# Wildfire Models – Concise Review

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***Abstract*— Theoretical fire model is aimed at speed of computation while approximating the key physics through only a few terrain - related inputs and tunable parameters representing fire intensity, hot gas and ember decay timescales, ignition delay due to relative humidity and local turbulence due to wind. These parameters were calibrated against controlled fire data and the model was then used to give reasonable predictions for fires of increasing complexity. The presented framework of models, both empirical and physical, allows improvements for more accurate representation of the flammable material characteristics, fire-induced flow modifications, and most other phenomena present in fires, hence providing an extendable and simple yet physically-realistic novel modeling approach.**

***Index Terms*— Forest Fire, FWI, FDI, Fire Vulnerability, Empirical Model, Physical Model, ROS**

## I. INTRODUCTION

The goal of wildfire modeling is to understand and forecast fire behavior using numerical simulation of wildfires. Wildfire modeling tries to limit damage, improve the safety of firefighters and the general public, and aid in wildfire suppression. The protection of watersheds, air quality, and ecosystems can all be aided by wildfire modeling. Wildfire modeling employs computational science to statistically analyze historical fire incidents to forecast spotting risks and front behavior. Past models of wildfire spread have included basic ellipses, egg- and fan-shaped models, among others (Figure 1 by Rothermel). Early analyses of wildfire behavior made consistent assumptions about the terrain and vegetation. However, a number of variables, such as wind speed and slope steepness, affect the precise behavior of a wildfire's front [1-4].

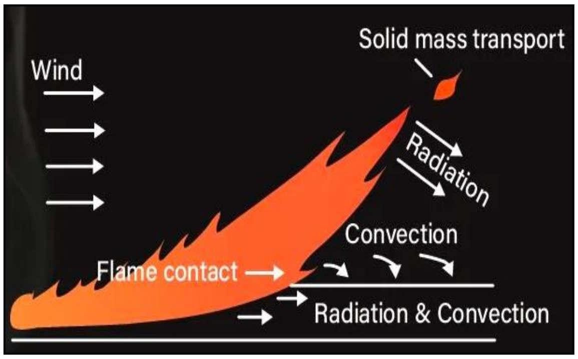

***Figure 1**: Phenomenon of fire growth*

Modern growth models depict fire growth as a continuously growing polygon by combining Huygens' Principle with historical ellipsoidal descriptions. The size of major wildfires can also be predicted using the extreme value theory. Even though major wildfires have a greater impact on fire policy than minor fires, they are frequently viewed as statistical outliers in normal analysis when they surpass suppression capacity.

Wildfire modeling is an effort to mimic fire behavior, including how quickly, in which direction, and how much heat it produces. The Fuel Model, or type of fuel, through which the fire is burning, is a crucial input for behavior modeling. The behavior of the fire, such as its quick rates of spread, fire whirls, and towering, well-developed convection columns, can also be modeled, as well as whether it starts on the ground (a "surface fire") and spreads to the tree crowns (a "crown fire"). Additionally, fire modeling makes an effort to calculate the effects of fire, including fuel consumption, tree mortality, smoke production, ecological and hydrological effects, and fuel consumption. The analysis of forest fire data and modeling the forest-fire, which inform us about fire vulnerability and fire spreading respectively, are the subject of the current review [5-7].

## II. MATERIALS AND METHODS

The data were gathered from research articles on international crown fire model trials and the forest-fire models because the study is based on secondary sources. To determine the fire vulnerability and predict the rate of fire spread, empirical models (fire weather index and fire danger index), fire-growth models (based on wave propagation principle), and flame-fuel interaction models (fire propagation based on heat transfer principles) have all been used in previous studies. All models allow us to foresee the occurrence of fires, which helps us to lessen their harmful consequences on both people and the environment. With the use of satellite and fire station systems, real-time forestry can modify the weather and wind to better forecast the size and shape of the fire [4, 8, 9].

