ASHRAE GreenGuide
Design, Construction, and Operation of Sustainable Buildings

(Tips for High performance Chiller Plant)

ASHRAE Talk
MCE ASIA, Marina Bay Sands Convention
09 Sept 2016

K Y Yow
Dir, Technical Center of Excellence
Trane, Ingersoll Rand
Agenda

- ASHRAE GreenGuide Introduction
- Recommendation of CHW/CW Large DT
- Pumping Efficiency Index (Kw/Rt)
- Understanding Cooling Tower
- Chiller Plant Performance Goal
- Summary of Key Recommendations
- Live DEMO of Local Site
- Q+A
ASHRAE GreenGuide

Available on Ashrae Bookstore
# Energy Distribution Systems

## Chapter Ten: Energy Distribution Systems

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- Hydronics: 243
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Chilled-Water Pumps. Historically, a design chilled-water temperature differential ($\Delta T$) across air-handling unit cooling coils of 10°F (5.5°C) was used, which resulted in a flow rate of 2.4 gpm/ton (2.6 L/min per kW). In recent years, the 60% increase in required minimum chiller efficiency from a 3.8 coefficient of performance (ASHRAE Standard 90-75, *Energy Conservation in New Building Design* [ASHRAE 1975]) to a 6.1 coefficient of performance (ANSI/ASHRAE/IES Standard 90.1-2013 *Energy Standard for Buildings Except Low-Rise Residential Buildings* [ASHRAE 2013]) has led to a reexamination of the assumptions used in designing hydronic media flow paths and in selecting movers (pumps) with an eye to reducing energy consumption.

The CoolTools team came to the following conclusion:

...the trend for most applications is that higher chilled-water delta-Ts result in lower energy costs, and they will always result in the same or lower first costs. (Taylor et al. 1999)

*Water Plant Design and Performance Specification Guide* (Taylor et al. 1999) recommends starting with a chilled-water temperature difference of 12°F to 20°F ($\pm 7$°C to 11°C). It is important to understand that for the chiller plant to use a higher chilled-
About CoolTools™

PG&E’s “CoolTools™” Project: A Toolkit to Improve Evaluation and Operation of Chilled Water Plants

281 Page Design Guide by CoolTools
Condenser Water Pumps. In the same manner, design for condenser water flow has traditionally been based on a 10°F (5.6°C) ΔT, which equates to 3 gpm/ton (3.2 L/min/kW). Today’s chillers will give approximately a 9.4°F (5.2°C) ΔT with that flow rate. The CoolTools guide states, “Higher delta-Ts will reduce first cost (because pipes, pumps, and cooling towers are smaller), but the net energy-cost impact may be higher or lower depending on the specific design of the chillers and tower.”

The CoolTools team, in their summary, state:

In conclusion, there are times you can “have your cake and eat it too.” In most cases larger DT’s and the associated lower flow rates will not only save installation cost but will usually save energy over the course of the year. This is especially true if a portion of the first cost savings is reinvested in more efficient chillers. With the same cost chillers, at worst, the annual operating cost with the lower flows will be about equal to “standard” flows but still at a lower first cost (Taylor et al. 1999).

They further recommend a design method that starts with a condenser water temperature difference of 12°F to 18°F (7°C to 10°C).
To reduce pressure drop, pipes and ductwork should be laid out prior to locating pumps, chillers, and air handlers.
Pipe Sizing - Energy vs Cost Balance

Sizing Considerations. The previous section, “Media Movers,” stated that reducing flow rates may reduce both installed cost (by reducing duct, pipe, fan, and pump sizes) and operating cost (by reducing pump and fan energy use). Decreased duct and pipe sizes also lead to less insulation. However, if the incremental installed cost savings would be relatively small, the design professional may want to leave pipe and duct sizes larger to minimize energy cost. The best designs begin with generalized ranges (as were stated above for chilled and condenser water) that are fine-tuned for the specific application. This fine-tuning may be done with commonly available analysis and design software.

