Variable Primary Flow Chilled Water Systems

William Bahnfleth, PhD, PE, FASHRAE, FASME
Penn State Department of Architectural Engineering
wbahnfleth@psu.edu

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VARIABLE PRIMARY FLOW CHILLED WATER SYSTEMS

By William P. Bahnfleth, PhD, PE

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Variable Primary Flow Chilled Water Systems

Variable primary flow is being adopted in chilled water system design with increasing frequency as a lower cost, more efficient alternative to primary/secondary design that is not as susceptible to low delta T syndrome. Subtopics include a review of variable primary flow and primary/secondary system types; causes and effects of low delta T syndrome and potential remedies; design considerations for variable primary flow, and, comparisons of variable primary flow and primary/secondary flow taken from case study and research literature.

Learning Objectives

- Distinguish between alternatives for chilled water system design
- Explain the potential benefits of variable primary flow
- Explain the key design characteristics of variable primary flow systems
- Describe the energy and economic benefits of variable primary flow

Outline

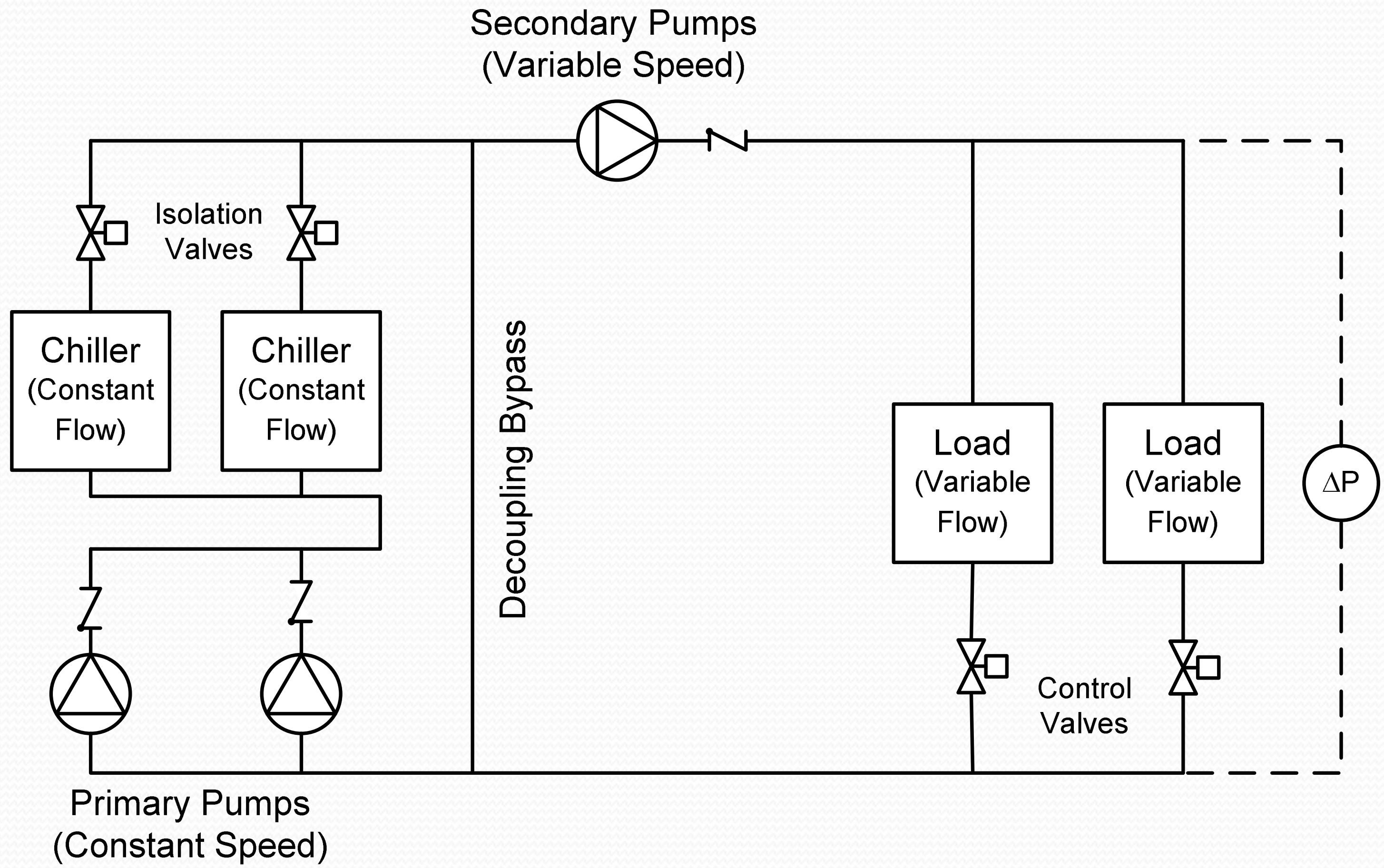
- Evolution of CHW Systems
- Low ΔT Syndrome
- Basics of Variable Primary Flow
- When is VPF *Not* the Best Solution?
- Performance of VPF Systems
- Opinions about VPF