## III. RESULTS AND DISCUSSION

### *Empirical Fire Modeling*

Future events can be predicted using conceptual models derived from experience and intuition from previous fires. Past fire data based model is called empirical model. It is also known as statistical model or stochastic model [2, 4]. For quick estimation of key parameters of interest, such as fire spread rate, flame length, and fireline intensity of surface fires at a point for particular fuel complexes, assuming a representative point-location wind and terrain slope, a number of semi-empirical fire spread equations have been developed. Quasi-steady equilibrium spread rate determined for a surface fire on flat land in no-wind conditions was calibrated using data from piles of sticks burned in a flame chamber/wind tunnel based tunnel to represent other wind and slope conditions for the fuel complexes tested. Such semi-empirical relationships and others regarding ground-to-crown transitions are applied in two-dimensional fire growth models, such as FARSITE, BEHAVE, SPREAD, CanFIRE, SPARK and PHOENIX Rapidfire. These models are used to calculate fire spread and other surface-level parameters. In order to control the growth of the fire, certain presumptions must be made in the above models. These models are the applications of the Huygens principle of wave propagation. Although more advanced implementations use a three-dimensional numerical weather prediction system to supply inputs to these fire growth models verified in the above models, such as wind velocity, the input was passive and the fire's impact onto the atmospheric wind and humidity are not taken into account. Cellular Automata (CA) uses fire spread similar to Huygens principle. Machine Learning of forest and forest maps obtained from input remote sensing satellites helps to input CA method [10,11].

Simplified empirical model is equation to predict fire danger index (FDI). Grassland FDI is modeled by *Equation 1* [12]. Similarly, forest FDI is modeled by *Equation 2* [12].

$$FDI = 2e^{\left(-23.6+5.01\, ln\, C+0.0281\, T-0.226\, \sqrt{RH}+0.633\, \sqrt{U_{10}}\right)} \qquad (1)$$

$$FDI = 2.0\, e^{\left(-0.450+0.987\, ln\, D-0.0345\, RH+0.0338\, T+0.0234\, U_{10}\right)} \qquad (2)$$

where T-Air Temperature (°C), C-Degree of Curing(%), RH-Relative Humidity (%), $U_{10}$-Wind speed in km/h measured at 10m height, and D – Drought Factor ($0<D<10$). Fire weather index (FWI) is also prevalent in many parts of the world to get fire vulnerability (https://glff.mesowest.org/tools/fwi/). Both FWI and FDI are calculated by measuring Air Temperature and Relative Humidity at local time 12am and at a height of 2m height, by measuring Wind Speed at 12am and at a height of 10m, and by measuring the daily snow depth and precipitation totaled over 24hours (Yesterday's reading). In real-time forestry, statistical model with Huygens's wave propagation is applied. To feed into forestry model, forest data is obtained from satellite, for example, using MODIS-TERRA spectrometer [13, 14]. Forest data includes elevation from sea level, slope of the terrain, Normalised Difference Vegetation Index (NDVI), Normalised Burn Ratio (NBR), Precipitation, Relative Humidity, Wind speed and Temperature. This model is very fast and used in fast firefighting in Canada (Figure 2).

