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Numerical study of fire spread using the level-set method with large eddy simulation incorporating detailed chemical kinetics gas-phase combustion model

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ABSTRACT

A fire code has been developed for the purpose of modelling wildland fires via Large Eddy Simulation (LES) and the use of the level-set approach to track the flame front. Detailed chemical kinetics have been considered via the strained laminar flamelet approach for the combustion process which included the consideration of the yields of toxic volatiles such as CO, CO_2 and soot production. Numerical simulations have been validated against an experimental study on the fire spread on a pine needle board under different slope angles. Peak temperatures and occurrence times during the propagation process were predicted with an overall average error of 11% and 3% respectively. This demonstrates that the flaming behaviour could be well predicted under different slope conditions. By incorporating the level set with the gas phase models, information including temperature field, toxic volatiles and soot particle concentrations can be realised in comparison to empirical fire spread models.

1. Introduction

Bushfires are frequently occurring fire incidents that could significantly disrupt the natural habitat and ecological system as well as affect prime agricultural land for animal grazing and diary production. In Australia alone, the landscape comprises of a majority of grasslands that are frequently ravaged by bushfires due to the prevailing hot and dry climate. One renowned fire incident was the occurrence of the Black Saturday bushfires which took place in the state of Victoria on February 2009. This fire incident claimed 173 lives, 413 injuries and an estimated total loss of 4.5 billion Australian dollars [1]. Good knowledge and understanding of the coupled physical and chemical behaviours involved during bushfires is essential for the prevention, planning and response, as well as recovery during such outbreaks which can reduce the massive damage to vegetation as well as human fatalities. Furthermore, the knowledge can also result in better planning and design of suburban areas and towns for fire hazard reduction and safety.

Understanding bushfires (also known as wildland fires) generally involve the utilisation of modern numerical methods to predict the fire spread behaviours. Fire spread models have been employed to assist analysts and firefighters to assess a multitude of situations and deploy different suppression strategies. In general, the fire spread models of wildland fires can be categorised into two broad approaches [2]: (i) physical models that attempt to represent the fundamental heat transfer and combustion mechanics; and (ii) empirical or semi-empirical models that are correlated by physical data obtained through laboratory experiments and real life bushfire incidents. In the past, fire spread models primarily aimed to investigate the rate of spread (ROS) and the involving burning region [3]. A typical empirical correlated fire spread models require the following variables as input to evaluate ROS: (i) the characteristics and quantification of the fuel (i.e. the total fuel load, moisture content and the combustion characteristics of the fuel); (ii) atmospheric conditions (i.e. wind speed, wind direction, temperature and humidity of surrounding air); (iii) topology of the landscape (i.e. surface area, ignition point and slope angle); (iv) and lastly, the characteristics of the fire (i.e. flame intensity and height).

The empirical model of Rothermel [4] has been extensively used in the wildland fire spread community within the United States of

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America [5]. It has formed the foundation for the development of many fire prediction systems. For example, the National Fire Danger Rating System [6] and BEHAVE [7] Fire Prediction System. This model was developed based on the combination of wind tunnel experiments on fuel beds [8] and field experiments of grassfires in Australia [9]. Rothermel's model had also gained a level of utilisation in several countries outside of the United States, such as Europe [10]. Currently, the fire spread model of Rothermel remains the core fire behaviour model in the US but support for other alternatives such as Balbi et al. [11] is actively growing in the community. The Canadian Fire Behaviour Prediction (FBP) System was a fire spread model that was parameterised for Canadian vegetation and climate developed by The Forestry Canada Fire Danger Group [12]. It is implemented in the Canadian Forest Fire Danger Rating System (CFFDRS) as well as the New Zealand Fire Danger Rating System. A detailed review of other empirical and quasi-empirical fire spread models can be found in Sullivan [3]. Although it is always ideal to use real life data to validate the fire spread models, it is difficult to apply them in a wider scope of applications since they are mostly based on specific experimental configurations. Furthermore, the performance of empirical fire models relies heavily on the quality of the input parameters and providing accurate inputs into the model can be very difficult to achieve in reality. Different techniques have been developed to minimise the uncertainty in model inputs and improve the efficiency of these models. For example, Bianchini et al. [13] developed an Evolutionary-Statistical System (ESS) that attempt to adjust input parameters in real time. Sanjuan et al. [14] developed a map partitioning method to minimise wind field uncertainty for fire spread prediction.

