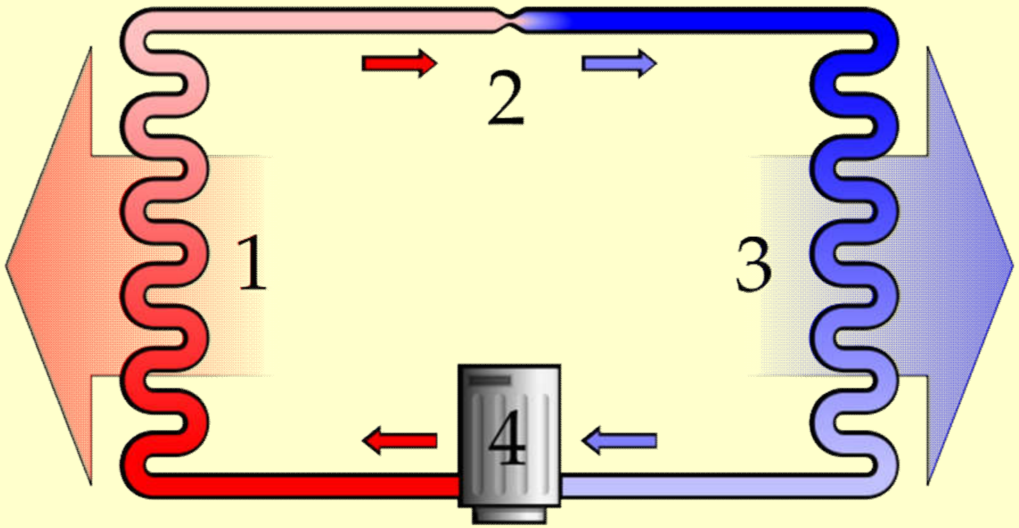
ASHRAE Hong Kong Chapter: Technical Workshop
27 Jun 2019 (Thu)



Fundamentals of Refrigeration

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Download presentation file:
http://ibse.hk/190627_ASHRAE-HKC_Refrigeration_Workshop.pdf

Jun 2019

World Refrigeration Day (WRD) 2019, Wednesday, 26 June 2019

https://worldrefrigerationday.org/

An international awareness campaign to raise the profile of the refrigeration, air-conditioning and heat-pump sector and focuses attention on the significant role that the industry and its technology play in modern life and society

26 June every year
(in commemoration of the birth date of Lord Kelvin)

(Video: World refrigeration day CLIMALIFE 2019 (2:12) https://youtu.be/XIz3dvkQDfM)

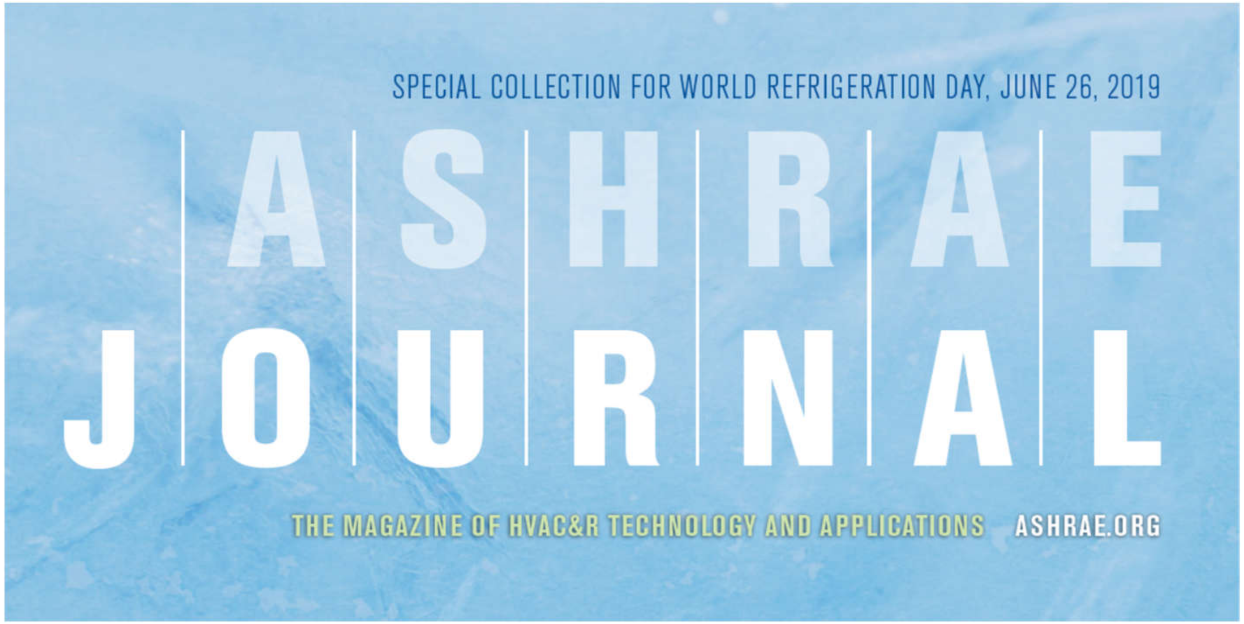
Number of refrigeration systems in operation worldwide per application

Applications	Sectors	Equipment	Number of units in operation
Refrigeration and food	Domestic refrigeration	Refrigerators and freezers	1.5 billion [1] [2]
	Commercial refrigeration	Commercial refrigeration equipment (including condensing units, stand-alone equipment and centralized systems)	90 million [1] [2]
	Refrigerated transport	Refrigerated vehicles (vans, trucks, semi-trailers or trailers)	4 million [3]
		Refrigerated containers (« reefers »)	1.2 million [2]
Air conditioning	Air conditioners	Air-cooled systems	600 million [2] [4]
		Water chillers	2.8 million [2]
	Mobile air-conditioning systems	Air-conditioned vehicles (passenger cars, commercial vehicles and buses)	700 million [5]
Refrigeration and health	Medicine	Magnetic Resonance Imaging (MRI) machines	25,000 [6]
Refrigeration in industry	Liquefied Natural Gas (LNG)	LNG receiving terminals	110 [7]
		Liquefaction trains	92 [7]
		LNG tanker fleet (vessels)	421 [7]
Heat pumps		Heat pumps (residential, commercial and industrial equipment, including reversible air-to-air air conditioners)	160 million [8] [9]
Leisure and sports		Ice rinks	13,500 [10]

(Adapted from: http://www.iifiir.org/userfiles/file/publications/notes/NoteTech_29_EN.pdf)

ASHRAE Journal: Special Collection for World Refrigeration Day, June 26, 2019

https://images.magnetmail.net/images/clients/ASHRAE/attach/Refrigeration-Applications_The_George_Briley_Collection.pdf



ASHRAE Refrigeration Page https://www.ashrae.org/technical-resources/refrigeration

- Refrigeration Resources:
  - ASHRAE Handbook – Refrigeration 2018
  - ASHRAE Handbook – Fundamentals 2017
    - Chapter 2. Thermodynamics and Refrigeration Cycles
    - Chapter 29. Refrigerants
    - Chapter 30. Thermophysical Properties of Refrigerants
    - Chapter 31. Physical Properties of Secondary Refrigerants

New definitions of five refrigeration keywords
[developed by ASHRAE and International Institute of Refrigeration (IIR)]

Cooling
1. Removal of heat, usually resulting in a lower temperature and/or phase change
2. Lowering temperature

Refrigeration
1. Cooling of a space, substance or system to lower and/or maintain its temperature below the ambient one (removed heat is rejected at a higher temperature)
2. Artificial cooling

