Variable Primary Flow Chilled Water Systems

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VARIABLE PRIMARY FLOW CHILLED WATER SYSTEMS

By William P. Bahnfleth, PhD, PE

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Outline

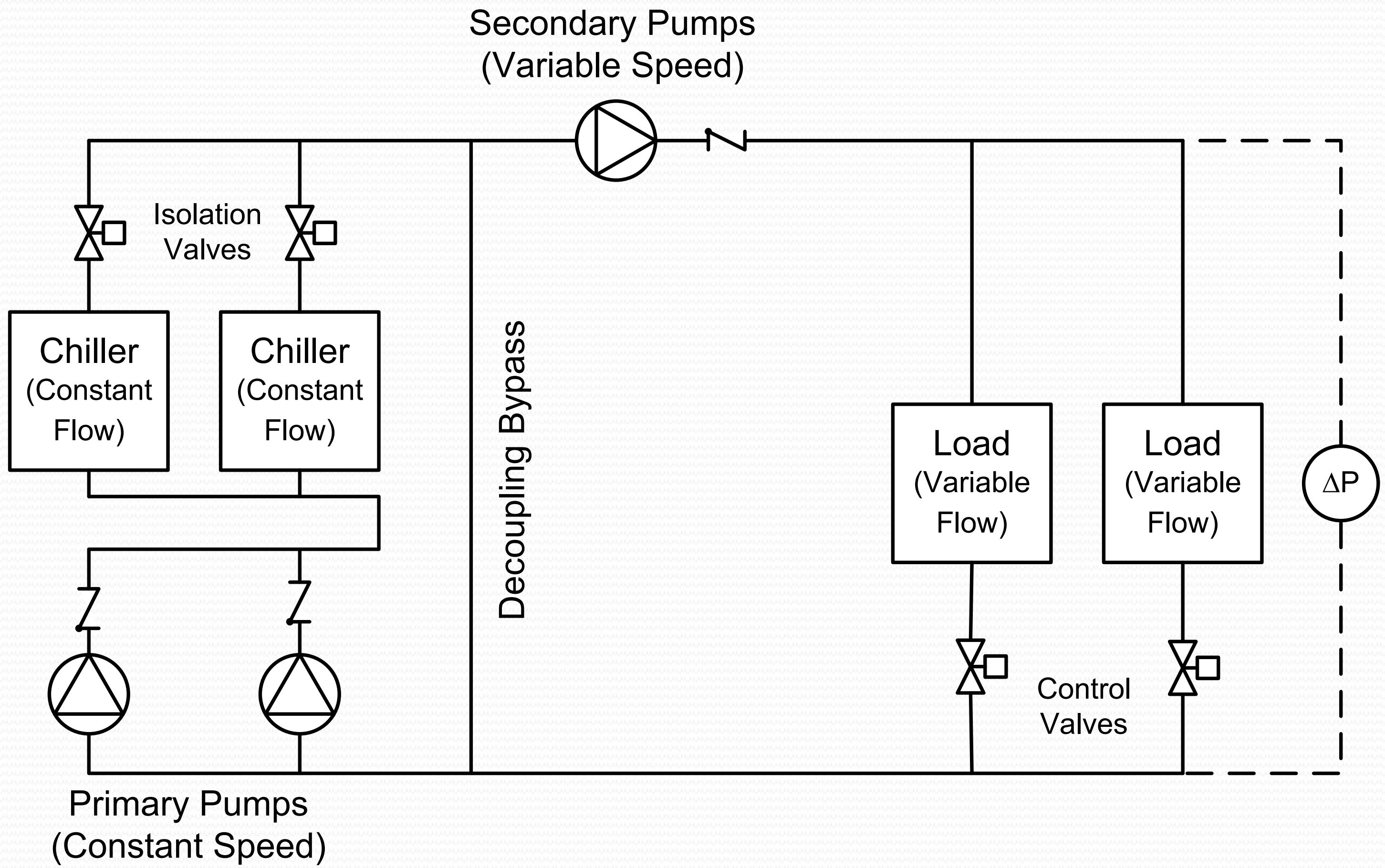
- Terminology and History
- Low ΔT Syndrome
- Basics of Variable Primary Flow
- Performance of VPF Systems

Definitions

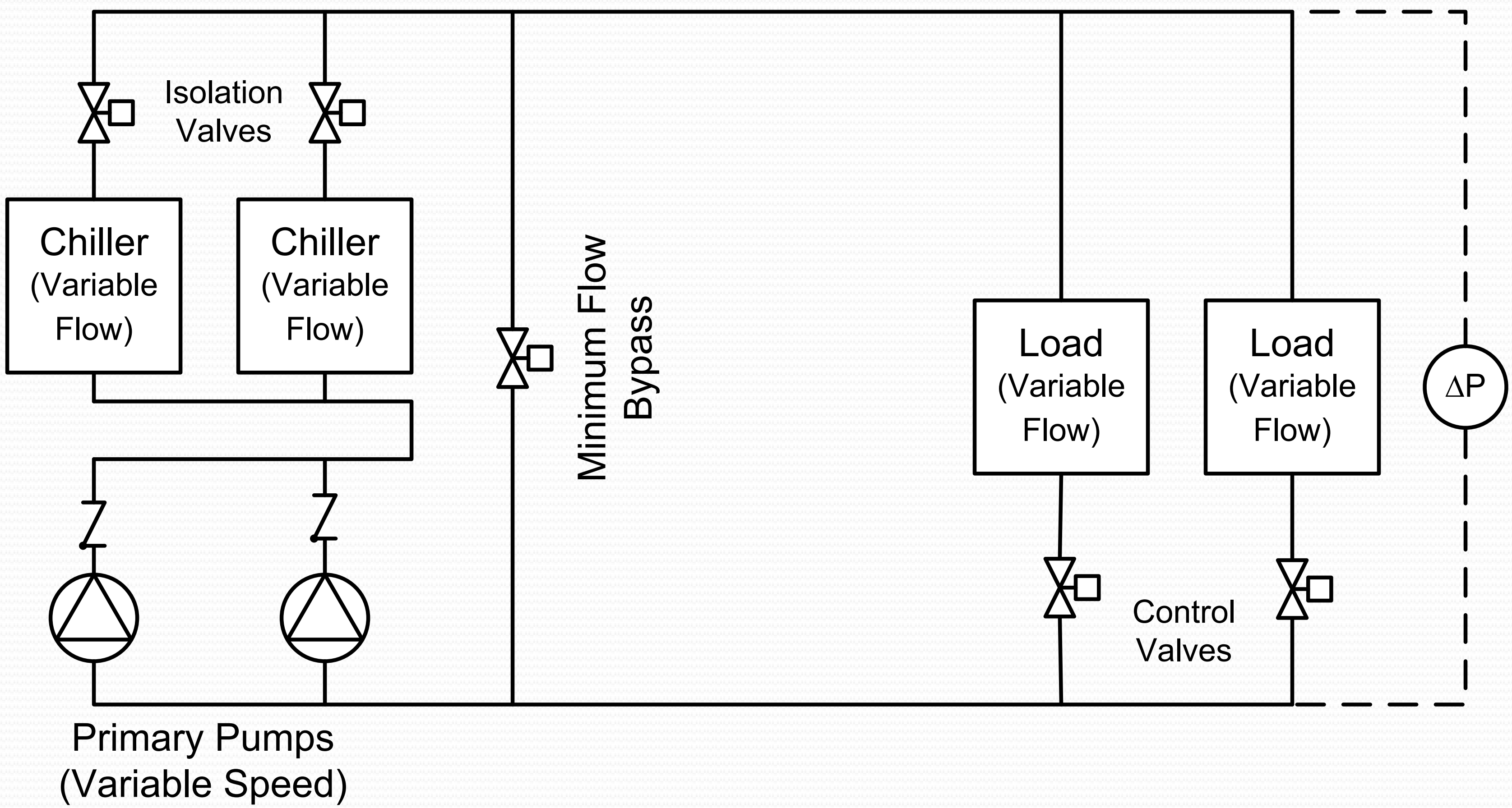
- Primary flow: chilled water flow through evaporators of chillers
- Secondary flow: chilled water flow from the chilled water plant to end-users and back

