Agenda and Objectives

Trane Engineers Newsletter Live Series

Variable-Speed Drives (VSDs) and Their Effect On HVAC System Components

Variable-speed drives (VSDs) can save energy, but the savings may not equal "the cube of the speed" in every case. This program looks at how VSDs affect the performance of pumps, cooling-tower fans, air-handler fans, and chillers, and discusses the differences in VSD control in each of these applications..

By attending this event you will be able to:

1. Explain why energy savings from VSDs vary by application and may not correspond to the "cube of the speed"
2. Summarize how other equipment in the system is affected when a VSD is added (to a condenser water pump, for example)
3. Identify control methods that can enhance the benefits of a VSD

Agenda

1) Fan Laws
   - a) Velocity-pressure relationships
   - b) Darcy-Weisbach equation
   - c) System relationships
   - d) Fan laws

3) Free Discharge Fans
   - a) System performance
   - b) Fan performance
   - c) Fan speed/efficiency curves
   - d) Cooling tower fans

4) Air handling fans
   - a) System resistance curves
   - b) Fan modulation
   - c) Control

5) Chilled Water Pumps
   - a) ASHRAE 90.1 requirements
   - b) Chilled water system pressure drops
   - c) Pump curves
   - d) System design options and comparisons
   - e) System control options
   - f) Energy savings

6) Condenser water pumps
   - a) Minimum allowable flow rate
   - b) Pump energy consumption
   - c) System interactions
   - d) Effect of variable condenser water flow on components
   - e) Additional effect of variable tower speed control
   - f) System energy comparisons
   - g) Guidance

7) Chillers
   - a) A commonly misused analogy
   - b) Compressor
   - c) The effect of Load and Lift
   - d) Comparative discussion
   - e) Rating methods
   - f) System analysis

Presenters

Trane Engineers Newsletter Live Series

Variable Speed Drives (VSDs) and Their Effect On System Components

(2006)

Lee Cline, PE | senior principal marketing engineer | Trane

Lee began his 25-year tenure with Trane as a factory service engineer for heavy refrigeration equipment. While in that role, he helped introduce the three-stage CenTraVac™ hermetic centrifugal chiller to the industry. He also served on the team that launched Integrated Comfort™ systems. Lee's considerable experience with building automation and control applications, coupled with his in-depth knowledge of Trane chillers, make him a valued member of the Applications Engineering and Systems Marketing team. He holds a patents in chilled-water system control and is a registered professional engineer in the State of Wisconsin. Lee earned a bachelor's degree in mechanical engineering from Michigan Technological University ("Michigan Tech").

Donald Eppelheimer, PE | senior principal applications engineer | Trane

Don has over 34 years of experience with Trane HVAC systems and their application. His expertise encompasses variable-air-volume systems and comfort cooling, with particular emphasis on direct-expansion refrigerant piping, chiller selection, chiller-plant design and control, thermal storage, and cold-air distribution. Don currently serves on the ASHRAE Journal review committee. He has also been a member of various ASHRAE committees, including TG/TB–Task Group for Tall Buildings, TC 9.1–Large Building Systems, and TC9.8–Large Building Applications. Don earned his BSME from Michigan State University.

W. Ryan Geister | manager, chiller field sales support | Trane

Ryan currently leads the product field sales support team for centrifugal and absorption chillers. During his 10 years with Trane, he helped develop and support Trane's design and analysis tools, managed the systems training portion of the Trane Graduate Training Program, and served as a regional sales manager. In these positions, Ryan garnered valuable experiences in many aspects of HVAC system design by working closely with engineers, contractors, owners, office management, and sales teams for myriad applications. Ryan was recently a featured speaker for the International District Energy Association (IDEA), the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), the American Society of Hospital Engineers (ASHE), and the Massachusetts Energy Efficiency Partnership (formerly MAIOF). He earned a bachelor's degree in engineering from the University of Illinois and his a master's degree in business from the University of Wisconsin.

VSDs and Their Effect on System Components

an
Engineers Newsletter Live
telecast

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AIA continuing education
Learning Objectives

Participants will learn the following about varying the speed of rotating equipment:

- **Varying speed theoretically affects energy consumption**
- **Theoretical performance doesn't occur in most HVAC situations**
- **Specific applications of different fans, pumps, and chillers yield varying levels of energy efficiency**

variable-speed drives (VSDs)
Today's Topics

- **Fundamentals**
  - Speed and performance
  - Fan laws
- **Practical application**
  - Control signal options
  - Effect on energy use

Today's Presenters

Don Eppelheimer
applications engineer

Lee Cline
systems marketing engineer

Ryan Geister
manager, absorption and centrifugal chillers

VSDs in HVAC systems
Effect on Components

- **Airside**
  - Cooling tower fans
  - Supply fans
- **Waterside**
  - Chilled water pumps (effect on chiller performance, system control)
  - Condenser water pumps (system interactions)
  - Chillers

Fundamentals: Speed, Performance, Fan Laws

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VSDs and their effect on system components

$$e = mc^2$$

speed of light	299,792,458 m/s
water	2 m/s
air	10–20 m/s

work = mass × resistance

Darcy-Weisbach Equation

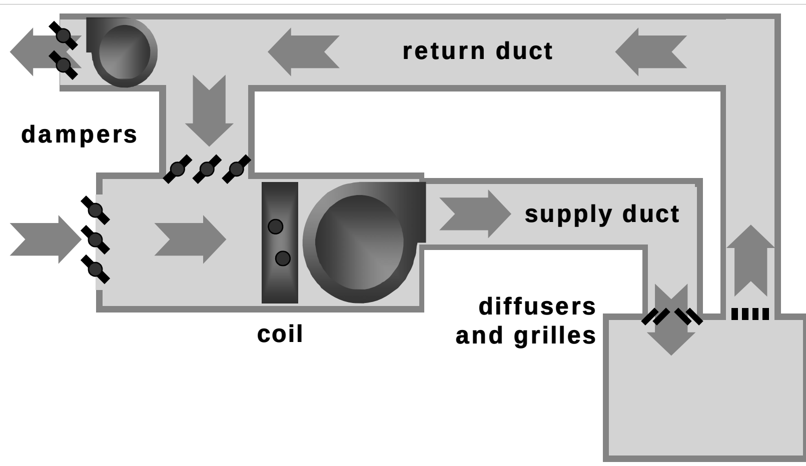
$$\Delta p = f \frac{L \rho V^2}{D \, 2 \, g_c}$$

- path length (L)
- fluid density (ρ)
- velocity (V)
- friction factor (f)
- path diameter (D)
- gravitational constant (g_c)

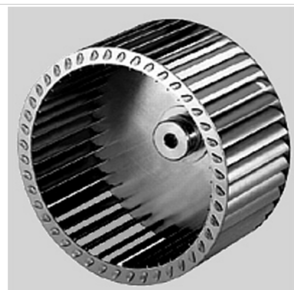
Darcy-Weisbach Equation

resistance α velocity²

System Resistance



Fan Laws



cfm α rpm

Δp α rpm^2

α cfm^2

hp α rpm^3

Chiller Laws?

resistance α velocity^2

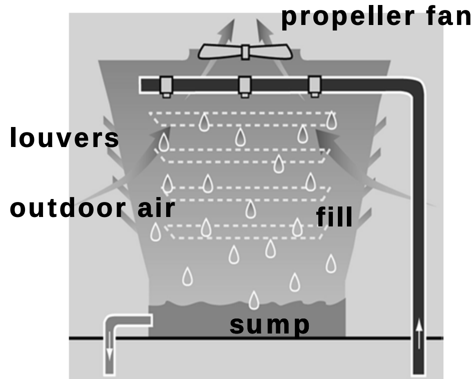
resistance α "lift"

Practical Application: Free Discharge Fans

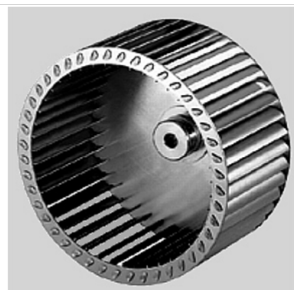
VSDs and their effect on system components

Free Discharge System

- Draw-through cooling tower
- Propeller fan



General Fan Performance

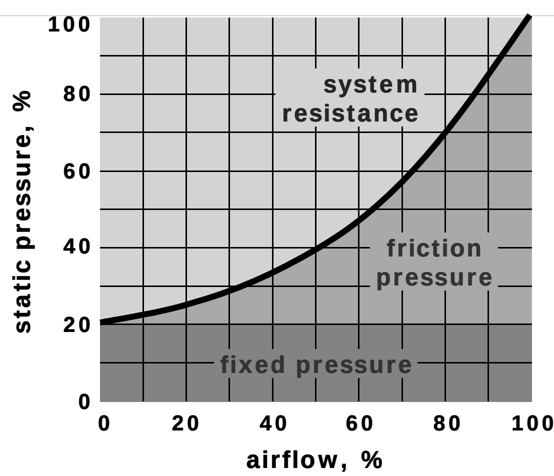


cfm α rpm

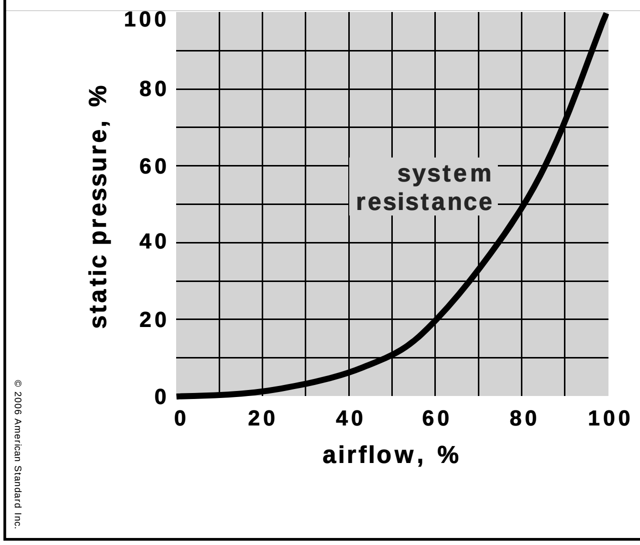
Δp α rpm^2

hp α rpm^3

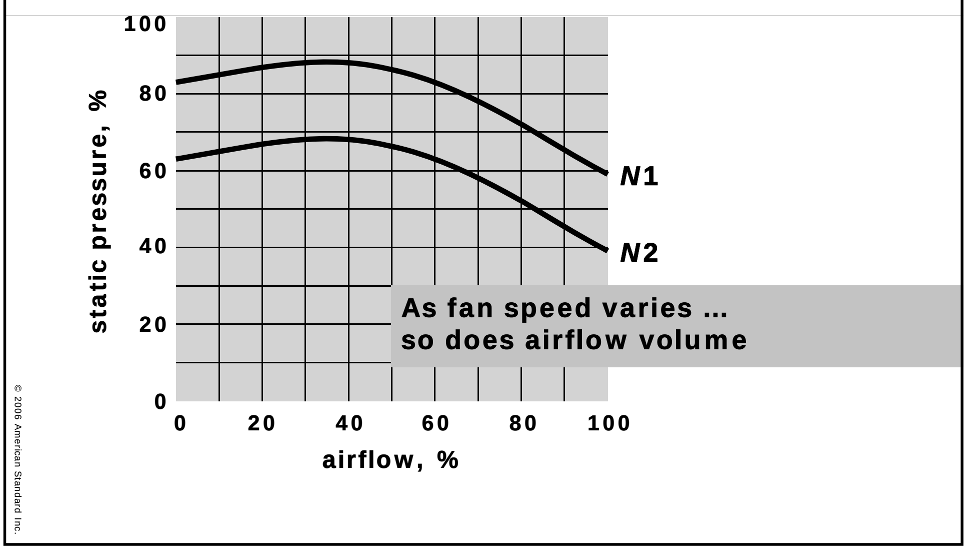
system performance
Static Pressure



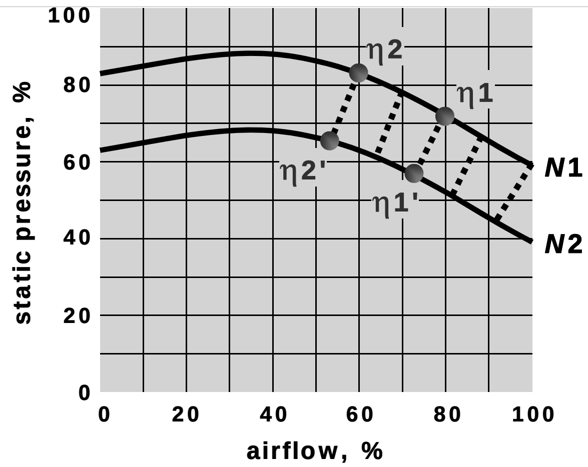
system performance
Free Discharge System



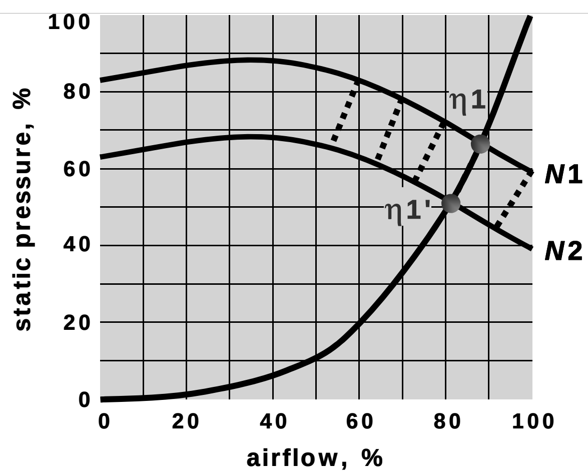
fan performance curves
Fan Speed (*N*)