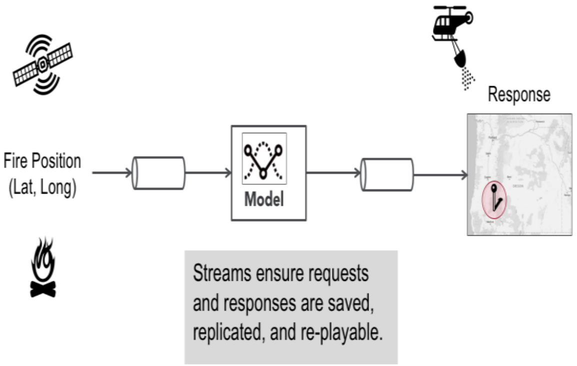

***Figure 2**: Real-time fire control in forestry*

*Physical Fire Modeling*

Model based on the laws of heat transfer is called physical model. It is also known as mathematical or analytical model. In this category of fire model, reaction-diffusion systems of partial differential equations are produced using two-dimensional, simplified physical models of fire spread based on conservation of energy principles. These models use radiation as the primary mode of heat transfer and convection to reflect the effects of wind and slope. A wildland fire component is added to more complex physical models of computational fluid dynamics, allowing the fire to feed back into the atmosphere. These models include the CAWFE, FIRETEC, FIRESTAR, WUI-FDS and DEVS-FIRE [3, 15]. These tools have different emphases and have been applied to better understand the fundamental aspects of fire behavior, such as fuel inhomogeneities on fire behavior, feedbacks between the fire and the atmospheric environment as the basis for the universal fire shape, and are beginning to be applied to wildland urban interface house-to-house fire spread at the community-scale. A full three-dimensional explicit treatment of combustion in wildland fuels by direct numerical simulation at scales relevant for atmospheric modeling does not exist, is beyond the capabilities of current supercomputers, and does not currently make sense due to the limited accuracy of weather models at spatial resolutions below 1 km. This is because the cost of added physical complexity is a corresponding increase in computational cost. For example, models by Clark use formulas created by Rothermel for the USA Forestry purpose to determine local fire spread rates using fire-modified local winds [1, 4]. As a result, even these more complex models parameterize the fire in some way. Furthermore, although FIRETEC contains prognostic conservation equations for the reacting fuel and oxygen concentrations, the computational grid is not fine enough to resolve the reaction rate-limiting mixing of fuel and oxygen, necessitating approximations to the subgrid-scale temperature distribution or the combustion reaction rates themselves. Additionally, because these models are too small to interact with meteorological models, the fluid motions are simulated using a computational fluid dynamics model that is contained inside a box considerably smaller than a normal wildfire. As an example, let us see a physical model proposed by Grishin of Russia and louded by Albini of USA, a model of importance to obtain rate of spread, ROS [8, 16, 17].

Grishin's model is a 100% physical fire spread model that considers the flame-fuel interaction – heating, drying, pyrolysis and combustion [8, 16]. The model utilises the conservation of mass, momentum and energy in both the solid and gas phases. The model uses a single spatiotemporal dimension and it also uses first-order Arrhenius reaction chemistry to model pyrolysis and combustion. During the development of the model it was assumed that turbulent transport processes in the vegetation can be modeled using turbulent exchange. The forest is considered as a multiphase, multistoried, spatially heterogenous medium outside the fire zone. Inside the fire zone, the forest is considered to be a porous-dispersed, seven-phase, two-temperature, single-velocity, reactive medium. The six phases within the combustion zone are: dry organic matter, water in liquid state, solid products of fuel pyrolysis, ash, gas and particles in the dispersed phase. The heat flux q is expressed as $q = \lambda_T \frac{\partial T}{\partial t}$, where $\lambda_T$-effective turbulent conductivity or eddy diffusivity, and T-temperature. Then, the energy equation is given by

$$\sum \left(\rho_i \varphi_i C_{p_i} + \rho_{C_p}\right) \frac{\partial T}{\partial t} + \rho_{C_p} W \frac{\partial T}{\partial x} \left[\lambda_T \frac{\partial T}{\partial x} - H(T - T_\infty)\right] \tag{3}$$

where $\rho_i$ – fuel density, $\varphi_i$ – volume fraction, $C_{p_i}$ – specific heat, $\rho_{C_p}$ – gas phase desnity, W - relative humidity, and H-enthalpy. The summation term includes four terms which represent dry organic matter, liquid water, condensed pyrolysis products and the mineral composition of the fuel. The convective cooling (Newton's law) is included with the term H($T$-

$T_\infty$), this emphasizes the fact that the model does not include the hydrodynamic aspects of heat flow, only the combustion. No information about the performance of the model (with respect to test fires or experimental fires) was found. Differential Equations are coded in Fortran, Pascal, C++, Python or Delphi and solved. It is a direct physical model and so approximation methods such as FDM, FEM, FVM, BEM or CFD are not used. Equation 3 is solvable by MATLAB, SCILAB and dedicated R program.

