Environmental, Energy Market, and Health Characterization of Four Wood-Fired Hydronic Heater Technologies

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Project Approach

- Test four OWHHs
  - Common, new, and multi-stage models
  - Fully characterize emissions, emission factors
  - 4/5 Fuel types
- Test under realistic, homeowner firing scenarios
  - 24 h, cordwood
- Health risk characterization
- Emission inventory projections for NY
- MARKAL technology assessment
Conventional/Single Stage HH

Natural updraft, fan-assisted, single-stage combustion (250,000 BTU/h). Rectangular firebox surrounded by a high capacity water jacket. The gases are forced into a combustion chamber where additional super-heated air is added, increasing the gas temperature. Load demand satisfied by regulation of an air damper.
Three-stage combustion process (160,000 BTU/h) in which wood is gasified in the primary combustion firebox. The hot gases are forced downward and mixed with super-heated air starting the secondary combustion. Final combustion occurs in a third, high temperature reaction chamber. Like the Conventional/Single Stage HH, this Three Stage HH is regulated by the opening and closing of a temperature controlled air damper.
European Two-Stage Pellet Boiler

This unit is a pellet burning HH rated at 40 kW (137,000 Btu/hour). Combustion occurs on a round burner plate where primary air is supplied. Secondary air is introduced through a ring above the burner plate. Fuel is automatically screw-conveyed from the bottom. Operation of the screw feeder is regulated by a thermostat. During normal operation, the fan modulates based on the measured oxygen level in the exhaust gas, maintaining 8-10% oxygen.
U.S. Two-Stage Downdraft Burner

A two-stage heater (150,000 BTU/h) with both gasification and combustion chambers. Air is added to the firebox continuously and is blown downwards. A thermal storage unit was simulated with the addition of a water/air heat exchanger.
<table>
<thead>
<tr>
<th>Properties</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pine</td>
</tr>
<tr>
<td>Ash</td>
<td>0.44%</td>
</tr>
<tr>
<td>Loss on Drying (LOD)</td>
<td>9.68%</td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>88.50%</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>11.06%</td>
</tr>
<tr>
<td>C: Carbon</td>
<td>51.72%</td>
</tr>
<tr>
<td>Cl: Chlorine</td>
<td>36 ppm</td>
</tr>
<tr>
<td>H: Hydrogen</td>
<td>6.57%</td>
</tr>
<tr>
<td>N: Nitrogen</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>S: Sulfur</td>
<td>&lt;0.05%</td>
</tr>
</tbody>
</table>

**Fuels**

### HH Sampling and Analytical Methods

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Method(s)</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total PM</td>
<td>ASTM 2515M5G</td>
<td>Integrated run</td>
</tr>
<tr>
<td>PM mass and size</td>
<td>Dilution + TEOM, ASTM 2515 for tot for total mass and ELPI for size distributions, ELPI or SMPS</td>
<td>Real time &amp; size distribution</td>
</tr>
<tr>
<td>CO</td>
<td>NDIR Method 10B</td>
<td>Real time</td>
</tr>
<tr>
<td>CO2</td>
<td>NDIR Method 3A</td>
<td>Real time</td>
</tr>
<tr>
<td>O2</td>
<td>Paramagnetic Method 3A</td>
<td>Real time</td>
</tr>
<tr>
<td>EC/OC</td>
<td>NIOSH 5040</td>
<td>Integrated run</td>
</tr>
<tr>
<td>PAHs, SVOCs</td>
<td>Method 0010, GC/MS</td>
<td>Integrated run</td>
</tr>
<tr>
<td>Gaseous VOCs</td>
<td>Summa canister, TO15</td>
<td>Integrated run</td>
</tr>
<tr>
<td>Aromatics</td>
<td>REMPI-TOFMS</td>
<td>Real time</td>
</tr>
<tr>
<td>PCDD/F</td>
<td>Method 23</td>
<td>Integrated run</td>
</tr>
<tr>
<td>THC</td>
<td>FID Method 25A</td>
<td>Real time</td>
</tr>
<tr>
<td>CH4</td>
<td>FID with reduction catalyst</td>
<td>Real time</td>
</tr>
<tr>
<td>N2O</td>
<td>GC</td>
<td>Integrated run</td>
</tr>
</tbody>
</table>
Appliance Heat Load Profile

- The heat load profile used throughout the testing program (non-exposure tests) was derived from Tom Butcher’s Energy-10 simulation for a 2500 sq-ft area home in Syracuse, New York.
- This heat load profile was calculated using an average hour per hour heat load for the first two weeks of January.
CO and CO$_2$ Emissions as a function of Syracuse Heat Load Demand, 24 h test
Conventional/Single Stage HH, Red Oak

The emission profiles are ~ independent of the heat load. Rather they appear to be primarily related to the fuel charging cycle under our conditions.
Heat Release Rate
Representative Run

Heat release during damper openings

Conventional/Single Stage HH, Red Oak
Heat Release Rate

Representative Run

European 2-Stage Pellet Burner
Heat Release Rate
Representative Run

Unit with simulated heat storage has non-cyclical heat release.