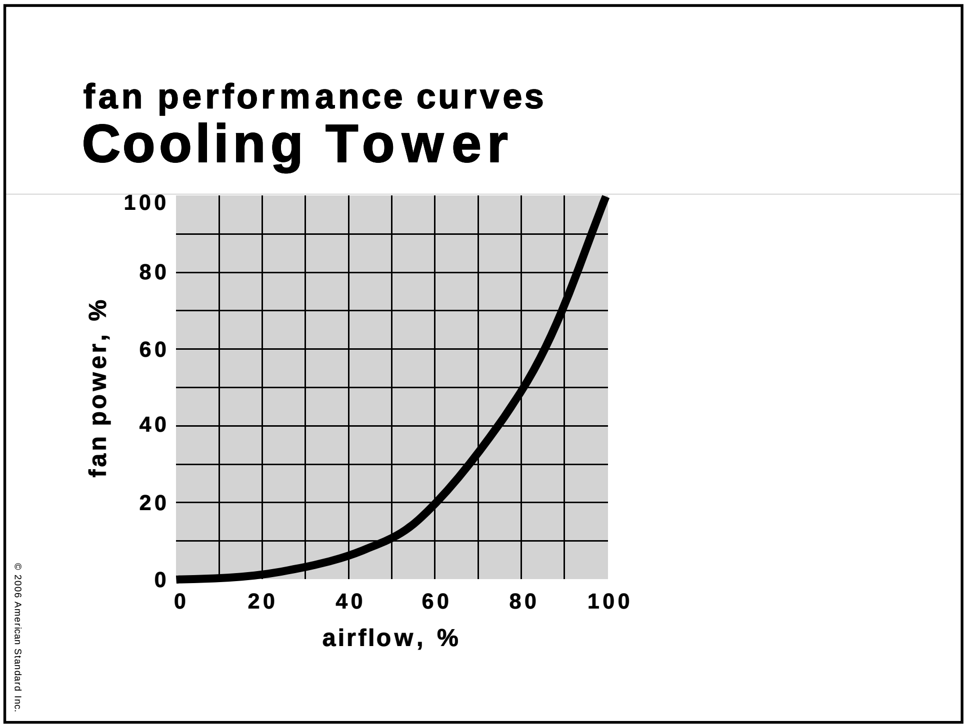


fan performance curves
Speed *N* vs. Efficiency η



performance curves
Fan and System




fan performance curves
Cooling Tower
fan power, %
0
20
40
60
80
100
airflow, %
0
20
40
60
80
100
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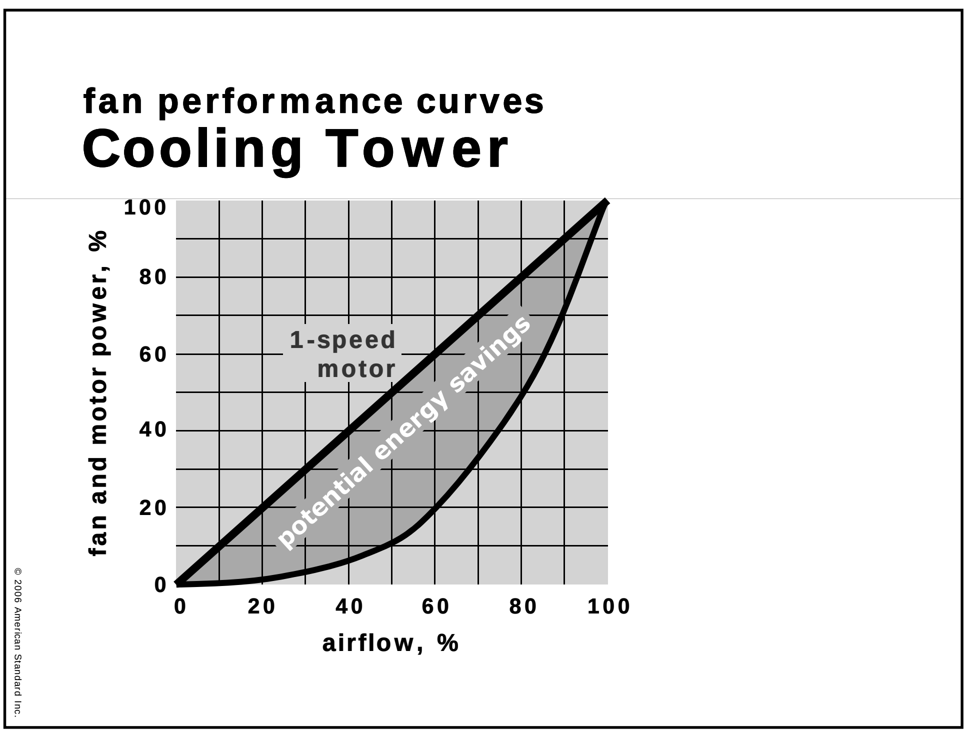
fan performance curves
Cooling Tower
fan and motor power, %
1-speed motor
potential energy savings
0
20
40
60
80
100
airflow, %
0
20
40
60
80
100
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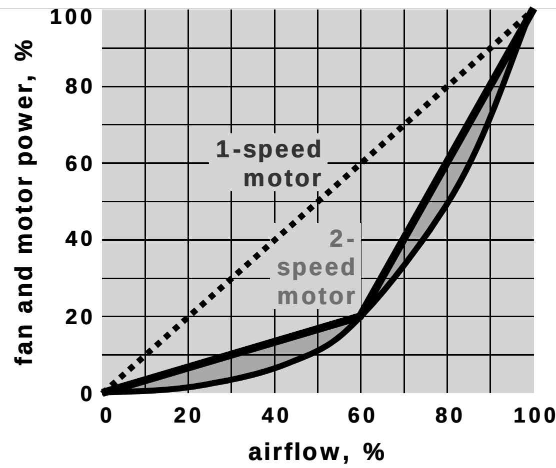
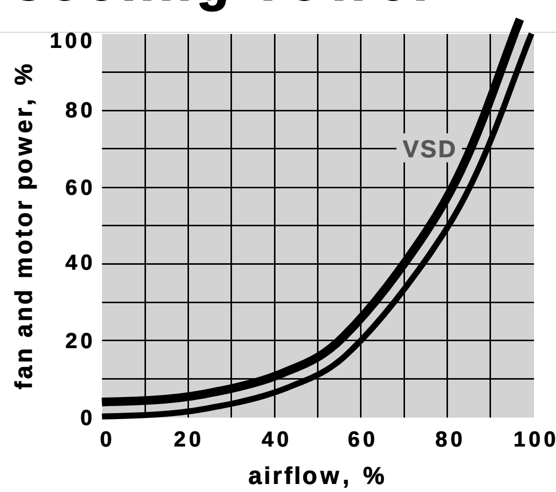
fan performance curves
Cooling Tower



fan performance curves
Cooling Tower

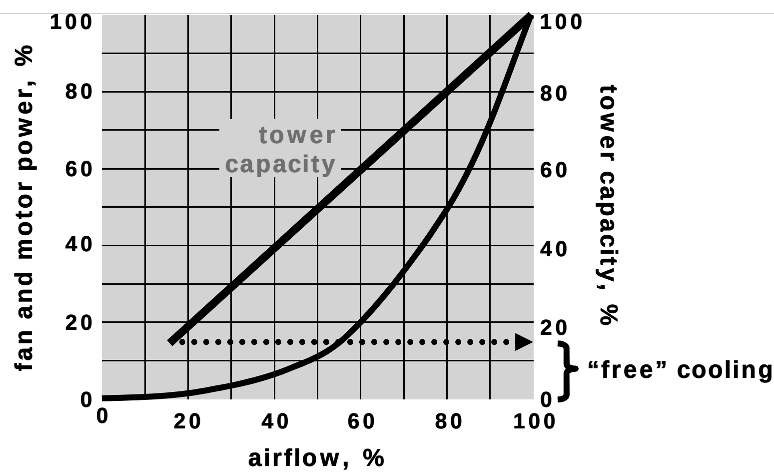


cooling tower application
Fan Energy Comparison

Control strategy	Energy use factor
1-speed fan cycling (base)	100% kWh
2-speed fan cycling	39% kWh
variable-speed control	19% kWh

source: Marley Technical Report H-001A

fan / tower performance curves
Free Cooling at Low Load



free discharge fans

Summary

- Performance approximates the "cube of the speed"
- Variable-speed drives (VSDs) are a great option for modulating capacity
- When considering VSDs for chilled water plants, start at the cooling tower

Practical Application: Ducted Indoor Fans

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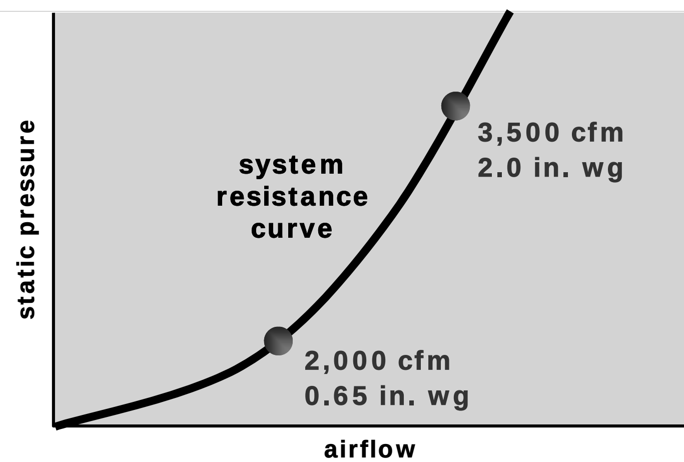
VSDs and their effect on system components

System Resistance

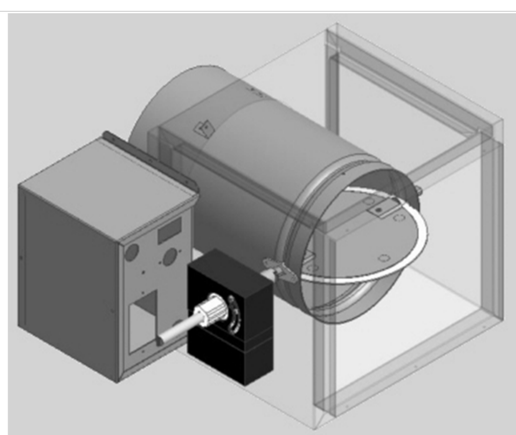
System Resistance

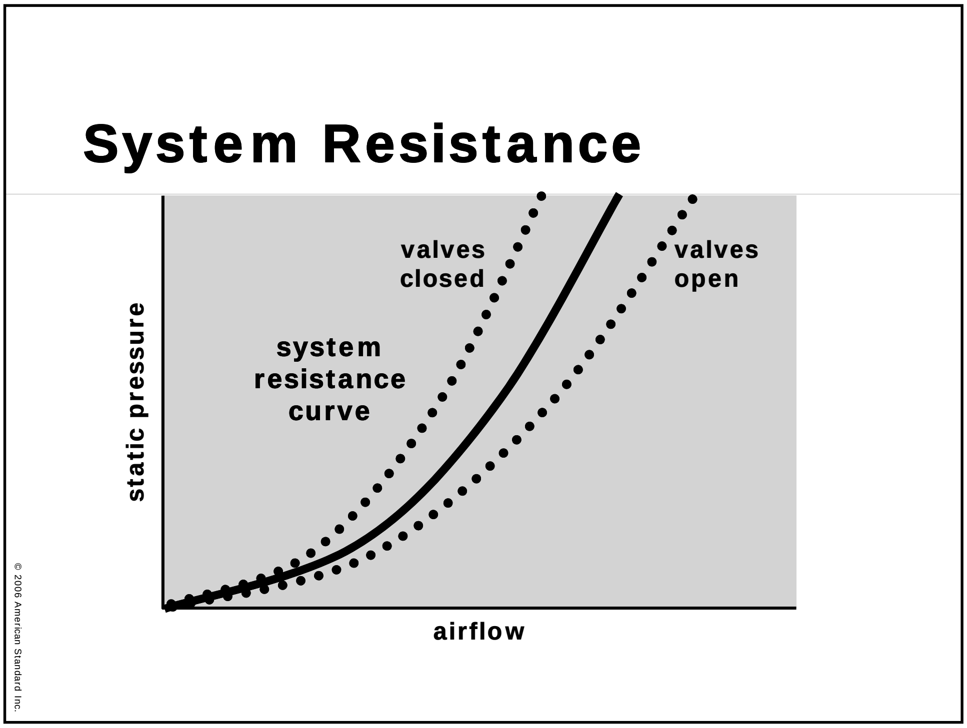
$$\Delta p = f \frac{L \rho V^2}{D\ 2\ g_c}$$