16.2.8 The effect of changes in pipe diameter on the friction in a system

\[
\left( \frac{D_1}{D_2} \right)^5 = \frac{Hf_2}{Hf_1}
\]

where

- \( D \) = Pipe Diameter
- \( Hf \) = Friction Loss
Pumping Efficiency: Water is Heavy: 1 M3 of Water weighs 1 TON
1 M3/S Flow = 6,600 RT (DT at 5.6 C)

Lower flow rates could allow smaller pipe sizes, and pipe size, along with flow, affects pumping energy. A goal should be established for the pump power to be selected. A small increase in some or all of the pipe distribution sizes could reduce the pump energy (horsepower or kilowatts) needed for the system. When this goal is established and attained in the finished design, the concept and energy usage will be achieved. A reasonable goal can be expressed using the water transport factor equation adjusted to reflect kilowatts (multiply horsepower by 0.746). Measurements of efficient designs indicate a performance of 0.026 kW/ton (0.007 kW/kWR [with kWR being refrigeration cooling capacity]) being served as a reasonable goal for 10°F (5.6 K) ΔT systems. Adjusting the flow rate and ΔP variables in this formula will quickly show the benefits of larger pipes or lower flow rates (greater ΔT).

Benchmark: 0.026 Kw/Rt

pump kW = \( \frac{(Q)(\Delta P)(sg)(9.81)}{(1000)(\eta_P)(\eta_M)} \)

where
- \( Q \) = flow rate, gpm (L/s)
- \( \Delta P \) = pump head, ft (m)
- \( sg \) = specific gravity (—)
- \( \eta_P \) = pump efficiency
- \( \eta_M \) = electric motor efficiency
Applying SS 553 Pumping System Design Criteria

SS 553 : 2009

10.5 Pumping system design criteria

10.5.1 Hydronic System Design and Control

Air-conditioning hydronic systems having a total pump system power exceeding 7.5 kW shall comply with 10.5.1.1, 10.5.1.2, 10.5.1.3 and 10.5.1.4.

10.5.1.1 Hydronic Variable Flow Systems

The pump power limitation for chilled water systems shall be 349 kW/m³/s. The pump power limitation for condensing water systems is 301 kW/m³/s.

Motors exceeding 15 kW shall have controls and/or devices (such as variable speed control) that will result in pump motor demand of no more than 30% of design wattage at 50% of design water flow.

CHW pump : Max 349 Kw per M3/S

CW pump : Max 301 Kw per M3/S

0.053 Kw/RT (DT 5.6C)
Chilled Water Pump:
Kw/Rt is function of (Flow per RT) and Head

Max 349 Kw per M3/S => approx Max 25 m Hd
Investing in Pumping Efficiency has Attractive ROI

Applying large DT and Oversize Pipe to Reduce Hd from 33m to 10m

This shows us we can reduce pumping energy by 71% by lowering the TDH from 100 to 30 ft (300 to 90 kPa) and selecting a more efficient pump. One author of this guide has personally measured systems with the characteristics indicated above. If the average cost of electricity per kWh is $0.08, and we are pumping for a 1000 ton (3517 kWR) chiller, the annual operating cost difference would be more than $37,000/yr.

If the system lasts 20 years, the improved system would save $740,000 in operating costs.
Condenser water Pump:
Kw/Rt is function of (Flow per RT) and Head

Conventional 5C DT to Large 8C DT

<table>
<thead>
<tr>
<th>Delta T</th>
<th>Flow/Rt</th>
<th>Cap/Flow</th>
<th>Pump Kw/Rt at different Heads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gpm/Rt</td>
<td>Lps/Rt</td>
<td>m3/s per Rt</td>
</tr>
<tr>
<td>Deg C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.34</td>
<td>0.210</td>
<td>0.000210</td>
</tr>
<tr>
<td>5.56</td>
<td>3.00</td>
<td>0.189</td>
<td>0.000189</td>
</tr>
<tr>
<td>6</td>
<td>2.78</td>
<td>0.175</td>
<td>0.000175</td>
</tr>
<tr>
<td>7</td>
<td>2.38</td>
<td>0.150</td>
<td>0.000150</td>
</tr>
<tr>
<td>8</td>
<td>2.09</td>
<td>0.131</td>
<td>0.000131</td>
</tr>
</tbody>
</table>

