Understanding the Dehumidification Performance of Air-Conditioning Equipment at Part-Load Conditions

Part 2: Test Results

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Project Scope

- Literature Review
- Lab Testing
- Field Testing
- Model Development and Validation
Laboratory Testing

- Test up to 10 direct expansion (DX) and chilled water coils in various configurations

- Experimentally determine:
  - off-cycle evaporation rates and decay profile
  - moisture-holding capacity of the cooling coil surfaces

- Compare measured cycling performance to the latent degradation model
Laboratory Testing Approach

- Each ON/OFF cyclic test completed at various air flows and entering conditions (coil ON/OFF, air flow always ON)
- Typically ON for 45 - 60 minutes, OFF for similar period
- Base tests repeated to get quasi-steady cyclic conditions

<table>
<thead>
<tr>
<th>Air Flow</th>
<th>Entering Coil Conditions (db / wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 / 67°F / 60°F dp</td>
</tr>
<tr>
<td>400 cfm / ton</td>
<td>#4 (or 3)</td>
</tr>
<tr>
<td>300 cfm / ton</td>
<td>#10</td>
</tr>
<tr>
<td>200 cfm / ton</td>
<td>#16</td>
</tr>
<tr>
<td>450 cfm / ton</td>
<td>#22</td>
</tr>
<tr>
<td>400-200 cfm / ton (ON &amp; OFF)</td>
<td>#25</td>
</tr>
<tr>
<td>Low suction</td>
<td>#1</td>
</tr>
<tr>
<td>High suction</td>
<td>#2</td>
</tr>
</tbody>
</table>
Laboratory Test Facility Instrumentation

- At total of 28 parameters are monitored at 15-second intervals and stored for analysis:
  - **Temperature**: Air and cooling coil temperatures at various locations using Type-T thermocouples at ± 1°F (0.6°C)
  - **Dew Point**: Air dew point entering and leaving the cooling coil using ± 0.36°F (0.2°C) dew point hygrometers
  - **Airflow**: Pressure drop across ASME MFC-3M-1984 orifice plate
  - **Refrigerant Pressure**: Evaporator outlet and liquid line pressures monitored using pressure transducers at 0.013% FS accuracy
  - **Condensate**: condensate measured using rain-gage tipping bucket at 0.0087 lbs/tip
  - **Electrical Consumption**: ± 0.5% watt-hour transducers
Latent Degradation Concepts

![Diagram showing Latent Capacity over Time]

- **Useful Moisture Removal**
- **Evaporation**

**Equations:**
- $t_{wet} = \frac{M_o}{Q_L}$
- $\gamma = \frac{Q_e}{Q_L}$

**Time ($t_o$) for first condensate to fall from pan**

**Moisture Removal**

$M_o \approx \text{Evaporation}$
Actual Laboratory Results

Integrated Moist (delay of 1.0 min)
Mass twet
Sens (lb & min): 1.98 17.0
Lat (lb & min): 1.97 16.9

16.3 min

79.9 F, 60.4 F dp, 51.5 % Run 4
1.5 hz, 76.6 psi, 967 cfm, 30.04 in Hg
Laboratory Testing – Balance

- Several checks of data validity:
  - Q-Psych vs. Q-Condensate
  - Steady-state trends OK?
  - Room conditions maintained over cycle?
Laboratory Testing – Off Cycle

- The off-cycle evaporation rate ($Q_e$) follows theoretical trends (except for #6, #9 & #24)
Reviewed specifications for 500 commercial and residential AC units.

- **Goal** was to determine
  - range of common coil geometries
  - Variation by equipment type

- Typical DX AC coil is 3-rows, 15 fpi
- Some variation by equipment type
- Some variation by size as well
# Measured Performance Parameters

<table>
<thead>
<tr>
<th></th>
<th>Cooling Capacity (ton / kW)</th>
<th>Fin Surface Area (ft² / m²)</th>
<th>Retained Moisture Mass (lb / kg)</th>
<th>Condensate Delay Time (min)</th>
<th>t&lt;sub&gt;wet&lt;/sub&gt; (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil 1</td>
<td>3.0 / 10.5</td>
<td>253.3 / 23.5</td>
<td>2.1 / 0.95</td>
<td>13.5</td>
<td>16.5</td>
</tr>
<tr>
<td>(Slanted slab, 3 row, 13 fpi, plain fins, orifice)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil 2 – Normal Flow</td>
<td>2.5 / 8.8</td>
<td>237.8 / 22.1</td>
<td>2.5 / 1.14</td>
<td>16.3</td>
<td>19.0</td>
</tr>
<tr>
<td>(A-coil, 3 rows, 15.5 fpi, lanced sine-wave fins, TXV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil 2 – Low Flow</td>
<td>1.5 / 5.3</td>
<td>237.8 / 22.1</td>
<td>2.5 / 1.14</td>
<td>33.3</td>
<td>35.4</td>
</tr>
<tr>
<td>(A-coil, 3 rows, 15.5 fpi, lanced sine-wave fins, TXV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil 4</td>
<td>1.8 / 6.3</td>
<td>138.3 / 12.8</td>
<td>1.9 / 0.86</td>
<td>23.5</td>
<td>18.5</td>
</tr>
<tr>
<td>(vert. slab, 2 rows, 14 fpi, wavy fins, orifice)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:  
1- Cooling capacity includes sensible and latent cooling at nominal conditions. Nominal conditions correspond to ASHRAE Test A or ISO T1 test points.
2- Surface area is gross fin area (coil face area x coil depth x fin spacing x 2).
3- Condensate delay time and t<sub>wet</sub> are at nominal conditions.
Laboratory Testing – SHR Degradation

