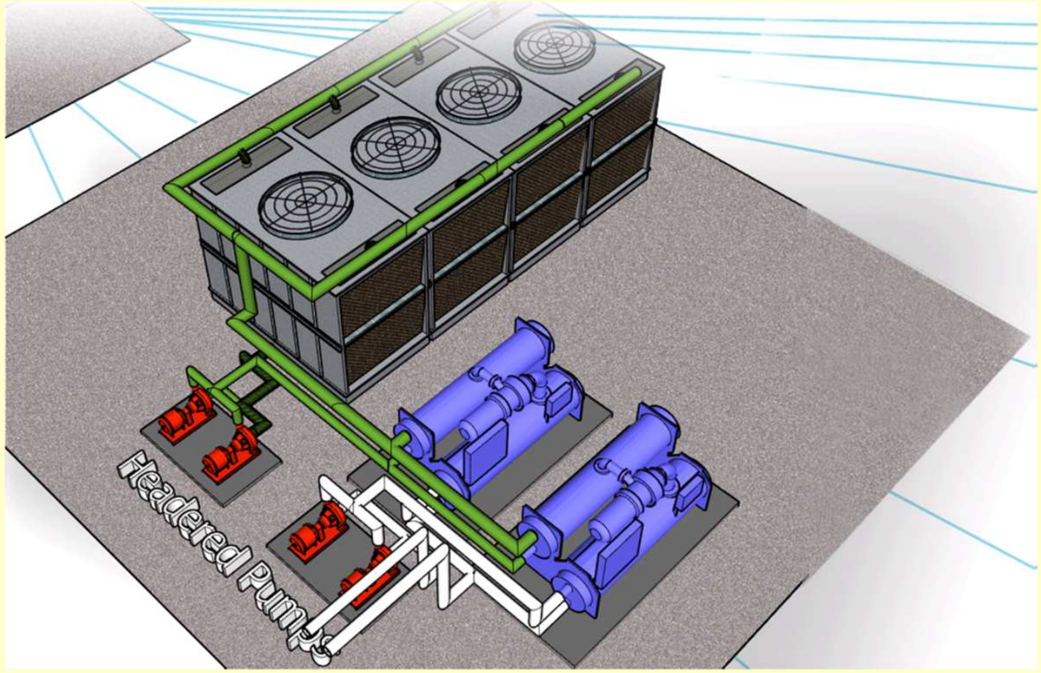
SPD5132 Indoor Environment and HVAC Systems

http://ibse.hk/SPD5132/



Chiller plant control and operation

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Dec 2016

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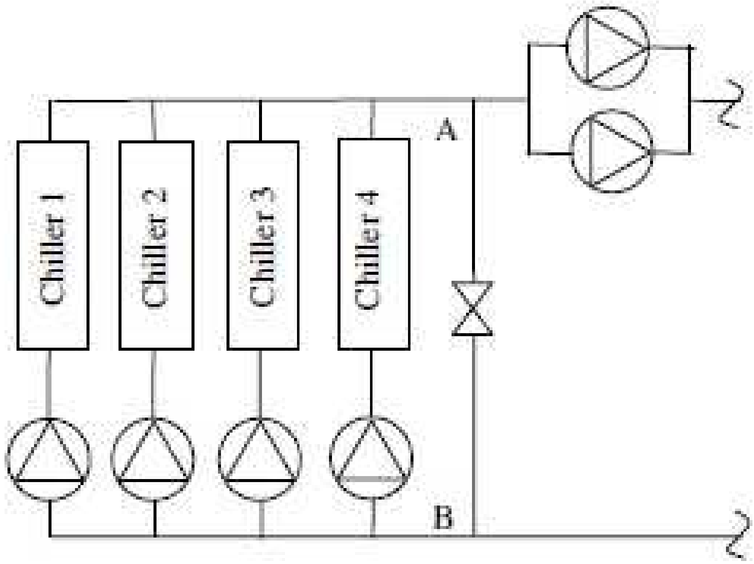

Types of chillers

- What is a Chiller?
  - Refrigeration machine that produces chilled water, to cool inside air for air conditioning system
- 2 types of chillers based on refrigeration cycle:
  - Vapour compression chiller
  - Absorption refrigeration chiller
- 2 types of chillers based on heat rejection:
  - Air-cooled chiller
  - Water cooled chiller

Refrigeration cycle -- vapour compression cycle

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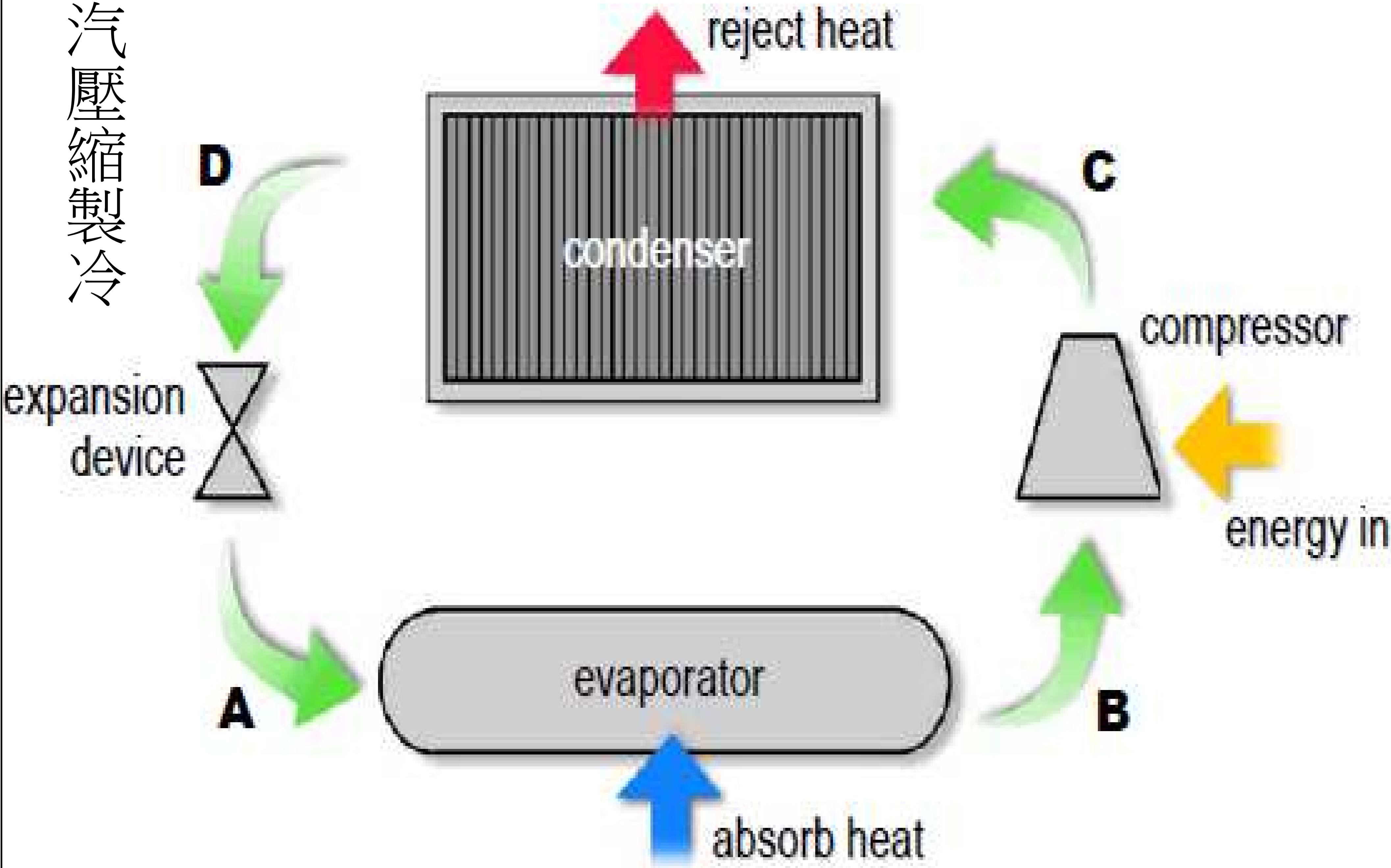
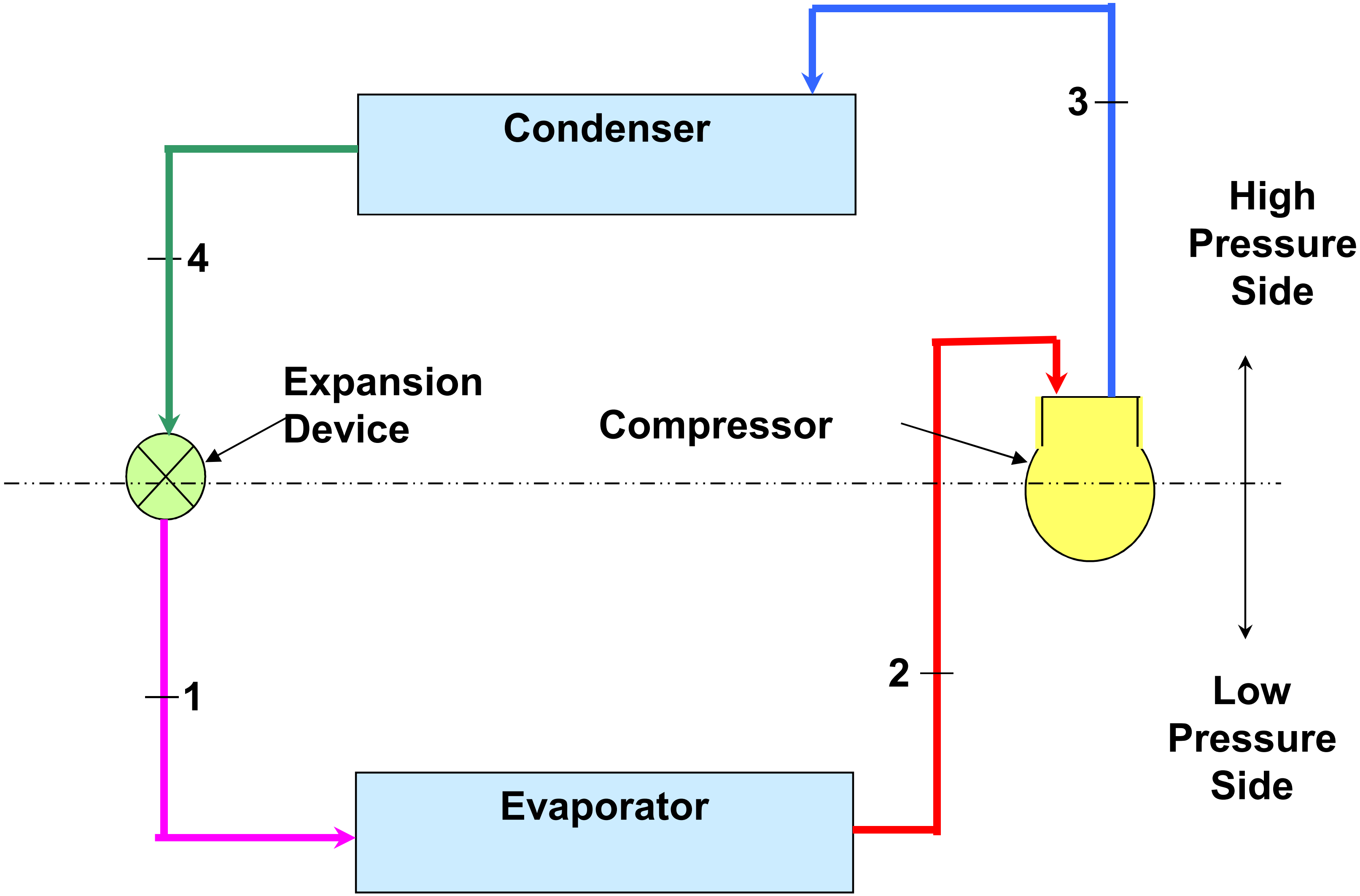
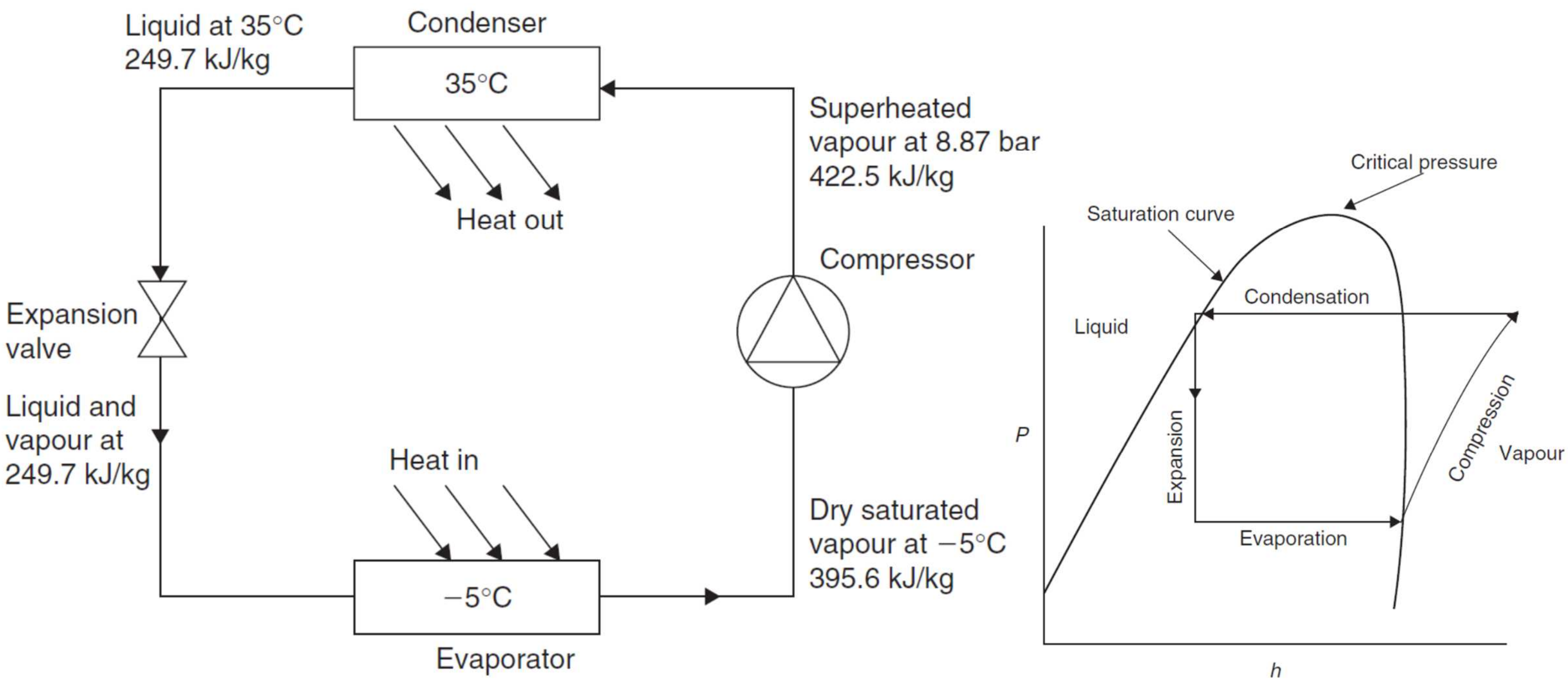


Refrigeration cycle -- vapour compression cycle



(Video: Refrigeration Cycle Video Animation (1:30) http://youtu.be/MqnyaUNxs9A)

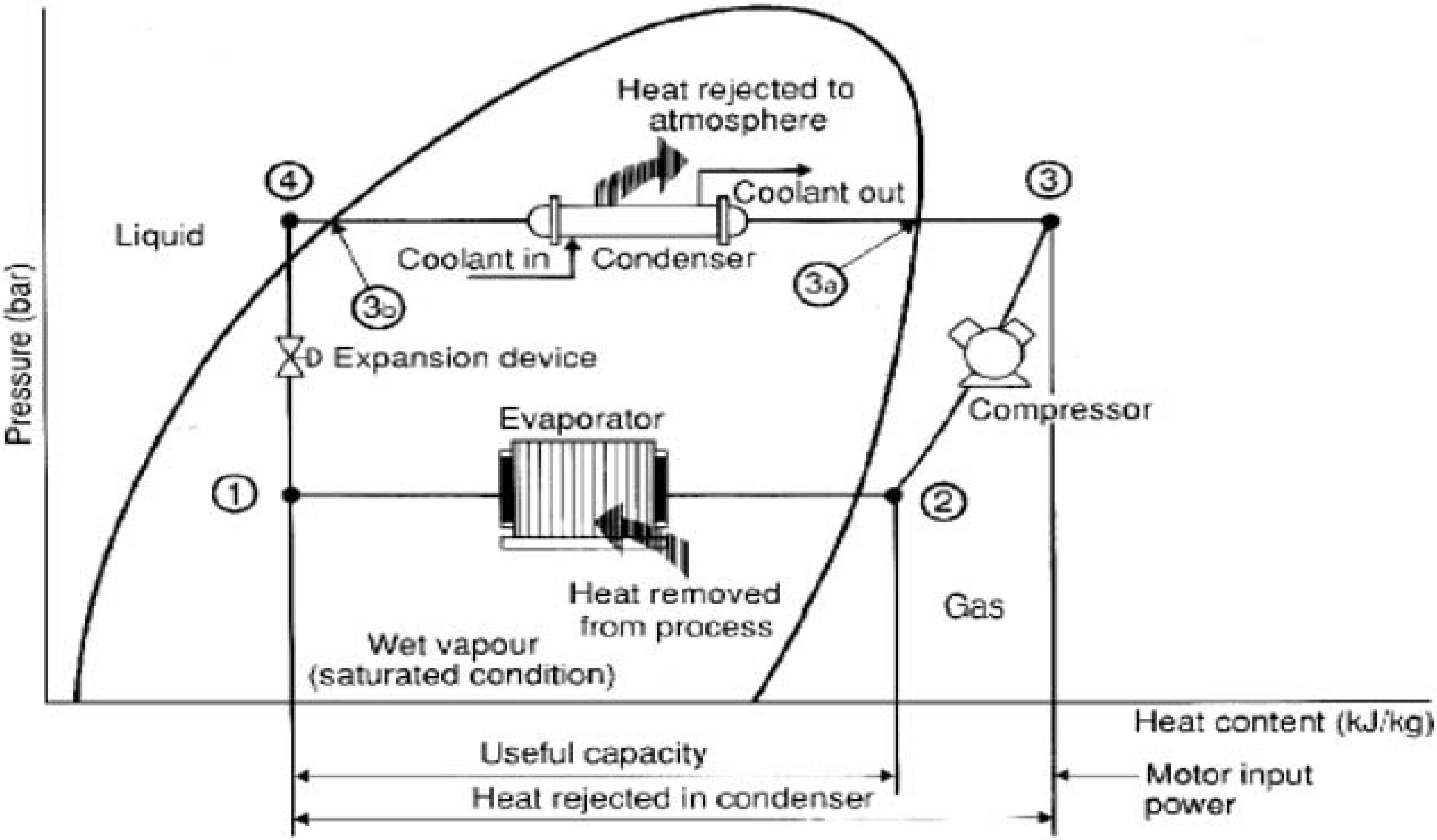
Simple vapour compression cycle with pressure and enthalpy values for R134a