Primary and secondary flows may be the same or different depending on system design

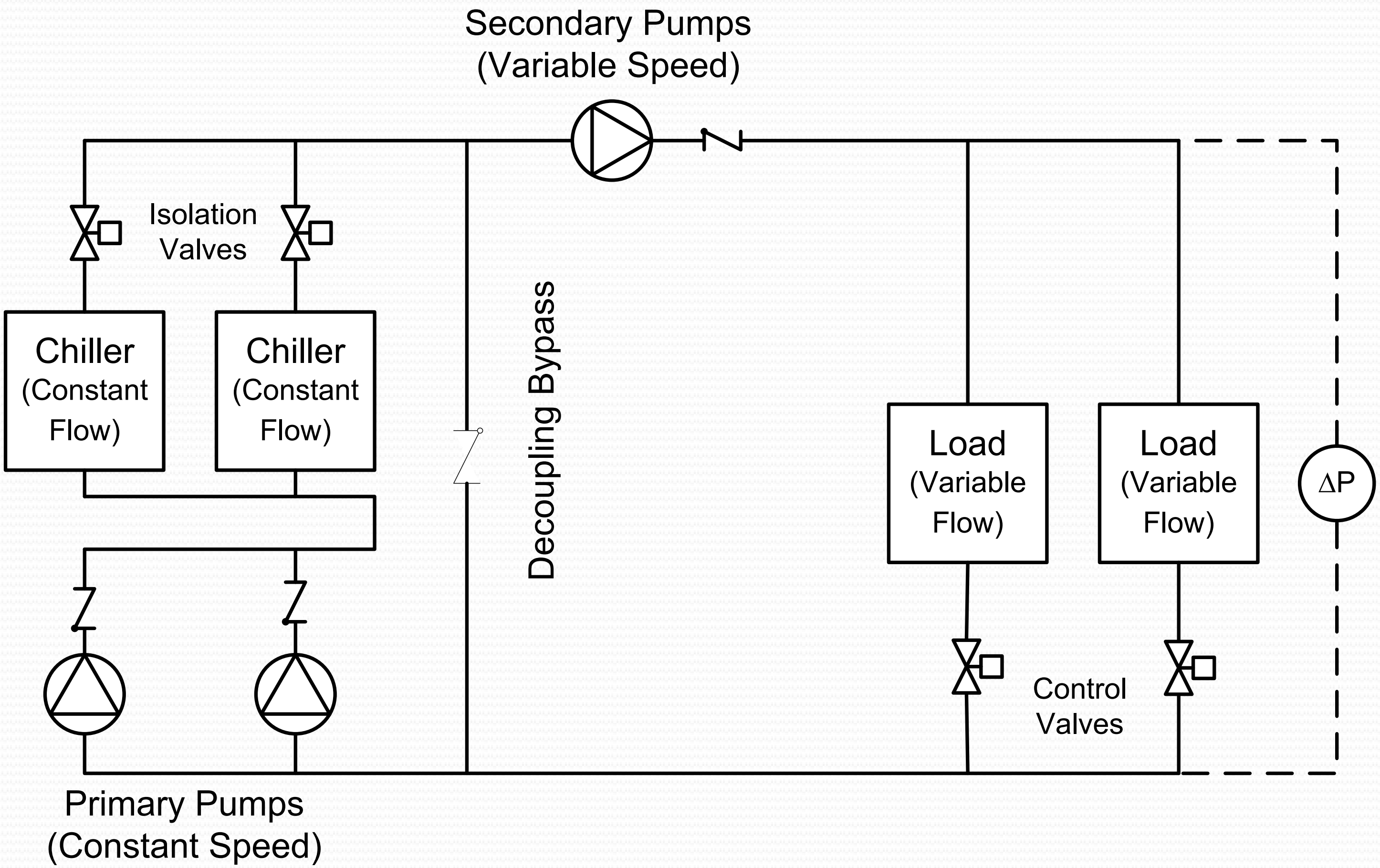
Constant Flow Primary/ Variable Flow Secondary Chilled Water System



Variable Primary Flow (Primary-Only) Chilled Water System



Partial VPF: Retrofit-P/S System with Bypass Check Valve



P/S has been the standard for many years—why change to VPF?

- Reduce initial system cost and space requirement by eliminating secondary pumps
- Reduce pump energy use associated with excess primary flow
- Solve ΔT-related problems that afflict some P/S system
- Permit maximum capacity of chillers to be utilized under favorable lift conditions

How much auxiliary and pump energy is there to be saved?

- ASHRAE 90.1-2019
  - WC Centrifugal, ≥ 600 ton
    - AHRI 550/590
    - 6.20 COP (0.560 kW/ton)
    - 6.41 IPLV (0.500 kW/ton)
  - Cooling tower fans
    - ≥40.2 gpm/hp (axial)
    - 3 gpm/ton
    - 92% motor efficiency
    - 0.06 kW/ton
- Condenser water pumps
  - ~50 ft hd
  - 3 gpm/ton
  - 80% overall efficiency
  - 0.04 kW/ton
- Chilled water pumps
  - ~120 ft hd, 2 gpm/ton
  - 80% overall efficiency
  - 0.06 kW/ton
- Total ~0.72 kW/ton (4.89 COP)
  - Chiller 78%
  - CW System 14%
  - CHW Pumping 8%
- Pumping and CT fan percentages may double in annual total, but chiller still consumes over 50% at a minimum

Some case studies claim 30 – 40% savings

History of Chilled Water Systems

(Durkin, T., Evolving Design of Chiller Plants, ASHRAE J., Nov. 2005)

Chilled Water Pumping System	***Installed Cost Factor***	***Operating Cost Factor***
Constant Flow c. 1988	1.000	1.000
Primary/Secondary c. 1990	0.900	0.950
Variable Primary c. 1996	0.867	0.937
Optimized VPF c. 2002	0.872	0.900

Low ΔT Syndrome

- Chilled water supply-return temperature difference to be smaller than design
  - Occurs continuously in some systems
  - Correlated with low load conditions in others
  - Sometimes a problem, sometimes a consequence of normal operation

Low ΔT Syndrome-Consequences

- Excess flow→increased CHW pump energy use
- Inability to load P/S chillers fully

$$\dot{Q}_{Design} = \rho c_p \dot{V}_{Design} \Delta T_{Design}$$

- Need to operate more chillers and auxiliaries to meet flow requirement than should be needed to meet load

How does VPF "cure" low ΔT?