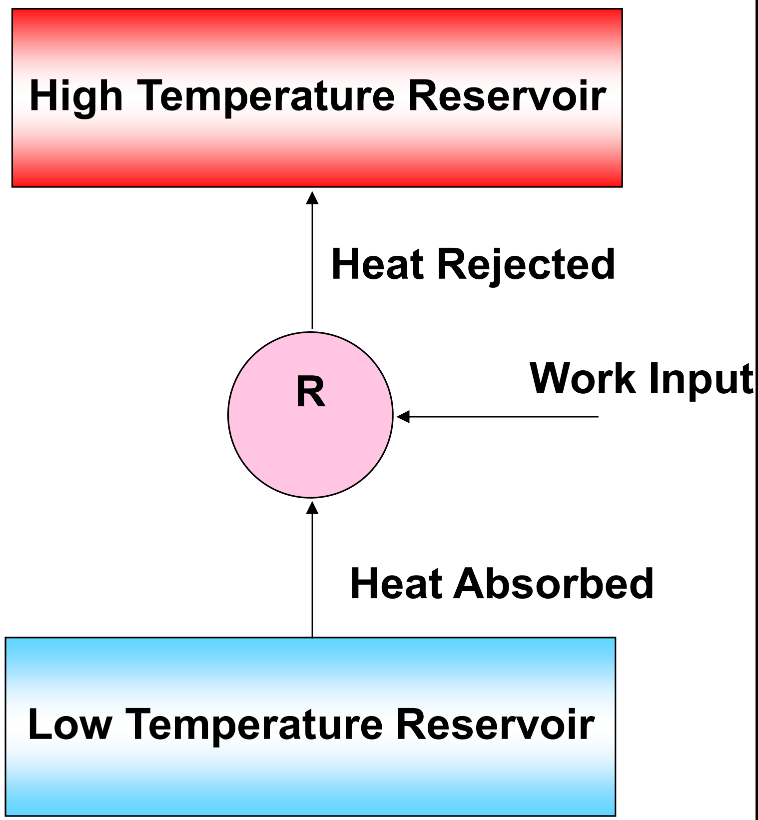
Chilling
• Cooling of a substance without freezing it

Freezing
• Solidification phase change of a liquid or the liquid content of a substance, usually due to cooling

Cold Chain
• Series of actions and equipment applied to maintain a product within a specified low-temperature range from harvest/production to consumption

(Source: https://eurovent.eu/sites/default/files/field/file/GEN%20-%201015.00%20-%20New%20definitions.pdf)

Contents



High Temperature Reservoir
Heat Rejected
R
Work Input
Heat Absorbed
Low Temperature Reservoir

1. Introduction

- Refrigeration

  製冷

  - The cooling effect of the process of extracting heat from a lower temperature heat source, a substance or cooling medium, and transferring to a higher temperature heat sink, to maintain the temperature of the heat source below that of surroundings
- Refrigeration systems
  - Combination of components, equipment & piping connected to produce the refrigeration effect

1. Introduction

- Refrigeration can offer cooling, dehumidifying, and also heating (by heat pump) for air conditioning
- Common space & product temperatures

  - Air Conditioning = 24 °C
  - High temperature refrigeration = 12 °C
  - Medium temperature refrigeration = 2 °C
  - Low temperature refrigeration = -23 °C
  - Extra low temperature refrigeration = -32 °C

} Industrial, food, cold chain, medicine, cryogenics

Thermal energy moves from left to right through five loops of heat transfer (i.e. heat pump)

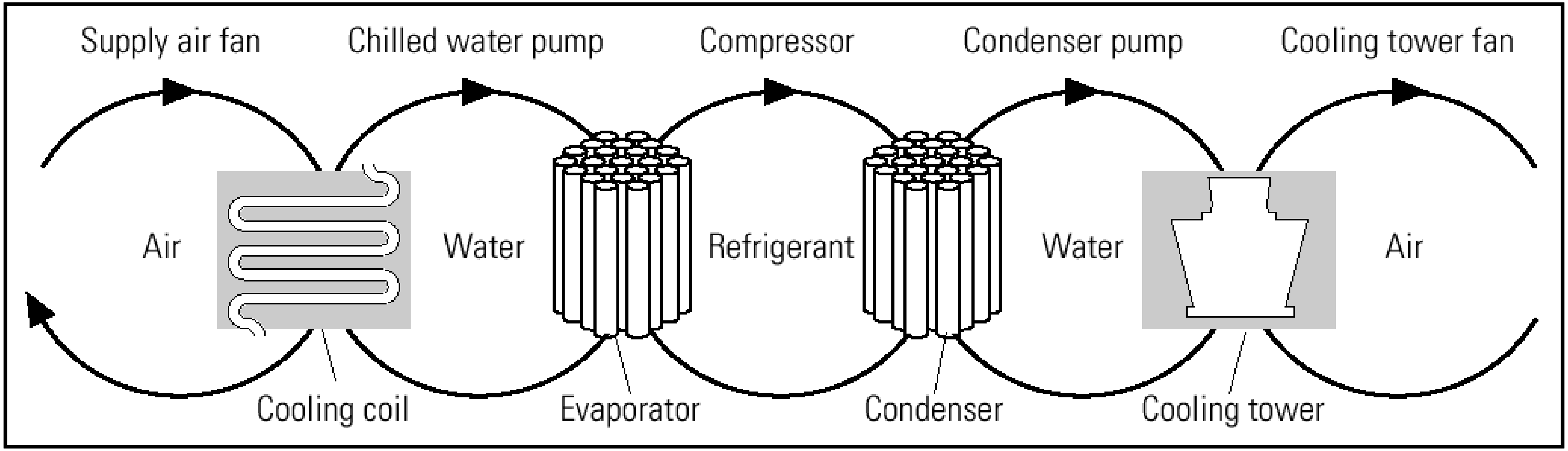
1) Indoor air loop

2) Chilled water loop

3) Refrigerant loop

4) Condenser water loop

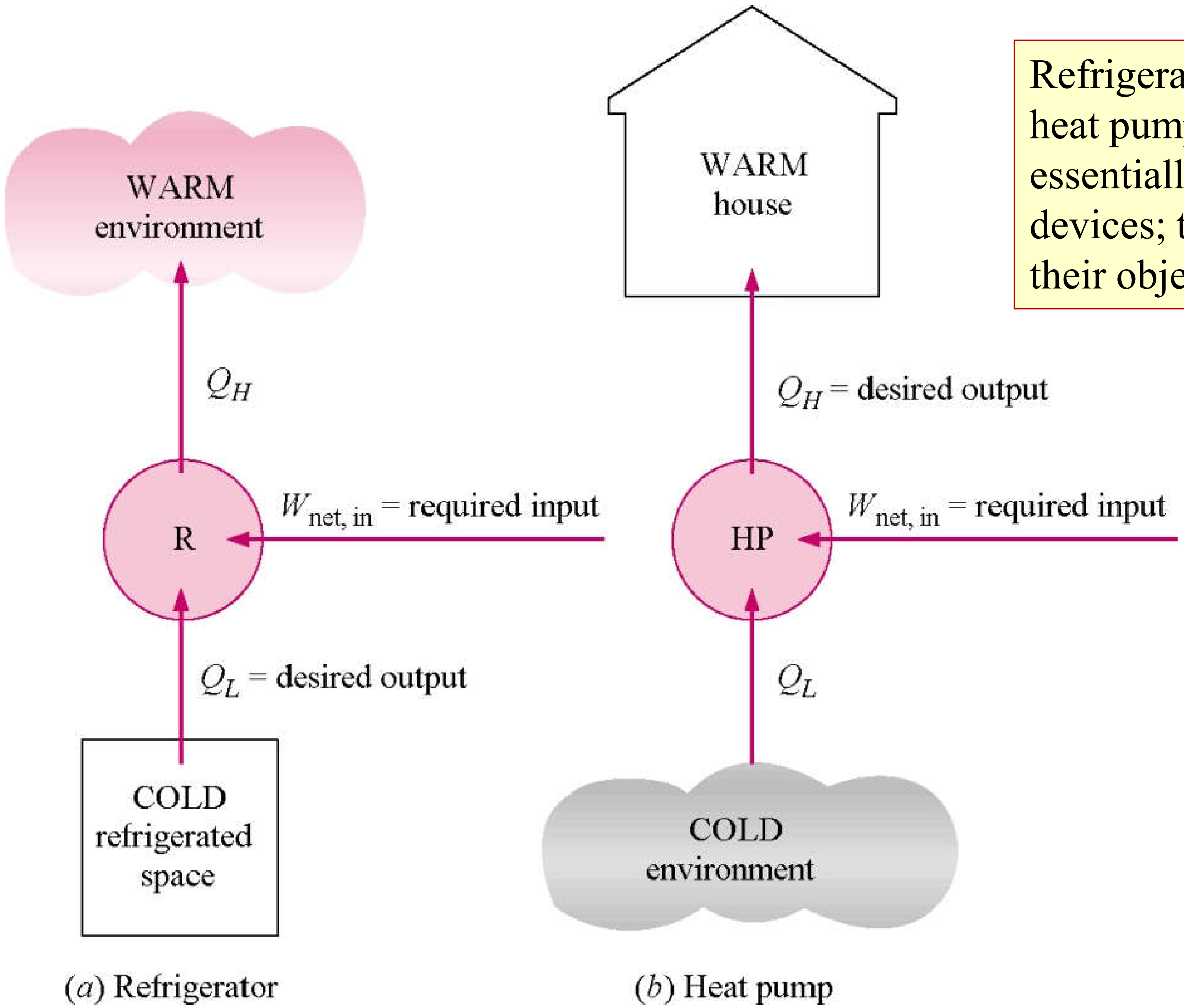
5) Cooling water loop



* The knowledge of refrigeration systems would help HVAC engineers in selection of the equipment and fitting it properly into overall system, defining practices consistent with safety and safety standards of the industry, and restrictive regulations on refrigerant production, recovery, and release for environmental concerns.