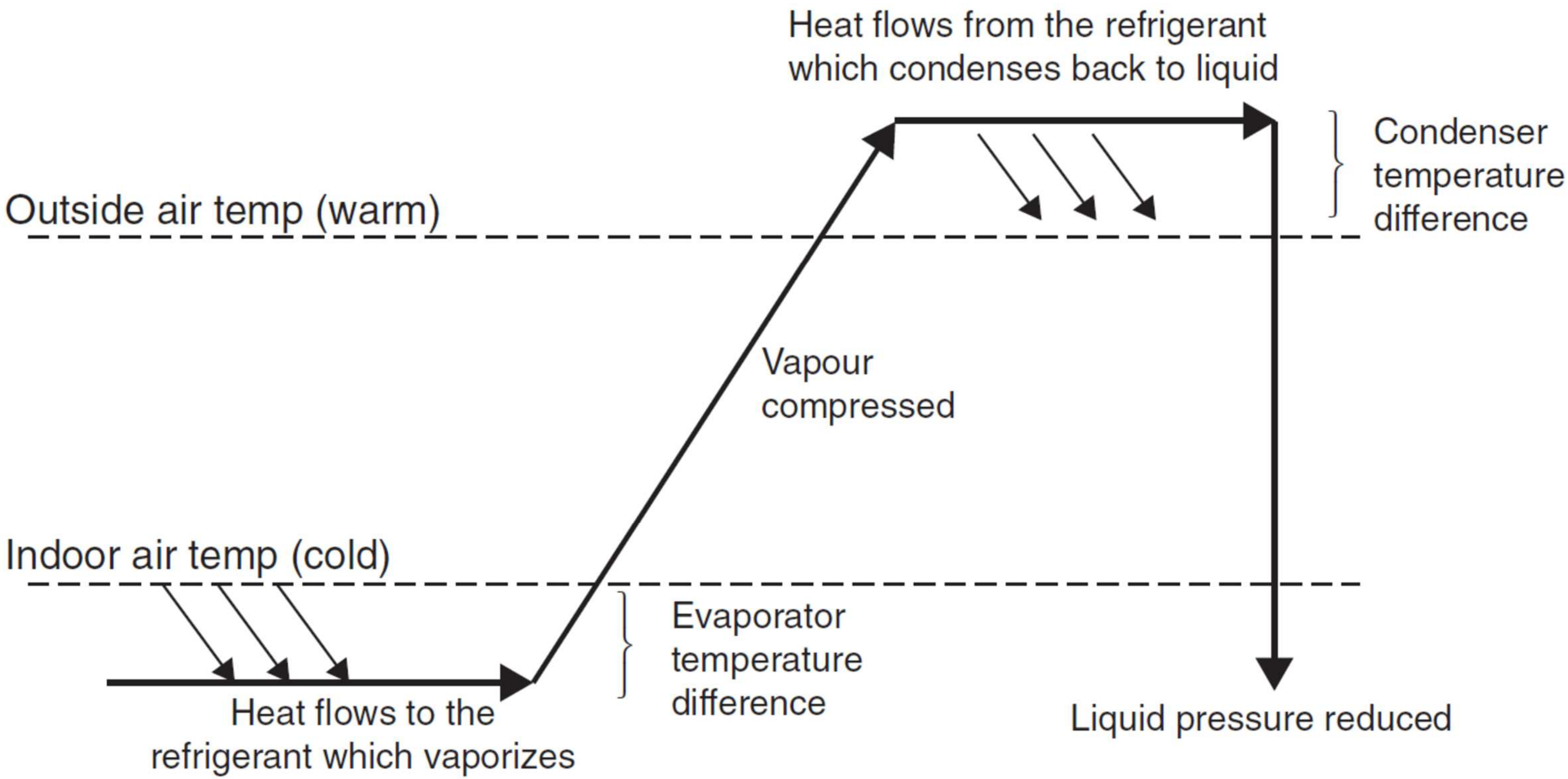
Can you explain the basic principles of the refrigeration cycle?

(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

Principle of vapour compression cycle (on a P-h diagram)



The temperature rise or ‘ lift ’ of the refrigeration cycle is increased by temperature differences in the evaporator and condenser



(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

Types of chillers

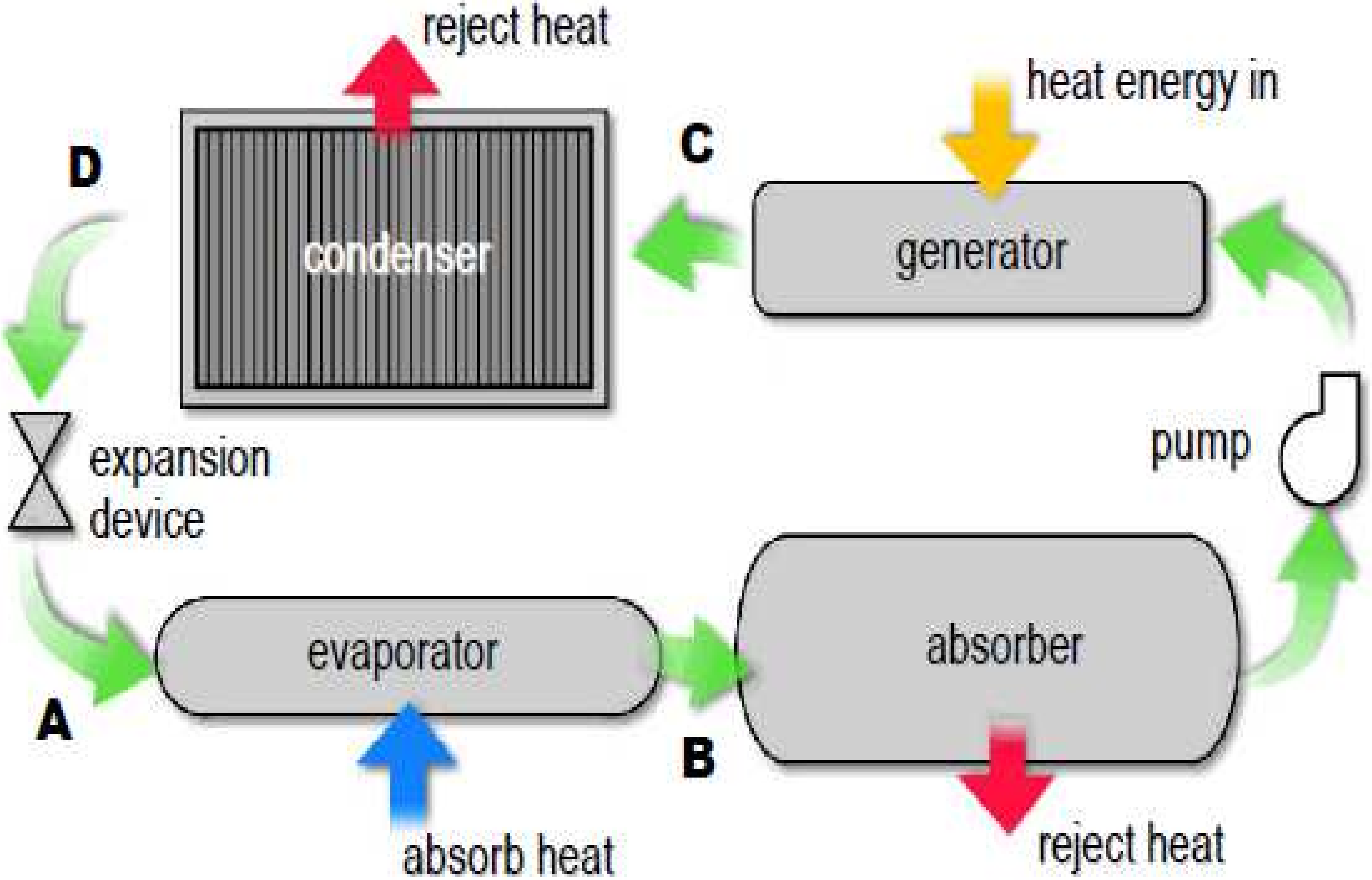
- Absorption refrigeration cycle
  - Such as ammonia and lithium bromide systems

吸收式製冷

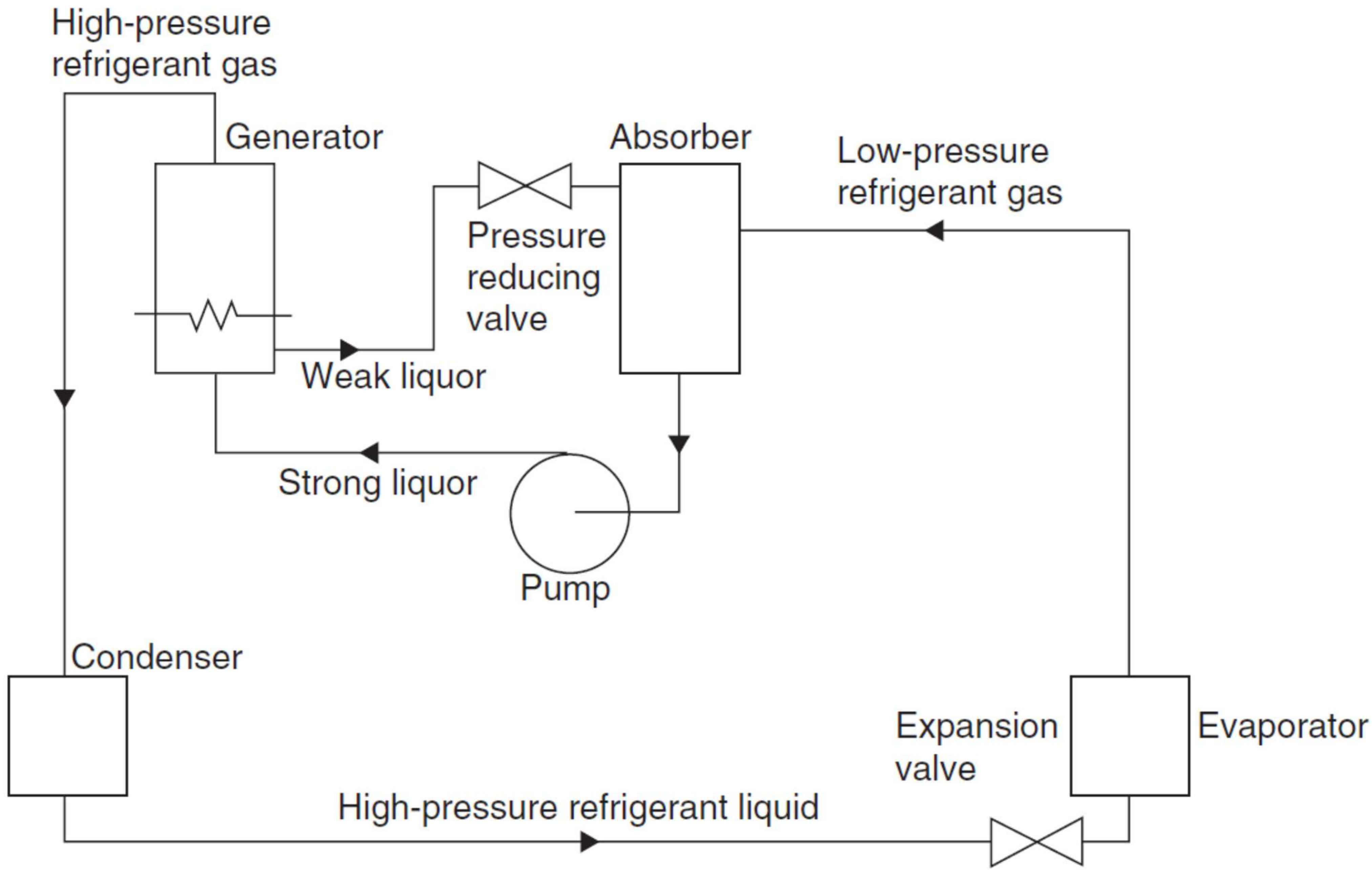
    - Absorption of ammonia gas into water, and of water vapour into lithium bromide
    - Refrigerant vapour from the evaporator is drawn into the absorber by the liquid absorbant. The liquor is then pumped up to condenser pressure and the vapour is driven off in the generator by direct heating
    - The heat energy to the generator may be any form of low-grade energy such as oil, gas, hot water or steam, or from solar radiation

(Video: Vapour absorption refrigeration system! Learn and grow (3:38) http://youtu.be/Ll8Ku-mFQxE)