Definitions

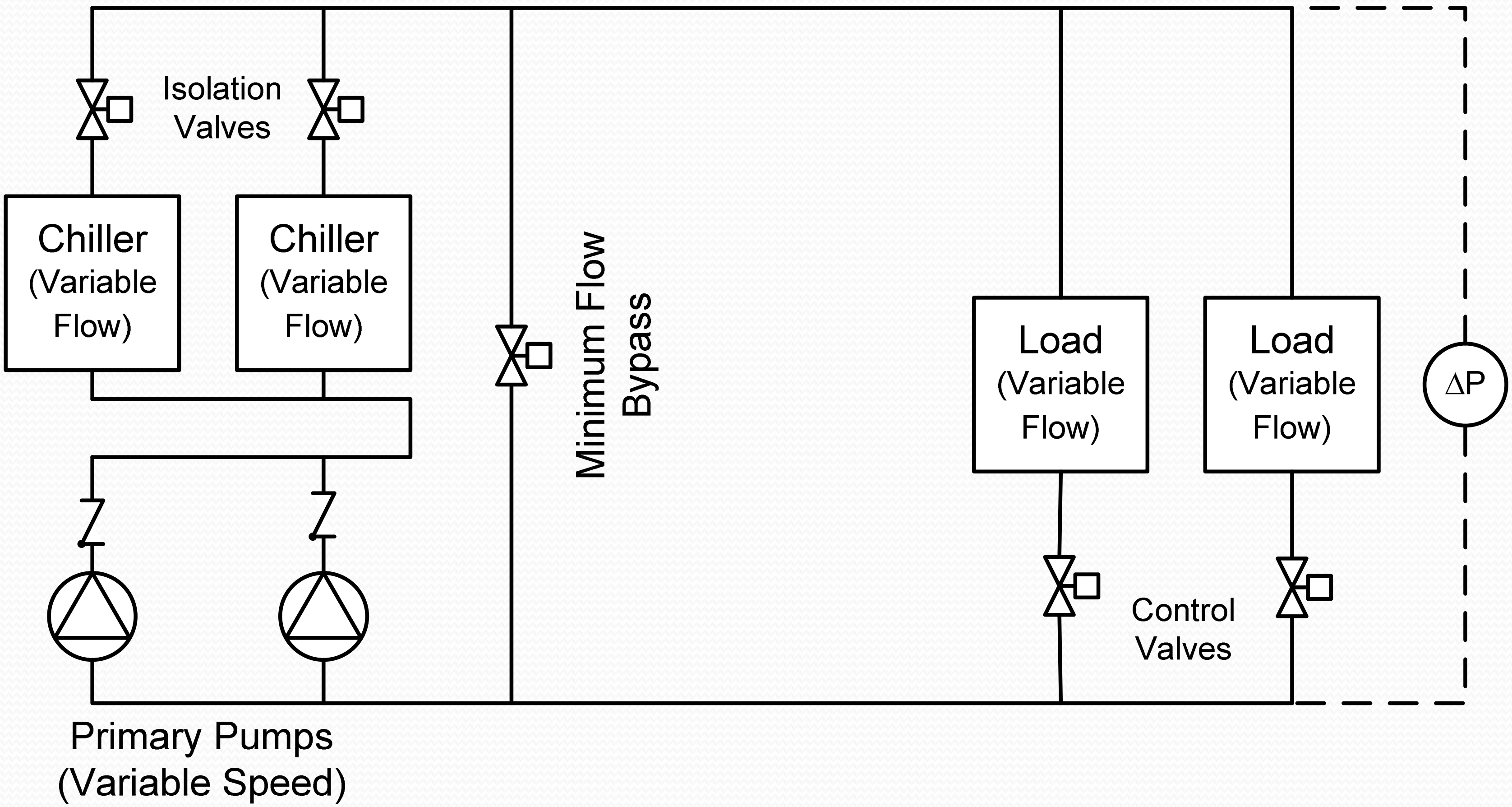
- Primary flow: chilled water flow through evaporators of chillers
- Secondary flow: chilled water flow from the chilled water plant to end-users and back

