposes. The HRR exhibited a close resemblance to the experimental data, with a deviation of only 9%. Similarly, the head spread rate had a deviation of 4.54% at a wind speed of 4.6 m/s. The findings highlighted that upslope terrain experienced the highest head spread rate due to increased wind turbulence. As wind speed increased from 3 to 9 m/s, the head spread rate varied by approximately 30-35 percent compared to downslope conditions. This corresponded to a higher heat release rate, with an average HRR of 214 kW at a wind speed of 9 m/s. Additionally, the study investigated the influence of slope angle on fire spread, finding that a 45º slope exhibited the greatest fire spread rate compared to 8º, 16º, 22º, and 31º slopes. These findings align with previous research emphasizing the importance of considering rate of spread of fire and slope angle in understanding fire behavior. Also performed simulation in FDS based on real example to calculate time required to spread fire. The study's insights contribute to formulating effective strategies for managing and controlling potential future wildfire outbreaks. By understanding the methodology employed in existing experiments and simulations, we can replicate these processes on different terrains, enabling better wildfire management.

Keywords: Numerical investigations, C064, grassland fires, slope, wind speed, Head spread rate, HRR

1. Introduction

Grassland fires are complex phenomena that have a significant impact on ecosystems, human lives, and the environment. Understanding the behavior and spread of these fires is crucial for developing effective fire management strategies. However, studying real-life grassland fires can be challenging due to their unpredictable nature and potential risks. Previous studies have highlighted the role of wind speed and slope angle in fire behavior. Wind speed can affect fire spread by increasing the supply of oxygen, intensifying flame height, and promoting the transport of firebrands. Slope angle, on the other hand, influences the gravitational force acting on the fire, potentially accelerating or decelerating the spread. Fire simulations offer a valuable tool for investigating and analyzing grassland fire behavior in a controlled and safe environment. These simulations utilize computational models and algorithms to replicate the dynamics of fire spread, considering various factors such as fuel

Email address: `patilankit061295@gmail.com` (Ankit Patil)

characteristics, weather conditions, and terrain features. By simulating grassland fires, researchers can gain insights into the underlying mechanisms and patterns of fire behavior, improving our understanding of these complex events. The objective of this research paper is to explore the applications and benefits of grassland fire simulations in enhancing our knowledge of fire behavior and aiding fire management efforts. These simulations enable us to study different scenarios, manipulate variables, and observe the outcomes without the risks associated with actual fires. Moreover, they provide a cost-effective approach for evaluating fire management strategies and assessing the effectiveness of various intervention techniques.

One significant advantage of grassland fire simulations is the ability to model and analyze fire behavior under different environmental conditions. By incorporating realistic fuel models, accurate weather data, and detailed terrain information, simulations can recreate specific grassland ecosystems and evaluate how different factors influence fire spread. This information is invaluable for developing and refining fire behavior prediction models, which in turn help inform decision-making in fire-prone regions. Additionally, fire simulations provide a platform for testing and optimizing fire management strategies. By simulating different scenarios, researchers can assess the effectiveness of prescribed burning, fire breaks, and other mitigation measures. These simulations allow for the evaluation of various intervention techniques without the potential risks and costs associated with implementing them in the field. Furthermore, grassland fire simulations contribute to our understanding of fire dynamics and provide insights into the potential impacts of fires on ecosystems, wildlife habitats, and air quality. By accurately modeling fire behavior, researchers can estimate heat release, emissions, and fire severity, helping to assess the ecological consequences of grassland fires and inform post-fire restoration efforts [1-4].

2. Past experiments

2.1. C064 Australian grassland fire experiment

This C064 experiment plays significant role for validation of our numerical investigations of grassland fires. In this experiment , the Commonwealth Scientific and Industrial Research Organization (CSIRO) conducted controlled grassland fire experiments in the vicinity of Darwin, Northern Territory, during July and August of 1986. These months correspond to the middle of the dry season when the grasses are fully cured and the weather conditions are warm and dry.

The experiments were conducted on flat plots of varying sizes, measuring either 100 m by 100 m, 200 m by 200 m, or 200 m by 300 m. Among the experiments, Case C064 focused on a specific plot area of 100 m by 100 m covered with kerosene grass, scientifically known as Eriachne burkittii. To initiate the fires in the experiments, two individuals equipped with drip torches were employed. These individuals walked in opposite directions along the upwind boundary of the plot, igniting the grassland fire in a controlled manner. The primary objective of the research was to determine the location of the maximum gas temperature within a 1 m wide and 1 m tall strip positioned along the centerline of the grass field. To obtain this data, aerial photography was utilized, allowing for accurate identification of the experimental points. The findings from this research provide valuable insights into the behavior of controlled grassland fires under specific environmental conditions. By analyzing the location of the maximum gas temperature, researchers can better understand the heat distribution and fire dynamics within the grassland ecosystem. The outcomes of this study contribute to the scientific understanding of grassland fire behavior, particularly during the dry season in similar environments. The results have practical implications for fire management strategies, aiding in the development of effective approaches for controlling and mitigating grassland fires in warm and dry conditions [5-7].

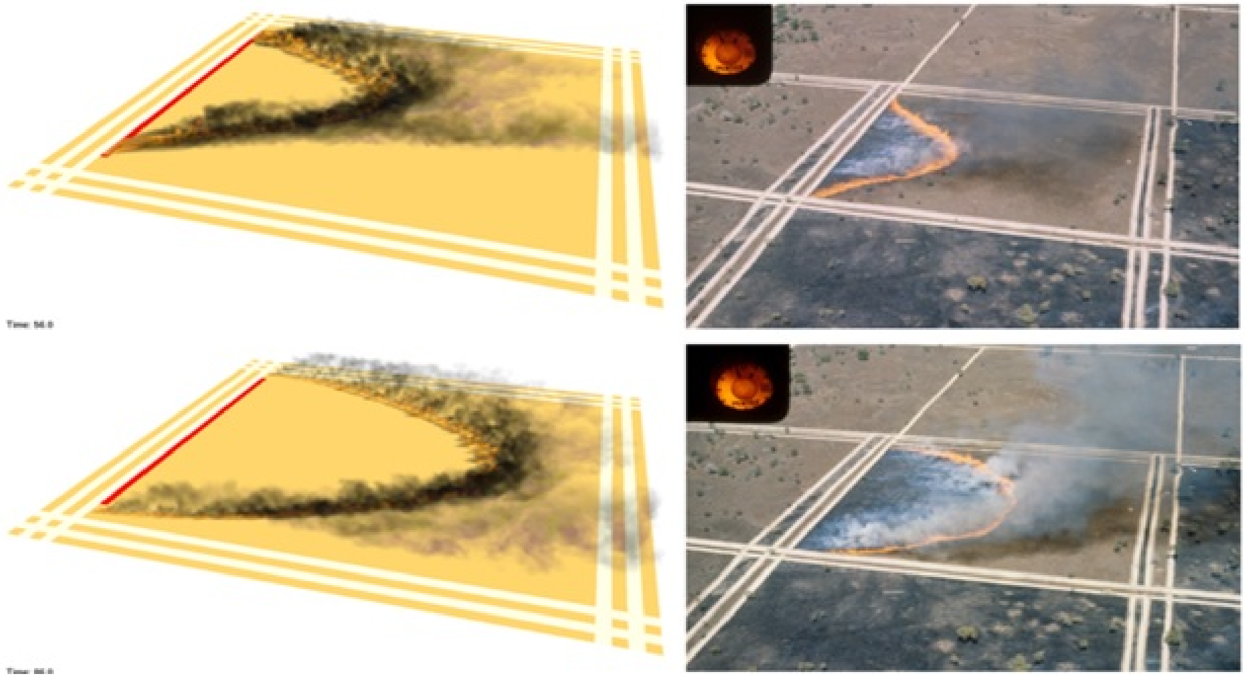

Figure 1: Snapshots of the simulation of CSIRO Grassland Fire compared to photographs of the fire [5-6]

2.2. Upslope experiment

In an upslope experiment conducted by Butler et al. at the USFS's Laboratory in Missoula, several parameters related to fire behavior were measured. The study aimed to investigate the rate of spread and fire behavior at different angles of slope, and it compared the experimental results with video camera footage. The experiment did not involve wind speed as a variable and focused on laboratory-scale conditions with a uniform fuel bed measuring 1 meter wide and 4.6 meters long. To measure the rate of spread and fire behavior, light sensors and a video camera were utilized as instruments. The light sensors provided data on the rate of spread of the fire, allowing for a quantitative analysis of fire speed in different slope angles. Video camera footage was used to capture visual information on the fire's behavior, providing qualitative insights into the fire dynamics and spread patterns. The outcomes of the experiment revealed that fire speed increased with slope angles. As the slope angle increased, the rate of fire spread became more rapid. This observation aligns with previous research indicating that higher slope angles correspond to increased rates of fire spread. The findings confirmed the influence of slope angle on fire behavior and provided experimental evidence to support this understanding. Furthermore, the study assessed the performance of the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) in reproducing the experimental results. WFDS, a computational model used for simulating fire behavior, was able to accurately replicate the observed fire behavior in the laboratory-scale experiment. This demonstrates the capability of WFDS in simulating and predicting fire spread in upslope conditions, further validating its application in fire research and management. The upslope experiment conducted by Butler et al. contributes to the body of knowledge on fire behavior in sloped terrain. By examining the rate of spread and fire behavior at different slope angles, the study provides insights into the dynamics of upslope fires. The findings have implications for fire management strategies in areas prone to sloped terrain, highlighting the need for careful consideration of slope angles in fire risk assessments and mitigation efforts [8-10].