Absorption refrigeration cycle

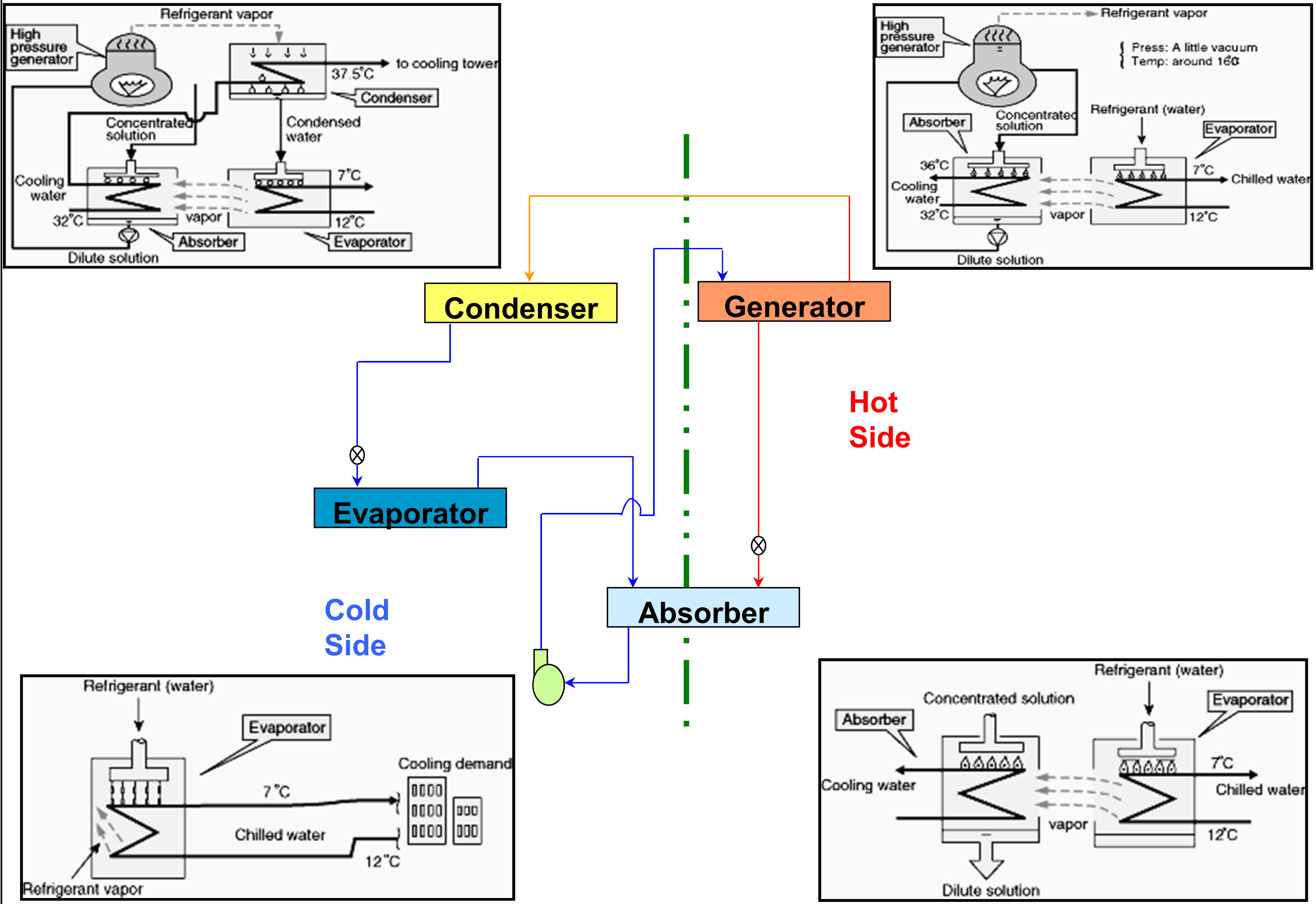


Absorption cycle: basic circuit



(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

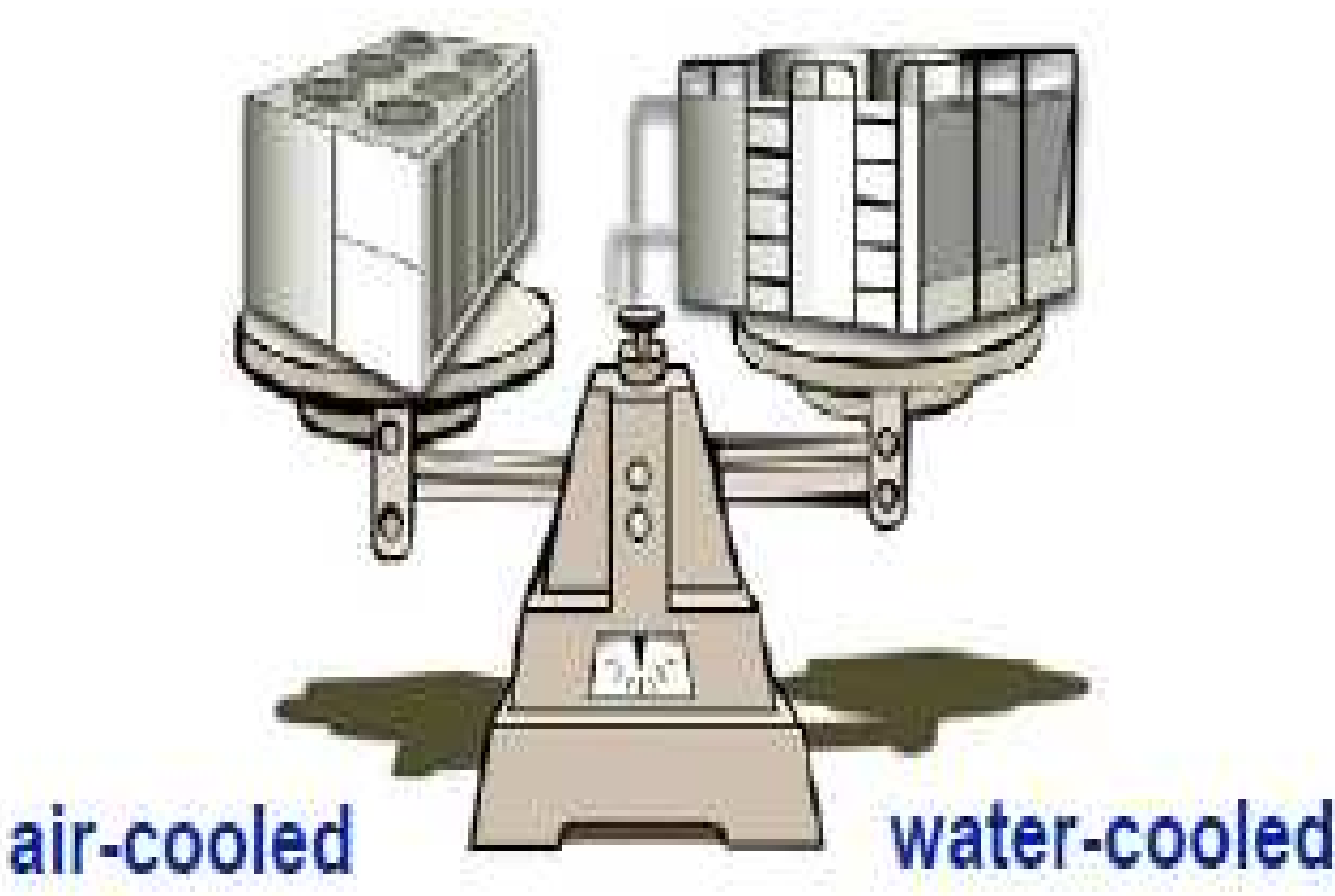
Vapour absorption refrigeration



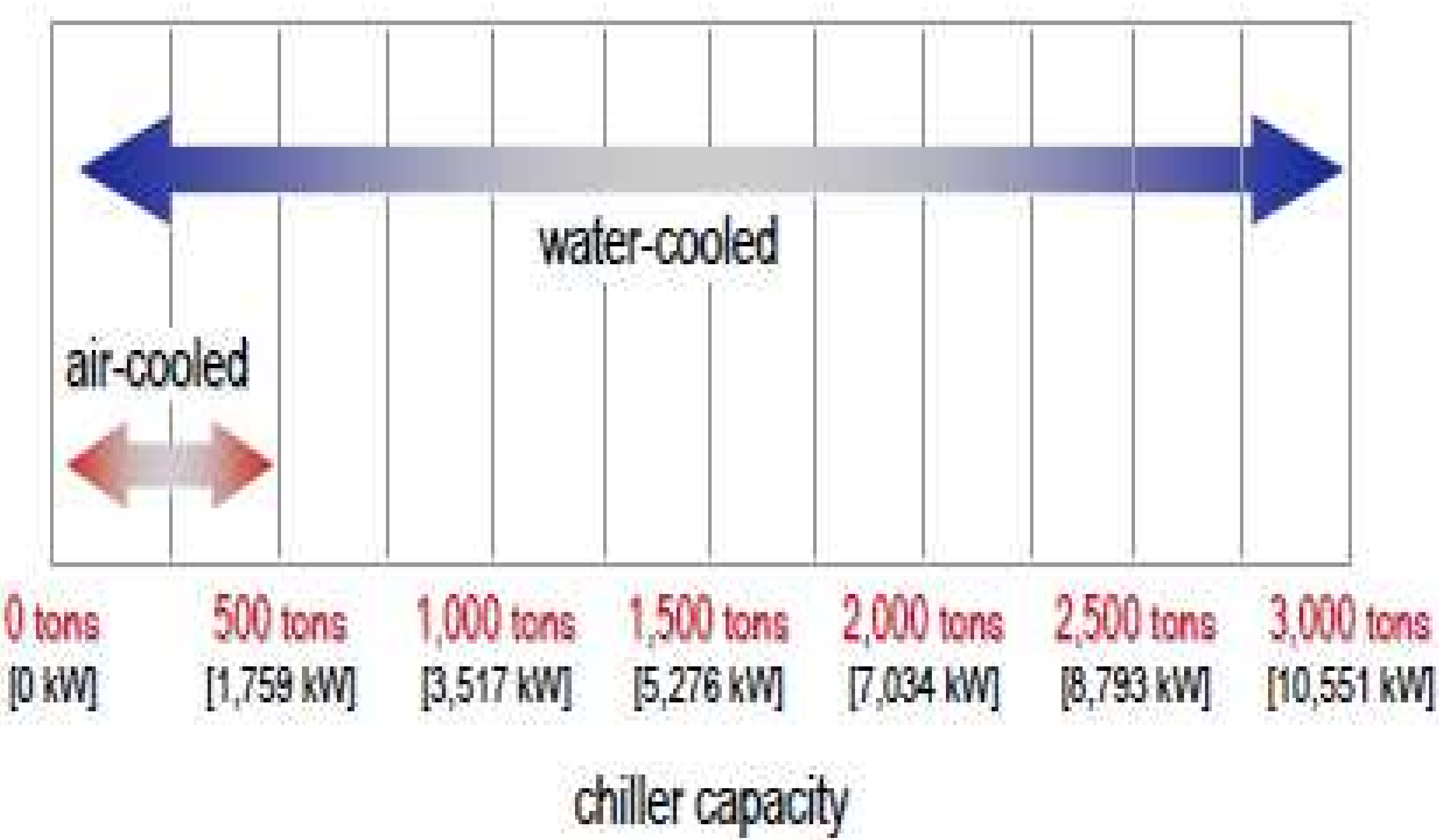
Comparison of vapour compression and absorption chillers

Vapour Compression Chiller	Absorption Water Chiller
Use a Compressor to move refrigerant around the system. Energy source for the compressor is an electric motor	Use heat to drive the refrigeration cycle. Energy sorce are steam, hot water or burning of oil or natural gas
Vary by type of compressor such as reciprocating, scroll, screw, centrifugal.	Use of absorption refrigeration cycle
Lower initial cost	Higher initial cost due to additional cost of heat transfer tubes & absorbent
In emergency situation, continous electricity required for electricity-driven chillers.	Minimal electricity needed for generator during emergency situations
Not applicble	Waste heat recovery - Wasted energy can be used to fuel an absorption chiller
Not applicble	Application in Cogeneration system

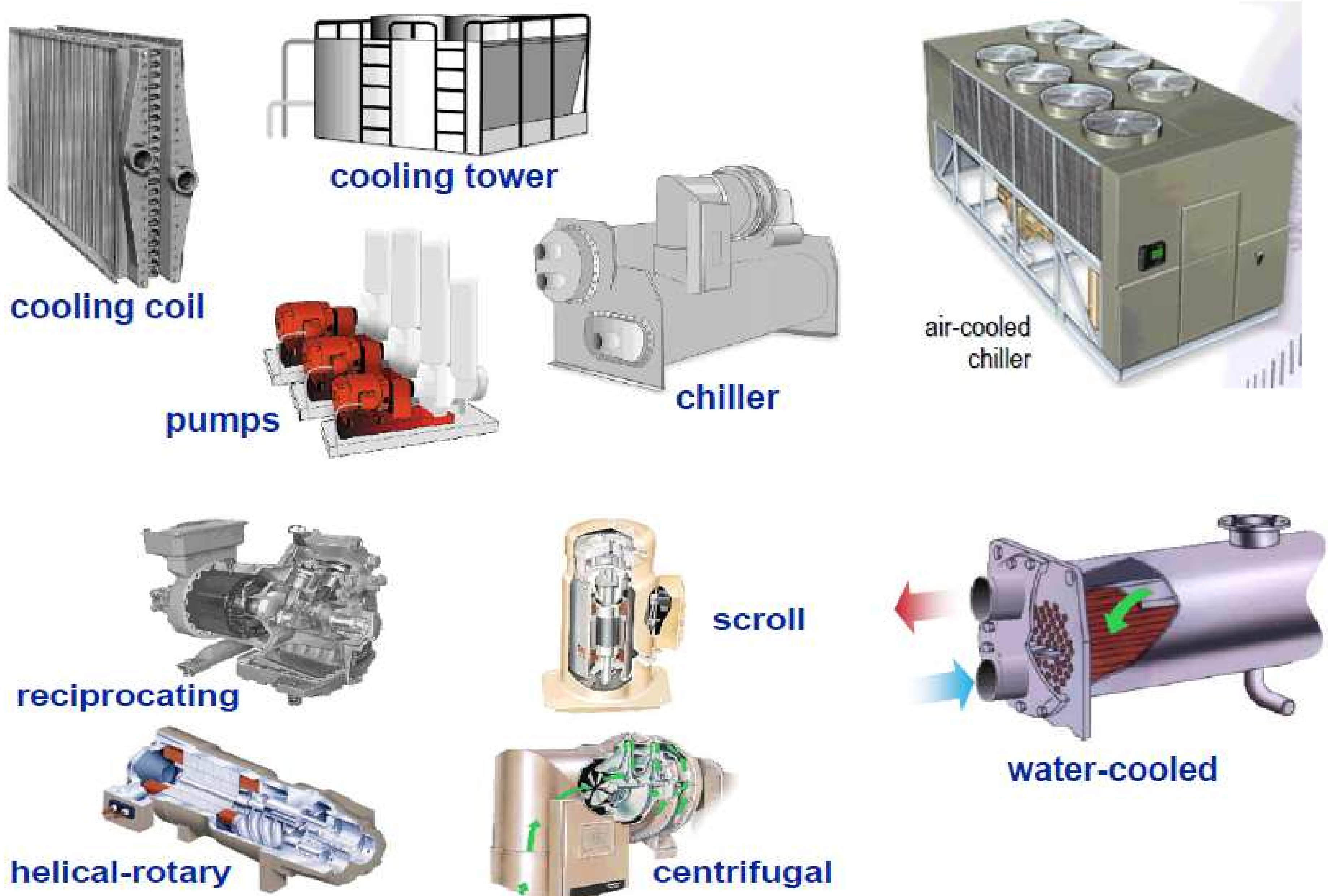
Air-cooled and water cooled chillers
(* see also lecture on heat rejection systems)



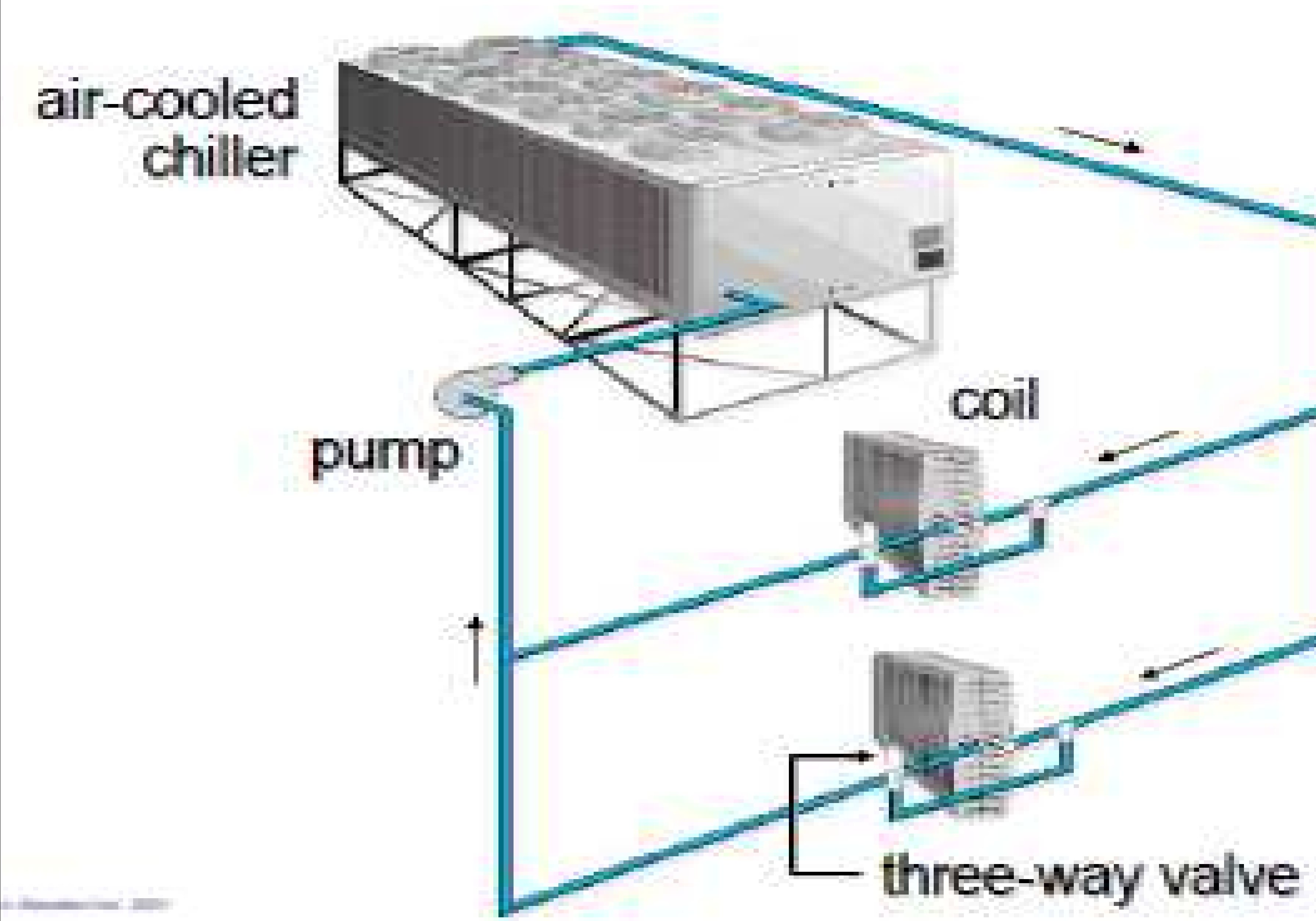
Application of air-cooled and water cooled chillers



