Evaluating a Downdraft Wood Fired Hydronic Furnace: Computational Fluid Dynamics Modeling and Analysis

Megan Karalus
karalm2@u.washington.edu

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Outline

1. Introduction
    - Motivation
    - Fundamental Concepts
    - Project Description
2. Benchmarking
3. Slots Study
    - Modeling Decisions
    - Convergence and Accuracy
    - Results and Discussion
4. Conclusions

Heating Your Home

Table: Energy sources for residential space heating (2001 Department of Energy Survey)

Fuel	Percentage
Natural Gas	60%
Electricity	23%
Fuel Oil	8%
Wood	3%
Other	6%

Using Wood as a Fuel

- Advantages: Potentially "carbon neutral"; Renewable; Local; Potentially lower cost
- Methods of Heating: Fire Places, Wood Stoves, OWHHs (Outdoor Wood-Fired Hydronic Heaters)

OWHH

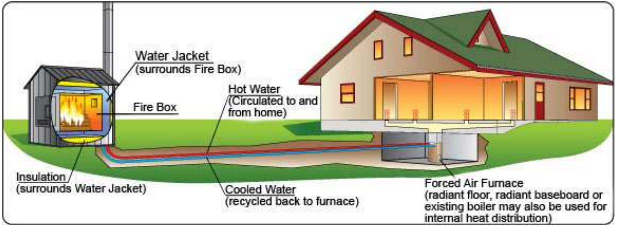

Figure: Typical OWHH Configuration

- National Ambient Air Quality Standards for six air pollutants; three for wood combustion: NO_x, PM, CO.
- OWHHs: EPA certification program to curb PM emissions. .
- Concerns: Efficiency, Emissions, Cost.

The Big Picture

Technical Challenges

1. Meet PM emissions standards for the EPA certification program.
2. Obtain high efficiency operation.

Approaches

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Wood Combustion and Particulate Emissions

Wood Combustion

1. Heating and Drying
2. Pyrolysis (Devolatilization)
    - Heat + Wood → Pyrolysis Gas
3. Combustion
    - Pyrolysis Gas + Air → Buoyant Diffusion Flame
    - Particulate Matter Formation and Oxidation
4. Char Oxidation

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Particulate Matter Formation

Two types:

1. Black Carbon
   - "soot"
   - blackbody radiator: red and yellow flame color
2. Brown Carbon
   - organic matter originating in solid pyrolysis
   - 90% of PM emissions in wood combustion

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PM Emissions

Particulate Matter that "escapes" the flame.

Addressing Emissions

Flame Behavior

- Buoyant Diffusion Flame
- Turbulent and Chaotic

Complete Combustion

1. Time
2. Temperature
3. Turbulence (fuel/air mixing)

Figure: Wood Fire (courtesy of Greenwood Technologies)

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A Problem of Fluid Dynamics

Case Study Furnace: The Aspen

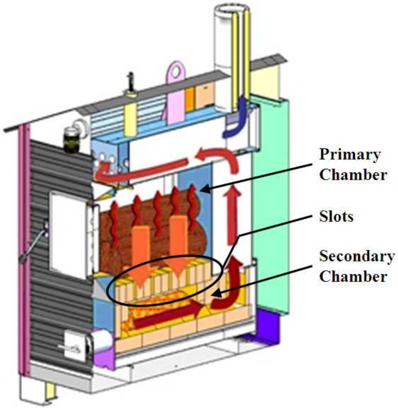

Figure: Operation Schematic

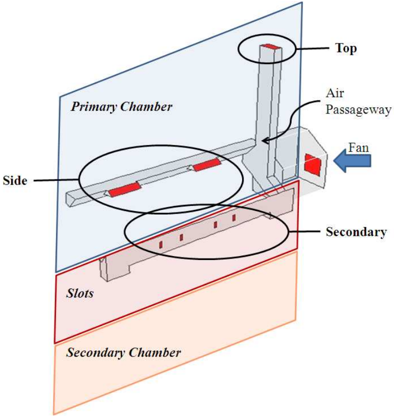

Figure: Air inlet passages and ports

Study Outline

- Focus: Particulate Matter Emissions
    - A Problem of Fluid Dynamics
- Case Study Furnace: The Aspen
    - Emissions and Cost
        1. Necessity of secondary air?
        2. Effect of slots alone?
- Benchmarking
    - EPA Test Method 28: Burn Rate, Emissions
    - Measurements: Air Distribution
- Modeling
    - Slots Study
    - Combusting, Computational Fluid Dynamics (CFD) Model: FLUENT