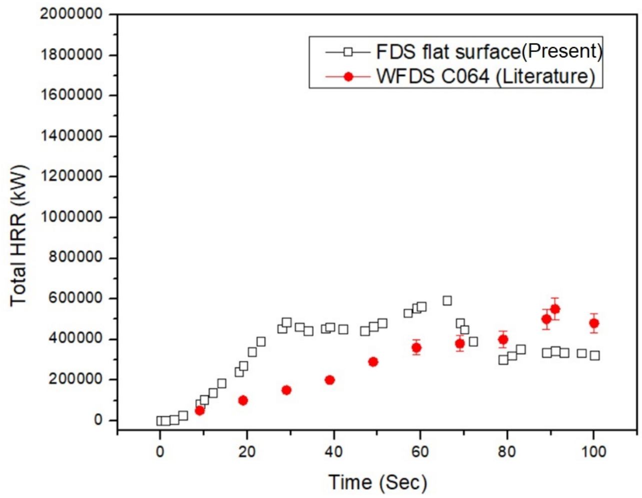

Figure 2: Comparison of HRR in C064 in WFDS with present simulation CO64 in FDS

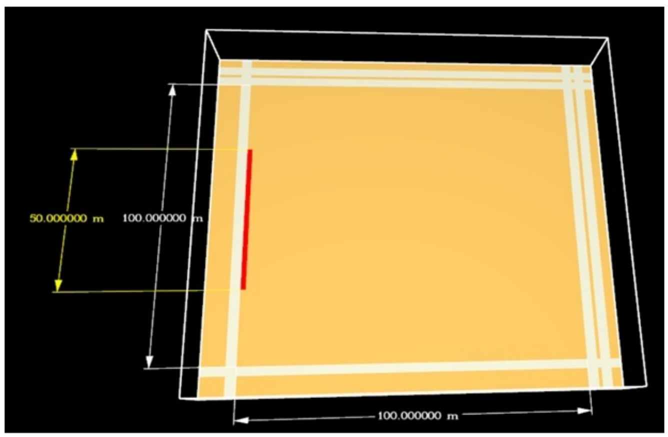

Figure 3: The flat surface terrain for numerical investigation of C064 experiment

3. Validation

In the comparison between the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) and the new Fire Dynamics Simulator (FDS) simulation for Case C064, the average heat release rate (HRR) was evaluated. The HRR was found to be 4.3×10^5 kW in WFDS and 3.9×10^5 kW in the new FDS simulation. This comparison allowed for an assessment of the performance and accuracy of the FDS simulation in estimating the HRR [7]. Fig-2, explains graphically the comparison of HRR in two scenarios. In Fig-3, the terrain devolved for the present numerical investigation. This terrain is similar to the C064 grassland experiment.

To validate the results, the WFDS results were used as a reference, and the deviation between the two simulations was approximately 9%. This validation process demonstrates the reliability and effectiveness of the new FDS simulation in capturing the essential characteristics of the C064 Australian grassland fire experiment. Furthermore, the numerical simulations conducted in this study were compared with experimental values reported in the existing literature. This comparison provides a comprehensive evaluation of the simulation results, ensuring their consistency and relevance to real-world scenarios. Overall, the comparison of HRR between WFDS and the new FDS simulation in Case C064 illustrates the capability of the FDS model to estimate the heat release rate accurately. The validation with WFDS results and comparison with experimental data further

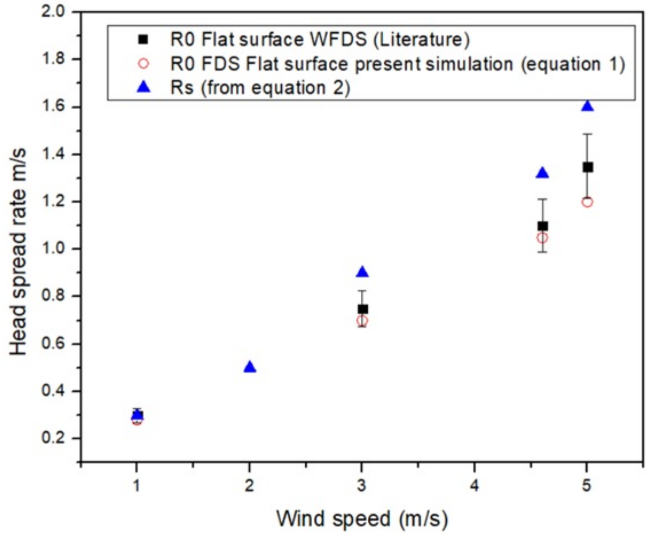

Figure 4: Head spread rate of fire at different wind speeds for comparison of literature values with FDS simulations of CSIRO grassland experiment

enhance the credibility and applicability of the numerical simulations in studying and understanding grassland fire behavior.

A comparison was conducted between the head spread rate of fire in the CSIRO Australian grassland experiment using the WFDS (Wildland urban interface fire dynamics simulator) and FDS (Fire Dynamics Simulator) simulations. The deviation between WFDS and FDS simulations for a wind speed of 4.6 m/s was found to be 4.54%. To ensure a comprehensive comparison with the literature data of head spread rate in the CSIRO grassland experiment, it was necessary to consider multiple wind speeds in the FDS simulation. Wind speeds of 1, 3, 4.6, and 5 m/s [7] were selected for the numerical investigation in FDS. The comparison revealed that the head spread rate values obtained from the FDS simulation closely matched the experimental values performed in WFDS. At a wind speed of 1 m/s, the experimental WFDS head spread rate was measured at 0.3 m/s, while the FDS simulation yielded a value of 0.28 m/s. Similarly, at 3 m/s, the experimental WFDS head spread rate was 0.75 m/s, and the FDS simulation showed a rate of 0.7 m/s. At a wind speed of 5 m/s, the experimental WFDS head spread rate was recorded as 1.35 m/s, while the FDS simulation resulted in a rate of 1.2 m/s. The results are graphically presented in Fig-4, illustrating the data of head spread rate in the CSIRO experiment.

These findings indicate a close agreement between the FDS simulation results and the experimental data obtained from the WFDS simulation, suggesting that the FDS simulation is capable of accurately predicting the head spread rate of fire in the CSIRO grassland experiment.

4. Simulation methodology

In our study, we applied the C064 simulation methodology to design terrains of various types: upslope, downhill, flat surfaces. For all these terrains, we used short grass with a height of 0.21 meters as the fuel in the simulations, as mentioned in references [11] and [14]. The domain dimensions were set differently depending on the terrain: 12 meters by 12 meters by 6 meters for upslope, downhill, and flat surfaces, with the simulation performed in a 6 meters by 6 meters area.

To enable meaningful comparisons, we selected three wind speeds based on previous research literature: 4.6, 6, and 9 meters per second [7] [12-13]. Varying the wind speeds allows us to analyze their influence on fire behavior. In our FDS modeling simulation, we considered an ambient temperature of 32ºC and a moisture fraction of 6.3% [11]. A level-set approach was used for all three conditions . The soot density was assumed to be 0.015 kg/kg in all four conditions, consistent with the reported values from the C064 experiment (Table 1). These assumed properties are summarized in Table 2, which can be adjusted according to specific circumstances. For instance, if unstable climatic conditions prevail, the Monin-Obukhov length may range from -500 to -350 [14-16].

