High-performance Chilled-water Systems

Susanna Hanson, CEM DGCP
Chilled-water system
Chilled-water system components
Connectivity
Diagnostics
Minimally-compliant Chiller Plant

<table>
<thead>
<tr>
<th>Conventional assumption for code range</th>
<th>0.75-0.90 kW/ton (annual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.1-2010     Chillers + towers + CW pumps</td>
<td>.68-.88</td>
</tr>
<tr>
<td>90.1-2013     Chillers + towers + CW pumps</td>
<td>.66-.86</td>
</tr>
</tbody>
</table>

It’s easy to operate in what would have been deemed “excellent,” just by meeting code.
Model ≠ Reality

• Assumption that flow perfectly varies with load
  • Coil performance assumptions
  • Hydronic dynamics ignored
  • Low delta T “syndrome”
  • Effect of instability on coil performance
  • If flow is unpredictable, so is pump energy
• Effects of above on equipment (pump and chiller) staging
  • Running more chillers (and pumps, and towers) than necessary
  • Chiller capacity assumed to follow load
    • Advanced models use a function of load and condensing pressure
    • None reduce chiller capacity based on low distribution delta T
• Simplified chilled water reset effects on chiller energy
  • No coil performance adjustments
Coil Performance, Traditional Energy Models

• Idealized generic coil curves
  • Models don’t let waterside affect airside, vice versa
• Same method we used forever
• New EnergyPlus based engines have some new capability
Coil Performance, New Models

- Air and waterside connected better
- Still doesn’t model instability and overcooling
- Still doesn’t model effects of occupant behavior
Responses to Discomfort and Their Effects

• **Occupant:**
  - lower zone setpoint – increases GPM, may increase fan speed
  - supplement airflow – fans appear under desks
  - complain

• **Operator:**
  - lower leaving air setpoint – decreases coil performance
  - pumps in manual, raise setpoint/speed – increases GPM, pressure
  - disable SA reset – lowers leaving air temp and increases reheat
  - reduce ventilation – lowers coil entering air temp, degrades coil perf

• All reduce system performance
  - Low delta T and poorer coil performance
  - Increase overcooling/reheat
  - “Out of flow-- out of chiller-- need another chiller…”
  - “Maybe I just need the system balancer back out here”
  - “We must need tertiary pumps”
The Engineers’ Dilemma

• Conservatism and unknowns
• Low pressure drop waterside
• Low pressure drop airside
• Fit in the box!
• Fit it in the budget!
• And we don’t have money for reverse return piping
• Or pressure independent control valves
• But OK spend money for balancing valves and balancers!
# Industry Recommendations

<table>
<thead>
<tr>
<th>Source</th>
<th>Chilled Water $\Delta T$ (ºF)</th>
<th>Condenser Water $\Delta T$ (ºF)</th>
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</thead>
<tbody>
<tr>
<td>ASHRAE 90.1-2016 requirement</td>
<td>$\geq 15$</td>
<td>NA</td>
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<tr>
<td>ASHRAE GreenGuide</td>
<td>12 - 20</td>
<td>12 - 18</td>
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<tr>
<td>Kelly and Chan</td>
<td>18</td>
<td>14</td>
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<tr>
<td>Taylor</td>
<td>$&gt;12$</td>
<td>15</td>
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</table>
Chilled Water Optimizations – ASHRAE 90.1

- Coil selection for 15°F $\Delta T$ or higher (57°F min return)
- Chilled water reset based on critical valve position
  - or -
- Pump pressure reset based on critical valve position
APD versus WPD versus Size
Configuration Options

- Coil face area
- Number of rows of tubes
- Tube diameter
- Number of fins
- Fin surface design
- Coil circuiting
- Turbulators
Construction Options

- Tube material
- Tube wall thickness
- Fin material
- Fin thickness
- Casing material
- Header type and material
- Coil coatings
Coil circuiting

- single-row serpentine
- dual-row serpentine
- partial-row serpentine
Water Velocity-Related Concerns

**Water velocity too low:**
- Tube fouling
- Air trapped in the coil
- Poor water distribution
- Risk of freezing

**Water velocity too high:**
- Tube erosion
- High water pressure drop
- Noise
Guidelines for Water Velocity

AHRI Standard 410
Forced-Circulation Air-Cooling and Air-Heating Coils
Laminar Flow ≠ Severe Capacity Drop-off

![Graph showing the relationship between Reynolds Number, water flow rate, and coil capacity. The graph compares pre-2001 AHRI prediction model (McAdams) and AHRI 410-2001 prediction model (Colburn-j heat transfer factor). The diagram highlights the distinction between laminar and transitional flow regimes.](image-url)
Supply-Water Temp and $\Delta T$

