Computational Fluid Dynamic Modeling of a Downdraft Wood-Fired Furnace

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Outline

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   - Motivation
   - Wood Combustion & Emissions
   - The Problem
   - Addressing the Problem

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   - Finite Volume

4 Results and Numerical Difficulties

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Motivation

- Heating your home with wood: OWHH (outdoor wood-fired hydronic heater)

![Typical OWHH Configuration](image)

**Figure:** Typical OWHH Configuration

- All large combustors regulated by the EPA based on National Ambient Air Quality Standards for six air pollutants, three of which are of interest to wood combustion:
  - PM emissions from OWHH's

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Motivation

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**Figure:** Typical OWHH Configuration

- All large combustors regulated by the EPA based on National Ambient Air Quality Standards for six air pollutants, three of which are of interest to wood combustion: $NO_x$, $PM$, $CO$.
- EPA recently adopted a voluntary certification program to curb $PM$ emissions from OWHH's
How Does Wood Burn?

- Wood is a biomass fuel composed of the 4 elements: CHON.
- Wood Combustion proceeds through 4 distinct but overlapping stages:

<table>
<thead>
<tr>
<th>Stages</th>
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<tbody>
<tr>
<td>1  Heating and Drying</td>
</tr>
<tr>
<td>2  Pyrolysis and Devolatilization</td>
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<tr>
<td>3  Flaming Combustion</td>
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<td>4  Char Oxidation</td>
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</tbody>
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- Governing processes: chemistry, heat transfer, fluid dynamics.
Emissions

- CO is an intermediate species produced during flaming combustion oxidized to CO$_2$.
- Two types of PM emissions: black carbon (i.e. soot, originates in the flame), and brown carbon (organic, originates in pyrolysis).
- CO and PM are emissions due to incomplete combustion - only an ‘emission’ if they escape the flame.

Criteria for Complete Combustion
Emissions

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Criteria for Complete Combustion

1. Time
2. Temperature
3. Turbulence (mixing)
The Aspen

Downdraft Unit

Figure: Schematic of the Aspen’s operation
The Problem(s)

- Good PM emission levels: 0.27 lbs/million BTU output (meets Phase II EPA certification limit of 0.32).
- Complicated design - ‘rule of thumb’, ‘trial and error’.
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Aspen

How can we ‘fine tune’ the Aspen’s design inorder to: (1) further reduce emission levels (2) reduce manufacturing cost?
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**General**

Can we develop a mathematical model that will predict wood combustion emissions?
A full description of the solid combustion process in an OWHH is not yet practical.

- Narrow the scope: peak PM emissions; correlate with peak CO emissions
- Model flaming combustion of pyrolysis gas during peak CO production (model can therefore be steady state - snapshot).
## Governing Equations Summary

<table>
<thead>
<tr>
<th>Equation Name</th>
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</table>
| **Continuity**       | \[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0
\] |
| **Momentum**         | \[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = - \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i
\] |
| **Energy**           | \[
\frac{\partial}{\partial t} (\rho h) + \frac{\partial}{\partial x_j} (\rho u_j h) = \frac{\partial P}{\partial t} + \frac{\partial}{\partial x_j} \left( \frac{k}{C_p} \frac{\partial h}{\partial x_j} - \rho u'_j h' \right) - \frac{\partial q_j^{R}}{\partial x_j}
\] |
| **Mixture Fraction** | \[
\frac{\partial}{\partial t} (\rho Z) + \frac{\partial}{\partial x_j} (\rho u_j Z) = \frac{\partial}{\partial x_j} \left( \rho D \frac{\partial Z}{\partial x_j} \right)
\] |
Simplifications and Approximations

- Need to solve these equations in a 3-D domain, but turbulence is involved - DNS is too expensive.
- Time average equations to remove ‘turbulent fluctuating components’ - introduce a turbulence ‘closure model’ (k-ε).
- Also need a radiation transport equation.
- Now we have **7 Partial Differential Equations** to solve in 3-D!
Finite Difference Method

Differential form of a generic conservation equation

\[
\frac{\partial (\rho u_j \phi)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \Gamma \frac{\partial \phi}{\partial x_j} \right) + q_\phi
\]  

The idea behind finite difference approximation is borrowed directly from the definition of a derivative:

\[
\left( \frac{\partial \phi}{\partial x} \right)_{x_i} = \lim_{\Delta x \to 0} \frac{\phi(x_i + \Delta x) - \phi(x_i)}{\Delta x}
\]

Extrapolate: replace the partial derivatives by approximations, resulting in one algebraic equation per grid node

Disadvantages: conservation is not enforced unless special care is taken; method is restricted to simple geometries.
Integral form of a generic conservation equation

$$\int_S \rho \phi \mathbf{v} \cdot \mathbf{n} dS = \int_S \Gamma \nabla \phi \cdot \mathbf{n} dS + \int_\Omega q_\phi d\Omega$$  (3)

Subdivide domain into finite number of small control volumes (CVs) with a grid that defines the control volume boundaries not the computational nodes.

Figure: A typical CV and the notation used for a Cartesian 2D grid (Ferziger).
Implementing the Method

- Approximate surface and volume integrals. Let $f$ be a component of the convective or diffusive flux vector in the direction normal to the CV face.

1st Order:
$$F_e = \int_{S_e} f dS \approx f_e S_e$$  \hspace{1cm} (4)

2nd Order:
$$F_e = \int_{S_e} f dS \approx \frac{S_e}{2} (f_{ne} + f_{se})$$  \hspace{1cm} (5)

- Must interpolate to find values at CV surface: *upwind scheme*

$$\phi_e = \phi_P + (x_e - x_P) \left( \frac{\partial \phi}{\partial x} \right)_P + ...$$  \hspace{1cm} (6)
Solution Strategy: linearize algebraic equations, form matrix, iterate.

Advantages:
- Can accommodate any type of grid
- Conservative by construction

Disadvantages:
- Methods of higher than second order accuracy are more difficult to develop in 3D
- Three levels of approximation necessary: integration, differentiation, and interpolation.
How to do this in real life....

- Need special ‘accomodations’ for Navier-Stokes Equations
- Software: Fluent

Errors

1. Modeling Errors: fuel choice, steady state assumptions, etc.
3. Iteration Errors: solution is not fully ‘converged’.
My Work

- Flame Structure
- Grid Dependence
- Emissions

Figure: Grid 1: 4.7 million cells

Figure: Grid 2: 5.6 million cells

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Issues

Grid Dependent Solution
- Numerical Diffusion
- Computational expense (24 hours, 6GB of RAM, parallel processing)

Under-prediction of stack emissions
- Turbulence modeling?
- Need a transient solution?

Difficult convergence
- buoyancy
- upwind interpolation - second order
The finite volume method has advantages and disadvantages.

The simulation cannot be considered a reliable predictor of full furnace performance during peak pyrolysis.

The simulation can be used to qualitatively understand furnace operation and suggest test scenarios to improve emissions performance and reduce manufacturing costs.
References