System Resistance



some devices don’t obey the rules for System Resistance




System Resistance
valves closed
valves open
system resistance curve
static pressure
airflow
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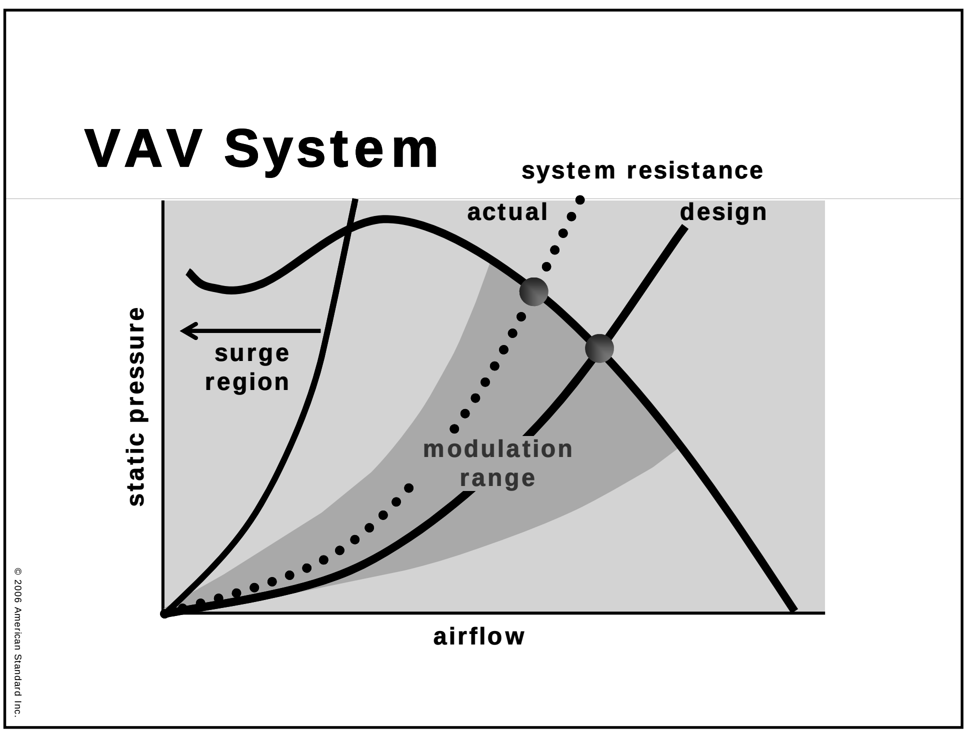
VAV System
system resistance
actual
design
surge region
modulation range
static pressure
airflow
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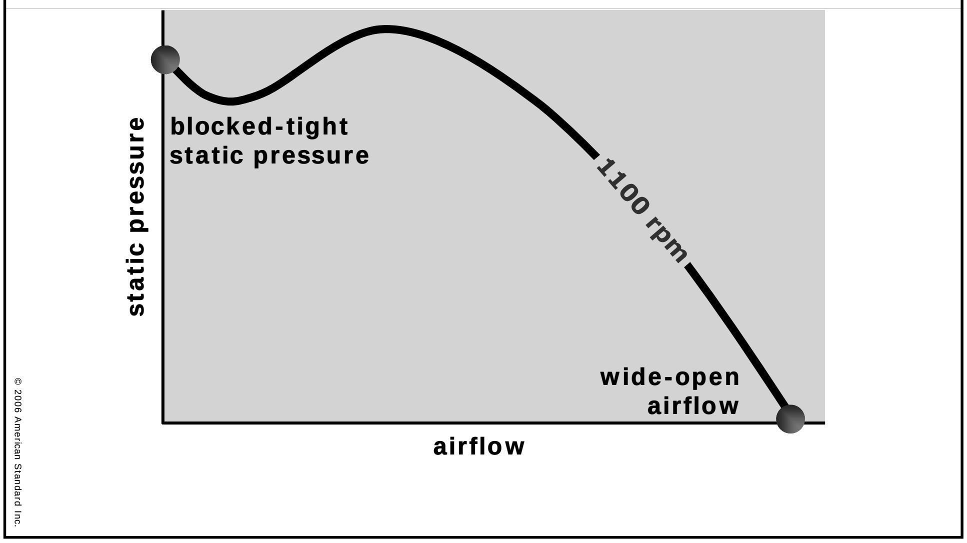
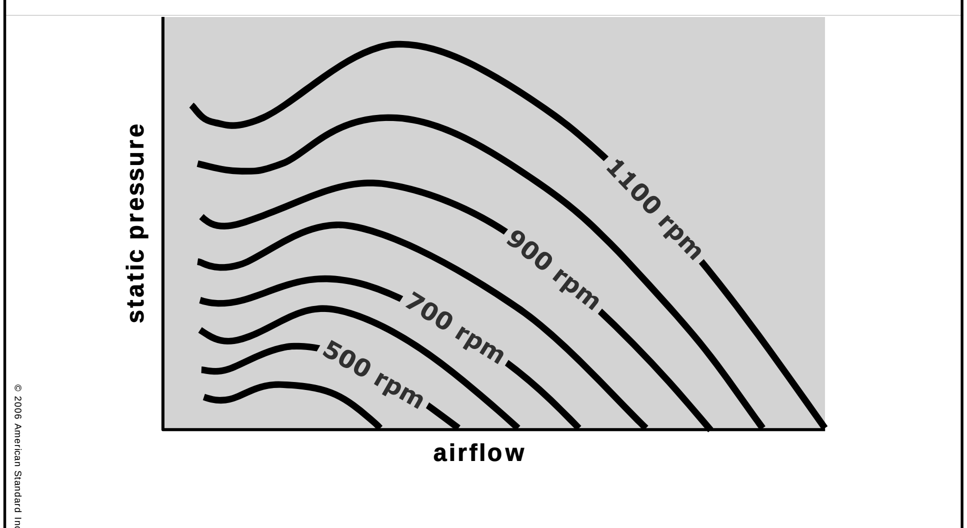
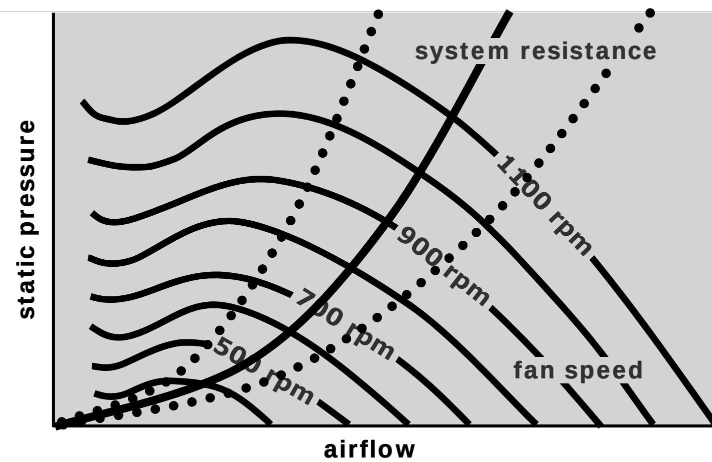
Fan Performance



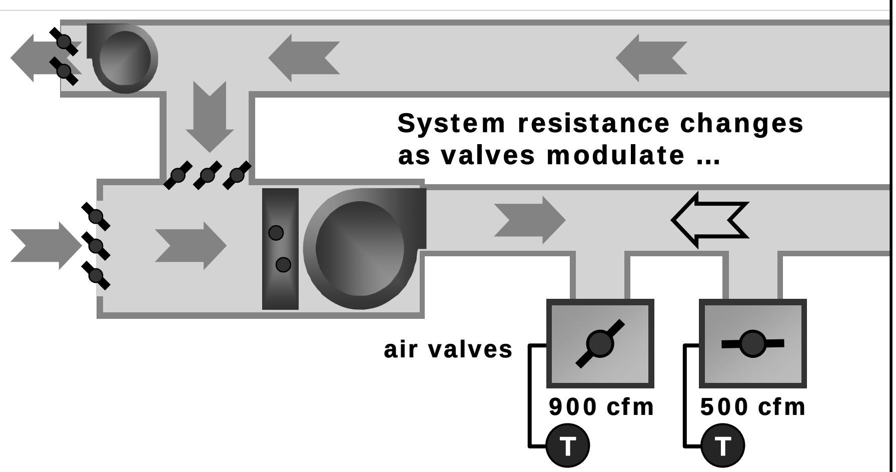
Fan Speed



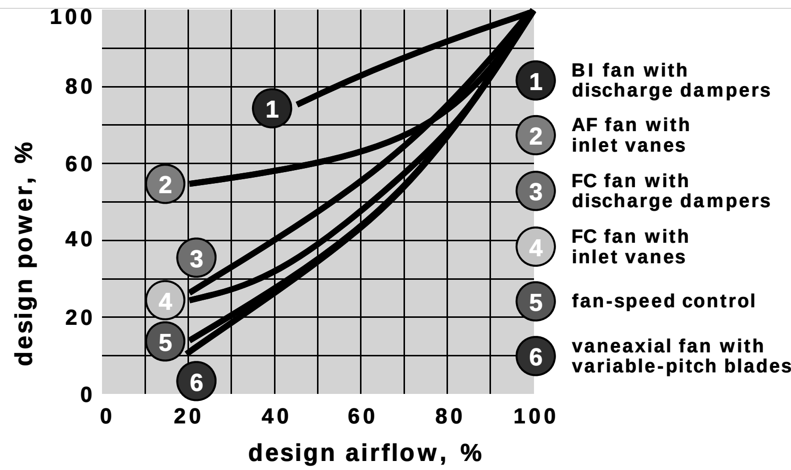
VAV System



VAV System



comparison of methods
Fan Modulation

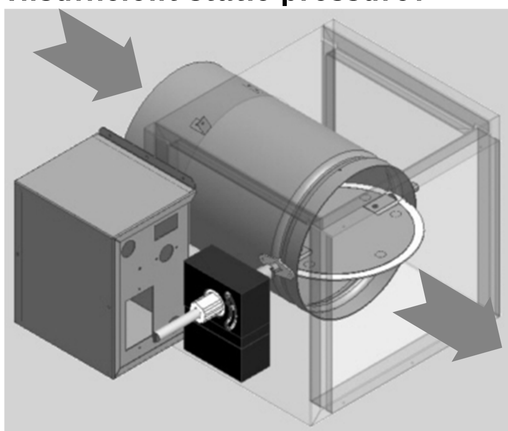


fan modulation
Objectives

- Produce adequate static pressure
- Eliminate excess static pressure
- Exploit diversity
- Maximize energy savings at fan
- Provide stable control
- Keep everyone comfortable

Static Pressure Control

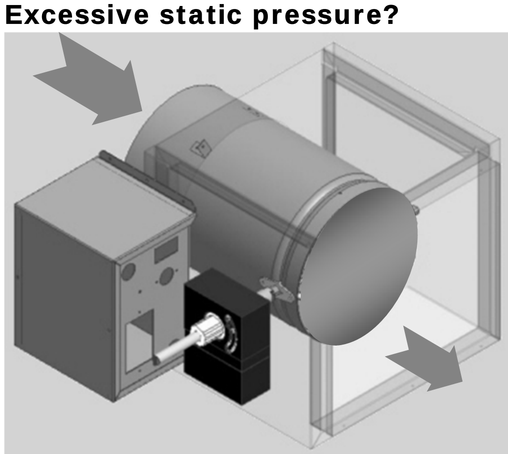
Insufficient static pressure?



VAV box delivers too little airflow

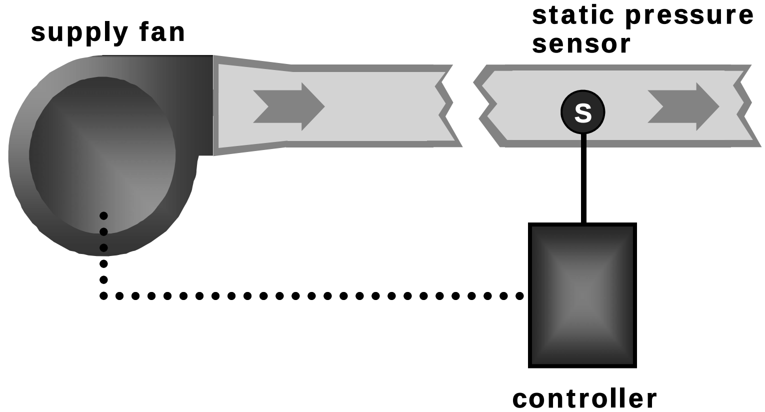
Static Pressure Control

Excessive static pressure?

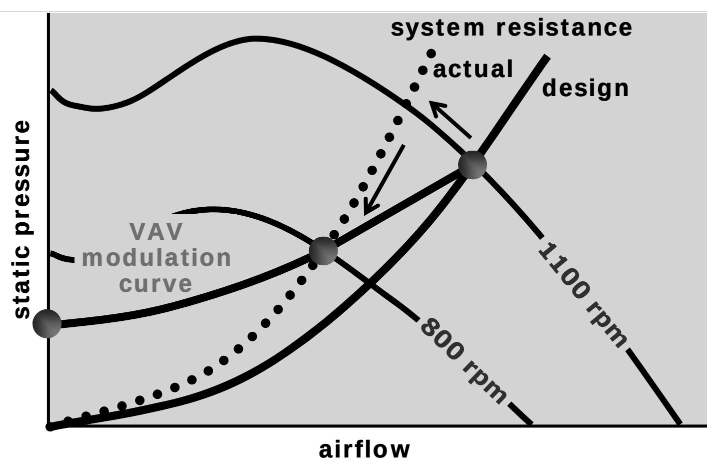


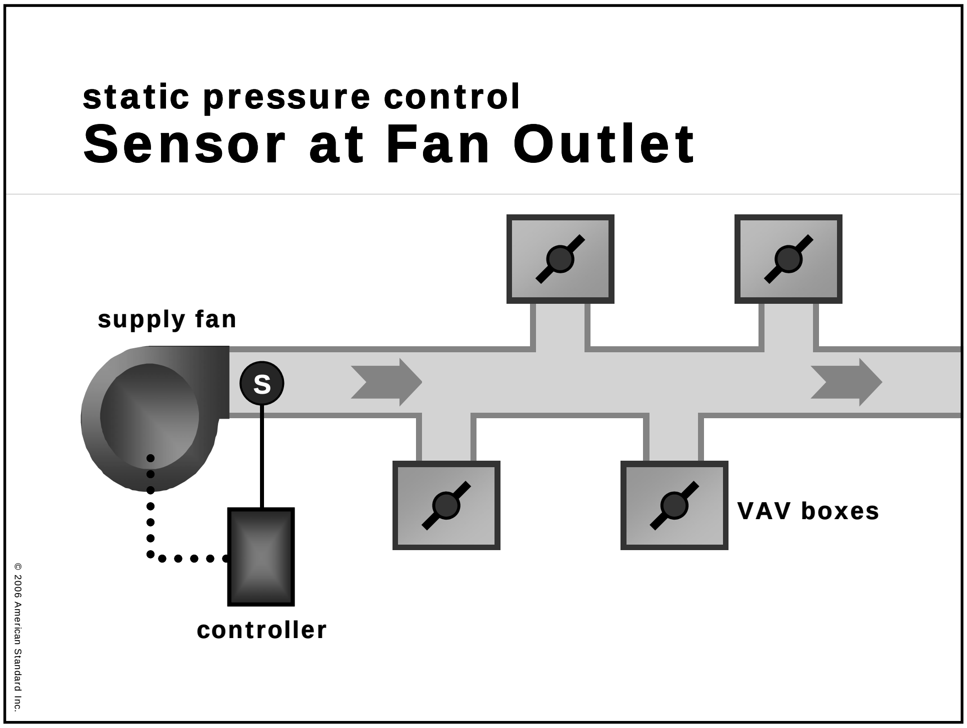
- **Wasted energy**
- **Poor comfort control**
- **Poor acoustics**