3.3 gpm/Rt => Head (20m) = System (17m) + Static Ht of Tower (3m)
2.1 gpm/Rt => Head (9.6m) = System (6.6m) + Static Ht of Tower (3m)

1/3 Flow Reduction => 2/3 Reduction in Kw/Rt

Using same pipe size, Kw/Rt drops from 0.058 to 0.018
Additionally CT performance improves with larger RANGE (DT)
**Assessment of LOW FLOW (CW) MUST include chiller PARTLOAD Operation**

<table>
<thead>
<tr>
<th>Delta T</th>
<th>Flow/Rt</th>
<th>Cap/Flow</th>
<th>Pump Kw/Rt at different Heads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Lps/Rt</td>
<td>m3/s per Rt</td>
</tr>
<tr>
<td>Deg C</td>
<td></td>
<td></td>
<td>Rt per M3/S</td>
</tr>
<tr>
<td>2</td>
<td>8.34</td>
<td>0.525</td>
<td>0.000525</td>
</tr>
<tr>
<td>2.78</td>
<td>6.00</td>
<td>0.378</td>
<td>0.000378</td>
</tr>
<tr>
<td>3</td>
<td>5.56</td>
<td>0.350</td>
<td>0.000350</td>
</tr>
<tr>
<td>4</td>
<td>4.17</td>
<td>0.263</td>
<td>0.000263</td>
</tr>
<tr>
<td>5</td>
<td>3.34</td>
<td>0.210</td>
<td>0.000210</td>
</tr>
<tr>
<td>5.56</td>
<td>3.00</td>
<td>0.189</td>
<td>0.000189</td>
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<td>6</td>
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<td>7</td>
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<td>0.131</td>
<td>0.000131</td>
</tr>
</tbody>
</table>

Partload
2 to 4 gpm/Rt
(Same pipe size)

Partload
3 to 6 gpm/Rt

5C DT: 0.053 Kw/Rt (100%) to 0.105 (50%) Increase 0.053 (Bigger Penalty)
8C DT: 0.018 Kw/Rt (100%) to 0.036 (50%) Increase 0.018
Running 1 x 100% vs 2 X 50% (Which is better?)

Design Head = 5 + 12 + 3 = 20m  3 gpm/rt (0.189 Lps/Rt)

Kw/Rt = \( \frac{\text{Flow Per RT (Lps/Rt)} \times \text{Hd (m)}}{100 \times 0.80 \times 0.90} \)

2 chiller at 50% : Kw/Rt = \( \frac{(2 \times 0.189 \text{Lps/Rt} \times 20\text{m})}{72} \) = 2 x 0.053 = 0.106 (increase of 0.066)

1 chiller at 100% : Kw/Rt = 0.189Lps/Rt x \( \frac{5+12/4+3}{72} \) = (0.189 x 15)/72 = 75% x 0.053 = 0.040

Be Careful about Running Extra Chiller & Pump
Also Smaller Range impacts Cooling Tower Kw/Rt
Variable-Flow/Variable-Speed Pumping Systems

Variable-speed pumping can dramatically increase energy savings, particularly when it is combined with demand-based pressure reset controls. Variable-speed pumps are typically controlled to maintain the system pressure required to keep the most hydraulically remote valve completely open at design conditions. The key to getting the most savings is placement of the differential pressure transducer as close to that remote load as possible. If the system serves multiple hydraulic loops, multiple transducers can be placed at the end of each loop, with a high-signal selector used to transmit the signal to the pumps. With direct digital control (DDC) systems, the pressure signal can be reset by demand and controlled to keep at least one valve at or near 100% open. If valve position is not available from the control system, a trim-and-respond algorithm can be employed.

VPF is now the Standard design for most Projects
PRO & CON of Variable Speed Pumping

**PRO**

- Both variable-flow and variable-speed control save significant energy.
- Variable-speed drives on pumps provide a “soft” start, extending equipment life.
- Variable-speed drives and two-way valves are self-balancing.
- Application of demand-based pressure reset significantly reduces pump energy and decreases the occurrence of system overpressurization, causing valves near the pumps to lift.
- Variable-speed systems are quieter than constant-speed systems.