EPA Test Method 28

- Measures: weight change; CO, CO_2, PM emissions; stack and water jacket temperatures.
- Four energy output conditions (categories)

Category	Percentage of Maximum Rated Output
1	$<$ 15%
2	16 to 24%
3	25 to 50%
4	100%

- Output for Categories 1-3 controlled by damper plate.
- Choose Category 4: Benchmarking and Modeling

Burn Rate and Emissions

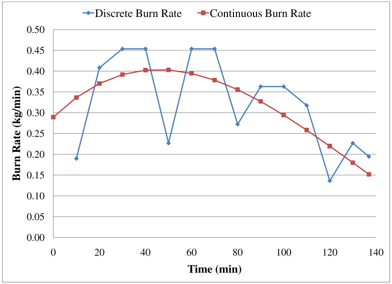

Figure: Category 4 discrete and continuous burn rate

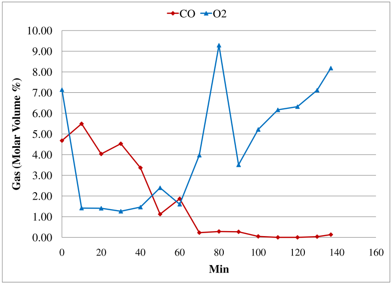

Figure: Gas mole fraction percentages from an EPA test Category 4 burn

Air Distribution

- Measured velocities in each port with pitot tube, assumed velocity profile, calculated volumetric flow rate.

Table: Flow split among air inlet ports

	Test 1	*Test 2*	
Inlet Areas	**Total CFM 79.4**	**Total CFM 86.9**	**Average**
Top	55%	59%	57%
Side	42%	39%	40%
Secondary	3%	2%	3%

- Total CFM to furnace measured with orifice: 61.7

Stoichiometry

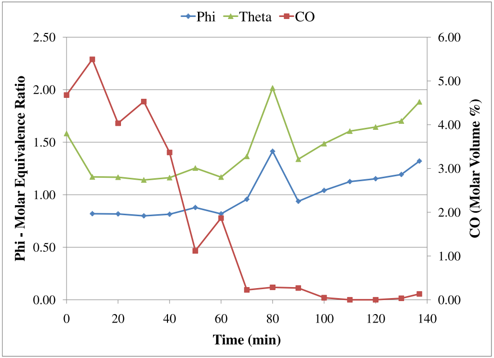

Figure: Excess air and equivalence ratio (surrogate fuel: CH_4)

$$C_wH_xO_zN_y + \overline{MC}H_2O_{(l)} + \Theta\omega(O_2 + 3.76N_2) \Rightarrow$$

$$\alpha CO_2 + (w-\alpha)CO + (x/2 + \overline{MC})H_2O + (y/2 + 3.76\Theta\omega)N_2 + \beta O_2$$

Verifying Total CFM of Inlet Air

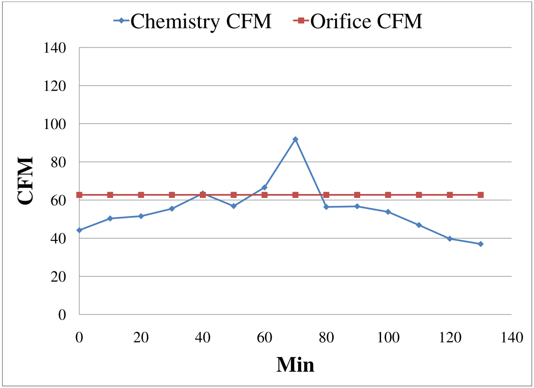

Figure: CFM (surrogate fuel: CH_4)

Equations

We need to account for the following physical phenomena...