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

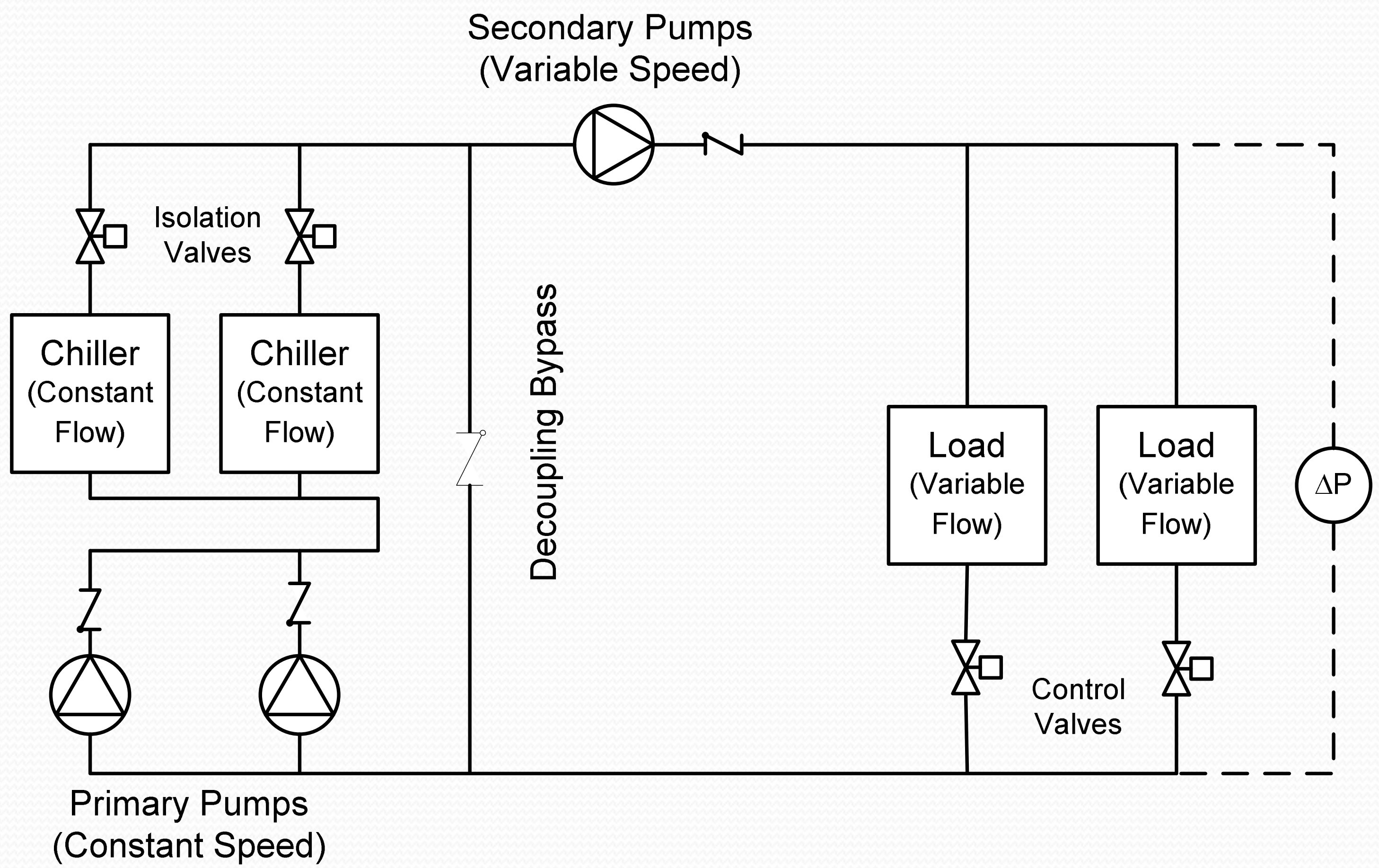
Constant Flow Primary/ Variable Flow Secondary Chilled Water System



Variable Primary Flow (Primary-Only) Chilled Water System



Pseudo-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 90.1-2010
  - WC Centrifugal, ≥ 300 ton
    - AHRI 550/590
    - 6.10 COP (0.58 kW/ton)
    - 6.4 IPLV (0.55 kW/ton)
  - Cooling tower fans
    - ≥38.2 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 ~0.74 kW/ton
  - 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

Anecdotal reports 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-Definition

- Chilled water supply-return temperature difference to be smaller than design
  - Occurs continuously in some systems
  - Correlated with low load conditions in others

Low ΔT Syndrome-Consequences

- Excess flow→unecessary 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

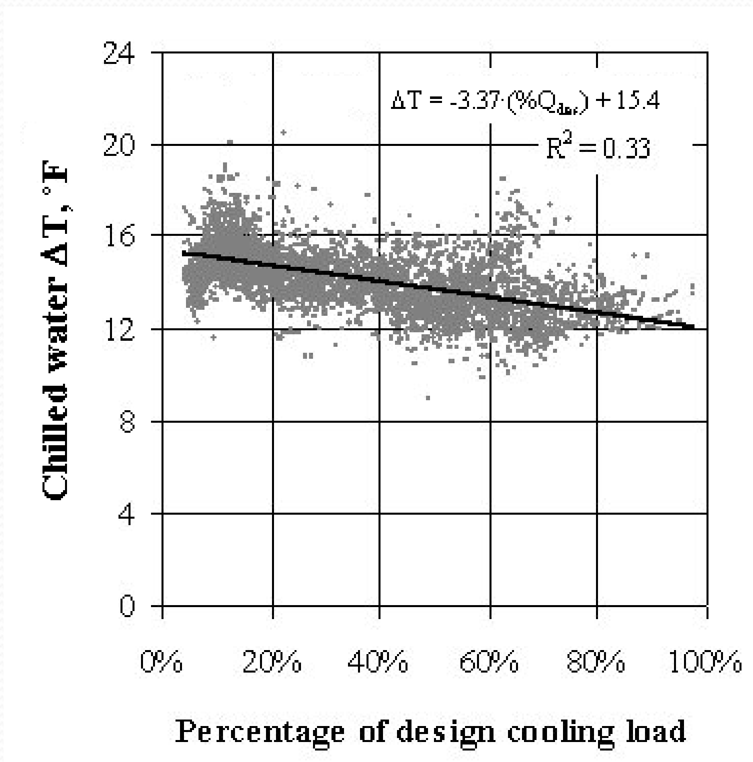
Why is VPF the cure?