(Source: *www.energyefficiencyasia.org*)

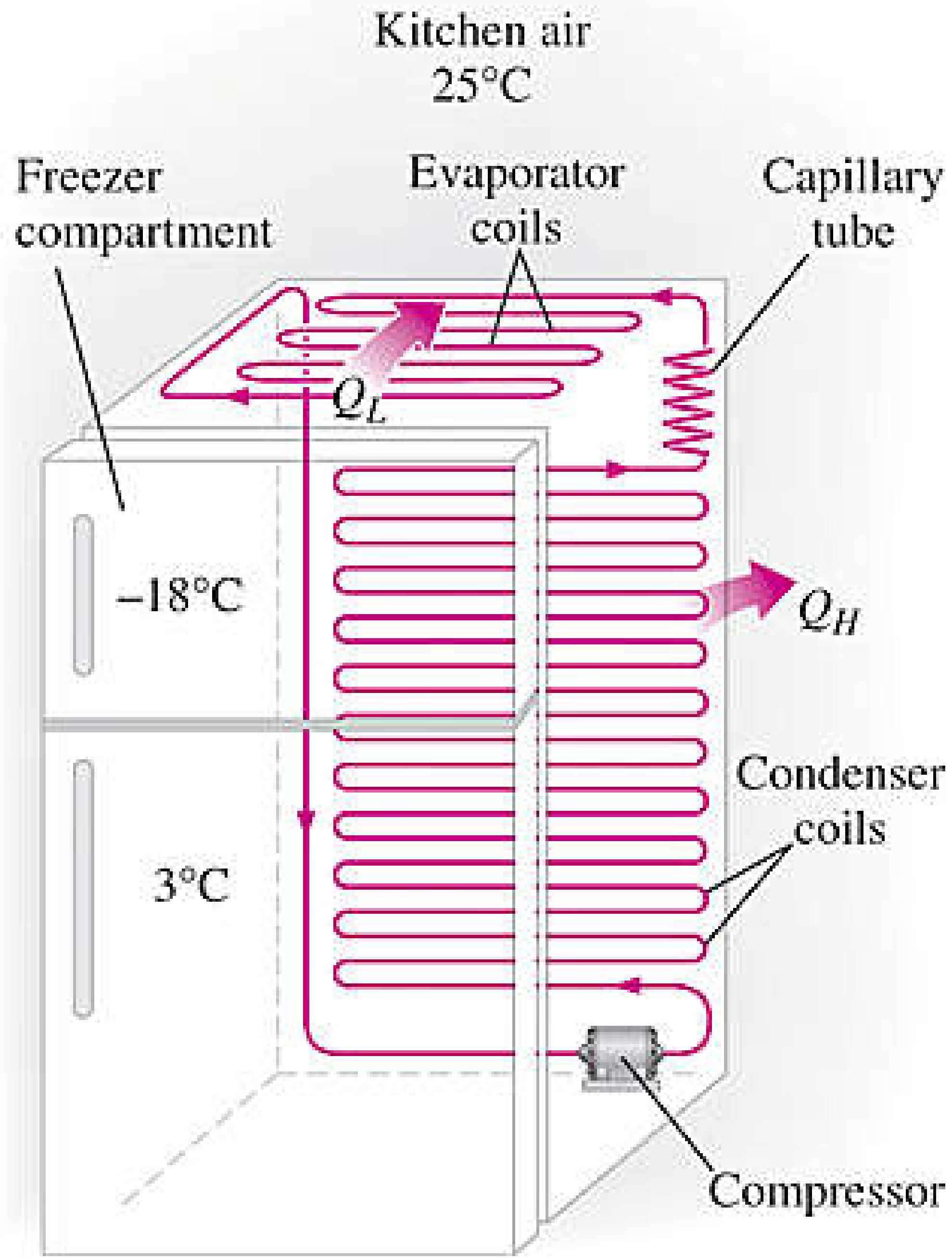
Basic principles of refrigerator and heat pump

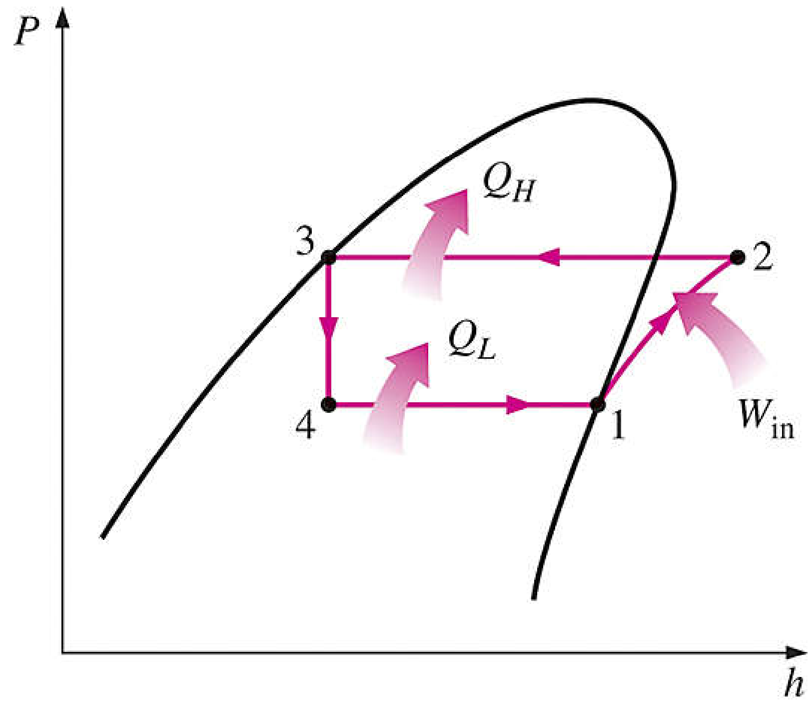


Refrigerators and heat pumps are essentially the same devices; they differ in their objectives only.

(Source: *Thermodynamics: An Engineering Approach*, 8th edition, by Yunus A. Çengel and Michael A. Boles)

An ordinary household refrigerator





$$\mathrm{COP_R} = \frac{q_L}{w_{\mathrm{net,in}}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$\mathrm{COP_{HP}} = \frac{q_H}{w_{\mathrm{net,in}}} = \frac{h_2 - h_3}{h_2 - h_1}$$

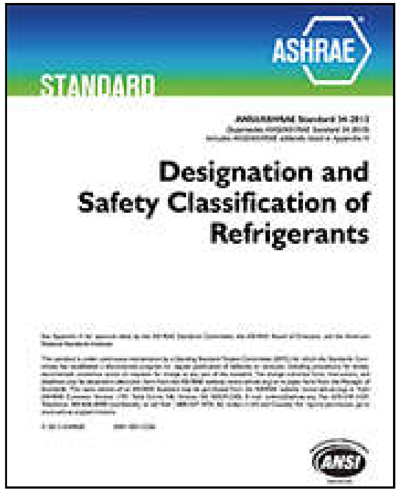
(Source: *Thermodynamics: An Engineering Approach*, 8th edition, by Yunus A. Çengel and Michael A. Boles)

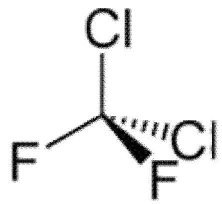
1. Introduction

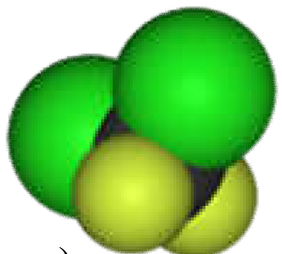
- Terminology
  - Refrigerant:
    - A primary working fluid to produce refrigeration in a refrigeration system
  - Cooling medium:
    - Working fluid cooled by refrigerant during evaporation to transport refrigeration from a central plant to remote equipment
  - Liquid absorbent:
    - Working fluid to absorb vaporised refrigerant (water) after evaporation in an absorption refrigeration system