Fan Control Loop



VAV System Modulation




static pressure control
Sensor at Fan Outlet
supply fan
S
VAV boxes
controller
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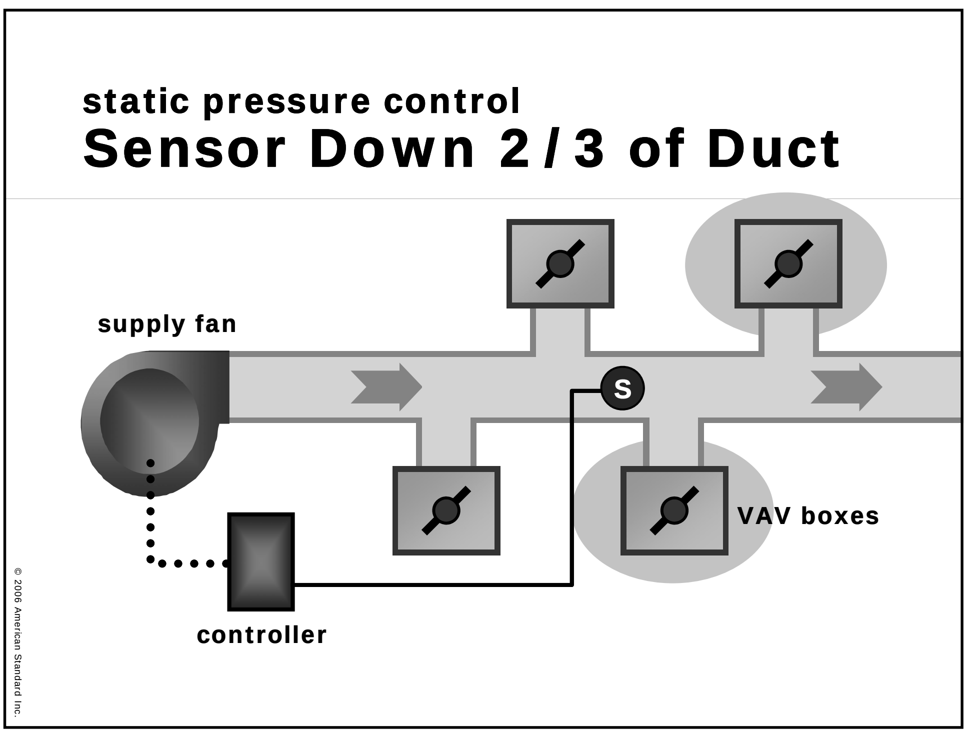
static pressure control
Sensor Down 2 / 3 of Duct
supply fan
S
VAV boxes
controller
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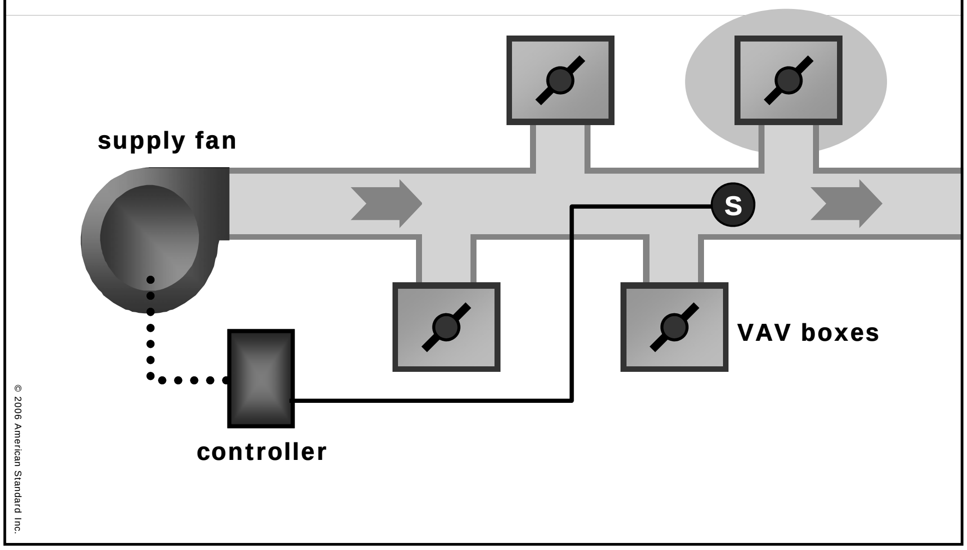
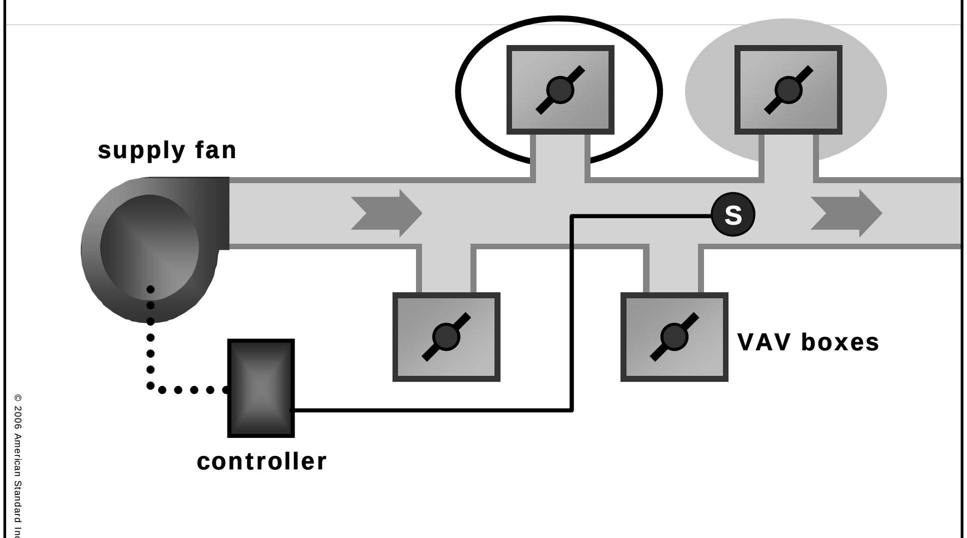
static pressure control
Sensor Down 3 / 4 of Duct

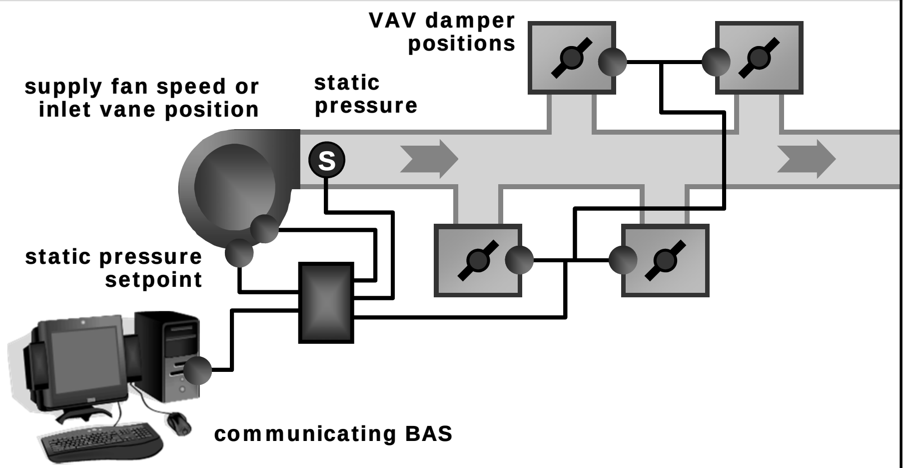


static pressure control
Sensor Down 3 / 4 of Duct



optimized static pressure control

Sensor at Fan Outlet



static pressure control methods

Performance Comparison

Control method	Airflow	Fan static pressure	Fan input power	Full-load power
	24,000 cfm (full load)	2.7 in. wg	22 hp	100%
Fan outlet	18,000 cfm	2.1 in. wg	13 hp	60%
Supply duct	18,000 cfm	1.9 in. wg	12 hp	55%
Optimized	18,000 cfm	1.5 in. wg	9.5 hp	43%

Practical Application: Pumping Water

VSDs and their effect on system components

why care about
Pump Energy

According to the DOE …

- Pumps represent 5% of industrial energy consumption
- Total cost of owning a pump is 90% energy consumption
- Pump energy consumption generally can be reduced by as much as 20%

pumping chilled water
ASHRAE 90.1-2001

Requires variable chilled water flow if:

- **Total pump power exceeds 75 hp**

  AND

- **System includes > 3 control valves**

pumping chilled water
ASHRAE 90.1-2001

Requires 30% design wattage at 50% flow if:

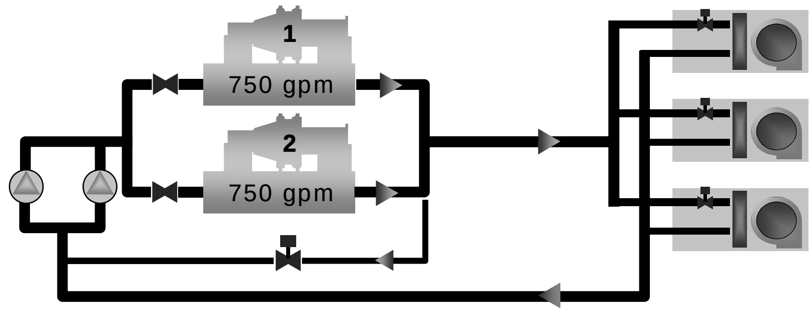
- **Any variable-flow pump motor $\geq$ 50 hp**

  AND

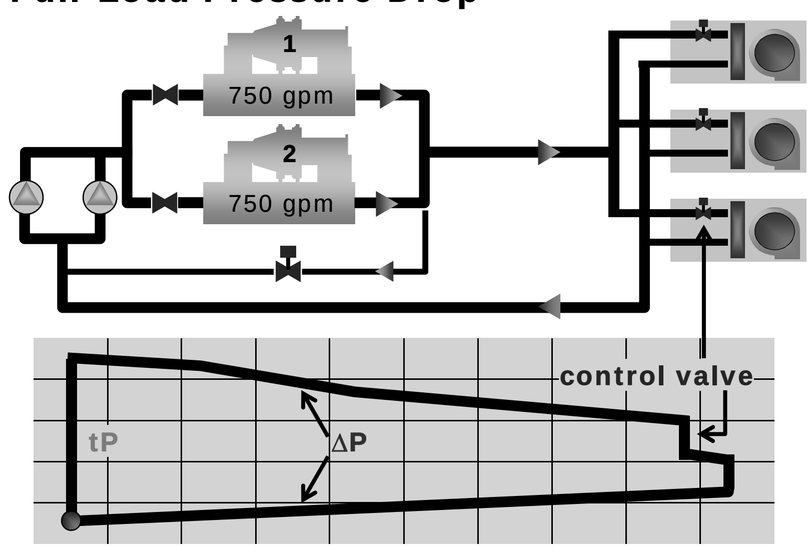
- **Design head pressure $\geq$ 100 ft**

Typical solution: Variable-speed drive

chilled water system
Variable Primary Flow

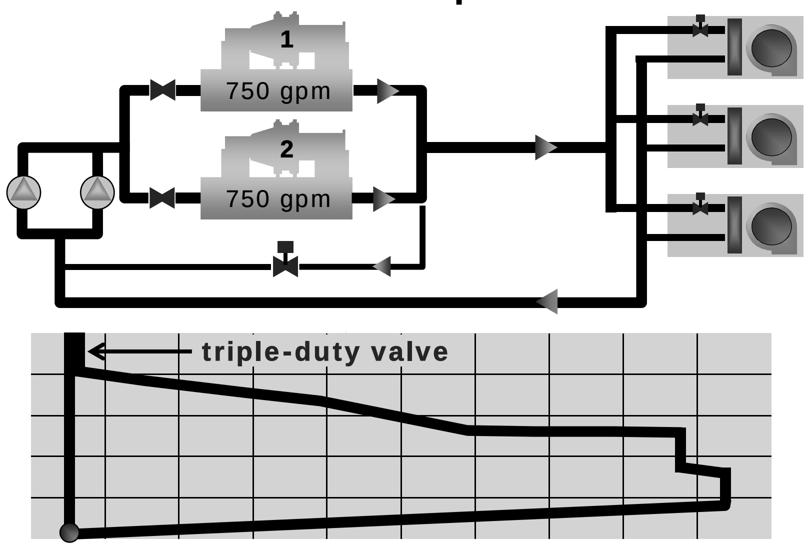


chilled water system
Full-Load Pressure Drop



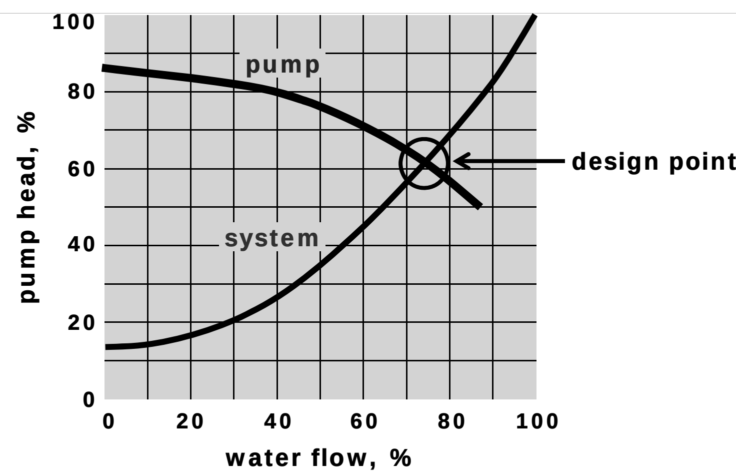
chilled water system

Full-Load Pressure Drop

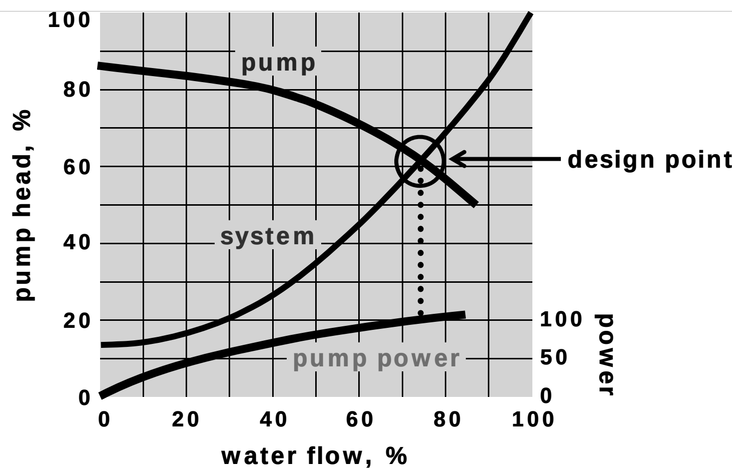


pumping system

Pump & System Curves



pump characteristics
Power



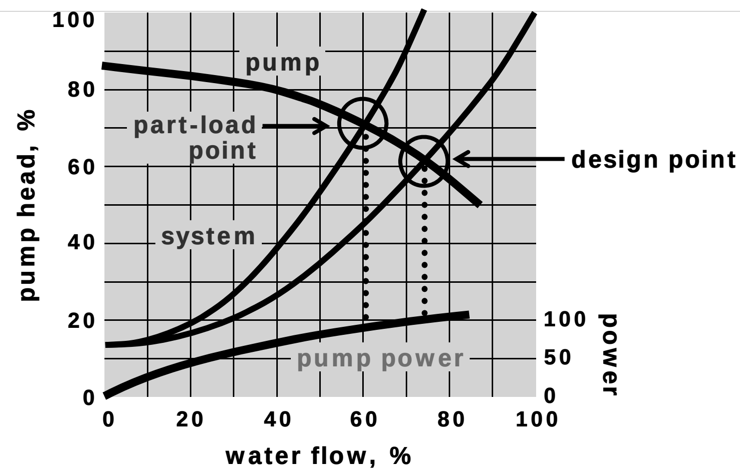
variable-flow water system
How Does It Unload?