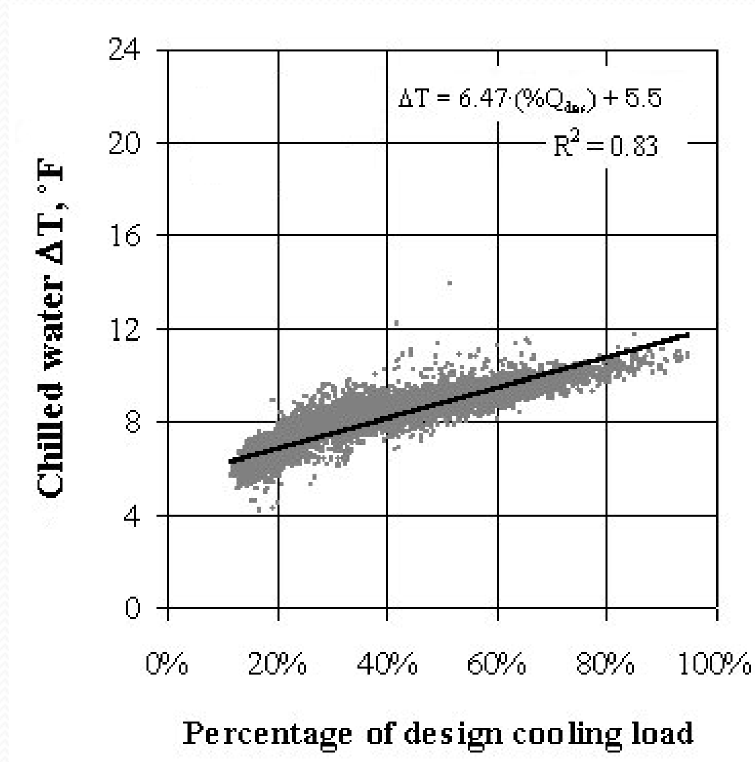
- For properly selected evaporators, flow can exceed design flow
- Increased flow compensates for reduced ΔT

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

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

VPF may be the cure, but is P/S the problem?





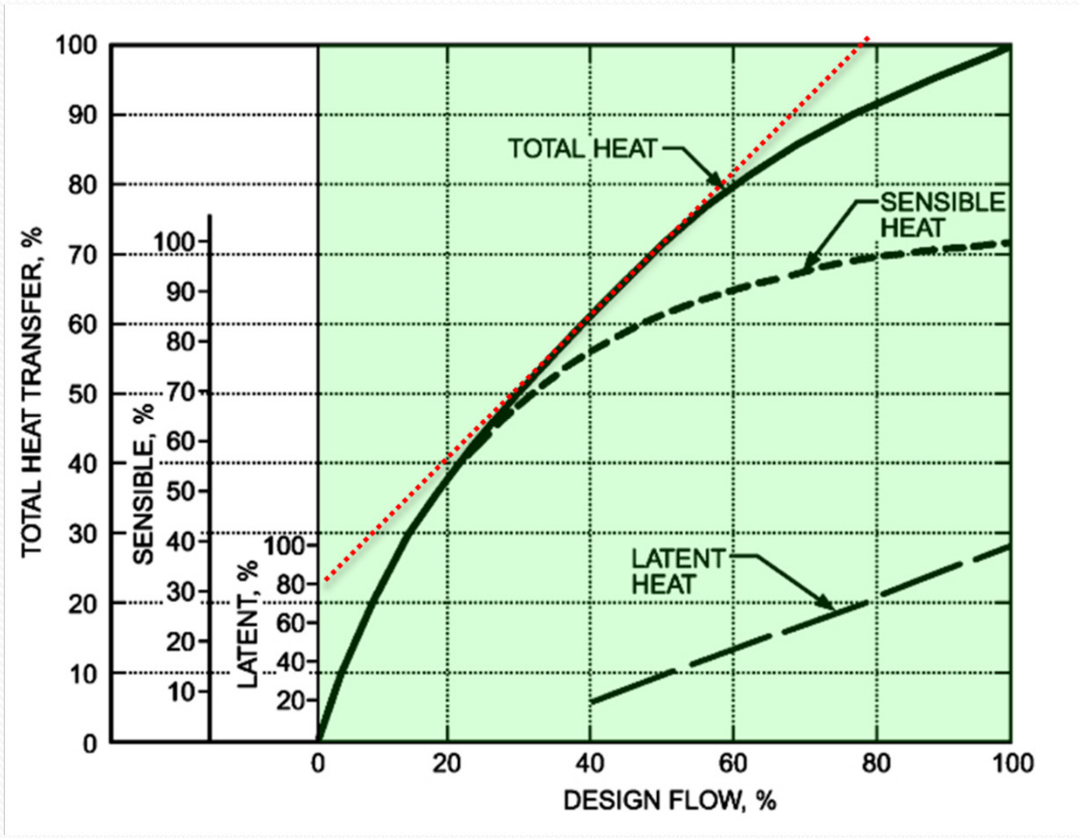
Data from two buildings connected to the same district primary/secondary system, 12°F design ΔT