1. Introduction

- Numbering system for refrigerants
  - For hydrocarbons & halocarbons (halogenated)
  - ANSI/ASHRAE Standard 34
    - 1st digit: number of unsaturated carbon-carbon bonds
    - 2nd digit: number of carbon atoms minus one
    - 3rd digit: number of hydrogen atoms plus one
    - Last digit: number of fluorine atoms
  - For example, R-11 = $CFCl_3$; R-12 = CF_2Cl_2 ; R-22 = CHF_2Cl; R-123 = $CHCl_2CF_3$
- Chlorofluorocarbons (CFCs)
  - Contains only chlorine, fluorine & carbon atoms
  - Cause ozone depletion & global warming





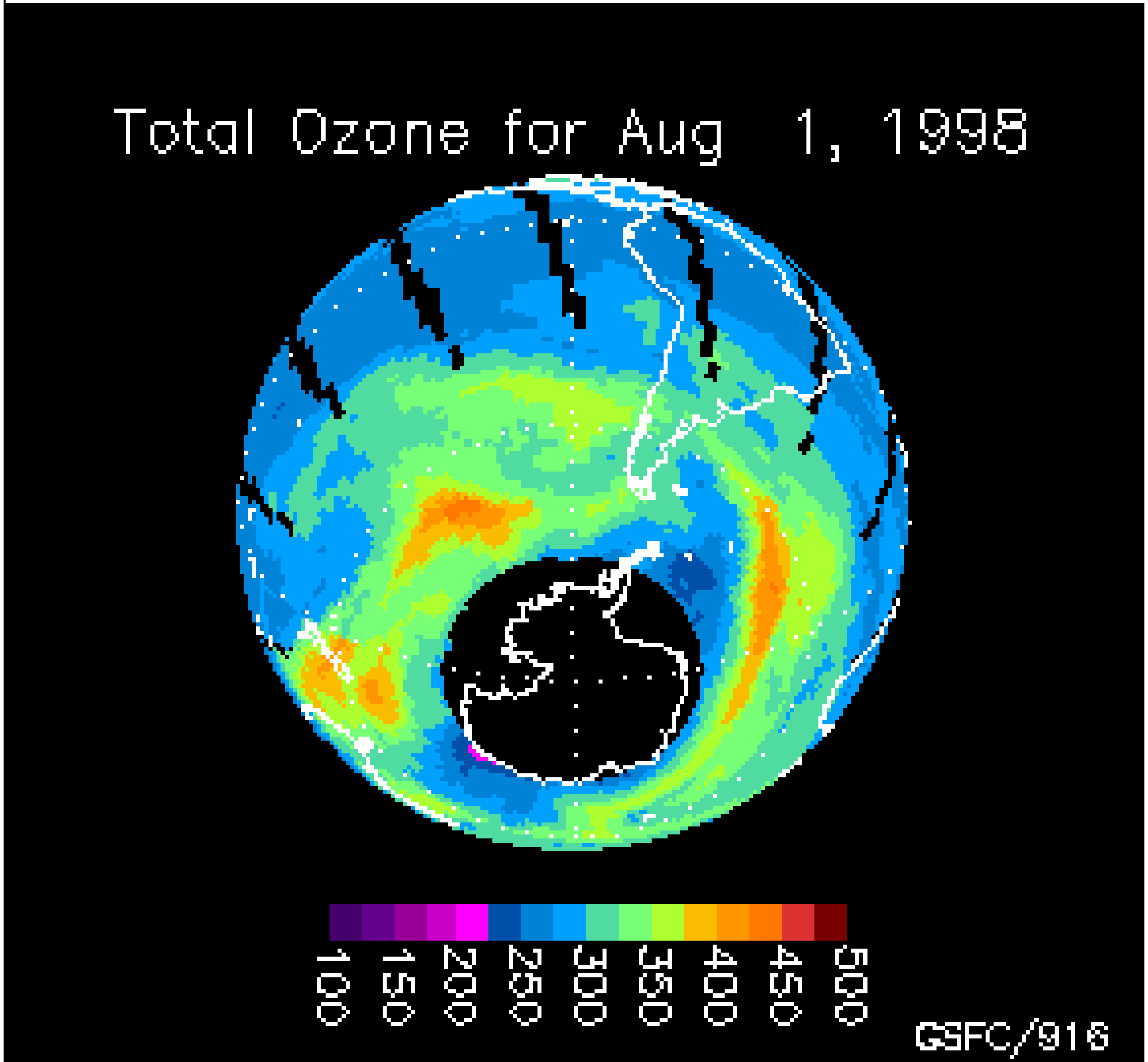


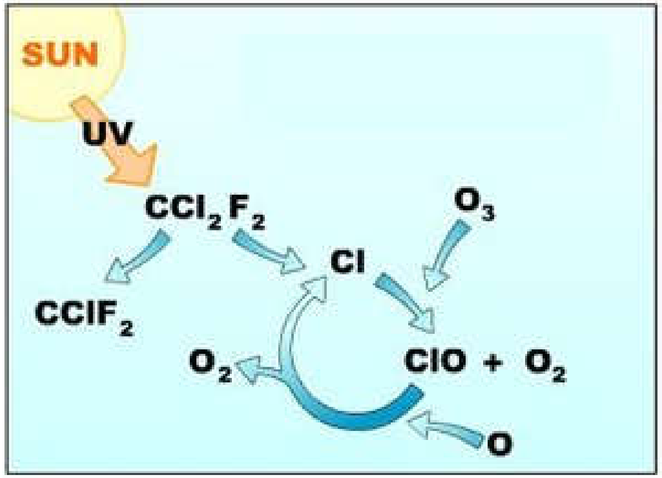
(* See also: https://www.ashrae.org/technical-resources/standards-and-guidelines/ashrae-refrigerant-designations)

1. Introduction

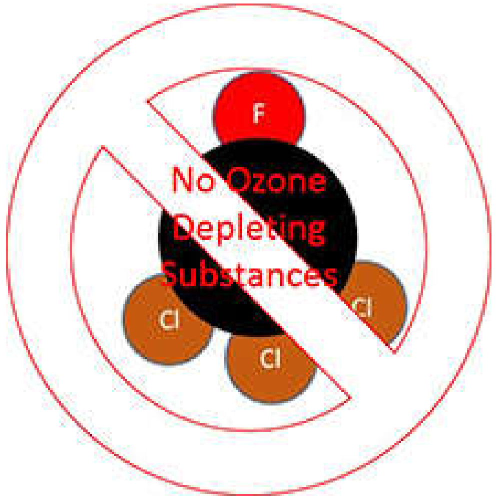
- Impacts of refrigerants
  - Ozone depletion potential (ODP)
    - Ratio of ozone depletion rate compared with R-11
  - Global warming potential (GWP)
    - Global warming effect compared with R-11
- Hydrofluorocarbons (HFCs)
  - Contains only hydrogen, fluorine, and carbon atoms and cause no ozone depletion
  - R-134a, R-32, R-125 and R-245ca