Depends on:

- **Chilled-water system curve**
- **Pump curve**
- **Pump control method**
  - ◆ Ride the curve
  - ◆ Different pump sizes
  - ◆ Vary the speed

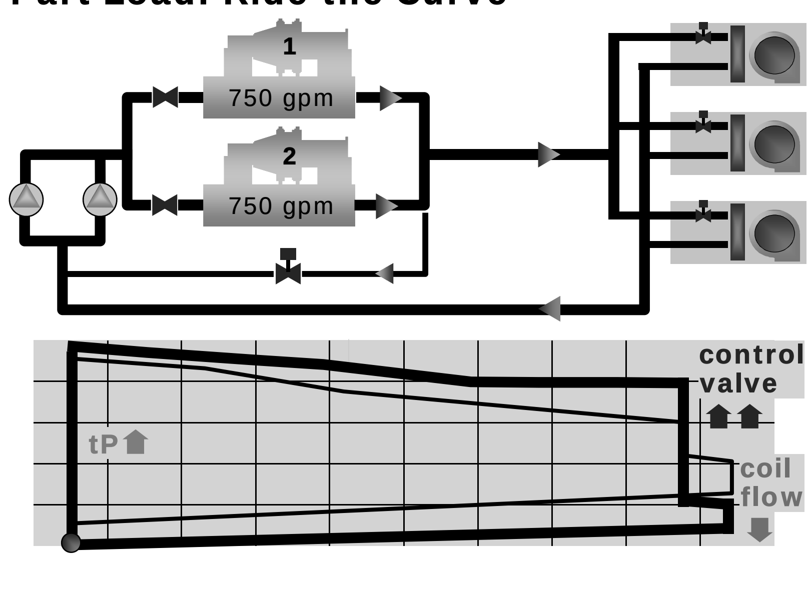
pump characteristics

Ride the Curve



chilled water system

Part Load: Ride the Curve



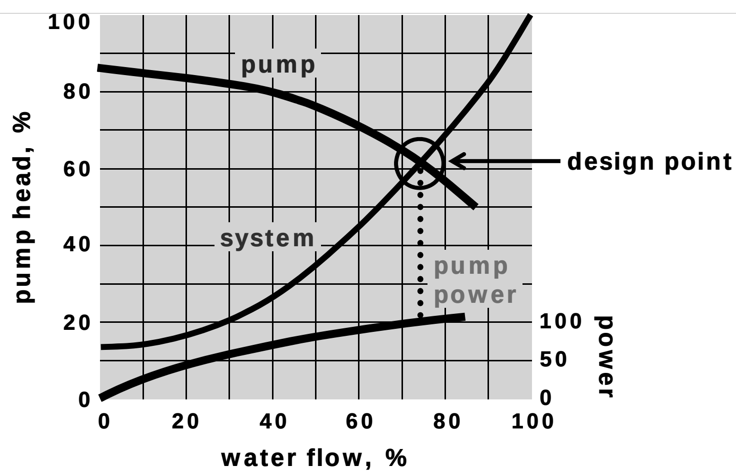
variable-flow water system
How Does It Unload?

safe zone

Depends on:

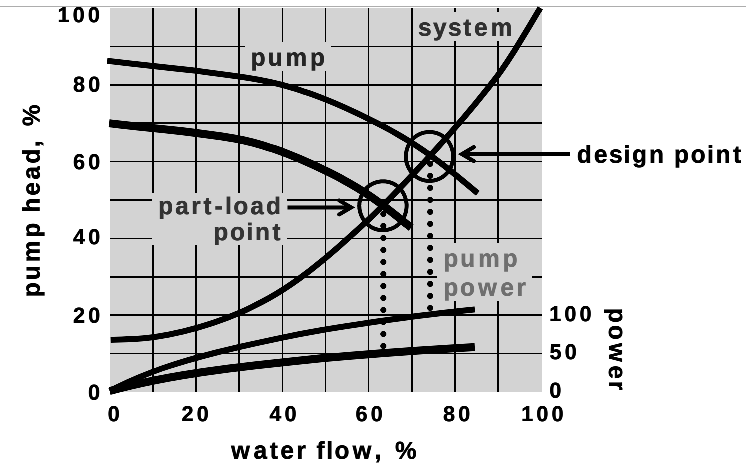
- **Chilled water system curve**
- **Pump curve**
- **Pump control method**
  - Ride the curve
  - Different pump sizes
  - Vary the speed

Pump Characteristics



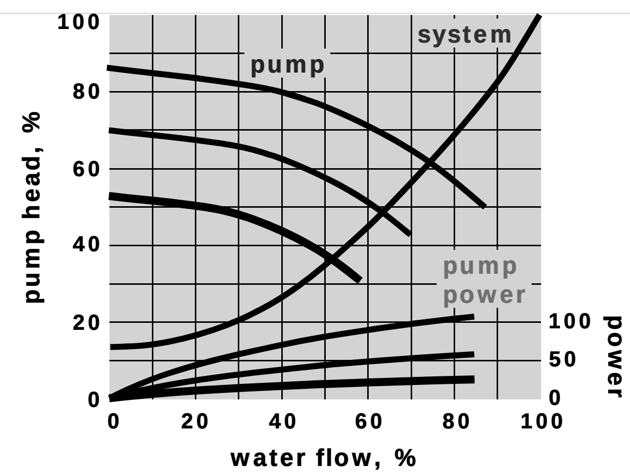
pump characteristics

Different Pump Sizes

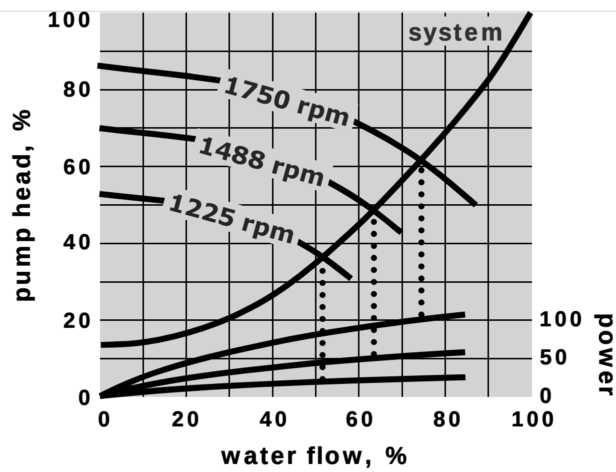


pump characteristics

Different Pump Sizes



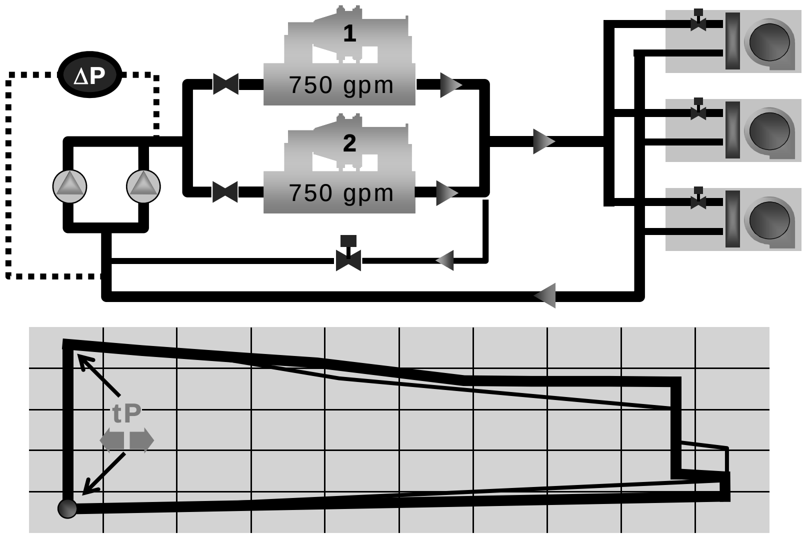
pump characteristics
VFD = Different Pumps



variable-speed pump
Control Methods

- Pressure control (ΔP) at pump
- Pressure control (ΔP) at end of system
- Critical-valve pressure reset

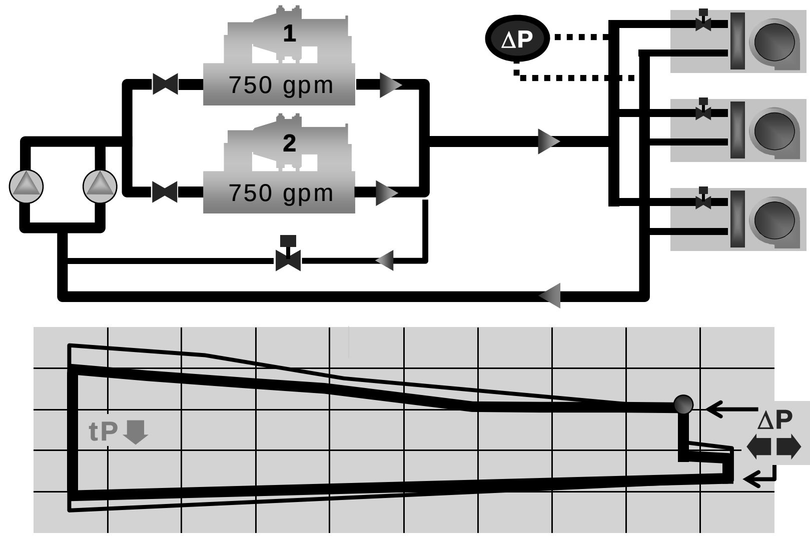
chilled water system
Part Load: ΔP at Pump



variable-speed pump
Control Methods

- Pressure control (ΔP) at pump
- Pressure control (ΔP) at end of system
- Critical-valve pressure reset

chilled water system
Part Load: ΔP at End of System

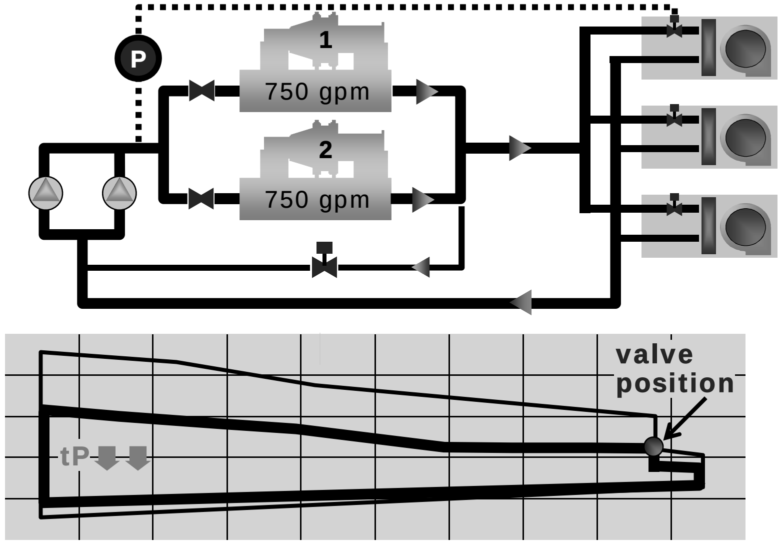


variable-speed pump
Control Methods

- Pressure control at pump
- Pressure control at end of system
- Critical valve pressure reset

