Physical description of Forest Fires

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Introduction

• Physical description of forest fires aim to understand the behaviour of forest fires and predict their spreading

• This research started 50 years ago in Australia, USA and USRR

• The involved mechanisms are very complex

• The operational objectives are to predict the fire spread and to estimate the impact of the fire
  - The predictions are done thanks to fire spread models inserted in simulators
  - The impacts are estimated thanks to modelling and experiment
Fire Spread Modelling

Where does the difficulty in the modelling of forest fire lay?

The Physical laws are known
GIS and weather models provide the Environmental data

Difficulty to model the time scales

Difficulties in modelling the huge variable variability (fuel gases …)

Combustion

Wind (O₂)

Wind, Topography

Heat transferts

Reaction (μm)

Fuel particule (mm to cm)

Vegetation species (20 cm to 20 m)

Plot scale in field experiments (100 m)

Fire scale (km)
Fire Spread Modelling

The problems in the modelling of forest fires are due to the numerical solving of mixed complex problems at different scales.

Three kinds of modelling:

• Empirical (Mc Arthur, 1966; simulator = Fire grass meter)

• Semi-empirical (Rothermel, 1972; simulator = Farsite or Behave)

• Physical
  • Simplified (Albini, 1981; simulator in development by our team)
  • Detailed (Grishin, 1996; simulator = Firetec or Firestar)
Two ways to describe fire spreading with physical modelling:

- Detailed models that describe as finely as possible the mechanisms
  
  **Drawbacks:** small times and lengths
  **Advantages:** detailed description of the phenomena

  **Knowledge and prevention**

- Simple models that only take into account the main mechanisms involved in fire spreading
  
  **Drawbacks:** less accurate and less general than detailed models
  **Advantages:** possibility to implement them at the field scale

  **Simulation**
Fire Spread Modelling

Detailed models – A multiphase model

- Gas Phase
  - Convection
  - Turbulence
  - Gas mixture
  - Combustion
  - Radiation
  - Soot

- Solid Phase
  - Heat transfer
  - Drying
  - Pyrolysis
  - Combustion
  - Radiation

Transfers
  - Mass
  - Heat
  - Momentum
  - Energy

Fuel layer

Control volume

Solid phase

Gas phase
Detailed models – A multiphase model

For each phase: Mass, species, momentum and energy balances

Example – Mass balance:
\[
\frac{\partial}{\partial t} \left( \rho_g \langle \rho_g \rangle + \rho_s \langle \rho_s \rangle \right) - \nabla \cdot \left( \rho_g \langle \rho_g \rangle \bar{V} \right) = \sum_k [\dot{M}]_{gk}
\]
\[
\frac{\partial}{\partial t} \left( \rho_s \langle \rho_s \rangle \right) = -[\dot{M}]_{k}^{\text{surf}} - [\dot{M}]_{k}^{\text{pr}}
\]

Interface relationships

Example – Interface equation for mass:
\[
[\dot{M}]_{gk} = [\dot{M}]_{k}^{\text{surf}} + [\dot{M}]_{k}^{\text{pr}}
\]

Sub-models

Example – Arrhenius type laws

Radiative Transfer Equation
\[
\bar{e} \cdot \bar{V} \left( \alpha_g \langle L^\alpha \rangle \right) + \sum_k \sum_p \int_{S_{pk}} \rho \langle L_g \rangle \bar{n}_g \cdot \bar{e} \, dS = -\alpha_g \langle L_0^\alpha \rangle + \alpha_g \langle a_{g} \rangle \langle L_0^\alpha \rangle
\]
Assumptions:
- One single equivalent phase
- Assumed flame geometry

Medium equivalent to the fuel
Radiation
Losses

Burned area
Heat release

Combustion area

Unburned area

Radiation
Advection
Fire Spread Modelling

Energy balance
\[ \frac{\partial T}{\partial t} + k_v \vec{V}_g \cdot \vec{\nabla}T = -k (T - T_a) + K \Delta T - Q \frac{\partial \sigma_k}{\partial t} + R \]

Radiative transfer
\[ \phi_{fl - dv} = a_v \epsilon_{fl} B T_{fl}^4 \int_{S_{fl}} \frac{\cos \varphi_{fl} \cos \varphi_v}{\pi r^2} dS_{fl} dS_v \]

Mass conservation
\[ \frac{\partial V_{g,x}}{\partial x} + \frac{V_{g,x}}{\rho_g} \frac{\partial \rho_g}{\partial x} = - \frac{V_{g,z}}{\delta} \frac{\partial \varphi}{\partial \delta} - \frac{1}{\rho_g} \frac{\partial \rho_g}{\partial \delta} \frac{\partial T}{\partial t} \]

Buoyancy
\[ V_{g,z}(\delta) = \chi \sqrt{2 \delta \left( \frac{T}{T_a} - 1 \right)} g \cos \phi_{si} \]

Perfect gas
\[ \rho_g T = \rho_a T_a \]
Fire Spread Modelling
Fire Spread Modelling
Fire Spread Modelling

Modelling Heterogeneity – Non flammable areas

- Burned
- Unburned
- Empty

- Modelling Heterogeneity
- Non flammable areas

- Physical description of forest fires
Experiments under controlled conditions (heat flux, flow)
Fire Impact

- Smouldering
Fire Impact

- Smouldering

**Fire Spread and Severity**

**Emissions**

![Graphs showing temperature, CO and CO2 yield, moisture content, and heat flux](image_url)

**BRE Centre for Fire Safety Engineering**
Fire Impact

- Thermal impact (but also influence on vegetation and wind on fire spread)
Fire Impact

- Thermal impact (but also influence on vegetation and wind on fire spread)

Limits of exposure

- Firefighter: 7000 W/m² (90 s)
- Unprotected person: 6400 W/m² (8 s)
Conclusions and perspectives

• Physical modelling of forest fires is a young science

• Two kind of tools are developed:
  • Fire spread simulation
  • Fire impact estimation

• Many improvements are necessary but simple answers can be provided

• A strong perspective is the coupling between fire and atmosphere:
  • Integration of satellite data to evaluate the fire
  • Using fire simulations to detect fires
  • Characterize the fire as a source of gases
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