Drissi extended Grishin's model with input data taken from International Crown Fire Model Experiment, ICFME [9, 18, 19]. Table 1 shows input data used by Drissi in his physical model. This model is two-dimensional and uses square cell meshing. Other possible options are square cell mesh and hexagonal cell mesh. But, square cell mesh is simple for calculation and best to represent the field completely. Figure 3 shows the prediction compared well with Australian ICFME. Fire contours predicted by the model is shown as red contour and ICFME as black square dots (■) after 56s (at left) and 86s (at right). As Drissi used huge amount of fire experiment data, this model is not 100% physical model and so is called as a semi-physical model [9, 20]. Model of semi-physical type is widely used for its completeness and simplicity (*https://github.com/Multielio/Wildfire-Simulator-v0.9*). In Figure 4, Tp-pyrolysis temperature and Ta-ambient temperature.

*Table1: Technical parameters used in Drissi's calculation*

| *Grassland Wildfire Parameters* | *Symbol (Unit)* | *Value* |
|---|---|---|
| *Ratio surface/volume* | $\sigma_k (m^{-1})$ | *12240* |
| *Char content / content of gaseous pyrolysis products* | $\nu char/FPC0$ | *0.20/0.80* |
| *Specific heat* | $c_{p,k}\,(Jkg{-}1K{-}1)$ | *1110+3.7*T* |
| *Stratum height* | $H(m)$ | *0.51* |
| *Density of fuel particle* | $\rho_k\,(kgm^{-3})$ | *512* |
| *Dry load* | $m''_{DFF},\,(kgm{-}2)$ | *0.313* |
| *Volume of solid phase fraction* | $\alpha_k$ | *0.0012* |
| *Initial Moisture content* | $FMC_0$ | *0.058* |
| *Pyrolysis temperature* | $T_{pyr}\,(K)$ | *500* |
| *Ignition temperature* | $T_{ign}\,(K)$ | *500* |
| *Critical content of pyrolysis products* | $FPC_{cr}$ | *0* |
| *Radiated Fraction* | $\chi_r$ | *0.35* |
| *Heat of combustion* | $\Delta h_c\,(J.kg^{-1})$ | *15.6×10⁶* |
| *Mean absorption coefficient of the flame* | $\kappa_f (m^{-1})$ | *0.4* |
| *Residence time of the flame* | $tc(s)$ | *5* |
| *Fuel bed absorptivity* | $a$ | *0.9* |
| *Flame height* | $H_f (m)$ | *2.04* |
| *Wind speed (at 2m Above Ground Level)* | $U(m.s^{-1})$ | *4.83* |
| *Relative humidity of the air* | $RH(\%)$ | *20* |
| *Cell Diameter* | $D\,(m)$ | *2.54* |
| *Ambient Temperature* | $T_\infty(K)$ | *307* |