Ozone depletion in the atmosphere

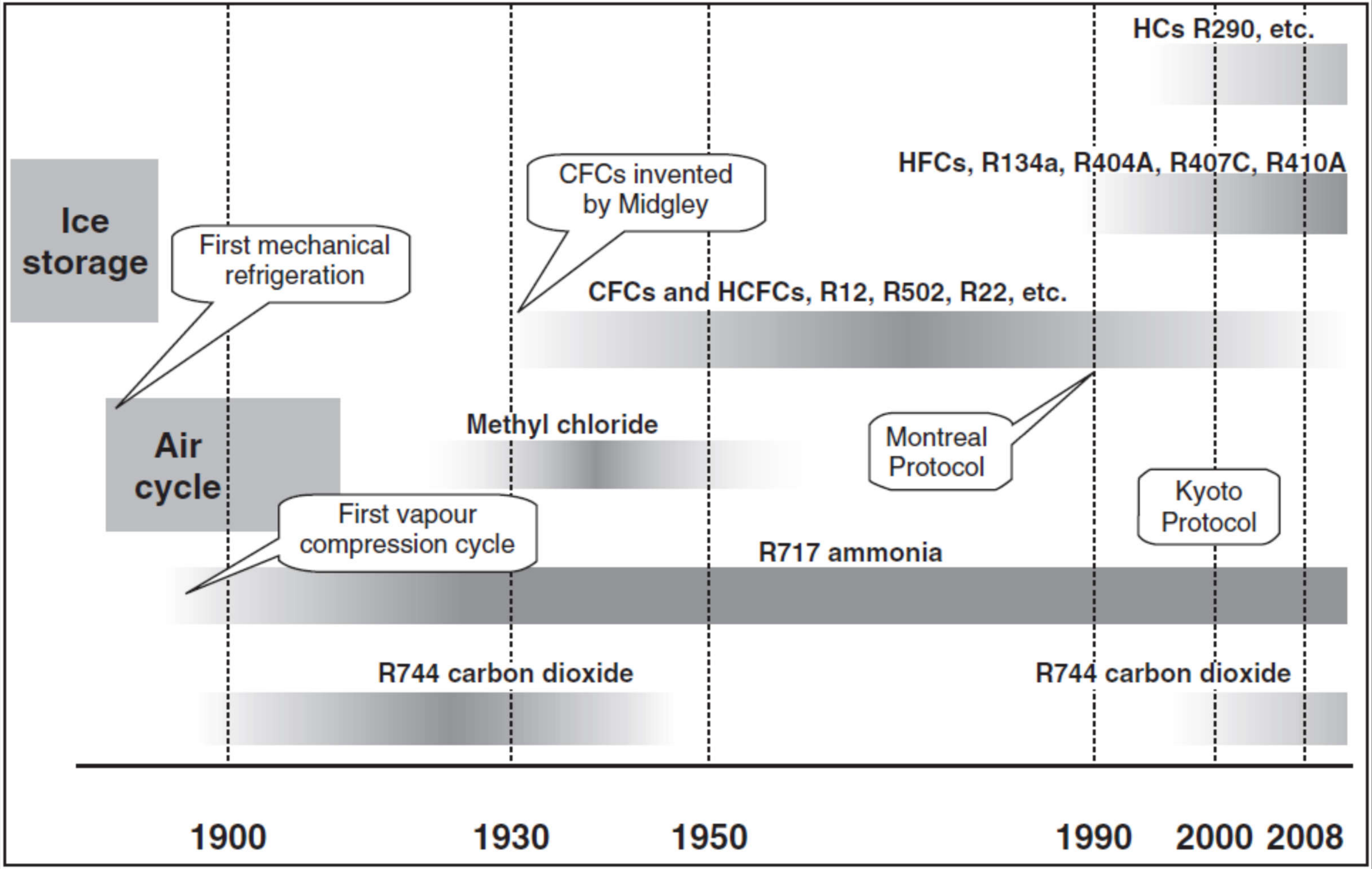




DESTRUCTION OF OZONE BY CFC



Time line for refrigerants

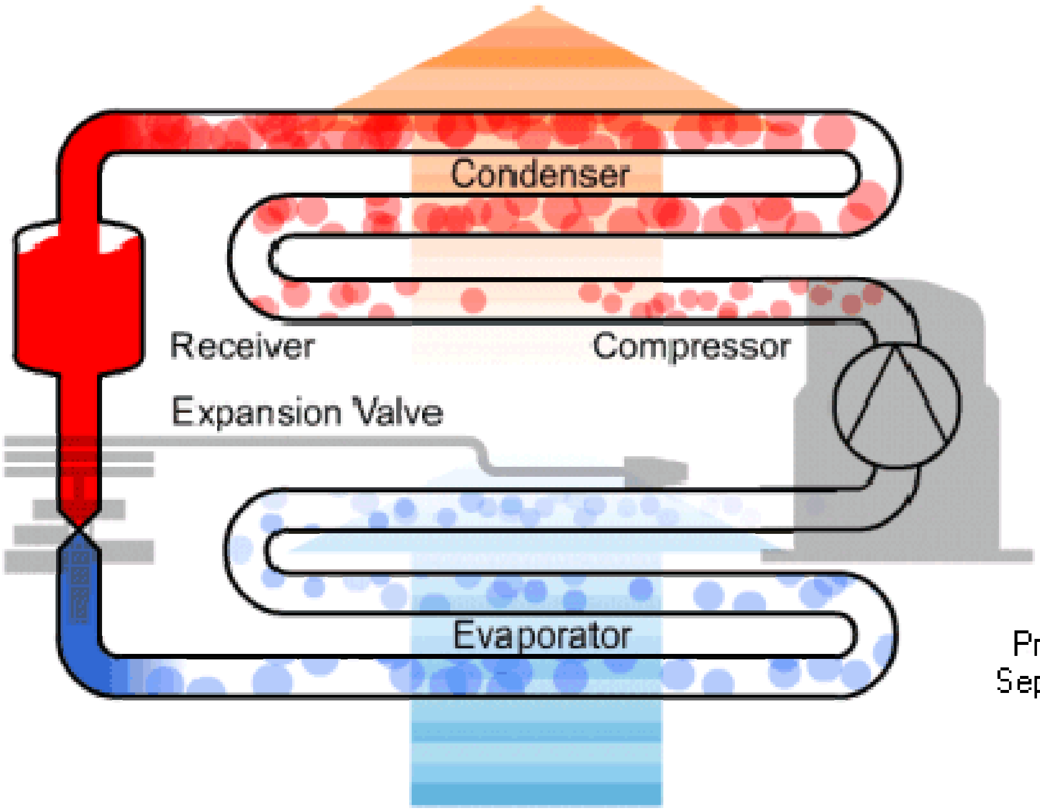


(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

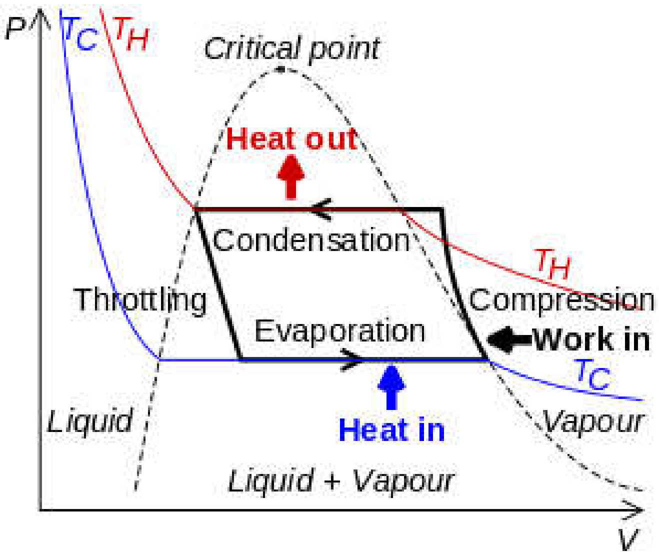
1. Introduction

- Three types of refrigeration systems:
  - Vapour compression 蒸氣壓縮
    - Mechanical refrigeration using compressors, condensers and evaporators
  - Vapour absorption 蒸氣吸收
    - Produce refrigeration effect by thermal energy input
    - Liquid refrigerant produce refrigeration during evaporation; the vapour is absorbed by an aqueous absorbent
  - Air or gas expansion (air or gas cycle) 空氣膨脹
    - Air or gas is compressed to a high pressure; it is then cooled by surface water or air and expanded to low pressure to produce refrigeration effect
    - For air conditioning and pressurization of aircrafts