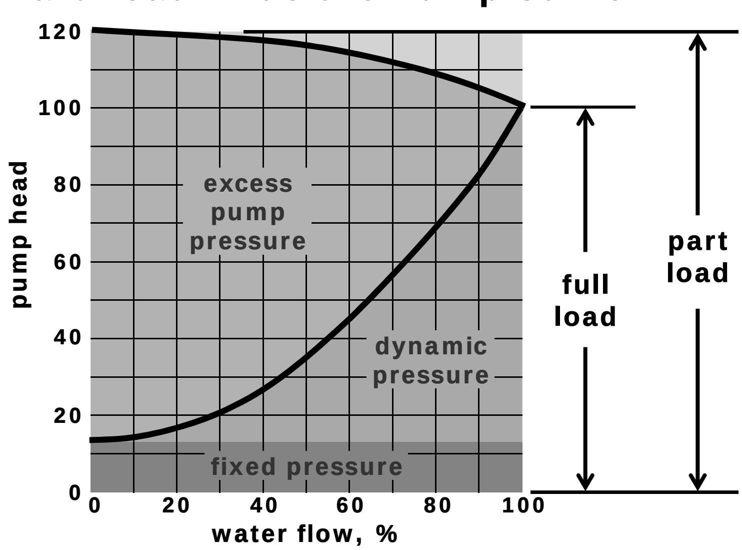
chilled water system

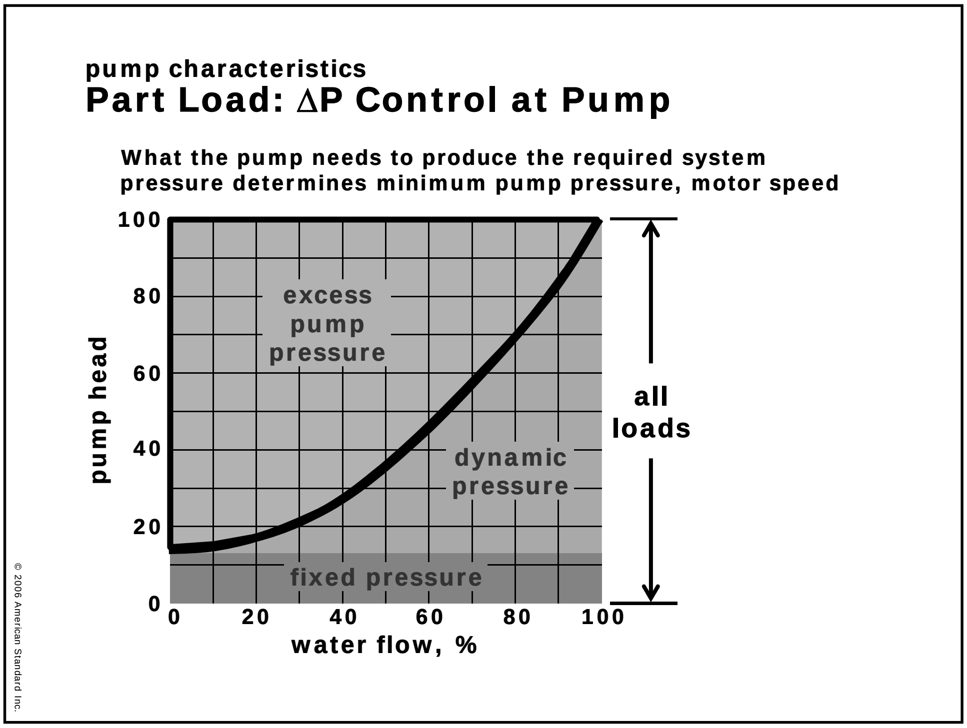
Part Load: Critical Valve Reset



pump characteristics

Part Load: Ride the Pump Curve




pump characteristics
Part Load: ΔP Control at Pump
What the pump needs to produce the required system pressure determines minimum pump pressure, motor speed
100
80
60
40
20
0
pump head
excess pump pressure
dynamic pressure
fixed pressure
all loads
0
20
40
60
80
100
water flow, %
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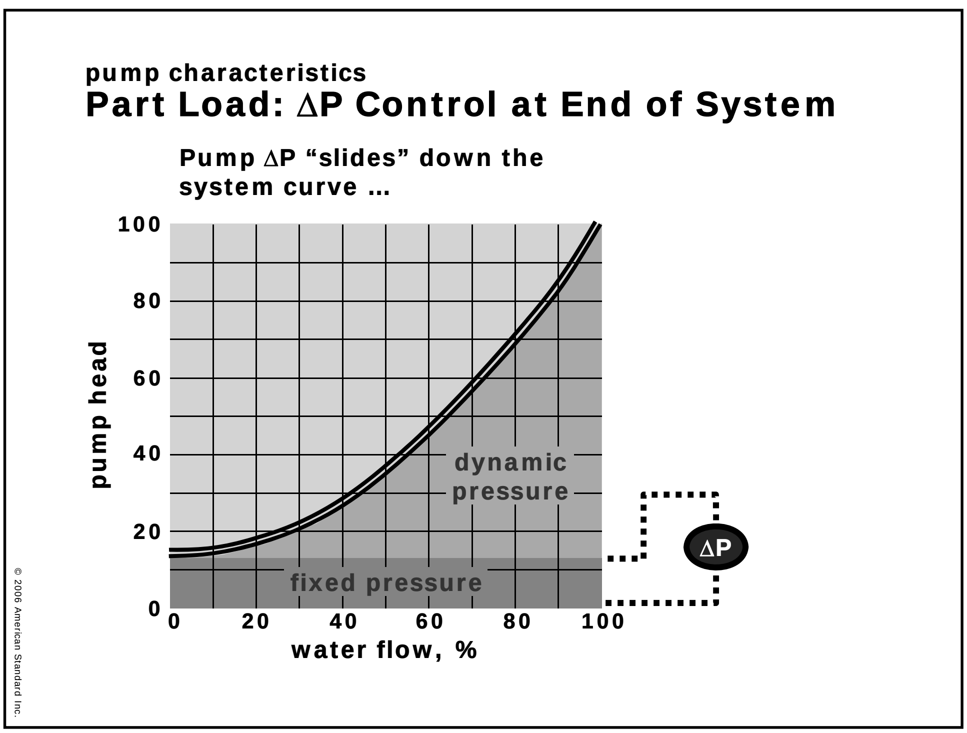
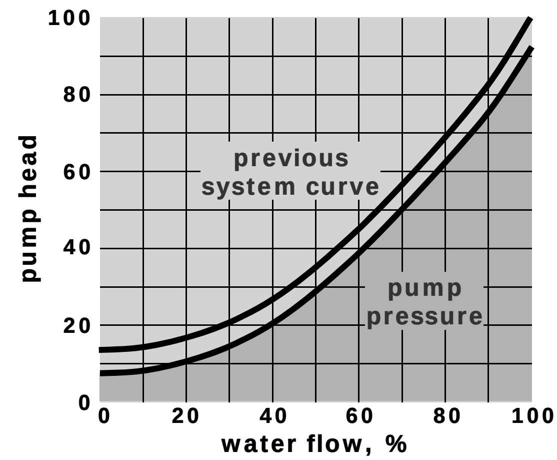

pump characteristics
Part Load: ΔP Control at End of System
Pump ΔP "slides" down the system curve …
100
80
60
40
20
0
pump head
dynamic pressure
fixed pressure
ΔP
0
20
40
60
80
100
water flow, %
© 2006 American Standard Inc.

pump characteristics

Part Load: Critical Valve Reset

Pump ΔP constantly reset to lowest possible value … almost all pressure drop is dynamic



variable-flow pumping

Summary

- **Energy savings depends on:**
  - Pump selections
  - Fixed vs. frictional pressure components
  - Control strategy
- **Energy savings can approach "cube of speed"**
- **Great application for variable-speed drives**

variable-flow condenser water

Pump Speed

- **Determining minimum speed**
- **How variable flow affects:**
  - Pump
  - Cooling tower
  - Chiller
- **Controlling flow to improve system performance**

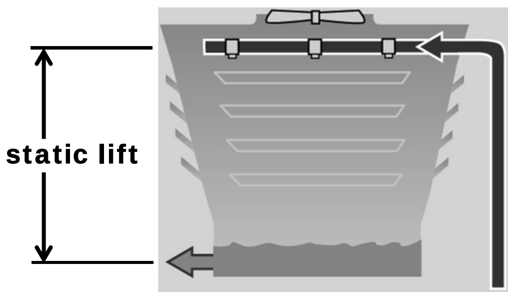
condenser water pump

Minimum Speed

Determinants:

- **Minimum condenser flow**
- **Tower static lift**
- **Minimum tower flow**
  - Nozzle selection
  - Performance
- **Compare curve with cubic**

cooling tower
Static Lift



cooling tower
Water Distribution

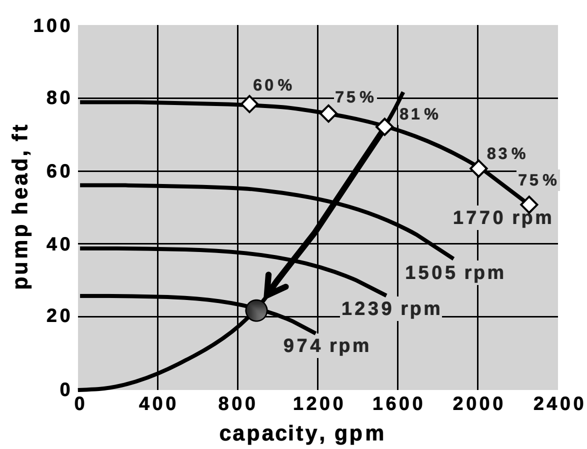
Example

1500 gpm system, 1770 rpm

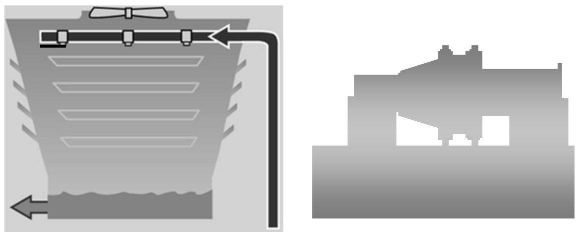
- Minimum flows:
  - Chiller 658 gpm
  - Tower 750 gpm
- Tower static lift 12.2 ft
- Pump:
  - Speed 974 rpm
  - Pump flow 875 gpm

variable condenser-water flow

Effect on Pump



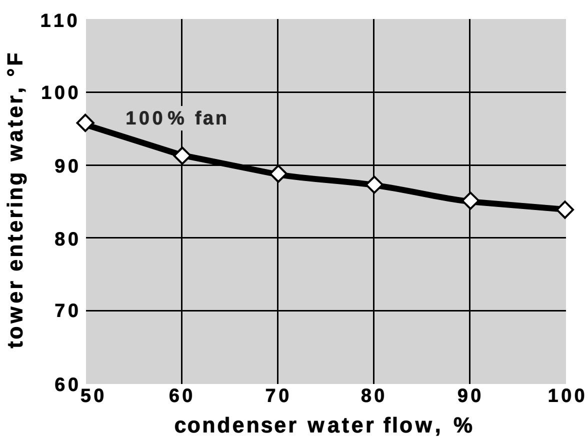
operating dependencies
Full Flow



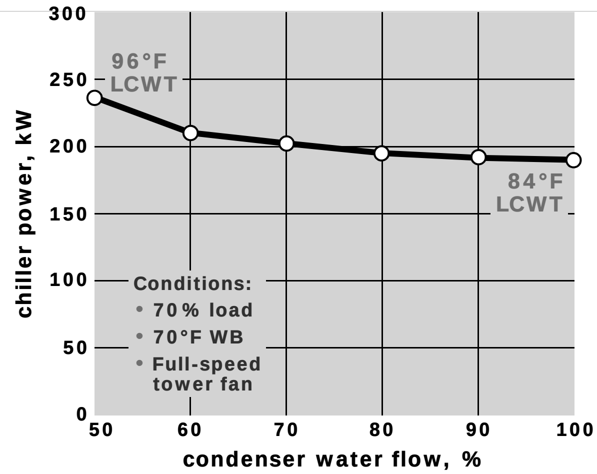
- Tower design
- Condenser water temperature & flow
- Heat rejection
- Wet bulb

- Chiller design
- Condenser water temperature & flow
- Load

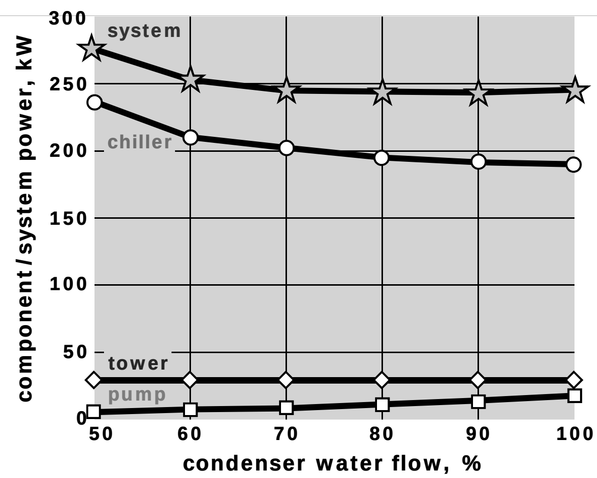
variable condenser water flow
Effect on Tower



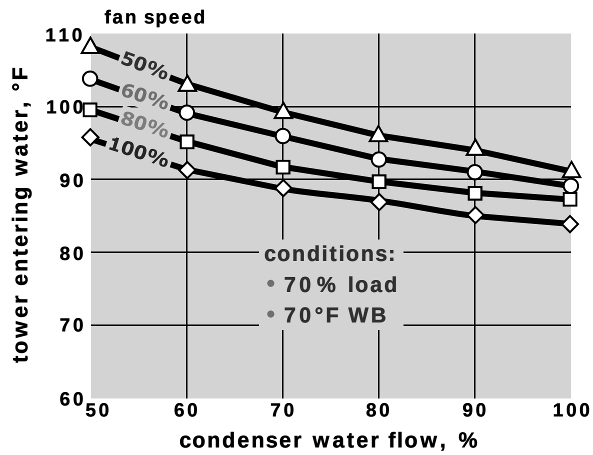
variable condenser water flow
Effect on Chiller



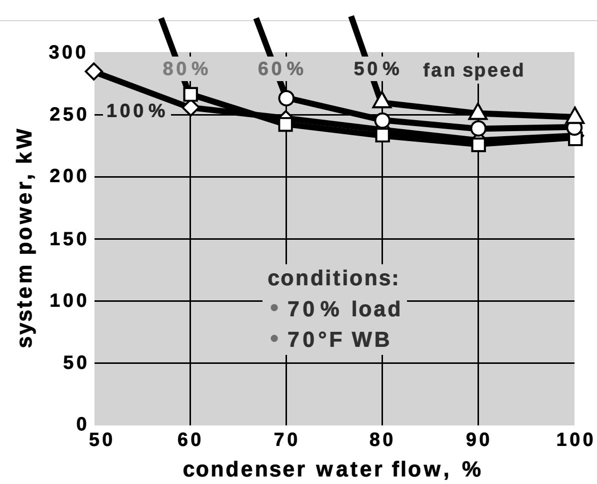
variable condenser water flow
Effect on System



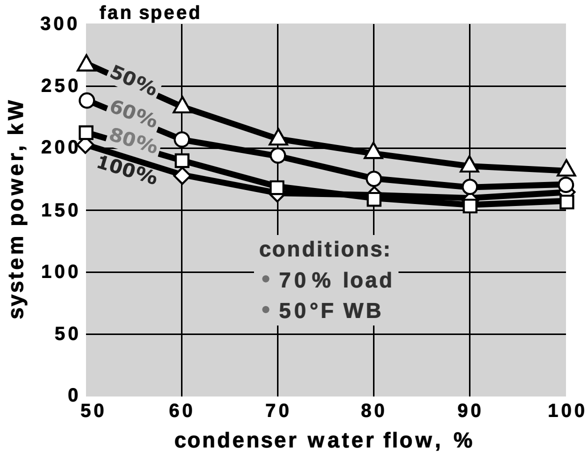
reducing flow & fan speed
Effect on Tower



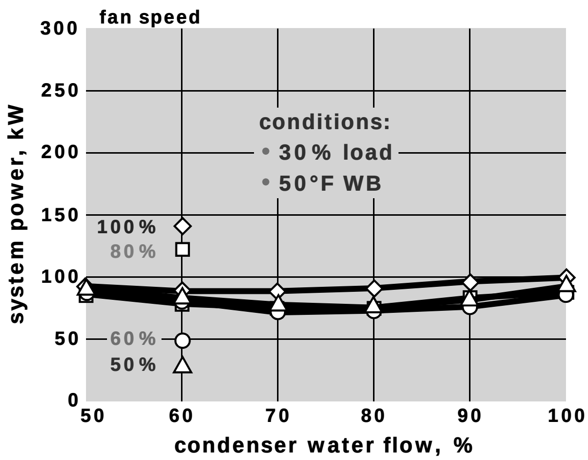
reducing flow & fan speed
Effect on System



reducing flow & fan speed
Effect on System



reducing flow & fan speed
Effect on System



variable condenser water flow

Summary

Determine what savings, if any, are possible

- Are pumps already low power?
- Can reducing tower-fan speed achieve most of the savings?

variable condenser water flow

Summary

If you decide to reduce flow:

- Find minimum condenser-water flow rate
- Examine system at various loads and wet-bulbs … keep chiller out of surge
- Document the sequence of operation
- Help commission the system

variable condenser water flow
Guidance

- **Can provide savings …**
  - Finding proper operating points requires more time, more fine-tuning
- **Two-step process:**
  1 Reduce design pump power
  2 Is variable condenser-water flow still warranted?