$Q_{\text{total}} = 329 \text{ MBh}$

8500 cfm

80°F DBT, 67°F WBT

55°F DBT, 54°F, 44°F

water $\Delta T$

supply-water temperature
<table>
<thead>
<tr>
<th></th>
<th>Value 1</th>
<th>Value 2</th>
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<tbody>
<tr>
<td>coil face area, ft(^2)</td>
<td>17</td>
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<tr>
<td>coil rows</td>
<td>6</td>
<td>6</td>
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<tr>
<td>coil fins, fins/ft</td>
<td>95</td>
<td>127</td>
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<tr>
<td>supply water temperature, °F</td>
<td>44</td>
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<tr>
<td>return water temperature, °F</td>
<td>54</td>
<td>57</td>
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<tr>
<td>water ∆T, °F</td>
<td>10</td>
<td>13</td>
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<tr>
<td>water flow rate, gpm</td>
<td>65.6</td>
<td>50.4</td>
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<tr>
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[Image of a cooling coil with specifications: 80°F DBT, 67°F WBT, 329 MBh, 8500 cfm, 80°F DBT, 67°F WBT]
Low-Flow Chiller Plants

![Graph showing chiller and pump kW at different temperature differences (ΔT).]
Low Delta-T (High Flow) Syndrome

• Symptom of poor heat transfer at the coil and impacts:
  • Energy
    • Excessive pump energy
    • Excessive fan energy
    • Excessive chiller energy
  • Comfort
    • Degrades dehumidification and temperature control
  • Capacity
    • Running out of chilled water distribution capacity
Why is Low Delta T Bad?

- Tough to model = tough business case
- Chillers get blamed
- Fouling gets blamed
- Filters get blamed
- System balancer gets blamed
- Engineer gets blamed
- Customers and occupants unhappy
Wasted Energy Transporting Tons

- \( Tons = \frac{(\Delta T \times GPM)}{24} \)

Solving for gpm...

- \( GPM = \frac{(Tons \times 24)}{\Delta T} \)

Pumping power...

- Frictional Head; Flow\(^2\)

- Water HP (bhp) = \( \frac{(GPM \times \text{head (ft)})}{3960} \)

- Water HP; Flow\(^3\); Delta T\(^3\)
Yes BUT, Coil Delta T is lower at Part Load
Is it physics or is it something else?

- AHRI Certified Coil
- Air Flow (VAV) unloading
- Entering air conditions matter
  $f(OA\%, \ OA\ temp)$
Reason 1: 3-Way control valves
undesirable mixing in variable flow systems

- Eliminate them!

Coil Delta T = 17°F
System Delta T = 8.5°F

50% Coil Load

CHWR = [(42° x 50) + (59° x 50)] / 100 = 50.5°
Reason 2: Supply air setpoint depression
overdriving coil capacity

1. 3-way control valves
2. Control setpoint depression
   • Avoid, limit and restore

- 55° LAT = 16° DT = 1.5 gpm/ton 😊
- 52° LAT = 11° DT = 2.2 gpm/ton 😞
- 50° LAT = 8.5°DT = 2.8 gpm/ton 😞
Effect of responses to discomfort

How does this happen?
Operator lowers leaving air setpoint
Operator disables supply air reset

+ 32% Total, +257% Latent

[Bar chart showing total cooling in tons for different leaving air temperatures, with annotations for Latent and Sensible cooling.]
Reason 3: Warmer chilled water supply
reduced heat transfer driving force “LMTD”

1. 3-way control valves
2. LAT setpoint depression
3. Warmer chilled water
   • *Chilled water reset only at part load*

- 42° CHWS = 16° DT = 1.5 gpm/ton 😞
- 47° CHWS = 7.5° DT = 3.2 gpm/ton 😞
- 50° CHWS = 5°DT = 4.8 gpm/ton 😞
Excessive CHW reset

- Warm supply water temperature causes Low $\Delta T$, High Flow
- Entering air temp is reduced at part load

### 8000 cfm Cooling Coil

<table>
<thead>
<tr>
<th>Total Capacity (MBh)</th>
<th>Coil Entering Water (°C)</th>
<th>Coil Leaving Water (°C)</th>
<th>Delta T (°C)</th>
<th>Flow (gpm)</th>
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</thead>
<tbody>
<tr>
<td>315</td>
<td>4.4</td>
<td>13.3</td>
<td>8.9</td>
<td>39.36</td>
</tr>
<tr>
<td>315</td>
<td>6.7</td>
<td>12.2</td>
<td>5.6</td>
<td>62.53</td>
</tr>
</tbody>
</table>

CHW reset OK in high DT designs and at chiller min flow in VPF system
Reason 4: Deficient control valves
poor flow control at full and part loads

1. 3-way control valves
2. LAT setpoint depression
3. Warmer chilled water
4. Deficient control valves

Control Valve Issues
1. Improperly Selected / Oversized
2. Worn-out
3. Unstable control
4. $29.95 (cheap)
5. 3-way valves
Reason 4: Deficient control valves
poor flow control