Low ΔT Syndrome-Causes

- Controls
  - Set points
  - Calibration
  - Interlocks that don't
  - Chilled water reset
- Control valves
  - Three-way valves
  - Oversized two-way valves
  - Valves that don't shut off against system head
- Coil issues
  - Air or water side fouling
  - Oversizing
  - Selected for ΔT < system ΔT
  - OA economizer / 100% OA
- Dumb stuff
  - Persistent reverse flow in P/S bypass
  - Coils piped parallel instead of counterflow

There are fixes for all of these problems that do not require variable primary flow

How oversized coils cause low ΔT

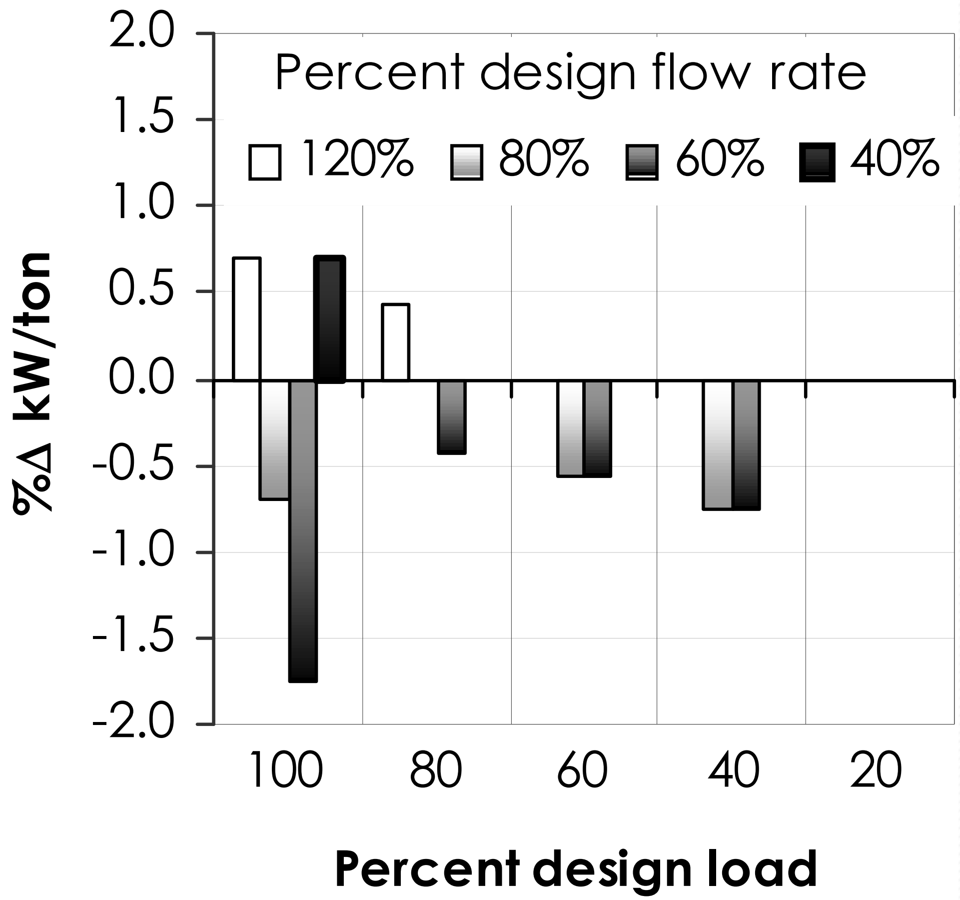


Red tangent line is 1:1 slope HT vs flow

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, Maximum 11 – 12 ft/s
  - ∴ maximum turndown for could be ~5.5:1 to ~8:1
  - More likely to select toward high end of range, but not at maximum velocity

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

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)