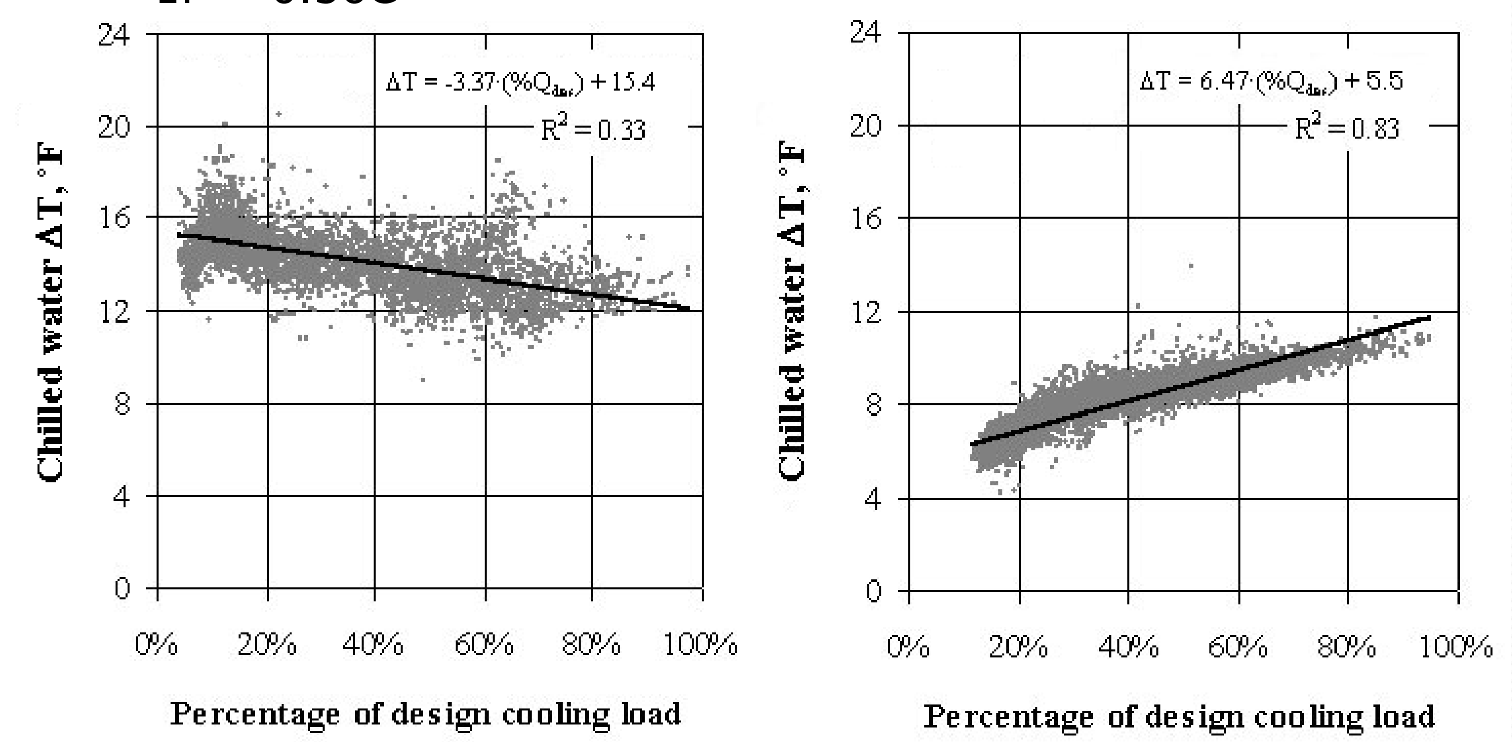
- Evaporator flow can exceed design flow
- Increased flow compensates for reduced ΔT

$$\dot{Q}_{Design} = \rho c_p \dot{V}_{Design+} \Delta T_{Design-}$$

- Chillers can achieve full capacity under wider range of conditions
- Not really a cure, more of a palliative

VPF may be a solution, but P/S is not the problem

1F = 0.56C



Data from two buildings connected to the same district primary/secondary system, 12°F (6.7°C) design ΔT

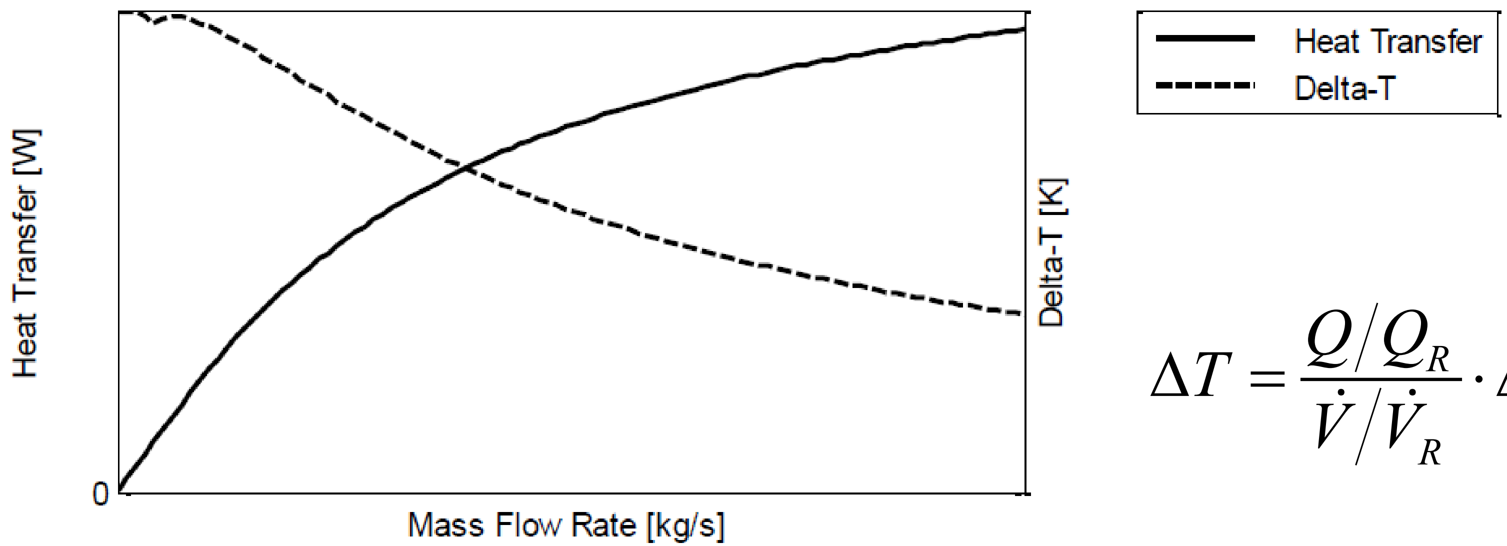
Low ΔT Syndrome-Causes

- Control errors
  - Set points
  - Calibration
  - Missing interlocks
- Control trade-offs
  - Chilled water reset
  - OA economizer
- Cooling coil issues
  - Air or water side fouling
  - Selected for ΔT smaller than system ΔT
- Control valves
  - Three-way valves
  - Oversized two-way valves
  - Valves that don’t shut off against system head

There are fixes the problems that do not require variable primary flow

Cooling coils and ΔT - flow

- Constant entering air conditions and entering water temperature, variable chilled water flow
- Coil saturation at high water flow - increasing flow with little increase in heat transfer

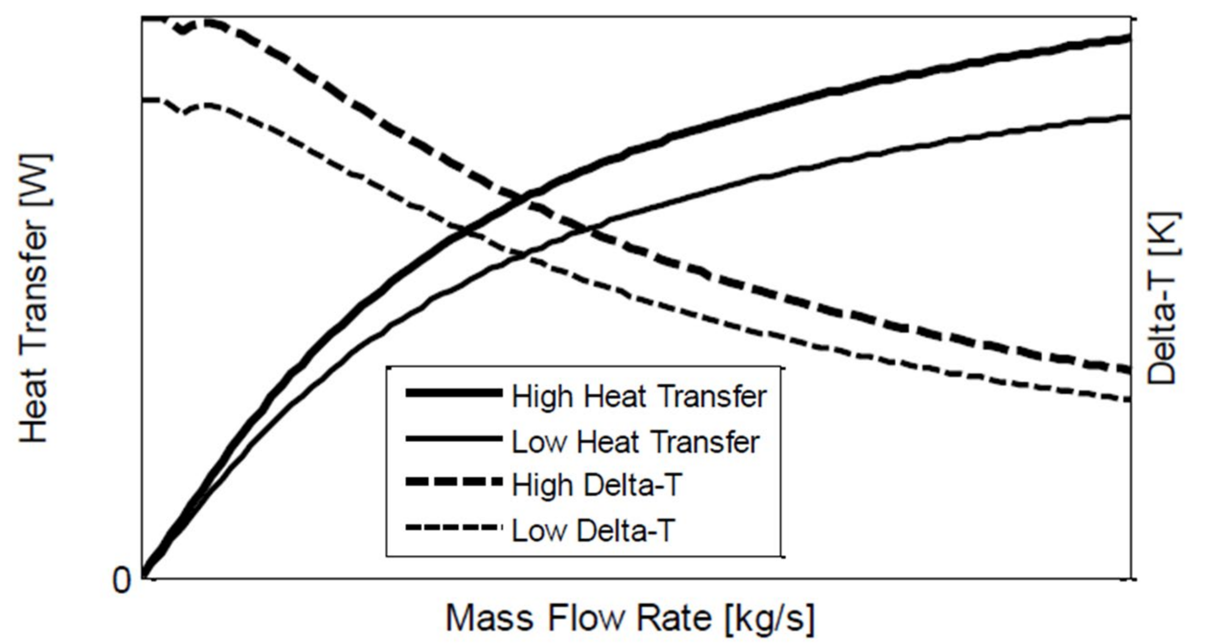


$$\Delta T = \frac{Q/Q_R}{\dot{V}/\dot{V}_R} \cdot \Delta T_R$$

Thuillard, Reider and Henze. 2014. Energy Efficiency Strategies for Hydronic Systems through Intelligent Actuators' ASHRAE Trans. 120(1).

Cooling coils and ΔT – CHW Reset

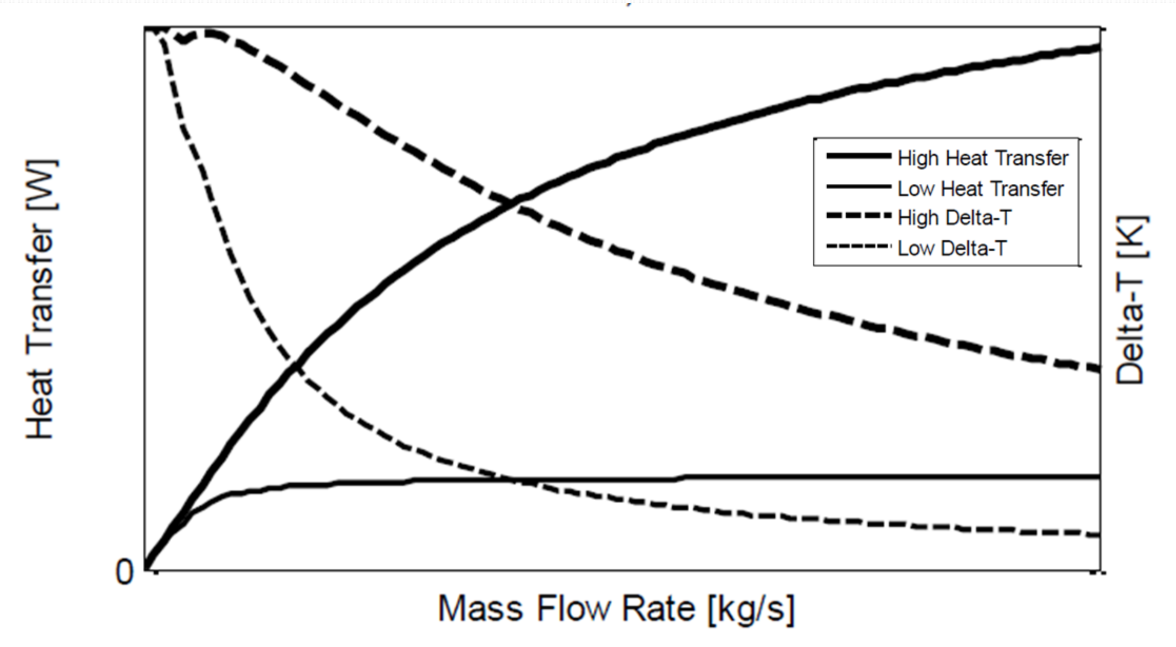
- Increase entering water temperature (low HT case)
- Reduces coil capacity and ΔT for fixed entering condition



Thuillard, Reider and Henze. 2014. Energy Efficiency Strategies for Hydronic Systems through Intelligent Actuators' ASHRAE Trans. 120(1).

Cooling coils and ΔT – VAV

- Low air flow (low HT case)/variable water flow
- Note much lower saturation flow for low HT case