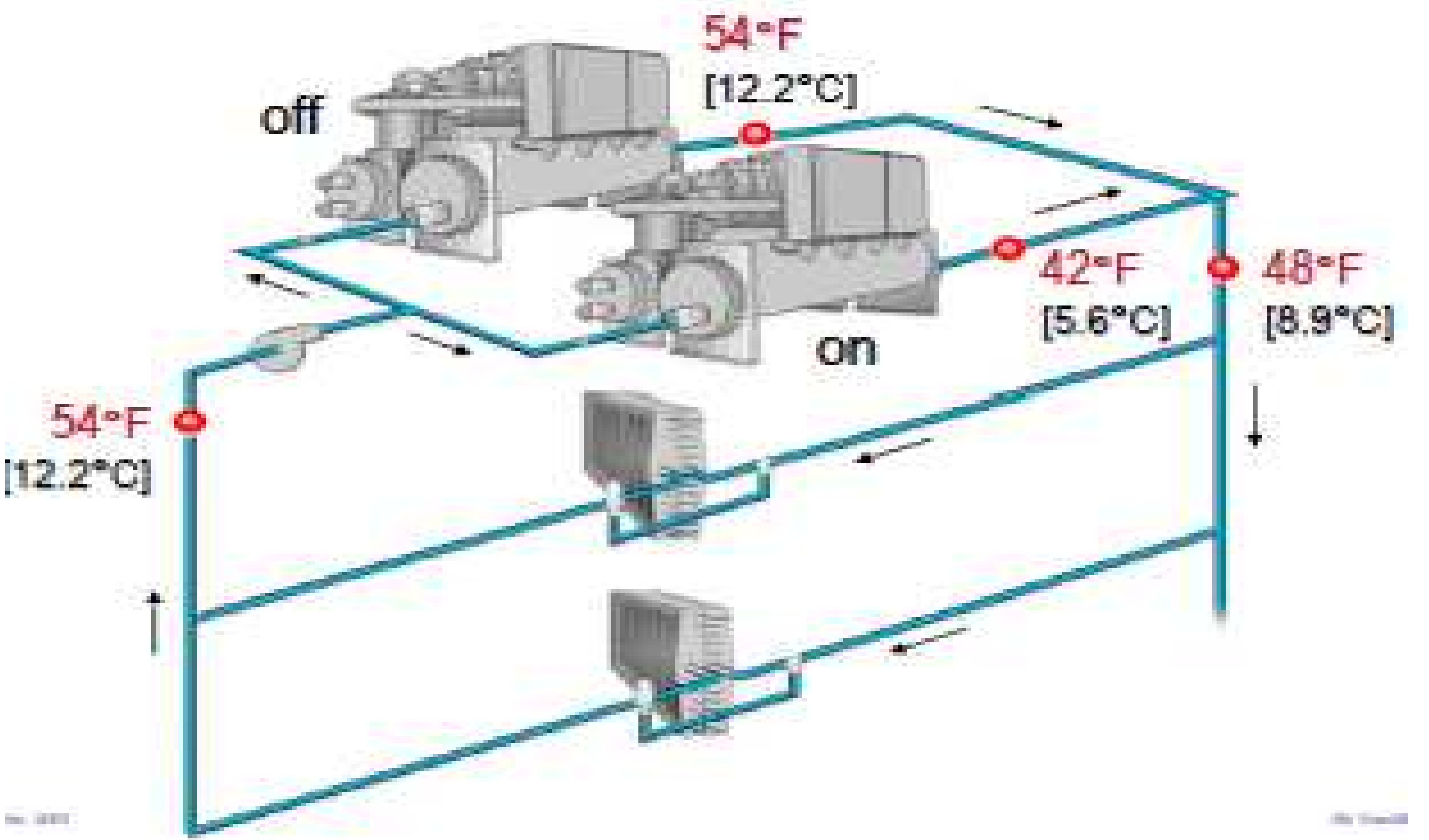
Chiller system components



Single chiller system



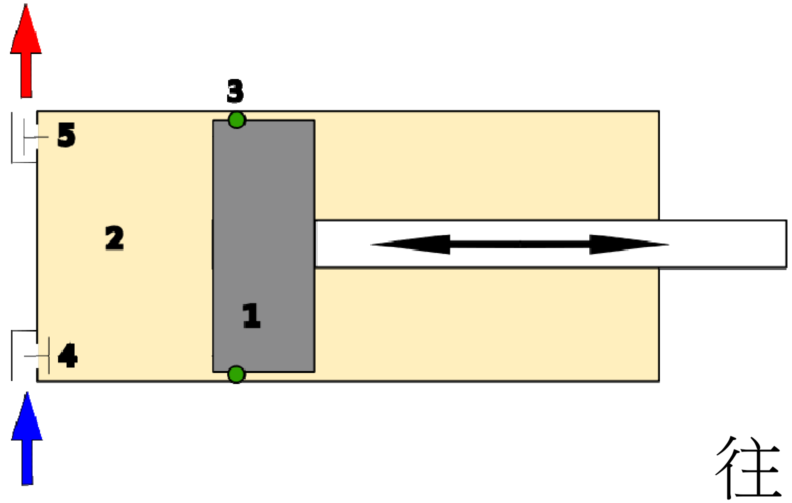
Parallel chiller system



Refrigeration systems

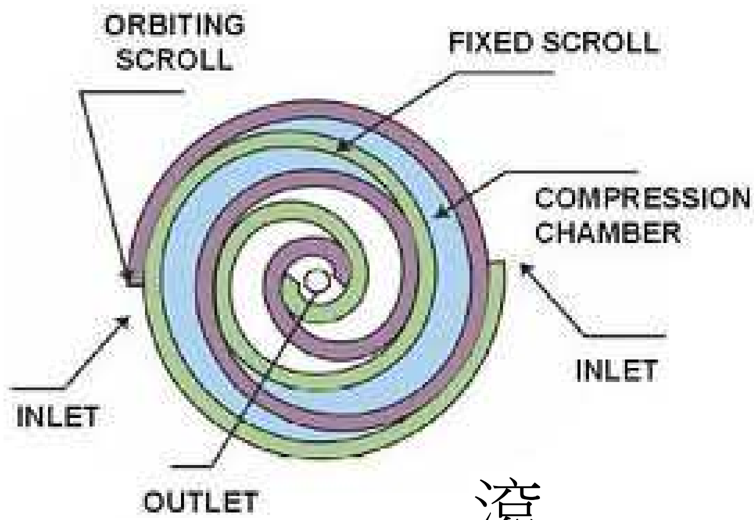
- Common types of compressors used in chillers (HVAC refrigeration plant):
  - Reciprocating -- piston-style, positive displacement
  - Rotary screw -- positive displacement; 2 meshing screw-rotors rotate in opposite directions
  - Scroll -- positive displacement; one spiral orbits around a second stationary spiral
  - Centrifugal -- raise the pressure by imparting velocity or dynamic energy, using a rotating impeller, and converting it to pressure energy

Common types of compressors used in chillers

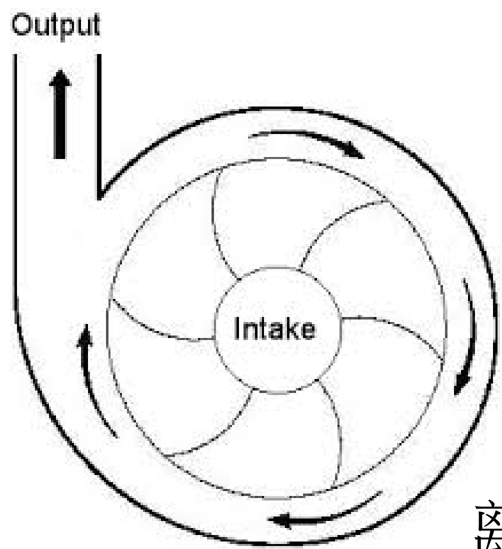


Reciprocating 往復式

Rotary screw 旋轉螺桿式

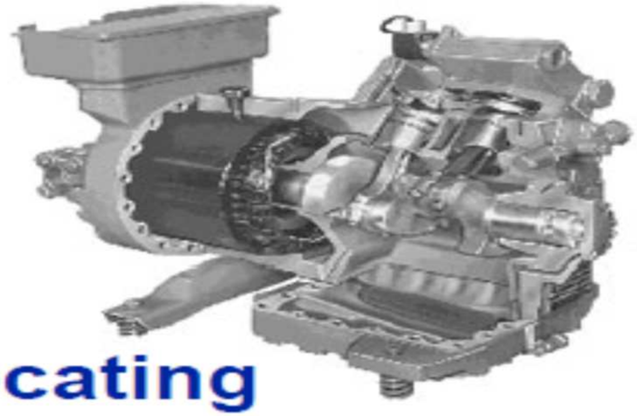


Scroll 滾動式



Centrifugal 離心式

Applications of different types of compressors in chillers



reciprocating

scroll

helical-rotary

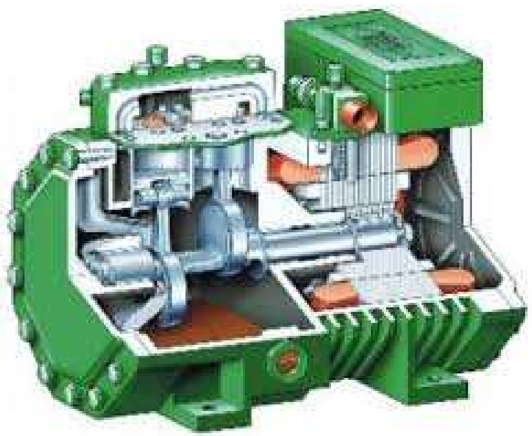
centrifugal

Compressor	Application
reciprocating	Used in small chiller
	Available in capacity up to 100 tons (350kw)
	Multiple Compressor used in a single chiller for capacities up to 200 tons(700kW)
scroll	Used in small water chiller less than 200 tons (700kw)
	10 to 15% more efficienct than reciprocating because of 60% fewer moving parts
	Available in hermetic configurations in capacity up to 15 tons (53kW) for use in water chiller
	Multiple are used in single chiller to meet larger capacities
helical-rotary	Used in medium sized water chiller 50 to 500 tons (175 to 1750kw)
	More reliable & better efficiency due to fewer moving parts
centrifugal	Used in large water chiller
	Available in prefabricated chiller from 100 to 3000 tons (350 to 10500kW) & up to 8500 tons (30000kW) as built-up machines
	High efficiency, superior reliability, reduced sound levels, relatively low cost as compared to others

Refrigeration systems

- Arrangement of compressor motor or external drive:
  - Open type 打開
  - Hermetic (or sealed) type 密封
  - Semi-hermetic (or semi-sealed) type 半密封





Refrigeration systems

- Common refrigeration systems in HVAC
  - 1. Direct expansion (DX) systems & heat pumps
  - 2. Centrifugal chillers
  - 3. Screw chillers
- Either single-stage or multistage
- Compressor lubrication
  - Use mineral or synthetic oil
  - Use magnetic bearing (oil-free chiller/compressor)*

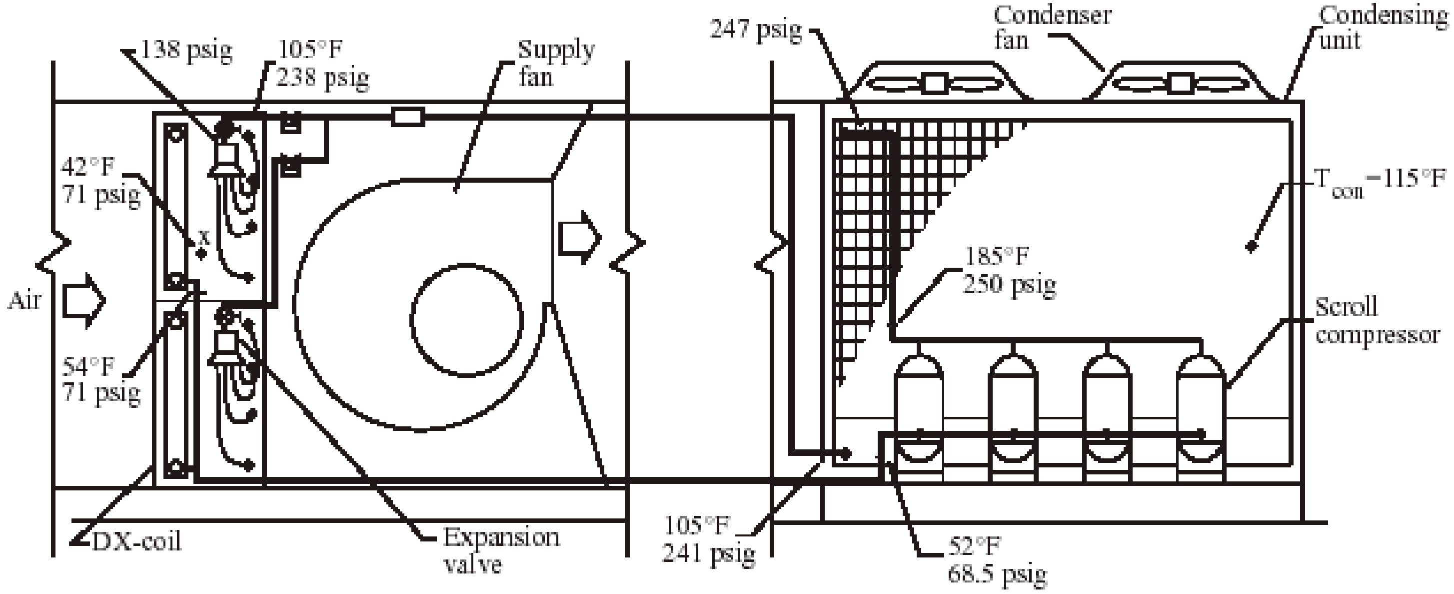
(*See also: Magnetic bearing oil free chiller http://www.diffcool.com/Magneticbearingoilfreech.htm)

Refrigeration systems

- Direct expansion (DX) systems
  - Part of the packaged air-conditioning system
  - R-22 and R-134a widely used
  - Range 3-100 TR (ton of refrigeration)
  - Components & accessories
    - Compressor(s): reciprocating and scroll
    - Condensers
    - Refrigeration feed
    - Oil lubrication
    - Refrigerant piping

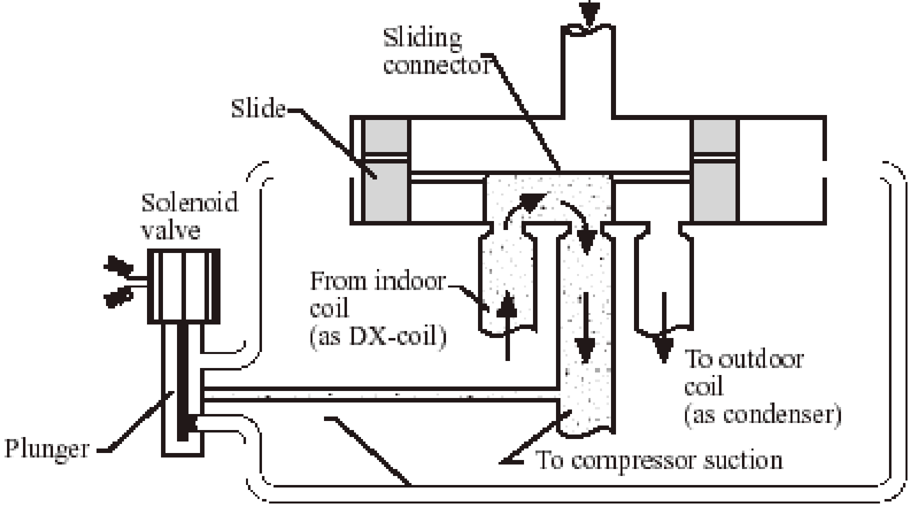
(See also: Direct Expansion Air Conditioning http://www.nrgmanagement.ca/direct-expansion-air-conditioning-)

Direct expansion (DX) system (air-cooled condenser)



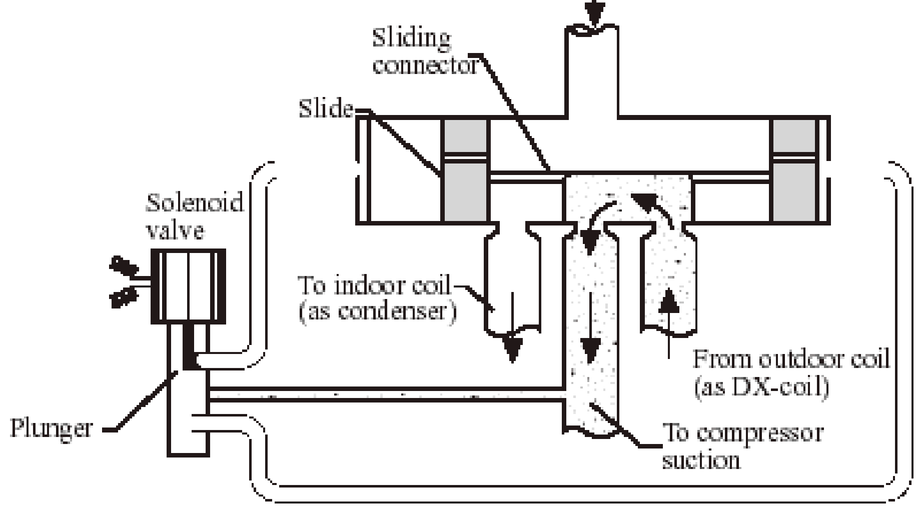
(a)

Cooling mode



(b)

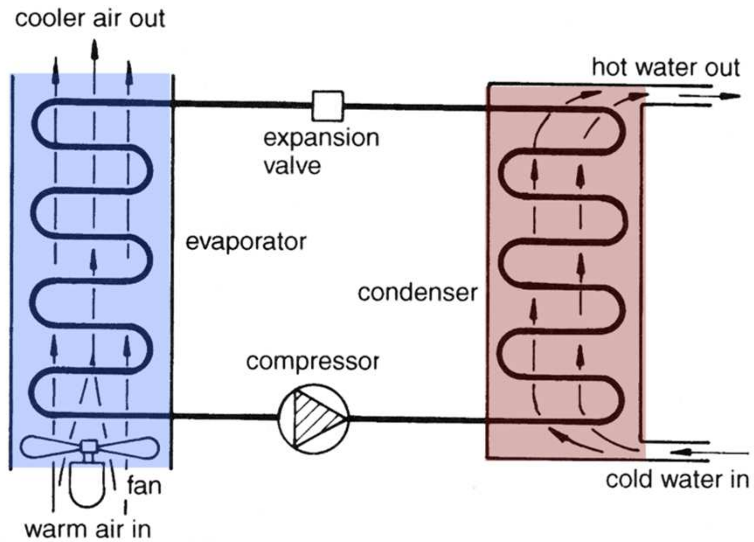
Heating mode



(c)

Refrigeration systems

- Heat pumps
  - Three types:
    - Air-source (air-to-air)
      - R-22 often used, range 1.5 to 40 TR
    - Water-source
    - Ground-coupled



  - Extract energy from ground, water, or ambient air
  - Cooling and heating mode operartion
    - Winter may require defrosting
  - High COP & EER (energy efficiency ratio)

