Residential Heat Best Practices I
Furnaces and Boilers

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Integrated Energy Systems
Better Buildings by Design 2009
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Advanced Combustion Technologies
Objectives

• Discuss space & water heating technologies for oil and gas
• Understand what makes heating systems efficient
• Appreciate advantages & disadvantages of various new “high efficiency” systems
• Be better able to assess suitability of newer technologies for comfort and efficient operation in new or existing housing
What are you looking for?
What is your prime energy choice?

- oil
- natural gas
- propane
- wood
- electricity
- other
Heat Distribution ?
“Conventional” Hydronic Heating

- Baseboard radiator
- Cast-iron radiator
- Supply pipe
- Cold water fill
- Return line
- Pump
- Expansion tank
- Boiler
- Relief valve
Radiant Floor?
Warm Air System

Furnace

Fan Coil (Hydro-Air)
A Blend/mix
What makes a combustion system energy-efficient and where is energy lost?
Fuels

• No. 2 oil
• Natural gas
• Wood
• Propane
• + electricity – fans/blowers, pumps, ...
FUEL PROPERTIES
(Ultimate Analysis)

- Carbon
- Hydrogen
- Sulphur
- Nitrogen
- Oxygen
- Ash (Na, K, Fe, heavy metals Hg, )
- Heating Value
## Ultimate Analysis & HHV for Different Fuels (Dry Basis)

<table>
<thead>
<tr>
<th>Property</th>
<th>No. 2 Oil</th>
<th>Nat Gas</th>
<th>Propane</th>
<th>Wood</th>
<th>Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>86.4%</td>
<td>71.6</td>
<td>81.7</td>
<td>49.7</td>
<td>49.8</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>13.3%</td>
<td>23.2</td>
<td>18.3</td>
<td>5.8</td>
<td>5.9</td>
</tr>
<tr>
<td>Sulphur</td>
<td>&lt;0.3%</td>
<td>trace</td>
<td></td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>4.3</td>
<td></td>
<td>0.08</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td></td>
<td></td>
<td>0.3</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.9</td>
<td></td>
<td>44.1</td>
<td>44.1</td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td></td>
<td>17-60</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>HHV, Btu/lb</td>
<td></td>
<td></td>
<td>8000</td>
<td>8100</td>
<td></td>
</tr>
<tr>
<td>HHV, Btu/…</td>
<td>140k/gal</td>
<td>1007/ft³</td>
<td>92.7k/gal</td>
<td>17-27M/fullcord</td>
<td>336/bag</td>
</tr>
</tbody>
</table>
To appreciate what makes today’s heating technologies work (and not), it will be useful to appreciate some Combustion System Principles.
Combustion Reactions

C + O₂ → CO₂
4H + O₂ → 2H₂O
S + O₂ → SO₂

Oxygen is required for combustion
“Air”

- Nitrogen @ 79.1%
- Oxygen @ 20.9%
Stoichiometric Air
the chemically exact amount of air (oxygen) to achieve complete combustion of Carbon, Hydrogen & Sulphur in the fuel
In order to ensure satisfactory combustion with minimal incomplete combustion, we need more air, what we call …
Excess Air

Amount of air greater than stoichiometric required for satisfactory combustion
Characterized by CO₂ or O₂ in flue gas

Excess Air = Total Air – 100%
Efficiency ? ? ?
First, a misused term ...
Combustion Efficiency

Measures how completely the fuel is burned to CO$_2$ & water vapour
With natural gas or oil, Combustion Efficiency (how completely the fuel is burned) is nearly always $>99.9\%$

With fireplaces, airtight woodburning stoves and furnaces, & flares, Combustion Efficiency can be $<90\%$

with very large amounts of incomplete combustion products

(serious air pollutants: VOC, PAH, CO, …)
Most times, when we think about efficiency, we are concerned with how effectively we are using the available energy in the fuel.
Efficiency = \frac{\text{Energy Out}}{\text{Energy In}} \times 100

In North America, heating value and "Energy In" are based on Higher Heating Value.

In Europe, they are most often based on Lower Heating Value, overestimating the efficiency by up to 12% (also gas turbines, cars)
Steady State Efficiency

- Usually the most efficient point of operation
- Like cruising on the highway
- Many smaller systems and certain industrial processes rarely operate in steady state
- Gives a base point of reference and guides system readjustment to compensate for performance degradation or to modify to increase performance
Equilibrium: Steady State Operation
Transient Efficiency

Many combustion systems (nearly all residential/commercial ones) do not operate in steady state for most of their operation. They cycle up and down, taking a significant time to reach equilibrium, if at all.

In general, transient systems are significantly less efficient than ones that operate in steady state.
Transient Operation

Transient/Cyclic Operation

Flue Gas Temperature, °C

Time, min
Transient Operation

Flue Gas Temperature, °C

Time, min

Burner On

Burner Off

Transition Operation

Flue Gas Temperature, °C

Time, min

Burner On

Burner Off
Excess Air

The extra amount of air above that theoretically needed for combustion, in order to actually get satisfactory burning.
Effect of Excess Air on Flue Gas Temperature and Efficiency.
Effect of Excess Air on Flue Gas Temperature and Efficiency

Decreasing Excess Air
Decreasing excess air:

- Lowers air demand
- Reduces mass flow and velocity thru the system
- Improves heat exchange
- Lowers flue gas temperature
- Increases efficiency!
Cycling & Post-Purging

- Operates on a fixed time length (say 30 sec) each time after the burner shuts off, to ensure combustion gases are evacuated from the system.
- Removes fixed amount of heat from unit each cycle.
- Loss is about 1.5% for a typical number of cycles per year (~2000 for normal furnace).
- If purge length is doubled, loss is doubled; similarly if no. of cycles doubles, loss doubles.
- If unit short-cycles and number of cycles increases to 10,000 (not uncommon) loss goes up 5x to 7.5%; to 20,000 means loss up to 15%.
Factors Affecting Overall Energy Consumption

<table>
<thead>
<tr>
<th>Demand</th>
<th>Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Req’d</td>
<td>S.S. Efficiency</td>
</tr>
<tr>
<td>Outdoor Temp</td>
<td>Transient</td>
</tr>
<tr>
<td>Thermostat</td>
<td>Comb &amp; Dil Air</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
</tr>
<tr>
<td></td>
<td>(FD/ID fans)</td>
</tr>
<tr>
<td></td>
<td>Circ fan/pump</td>
</tr>
<tr>
<td>Heat Losses</td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td></td>
</tr>
<tr>
<td>Infiltration</td>
<td></td>
</tr>
<tr>
<td>Off-Cycle</td>
<td></td>
</tr>
<tr>
<td>(near, long)</td>
<td></td>
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</tbody>
</table>
Seasonal or Annual Fuel Utilization Efficiency (AFUE)

This is a cumulative (average) efficiency of a system over a year or other extended period in response to varying conditions.

It works quite well for warm air furnaces, but can misrepresent efficiency of some boiler technologies and of integrated space/water heating systems.
Carbon & Hydrogen in Fuels

Natural Gas has high hydrogen & a low level of sulphur.
Oil has significant sulphur + part.
Hydrogen Losses for Different Fuels

- Lignite
- Wood
- No.6 Oil
- No.2 Oil
- Propane
- Nat Gas
<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Energy Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Oil</td>
<td>140 kBtu/gal</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1 007 Btu/ft³</td>
</tr>
<tr>
<td></td>
<td>100700 Btu/therm</td>
</tr>
<tr>
<td>Propane</td>
<td>92.7 kBtu/gal</td>
</tr>
<tr>
<td>Electricity</td>
<td>3413 Btu/kwh</td>
</tr>
<tr>
<td>Mixed Hardwood</td>
<td>26 Mbtu/fullcord</td>
</tr>
<tr>
<td>Wood Pellets</td>
<td>336 kBtu/bag or 16.8 MBtu/ton</td>
</tr>
<tr>
<td>Coal</td>
<td>24 Mbtu/ton</td>
</tr>
</tbody>
</table>
Oil-Fired Systems
Most crucial element to achieve good performance and high efficiency is the oil burner.
Retention Head Burner
Retention Head Oil Burner