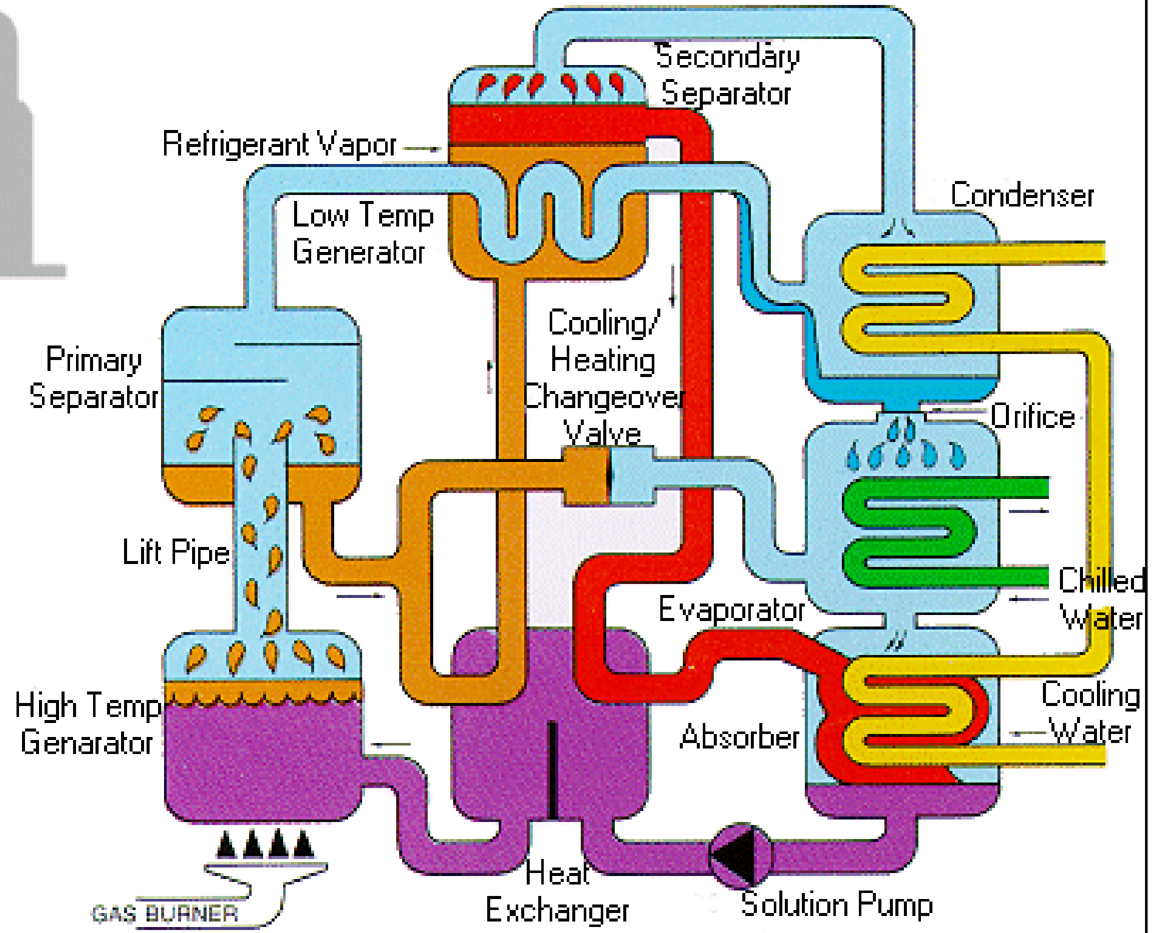
Vapour compression system



Refrigeration Cycle



Vapour absorption system

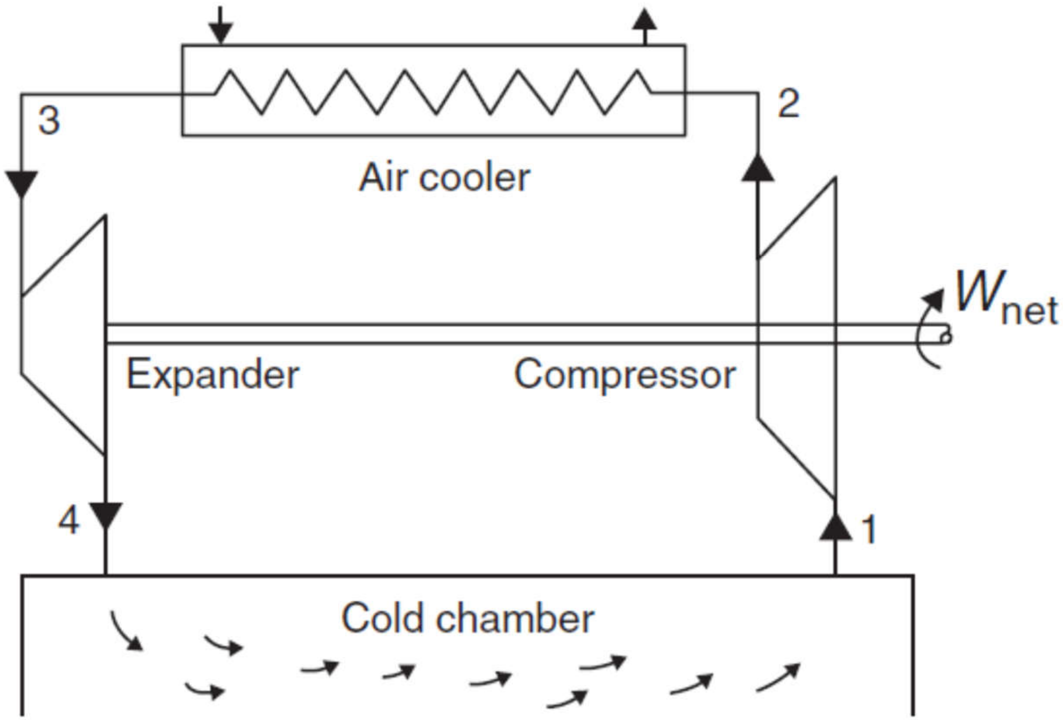


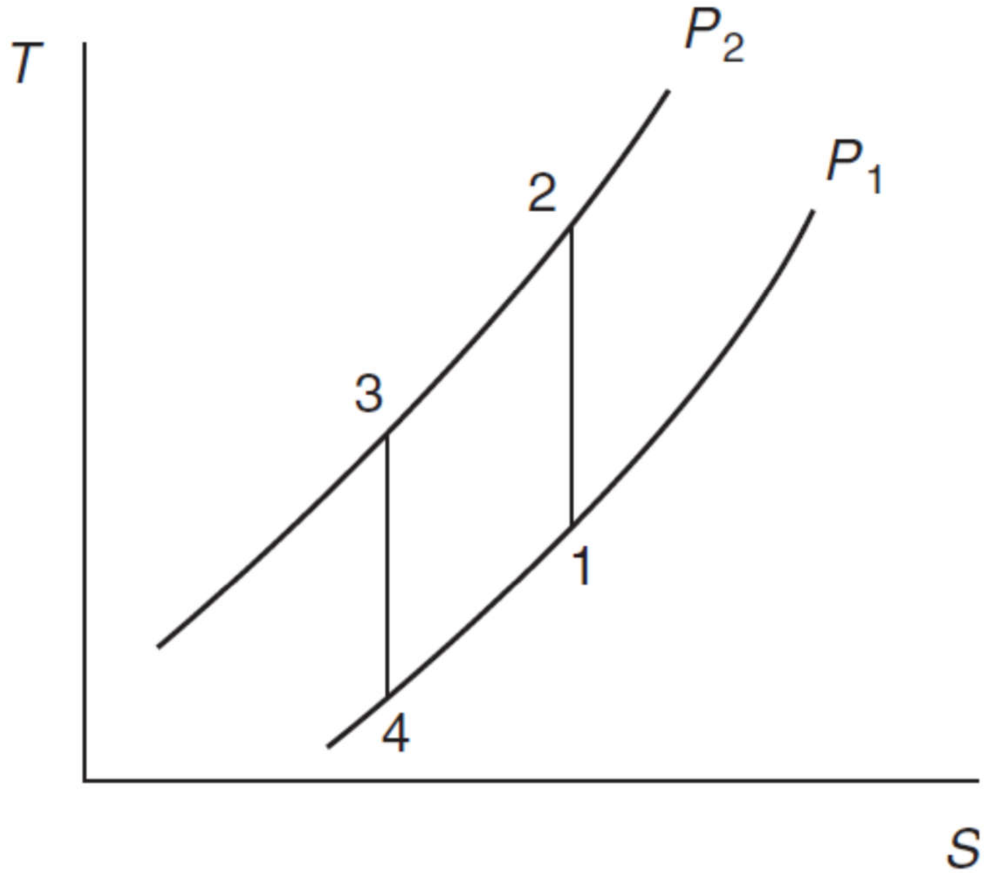
Videos:

VAPOUR COMPRESSION REFRIGERATION SYSTEM ! LEARN AND GROW (3:34)
http://www.youtube.com/watch?v=cobFAMZDS0o

VAPOUR ABSORPTION REFRIGERATION SYSTEM ! LEARN AND GROW (3:38)
http://www.youtube.com/watch?v=Ll8Ku-mFQxE

The air cycle – the work from the expander provides a portion of the work input to the compressor