Typical Flow Rate Change Limits

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

Low-Flow Bypass

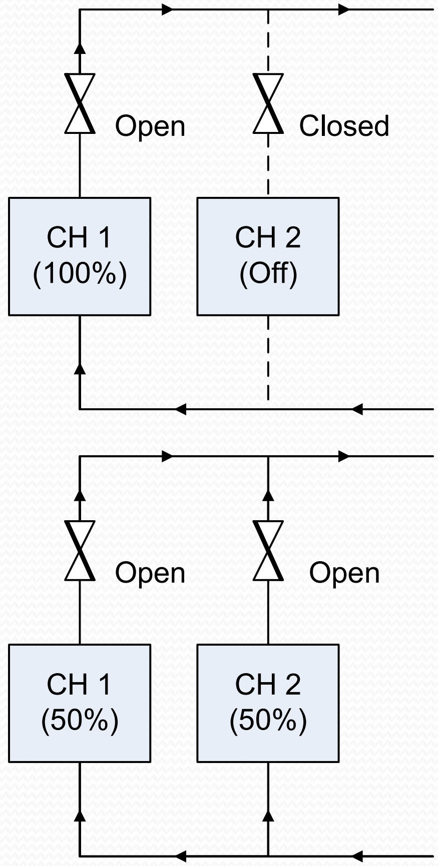
- Why?
  - Prevent extended operation of chillers below minimum flow
  - Sometimes omitted in plants with significant base load
- What
  - Normally closed bypass that opens when evaporator flow is below set point
  - Three-way valve(s) on selected loads
- Issues
  - Valve selection
  - Flow measurement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

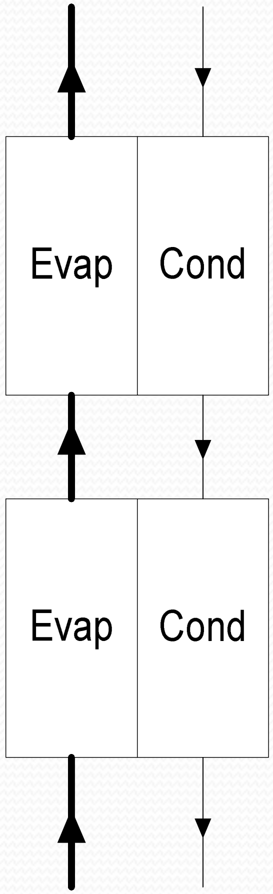


Chiller Staging

- 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



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

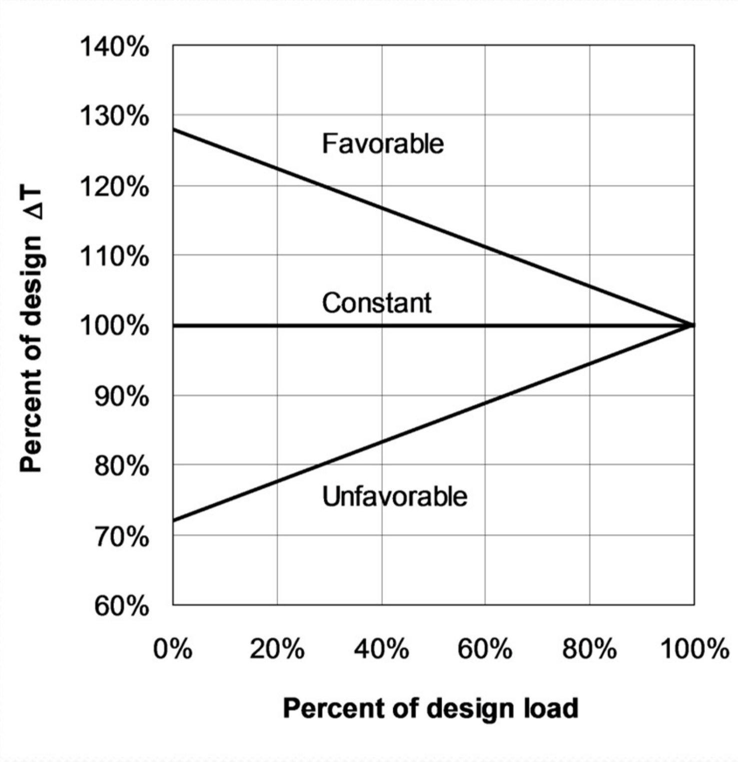
System Types

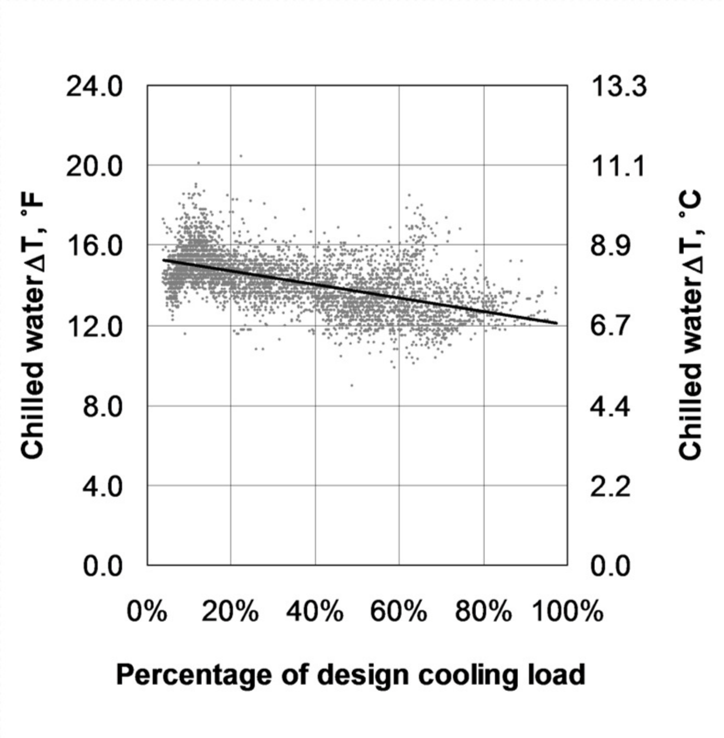
- Constant flow primary-only
- Constant flow primary/variable flow secondary
- Variable primary flow
- Primary/secondary with bypass check valve