- Better fuel-air mixing (EA - 50%)
- Fair resistance to stack and house pressure fluctuations/depressurization
- Resists off-cycle flow loss
- Firing rate down to 70kBtu with good EA
- Efficiency should be 80-83%
- Should have delayed action solenoid valve to reduce soot/degradation
Hi Static Burner
High-Static Oil Burner

- Excellent fuel-air mixing (EA - 25%)
- Stable under stack (exhaust) pressure fluctuations
- High resistance to house depressurization
- Zero off-cycle flow loss (ex post-purge)
- Firing rate down to 70kBtu with good EA
- Efficiency should be 82-86%
- Minimal sooting/degradation
- Should be burner of choice
Two-Stage Burner

- Excess air must be controlled for both rates
- If flue gas minimum temperature is governed by low fire, then high fire condition will be inefficient
- If the reverse, or a compromise, danger of corrosion of tail end of unit or in venting system
- If furnace, we see no evidence of energy savings with 2 stage operation
- By reducing the number of cycles, start-up & shut-down emissions and subsequent degradation may be reduced
Combustion Air for Oil Burners
(70 kBtu/h; 18 k ft³ house)
Combustion & Dilution Air for Oil Burners
(70 kBtu/h; 18 k ft³ house)
Air Demands

• Cast iron head burner 100% excess air
• Retention head burner 50% excess air
• High static burner 25% excess air
• Barometric damper 1-5 times air for combustion
• Combustion air related to air change for 1500 ft² two storey + 750 ft² basement gives 1.0 AC = 18000 ft³
“Direct Vent” Oil Furnace

• High static burner
• No dilution device
• Low air requirements
• No off-cycle loss
• Minimal flue travel (insulated pipe)
• Can be sealed combustion
• Potential for high efficiency (~86%)
What about an Oil-Fired Condensing Furnace?
Dewpoints for Different Fuels

- Natural Gas
- Propane
- No. 2 Oil

Excess Air, %

°C
Condensing Oil Furnace

- Much less energy tied up in latent heat than gas
- Dewpoint is low, but return air such that condensing occurs
- Condensate is very acidic, due to S in oil – best to use low S oil
- Heat exchanger must be VERY hi grade – Al-29-4C
- Sooting can result in “acid smut” which increases corrosive action – use good high-static burner
- New very low S oil more suitable
Oil Boilers
Condensing Oil-fired Boiler

- High efficiency possible by recovering latent heat from water vapour in flue gas.
- Similar issue to condensing furnaces re potential for latent heat recovery, and corrosion potential; low S oil better much better
- Typical return water temperature (except for radiant floors) is above dewpoint, so make every effort to lower it: outdoor reset, lower flow rates, preheat cold service water
Condensing for Part of the Season

Part of heating season boiler can operate in condensing mode (%)

Baseboard oversize factor

Gas - Minneapolis
Gas - Long Island
Oil - Minneapolis
Oil - Long Island
Service (Tap) Water Heating
Combined Space-Water Heating
However, this does **not** mean: “Combo” Conventional Tank Water Heater with Fan Coil

- Relatively cheap
- High flue gas temperature
- Reduced life
- Inefficient
- Much lower AFUE than furnaces, because standard does not apply
- **Not recommended**!
Tankless Coil Boiler or Tank-within-Tank Boilers

- Very inefficient summer and overall operation
- Large number of cycles with inherent inefficiency and sooting
- **Not recommended !!**
However, well-conceived combined systems for space and water heating can be an effective way around the technical limitation of oversizing with oil-fired equipment in energy efficient housing.
Efficient Oil-Fired Space/Water Heating Systems
Gas-Fired Systems
Conventional Gas Furnace