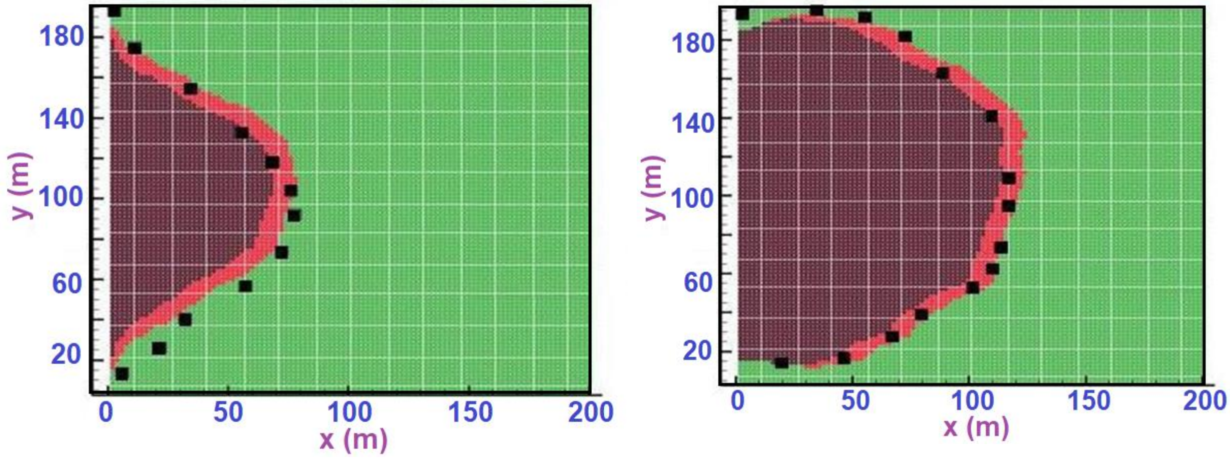

***Figure 3**: Drissi model output versus Australian ICFME data*

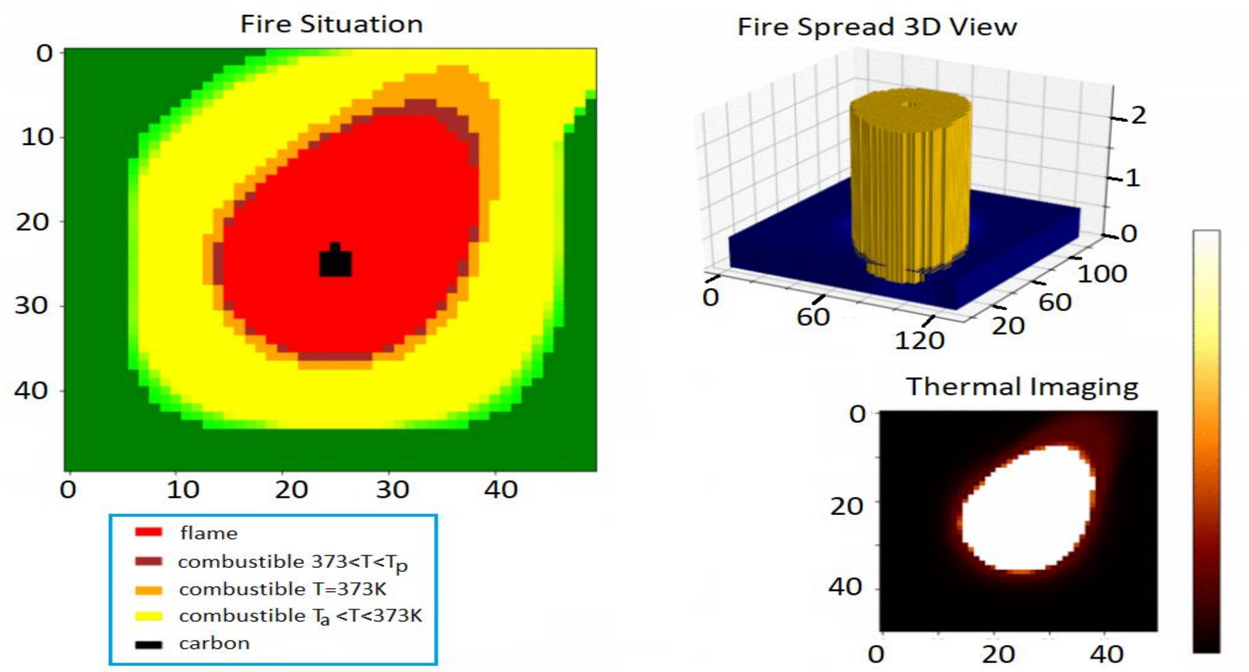

***Figure 4**: Output of Github's Online Wildfire Simulator*

## IV. CONCLUSION

Like all models in computational science, fire models need to strike a balance between fidelity, availability of fire data, and fast execution. Wildland fire models span a vast range of complexity, from simple cause and effect principles to the most physically complex presenting a difficult supercomputing challenge that cannot hope to be solved faster than real time. Lot of wildfire have been developed so far, but a lot of chemical and thermodynamic questions related to fire behaviour are still to be resolved. In forestry, these models along with satellite fire data are very fast, with little approximation.

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