Developing a mid-scale portable wind tunnel for laboratory and field experiments

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Special Thank to Giovanni DiCristina
What We Do

A. Numerical Modeling

B. Small-scale laboratory experiments

C. Mid-scale laboratory experiments

D. Small-scale field experiments

E. Operational burn observations

What we do
Motivation
Motivation

Time Scales

Wind (O₂)

Wind, Topography

Space Scales

Combustion

Heat transfer

Reaction (μm)

Fuel particule (mm to cm)

Vegetation species (20 cm to 20 m)

Plot scale in field experiments (100 m)

Fire scale (km)

Atmospheric scale (100 km)
Motivation

- We need CFD-based detailed physical models
- Those models are still models of knowledge.
- Can we capture the physics? What does it mean?
- How much physics is enough?
Physical/Chemical Phenomena to Look

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

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

Transfers
- Mass
- Heat
- Momentum
What to Model?

Multiphase model - The conservation equations are solved in every control volume in which the gas phase and the solid phase coexist.

- Physical laws
  - Available Fuel
  - Available oxygen
  - Heat transfers

- Environmental parameters
  - Vegetation properties (species, moisture content …)
  - Atmospheric data (wind field, air humidity …)
  - Topography
What to Model?

- For each phase: Mass, species, momentum and energy balances
  
  **Example – Mass balance:**
  
  \[
  \frac{\partial \left( \alpha_g \langle \rho_g \rangle \right)}{\partial t} + \nabla \cdot \left( \alpha_g \langle \rho_g \mathbf{V}_g \rangle \right) = \sum_k [\dot{M}]_{gk}
  \]

  \[
  \frac{\partial \alpha_k \langle \rho_k \rangle}{\partial t} = -[\dot{M}]_{k}^{surf} - [\dot{M}]_{k}^{pr}
  \]

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

- Radiative Transfer Equation
  
  \[
  \bar{\varepsilon} \nabla \left( \alpha_g \langle L_g^{\Omega} \rangle \right) + \sum_k \sum_p \int_{S_{pk}} L_g^{\Omega} \bar{n}_g \bar{\varepsilon} dS = -\alpha_g \langle a_g \langle L_g^{\Omega} \rangle \rangle + \alpha_g \langle a_g \langle L_0^{\Omega} \rangle \rangle
  \]

- Sub-models
  
  **Example – Arrhenius type laws**
What to Model?

• Fuel consumption depends on fire dynamics!
• Difficult to differentiate what was burned during the fire from after the fire.
Approaches

Experiments

Combustion

- Microscopic (TGA, DSC)
- Bench laboratory scale (small scale static fires or spreads)
- Large laboratory scale (large scale static fires or spreads)
- Field scale (from small shrub to tree canopy)
- Uncontrolled fires (observation)

Maximal control

Thermal transfer

Turbulence

No control

Experiments
Approaches

• Understanding the fuel

• Multi-scale, combined experimental and numerical approach

**Experimental**
- Bench scale
  - Well controlled conditions – isolate property or behavior
  - Easily repeatable
- Field scale

**Numerical**
- Field scale
  - Cheap to simulate many scenarios
  - Requires fundamental physics to be well defined
- Bench scale
  - Allows investigation and testing of mathematical formulations
  - Unpredictable conditions
  - Cost & risk prohibit high repetition
Wind Tunnel

- Housed in Fire Protection Eng. lab at WPI
- 5m long diverging section
  - 2.26 x 1.5 m flow area
- 6m long test section
  - 2.16 x .9 m windows
- Up to 6 m/s
- Turbulence intensity at test section inlet ≤ 20 %
Wind Tunnel

- Tunnel Body
- Windows
- Fans and Shape Transition Part
- Test Section

- Up to 6 m/s, 2.26 m x 1.5 m cross-sectional area, 6 m long test section.
Wind Tunnel

- Two axial fans (15,000 cfm each)
  - High-temperature ceramic windows (Good IR transmission)
- Tunnel Body
- Up to 6 m/s, 2.26 m x 1.5 m cross-sectional area, 6 m long test section.
Wind Tunnel