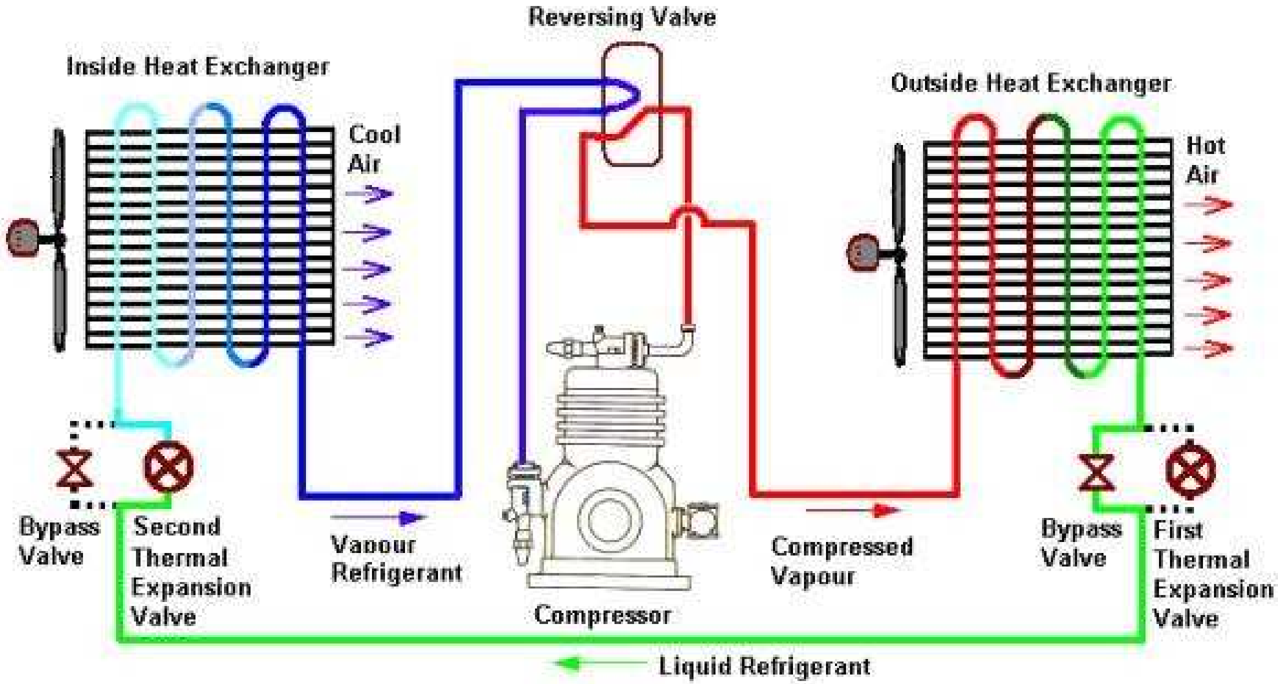


Fig. 1 - Heat Pump in Cooling Mode

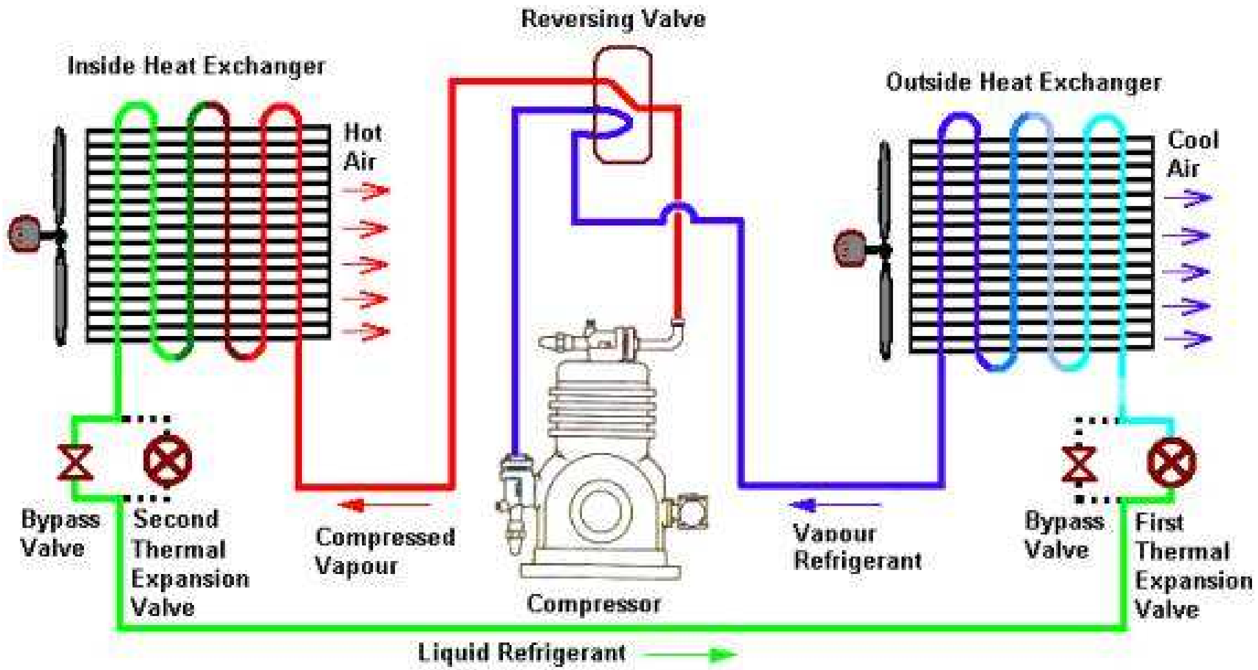


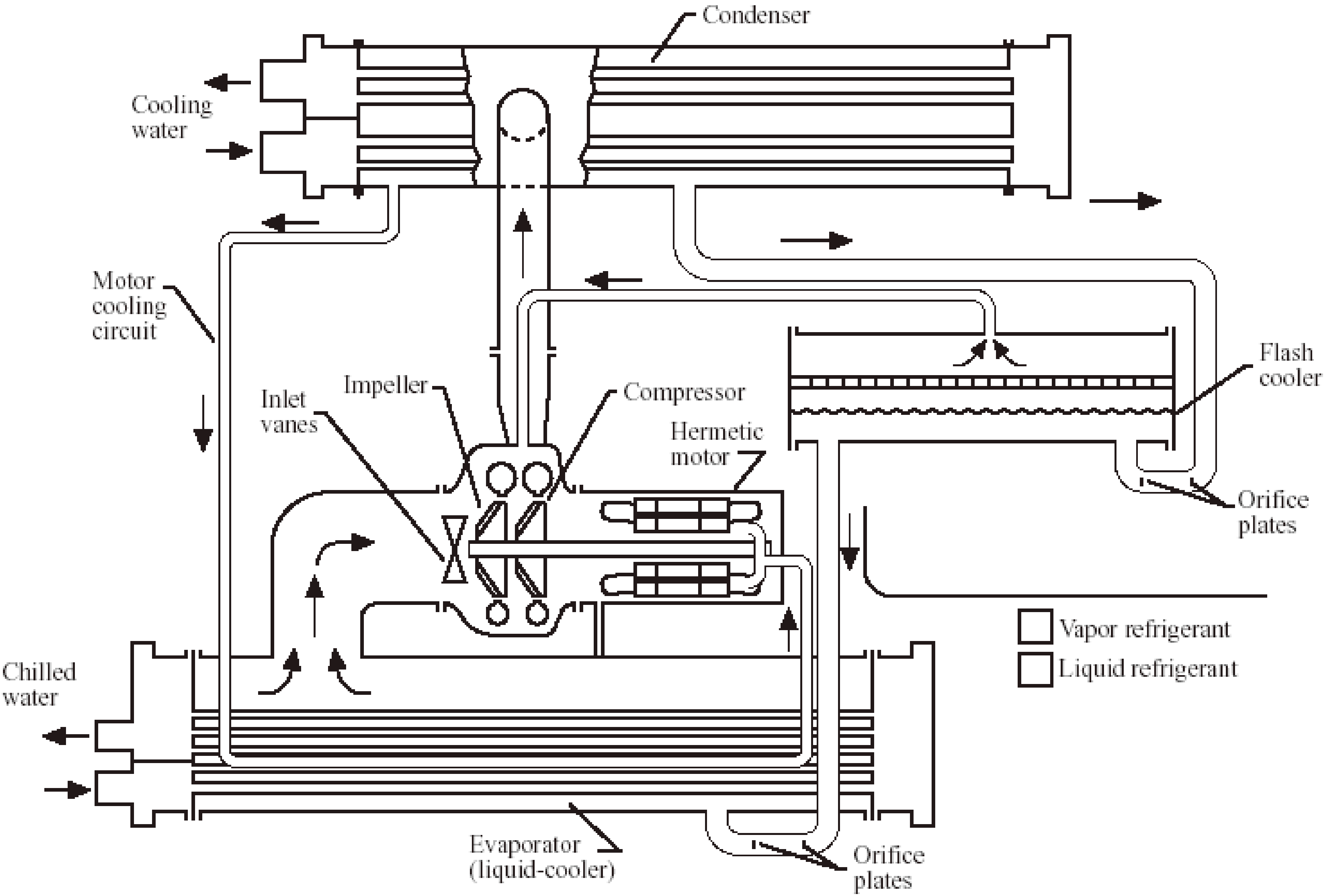
Fig. 2 - Heat Pump in Heating Mode

Refrigeration systems

- Centrifugal chillers
  - Chiller = a refrigeration machine using a liquid cooler as an evaporator to produce chilled water
  - R-11, R-12, R-22 were used
    - R-11 replaced by R-123
    - R-12 replaced by R-134a

  - System components
    - Centrifugal compressor, evaporator, condenser, flash cooler, orifice plates & float valves, purge unit (optional)

Two-stage water-cooled centrifugal chiller



Refrigeration systems

- Centrifugal chillers (cont'd)
  - Performance rating: AHRI Standard 550
    - Coefficient of performance (COP) and Integrated part-load value (IPLV)
    - Water-cooled chillers: COP = 5 (= 0.7 kW/TR)
    - Air-cooled chillers: COP = 2.5 to 2.8 (1.26-1.4 kW/TR)
  - Capacity control:
    - Inlet vanes and variable compressor speed
    - Centrifugal compressor performance map
  - Partload operation

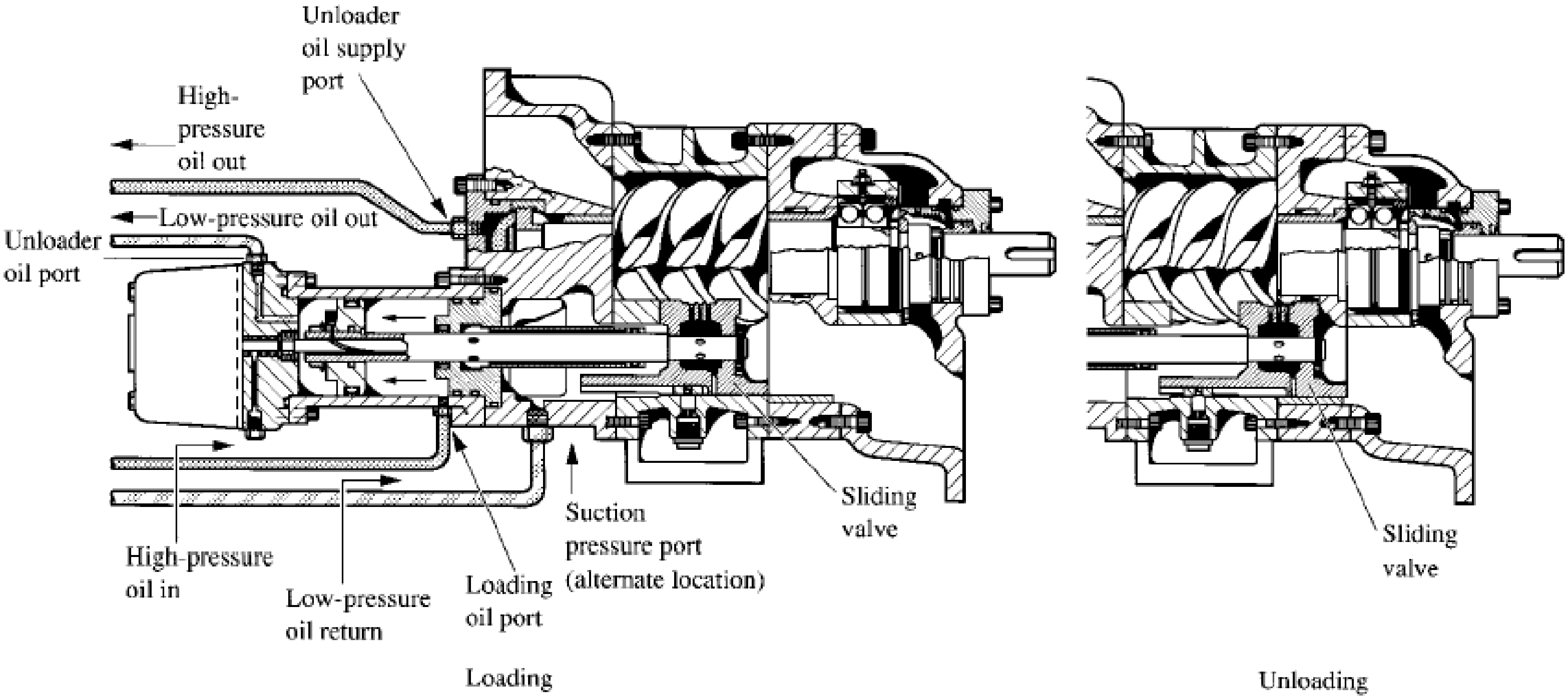
Refrigeration systems

- Centrifugal chillers (cont’d)
  - Specific controls
    - Chilled water leaving temperature and reset
    - Condenser water temperature control
    - On/off of multiple chillers based on measured coil load
    - Air purge control
    - Safety controls e.g. oil pressure, freezing protection, etc.
  - Incorporating heat recovery
    - Double-bundle condenser

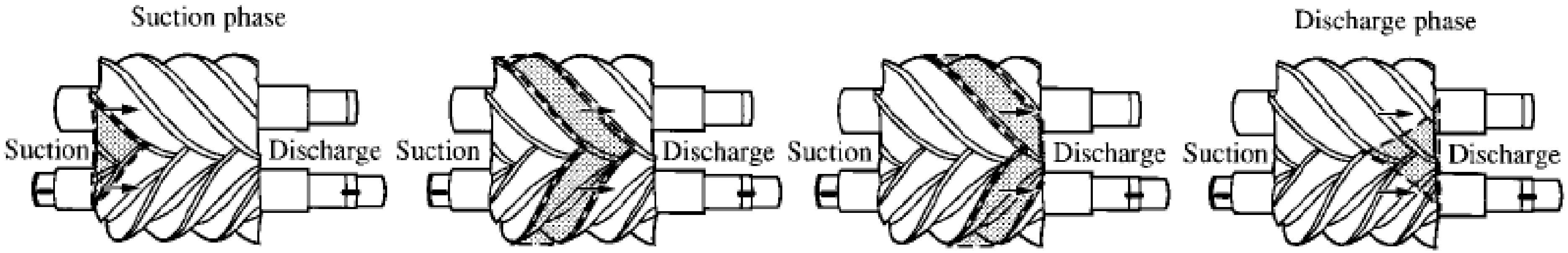
Refrigeration systems

- Screw chillers
  - Helical rotary chiller: use screw compressor
    - Twin-screw compressors are widely used
    - Capacity 100 to 1000 TR
  - Variable volume ratio
  - Economizer
    - Similar to a two-stage compound system w/ flash cooler
  - Oil separation, oil cooling and oil injection
    - Oil slugging is not a problem

Twin-screw compressor



(a)



(b)

Chiller performance

- Tons of refrigeration (TR)
  - One TR is the amount of cooling obtained by one ton of ice melting in one day i.e. 12,000 Btu/hr, 3024 kcal/hr or 3.516 thermal kW
- Net refrigerating capacity
  - A quantity defined as the mass flow rate of the evaporator water multiplied by the difference in enthalpy of water entering and leaving the cooler, expressed in kW, Btu/hr, kcal/hr, or tons of refrigeration

Chiller performance

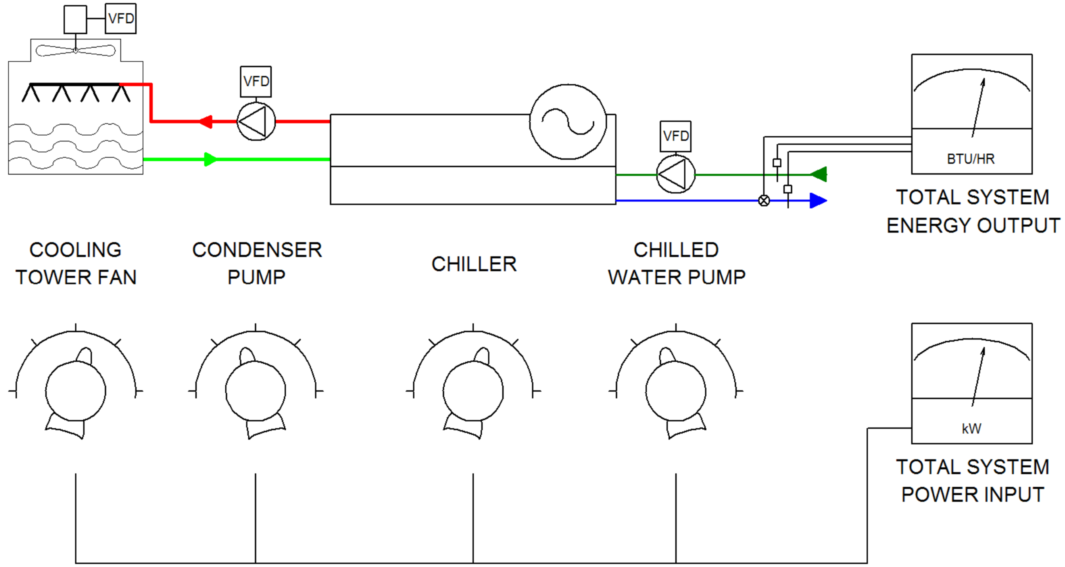
- kW/ton rating
  - Commonly referred to as efficiency, but actually power input to compressor motor divided by tons of cooling produced, or kilowatts per ton (kW/ton)
    - Lower kW/ton indicates higher efficiency
    - kW/TR as a reference energy performance indicator
- Coefficient of performance (COP)
  - Chiller efficiency measured in cooling output divided by electric power input