U.S. 2-Stage Downdraft Burner with Thermal Storage
## Efficiencies

<table>
<thead>
<tr>
<th>Units</th>
<th>Thermal Efficiency (%)</th>
<th>Boiler Efficiency</th>
<th>Combustion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional/Single Stage HH/Red Oak</td>
<td>Average 22</td>
<td>NC</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>STDV 5</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Conventional/Single Stage HH/Red Oak and Refuse</td>
<td>Average 31</td>
<td>NC</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>STDV 2.2</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>Conventional/Single Stage HH/White Pine</td>
<td>Average 29</td>
<td>NC</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>STDV 1.8</td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>Three Stage HH/Red Oak</td>
<td>Average 30</td>
<td>NC</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>STDV 3.2</td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td>European 2-Stage Pellet Burner</td>
<td>Average 44</td>
<td>86</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>STDV 4.1</td>
<td>3.5</td>
<td>0.16</td>
</tr>
<tr>
<td>U.S. 2-Stage Downdraft Burner Red Oak</td>
<td>Average IM</td>
<td>83</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>STDV 0.71</td>
<td></td>
<td>0.79</td>
</tr>
</tbody>
</table>

NC = Not calculated.  IM = Insufficient measurements taken for this calculation
Mass of Fuel Needed for a 24 Hour Syracuse Heat Load

- Conventional HH RO: 350 lbs
- Conventional HH WP: 300 lbs
- Three Stage HH RO: 250 lbs
- European Pellet: 200 lbs
- US DownDraft: 150 lbs

Hydronic Heater Unit and Fuel Type
Emissions are primarily related to time-since-charging rather than heat load demand.
Carbon Monoxide Emission Factors

Hydronic Heater Unit and Fuel Type

Heat Input:
- Conventional HH RO
- Conventional HH WP
- Three Stage HH RO
- European Pellet
- US DownDraft

Heat Output:
- Conventional HH RO
- Conventional HH WP
- Three Stage HH RO
- European Pellet
- US DownDraft
PM Generated per Syracuse Day for All Six Unit/Fuel Combinations

Hydronic Heater Unit and Fuel Type
PM Emission Factors

Hydronic Heater Unit and Fuel Type

Heat Output

Heat Input
PM. Comparison of Current Data to EPA Method 28 OWHH

This project

Others’ work, EPA Method 28

Large variation in PM emissions from different technologies
Significant organic carbon contribution with emission factor a function of technology type.
Total PAH Emission Factors

Higher PAHs from White Pine
Fuel and technology-induced variations in Dioxin emissions.
In the Mid-Atlantic region (including New York, New Jersey, and Pennsylvania), optimization based solely on costs and technology efficiency predicts that wood heat is likely to remain a relatively small market share of total residential space heating demands.
In the scenarios analyzed, wood heat units had a limited impact on the broader market for residential fuels and electricity. However, wood heat emissions dominated the total PM emissions from total residential energy usage over all scenarios.
The evolution of the technology mix within the market for wood heat will have a major impact on both residential PM emissions and, consequently, total PM emissions. Depending on the rate of changeover from less efficient, higher emitting units and emissions performance of newer units, residential PM emissions could increase substantially, peaking in the next 5-10 years, or drop by nearly half.
* At typical HH efficiencies and cord wood prices, an HH has a higher lifetime cost than competing technologies
* Fuel price and device efficiency are the primary components of heating costs, not the capital cost of equipment
* The low efficiency of HHs contributes to their high relative lifetime cost
* A free or very low cost wood supply can tilt the lifetime cost balance in favor of HHs
* Under these conditions, HHs are considerably more expensive than high efficiency indoor boilers with hot water storage, however
Emission Conclusions

• In general, over a 20-fold variation in emissions was observed between these four technologies.
• Thermal efficiencies (heat delivered/heat input) varied by 2-fold, depending on technology.
• Emissions are highly cyclic for the units that respond to heat demand with damper openings.
• For these same units, nuisance odor was significant despite use of the building’s air cleaning system.
• The magnitude of emissions depend on the amount of time passage after charging the appliance with fuel rather than on the heat load.
Emission Conclusions

- White pine had the highest total PM and PAH mass emissions.
- The identified and quantified SVOCs account for 9% w/w of the PM emitted, of which ~25% was levoglucosan.
- CH₄ is about 10% of the THC emissions.
- CO concentrations on the order of 1-8% were observed.

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