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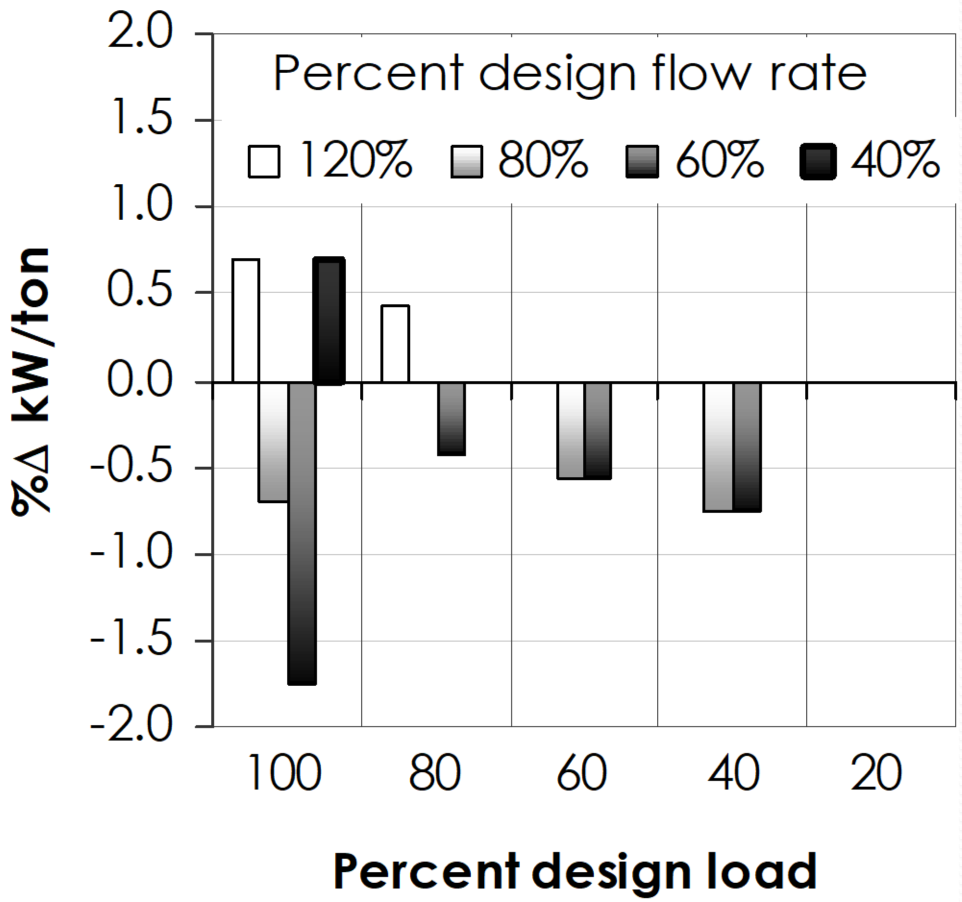
Design Issues for VPF

- Chiller performance
  - Effect of variable flow on energy use
  - Range of evaporator flow
  - Rate of change of evaporator flow
- Controls and instrumentation
  - Bypass location and control
  - Pump staging
  - Chiller staging

VPF Has Little Impact on Chiller Performance



Evaporator Flow Rate Range-Determined by Tube Velocity Limits

- Velocity constraints
  - Too high—tube damage
  - Too low—loss of heat transfer coefficient
- Typical range for flooded evaporators
  - Minimum: 1.5 – 2 ft/s (0.46 – 0.61 m/s), Maximum 11 – 12 ft/s (3.35 – 3.66 m/s)
  - ∴ turndown ~5.5:1 to ~8:1
- Typical constant flow selection velocity permits more flow beyond design than needed
- Higher velocity selection for VPF allows more turndown, small penalty for higher design dP because most operation is at reduced flow

Rate of Change of Evaporator Flow-Effect of Chiller Age and Type

- Older chillers (~1980s or earlier) less suitable due to control limitations
  - Stability
  - Paddle proof-of-flow device
- Absorption chillers less suitable than vapor compression due to cycle differences

Typical Flow Rate Change Limits

Compressor	To Keep Chiller On-Line (%/min)	To Maintain Temperature Control (%/min)	Temperature Tolerance (°F/°C)
Scroll	30	10	±2/1.1
Screw	50	10 30	±0.5/0.3 ±2/1.1
Centrifugal	30	10 30	±0.5/0.3 ±2/1.1
Centrifugal with enhanced flow management	50	30 50	±0.5/0.3 ±2/1.1

Rate of Change of Evaporator Flow-Effect of Turnover Time

- Turnover time
  - Time required for one system volume to circulate
- Shorter turnover time makes system less stable
- Some manufacturers recommend minimum turnover time or equivalent, e.g., 6 gal/installed ton (6.5 L/kW)

Low-Flow Bypass

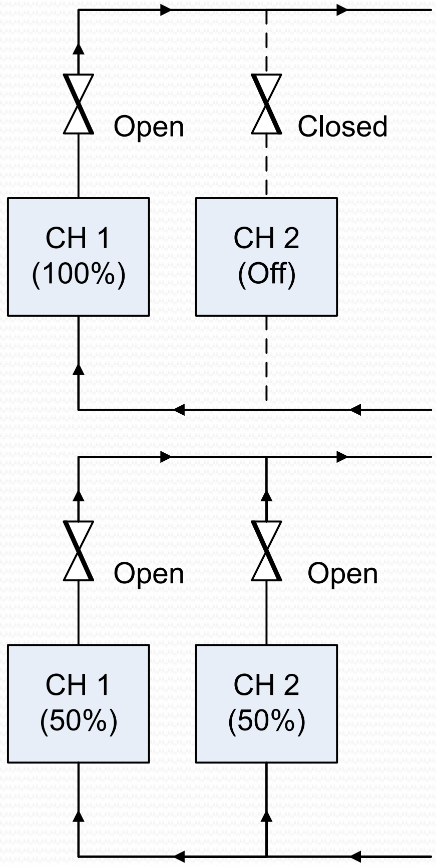
- Why?
  - Prevent extended operation of chillers below minimum flow
  - Sometimes omitted in plants with significant base load
- What
  - Normally closed bypass that opens when evaporator flow is below set point
  - Three-way valve(s) on selected loads
- Issues
  - Valve selection
  - Flow measurement accuracy
  - Detracts from pump energy savings

Pump Staging

- Pumps
  - Need not be matched to chillers like P/S
  - Dispatch like secondary pumps based on demand from loads (e.g., remote ΔP or valve position)
  - Typically headered, so flow must be controlled at each chiller

Chiller Staging

- Stage based on on/off using
  - Flow (within limits)
  - Capacity
- Potential problem
  - Sudden loss of flow to fully loaded chillers when adding a chiller
  - Flow changes by N/(N+1) for identical chillers
  - Sudden drop in flow may cause safety trip

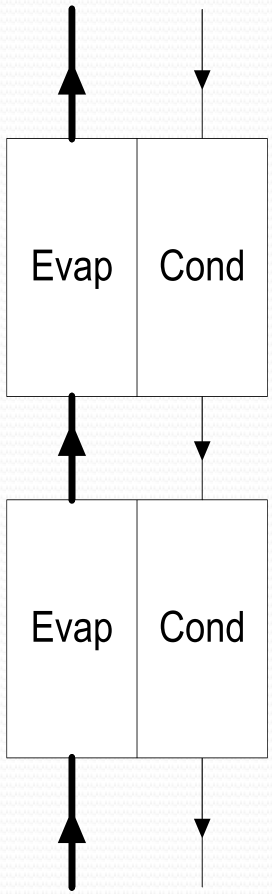


Chiller Staging

- Recommended solution for parallel chillers
  - Unload active chillers to 50-60% capacity before starting next chiller
  - Open isolation valves *slowly*
- Problem with recommended solution
  - Limiting capacity means supply temperature will rise
  - May be problem for process loads