- Assembled View.
Wind Tunnel

• Parts Breakdown
• Portable!
Wind Tunnel: Demonstration

Yew shrub
Pine needle litter

Top view

$U_\infty$

30cm

30cm
Flow Field Characterization

- Pitot probe array
  - 7 pitot probes connected to differential pressure transducers
  - Evenly spaced across exit to test section

\[ p_t = p_s + \left( \frac{\rho u^2}{2} \right) \]
\[ u = \sqrt{\frac{2(p_t - p_s)}{\rho}} \]
Flow Field Characterization

- Pitot probe array
  - 7 pitot probes connected to differential pressure transducers
  - Evenly spaced across exit to test section
Measurement Tools

- Mass loss measurements
- Thermocouples
- Heat flux
- Pitot probe array
- Large optical access
  - PIV, IR imaging, and other optical techniques

Particle Image Velocimetry

Image Courtesy by DLR
Particle Image Velocimetry

Image Courtesy by Dantec Inc.

Image Courtesy by Turney et al.

Turney et al., MST Vol. 20
Particle Image Velocimetry

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Turney et al., MST Vol. 20
Preliminary Tests: Dowel Burn

- Ignition and fire spread study of in-line array of dowels
- Suspended linear array
- Subjected to freestream flow
  - 1, 2, 3 m/s
- Effect of spacing on spread at multiple diameters
- Within spread region explore dynamics
Dowel Burn: Critical Spacing

- Flame is purely buoyant at no flow
- Gradually tilts with increasing flow speed
- Spacing where flame propagation is stopped

Froude Number ($Fr$) = \( \frac{\text{Flow Momentum}}{\text{Gravity}} \)
Dowel Burn: Spread Rate

- Normalized by pilot ignition
- Spread rate trend sustains linearity
- 0.5 cm spacing behaves as expected
- 1 cm spread rate decreases at greatest velocity
Dowel Burn: Spread Rate

- Normalized by pilot ignition
- Spread rate trend sustains linearity
- 0.5 cm spacing behaves as expected
- 1 cm spread rate decreases at greatest velocity

<table>
<thead>
<tr>
<th>spacing [cm]</th>
<th>0 m/s</th>
<th>1 m/s</th>
<th>2 m/s</th>
<th>3 m/s</th>
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<tr>
<td>0.5</td>
<td>0.0453</td>
<td>0.260</td>
<td>0.407</td>
<td>0.536</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>0.224</td>
<td>0.385</td>
<td>0.309</td>
</tr>
</tbody>
</table>
Dowel Burn: Spread Rate

- Leading cylinder wake regimes
- Vortex shedding induces air entrainment
  - Partial premixing
- Strength and frequency change until entrainment is reduced.
  - Reaction now comparatively rich
- Convective cooling

Fire spread rate, \( s = 1\text{cm} \)

\[
\begin{align*}
0.224 \text{ 1/s} \\
0.385 \text{ 1/s} \\
0.309 \text{ 1/s}
\end{align*}
\]
Dowel Burn: Drag

- 10 element array
- 1 cm spacing
- Time averaged velocity field measurement
Dowel Burn: Drag

Momentum In → Control Volume → Momentum Out

Drag
Dowel Burn: Drag
Vegetation Burning

• Two test beds
  • Shrub and pine needle
  • Shrub, pine needle, branches

• Collected velocity measurements along bed for leaf and no leaf conditions at multiple freestream velocities

• Lidar scanning
Vegetation Burning

• Two test beds
  • Shrub and pine needle
  • Shrub, pine needle, branches

• Collected velocity measurements along bed for leaf and no leaf conditions at multiple freestream velocities

• Lidar scanning

Image Courtesy by M. Gallagher
Modeling Validation

• Two test beds.
  • Pine needle layers only
  • Pine needle and shrubs

• Lidar scan fuel bed for modelling input

• Measure flow properties (velocity, drag, turbulent intensity) across fuel bed

• Burn
  • During burn, thermocouples can be used for simultaneous cross-correlation velocimetry and temperature.
  • Cameras to record spread
  • Potentially use load cell for mass loss measurements

• Re-scan with Lidar

• Initial vegetation scan and flow field information fed into model (WFDS or other)
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Moving Forward

- Mid-scale laboratory tests
  - Test Simplified fuels
  - Test the wind tunnel in the open
  - Add measurement techniques
  - Test various vegetation configurations

- Small-scale field tests
  - Conduct cold flow test
  - Conduct fire spread experiments with actual fuel
Thanks!

• Any questions and inquiries
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