Air cycle refrigeration works on the reverse Brayton or Joule cycle.

$$COP_R = \frac{q_L}{w_{net,in}} = \frac{q_L}{w_{comp,in} - w_{turb,out}}$$

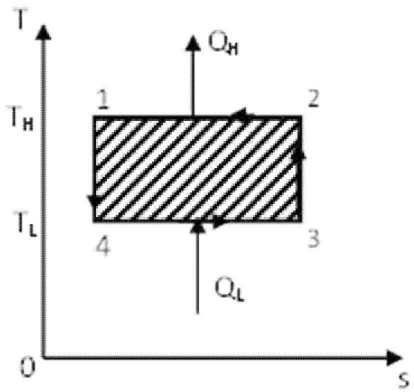
(* See also: Air cycle machine - Wikipedia http://en.wikipedia.org/wiki/Air_cycle_machine)

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

1. Introduction

- Modern refrigeration and air-conditioning equipment is dominated by vapour compression refrigeration technology built upon the thermodynamic principles of the reverse Carnot cycle*
- Refrigerant changes phases during cooling and used again and again

$$COP_R = \frac{Q_L}{W_{rev}} = \frac{Q_L}{-Q_H - Q_L}$$

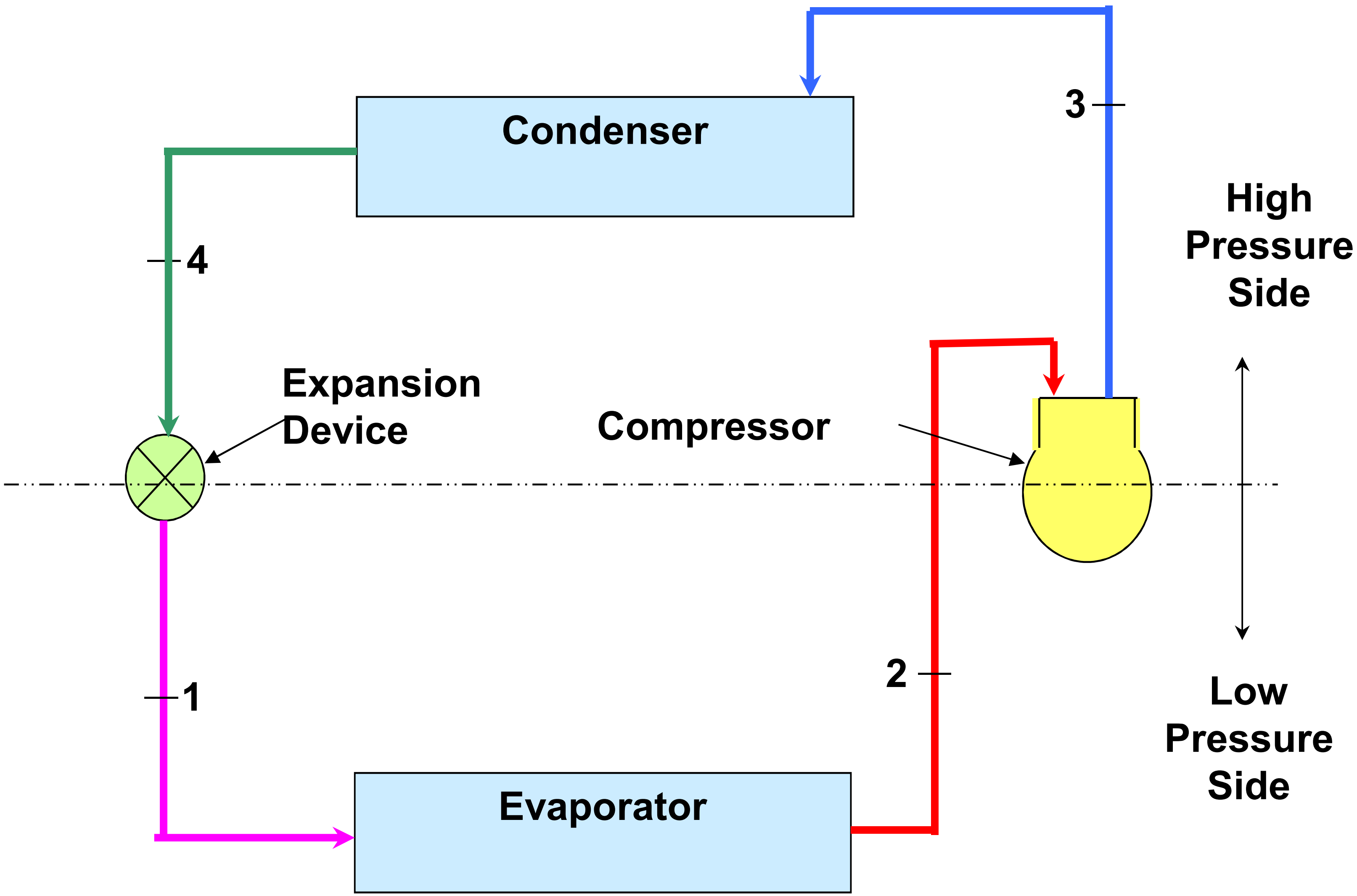


(* See also: The Reversed Carnot Cycle http://thermodynamics-engineer.com/429-2/)

2. Basic principles

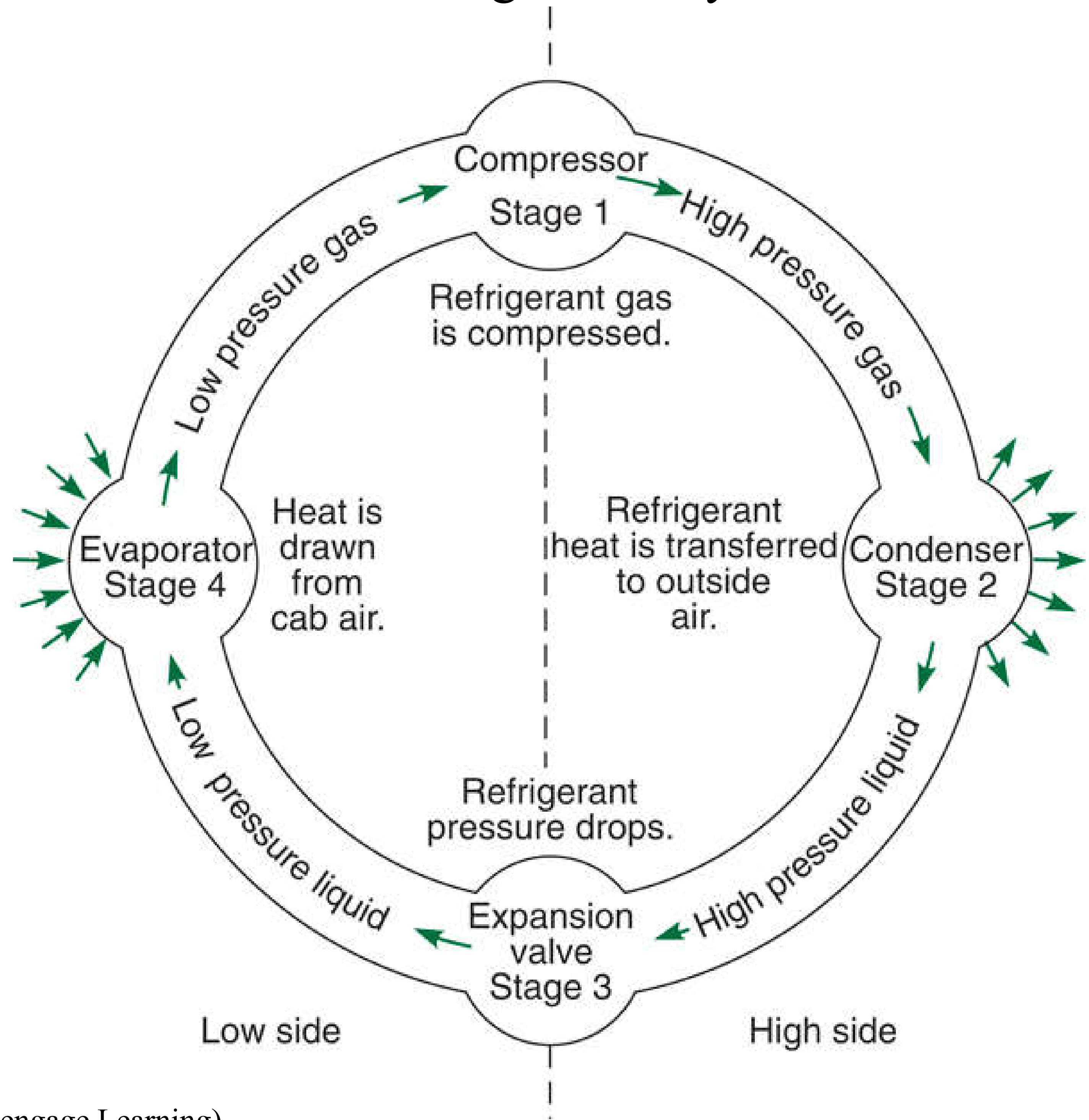
- Refrigeration process
  - Change of thermodynamic properties and the energy & work transfer
  - 1 ton of refrign. (TR) = 12,000 Btu/h (3.516 kW)
- Refrigeraton cycles
  - Closed cycle and open cycle
  - Vapour compression cycles:
    - Single-stage, multi-stage, compound, cascade
    - Pressure-enthalpy (*p-h*) or Mollier diagram
    - Temperature–entropy (*T-s*) diagram