Chiller performance

- Energy efficiency ratio (EER)
  - Performance of smaller chillers and rooftop units is frequently measured in EER rather than kW/ton
  - EER is calculated by dividing a chiller's cooling capacity by its power input at full-load conditions
    - The higher the EER, the more efficient the unit
- Test standard and efficiency requirements
  - Test standard for chillers: AHRI 550/590
  - Mandatory efficiency requirements for minimum chiller performance: ASHRAE Standard 90.1

Chiller performance

- The overall energy consumption includes:
  - Compressor kW
  - Chilled water pump kW
  - Condenser water pump kW
  - Cooling tower fan kW



Chiller performance

- Chiller plant efficiency metrics
  - Overall chiller plant performance
    - Total tonnage
    - Total kW (including chillers and auxiliaries)
  - Individual chiller efficiency
    - Chiller tonnage
    - Compressor kW
  - Individual chiller lift
    - Lift is defined as the difference between the refrigerant saturated condensing and evaporating temperatures

Chiller performance

- Chiller plant efficiency metrics (cont'd)
  - Individual compressor isentropic efficiency
    - Suction and discharge temperatures
    - Suction and discharge pressures
  - Individual heat exchanger effectiveness
    - Approach temperatures
    - ΔT on chilled water and cooling tower water

Chiller performance

- Heat transfer at chiller (evaporator/condenser)
  - $q_w = c_{pw} \times \rho \times V_w \times \Delta t$
  - where
    - q_w = capacity of chiller evaporator/condenser (kW)
    - c_{pw} = heat capacity of water = 4.19 kJ/kg.K
    - ρ = density of water = 1,000 kg/m^3
    - V_w = volume flow rate of chilled/condensing water (L/s)
    - Δt = temperature difference across the unit (°C)
  - Often, heat transfer at condenser = 1.2 x heat transfer at evaporator (i.e. chiller capacity)

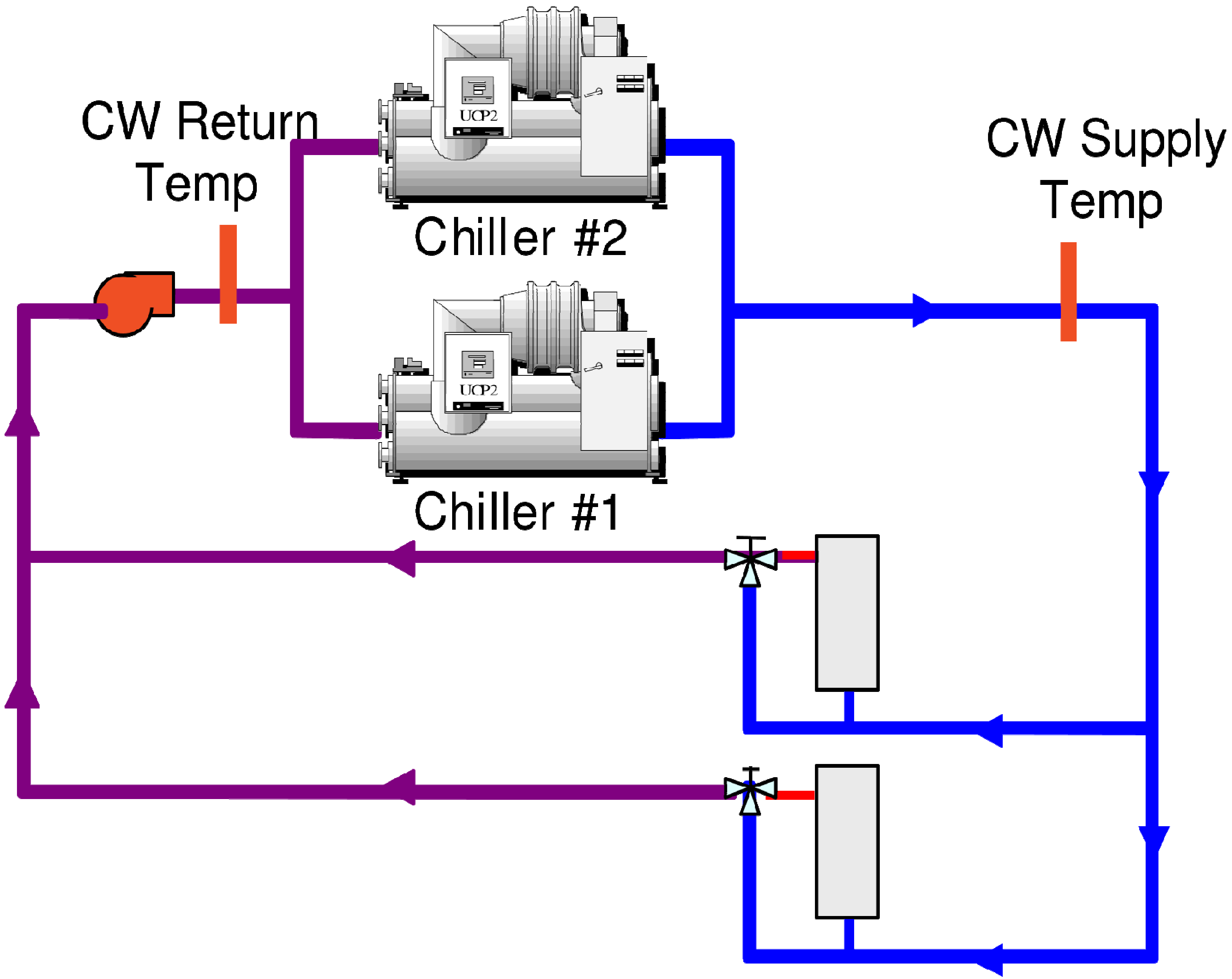
Chiller performance

- Example: For a 350 kW chiller with a 7 °C rise in chilled water temperature and a 4.5 °C drop in cooling tower's condensing water, calculate the volume flow rates of chilled and condensing water.
- Answers:
  - First, determine the flow in the evaporator (chilled water):
    - 350 kW = 4.19 kJ/kg.K x 1,000 kg/m^3 x V_{we} x 7 °C
    - => V_{we} = [350 / (4.19 x 1,000 x 7)] x (1,000 L/s per m^3) = **11.9 L/s**
  - Next, find the flow in the condenser (condensing water):
    - 1.2 x 350 kW = 4.19 kJ/kg.K x 1,000 kg/m^3 x V_{wc} x 4.5 °C
    - => V_{wc} = [1.2 x 350 / (4.19 x 4.5)] = **22.2 L/s**

Chiller performance

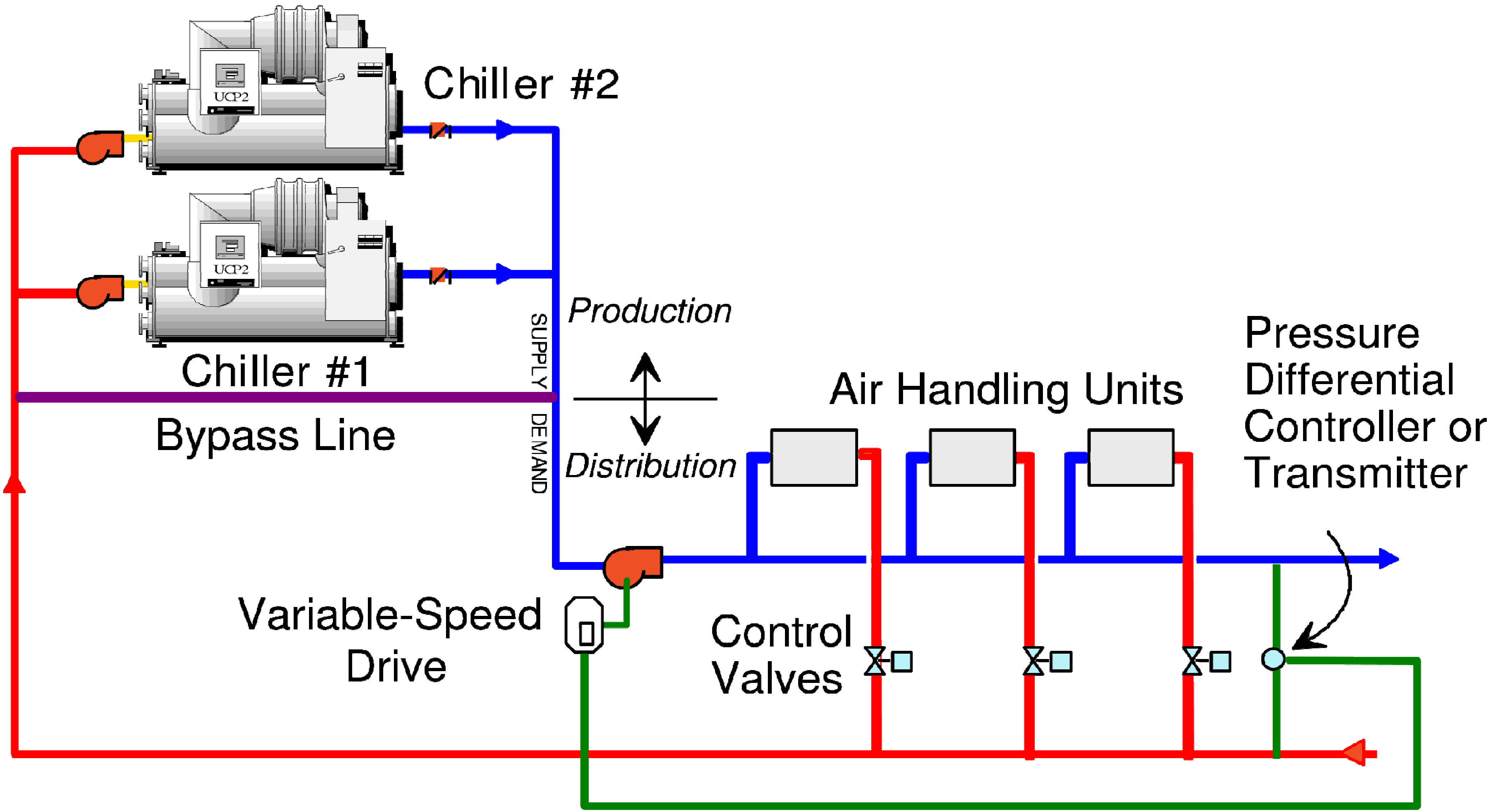
- Pumping arrangements (* see also lecture on water-side systems)
  - 1. Constant flow
  - 2. Primary-secondary (decoupled) flow
    - Distribution piping is decoupled from chiller piping
    - Constant primary flow through the operating chiller(s) and variable secondary flow through the loads
    - A bypass pipe between the two balances the primary flow with the secondary flow
  - 3. Variable-primary flow (VPF)
    - Advanced chiller controls that permit varying the flow through the chillers

Constant flow



(Source: Trane)

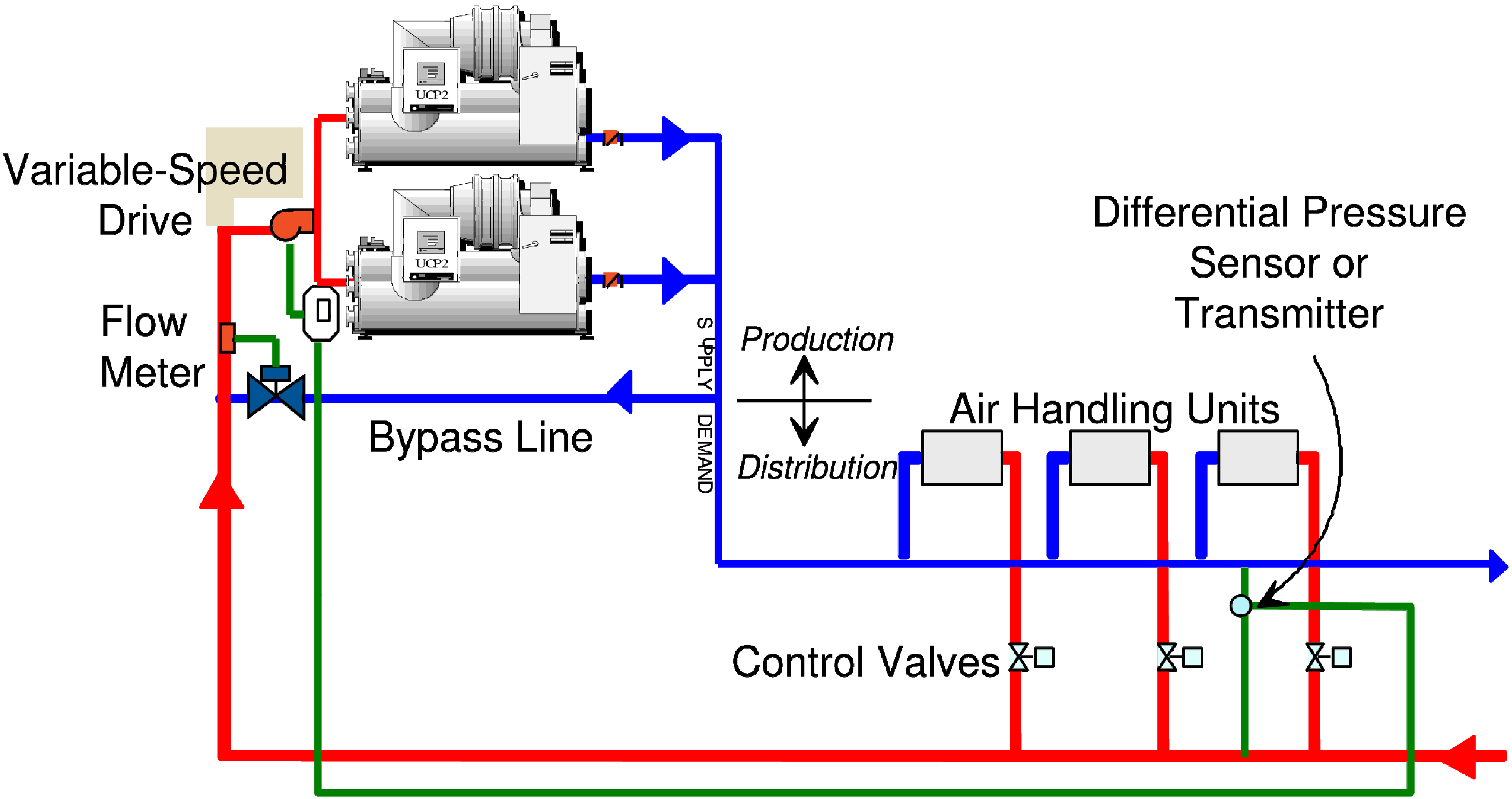
Variable flow – decoupled (primary-secondary flow)



Old paradigm: Variable flow causes low temperature trips, locks out chiller, requires manual reset (may even freeze). Hence, maintain constant flow through chillers in the primary loop.

(Source: Trane)

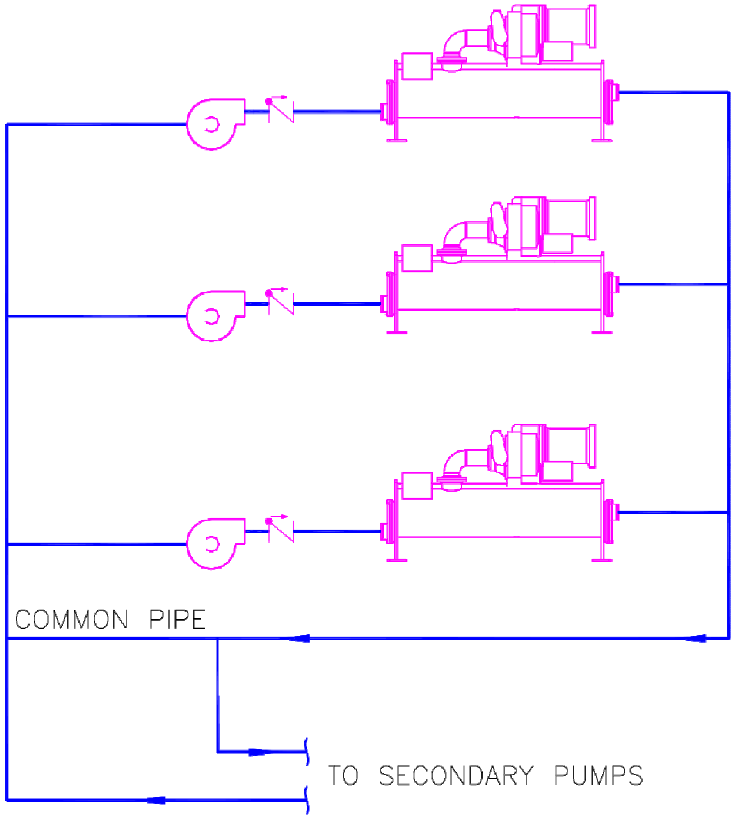
Variable-primary flow (VPF)

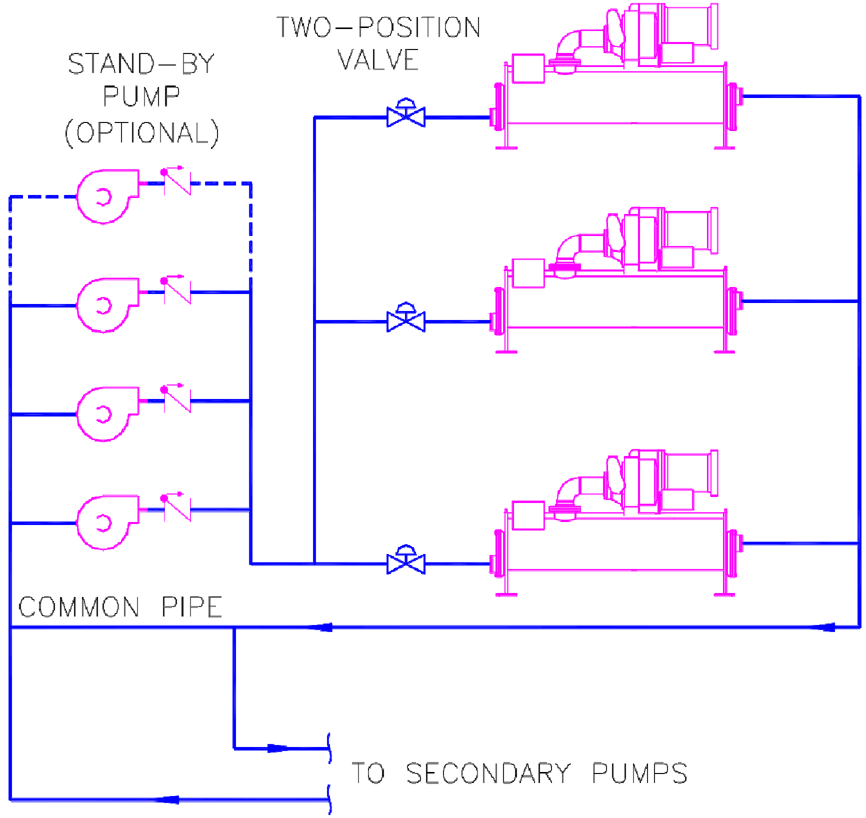


New paradigm: Modern controls are robust and very responsive to both flow and temperature variations. Thus, variable flow is OK within range and rate-of-change specified by chiller manufacturer.