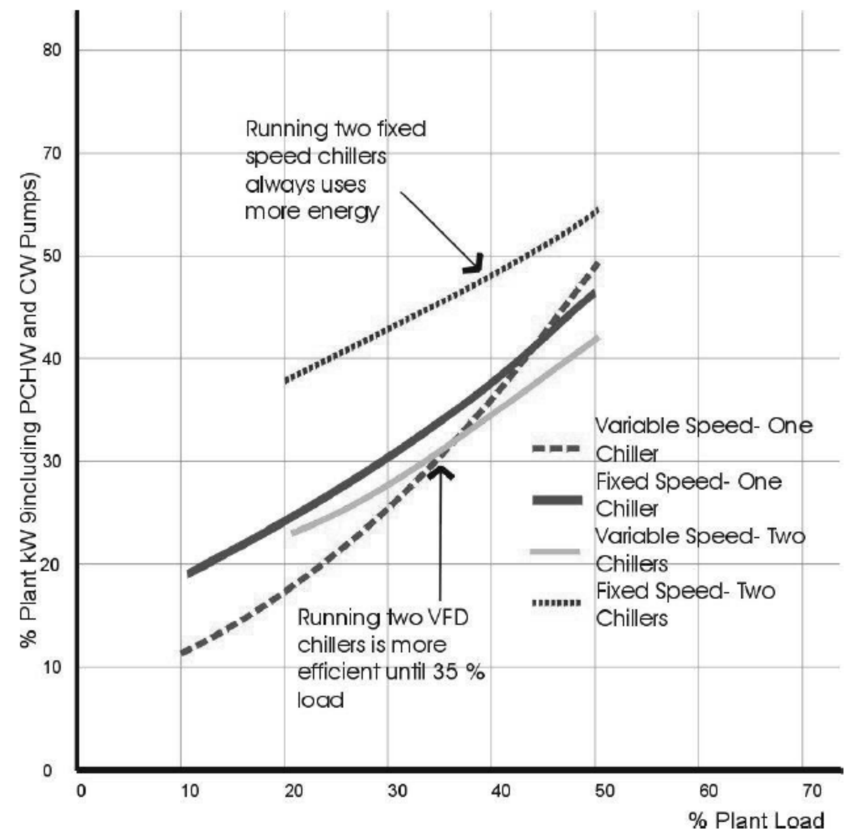
Chiller Staging

- Another approach—series chillers
  - Two machines or dual compressor assembly
  - Unlike parallel arrangement, flow does not change when second compressor starts
  - Temperature maintained, no upset of lead chiller load
  - Drawback: pressure drop through series evaps and condensers



Chiller Staging

- Constant speed vs. variable speed
  - Constant speed – minimum number required to meet load typically uses least energy
  - Variable speed – more may be better, little or no flow above design



Two-chiller plant part-load performance with and without VFDs.

Instrumentation

- Accurate flow measurement for each evaporator – but could be a single meter
- Reliable proof of flow on each evaporator

Best Applications for VPF

(Mostly from Taylor, S. Primary-Only vs. Primary-Secondary Variable Flow Systems, ASHRAE J., Feb. 2002)

- Better for VPF
  - Plants with more than 3 chillers
  - Plants with significant base load
  - System tolerant of CHW T fluctuations
  - Operations staff able and willing to maintain controls
- Better for P/S
  - Reliability a high priority
  - Limited on-site operations expertise

VPF Performance

- Glowing anecdotes, but few case studies w/operating data
  - What is the baseline? Start with lousy system→big savings
  - Multiple changes—which did what?
  - What else could have been done?
  - Before/after comparisons with no adjustment for weather or other operating conditions
- No research quality measurements
- Simulation-based studies

Modeling Results

(Bahnfleth, W. and E. Peyer. 2004. ARTI 21-CR/611-20070-01&02)

- Objectives
  - Compare energy use and economic performance
  - Identify specific areas in which energy use differs
  - Draw conclusions that have broad application, if possible
- Approach
  - Parametric simulation-based study of energy usage, life-cycle cost and payback for a variety of conditions
  - Baseline is a P/S plant that works at design and has no major part load pathologies

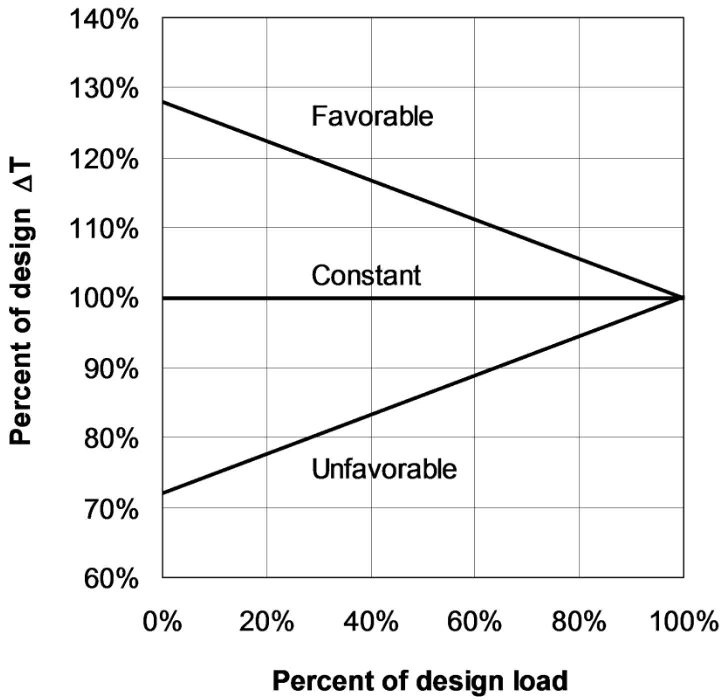
System Types

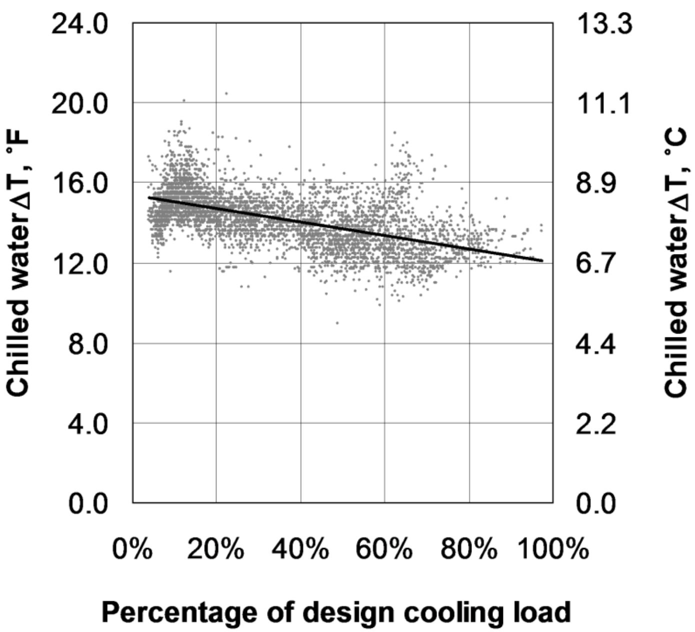
- Constant flow primary-only
- Constant flow primary/variable flow secondary
- Variable primary flow
- Primary/secondary with bypass check valve

Equipment and Plant Arrangement

- Chillers
  - Constant speed electric water cooled centrifugal
  - 0.58 kW/ton at 44°F/85°F (6.06 COP at 6.7 °C/29.4°C)
- 12°F (6.7 °C) CHW ΔT
- 3 gpm/ton (3.2 L/min-kW) CW
- Two-speed fan towers
- Parallel chillers, pumps, towers
- 1-5 chillers
- 120 – 170 ft (36.6 – 51.8 m) total pumping head, 50 ft (15.2) for primary