1. 3-way control valves
2. LAT setpoint depression
3. Warmer chilled water
4. Deficient control valves
   • Specify quality valves specific to use

8th floor control point
20 ft pd

2nd floor pressure
90 ft pd
Reason 4: Deficient control valves

poor flow control

1. 3-way control valves
2. LAT setpoint depression
3. Warmer chilled water
4. Deficient control valves

Pressure independent valves? (PICV)

- Not always required
- Reverse return piping can help
- Can be beneficial

1. Mechanical
2. Electronic
Pressure Independent Control Valves

- Mechanical PI valve
- Electronic PI valve

Modulating control valve
Pressure regulating valve

FLOW

CONTROL SHAFT ROTATES TO MODULATE FLOW
SPRINGS
PISTON
SEAL
CONTROL SURFACES

1/2” - 2”
1.65-100 GPM

2 1/2” - 6”
80-713 GPM
Mechanical PI Valves

Advantages:
• More compact
• Will accept any rotary actuator
• Easier to select
• No additional power, programming, or sensor installation
• Now available with data sharing
Electronic PI Valves

Advantages:
• Potential for lower hardware costs
• Provides load measurement
• Programmable for various operation methods:
  • Flow limiting
  • ΔT limiting
  • Energy limiting
• BACnet™ Communication to BAS system for data sharing.
  (requires licensing and commissioning another BACnet device)
PI Valves—Summary

• Advantages:
  • More stable and accurate
    • Increased delta T
  • Easier to select
  • Easier to install
  • May be cost neutral
Reason 5: Tertiary pumping
undesirable mixing is hard to prevent

1. 3-way control valves
2. LAT setpoint depression
3. Warmer chilled water
4. Deficient control valves
5. Tertiary pumping / bridge tender circuits
   - Don’t mix to the return - simply pressure boost
Why is Low Delta T Bad for the chiller plant?

**Normal Operation** (16° ΔT)

- 1000 gpm / 42 F
- 1000 gpm / 54.8 F
- 200 gpm / 42 F
- 300 gpm / 42 F
- 500 gpm / 42 F

Load Coils:
- 200 tons / 58 F
- 333 tons / 58 F

80% Load Coil Load
Why is Low Delta T Bad for the chiller plant?

Harmless? LDT (12.8° ΔT)

Pump Energy
+25% to +80%

80% Load Coil Load
Why is Low Delta T Bad for the chiller plant?

Moderately Low Delta-T (10° ∆T)

- 1000 gpm / 42 F
- 100 gpm / 53 F
- 200 tons / 53 F
- 333 tons / 53 F
- 480 gpm / 43 F
- 800 gpm / 43 F

- 0% CHWR
- 64% Pump Energy
- 80% Load Coil Load

The vortex of death
Why is Low Delta T Bad for the chiller plant?

Severe Low Delta-T (6.4° ∆T)

Chiller Energy

Pump Energy

80% Load Coil Load
Why is Low Delta-T Bad?

Energy
• Excessive pump energy
• Increased chiller plant energy
  • More pumping energy
  • Chillers running at inefficient load points.

Capacity
• Running out of distribution capacity
• Chiller won’t load

Leads to overrides/manual operation
Case Study

- Demonstrated some AHU control problems
- Two floors:
  - 3rd floor AHU kept existing conventional valves
  - 4th floor AHU retrofitted with PI valves
Case Study

Temp/pressure/valve test w 4th floor 26300-30000

3rd floor (conventional)
4th floor (PI valve)

3rd floor CHW Delta T
4th floor CHW Delta T
Some Causes of Low Delta T

Flow Control
• Three-way valves
• Cheap control valves
• Uncontrolled loads
• Excessive pump pressure
• Building “bridge circuits”

Load
• Undersized coils
• Improper AHU setpoints

Maintenance
• Dirty filters or coils
• Coils piped backwards

Control
• Low AHU set points
• Unstable valve control
• Control calibration
• Improper CHW reset
• Diluted CHW supply temp
Low Delta-T Syndrome

What is the number one thing you can do to improve the performance of a chiller plant?

FIX THE AIR SIDE!
Low Delta-T Syndrome

Some Band-Aids...

- Lower the chiller’s setpoint
- Open the chiller balancing valves to allow more “constant” flow to the chillers
- Convert to Variable Primary / Variable Secondary
- Convert to Variable Primary Flow

But the best thing to do is: FIX THE AIR SIDE!
Avoiding Low Delta-T is a Discipline

• AHU maintenance
• AHU setpoint vigilance
• Pumping pressure vigilance
• Coil selection requirement compliance
• Coil control valve specification compliance
  • “Pressure independent” valves help
• AHU control commissioning
All Systems Have Issues

• All systems require attention to maintain peak performance
• All systems have deficiencies in their energy models
• Most energy can be saved in operation
• Better design choices make it easier to do so
• Get more data and turn it into intelligence
Questions...