Design Approach and Performance Analysis of a Small Integrated Heat Pump (IHP) for Net Zero Energy Homes (ZEH)

K. Rice, R. Murphy, V. Baxter

Building Technologies Integration Program
Oak Ridge National Laboratory

International Refrigeration & AC Conference
Purdue University
July 14, 2008
Net Zero Energy Home (ZEH) Definition:

A home with greatly reduced energy use (60% to 70% less) through envelope and equipment efficiency improvements, with the balance of energy needs supplied by renewable technologies.

HVAC & Water Heating Program Supporting Goal:

Develop equipment that can reduce HVAC/WH energy use by 50% (from DOE Building America benchmark) in net ZEHs while providing indoor humidity control with no increase (or preferably a decrease) in net monthly costs for mortgage and utilities.

Scoping studies at ORNL identified integrated heat pump (IHP) as highest ranking concept.
Focus of this presentation

- Review design concept and analysis approach
- Compare components and performance of AS-IHP to previous U.S. IHP design
  - In four basic operation modes
- Summarize predicted energy savings relative to current minimum efficiency baseline
  - For both air- and ground-source IHP configurations
  - In five U.S. climates
  - For 1800 ft² (167 m²) ZEH
AS-IHP Concept

- Full integration to space condition, heat water, dehumidify, and ventilate as needed using a single VS compressor

- Concept shown at right – multiple possible modes
  - Space H or C / w ventilation
  - Dedicated water heating or heat recovery
  - Dedicated dehumidification w or w/o WH
  - Ventilation air only w or w/o conditioning

- Lab prototype constructed and tested

Possible AS-IHP packaging approach
IHP – System Simulation/Design Approach

- Lab test data used to calibrate hardware-based variable-speed equipment model
  - DOE/ORNL Heat Pump Design Model (HPDM)
    - Including new fluted tube-in-tube model for w-to-r HX
- Calibrated HPDM used for design optimization and control assessments
  - Established target compressor and fan speed ranges for major operation modes as functions of ambient
    - initially for lab prototype system components (R-22 based)
    - later re-optimized design and speed/control relationships for VS R-410A system
  - control approach is to vary fan speeds and condenser subcooling as a function of compressor speed
  - details provided in referenced ORNL reports
AS-IHP, Target Compressor Speed Ranges

Target Compressor Speed Ratio vs Ambient
-- Space Conditioning and WH Modes --

Ambient (C)
-12.2 -1.1 10.0 21.1 32.2 43.3

Speed Ratio
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

Ambient (F)
10 30 50 70 90 110

- AS-IHP
- 79 Hz Design Cooling

- Space Heating
- Water Heating
- Space Cooling
Comparison to Previous U.S. IHP Product

- **Carrier/EPRI HYDROTECH 2000**
  - Circa 1990
  - VS reciprocating compressor and indoor blower (BPM motors)
  - 2-ton (7kW) cooling design
    - 32 to 73 rps max compressor speed
  - R-22 refrigerant
  - Dedicated water heating and partial heat recovery modes

- **Proposed IHP design**
  - VS rotary compressor and both fans (BPM motors)
    - mass-produced multi-split compressor (28 to 118 rps max speed)
  - Smaller 1.25-ton (4.4 kW) cooling design
  - R-410A refrigerant
  - Dedicated water heating and full heat recovery modes
Space Cooling, Capacity Comparisons

Cooling Capacity, HYDROTECH vs ZEH AS-IHP

Ambient (°C)

18.3 23.9 29.4 35.0 40.5 46.1

Cooling Capacity (Mbtu/h)

0.0 1.5 2.9 4.4 5.9 7.3 8.8

Ambient (°F)

65 75 85 95 105 115

Cooling Capacity (kW)

HYDROTECH, 55 Hz
HYDROTECH, 40 Hz
HYDROTECH, 32 Hz
ZEH AS-IHP, 79 Hz
ZEH AS-IHP, 45 Hz
ZEH AS-IHP, 28 Hz
Space Cooling, Capacity Comparisons

Cooling Capacity, HYDROTECH vs ZEH AS-IHP

Ambient (°F) 18.3 23.9 29.4 35.0 40.5 46.1
Cooling Capacity (Mbtu/h) 30 25 20 15 10 5

Ambient (°C) 65 75 85 95 105 115
Cooling Capacity (kW) 18.3 23.9 29.4 35.0 40.5 46.1

