Generalized heuristic control for direct expansion (DX) cooling systems with capacity modulation and variable air flow

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Outline

• Introduction
• Component models
• Fan-duct systems
• Optimal operations
• Control heuristics
• Energy saving assessment with simulation
Motivation:
- Direct expansion (DX) air conditioning systems are widely used in small- to medium-sized commercial buildings
- More DX units are equipped with variable speed drives (VSD) since VSD becomes more affordable
- Need an implementable and model-free control strategy

Approach:
- DX units with different types of compressors are modeled from catalog data
- Different fan-duct system characteristics are considered
- Optimization is performed to the integrated system model
- Obtain a generalized control heuristics from the optimal results
## DX models

### Component-model descriptions:

<table>
<thead>
<tr>
<th>Compressor</th>
<th>Input-output forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Empirical catalog model</td>
<td>$[P_{comp}, m_r] = \text{Compressor}(T_{evap}, T_{cond}, \text{Stage})$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Condenser &amp; evaporator</th>
<th>Input-output forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Effectiveness-NTU method</td>
<td>$[q_{tot}, q_{sen}] = \text{Evap}(T_{evap}, V, T_{air,db, evap}, T_{air,wb, evap})$</td>
</tr>
<tr>
<td>• Correlate heat transfer coefficients to air and refrigerant mass flow rates</td>
<td>$q_{cond} = \text{Cond}(T_{cond}, T_{amb}, m_r)$</td>
</tr>
</tbody>
</table>

$X$: external inputs (boundary condition).

$X$: internal variables that need to be solved iteratively

### Model integration:

Solve

$$
\begin{align*}
q_{tot} + 0.95 \times P_{comp} &= q_{cond} \\
T_{sc} &= 15 \text{ F}
\end{align*}
$$

for

$$
\begin{bmatrix}
T_{evap} \\
T_{cond}
\end{bmatrix}
$$

### Input-output form:

$$
[P_{comp}, q_{tot}, SHR, T_{sup}] = DX(T_{air,db, evap}, T_{air,wb, evap}, T_{amb}, V, \text{Stage})
$$
Integrated model

V=5000cfm; Tdb=26C; Twb=20C; Tamb=32C

Cap kW

Power kW

SHR

COP

Tevap C

Tcond C
Integrated model
Duct system characteristics

\[ ESP = \Delta P_{fan,\text{downstream}} + \Delta P_{fan,\text{upstream}} \]

\[ \Delta P_{fan,\text{downstream}} = P_{sup} - P_{zone} = A \cdot V^2 \]

\[ \Delta P_{fan,\text{upstream}} = P_{zone} - P_{fan,\text{inlet}} = B \cdot V^2 \]

**Constant static pressure**

\[ ESP = \Delta P_{fan,\text{downstream}} + \Delta P_{fan,\text{upstream}} = D + B \cdot V^2 \]

**Resetting static pressure**

\[ ESP = \Delta P_{fan,\text{downstream}} + \Delta P_{fan,\text{upstream}} = (A + B) \cdot V^2 = C \cdot V^2 \]
Fan-duct systems

Constant static pressure

Resetting static pressure
Fans

Three types of fans are considered:

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter (in)</th>
<th>Maximum SP (inwc)</th>
<th>Maximum HP (bhp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC (forward curved)</td>
<td>25</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>AF (airfoil)</td>
<td>22</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>Q (vaneaxial)</td>
<td>36.5</td>
<td>5</td>
<td>30</td>
</tr>
</tbody>
</table>
Problem formulation:

\[
T_{\text{sup, opti}} = \arg \min_{T_{\text{sup}}} P_{DX} \left( \frac{T_{\text{air,db, evap}}, T_{\text{air,wb, evap}}, T_{\text{amb}}, V, T_{\text{sup}}}{} \right) + P_{\text{fan}}(V)
\]

\[
\begin{align*}
q_{\text{sen}} &= q_{\text{sen}, \text{req}} \\
\text{SHR} &< \text{SHR}_{\text{max}} \\
V_{\text{min}} &< \dot{V} < V_{\text{max}} \\
\text{Stage} &\in [0, 1] \\
T_{\text{min}} &< T_{\text{sup}} < T_{\text{max}}
\end{align*}
\]

- \text{SHR}_{\text{max}} -- dehumidification lower limit
- Overbar variable -- boundary condition or requirements
Visualization of optimization results

- RH=62; Tamb=25; Tdb=23; Qsen=45
- RH=62; Tamb=35; Tdb=23; Qsen=45
- RH=36; Tamb=35; Tdb=23; Qsen=45
- RH=40; Tamb=30; Tdb=26; Qsen=75