(Source: Trane)

Primary chilled water pump options





<u>Dedicated pumping advantages</u>:

- Less control complexity
- Custom pump heads w/ unmatched
- Usually less expensive if each pump systems is adjacent to chiller served
- Pump failure during operation does not cause multiple chiller trips

<u>Headered pumping advantages</u>:

- Better redundancy
- Valves can "soft load" chillers with primary-chillers only
- Easier to incorporate stand-by pump

(Source: Taylor Engineering http://www.taylor-engineering.com)

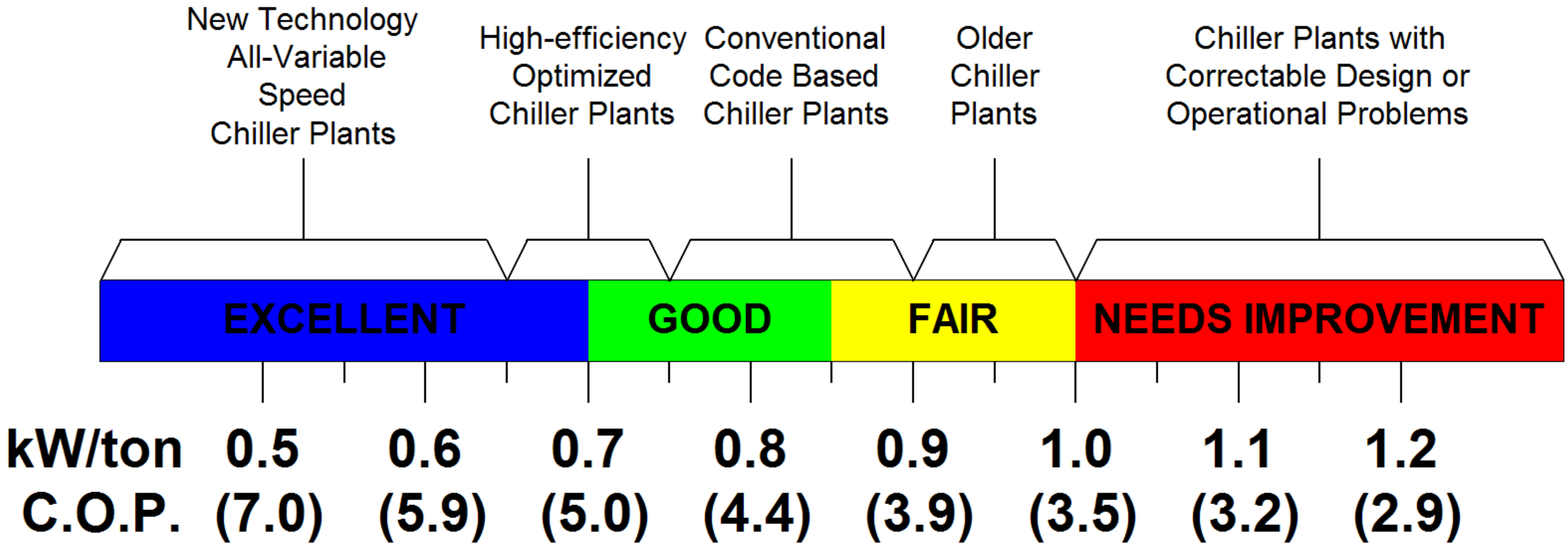
Chiller performance

- Design objectives:
  - Reliable chilled water flow
  - Operating cost (energy efficiency)
  - Operator safety
  - Environmental awareness
  - Reduced maintenance cost
- Aim: deliver chilled water to all loads under various load conditions as efficiently as possible

Chiller performance

- Understanding loads and their impact on design
  - Peak design load: determine overall plant capacity
  - Cooling load profile: describes how the load varies over time to design the plant to stage efficiently
- Operating kW/ton achievable in today's plants (includes chillers, cooling towers and pumps)
  - 0.5 - 0.7 Excellent
  - 0.7 - 0.85 Good
  - 0.85 - 1.0 Fair
  - > 1.0 Needs Improvement

Benchmarking of chiller plants



AVERAGE ANNUAL CHILLER PLANT EFFICIENCY IN KW/TON (C.O.P.)
(Input energy includes chillers, tower fans, and condenser & chilled water pumping)

Based on electrically driven centrifugal chiller plants in comfort conditioning applications with 42F (5.6C) nominal chilled water supply temperature and open cooling towers sized for 85F (29.4C) maximum entering condenser water temperature.
Local Climate adjustment for North American climates is +/- 0.05 kW/ton

(Source: Steps to a more efficient chiller plant http://www.automatedbuildings.com/news/jan01/articles/hartman/hrtmn2.htm)

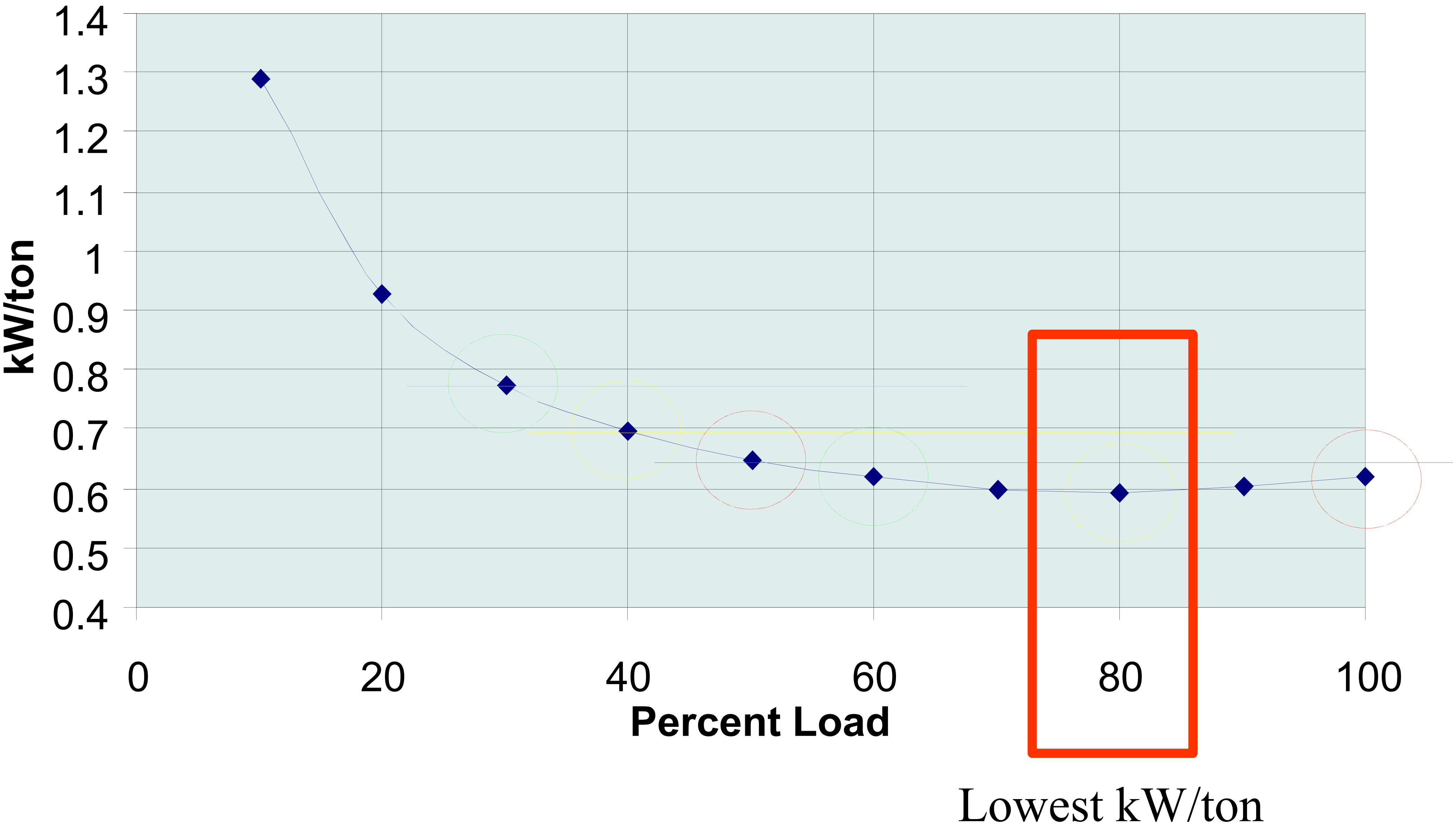
Chiller plant control

- Chiller plant control
  - Load determination and capacity matching
  - Chiller sequencing and rotation
  - Chiller setpoint control
  - Failure recovery
  - User interface
  - System optimization
- Installation and operation reliability and efficiency

Chiller plant control

- Load determination
  - When to add or subtract a chiller?
  - What is the optimal sequencing for chillers?
    - Should I run one chiller at 100% or two chillers at 50%?
    - The givens…
      - Whether you run one chiller or two…
        - The building load does not change
        - The outside wet bulb temperature does not change
      - When you run two chillers…
        - You may double the number of pumps
        - You may double the number of tower cells

Unloading at constant condenser water temperature (constant speed centrifugal chiller)



(Source: Trane)

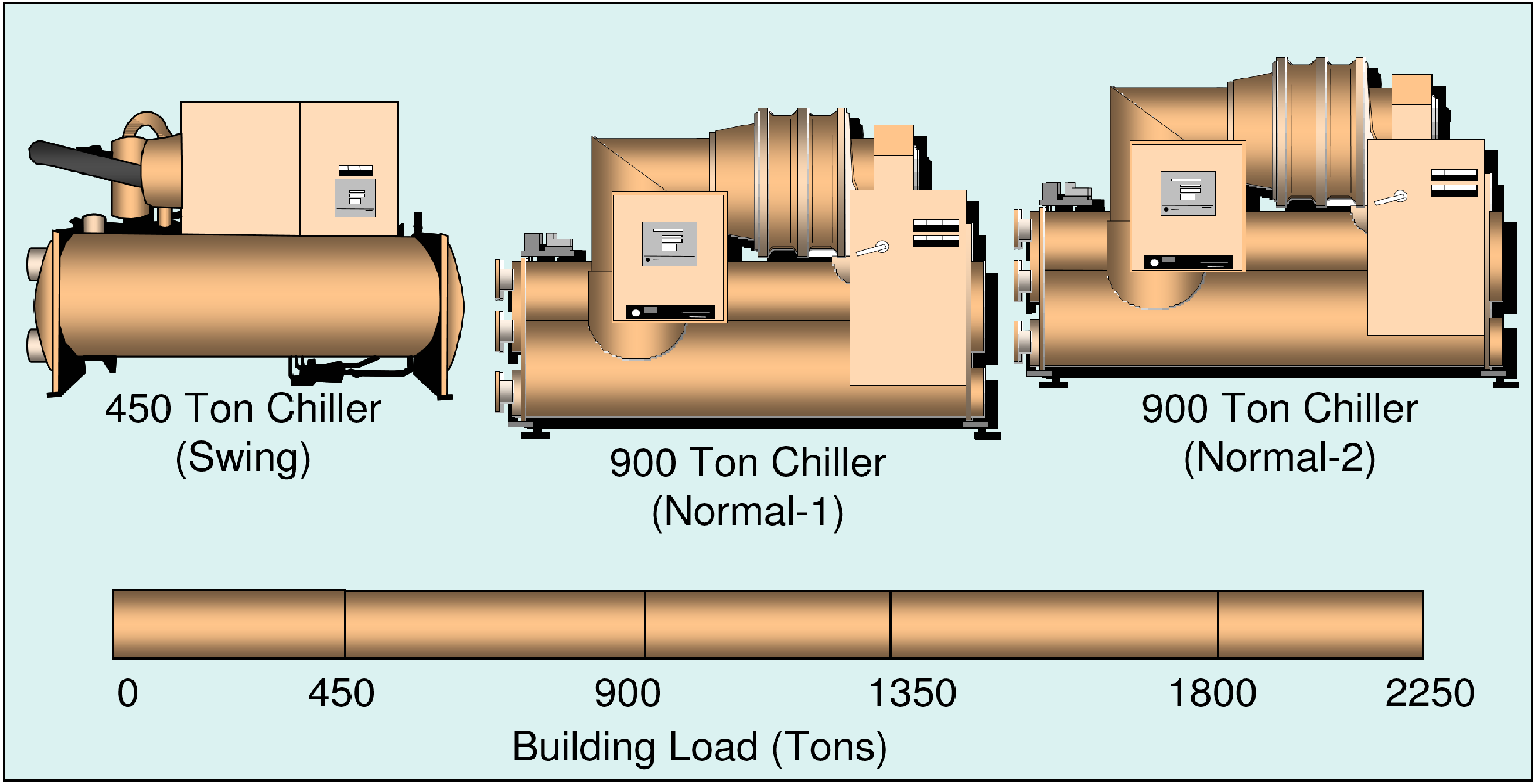
Chiller plant control

- Capacity matching
  - Turn the right chiller on
  - Dependent on chiller plant design

• Normal	- identical chillers
• Base	- heat recovery/super efficient
• Peak	- back up/alternate energy source/inefficient
• Swing	- match the load!
• Custom	- mix and match/nested CPC objects

Reduce operating costs

Capacity matching for multiple chillers



(Source: Trane)

Chiller plant control

- Chiller sequencing and rotation
  - To reduce operating costs and maintain reliable chilled water by flexible rotation
  - Which chiller is next?
    - Schedule based
    - Run-time
    - Manual operator decision
    - Customized
      - Number of starts
      - Other?