Application of mathematical modelling on bushfires has become increasingly popular due to the rapid advancement of numerical methodologies and computational power. These range from basic flame front tracking models such as FARSITE [15], BehavePlus [7] and PHOENIX-rapidfire [16] and many others [17,18] to complex three-dimensional (3D) computations fluid dynamics (CFD) models such as FIRETEC [19] and WFDS [20]. Flame front tracking models simulate the spread of fire without implementing the pyrolysis process of grasslands or vegetation. These are so-called front tracking tools that consist of various algorithms designed to expand a fire perimeter base on a set of rules that govern the rate of fire spread. The spread rate is often calculated from empirical models. Therefore, they can also be described as extensions of empirical models to take advantage of the rapid advancements in numerical methods and computational power. The front tracking approach is also compatible on a regional scale perspective (i.e. tens to hundreds of kilometres). The flame front is represented as a two-dimensional interface thus, giving a considerable saving in computational cost over three- dimensional CFD models. The two most common methods used in this type of fire propagation are the cellular method and level-set method. Both approaches discretise the surface into a grid. Cellular methods update the state of the grid over time according to a rule set that assumes the shape of the fire front such as an elliptical shape [21].

Level-set method [22] is a more recent approach that does not require any prior assumptions on the shape of the fire front. In this method, the fire front is described as a discretised set of cells that expand at a given rate of spread. The state of each cell is represented by the value of the level-set function. This approach offers a few key advantages for modelling wildland fire spread. The calculation of the fire spread rate is highly dependent on the fuel properties and environmental conditions that can vary across the landscape. These variables can be stored at each individual cell to compute a variable spread rate that evolves according to the vegetation and topology. In addition, the level-set method is able to calculate the normal vector to the fire front which is also necessary to model wind-aided fire spreads. The merging of separate fire fronts is handled automatically without any additional algorithm and the ignition points naturally evolved into an elliptical form, according to the test conducted by Rehm and McDermott [23]. Moreover, the level-set method is relatively easy to implement and couple with physical based models because the same computational grid can be used by both models. In summary, the level-set is a very powerful method to track the propagation of wildland fire spread and have been incorporated by many fire models such as BEHAVE [7] and WRF-SFIRE [24].

Currently, physical fire spread models of wildland fires adopt a single- or two-step simplified chemistry combustion model. FIRETEC [19] is a three-dimensional wildland fire model that uses a hydrodynamics model HIGRAD [25,26] specifically to solve high gradient atmospheric flows. FIRETEC incorporates a simplified single-step solid-gas phase reaction to model the entire combustion process. A critical temperature of 500 K [19] is used as an ignition criteria for combustion (i.e. the combustion process is initialised when the temperature exceeds 500 K). The Wildland Fire Dynamic Simulator (WFDS) is built upon the widely recognised Fire Dynamic Simulator (FDS), designed to simulate fires within building compartments [27]. It is developed by the National Institute of Standards and Technology (NIST) and the US Forest Services. WFDS incorporates a multiphase fire propagation model by Morvan and Dupuy [28]. The model operates under the assumption that combustion occurs predominantly above the surface fuel bed. It incorporates solid fuel pyrolysis which is assumed to occur at a temperature of 127 °C. Gas phase combustion is modelled with a mixture fraction based approach using a single-step reaction. Thermal Radiation is simulated using the P1 radiation model and soot production is assumed as a fraction of the mass of fuel gas consumed during combustion [29]. A sub-grid scale (SGS) turbulence based on Large Eddy Simulation (LES) is used to describe the turbulence flow [30]. The consideration of detailed chemistry combustion is a relatively new area in the field of wildland fire modelling. This is mainly due to the fact that detailed chemistry combustion models are usually not practical owing to its enormous amount of computational burden, which is attribute to the numerous chemical reactions and species needed to be considered and resolved, as well as the demand of a highly refined computational grid size (<1 m) [31] Thus far a trade-off to simplify the comprehensive kinetic schemes while maintaining prediction accuracy remains a challenge [32].

On the other hand, the majority of empirical fire spread models underestimate the effect of slope on the rate of fire spread. In recent years, a considerable amount of efforts have been made to address the heat transfer mechanisms and the influence of slope on the rate of fire spread [33–35]. However, these models remain unsuccessful for higher slope angles (especially for angles greater than 20°) [36]. Although the two main approaches (physical and empirical) to fire modelling are mainly developed to serve different purposes, coupling the two into a hybrid model could have potential to overcome the limitations of existing fire spread models. In this study, a fire code has been developed for the purpose of modelling wildland fires via Large Eddy Simulation (LES) and the use of the level-set approach to track the flame front. The aim is to provide addtional information on the flaming behaviours which cannot be produced by empirical fire spread models. This includes the prediction of combustion rate, intermediate and major gas species, as well as smoke production. Furthermore, this study will provide a preliminary study to investigate the viability of coupling the level-set method with detailed chemistry combustion and create the framework for a fully coupled fire spread model with two-way interaction between the fire spread model and combustion model. The key objectives can be summarised in the following: