Numerical Prediction of Fire Propagation in Idealized Wildland and Urban Canopies

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Numerical Prediction of Fire Propagation in Idealized Wildland and Urban Canopies

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Introduction

• WUI – Wildland Urban Interface
  – 9% of US land area is WUI
  – 39% of all houses are in WUI
  – up to 79% on east coast are in WUI
• Wildland/Urban Canopies
• Numerical Simulation
• CFD and Idealized Fire
Wildland-Urban Interface

• Intermix region
  – > 50 % vegetation
  – > 1 house/40 acres (16 ha)

• Interface region
  – < 50 % vegetation
  – > 1 house/40 acres (16 ha)
  – ~ 1.5 miles from region with > 75 % vegetation
Fires in the WUI Forest /Grasslands/Urban Interface

Of the 10 largest fire loss incidents in US history, 4 occurred pre-1907 and 4 were WUI fires - all occurred within the last 15 years (NFPA).
The Great Peshtigo Fire of 1871

- The fire
  - Hurricane force winds
  - 60 & 50 mile swaths
  - Peshtigo river literally boils people to death
Peshtigo, Wisconsin (1871)
Deadliest Fire in American History

- The death toll was **four times higher than the famous Chicago fire**, which **ignited the same day**.
- Peshtigo, WI fire: Oct 8, 1871
  - 1,500,000 acres or 2,400 square miles
  - 3,780,000 acres or 5,900 square miles in WI & MI combined
  - Largest and deadliest in US history
- Hayman, CO fire: June 9-July 3, 2002
  - 138,000 acres or 216 square miles
  - Largest in CO history
Peshtigo Fire Region (contd)

Approximate Area Burned in the Great Fires of 1871
Eleven weeks of dry weather culminated in a clash of hot and cold fronts, generating 60 mph wind with dry lightning that sparked multiple fires growing into a monster blaze. The resulting blowup tore into town like a hurricane with the pounding sound of a thousand locomotives. Such a firestorm burns at 2000 degrees Fahrenheit and moves at 110 mph or more. It is likely, although not proved, an F5 tornado, the strongest possible, struck Peshtigo simultaneous with the fire. Fireballs shot through the air and ignited buildings and people hundreds of yards away. There was virtually no escape, because breathing the superheated air collapsed victims' lungs. Some survived by ducking underwater. But people caught in treeless clearings were torched like marshmallows.
Artist Mel Kishner's conception of the terrorized populace fleeing down Oconto Avenue toward the protection of the river.
Wild Fire Statistics USA

Average Number of Fires and Acres Burned

- Average Number of Fires
- Average Acres Burned

Dates:
- 1919-1929
- 1930-1939
- 1940-1949
- 1950-1959
- 1960-1969
- 1970-1979
- 1980-1989
- 1990-1999

Number of Fires
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
110,000
120,000
130,000
140,000
150,000

Acres Burned
0
5,000,000
10,000,000
15,000,000
20,000,000
25,000,000
30,000,000
35,000,000
40,000,000
45,000,000
Why is the problem hard to solve?

- Range of scales and multitude of driving factors
WUI Canopy Flow Fields
Agricultural Canopies

- Peg canopy studies
  - Velocity profiles
  - Turbulence profiles
  - Diffusion rates from point and line sources
  - Drag measurements
- Flexible strip studies
- Plastic tree studies
- Trees on hills studies
Peg Canopy Profiles

PEG ARRAYS STUDIED

\[
\begin{array}{ccc}
 x (\text{cm}) & y (\text{cm}) & \text{ARRAY} \\
 1.27 & 1.27 & \text{DIAG.} \\
 2.54 & 2.54 & \text{SQ.} \\
 2.54 & 2.54 & \text{DIAG.} \\
 5.08 & 5.08 & \text{SQ.} \\
\end{array}
\]

Tree Layer

Edge of Velocity Boundary Layer

Inner Boundary Layer Caused by Canopy

15m Smooth

10m Rough

h = 9cm

L = 0.5cm

Tourin; Deciduous forest (summer 1966)

1.27 x 1.27cm (Diag), (x = 9.3m, 10.3m)

Plastic model trees (18 cm high, 5 cm trunk space)

Japanese larch (Allen, 1968)

Wisconsin deciduous forest (Shinn, 1969)
Fire Types
Fuels & Fire Path
Urban Canopies

- 2-D models
  - Flat roofs
  - Slanted roofs
- 3-D model
  - Equal height
    - Blocks
    - Rectangular prisms
  - Variable height
- 3-D specific sites
CFD Simulation of Fluid Motions in WUI Canopies
Wildland Fire Model Triangle

Zone Type Model: Urban Fire Spread Model

Field Type Model: WUI-FDS Model
Zonal Model for Urban Fires

- Ensemble of single compartment zones with radiation and heat exchange to initiate ignition.
- Urban fire spread predicted by integrating simulation of individual fires.
Urban Fire Spread Model

Temperature rise due to wind blown fire plume

Firebrand spotting

Thermal radiation heat transfer from fire involved building
U = 5 (m/s)

30 min

60 min

90 min

120 min

U = 0 (m/s)

U = 5 (m/s)

Fire Spread

bldg.[A]: fire origin
bldg.[B]
bldg.[C]
bldg.[D]
Full Physics WFDS Model
Joint Forest & Building Canopy

Rehm et al. (2002) used FDS to simulate flows downwind of wooded areas over a building complex. Trees were simulated as composed of different size beads strung along lines of trunk and branches. Resultant momentum sinks were included in a modified sub-grid scale LES turbulence model.
Velocity at 3m height downwind of tree line
WFDS Simulation of Burning Douglas Fir Experiment

NIST
DOUGLAS FIR TREE BURN EXPERIMENT & WFDS SIMULATION

height = 2.9 m, $\rho_{\text{bulk}}$ = 8 kg/m$^3$, M = 24%
WFDS Simulation of WUI Situation
CFD Simulation of Fire in Idealized Canopies

- Limit study to buoyancy and mass burning rate scaling.
- Canopy simulated as porous fluid zone.
- Initially look only for gross behaviors.
- CFD vehicle will be FLUENT 6.1.22
2-d Fires in Porous Zones

- **Domain:**
  - 300 x 60 m

- **Porous zone:**
  - 100 x 6 m

- **Heat source:**
  - 2 x 4 m; 100kW/m³

- **SKE & LES turbulence models**

- **Power law profile**
  - $p = 0.14$, $U_{10\text{m}} = 1$ m/s

- **Turbulence inlet**
  - $I_T = 10\%$
Buoyant Plumes in Turbulent BL
Meroney (1979)

Meteorological wind-tunnel, $\delta = 1.27$ m, $z_o = 1.22 \times 10^{-5}$ m, $p = 0.12$, $U$ varies.

Helium line source, 1.22 m wide, $Q$ varies.
Flames in Boundary Layers
Maruyama and Tanaka (2002)

a. Variation of the mean velocity profiles

b. Variation of the temperature and the velocity fluctuation with fire.
3-d Fires in Porous Zones

- **Domain:**
  - 300 x 300 x 60 m

- **Porous zone:**
  - 100 x 100 x 6 m

- **Heat source:**
  - 2 x 4 x 90 m; 100kW/m³

- **SKE & LES turbulence models**

- **Power law profile**
  - $p = 0.14$, $U_{10m} = 1$ m/s

- **Turbulence inlet**
  - $I_T = 10\%$
No Porous Canopy

Temperature Contours

Temperature Contours, Y = 6

Velocity Vectors, Y = 2 m

Velocity Contours, Y = 2 m
No Porous Canopy
WFDS Simulation of Australian Grassland Experiment
Mell et al. (2006)

- Cheney et al. (1993, 1995) Northern Territory, AU.
- Natural grass, 200 m x 200 m plot; 5 m/s wind left to right Ignition length 175m, t = 56 sec.
- WFDS simulation, t = 56 sec.
Porous canopy
Diagnosis by the Wind Doctor

- Smoke and fire generated in forest and urban canopies is a major modern hazard.
- Fire spread is significantly influenced by the porous nature of the canopies.
- Understanding of the phenomena requires joint consideration of fluid flow in porous media, combustion, and radiation.
- CFD provides a valuable way to analyze the fire mechanics, predict fire spread, and evaluate mitigation strategies.
Fire Rainbow

This is a Fire Rainbow - the rarest of all naturally occurring atmospheric phenomena. The picture was captured on the Idaho/Washington border. The event lasted about 1 hour. March 22, 2007. Clouds have to be cirrus, at least 20k feet in the air, with just the right amount of ice crystals and the sun has to hit the clouds at precisely 58 degrees.