Computational Fluid Dynamic Modeling of a Downdraft Wood-Fired Furnace

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Outline

Motivation

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

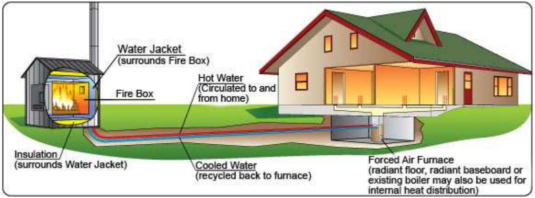

Figure: Typical OWHH Configuration

- 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: .
- EPA recently adopted a voluntary certification program to curb *PM* emissions from OWHH's

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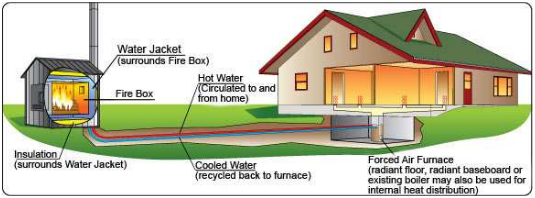

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- EPA recently adopted a voluntary certification program to curb PM emissions from OWHH's

How Does Wood Burn?

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

Stages

1. Heating and Drying
2. Pyrolysis and Devolatilization
3. Flaming Combustion
4. Char Oxidation

- Governing processes: chemistry, heat transfer, fluid dynamics.

Emissions

- CO is an intermediate species produced during flaming combustion oxidzed 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.

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Criteria for Complete Combustion

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

The Aspen

- Downdraft Unit

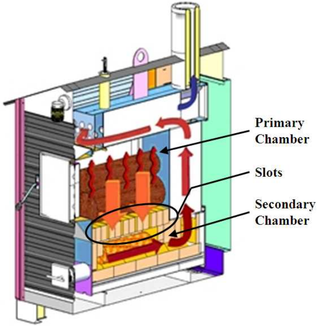

Figure: Schematic of the Aspen's operation

The Problem(s)

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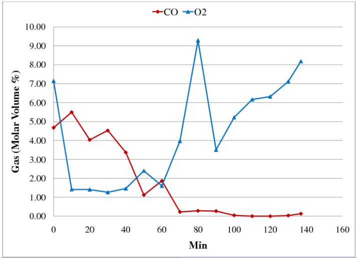
General

Can we develop a mathematical model that will predict wood combustion emissions?

A Problem of Fluid Dynamics

- 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

Equation Name	**Equation**
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	$\frac{\partial}{\partial t}(\rho h) \quad + \quad \frac{\partial}{\partial x_j}(\rho u_j h) \quad = \quad \frac{\partial P}{\partial t} \quad +$ $\frac{\partial}{\partial x_j}\left(\frac{k}{C_p}\frac{\partial h}{\partial x_j} - \rho u'_j h'\right) - \frac{\partial \dot{q}_j^R}{\partial x_j}$
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 Parital Differential Equations to solve in 3-D!**

Finite Difference Method

Differential form of a generic conservation equation

$$\frac{\partial(\rho u_j \phi)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma \frac{\partial \phi}{\partial x_j}\right) + q_\phi \qquad (1)$$

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

$$\left(\frac{\partial \phi}{\partial x}\right)_{x_i} = \lim_{\Delta x \to 0} \frac{\phi(x_i + \Delta x) - \phi(x_i)}{\Delta x} \qquad (2)$$

- 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.

Finite Volume Method

Integral form of a generic conservation equation

$$\int_S \rho\phi\mathbf{v}\cdot\mathbf{n}d\mathbf{S} = \int_{\mathbf{S}} \boldsymbol{\Gamma}\nabla\phi\cdot\mathbf{n}d\mathbf{S} + \int_{\boldsymbol{\Omega}} \mathbf{q}_{\phi}d\boldsymbol{\Omega} \qquad (3)$$

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

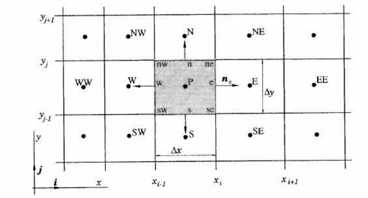


Figure: A typical CV and the notation used for a Cartesian 2D grid (Ferziger)

Finite Volume Method cont....

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.

$$\text{1st Order:} \quad F_e = \int_{S_e} f dS \approx f_e S_e \tag{4}$$

$$\text{2nd Order:} \quad F_e = \int_{S_e} f dS \approx \frac{S_e}{2}(f_{ne} + f_{se}) \tag{5}$$

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

$$\phi_e = \phi_P + (x_e - x_P)\left(\frac{\partial \phi}{\partial x}\right)_P + \dots \tag{6}$$

Finite Volume Method cont...

Solution Strategy: linearize algebraic equations, form matrix, iterate.

Advantages:

- Can accomodate 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....

- Necessary Components: Equations, Domain, CFD package, Boundary Conditions.
- Need special ‘accomodations’ for Navier-Stokes Equations
- Software: Fluent

Errors

1. Modeling Errors: fuel choice, steady state assumptions, etc.
2. Discretization Errors: grid dependency, numerical diffusion.
3. Iteration Errors: solution is not fully ‘converged’.

My Work

- Flame Structure
- Grid Dependence
- Emissions

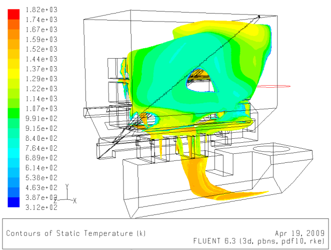


Figure: Grid 1: 4.7 million cells

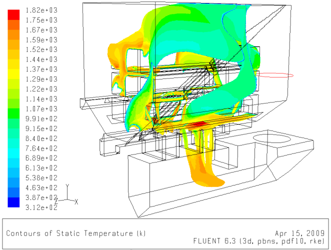


Figure: Grid 2: 5.6 million cells

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

Conclusions

- 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 peformance and reduce manufacturing costs.

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- J. H. Ferziger and M. Peric. *Computational Methods for Fluid Dynamics. Springer, third edition, 2002.*
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- *M. Huttenen, J. Saastamoinen, and et. al. Emission formation during wood log combustion in fireplaces - Part I: Volatile Combustion Stage. Progress in Computational Fluid Dynamics, 6(4/5):200-208, 2006.*