Load vs. ΔT

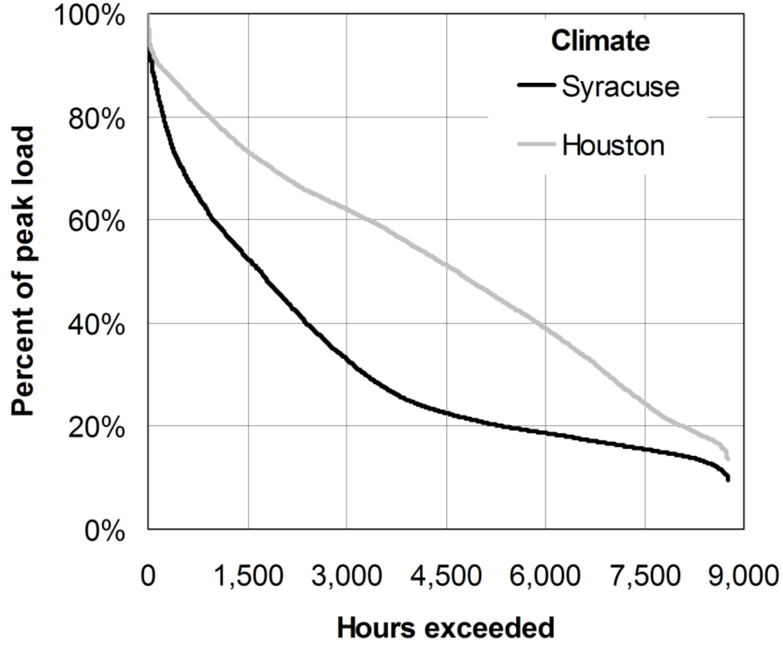




Note-Design ΔT is attained at full capacity.

Load Types and Climate

- Load types
  - 500 ton (1758 kW) office
  - 1,500 ton (5275 kW) medical center plant
  - 4,500 ton (15,826) district cooling system
- Climate
  - Syracuse, NY
  - Houston, TX
  - Phoenix, AZ



Simulation Methodology

- Model only plant—distribution/loads represented by system curve
- Calculate hourly load profiles using public domain whole-building energy program
- Validate load profiles by comparison with actual load profiles
- Plant flow requirement a function of load and load vs. ΔT scenario

Simulation Methodology

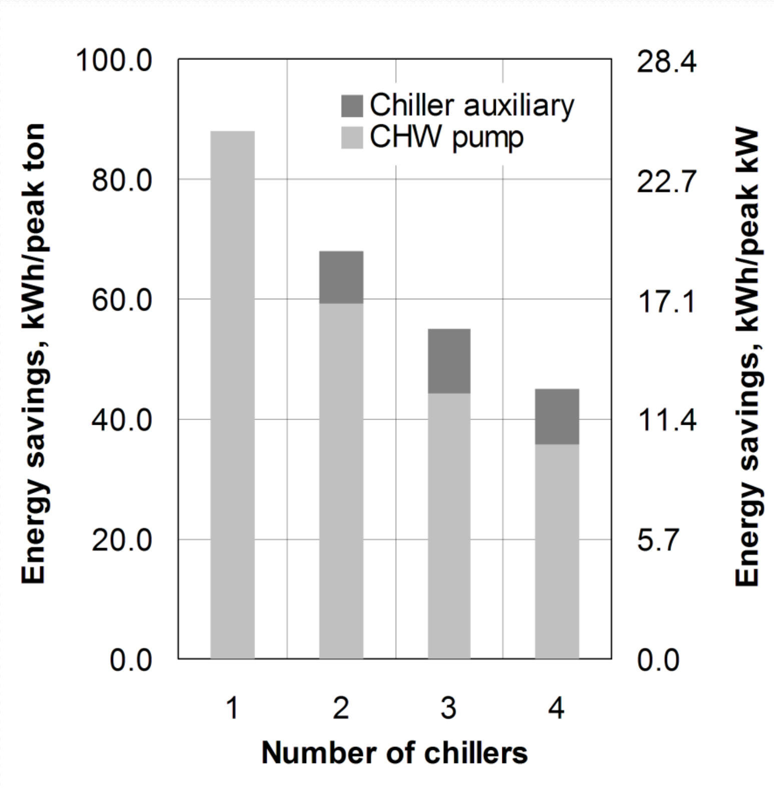
- Polynomial component models for chillers, pumps, towers
- Chiller flow rate 30 -120% of design
- Control CT's to minimize CW temperature with low cutoff of 60°F (15.6 °C)
- Chiller energy consumption not a function of CHW ΔT

Energy Use Results

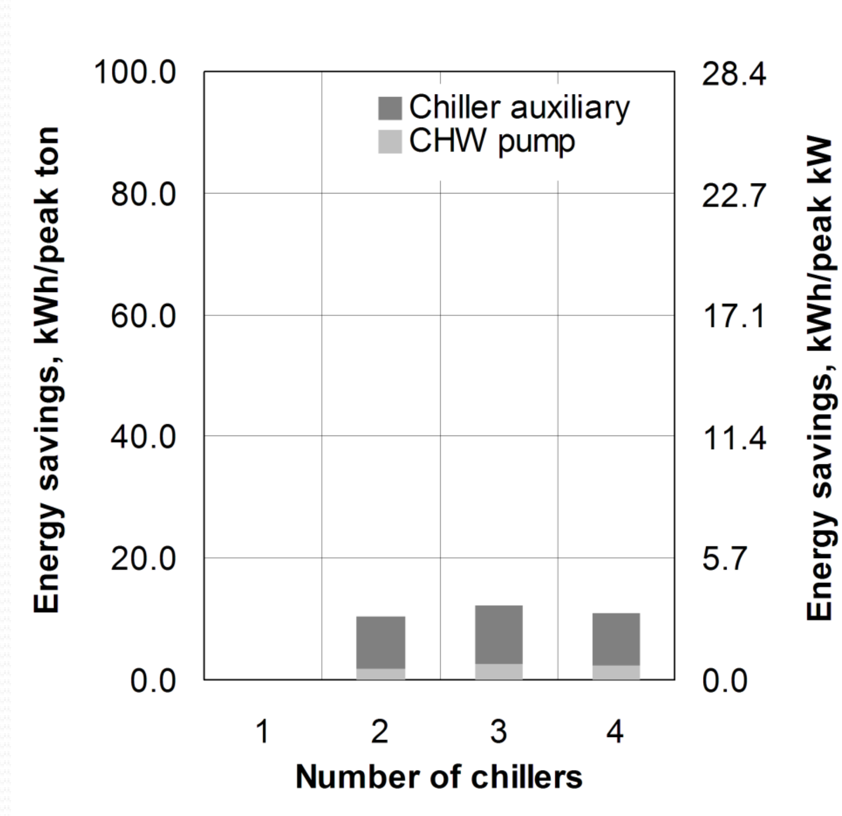
(Houston Office)

- Energy savings relative to P/S
  - Plant
    - 3 – 7% with VPF
    - 0 – 4% with P/S check valve
  - VPF CHW pump 24-42%
  - VPF CW system 0 – 13%
  - VPF chiller 0 – 2%
  - ***More chillers → lower savings***
    (but not necessarily lowest energy use)