**CON**

- Variable-speed drives add cost to the system. (They may not be cost-effective on hot-water systems.)
- Demand-based supply pressure reset can only be achieved with DDC of the heating/cooling valves.
- Variable flow on condenser-water systems with open towers requires that supplementary measures be taken to keep the fill wet on the cooling towers. Cooling towers with rotating spray heads or wands can accept a wide variation in flow rates without causing dry spots in fill. Fitting the cooling tower with variable-speed fans can take advantage of lower flow rates (there’s more free area) to reduce fan energy while providing the same temperature of condenser water.
System Design Considerations

When a designer puts together a chilled-water plant, there are many design parameters to optimize. They include fluid flow rates and temperatures, pumping options, plant configuration, and control methods. For each specific application, the design professional should understand the client’s needs and desires and implement the chiller plant options that best satisfy him or her.

**Fluid Flow Rates.** Flow rates were discussed in the “Media Movers” section of Chapter 10.

**Fluid Temperatures.** To allow lower flow rates, the chiller must be able to supply colder chilled-water temperatures and to tolerate higher condenser leaving temperatures.

**Pumping Options.** Pumps may be selected to operate with a specific chiller or they may be manifolded.

- Pump-per-chiller arrangement advantages include the following:
  - Hydronic simplicity
  - Chiller and pump are controlled together
  - Pumps and chillers may be sized for one another

Manifolded-pump arrangement advantages include the following:

- Simpler redundancy
- Pumps may be centrally located
Understanding Cooling Tower

Approach: To – Twb
Range: Ti - To

\[
EFF = \frac{(Ti-To)}{(Ti-Twb)} \times 100
\]

Reducing Flow => Increase DT => More HR capacity => Hz reduction optimisation
## Cooling Tower Performance

**Table 3 – Performance requirements for heat rejection equipment**

<table>
<thead>
<tr>
<th>Equipment type</th>
<th>Total system heat rejection capacity at rated conditions</th>
<th>Subcategory or rating condition</th>
<th>Performance required$^a$</th>
<th>Test procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller or axial fan cooling towers</td>
<td>All</td>
<td>35.0 °C entering water 29.4 °C leaving water 23.4 °C wet outdoor air</td>
<td>≥ 3.23 L/s.kW</td>
<td>CTI ATC-105</td>
</tr>
<tr>
<td>Centrifugal fan cooling towers</td>
<td>All</td>
<td>35.0 °C entering water 29.4 °C leaving water 23.4 °C wet outdoor air</td>
<td>≥ 1.7 L/s.kW</td>
<td>CTI ATC-105</td>
</tr>
</tbody>
</table>

$^a$ For the purpose of this table,
- cooling tower performance is defined as the maximum flow rating of the tower divided by the nameplate rated motor power
- air-cooled condenser performance is defined as the heat rejected from the refrigerant divided by the nameplate rated motor power

Note: CTI rating is based on 23.4°C (vs 27°C typical Spore selection) Compliance is not an issue.
### Chiller Plant Performance Goals

#### Table 10-1: Example Performance Goals

<table>
<thead>
<tr>
<th>Component</th>
<th>Typical kW/ton (kW/kWR)</th>
<th>Efficient kW/ton (kW/kWR)</th>
<th>Delta kW/ton (kW/kWR)</th>
<th>% Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller</td>
<td>0.62 (0.1763)</td>
<td>0.485 (0.1379)</td>
<td>0.135 (0.0384)</td>
<td>22%</td>
</tr>
<tr>
<td>Cooling tower</td>
<td>0.045 (0.0128)</td>
<td>0.012 (0.0034)</td>
<td>0.033 (0.0094)</td>
<td>73%</td>
</tr>
<tr>
<td>Condenser water pump</td>
<td>0.0589 (0.0167)</td>
<td>0.022 (0.0063)</td>
<td>0.0369 (0.0104)</td>
<td>63%</td>
</tr>
<tr>
<td>Chilled-water pump</td>
<td>0.0765 (0.0218)</td>
<td>0.026 (0.0074)</td>
<td>0.0505 (0.0144)</td>
<td>66%</td>
</tr>
<tr>
<td>Total water-side system</td>
<td>0.8004 (0.2276)</td>
<td>0.545 (0.155)</td>
<td>0.2554 (0.0726)</td>
<td>32%</td>
</tr>
</tbody>
</table>