By adopting these simulation parameters and assumptions, we aim to provide a simplified and practical approach to studying fire behavior in different terrains. These settings can be modified to suit specific scenarios and account for variations in climatic conditions or other factors of interest.

In FDS, different simulation models are employed for modeling wildland fires, including the Lagrangian model, boundary fuel model, and level set model. Each model has its unique characteristics and application: 1. Particle Model: The Lagrangian model represents vegetation as a collection of Lagrangian particles that undergo heating during the fire simulation. 2. Boundary Fuel Model: The boundary fuel model treats ground vegetation as a porous solid with a thickness equal to the vegetation height. Heat transfer through convection and radiation is considered in this model. 3. Level Set Model: In the level set model, the fire front propagates based on empirical rules. Spread rates for various vegetation types and wind speeds are experimentally determined and utilized.

Both the Particle Model and Boundary Fuel Model utilize a common pyrolysis model and predict the fire spread rate. On the other hand, the Level Set Model relies on empirical data for fire spread rates under different conditions.

For simulating large-scale wildland fires where fine-grained grid resolution is not feasible for physics-based fire spread prediction, FDS incorporates an empirical level set model [6]. This approach, based on the Lagrangian-based fire front-tracking model FARSITE, reproduces the Rothermel-Albini surface fire spread rate equations. It assumes that a surface fire spreading from a point, under specific wind, slope, and vegetation conditions, has an elliptical-shaped fire front with a fixed length-to-breadth ratio for a given wind speed [6].

To activate the level set feature in FDS, the parameter $LEVEL\_SET\_MODE$ on the MISC line must be set to one of the following values: 1, 2, 3, or 4:

$LEVEL\_SET\_MODE = 1$: Only the level set simulation is performed without considering wind or fire.

$LEVEL\_SET\_MODE = 2$: The wind field is established over the terrain, but it remains unchanged after the fire ignites.

$LEVEL\_SET\_MODE = 3$: The wind field follows the terrain, but no actual fire is simulated. Only front-tracking is performed.

$LEVEL\_SET\_MODE = 4$: The wind and fire are fully coupled. When the fire front reaches a surface cell, it burns for a specific duration with a provided heat release rate per unit area based on the fuel model.

Level-set model is based on Rothermel-Albini fire spread equations. These equations are as follows

Rothermel fire spread model [14]

$$\text{ROS} = 0.000975 \times (\beta \cdot \sigma + \gamma) \times (1 + 3.81 \times \left(\frac{\text{wind Speed}}{\beta \cdot \sigma + \gamma}\right)) \times (1.47 \times \left(\frac{\text{fuel Moisture}}{\beta \cdot \sigma + \gamma}\right)^{1.5}) \times \text{slope Factor} \tag{A}$$

$$\text{Packing Ratio} = \frac{\text{Total Volume of Area}}{\text{Volume of Fuel Particles}} \tag{a}$$

Albini Fire Spread Model [35]:

The Albini fire spread model provides an estimate of the forward rate of spread of a fire based on fuel characteristics, weather conditions, and slope. The formula is as follows:

$$\text{ROS} = \frac{3.937 \cdot (\text{fuel Size}^{1.5}) \cdot (\text{windSpeed}^{0.7}) \cdot (1 - \text{moisture Content})}{\text{fuel Bed Depth} \cdot \text{slope Factor}} \tag{B}$$

In the Fire Dynamics Simulator (FDS), the heat release rate (HRR) can also be expressed in terms of the heat of reaction, denoted as ΔHc. The heat of reaction represents the amount of energy released per unit mass during the combustion process. The equation for HRR in terms of the heat of reaction is as follows:

$$HRR = \Delta\text{hc} \times \dot{m} \tag{C}$$

In the current simulation conducted on three terrains with a 6m x 6m area, the level set mode is employed. The level set mode is also applied in case studies and real-life examples. However, for validation purposes using the C064 experiment, the boundary fuel model is used in a 100m x 100m terrain containing short grass.

In all present simulations, the presence of fire is commonly determined based on a threshold temperature of 600°C. According to this criterion, a fire is considered to exist when the temperature exceeds 600°C. The temperature of a grass fire can vary depending on factors such as fuel moisture, weather conditions, fuel loading, and fire behavior. While specific temperature ranges can vary, scientific literature generally reports flame temperatures for grass fires in the range of approximately 600°C to 900°C (1112°F to 1652°F) [36-37].

In terms of heat release rate, the fire is defined for the grass fires are generally characterized by a range of 500 to 1500 kW/m$\hat{2}$, However, it is important to note that these values are approximate and can vary depending on the specific conditions of the fire. Such as fuel moisture content, fuel loading, combustion efficiency, and fire behavior. [38].

5. Grid independency test

In order to ensure accurate results in fire simulations, a grid independence test is performed. This test examines the relationship between the size of the mesh cells and the width of the ignition line. It is essential to ensure that the size of the mesh cells is either equal to or smaller than the width of the ignition line. For instance, if the width of the ignition line measures 2.4 meters, the size of the mesh cells should be equal to or less than 2.4 meters. If the mesh cell size exceeds 2.4 meters, the simulation will not generate a fire. This requirement ensures that the mesh resolution adequately captures the details and dynamics of the fire [17-18].

Conducting a grid independence test is a crucial step in fire simulations as it enables the determination of an optimal mesh resolution. By selecting a mesh size that appropriately captures the fire dynamics without sacrificing computational efficiency, the simulation output can provide accurate and reliable values for further analysis and interpretation. In the context of the upslope condition, the ignition line width is determined to be 0.2 meters. Consequently, for the grid independence test, grid sizes equal to or smaller than 0.2 meters are considered. Any grid size larger than 0.2 meters does not result in the generation of a fire within the simulation. The selected grid sizes for evaluation include 0.2m, 0.18m, 0.16m, 0.15m, 0.125m, and 0.11m. This grid independancy test for present simulation.

Table 1: The tabular representation of average HRR concerning time for different grid sizes for upslope conditions at wind speed 4.6 m/s.

Grid independence test (m)	HRR (kW)
0.12	192
0.125	192
0.15	199
0.16	202
0.18	207
0.2	213

In the case of upslope conditions at a wind speed of 4.6 m/s, it was observed that the deviation in HRR between grid sizes of 0.11-0.2m exceeded 10%. To select the most appropriate grid size, it is necessary to identify a grid size with a deviation equal to or less than 10% compared to a reference grid size of 0.2m. Among the grid sizes tested, namely 0.15m, 0.16m, and 0.18m, one of them can be selected as the optimum grid size. The deviation in HRR with respect to the 0.2m grid size should meet the criterion of being equal to or less than 10% to ensure accuracy in the simulation results. In Table-1 represents the average value HRR in upslope conditions at the wind speed of 4.6 m/s

By performing the grid independence test and considering the deviation thresholds, researchers can determine the appropriate grid size that provides a balance between computational efficiency and accuracy in capturing the fire behavior phenomena.

6. Results and discussion

6.1. Effects of wind speed on fire spread

Figure 5 provides a comprehensive illustration of the grassland plot, offering a clear depiction of the key elements involved in the simulation. It highlights the precise positioning of the ignition line, the fuel-containing grassland plot, the domain encompassing the simulation, and the direction of the wind speed. This schematic diagram serves as a valuable tool for simulating forest fires across surfaces that house fuel [7].