HYDROTECH, 55 Hz
HYDROTECH, 40 Hz
HYDROTECH, 32 Hz
ZEH AS-IHP, 79 Hz
ZEH AS-IHP, 45 Hz
ZEH AS-IHP, 28 Hz
Space Cooling, Efficiency Comparisons

Cooling Efficiency, HYDROTECH vs ZEH AS-IHP

- Ambient (°C)
  - 18.3
  - 23.9
  - 29.4
  - 35.0
  - 40.6
  - 46.1

- Cooling EER (Btu/W-h)
  - 30
  - 25
  - 20
  - 15
  - 10
  - 5

- Cooling COP
  - 8.8
  - 7.3
  - 5.9
  - 4.4
  - 2.9
  - 1.5

- Ambient (°F)
  - 65
  - 75
  - 85
  - 95
  - 105
  - 115

Legend:
- ZEH AS-IHP, 28 Hz
- ZEH AS-IHP, 45 Hz
- ZEH AS-IHP, 79 Hz
- HYDROTECH, 32 Hz
- HYDROTECH, 40 Hz
- HYDROTECH, 55 Hz
Space Cooling, Efficiency Comparisons

Cooling Efficiency, HYDROTECH vs ZEH AS-IHP

Ambient (°C)

 Cooling EER (Btu/W-h)

30 25 20 15 10 5 1.5 2.9 4.4 5.9 7.3 8.8

Ambient (°F)

5 10 15 20 25 30 35 40 45 50

Cooling COP

ZEH AS-IHP, 28 Hz
ZEH AS-IHP, 45 Hz
ZEH AS-IHP, 79 Hz
HYDROTECH, 32 Hz
HYDROTECH, 40 Hz
HYDROTECH, 55 Hz
Space Heating, Capacity Comparisons
Space Heating, Capacity Comparisons

Heating Capacity, HYDROTECH vs ZEH AS-IHP

Ambient (°C)

-17.8 -12.2 -6.7 -1.2 4.4 9.9 15.5

0 10 20 30 40 50 60

Heating Capacity (Mbtu/h)

HYDROTECH, 73 Hz
HYDROTECH, 46 Hz
HYDROTECH, 32 Hz
ZEH AS-IHP, 118 Hz
ZEH AS-IHP, 58 Hz
ZEH AS-IHP, 28 Hz

Ambient (°F)

0 10 20 30 40 50 60

0.0 1.5 2.9 4.4 5.9 7.3 8.8 10.3

Heating Capacity (kW)
Space Heating, Efficiency Comparisons

Heating Efficiency, HYDROTECH vs ZEH AS-IHP

Ambient (°C)

COP

ZEH AS-IHP, 28 Hz
ZEH AS-IHP, 58 Hz
ZEH AS-IHP, 118 Hz
HYDROTECH, 32 Hz
HYDROTECH, 46 Hz
HYDROTECH, 73 Hz
Space Heating, Efficiency Comparisons

Heating Efficiency, HYDROTECH vs ZEH AS-IHP

Ambient (°C)

COP

-17.8 -12.2 -6.7 -1.2 4.4 9.9 15.5

ZEH AS-IHP, 28 Hz
ZEH AS-IHP, 58 Hz
ZEH AS-IHP, 118 Hz
HYDROTECH, 32 Hz
HYDROTECH, 46 Hz
HYDROTECH, 73 Hz

Ambient (°F)
Dedicated Water Heating, Capacity Comparisons

Dedicated Water Heating Capacity, HYDROTECH vs ZEH AS-IHP

- Ambient (°C) vs Capacity (Mbtu/h)
- Ambient (°F) vs Capacity (kW)

108°F (42.2°C) Inlet Water Temperature

HYDROTECH, 32-70 Hz
ZEH AS-IHP, 45-90 Hz
Dedicated Water Heating, Efficiency Comparisons

Dedicated Water Heating COP, HYDROTECH vs ZEH AS-IHP

-6.7 4.4 15.6 26.7 37.8

COP

Ambient (ºC)

108ºF (42.2ºC) Inlet Water Temperature

ZEH AS-IHP, 45-90 Hz

HYDROTECH, 32-70 Hz

Ambient (ºF)
Combined SC & HR, Capacity Comparisons

Delivered Capacities for ZEH AS-IHP vs HYDROTECH
Cooling / Heat Recovery Mode

- HYDROTECH QC, 32-55 Hz
- HYDROTECH QWH, 32-55 Hz
- ZEH AS-IHP QWH, 28-79 Hz
- ZEH AS-IHP QC, 28-79 Hz

Delivered Capacity (Mbtu/h)