- Simulated real operating cycles at various runtime fractions (for a given thermostat)
- Each sequence repeated 3 times to reach quasi-steady state conditions

<table>
<thead>
<tr>
<th>Run</th>
<th>CONST FAN</th>
<th>AUTO FAN</th>
<th>Number of Times Test Repeated</th>
<th>ON Time (minutes)</th>
<th>OFF Time (minutes)</th>
<th>Runtime Fraction (-)</th>
<th>Cycle Rate (cycles/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>41</td>
<td></td>
<td>2</td>
<td>45</td>
<td>45</td>
<td>0.500</td>
<td>0.667</td>
</tr>
<tr>
<td>32</td>
<td>42</td>
<td></td>
<td>3</td>
<td>30</td>
<td>6</td>
<td>0.833</td>
<td>1.667</td>
</tr>
<tr>
<td>33</td>
<td>43</td>
<td></td>
<td>3</td>
<td>16</td>
<td>7.25</td>
<td>0.688</td>
<td>2.581</td>
</tr>
<tr>
<td>34</td>
<td>44</td>
<td></td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>0.500</td>
<td>3.000</td>
</tr>
<tr>
<td>35</td>
<td>45</td>
<td></td>
<td>3</td>
<td>7</td>
<td>17.5</td>
<td>0.286</td>
<td>2.449</td>
</tr>
<tr>
<td>46</td>
<td>3</td>
<td></td>
<td>3</td>
<td>5.5</td>
<td>55</td>
<td>0.091</td>
<td>0.992</td>
</tr>
</tbody>
</table>
Laboratory Testing – SHR Degradation (cont.)

Model matches measured data at nominal entering conditions
(80F db, 60.4F dp)
Laboratory Testing – SHR Degradation (cont.)

Model also matched measured data at other entering conditions!
(75F db, 64F dp)
Model also matched measured data at reduced air flow rate (300 cfm / ton)

Laboratory Testing – SHR Degradation (cont.)

Steady State SHR = 0.705 (based on condensate)
Laboratory Testing – SHR Degradation (cont.)

Coil 2 showed little impact

Steady State SHR = 0.751 (based on condensate)

AUTO Fan Mode
Coil 1 showed more impact!
Coil 4 showed even more impact. Rerunning this test to confirm.
Field Testing

- Seven field test sites were recruited:
  - **Residential (5 units at 4 sites)**
    - 5-ton single-speed residential DX system in Connecticut
    - Two single-speed DX units (2.5-ton and 3-ton) at a Virginia residence
    - 3.5-ton residential DX system in Florida (single-speed condensing unit with variable speed air handler)
    - 3-ton residential DX system in Florida (two-speed condensing unit with variable speed air handler)
  - **Commercial (3 units at 3 sites)**
    - 10-ton commercial rooftop DX unit in Boston (2 stage)
    - Commercial constant-air-volume chilled water coil in Florida (3 ton)
    - Commercial variable-air-volume chilled water coil in Florida (7 ton)
Field Testing Approach

- Collect data on real world system performance
- Approx. 20 parameters measured on each system, similar to lab points
- 10-second scans, 1-minute avg or sum stored
- Daily data download and screening
Field Testing – SHR Degradation

Significant AUTO fan degradation!

Steady State SHR = 0.855

- Auto Fan Mode (08/18/02 to 09/04/02)
- Constant Fan Mode (08/18/02 to 09/04/02)
  (Model: twet=15 min, gamma=2.2, Nmax=3)
Field Testing – Condensate Delay

- Delay time is a good surrogate for $t_{\text{wet}}$
- Must find cycles where coil was dry
- 16 minutes
**Field Testing – Delay Time Trend**

- Delay time a function of entering dew point
Lab + Field: Retained Moisture

Moisture per total gross fin area
(gross area = face area x depth x fin spacing x 2)
Lab + Field: Range of Delay Times
Summary

- Project due to end Sept 2003 (extension to early 2004)
- Complete lab testing of 4 more coils
- Complete field measurements at 3 remaining sites
- More data analysis (individual tests and overall trends)
- Refine latent degradation model, extend to other configurations: AUTO fan, staged coils, CHW
- These results will be published at the upcoming ASHRAE Meeting in Edinburgh, Scotland (Sept 2003)
- Final project results will be presented at future ASHRAE conferences
- Future work would be to gather more laboratory data on different coil configurations, and work with manufacturers to devise and evaluate solutions
Questions?