Equipment and Plant Arrangement

- Chillers
  - Constant speed electric water cooled centrifugal
  - 0.58 kW/ton at 44°F/85°F
- 12°F CHW ΔT
- 3 gpm/ton CW
- Two-speed fan towers
- Parallel chillers, pumps, towers
- 1-5 chillers
- 120 – 170 ft total pumping head, 50 ft for primary

Load vs. ΔT

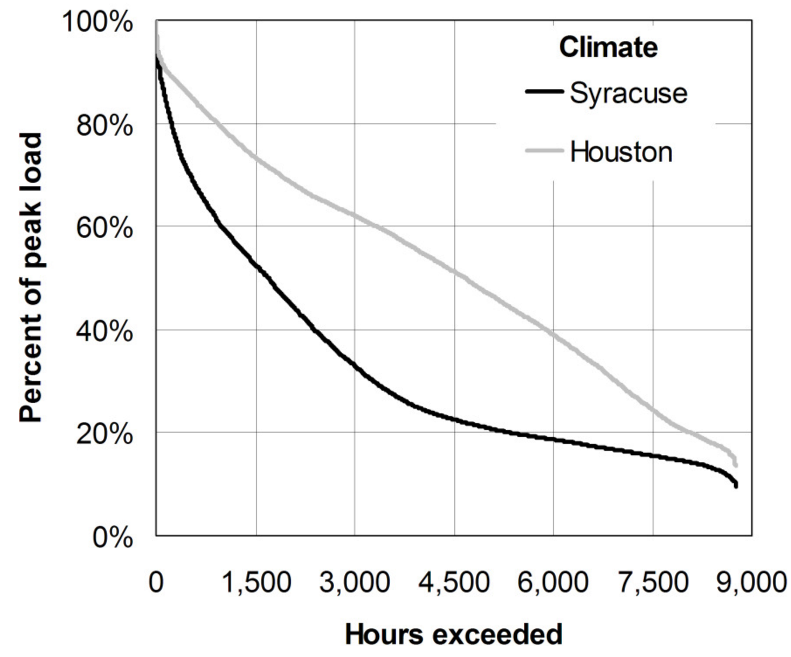




Note-Design ΔT is attained at full capacity.

Load Types and Climate

- Load types
  - 500 ton office
  - 1,500 ton medical center plant
  - 4,500 ton 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

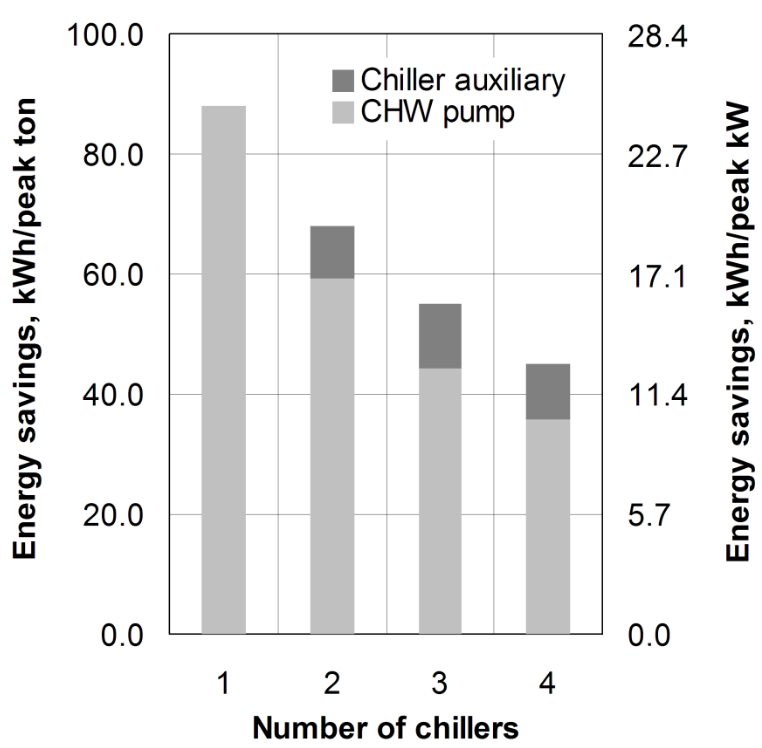
Simulation Methodology

- 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
- Chiller energy consumption not a function of CHW ΔT