- Naturally aspirating
- Highly susceptible to depress & spillage
- Draft hood (extra heated air loss)
- Continuous pilot (energy waste)
- Large off-cycle loss
- Low seasonal efficiency (~60%)
- Now an “antique”!
Mid-Efficiency Gas Furnace
Mid-Efficiency Gas Furnace

- Powered exhaust
- Electronic ignition
- No dilution air
- So-so resistance to depressurization
- Probs with side-wall vent -No plastic!
- Should NOT be efficient ( <81% )
- Oversizing loses efficiency and gives short-cycle condensation/corrosion problems with furnace or vent
- Now an antique in Canada
High Efficiency Condensing Furnace

*****
High-Efficiency Gas Furnace

- Powered exhaust
- Electronic ignition
- No dilution air
- High resistance to depressurization
- Excellent side-wall vent - plastic!
- Should be well above 90%
- Efficiency improves with slight oversizing
Effects of Brushless DC Motors in Fan/Motor Sets on Electrical Use/Gas Consumption in Heat/Ventilation/Air Conditioning Distribution
Gas Consumption with ECM & PSC Motors

**Graph:**
- ECM Benchmarking & Results, January - May 2002,
- Furnace Gas Consumption

Mathematical equations:
- \( y = 0.9774x + 35.801 \quad R^2 = 0.991 \)
- \( y = 0.9891x + 2.9946 \quad R^2 = 0.998 \)

Legend:
- + Benchmark
- × Results
- 1:1
- Linear (Benchmark)
- Linear (Results)
## Electricity Consumption & Air Flows

<table>
<thead>
<tr>
<th></th>
<th>Low Speed Circulation</th>
<th>High Speed Heating</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ECM</strong></td>
<td>16.5 w @ 448 cfm</td>
<td>284 w @ 1215 cfm</td>
</tr>
<tr>
<td><strong>PSC</strong></td>
<td>350 w @ 960 cfm</td>
<td>490 w @ 1317 cfm</td>
</tr>
</tbody>
</table>
Results

• Sig increase in gas use & $$ electric saving with efficient electric motor (ECM) vs conventional PSC in continuous circulation warm air system

• $ saving and reduction in air conditioning requirement with efficient ECM motor

• Now looking at replacing PSC pump motors with brushless DC units
What about two-stage furnaces?
Dual Firing Rate Furnaces at Low Fire

Lower speed in ducts can result in “better” heat exchange to duct, resulting in greater heat loss, less heat to registers & increased t/s & furnace operation.
What about two-stage condensing furnaces?

- Compared to condensing furnace with PSC circ fan motor, 2-stage furnace with ECM gave increased gas use.
- Increased operation time (~ doubled) may lead to sig. increase in electrical use, esp if PSC motor used with ID fan.
- Loss of heat to distribution system may give less heat to some registers and result in homeowner upping the thermostat.
- No evidence of gas savings, in spite of claims.
- May give increased comfort.
- May be only way of getting ECM fan motor.
What about two-stage mid-efficiency furnaces?

- Compared to furnace with PSC circ fan motor, 2-stage furnace with ECM gave increased gas use.
- Increased operation time (~ doubled) may lead to significant increase in electrical use if PSC motor used.
- If PSC used for circ fan, major electricity cost increase.
- Loss of heat to distribution system may give less heat to some registers and result in homeowner upping the thermostat.
- If efficiency maintained on low fire, high risk of condensation and corrosion of primary heat exchanger and vent system.
- 2-Stage mid-efficiency furnaces **NOT recommended**
Gas Boilers
Remember the Conventional Gas Furnace with natural draft and dilution air

Did NOT meet AFUE std and has been off the market for 15 years!
“Antique” Conventional Boilers (natural draft) are still available!
(at low real efficiencies)
Newer Gas-Fired Boilers
Major Advances in Gas Burners
- High modulation
- Power Burners
The New Gas Burner World

- Power burners (forced draft)
- Low excess air (EA)
- Good modulation with EA control
- Low NOx
- Usually on boilers, not furnaces
- Provide a more assured pathway to high efficiency condensing
- Gun, metal matrix or ceramic (cylinder, cone, plate)
Recent Major Advances in Gas Boilers
Can a condensing boiler condense?