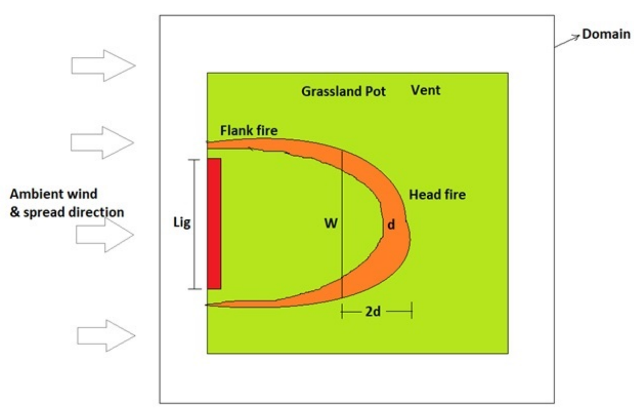

Figure 5: Schematic of grassland pot, Lig- Ignition line, d- depth of head fire, W- Width of simulated head fire [11]

The schematic facilitates the determination of two significant values: the width of the simulated head fire (W) and the depth of the fire. These values can be obtained by examining the top view of the simulation. By utilizing equation (1) with

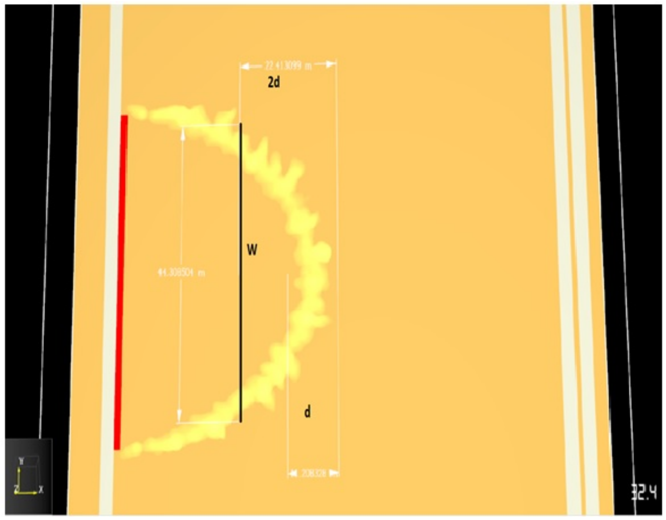

Figure 6: To calculate the value of ‘d’ in FDS simulation

the values of ’d’ and ’W’, the head spread rate of the fire can be calculated. Notably, the head spread rate is influenced by the moisture content in the fuel (M), the width of the simulated head fire (W), and the speed of the wind.

The impact of wind speed on fire behavior is crucial to consider. Higher wind speeds can greatly enhance the spread rate of a fire. This occurs because the wind supplies additional oxygen, intensifying combustion and fueling the fire’s growth. The velocity of the wind directly affects the speed at which the fire propagates through available fuel. Figure 7 explicitly emphasizes the correlation between increased wind speed and a higher rate of fire spread.

Understanding the intricate relationship between wind speed, topography, and other influencing factors is essential in comprehending and predicting fire behavior accurately. The schematic representation presented in Figure 5 and Figure 6 and the observation regarding wind speed and fire spread in Figure 7 contribute significantly to our understanding of the dynamics and complexities involved in simulating and analyzing fire behavior.

The head fire spread rate (R0) can be determined using the empirical formula provided, which takes into account the measured wind speed (U2), head fire width (W), and fuel moisture (M). These values can be calculated through simulations, referring to Figure 5 mentioned above [7]. Equation (1) is used to calculate the head fire spread rate (R0). It incorporates various factors such as wind speed, fuel characteristics, and slope angle to estimate the rate at which the fire front advances. The equation is given by:

$$R0 = (0.165 + 0.534U2)\exp\left(\frac{[-0.859 - 2.036U2]}{W}\right)\exp(-0.108M) \tag{1}$$

In this equation, U2 represents the wind speed at a height of 2 meters, W represents the fuel load parameter, and M represents the moisture content of the fuel. The equation takes into account the effects of wind speed, fuel properties, and moisture content on fire spread. Equation (2) is used to calculate the quasi-steady spread rate (Rs), which is an approximation of the fire spread rate under steady-state conditions.

The equation is given by:

$$Rs = (0.165 + 0.532U2)\exp(-0.108M) \tag{2}$$

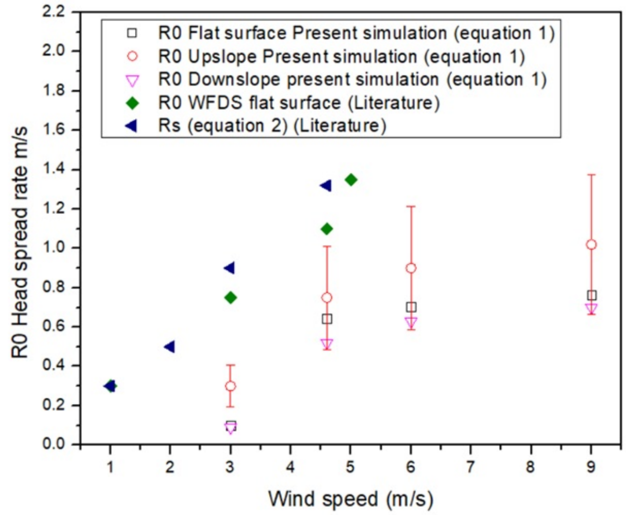

Figure 7: Spread rate of head fire versus wind speed of height 2m, comparison of upslope, flat surface, and downslope with experimental results.

Similar to Equation (1), this equation incorporates wind speed (U) and fuel moisture content (M) to estimate the fire spread rate. It provides an approximation of the fire spread rate when the fire is considered to be in a quasi-steady state. Equation (3) is used to estimate the wind speed (U) at a height (z) based on the wind speed at a reference height of 2 meters (U2).

The equation assumes a logarithmic wind profile suitable for smooth terrain and is given by:

$$U(z) = U_{2i}\left(\frac{z}{2}\right)^{\frac{1}{7}} \quad (3)$$

In this equation, U2i represents the initial wind speed at 2 meters. The equation allows for the estimation of wind speed at different heights using a logarithmic wind profile relationship, which describes how wind speed varies with height in the atmospheric boundary layer [14-15]. These equations are commonly used in fire behavior modeling to estimate fire spread rates based on wind speed, fuel characteristics, and slope angle. They provide valuable insights into understanding and predicting fire behavior in wildland fuel environments. Simulations have been conducted using three different wind speeds: 3m/s, 4.6 m/s, 6 m/s, and 9 m/s. The graph below illustrates the resulting head fire spread rates obtained from these wind speeds, utilizing Equation (1) [7].

6.2. *Effect of slope on the rate of spread of fire*

The slope of the terrain can have a significant effect on the spread rate of fire. Steep slopes can enhance the spread rate of fire. The steeper the slope, the greater the potential for the fire to accelerate. The uphill direction of the slope provides an additional upward draft that increases the availability of oxygen, allowing the fire to burn more vigorously. Fig 8 represents the rate of spread of fire in terms of slope angles. As the slope angle increases, the fire spread rate also increases. The various angles were considered from 0º to 45º. The maximum spread rate achieved Fires tend to spread more rapidly uphill compared to the level ground or downhill. The convection currents created by the slope can drive the fire upslope, allowing it to progress more quickly in that direction. It is important to consider the slope factor in fire behavior predictions and firefighting strategies.

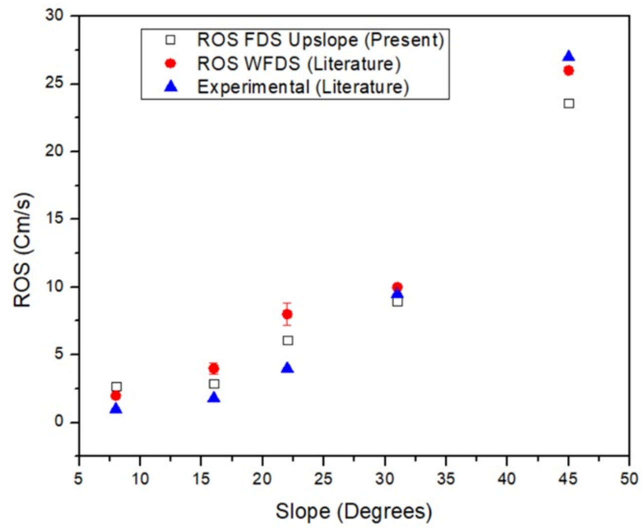

Figure 8: Comparison of Rate of Spread (ROS) for different fuel bed slopes. The graph includes data points for WFDS ROS, FDS ROS, and Experimental ROS.

No wind speed was considered in both the experimental setup and the simulations conducted using FDS and WFDS [8]. The experimental validation was performed using a fuel bed depth of 7.62 cm and a packing ratio of 0.01. Four angles, namely $\angle 8$, $\angle 16$, $\angle 22$, $\angle 31$ and $\angle 45$, representing the incline of the uphill surface covered with short grass, were utilized for validation purposes. The properties of the short grass used in the simulations were derived from the C064 experiment. The slope of the terrain emerged as a significant variable in this experimental condition. Figure 8 presents a graphical representation of the rate of spread (ROS) of fire across different angles. In the upslope condition, the Fire Dynamics Simulator (FDS) simulation produced various rates of spread at different angles. Comparing these results with existing literature data, several observations can be made.