Ambient (ºF)

65 75 85 95 105 115

18.3 23.9 29.4 35.0 40.6 46.1

Delivered Capacity (kW)

Full HR

Partial HR

108ºF (42.2ºC) Inlet Water Temp
Combined SC & HR, Efficiency Comparisons

Combined Efficiency for ZEH AS-IHP vs HYDROTECH
Cooling / Heat Recovery Mode

Ambient (°C)

Combined EER (Btu/W-h)

Combined COP

- ZEH AS-IHP, 28-79 Hz
- HYDROTECH, 32-55 Hz

108°F (42.2°C) Inlet Water Temp
IHP – Seasonal Performance Analysis

- Calibrated HPDM linked to TRNSYS simulation engine
  - Enabled sub-hourly analysis of IHP annual performance
    - using optimized R-410A based design
    - simulated multiple modes of operation per t-stat calls
    - linked with domestic water tank for inlet water temp history

- Later used offline-HPDM-generated modal performance maps
  - With multi-parameter interpolation
  - Faster more robust approach than direct call

- Baseline system – individual systems to deliver same energy services
  - air-source heat pump + electric storage water heater + stand alone
dehumidifier + whole-house ventilation system
  - current or proposed minimum efficiency levels

- Predicted performance on following slides
## IHP – Performance Comparison in 167m² NZEH in Atlanta, GA

### Efficiency Equivalent

<table>
<thead>
<tr>
<th></th>
<th>Baseline (air/air heat pump + electric resistance water heater)</th>
<th>AS-IHP</th>
<th>GS-IHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSPF (W/W)</td>
<td>2.67</td>
<td>3.82</td>
<td>4.48</td>
</tr>
<tr>
<td>CSPF (W/W)</td>
<td>3.49</td>
<td>5.34</td>
<td>5.76</td>
</tr>
<tr>
<td>WH Energy Factor (W/W)</td>
<td>0.89</td>
<td>3.30</td>
<td>3.57</td>
</tr>
</tbody>
</table>

### % Energy Use

- **Baseline**: 
  - Heating: 100%
  - Cooling: 100%
  - WH: 100%
  - Overall: 100%

- **AS-IHP**: 
  - Heating: 70%
  - Cooling: 50%
  - WH: 30%
  - Overall: 40%

- **GS-IHP**: 
  - Heating: 80%
  - Cooling: 60%
  - WH: 20%
  - Overall: 50%

**Base system – Rated SEER/HSPF/EF – 13/7.7/0.90**
## IHP – Unit Sizing and Energy Savings Predictions for 1800 ft² (167 m²) ZEH in 5 U.S Locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Heat Pump Cooling Capacity</th>
<th>% Energy Savings Versus Baseline HP w Electric WH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tons (kW)</td>
<td>AS-IHP</td>
</tr>
<tr>
<td>Atlanta</td>
<td>1.25 (4.4)</td>
<td>53.7</td>
</tr>
<tr>
<td>Houston</td>
<td>1.25 (4.4)</td>
<td>53.7</td>
</tr>
<tr>
<td>Phoenix</td>
<td>1.5 (5.3)</td>
<td>48.4</td>
</tr>
<tr>
<td>San Francisco</td>
<td>1.0 (3.5)</td>
<td>67.2</td>
</tr>
<tr>
<td>Chicago</td>
<td>1.25 (4.4)</td>
<td>45.6</td>
</tr>
</tbody>
</table>
IHP – Conclusions

- Somewhat higher system efficiency possible with present VS technology applied to smaller capacity designs
  - relative to previous U.S. product in early 90’s
- IHP system simulations show significant energy savings compared to current baseline equipment system for ZEH application over a range of US climate types
  - AS-IHP: Meeting target savings except in hot/dry or cold climates
  - GS-IHP: Above 52% target savings in all 5 climates
- Findings suggest areas to improve some aspects of ZEH AS-IHP performance
  - cooling performance in hot/dry climates
  - combined space conditioning and water heating
    - by simultaneous use of both available condensers
      - especially in colder climates
• Questions or Comments?