- Yes, if radiant floor
- Likely, if fan coil
- Difficult but possible if convectors or radiators and conventional hydronic, as with . . .
Dewpoints for Different Fuels

Excess Air, % vs °F

- Natural Gas
- Propane
- No. 2 Oil
Ensuring Condensing Boiler Efficiency

- Outdoor reset to lower supply temp.
- Increased heat exchange
- Preheat service water
- Condensing Boiler
- Return water below flue gas dewpoint!
Gas Water Heaters
Conventional Gas Water Heater

- Naturally aspirating
- Requires a chimney
- Continuous pilot (energy waste)
- Draft hood (extra heated air loss)
- Highly susceptible to spillage
- Large off-cycle loss
- Low seasonal efficiency (~ 55%)
- Should be an “antique”!
Power-Vented Water Heaters

- Pilot light or not
- Draft hood
- High on- and off-cycle losses
- High resistance to depressurization
- Minimal efficiency improvement
Condensing Tank Water Heater

> 90% efficient, as mains water provides driving force for condensing
Tankless Water Heaters

Wide range of technologies and efficiencies

Examining performance in lab and field (along with hot water use trial) to optimize performance and develop appropriate seasonal efficiency test procedure including cold ambients and short cycling
Hot Water Use per Family

A = Adult
C = Child

Average Daily Volume Draw (Litres)

Test Site #
Daily Fraction Hot Water Use vs Duration

Fraction of Daily Volume Drawn vs Duration of Draw (s)

- 30%
- 18%
- 7%
- 33%
- 12%
Natural Gas vs Propane

- Natural gas has a higher hydrogen content, so produces more water vapour.
- Higher dewpoint with natural gas, so easier to condense than propane.
- Propane condensing furnaces less efficient than NG.
- Propane mid-efficiency furnaces or boilers more efficient than natural gas.
- Propane boilers even more difficult to condense than natural gas.
Combined Space-Water Heating Systems
CCHT

Performance of Combo Systems in “almost” real-life conditions
Efficiency of Tank-Based Combo’s vs Outdoor Temperature
Efficiency with Tankless Combo

Figure 9: Combo1, Combo2, Combo3 and Combo4 efficiencies vs. outdoor temperature
Inefficient “Instantaneous” Segregated, Non-Condensing Boiler with Modulation

Flue Gas Analysis

SU02, Mixed

Graph showing temperature and concentration over time.
Efficient Low Mass Condensing Boilers with Segregated Tap water
Warm Air Systems

- Proper duct design
- Ducts inside house envelope
- Ducts well-sealed (mastic)
- Adequate returns (ALL bedrooms)
- Insulate basement duct runs
- Facilitates condensing op (gas only)
- Rapid thermal response (setback)
- Allows whole-house ventilation
- Consider small dia, hi-vel ducts
Hydronic Systems

- High mass, less temperature fluctuations
- Many find greater comfort
- Not subject to “heat” leakage
- Pipes should be insulated
- Less suitable for setback savings
- Difficult to have condensing (gas)
- Can be adjusted for outside temperature (outdoor reset) for some boilers
- Require additional means for ventilation
Summary

• With oil, high static burners in efficient boiler systems, and the option of heating service water externally with excess heat, offers high potential for efficiency and customer satisfaction.

• With warm air gas, central condensing furnaces or boilers + fan coils, both with EE motors, are attractive.

• Advanced, modulating burners are making condensing gas boilers very attractive, if care is taken to ensure the total system allows condensation.
Review of Objectives

• Discuss new space & water heating technologies for oil, gas and wood
• Understand what makes heating systems efficient
• Appreciate advantages & disadvantages of various new “high efficiency” systems
• Be better able to assess suitability of newer technologies for comfort and high efficiency operation in new or existing housing
Heating Publications

http://energy-publications.nrcan.gc.ca/index_e.cfm

under Consumers:
Heating, Cooling & Ventilation
Kansas City, MO

2009

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