Practical Application: How VSDs Affect Chillers

engineers newsletter LIVE

VSDs and their effect on system components

VSDs and Chiller Laws

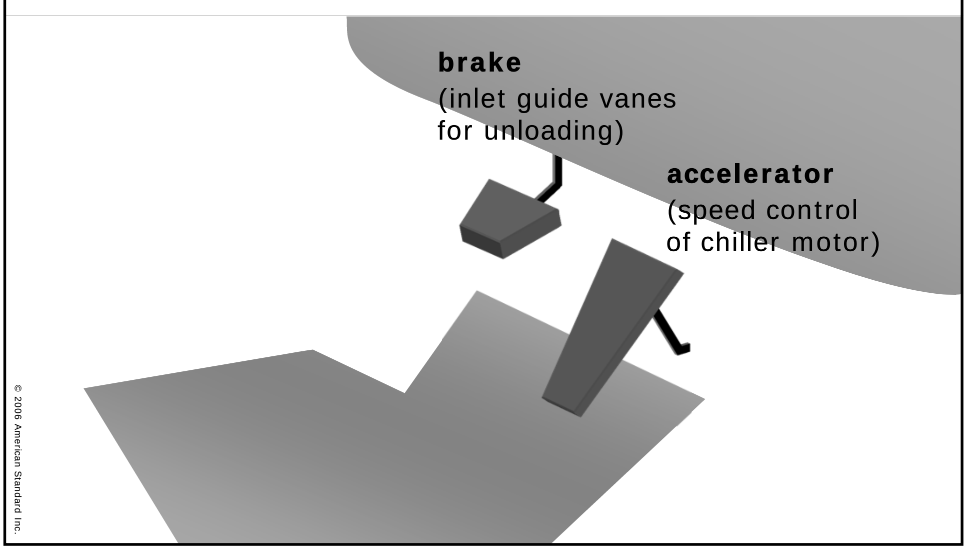
Variable-speed drives benefit centrifugal compressors in water chillers

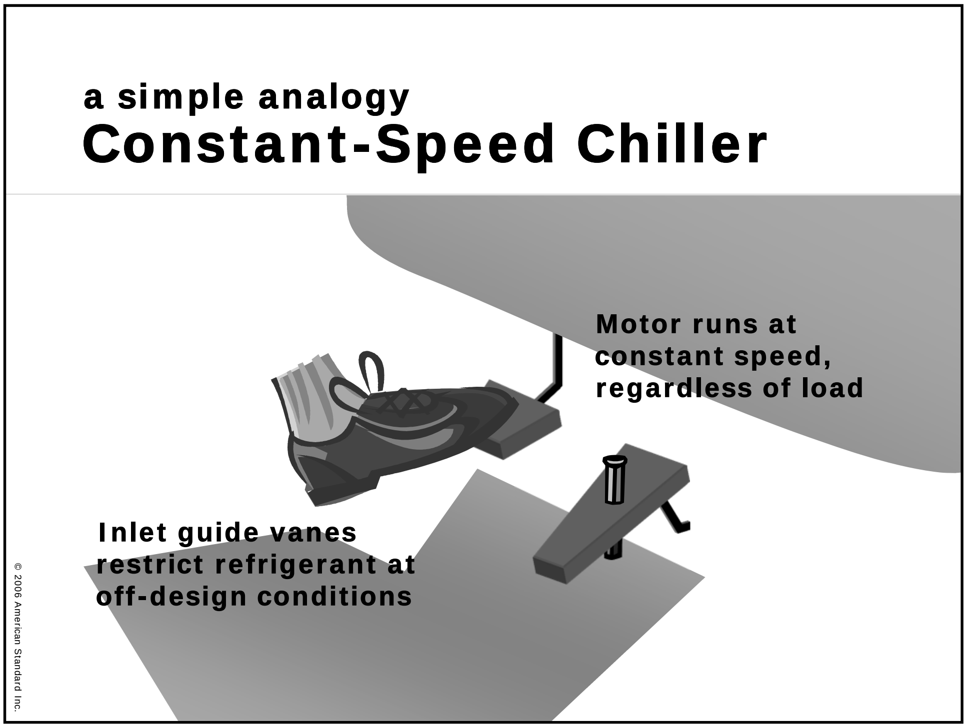
- Review “chiller laws”
- Explore scientific cause-and-effect relationships
- Maximize benefits

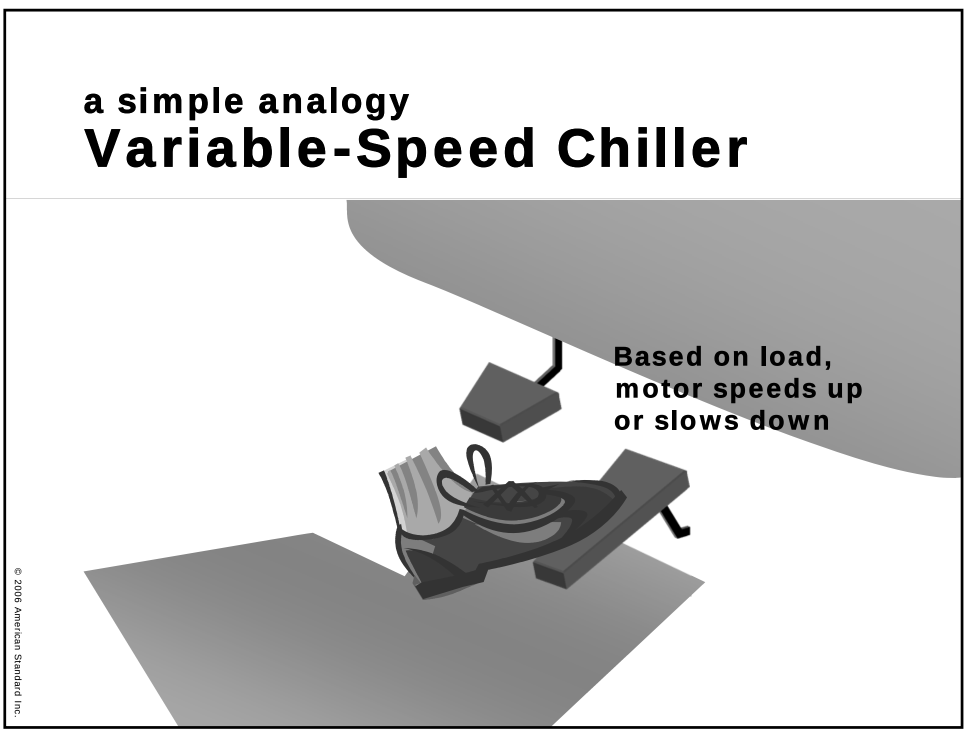
resistance α velocity²

resistance α “lift”

VSD and centrifugal chillers
A Simple Analogy




a simple analogy
Constant-Speed Chiller
Motor runs at constant speed, regardless of load
Inlet guide vanes restrict refrigerant at off-design conditions
© 2006 American Standard Inc.


a simple analogy
Variable-Speed Chiller
Based on load, motor speeds up or slows down
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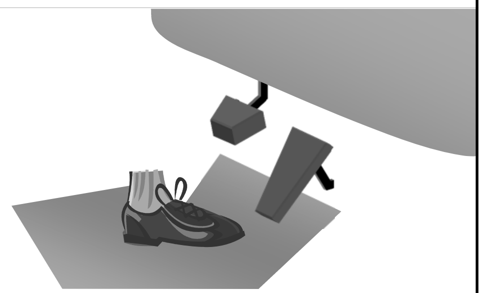
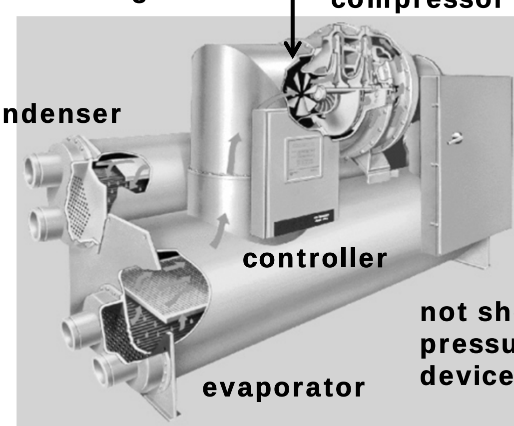
VSDs and centrifugal chillers
An Analogy

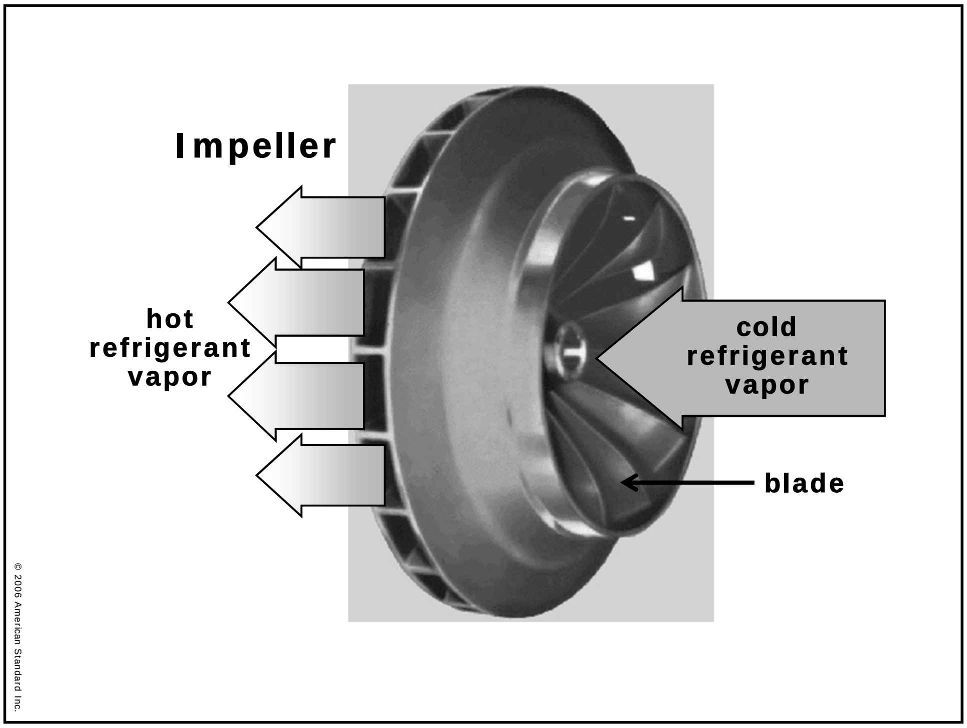


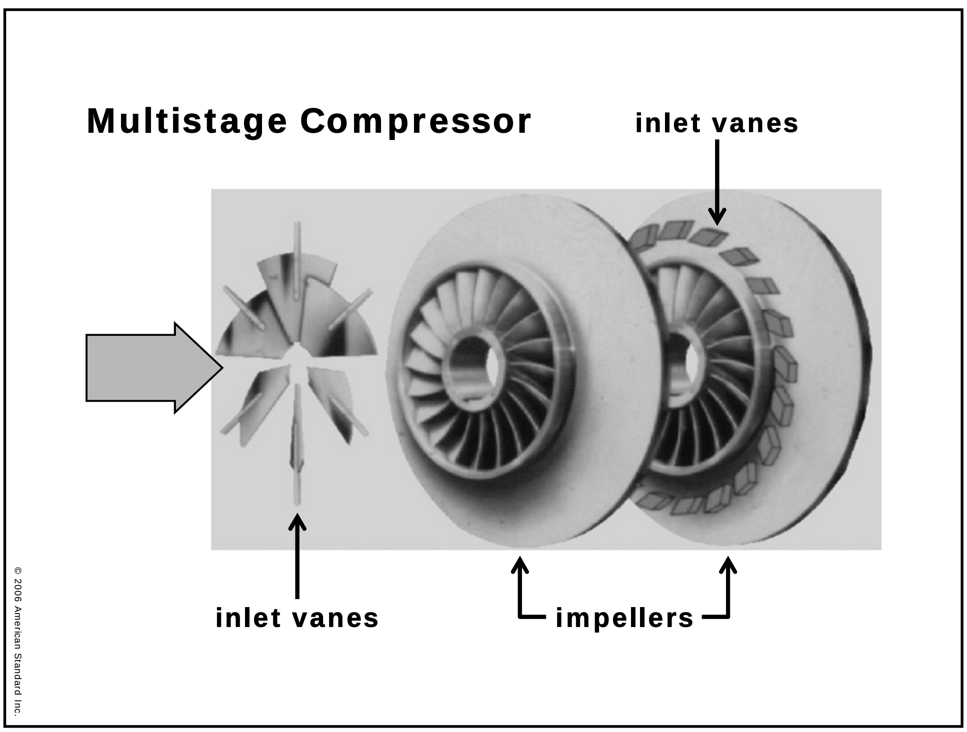
In each case:

- **Energy is wasted**
- **Mechanical wear-and-tear is increased**

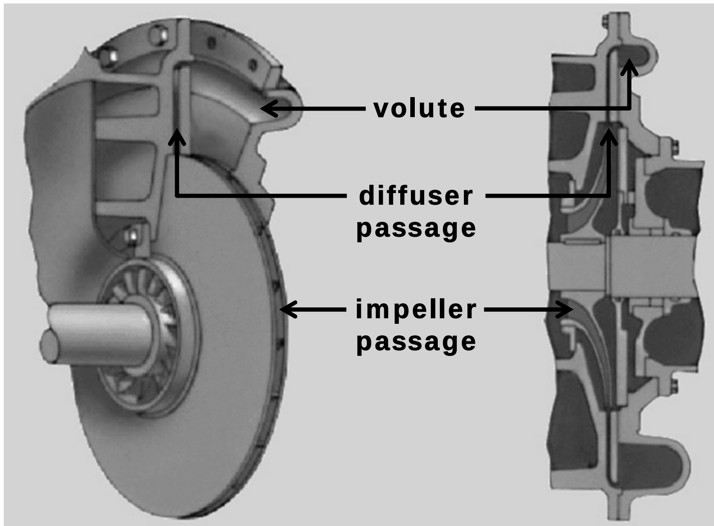
Typical Centrifugal Chiller



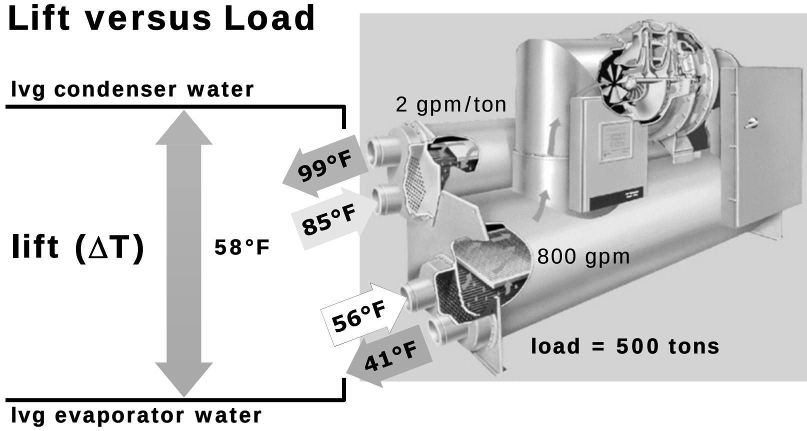

Impeller
hot refrigerant vapor
cold refrigerant vapor
blade
© 2006 American Standard Inc.


Multistage Compressor
inlet vanes
inlet vanes
impellers
© 2006 American Standard Inc.