Tsup C

Ptot kW

SHR
Control heuristics:

Increase the supply air temperature setpoint until the SHR upper bound is reached

Get $T_{\text{zone}}$, $RH_{\text{zone}}$ and $SHR_{\text{DX}}$

Initial $T_{\text{sup}}=14.2^\circ\text{C}$

$RH>60\%$ for any zone

$T>T_{\text{setpoint}}$ for any zone

$SHR=1$

$T_{\text{sup}}=T_{\text{sup}}-0.25^\circ\text{C}$

$T_{\text{sup}}=T_{\text{sup}}-0.25^\circ\text{C}$

$T_{\text{sup}}=T_{\text{sup}}-0.25^\circ\text{C}$

$T_{\text{sup}}=T_{\text{sup}}+0.25^\circ\text{C}$
Compare heuristic & optimal control

1. **Graph 1:**
   - **Tdb=23C; RH=62; Tamb=25C; Qsen=75kW**
   - X labels:
     - 1st character indicates compressor type: D-digital scroll; V-variable speed
     - 2nd character indicates pressure control: R-resetting; C-constant
     - 3rd character indicates fan model series
   - Energy saving %

2. **Graph 2:**
   - **RH=62; Tamb=25; Tdb=23; Qsen=45**
   - Energy saving %

3. **Graph 3:**
   - **RH=36; Tamb=35; Tdb=23; Qsen=45**
   - Energy saving %

4. **Graph 4:**
   - **Tdb=23C; RH=36; Tamb=35C; Qsen=75kW**
   - X labels:
     - 1st character indicates compressor type: D-digital scroll; V-variable speed
     - 2nd character indicates pressure control: R-resetting; C-constant
     - 3rd character indicates fan model series
Compare heuristic & optimal control

T_{db}=23^\circ\text{C}; \ RH=62; \ T_{amb}=35^\circ\text{C}; \ Q_{sen}=75\text{kW}

| X labels: |
| 1st character indicates compressor type: |
| D-digital scroll; V-variable speed |
| 2nd character indicates pressure control: |
| R-resetting; C-constant |
| 3rd character indicates fan model series |

T_{db}=26^\circ\text{C}; \ RH=40; \ T_{amb}=30^\circ\text{C}; \ Q_{sen}=75\text{kW}

R_{H}=62; \ T_{amb}=35; \ T_{db}=23; \ Q_{sen}=45

R_{H}=40; \ T_{amb}=30; \ T_{db}=26; \ Q_{sen}=75

Energy saving %

Energy saving %
Energy saving assessment-- simulation

Simulation model description:
- 9 zone building with total area of 20,000 sq. ft.
- Data driven envelope model
- Night setup strategy and assume perfect setpoint tracking
- Simulate for a 100-day cooling season with TMY2 data
Climate zones for simulation

- Four cities are chosen to represent different climates
- DX unit is scaled according to the peak load
Simulation results

Location: PHL

- SHR
- T\textsubscript{lg} C
- Plot kW
- Mean RH

Location: Phoenix

- SHR
- T\textsubscript{lg} C
- Plot kW
- Mean RH
Simulation results:

<table>
<thead>
<tr>
<th></th>
<th>Qsen on DX coil (MWh)</th>
<th>Qlatent on DX coil (MWh)</th>
<th>Energy consumption (MWh)</th>
<th>Mean zone RH %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philadelphia</td>
<td>130.1</td>
<td>130.4</td>
<td>15</td>
<td>17.5</td>
</tr>
<tr>
<td>Miami</td>
<td>143</td>
<td>142.6</td>
<td>31.1</td>
<td>31.4</td>
</tr>
<tr>
<td>Phoenix</td>
<td>173.1</td>
<td>172.7</td>
<td>7.75</td>
<td>11.9</td>
</tr>
<tr>
<td>Madison</td>
<td>120.5</td>
<td>122.1</td>
<td>8.3</td>
<td>10.5</td>
</tr>
</tbody>
</table>

* Comfort improves in addition to energy savings (not listed in the table)
Conclusion

• Variable speed compressor provides better part-load performance than digital scroll compressor in a DX unit

• For both types of compressor, peak efficiency occurs when the coil condition changes from wet to dry

• *Control heuristics*: increase $T_{sup}$ until a SHR upper bound is reached

• The proposed heuristics provide near-optimal control at any operating condition

• Heuristics leads to more energy savings for systems equipped with variable speed compressor and under constant pressure control

• Significant energy savings can be achieved for a whole cooling season, but is highly dependent on the climate
Thank you!

Q&A