At an angle of 16º, the FDS simulation indicated a rate of spread of 2.9 cm/s. Similarly, at an angle of 8º, a rate of spread of 2.7 cm/s was observed. These values closely align with the literature data, suggesting agreement between the simulation and established findings. Furthermore, the FDS simulation yielded a rate of spread of 6.09 cm/s at an angle of 22º, while at an angle of 31º, the rate of spread increased to 9 m/s. These findings also close to the literature data, indicating a deviation between the simulation and the established knowledge. Lastly, at an angle of 45º, the FDS simulation recorded a rate of spread of 23 cm/s. In the case of literature values, its about 26-27 Cm/s observed.

These findings illustrate the variations in fire behavior observed across different angles in the upslope condition. The accompanying illustrations depict a systematic approach for calculating various angles on an uphill slope. By strategically selecting reference points and employing trigonometric principles, one can determine the desired angles with precision. To begin, consider a given slope or incline. By identifying key points along the slope, such as the base and the apex, one can establish a reference frame for angle calculations. The deviations between the simulation results and the experimental data highlight the intricacies and uncertainties associated with accurately modeling and simulating grassland fires. Factors such as fuel properties, heat transfer mechanisms, and variations in slope contribute to the observed variations. The importance of conducting comparative studies to assess the capabilities and limitations of simulation models in capturing real-world fire dynamics is emphasized.

6.3. *Effect of wind speed on the heat release rate of different terrains*

Fires burning on upslope terrain exhibit distinct characteristics that result in an increased heat release rate compared to fires on flat terrain. These effects can be attributed to factors such as preheating of the fuel and increased turbulence caused by the upslope wind. Preheating of the fuel is a significant factor contributing to the higher heat release rate in upslope conditions. As the fire moves against the upslope wind, it preheats the fuel ahead of the flame front. This preheating process dries out the fuel, making it more susceptible to ignition and leading to an increased heat release rate (McRae et al., 2006) [19]. In the case of short grass as the fuel type, the preheating of the grass by the flame increases its dryness and ignitability, resulting in enhanced combustion.

The upslope wind also induces increased turbulence due to the interaction between the wind flow and obstacles such as ridges and vegetation. This turbulence promotes better mixing between fuel and air, facilitating more efficient combustion and contributing to a higher heat release rate (Finney, 2004) [20]. The turbulence created by the upslope wind enhances the transport of heat and combustion products, leading to increased fire intensity and spread. In Figure 9, the wind velocity vectors clearly demonstrate the direction of fire spread, which coincides with the direction of the wind. This alignment between wind direction and fire spread is particularly advantageous in upslope conditions. The wind conditions observed in the figure are favorable for the rapid spread of fire in an upslope terrain.

The wind plays a crucial role in fire behavior as it provides additional oxygen to fuel combustion and transports heat and burning embers, effectively promoting the forward movement of the fire front. In the case of upslope terrain, where the fire is moving against the upslope wind, the combined effect of wind and slope creates an optimal scenario for fire spread. The wind velocity vectors pointing in the direction of fire spread indicate that the wind is pushing the flames uphill, facilitating the upward movement of heat, combustion products, and burning particles. This interaction between the upslope wind and the fire creates an upward draft that intensifies the fire's growth and accelerates its spread along the slope.

The presence of such wind conditions, aligned with the direction of fire spread, is highly influential in determining the rate and extent of fire propagation in upslope terrain. Understanding the relationship between wind patterns and fire behavior in different topographic settings is vital for accurately predicting fire spread and developing effective strategies for fire management and suppression. Overall, Figure-9 highlights the importance of wind dynamics in upslope fire spread and underscores the need to consider wind direction and speed when assessing fire behavior in complex terrain [21-22].

Fires burning on downslope terrain generally experience a decrease in heat release rate compared to fires on flat terrain. The primary factors contributing to this effect are: a. Reduced fuel availability: Fires on downslope terrain may burn through the available fuel more rapidly due to the downhill movement of flames. Once the fuel is depleted, the heat release rate decreases. This phenomenon is discussed by Mell et al. (2007) [23], where they highlight the rapid consumption of fuel on downslope terrain leading to a decrease in fire intensity. b. Disrupted wind flow: The downhill wind can disrupt the natural wind flow patterns around the fire. This disruption can reduce the oxygen supply to the fire and hinder the combustion process, resulting in a lower heat release rate. The disrupted wind flow on downslope terrain and its impact on fire behavior is discussed by Finney et al. (2013) [22], who emphasize the influence of wind patterns on the heat release rate and spread of wildfires.

Figure 10 illustrates the pattern of wind flow on downslope terrain, showing a decrease in wind velocity vectors towards the bottom of the hill. This indicates that the wind flow is not favorable for fire spread in the downhill direction.

Fires burning on flat terrain exhibit a more consistent and predictable heat release rate compared to fires on sloped terrain. On flat terrain, the absence of significant slope-related effects allows for a more uniform fuel supply, air circulation, and

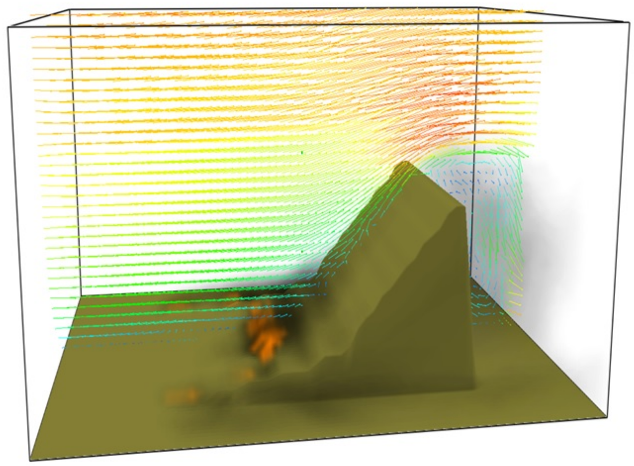

Figure 9: The wind velocity vectors supports the fire and increases its rate of speed.

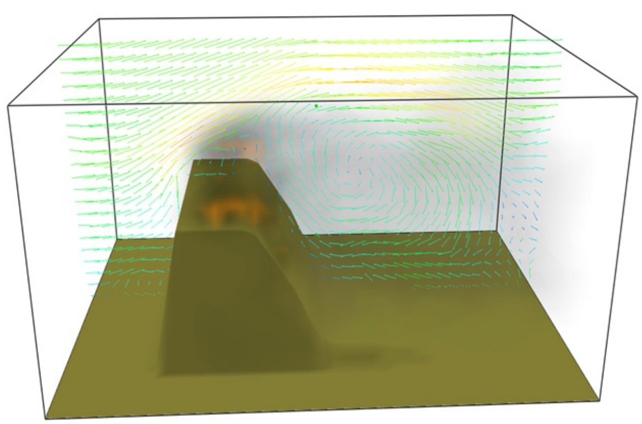

Figure 10: Disrupted wind flow on downhill fire spread, represented by velocity vectors.

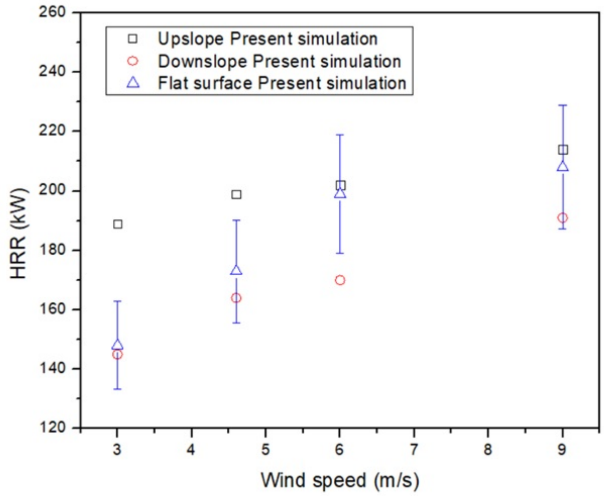

Figure 11: The average HRR of different terrains: upslope, downslope and flat surface terrain.

combustion process, resulting in a relatively stable heat release rate.

The heat release rate on flat terrain is influenced by various factors, including fuel characteristics, wind speed, and fire size. Fuel properties such as moisture content, composition, and arrangement play a crucial role in determining the rate of combustion and subsequent heat release. Wind speed affects the availability of oxygen for combustion and can influence the intensity and spread of the fire. Fire size, both in terms of its spatial extent and duration, also contributes to the overall heat release rate [27].