Chiller plant control sequencing
(Steps of capacity in a typical chiller plant)

Step	**Chiller 1** (Base)	**Chiller 3 (Swing)**	**Chiller 4 (#1)**	**Chiller 5 (#2)**	**Chiller 2 (Peak)**
1	ON	OFF	OFF	OFF	OFF
2	ON	ON	OFF	OFF	OFF
3	ON	OFF	ON	OFF	OFF
4	ON	ON	ON	OFF	OFF
5	ON	OFF	ON	ON	OFF
6	ON	ON	ON	ON	OFF
7	ON	ON	ON	ON	ON

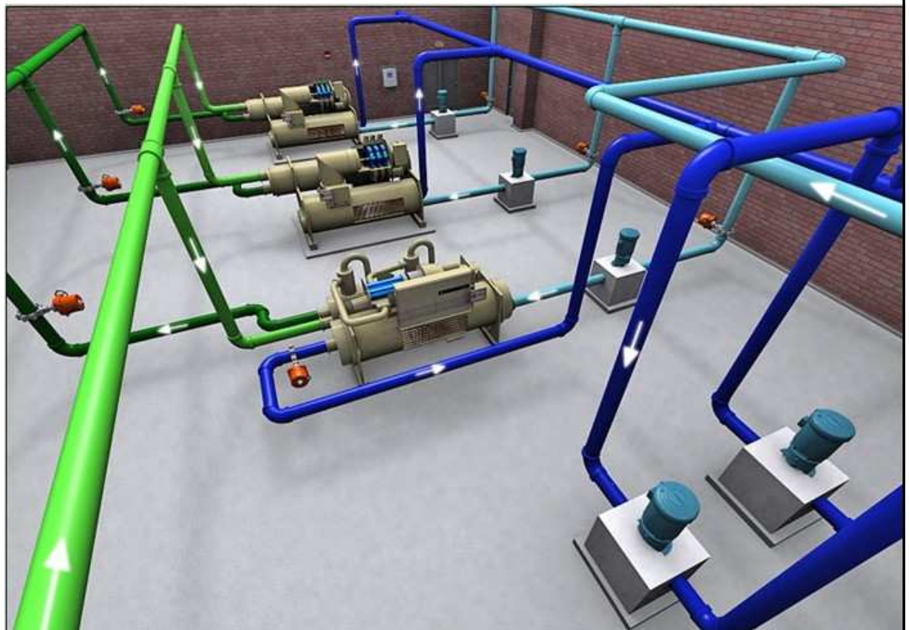
(Source: Trane)

Chiller plant control

- Chiller setpoint control
  - Must maintain reliable chilled water
  - Unload before start
  - Keep chillers online
  - Ride out flow transients on startups
    - Deals with less sophisticated chiller controllers
  - Variable flow / multiple pump systems
  - Low supply water temperatures

Chiller plant control

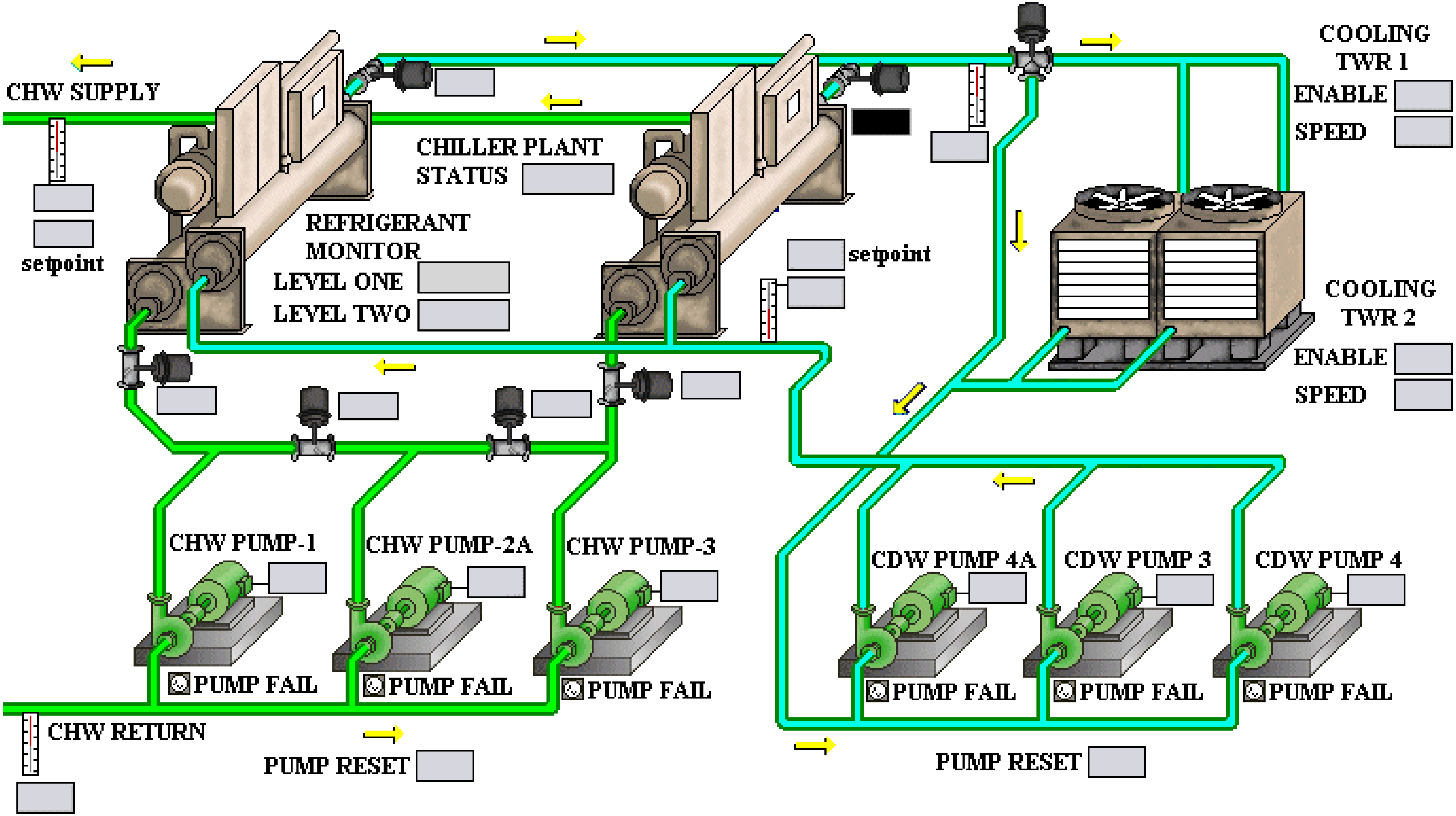
- Failure recovery
  - Keep chilled water flowing
  - No manual intervention required
  - Follow the standard sequence
  - Multiple failure inputs
    - Chiller level
    - System level
  - Fast restarts



Chiller plant control

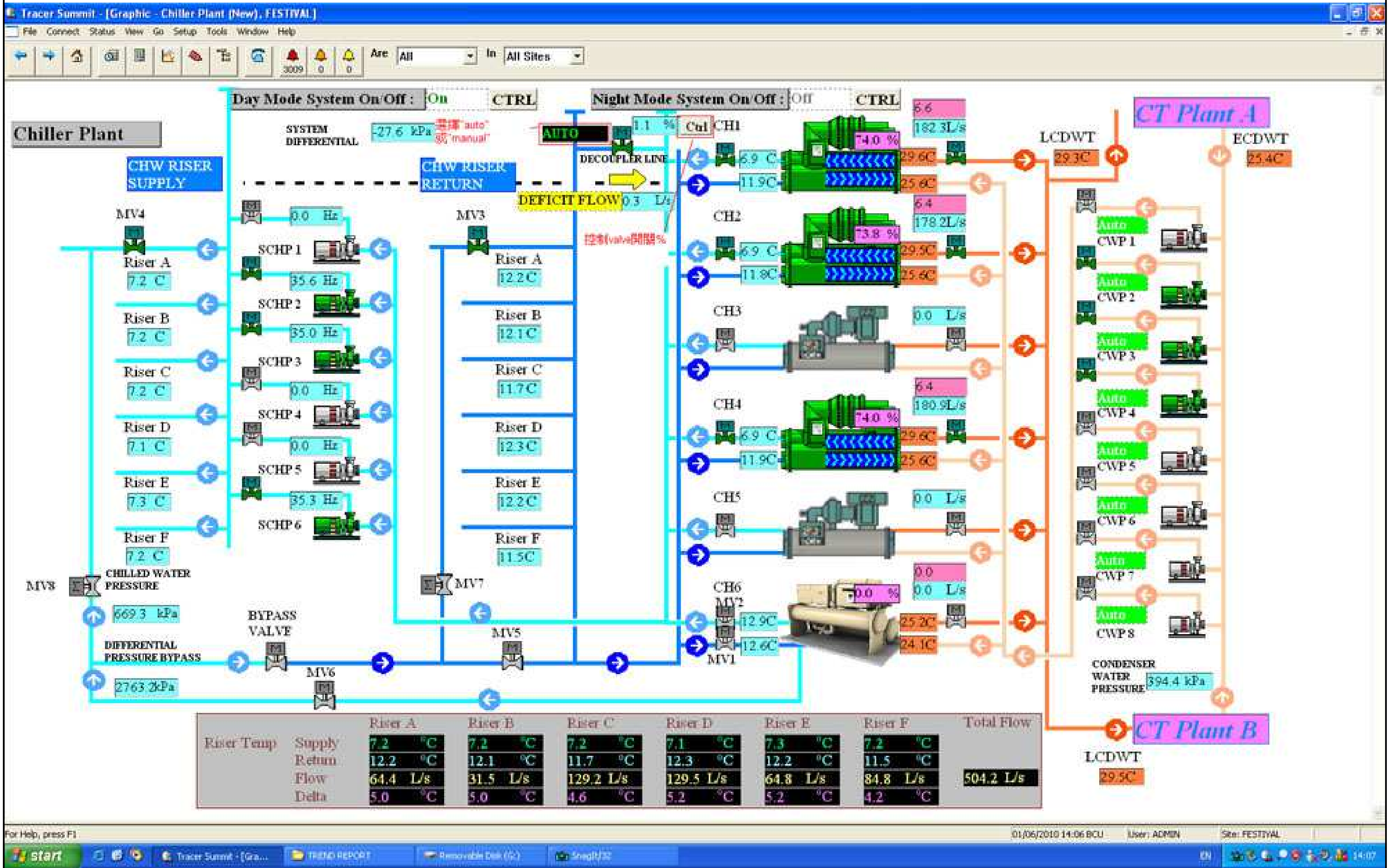
- User interface
  - Informative display
  - Easy to operate
  - Benefits of intuitive user interface
    - Minimize training time
    - Minimize undesirable manual control
    - Maximize operator efficiency
  - Reduced operational and training costs

Example of chiller plant control interface



(Source: Trane)

Example of chiller plant control interface

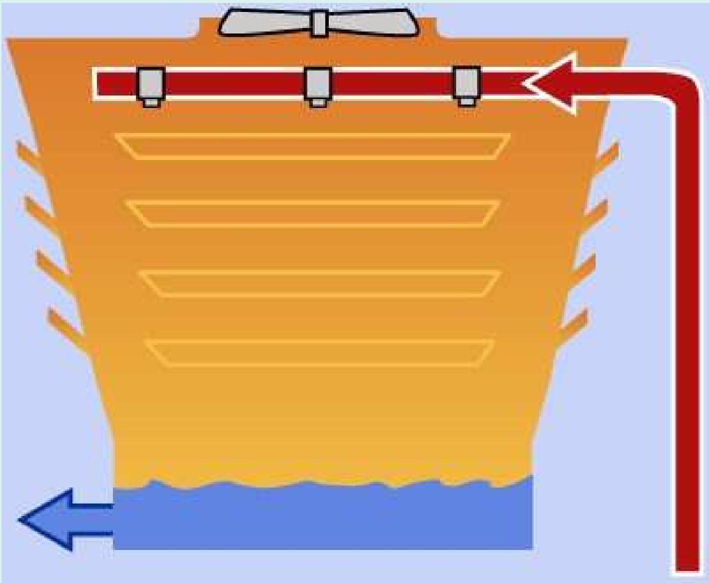


(Source: Trane)

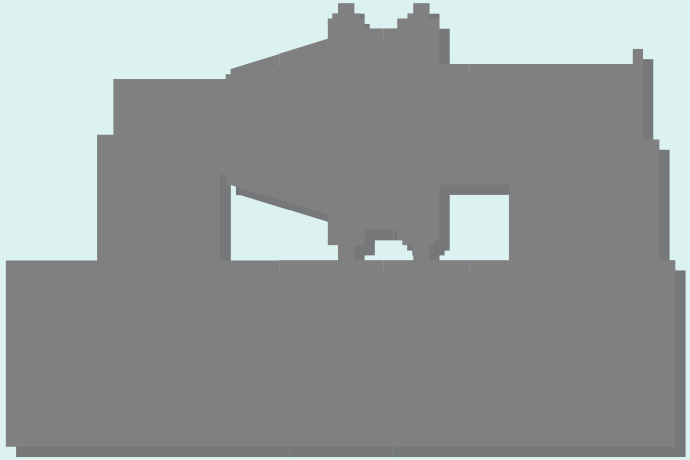
Chiller plant control

- System optimization
  - Colder chilled water reduces energy consumption
    - Chilled water pumps
  - Warm condenser water reduces energy consumption
    - Condenser water pumps
  - Cooling tower control reduces energy consumption
    - Cooling tower fans
    - Chiller

Chiller – cooling tower optimization
(tower setpoint optimization)



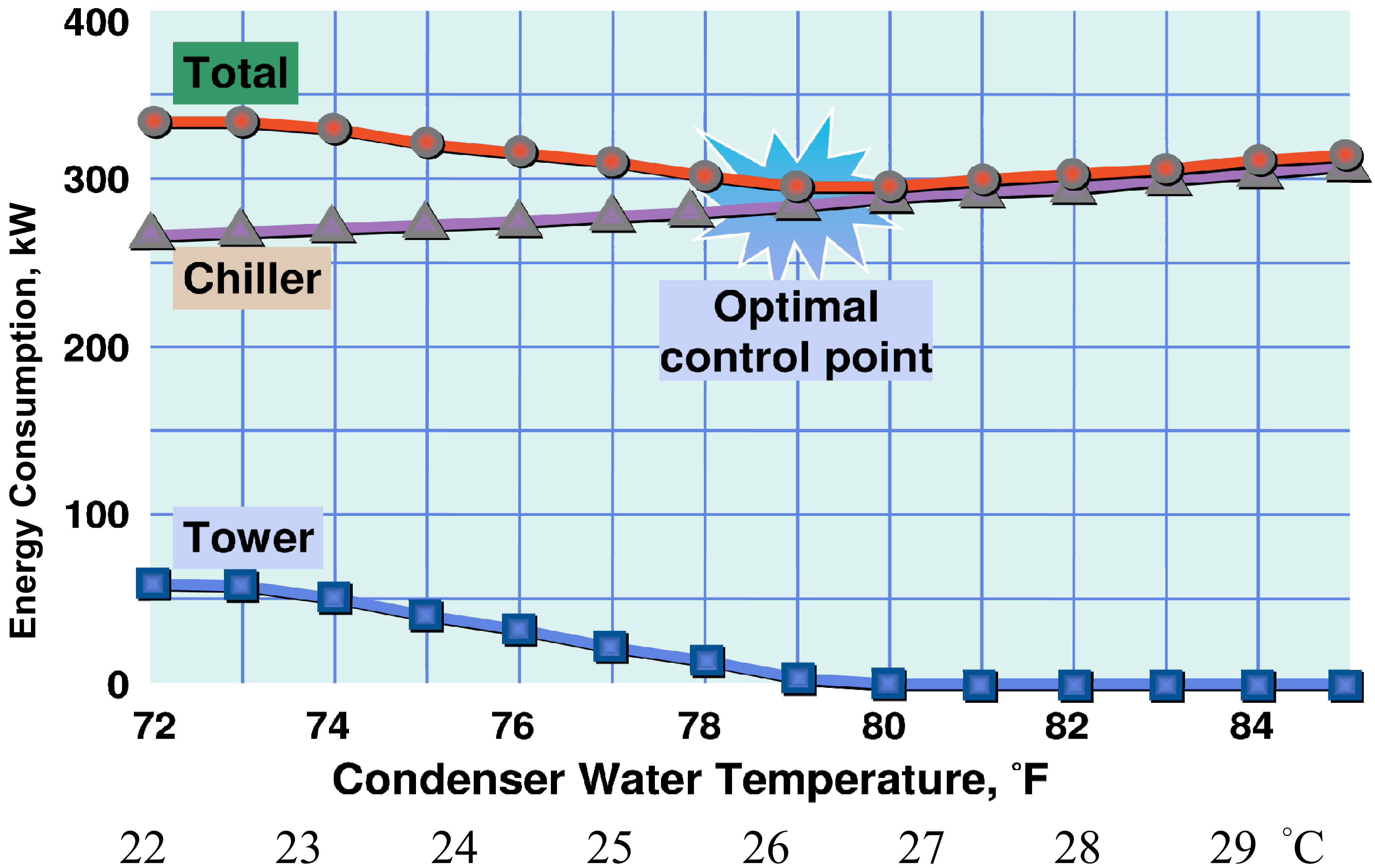
- Load
- Condenser water temperature
- Wet bulb
- Tower design



- Load
- Condenser water temperature
- Chiller design

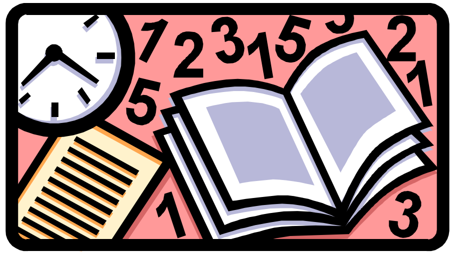
(Source: Trane)

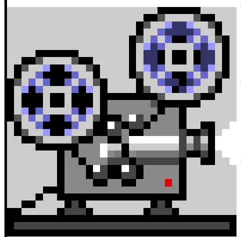
Chiller – cooling tower interaction (optimized control strategies)



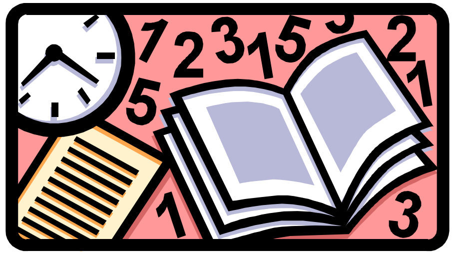
(Source: Trane)

Further Reading



- Videos:

  - Chiller Basics - How they work (16:36) http://youtu.be/0rzQhSXVq60
  - How Chillers work Part 2 (41:44) http://youtu.be/3ZpE3vCjNqM
  - How a Chiller, Cooling Tower and Air Handling Unit work together (16:45) http://youtu.be/1cvFlBLo4u0
  - Chiller Plant Operations (11:30) http://youtu.be/PklOP7V7p04
  - Chiller Installation at York University Central Utility Building ?Keele Campus (4:13) http://youtu.be/DTCxlz9dPTA
- Improve chiller plant efficiency!
  - http://www.automatedbuildings.com/news/jan01/articles/hartman/hrtmn.htm
- Steps to a more efficient chiller plant
  - http://www.automatedbuildings.com/news/jan01/articles/hartman/hrtmn2.htm

References



- Chiller System Design and Control, Trane Applications Engineering Manual
  - http://www.tranebelgium.com/files/book-doc/12/en/12.lvkrkymx.pdf
- Chilled Water Plant Design Guide
  - http://www.taylor-engineering.com/Websites/taylorengineering/images/guides/EDR_DesignGuidelines_CoolToolsChilledWater.pdf
- Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed., Butterworth-Heinemann/Elsevier, Amsterdam and Boston.