Efficient Plant typically has Ratio 85:15 to 90:10 (chiller : Ancillary)
Singapore Project achieving 0.55 Kw/Rt
Singapore Site vs GreenGuide Example

<table>
<thead>
<tr>
<th>Component</th>
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<td>0.545 (0.155)</td>
</tr>
</tbody>
</table>

Efficiency Table

<table>
<thead>
<tr>
<th>Total CHW Ton</th>
<th>3598</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller</td>
<td>0.503</td>
</tr>
<tr>
<td>CHWP</td>
<td>0.015</td>
</tr>
<tr>
<td>CWP</td>
<td>0.024</td>
</tr>
<tr>
<td>CT</td>
<td>0.005</td>
</tr>
<tr>
<td>SYSTEM</td>
<td>0.547</td>
</tr>
</tbody>
</table>

Chilled-water pump

<table>
<thead>
<tr>
<th>chws (°C)</th>
<th>6.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>chwr (°C)</td>
<td>13.94</td>
</tr>
<tr>
<td>chwf (lps)</td>
<td>72.02</td>
</tr>
<tr>
<td>chw Tons</td>
<td>662.5</td>
</tr>
<tr>
<td>ΔT (°C)</td>
<td>7.71</td>
</tr>
</tbody>
</table>

6C, Tropics

6.7C, Temperate?
Site at 0.52 Kw/Rt (7.6C CHW)
Recommended Design Strategies for HP Chiller Plant

1. Use super high efficiency chillers, Pumps, CTs (*Do better than SS530 Requirements*)
2. Low flow low pressure CHW and CW system (*Large DT where Necessary*)
3. Variable primary CHW flow system (*saves 20-25% VS Pri-Sec*)
4. Chiller tower optimization (*Add VSD + extra HR capacity*)
5. Extensive continuous high precision monitoring (*SS 591-2013*)

GOOD DESIGN + SMART OPERATION = SUSTAINABLE Performance
Underlying Elements of Optimisation

Three Parameters that drives Performance of Chiller plant component equipment

Temperature
(CHW/CW/WB)

FLOW
(CHW/CW/CT Fan)

Pressure
(Refrigerant/Pump Hd)

Optimsation is about the tradeoffs between these parameters
LIVE DEMO
(Subject to Site Availability)
Thank You

Q + A
# COOLTOOLS™ Chilled Water plant Design Guide

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Chilled-Water Plants Overall Design

From July 2011 to June 2012, *ASHRAE Journal* has published a series of five articles (authored by S. Taylor) describing a systematic approach to the design of chilled-water plants.

This series of articles also summarized the ASHRAE Self-Directed Learning (SDL) course called “Fundamentals of Design and Control of Central Chilled-Water Plants” and the research that was performed to support its development. The series included five segments, as follows
“Chilled-water distribution system selection” (ASHRAE Journal, July 2011). This article discussed distribution system options, such as primary-secondary and primary-only pumping, and provided a simple application matrix to assist in selecting the best system for the most common applications.

“Condenser water distribution system selection” (ASHRAE Journal, September 2011). This article discussed piping arrangements for chiller-condensers and cooling towers, including the use of variable-speed condenser water pumps and water-side economizers.

“Pipe sizing and optimizing ΔT” (ASHRAE Journal, December 2011). This article discussed how to size piping using life-cycle costs, then how to use pipe sizing to drive the selection of chilled-water and condenser water temperature differences (ΔTs).

“Chillers and cooling tower selection” (ASHRAE Journal, March 2012). This article addressed how to select chillers using performance bids and how to select cooling tower type, control devices, tower efficiency, and wet-bulb approach.

“Optimized control sequences” (ASHRAE Journal, June 2012). This article included a discussion of how to optimally control chilled-water plants, focusing on all variable-speed plants.