Energy Use Results



VPF vs. P/S

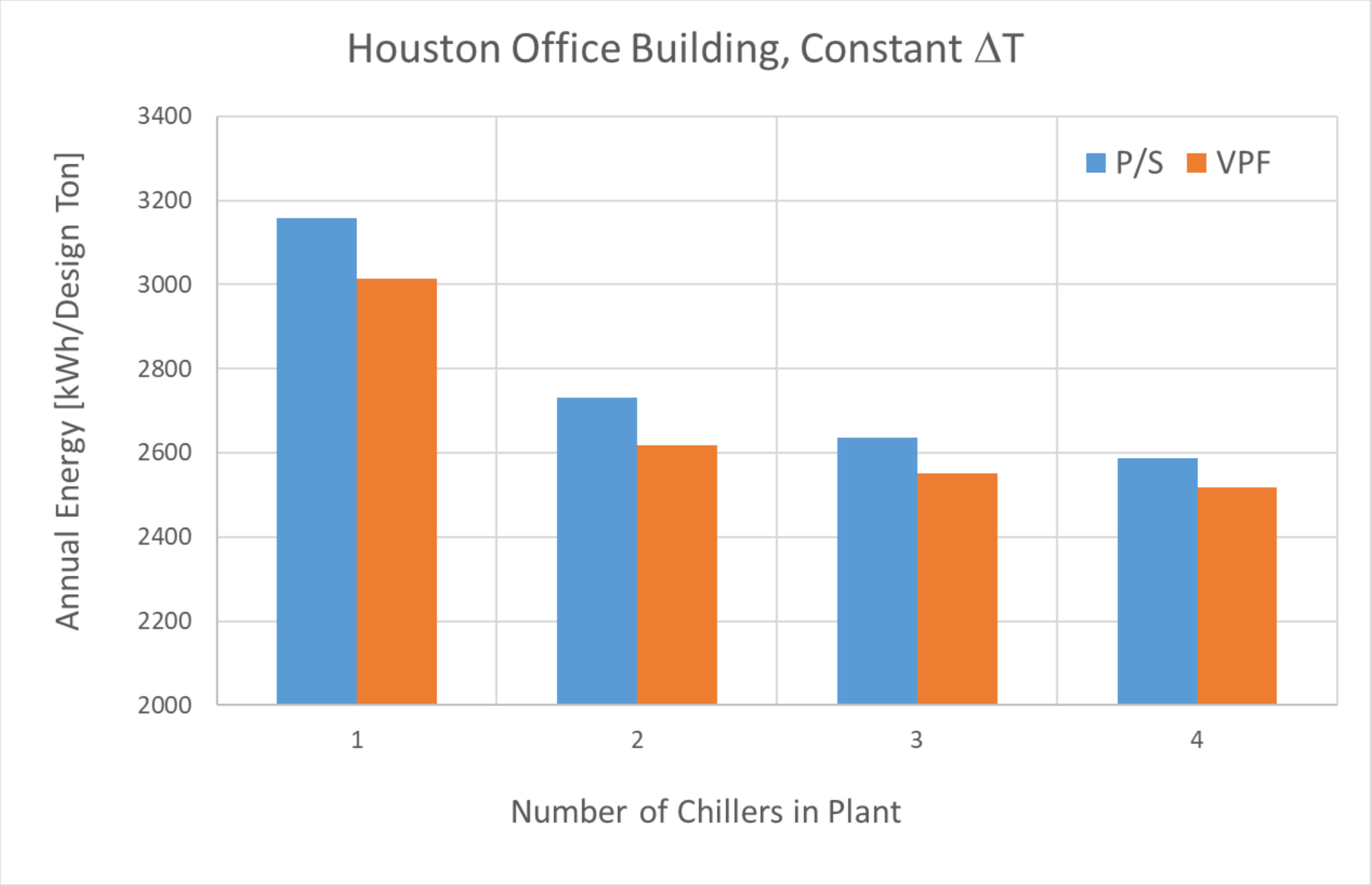


P/S-check vs. P/S

Houston Office, Constant ΔT

Energy Use Results

(Houston Office, Constant ΔT)



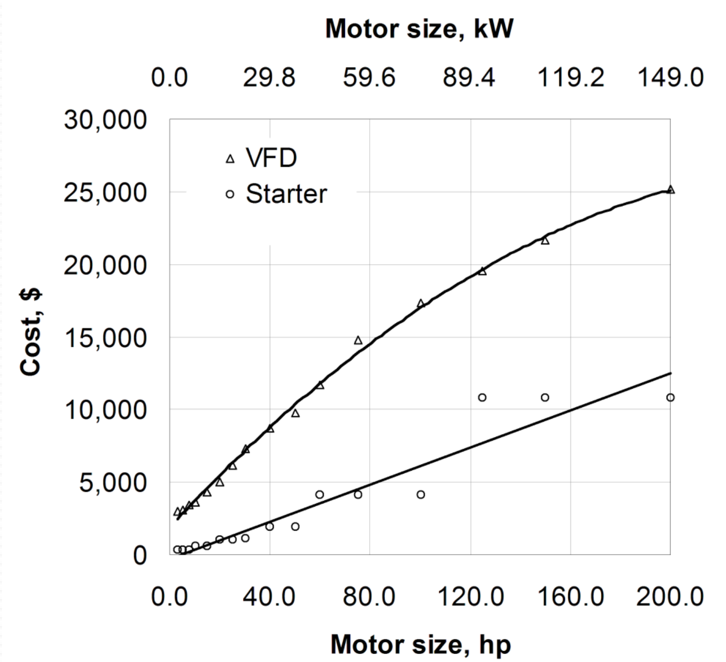
Energy Use Results

- Load vs. ΔT scenario
  - Differences in savings with ΔT trend were small
  - Somewhat larger when "favorable"
  - Outcome could be different for systems that always fall short of design ΔT
- Effect of load type and climate
  - More load → more savings

Economic Analysis

(Houston)

- Capital costs validated by a mechanical contractor
- Regressions to give continuous functions of size
- 4-8% capital cost savings for VPF relative to P/S



Economic Analysis

- Life-cycle cost
  - 20 year life
  - $0.035/kWh electric use +$12/kW peak demand charge
  - Department of Commerce fuel escalation factors, discount rate
- $80-130/design ton ($22.8-$37.0/design kW) savings for VPF relative to P/S (3-% of LCC)

Caveats

- Did not look at every possible configuration or operating scenario
  - Unequal sized chillers, variable speed drive chillers, air-cooled chillers, series chillers, systems with thermal storage, ΔT always below design, effect of maximum and minimum flow limits…
  - *Currently investigating effect of tube velocity selection point, variable speed vs. constant speed chillers*
- Larger savings for retrofit of poorly operating systems could be larger
- Bypass check valve needs a problem system to show its value (but there are usually other ways to fix the problem)

Conclusions

- We know how to design VPF systems that work
- Economics are positive—first cost savings + some operating savings—still arguing about the size of the benefit
- Greatest savings should be realized in plants with small number of chillers, but they are the most difficult to operate
- High loads (climate, occupancy) increase savings
- Detailed data from the field is needed, in part to validate analysis

Q & A