In Fig-111, its observes that in upslope conditions, the average heat release rate (HRR) of the fire varies with different wind speeds. At a wind speed of 4.6 m/s, the average HRR was recorded as 199 kW, which increased slightly to 202 kW at 6 m/s, and further to 214 kW at 9 m/s. These findings indicate that higher wind speeds contribute to a higher average heat release rate in upslope fire scenarios.

On flat terrain, the average HRR values were relatively lower compared to upslope conditions. At a wind speed of 4.6 m/s, the average HRR observed was 173 kW, which increased to 199 kW at 6 m/s, and further to 208 kW at 9 m/s. The absence of significant slope-related effects on flat terrain results in relatively lower average heat release rates compared to upslope conditions.

In downslope conditions, the average HRR was observed at different wind speeds. At 4.6 m/s, the average HRR recorded was 164 kW, which increased slightly to 170 kW at 6 m/s, and further to 191 kW at 9 m/s. As the fire descends the slope, the wind speed decreases, influencing the fire's projection and resulting in slower fire spread. In some cases, the fire may even be extinguished before reaching the bottom of the slope. These observations demonstrate the influence of wind speed on the average heat release rate and combustion behavior of fires in different terrain conditions. Higher wind speeds generally contribute to increased fire intensity and average heat release rate, while lower wind speeds can impede fire projection and result in slower combustion [26-27]

Higher wind speeds generally promote increased fire spread and higher heat release rates. However, there is a limit to the beneficial effect of wind speed on fire behavior. Research indicates that at wind speeds exceeding 18 m/s, the fire can be extinguished, leading to a significant reduction in the heat release rate. This is because extremely high wind speeds disrupt the fire's oxygen supply and disrupt the combustion process, making it difficult for the fire to sustain itself. Consequently, the heat release rate decreases when the wind speed surpasses this threshold.

Comparative analysis suggests that among the wind speeds evaluated, a wind speed of 12 m/s resulted in the maximum heat release rate. This finding implies that there is an optimal wind speed range within which fire behavior, including heat release rates, is maximized. Beyond this range, either insufficient or excessive wind speed can negatively impact the fire's intensity and heat release capabilities [29-31].

It is important to consider these wind speed thresholds and their impact on fire behavior to effectively predict and manage fire spread and associated heat release rates in various scenarios. While it is true that high wind speeds can affect the behavior and intensity of fires, the notion that wind speeds exceeding 18 m/s can extinguish a fire is not universally applicable and requires further clarification. However, for larger and more intense fires, high wind speeds may not be sufficient to completely extinguish the fire. These fires can generate their own heat and create their own wind patterns, making them more resilient to external wind effects. Additionally, other factors such as the type and arrangement of fuel, topography, and weather conditions can significantly influence fire behavior and its response to wind.

Adverse weather conditions can vary, and among them is what is commonly referred to as "fire weather." Fire weather encompasses a combination of factors such as high temperatures, dry air, and strong winds that create an environment conducive to the ignition and rapid spread of fires. Furthermore, the impact of wind extends beyond the fire itself, as it has the ability to carry smoke over vast distances. A notable instance of this occurred in 2020 when wildfires in California, Oregon, and Washington caused a reddish haze to envelop the skies across the continent [33].

7. Real-world examples

7.1. Example-1

On March 15, 2023, a distressing incident occurred in rural Kansas, specifically in Riley County, USA, where two initially small fires rapidly escalated into larger wildfires. The prevailing weather conditions at the time were characterized by dryness and high wind speeds, reaching a magnitude of 45 mph (20.116 m/s). The terrain itself presented a challenging topography, with steep and rocky features, and was laden with dry fuel. The combination of these factors, compounded by the forceful winds, posed significant difficulties in controlling the spread of the fires [32].

One of the fires endured for an extensive duration, exceeding four hours (let us assume four hours thirty minute), resulting in an estimated burn area of approximately 400 acres, it means rate of spread of fire is around 99.9 $m\hat{2}$/s. In an attempt to gain further insights into this calamitous event, practical data was utilized to simulate the scenario within the Fire Dynamics Simulator (FDS).

The simulation involved employing a domain size of $140m \times 120m \times 20m$, with a total of 336,000 mesh cells. Within this domain, a representative section measuring $100m \times 70m$ (equivalent to 1.72 acres) was selected, designed to capture the steep and rocky terrain, which was predominantly covered by dry grass acting as fuel. Tall grass were assumed and properties taken from Australian grassland fire experiment. [7]. The wind speed input for the simulation was set at 20 m/s, mirroring the conditions present during the incident. To account for the unstable wind conditions, Monin Obukhov length (L) was determined to be -350 [6]. Also assume fuel bed consist of tall grass with 5.8% of moisture [7].

Upon conducting the simulation, it was revealed that the fire within the defined domain required 50 seconds to propagate and traverse a distance of 100m×70m. By extrapolating this information, it can be inferred that the simulated fire would require approximately 3 hrs. 22 mins to engulf and burn a larger area of 400 acres if the wind speed is constant throughout the time. Also for trial error method, we had taken two more wind speed 15m/s and 25m/s respectively. To ensure the rate of spread of fire. This simulation provides valuable insights into the behavior of the fire under the given circumstances, shedding light on the potential time required for the wildfire to spread across a considerable land area. However, it is important to note that these findings are based on the assumptions, parameters, and limitations of the simulation model employed. Real-world conditions and complexities may introduce additional variables and uncertainties that should be taken into consideration when analyzing and responding to such fire incidents in practice.

Table 2: Simulation data of wind speed and rate of spread of fire in m^2/s

S.N.	Wind speed (m/s)	Rate of spread (Sq. meter per sec)
1	15	113.08
2	20	139
3	25	154.5

Table-2 provides information on the rate of spread in square meters per second, which represents the three-dimensional spread of fire across terrain. This measurement reflects the total area that the fire covers as it continues to spread. On the other hand, the rate of spread in meters per second represents line fire, indicating that it only considers the two-dimensional aspect of fire spread along a line.

To validate the two-dimensional rate of spread, we can refer to the steady state equation (2), which is expressed as

$$Rs = (0.165 + 0.532U2)\exp(-0.108M)$$

This equation allows us to calculate the rate of spread based on the wind speed (U) and the moisture content (M) in the surrounding environment. By plugging in the corresponding values for U and M, we can estimate the rate at which the fire will propagate in a two-dimensional manner. Fig-12 presents a graphical representation of the rate of spread versus different wind speeds. This visual depiction helps us understand the relationship between wind speed and the rate at which the fire spreads.

In summary, the FDS simulation, utilizing practical data from the devastating wildfires in Riley County, Kansas, on March 15, 2023, highlighted the challenges posed by the dry and windy conditions, steep terrain, and dry fuel. By simulating the scenario, it was estimated that it would take approximately 3 hours 22 mins. for a fire to consume a 400-acre land area with constant 20m/s, providing valuable insights for firefighting and emergency response efforts in similar situations. . In the actual scenario of a 400-acre burning area, the wind speed exhibited a fluctuation ranging between 15 and 20 m/s.

Visualizing the Uncertainty: Error Bars Reflecting the Deviation in Rate of Spread (Rs). Within the captivating graph depicting the rate of spread (Rs) versus wind speeds, an invaluable element has been incorporated to enhance our understanding—error bars. These error bars serve as visual indicators of the inherent uncertainty in the estimation of Rs and provide valuable insights into the potential deviation from the calculated values.

Carefully designed to represent up to a 10% deviation from the estimated Rs, these error bars act as an essential tool for comprehending the range of possible outcomes. By encompassing this uncertainty, the graph imparts a realistic perspective on the potential variability in fire spread rates.

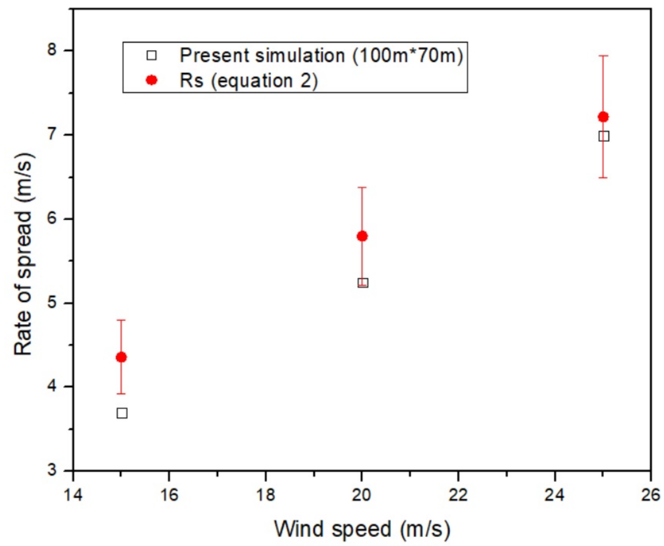

Figure 12: Two dimensional fire spread rate of simulation of example -1 performed on (100m×70m) steep and rocky terrain .