Centrifugal Compressor



Lift versus Load

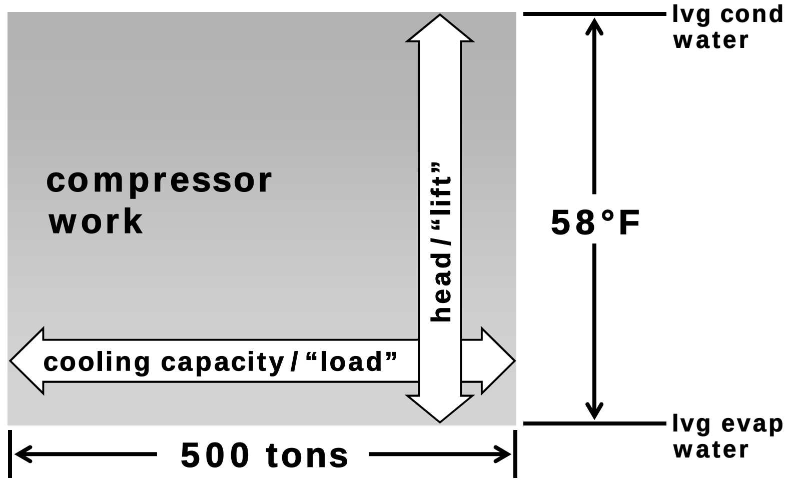


$$\text{lift} \ \alpha \ P_{cnd} - P_{evp}$$

$$\text{lift} \ \alpha \ T_{lvg\ cnd} - T_{lvg\ evp}$$

$$\text{load} \ \alpha \ \text{gpm} \times (T_{lvg\ cnd} - T_{lvg\ evp})$$

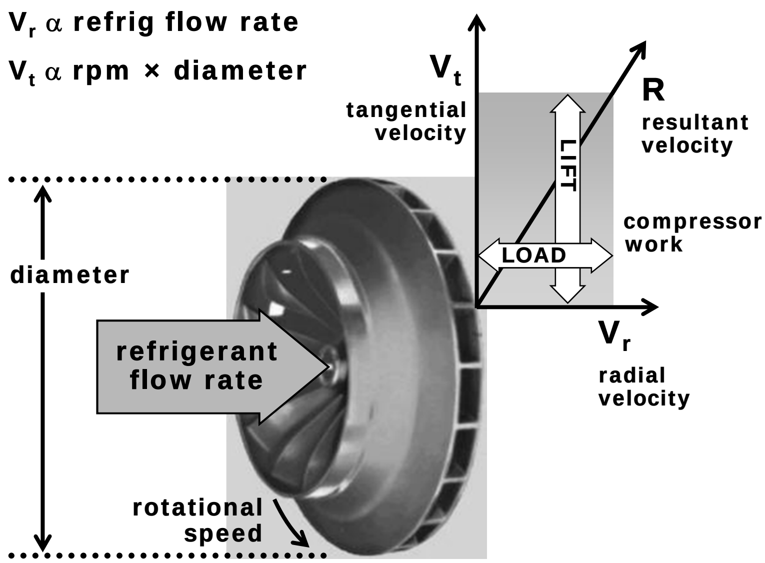
Compressor Work and Chiller Efficiency



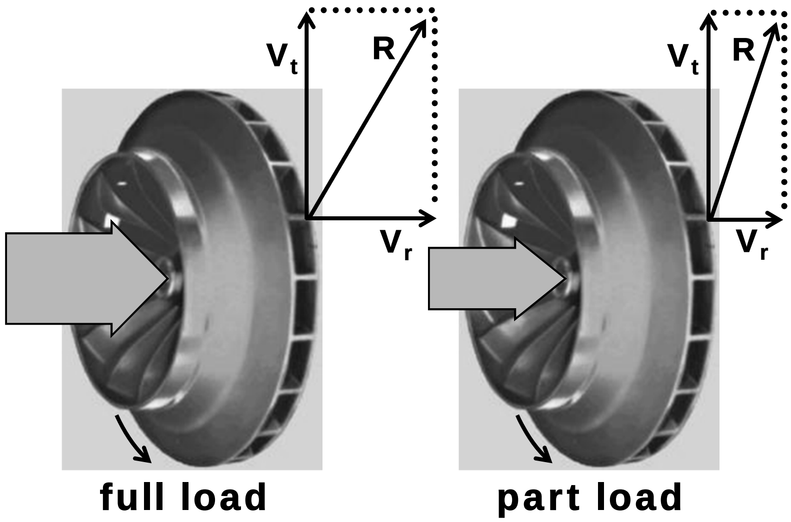
Impeller Dynamics

$V_r \propto$ refrig flow rate

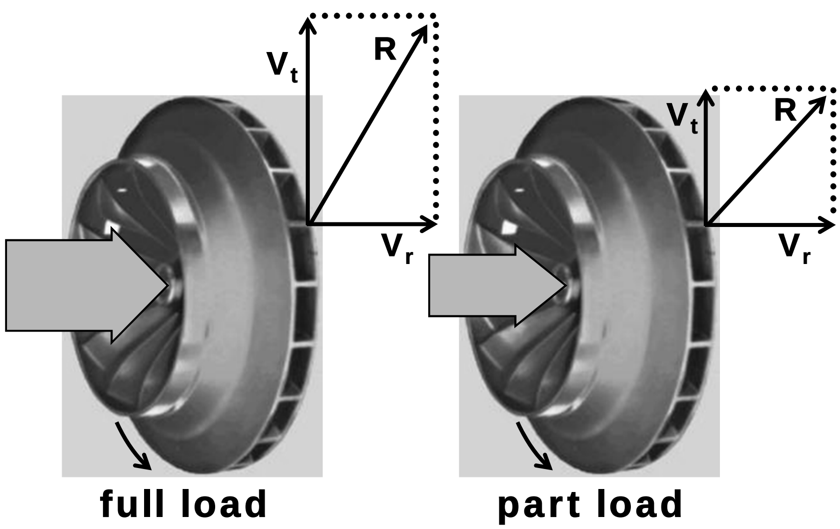
$V_t \propto$ rpm × diameter



Compressor Response to Load

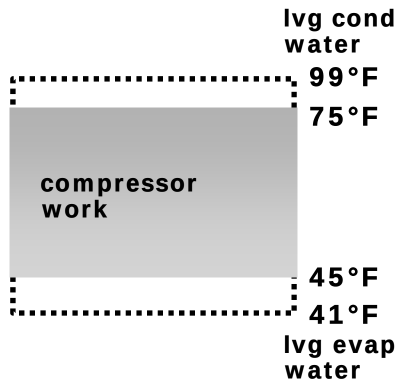


Compressor Response to Lift

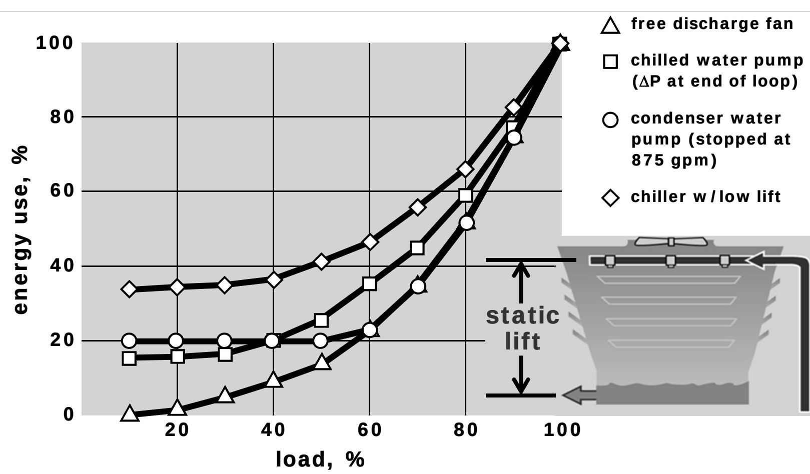


Lessons Learned

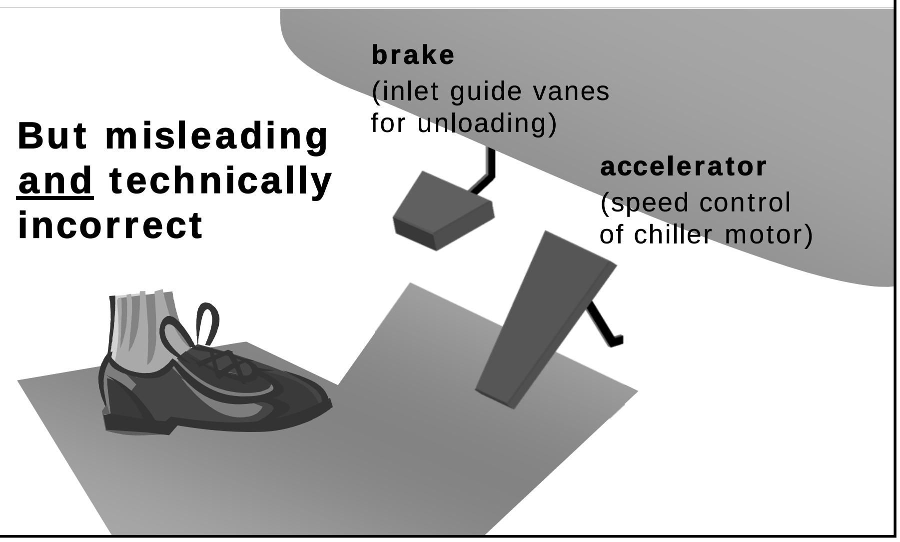
- **To reduce lift:**
  - Decrease condenser pressure by reducing leaving-tower water temperature
  - Increase evaporator pressure by raising chilled water setpoint
- **VSDs optimize chiller <u>lift</u> efficiency**



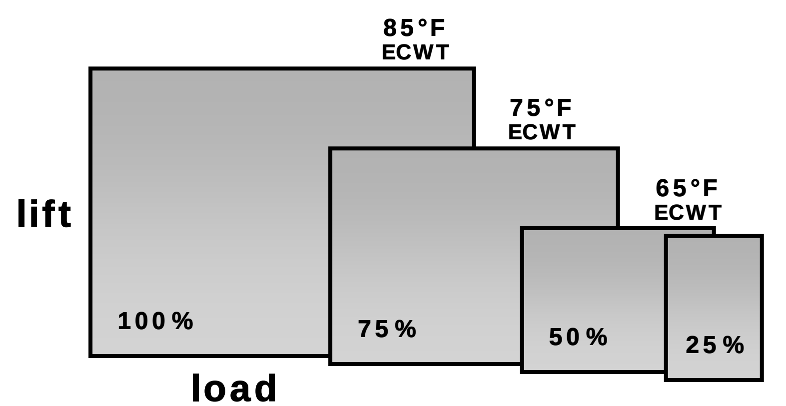
various system components
Energy Use



VSDs and centrifugal chillers
A Simple Analogy



chiller efficiency at part load
IPLV and NPLV Conditions



VSDs and centrifugal chillers
A Closer Look at IPLV

Load	Weighting	ECWT	kW/Ton
100%	0.01	85°F	0.572
75%	0.42	75°F	0.429
50%	0.45	65°F	0.324
25%	0.12	65°F	0.393

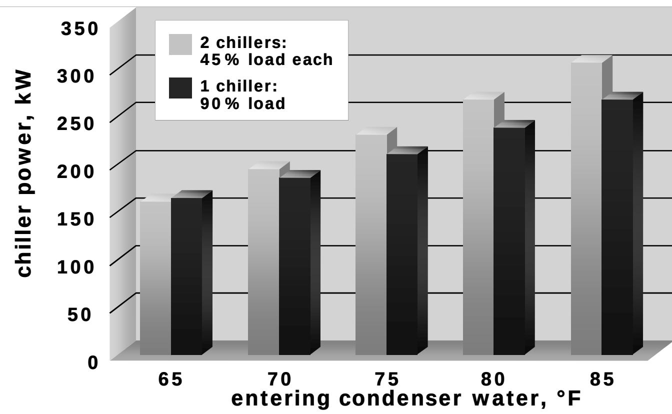
VSDs improve part-lift performance, so running two chillers with VSDs at part load seems more efficient than one chiller at double the same load, but …

VSDs and centrifugal chillers
Performance at 90% Load

ECWT	2 Chillers*	1 Chiller	Difference
85°F	306.4	268.0	–38.4
80°F	268.0	238.0	–30.0
75°F	230.8	210.6	–20.2
70°F	195.2	185.7	–9.5
65°F	160.3	164.3	+4.3

Note: Data shows only chiller power. *Load equally divided

VSDs and centrifugal chillers
Performance at 90% Load



Conclusion: 1 chiller uses less power than 2 chillers

Analyze the System

- **Model:**
  - Building use
  - Local weather
  - Economizers
  - Utility rates
  - System design
- **Use programs like TRACE™, DOE 2.x, Chiller Plant Analyzer, HAP**

VSDs and centrifugal chillers
Summary

- **VFDs improve chiller part-lift performance**
  - Lots of operational hours
  - Reduced condenser water temperatures
  - Higher costs of electricity
- **IPLV is not an economic tool**

Answers to Your Questions

engineers newsletter LIVE

VSDs and their effect on system components

wrap-up
VSD Effect Differs

- **Cubic relationship to speed only occurs in "free discharge" systems**
- **Control parameters affect savings**
- **In chillers, external parameters define lift (pressure difference)**

wrap-up
VSD Effect Differs

- **Cooling towers: Nearly cubic**
- **HVAC fans: Not cubic**
  - Depends on control strategy
  - Fan pressure optimization is best
- **Chilled water pumps: Not cubic**
  - Affected by valves and control method
  - Consider pump pressure optimization based on critical valve

wrap-up
VSD Effect Differs

- **Condenser water pumps: Not cubic**
  - Must meet minimum flow or pressure
    - Tower static lift
    - Minimum condenser water flow
    - Minimum tower flow
  - Reduced flow affects chiller and tower performance
  - Before applying a VFD, reduce pump design power (CW flow rate)

wrap-up
VSD Effect Differs

- **Power for any chiller is reduced at part load and lift**
- **Chiller savings? Not even close to cubic**
  - VFD helps more at part-lift conditions
  - MUST reduce lift for VSD to slow down and give benefit
  - Use same condenser water temperature to compare constant- and variable-speed chillers

VFDs and Gensets

Trane Engineers Newsletter volume 35-1

"How VFDs Affect Genset Sizing" by Court Nebuda

www.trane.com/commercial/location.aspx?item=5

references for this broadcast

Where to Learn More

- **2005 ENL "Cooling Towers and Condenser Water Systems"**
  http://www.trane.com/bookstore/catalog.asp?sectionid=14
- **Bibliography**

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2006 ENL Broadcasts

- **May 3** **HVAC systems and airside economizers**
- **Sep 13** **HVAC design for places of assembly**
- **Nov 8** **Energy-saving designs for rooftop systems**