Conservation Equations:	*Mass*
	Momentum
	Energy
Turbulence:	*Favre Averaged Navier-Stokes*
	Closure Model: Realizable k-ε
Chemistry:	*Mixture Fraction*
Radiation:	*Discrete Ordinance Model*

- Many partial differential equations to solve simultaneously.
- Steady State: “Snapshot” in time at peak pyrolysis.

Modeling Assumptions and Boundary Conditions

- No Particulate Matter Model: Use CO as indicator
- "Snapshot" of furnace operation so all boundary conditions set as averages of the test data from the 40th to the 60th minute: Burn Rate and Surface Temperatures.
- Air Flow Rate: 62 CFM

Table: Surrogate pyrolysis fuel (Huttenen, 2006)

	Mole Fraction
Species	Composition 2 (%)
CO_2	9.6
CO	38.3
CH_4	23.9
H_2O	10.0
H_2	18.2

Sources of Error

1. Modeling Errors
    - Approximations: fuel choice, steady state assumptions, etc.
2. Discretization Errors
    - Grid Dependency
3. Iteration Errors
    - Convergence Criteria

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Grid Dependence: Flame Structures

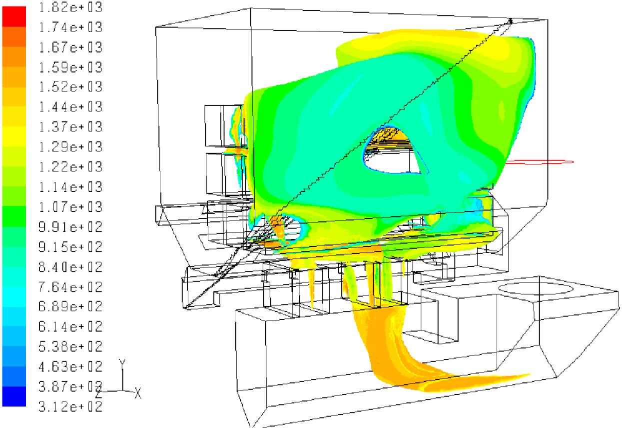

Figure: Grid 1: 4,763,875 elements

Grid Dependence: Flame Structures (cont...)

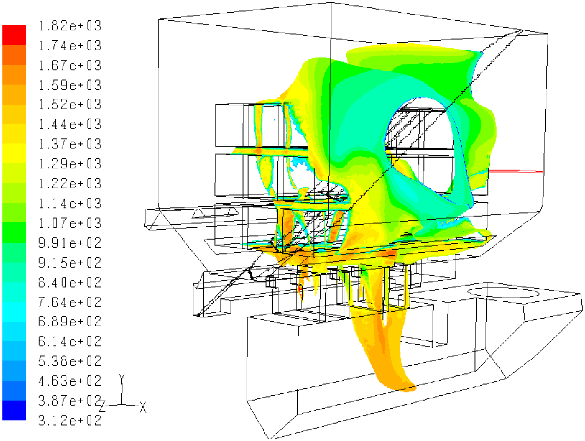

Figure: Grid 2: 5,409,456 elements

Grid Dependence: Flame Structures (cont...)

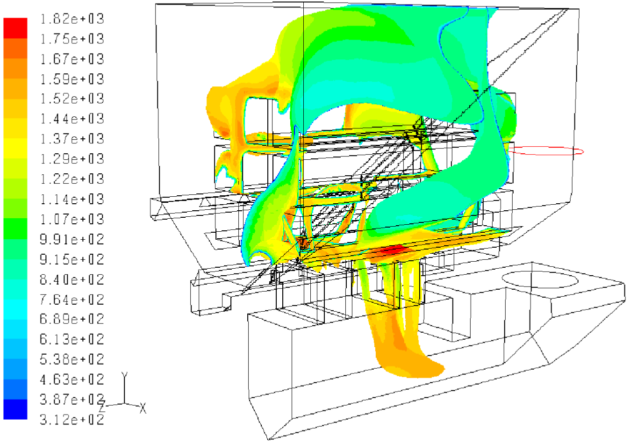

Figure: Grid 3: 5,615,316 elements

Grid Dependence: CO concentration

Table: Comparison of CO mole fractions at the top and bottom of each slot for three grid resolutions