Figure 13: Pictures of real wildfire scenario of Riley County.

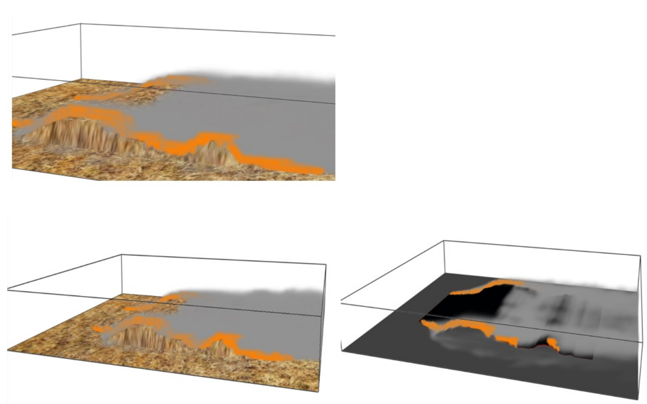

Figure 14: Pictures of simulation of fire spread in FDS- Smokeview.

7.2. *Example-2*

In the hilly region of Uttarakhand, India, forest fires are a common occurrence. However, the fire that occurred on April 20, 2016, in Tehri Garhwal was particularly intense. This incident took place during the daytime and posed a significant threat as the fire dangerously approached the fields and even caused stones to tumble onto the roofs of houses.

In the simulation of fire spread on hill, the area covered a rectangular region measuring 240m × 200m, while the simulation domain had dimensions of 350m × 300m × 150m to account for the three-dimensional nature of fire behavior. A grid cell size of 2.5m was employed to ensure sufficient resolution for capturing fire spread dynamics. To initiate the fire, a 100m long and 3m wide ignition line was introduced within the simulation area. The simulation was performed in level set mode using the FDS software.

When a fire spreads upslope, the resulting smoke becomes dense and takes on a white appearance. This is attributed to the fire's high rate of combustion in this direction, surpassing what is observed during downslope spread. The upward trajectory of the fire release an abundance of energy, contributing to this captivating visual spectacle. In Fig-17 provides a striking visual representation of the relationship between heat release rate (HRR) and fire behavior in different slope conditions. Notably, it demonstrates that during upslope conditions, the HRR reaches its peak, signifying a maximum release of heat energy. However, as the fire transitions into a downslope trajectory, the HRR gradually diminishes.

Figure 15: The fire is moving from the top of the hill towards the bottom, following the slope of the terrain.

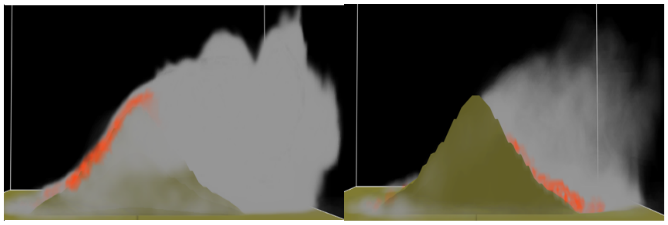

Figure 16: The fire is moving from the top of the hill towards the bottom, following the slope of the terrain.

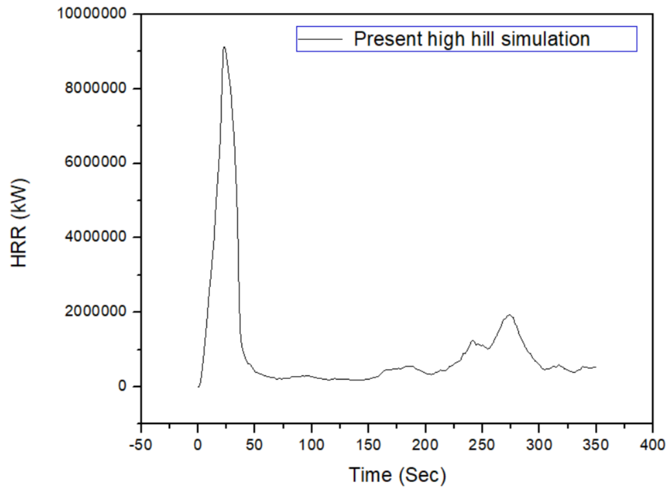

Figure 17: HRR of present high hill simulation

This decrease in HRR during downslope propagation can be attributed to several factors. Firstly, the change in slope angle affects the availability and arrangement of fuel, leading to a slower rate of combustion. Additionally, the downslope movement causes the fire to encounter a different set of environmental conditions, such as decreased fuel availability and altered airflow patterns, which can impede the fire's progress and subsequently reduce the HRR. Interestingly, after approximately 200 seconds, an intriguing phenomenon emerges. The HRR begins to rise once again, albeit to a limited extent. This occurrence can be linked to an increase in the rate of spread (ROS) of the fire during downslope conditions. As the fire gains momentum and spreads more rapidly, the HRR experiences a corresponding surge, albeit not to the same intensity observed during upslope conditions. This intricate interplay between ROS and HRR unveils the complex nature of fire behavior and highlights the dynamic relationship between slope, fire spread, and heat release.

Based on a thorough examination of a real-life example, a valuable lesson has been learned: relying solely on lab-scale experiments and theoretical concepts is inadequate for making definitive judgments. To gain a comprehensive understanding, it is crucial to not only observe actual wildfires but also simulate them for further analysis. By combining empirical data from real-life situations with the controlled environment of simulations, researchers can enhance their comprehension of the complex dynamics of wildfires. This approach allows for a more accurate evaluation of the variables involved, such as wind speed, topography, and fuel characteristics. Consequently, it is evident that a multidimensional approach that combines both real examples and simulations is essential for drawing accurate conclusions and making informed decisions regarding wildfire management and prevention.

Conclusion

The numerical investigations conducted on grassland fires with varying wind speeds and fuel bed slopes provided valuable insights into the behavior of these fires. The study focused on head spread rate and Heat Release Rate (HRR) as key parameters. The results showed that wind speed plays a significant role in fire spread. The fire head spread rate was found to be maximum in upslope terrain due to increased wind turbulence. As the wind speed increased from 3 to 9 m/s, the head spread rate varied by approximately 30-35% compared to downslope conditions. The maximum head spread rate in upslope conditions led to a corresponding increase in the heat release rate. At a wind speed of 9 m/s, the average HRR reached 214 kW, indicating the substantial release of heat. Additionally, the study investigated the influence of slope angle on fire spread and revealed that the fire spread rate was greatest at a 45º slope compared to 8º, 16º, 22º and 31º slopes. This aligns with prior research highlighting that steeper slope angles contribute to increased rates of fire spread. The validation of WFDS results using the C064 Australian grassland fire experiment demonstrated a close resemblance between the calculated HRR and the experimental data, with a deviation of only 9% and 4.54% deviation in head spread rate at a wind speed of 4.6 m/s. This validation adds credibility to the numerical investigations and the findings derived from them. Furthermore, the study performed simulations using the Fire Dynamics Simulator (FDS) based on real-world examples to calculate the time required for fire to spread. This approach provided valuable insights into the dynamics of fire spread under specific conditions and further contributed to understanding the factors influencing fire behavior. Overall, the study underscores the importance of considering wind speed and slope angle in understanding fire behavior. The increased head spread rate in upslope conditions leads to greater heat release, highlighting the significance of fuel preheating. The insights gained from this research contribute to our knowledge and understanding of wildfires. Moving forward, the application of numerical methods can assist researchers in conducting further studies and investigations into wildfires, enabling better preparedness and management strategies.