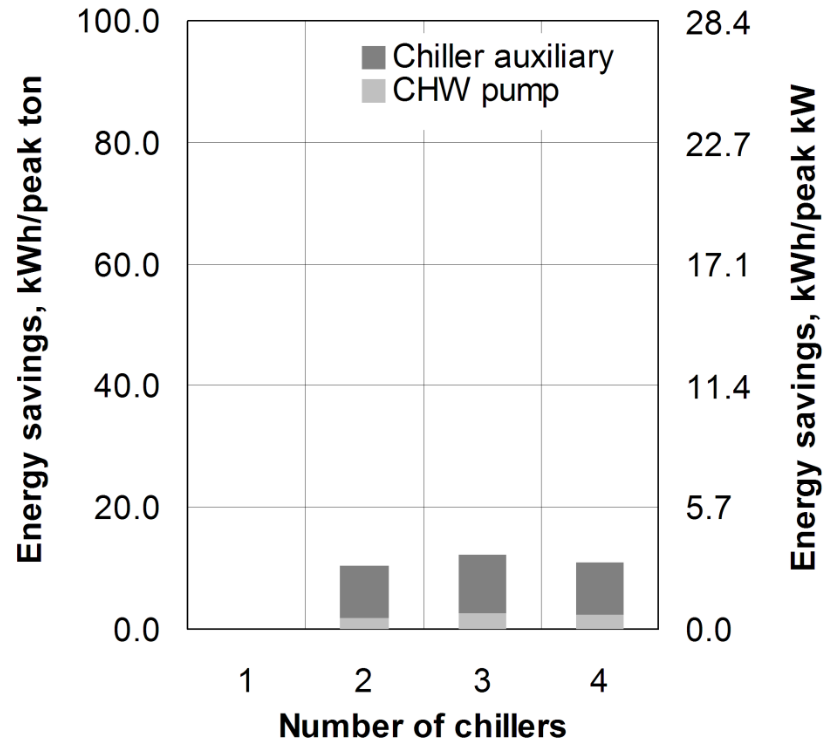
Energy Use Results

- For range of conditions modeled
  - VPF reduced total plant energy use ≤ 5%
  - Check valve modification of P/S had little effect
  - ***More chillers → lower savings***
  - Sources of savings
    - Most savings due to pump energy reduction (20-40%)
    - Chiller and auxiliary use ~equal

Energy Use Results



VPF vs. P/S



P/S-check vs. P/S

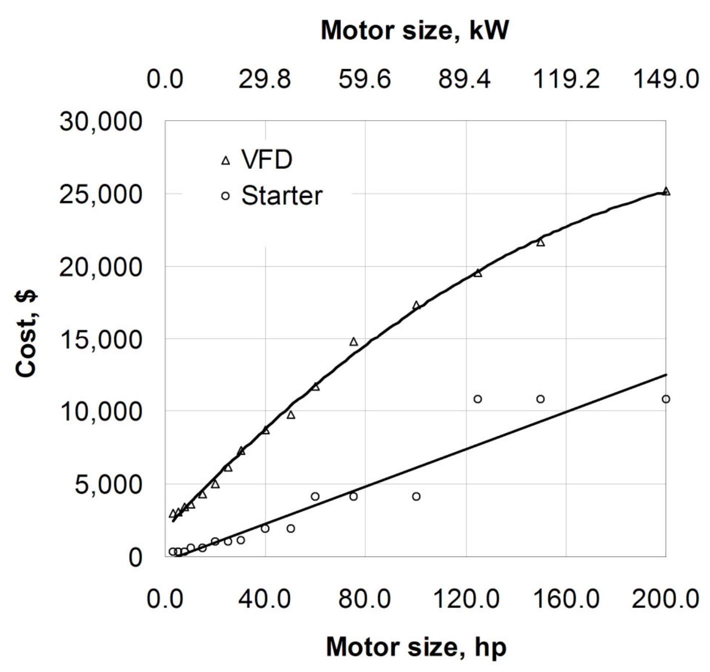
Syracuse Office Building Load

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

- Capital costs validated by a mechanical contractor
- Regressions to give continuous functions of size
- 4-6% 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 savings for VPF relative to P/S (3-5% 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…
- 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)

Survey

- Survey posted to web site (no longer active)
- Subjects identified through notice in journal, personal contacts, walk-ins
- Generic questions and questions tailored to participant category – manufacturer/designer/owner
- A sample of of information/opinion, not a statistical profile

Summary

- Manufacturers attitude toward VPF increasingly supportive
- Guidance on VPF is improving, but more credible documentation of performance is needed
- Most designers and owners with actual experience consider variable primary flow successful in appropriate applications
- Problems generally relate to set up of more complex controls

Other views

- Moses (HPAC July, 2004) summarizes experiences from 300 successful projects from 100 – 10,000 tons
- Taylor (ASHRAE J, February 2002) "The primary-secondary system may be a better choice for buildings where fail-safe operation is essential or on-site operating staff is unsophisticated or nonexistent."

Other views

- Eppelheimer (ASHRAE Trans. 1996)
  - "Can evaporator flow be varied in large centrifugal chillers, or any chiller for that matter? With the possible exception of absorption chillers, the answer is "yes, of course." But the second question might very well by "Why would you?"
- Schwedler and Bradley (1999, 2002)
  - An Idea for Chilled Water Systems Whose Time Has Come: Variable-Primary-Flow Systems
  - Variable-Primary-Flow Systems Revisited

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