		Slot Number			
	Grid Number	1	2	3	4
Top (mole fraction %)	Grid 1	0.09	0.96	6.63	6.77
	Grid 2	0.32	0.98	5.09	4.90
	Grid 3	0.49	0.89	5.30	4.30
Bottom (mole fraction %)	Grid 1	0.00	0.11	5.48	6.07
	Grid 2	0.00	0.02	4.46	4.27
	Grid 3	0.00	0.00	4.76	3.50

Grid Dependence: CO concentration (cont...)

Table: Comparison across three grids of the change in CO concentration through the slots

		Slot Number				
	Grid Number	1	2	3	4	**Average**
Change (mole fraction %)	Grid 1	0.09	0.85	1.15	0.70	**0.69**
	Grid 2	0.32	0.96	0.63	0.63	**0.62**
	Grid 3	0.49	0.89	0.53	0.81	**0.67**

Review...

Questions:

1. Necessity of secondary air?
2. Effect of slots alone?

Scenarios:

1. With Secondary Air
2. Without Secondary Air

Air Distribution

Table: Comparison of measured and calculated air flow rates for each air inlet area, reported as percentages of the total air flow rate

		Secondary	Side	Top
	Measurements	**3%**	**40%**	**57%**
With Secondary Air	FLUENT - Cold	16%	37%	47%
	FLUENT - Burn	15%	35%	50%
Without Secondary Air	FLUENT - Cold	-	45%	55%
	FLUENT - Burn	-	42%	58%

Megan Karalus `karalm2@u.washington.edu`

Visualizing Secondary Air Addition

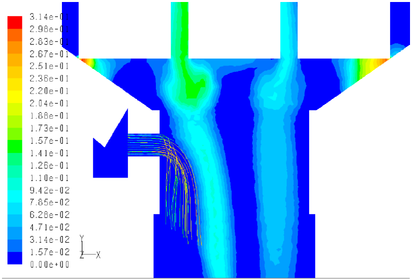

Figure: With Secondary Air

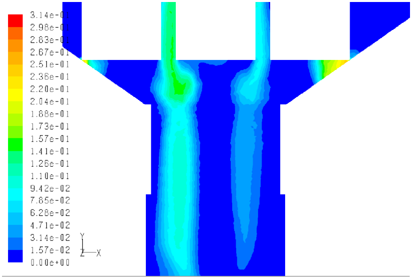

Figure: Without Secondary Air

Contours of CO mole fraction and the influence of secondary air addition

CO Behavior in the Slots

Table: Comparison between simulation scenarios of CO mole fractions behavior in the slots

		Slot Number				
	Scenario	1	2	3	4	**Average**
Top (mole fraction %)	1	0.49	0.89	5.30	4.30	**2.85**
	2	0.32	0.43	4.33	3.61	**2.20**
Bottom (mole fraction %)	1	0.00	0.00	4.76	3.50	**2.18**
	2	0.00	0.00	4.12	3.35	**1.90**
Change Through Slots	1	0.49	0.89	0.53	0.81	**0.67**
	2	0.31	0.43	0.21	0.26	**0.30**

Scenario 1: With Secondary Air

Scenario 2: Without Secondary Air

Conclusions

1. CO and therefore PM emissions are due to mixing limited combustion.
2. The slots by themselves do contribute to CO oxidation, and therefore PM reduction.
3. Current furnace operates closer to the conditions of Scenario 2 with no secondary air.
4. Recommend EPA test of the Aspen under strict Scenario 2 conditions.
5. Grid dependence of solution prevents simulations from being used as a predictor of full furnace performance during peak pyrolysis.

Acknowledgements

- Prof. Kramlich
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Questions?