Appendix

The Simple Very Large Eddy Simulation (SVLES) method in FDS (Fire Dynamics Simulator) is based on the filtered Navier-Stokes equations. The equations are solved in a discretized form on a computational grid. The SVLES approach applies a box filter to the Direct Numerical Simulation (DNS) equations to obtain the filtered equations. The filtered equations for the conservation of mass, momentum, and energy in SVLES can be written as:

$$\frac{\partial \overline{\rho}}{\partial t} + \nabla \cdot (\overline{\rho}\mathbf{u}) = 0 \tag{Conservation of mass}$$

$$\frac{\partial \overline{\rho}\mathbf{u}}{\partial t} + \nabla \cdot (\overline{\rho}\mathbf{u} \otimes \mathbf{u}) = -\nabla \overline{p} - \nabla \cdot \overline{\tau} + \overline{\rho}\mathbf{g} + \mathbf{f}_d + \dot{m}_b'''\mathbf{u}_b \tag{Conservation of momentum}$$

$$\frac{\partial \overline{\rho}E}{\partial t} + \nabla \cdot (\overline{\rho}\mathbf{u}E) = -\nabla \cdot (\overline{p}\mathbf{u}) - \nabla \cdot (\overline{\tau} \cdot \mathbf{u}) + \nabla \cdot (\overline{\mathbf{q}}) + \overline{\rho}\mathbf{u} \cdot \mathbf{g} + \mathbf{u} \cdot \mathbf{f}_d + \dot{m}_b'''\mathbf{u}_b \cdot \mathbf{h}_b \tag{Conservation of energy}$$

References

[1] Mell, W., Jenkins, M., & Manzello, S. (2019). Wildland Fire Dynamics Simulator (WFDS) Technical Reference Guide. NIST Special Publication 1226, National Institute of Standards and Technology.

[2] Filkov, A., & Richard, M. (2016). Numerical modelling of grassland fires: A review. Procedia Engineering, 147, 903-908.

[3] Sánchez-Monroya, X., Mell, W., Torres-Arenas, J., & Butler, B. W. (2019). Numerical simulation of grassland fires using WFDS: Validation and sensitivity analysis. Fire Safety Journal, 109, 103199.

[4] Jenkins, M., Mell, W., & Weinschenk, C. (2008). Development of a fire spread model within a large-eddy simulation framework. Journal of Applied Meteorology and Climatology, 47(2), 325

[5] National Institute of Standards and Technology (2023). Fire Dynamics. https://www.nist.gov/el/fire-research-division-73300/firegov-fire-service/fire-dynamics

[6] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt. Fire Dynamics Simulator, User's Guide. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2013.

[7] W. Mell, M.A. Jenkins, J. Gould, and P. Cheney. A physics-based approach to modeling grassland fires. International Journal of Wildland Fire, 16(1):1–22, 2007.

[8] X. Sanchez-Monroy, W. Mell, J. Torres-Arenas, B.W. Butler. Fire spread upslope: Numerical simulation of laboratory experiments. Fire Safety Journal 108 (2019)

[9] J.-l. Dupuy, Slope, and fuel load effects on fire behavior: laboratory experiments in pine needles fuel beds, Int. J. Wildland Fire 5 (3) (1995) 153–164.

[10] D.A. Portier, J.A. Valette, The Effects of Slope and Fuel Bed Width on Laboratory Fire Behaviour, (2011).

[11] D.R. Weise, G.S. Biging, Effects of wind velocity and slope on flame properties, Can. J. For. Res. 26 (1996) 1849–1858

[12] Jasmine Innocent, Duncan Sutherland, Nazmul Khan and Khalid Moinuddin A B, Physics-based simulations of grassfire propagation on sloped terrain at field scale: motivations, model reliability, rate of spread and fire intensity, International Journal of Wildland Fire - `https://doi.org/10.1071/WF21124Publishedonline:20January2023`

[13] Erik L. Johnsson, Alexander Maranghides. Effects of Wind Speed and Angle on Fire Spread along Privacy Fences. National Institute of Standards and Technology Technical Note 1894 Natl. Inst. Stand. Technol. Tech. Note 1894, 27 pages (July 2016)

[14] R.C. Rothermel. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Research Paper INT-115, Intermountain Forest and Range Experiment Station, USDA Forest Service, Ogden, Utah, January 1972. `http://www.treesearch.fs.fed.us/pubs/32533.30,32,70`

[15] F.A. Albini. Estimating Wildfire Behavior and Effects. Research Paper INT-30, Intermountain Forest and Range Experiment Station, USDA Forest Service, Ogden, Utah, 1976. `https://www.fs.fed.us/rm/pubs\_int/int\_gtr030.pdf`

[16] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt. Fire Dynamics Simulator, Technical Reference Guide, Volume 1: Mathematical Model. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2013

[17] Roache, P. J. (1998). Verification and validation in computational science and engineering. Hermosa Publishers.

[18] AIAA Guide for the Verification and Validation of Computational Fluid Dynamics Simulations, AIAA G-077-1998.

[19] McRae, D. J., et al. (2006). "Estimating heat release rates of wildland fires using infrared imaging radiometers." Canadian Journal of Remote Sensing, 32(5), 415-426.

[20] Finney, M. A. (2004). "A computational method for optimizing fireline placement." International Journal of Wildland Fire, 13(3), 327-337.

[21] Butler, B. W., Cohen, J. D., & Latham, D. (1997). The importance of surface airflow for wildland fire behavior. International Journal of Wildland Fire, 7(4), 221-235.

[22] Finney, M. A., Cohen, J. D., Forthofer, J. M., McAllister, S. S., Gollner, M. J., Gorham, D. J., ... & Saito, K. (2013). Role of buoyant flame dynamics in wildfire spread. Proceedings of the National Academy of Sciences, 110(38), 15277-15281.

[23] Mell, W., Maranghides, A., McDermott, R., & Manzello, S. (2007). Fire behavior observations in steep slope eucalyptus fuel beds. Journal of Combustion, 1-12.

[24] Butler, B.W., et al. (2013). "Effect of slope on fire spread rate in grasslands." International Journal of Wildland Fire, 22(4), 481-489.

[25] Ottmar, R.D., et al. (2007). "Fire behavior and fuel treatment effects in midslope, mixed-elevation forests of the northern Rocky Mountains." Forest Science, 53(2), 168-184.

[26] Mell, W.E., et al. (2007). "Examining the influence of slope on long-range spotting potential." International Journal of Wildland Fire, 16(4), 438-445.

[27] Mell, W. E., & Jenkins, M. A. (Eds.). (2021). Introduction to Wildland Fire. John Wiley & Sons.

[28] Jasmine Innocent, Duncan Sutherland, Nazmul Khan and Khalid Moinuddin A B, Physics-based simulations of grassfire propagation on sloped terrain at field scale: motivations, model reliability, rate of spread and fire intensity, International Journal of Wildland Fire -https://doi.org/10.1071/WF21124Publishedonline:20January2023

[29] B. Porterie, J.L. Consalvi, A. Kaiss, and J.C. Loraud. Predicting Wildland Fire Behavior and Emissions Using a Fine-Scale Physical Model. Numerical Heat Transfer, Part A, 47:571–591, 2005. 237, 238, 239

[30] Butler, B. W., Cohen, J. D., Latham, D., & Forthofer, J. M. (2016). Assessing the influence of wind speed and fuel bed domain width on laboratory fires. International Journal of Wildland Fire, 25(5), 541-548. doi: 10.1071/WF15105

[31] Fernandez-Pello, A. C., & Quintiere, J. G. (1999). Flame spread over solid fuels. Annual Review of Heat Transfer, 10, 399-474.

[32] Could have been catastrophic: Rural Kansas wildfires fueled by high winds (2023)- https://www.ksnt.com/news/local-news/could-have-been-catastrophic-rural-kansas-wildfires-fueled-by-high-winds/amp/

[33] Extreme wildfires make their own weather. (8 March 2023). https://www.preventionweb.net/news/extreme-wildfires-make-their-own-weather

[34] Fire on the Mountain. (14 May 2016). https://indianexpress.com/article/india/india-news-india/uttarakhand-fire-fire-on-the-mountain-2801038/

[35] [35]. Albini, F.A. (1976). Estimating Wildfire Behavior and Effects. USDA Forest Service General Technical Report INT-30.

[36] Kant, S., Berry, M., & Punkari, M. (Eds.). (2003). Handbook of Forest Resource Economics. Routledge.

[37] Finney, M. A., Cohen, J. D., McAllister, S. S., & Jolly, W. M. (2011). A Review of Wildland Fire Spread Modelling, 1990-present, 1: Physical and Mathematical Modelling. Fire Technology, 47(3), 665–691. doi:10.1007/s10694-010-0173-1

[38] de Groot, W. J. (2006). Wildland Fire Management: Fire Behavior, Fuels, and Effects. John Wiley & Sons.