Refrigeration cycle -- vapour compression cycle



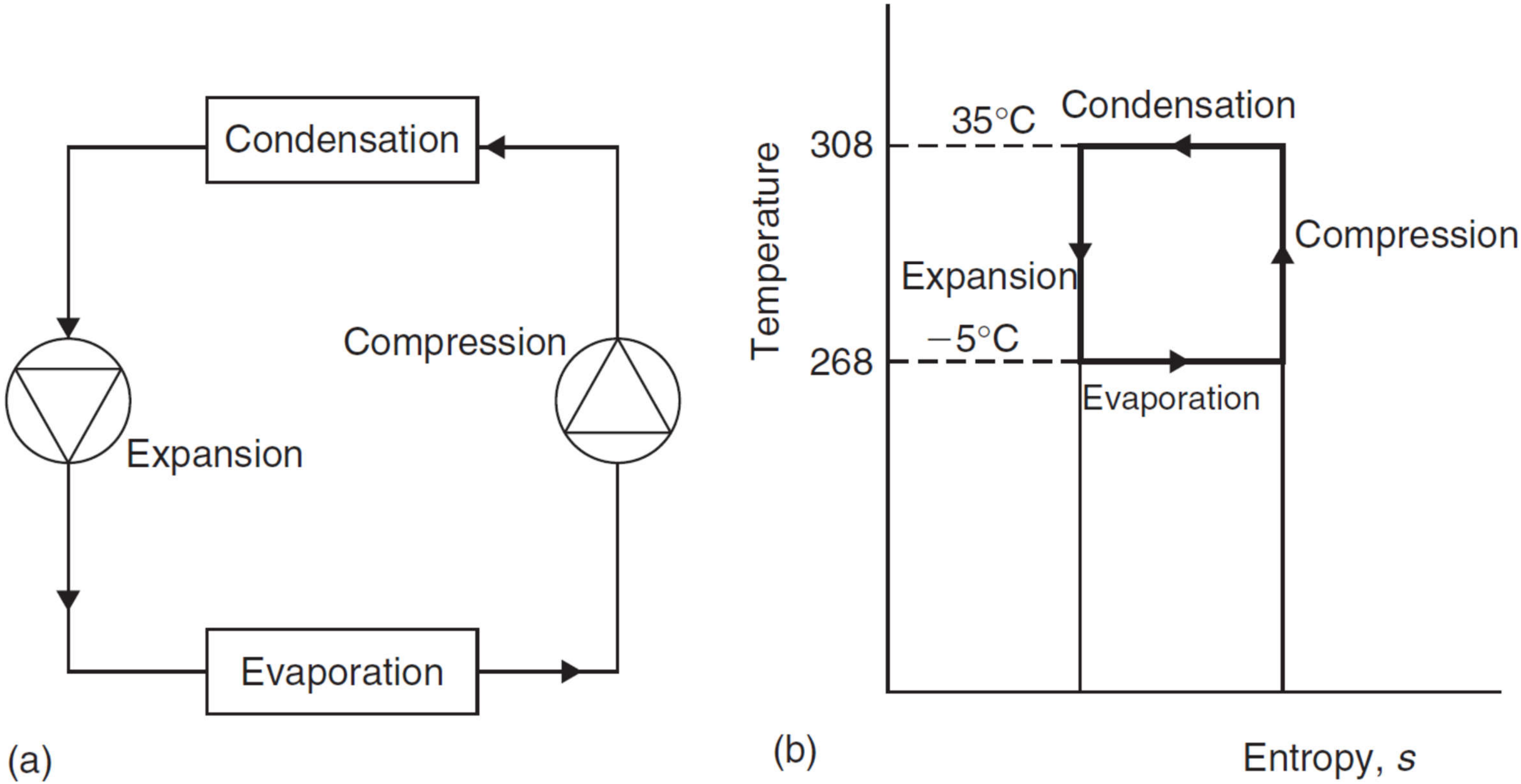
(Video: Refrigeration Cycle Video Animation (1:30) http://www.youtube.com/watch?v=MqnyaUNxs9A)

The refrigeration cycle



(Source: Delmar, Cengage Learning)

The ideal reversed Carnot cycle:
(a) circuit and (b) temperature–entropy (*T*-*s*) diagram

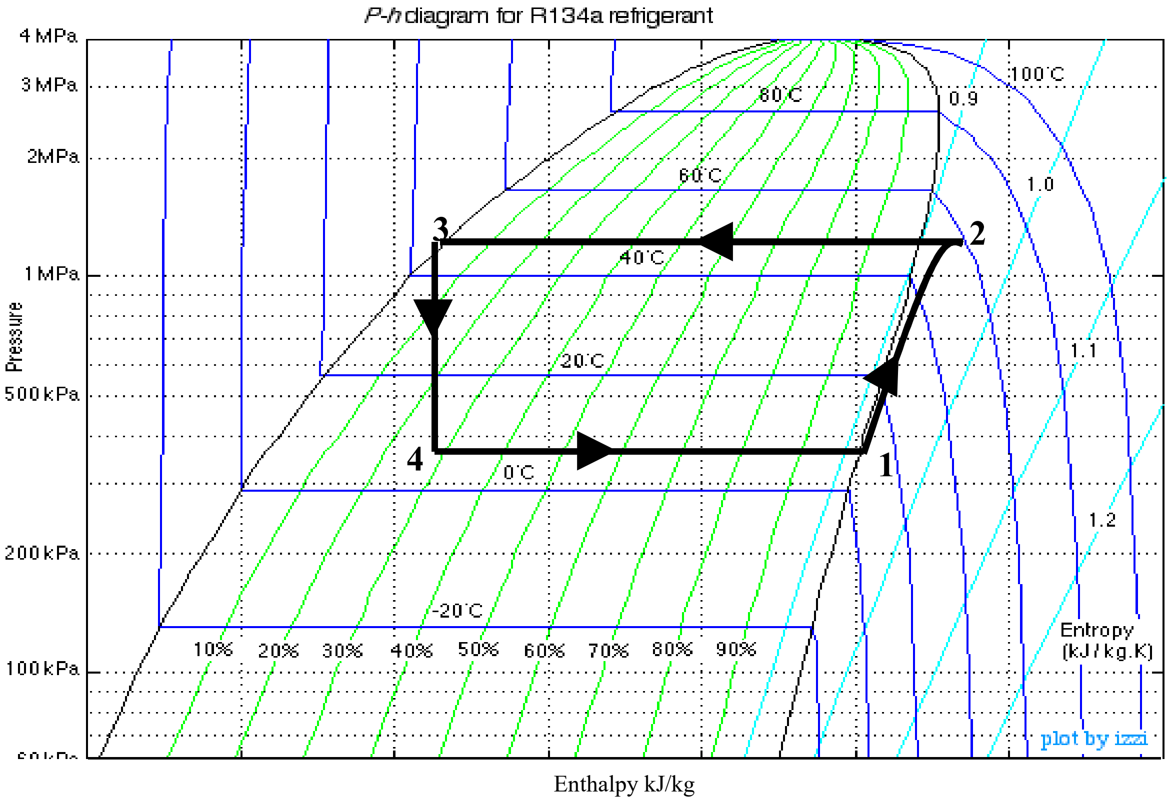


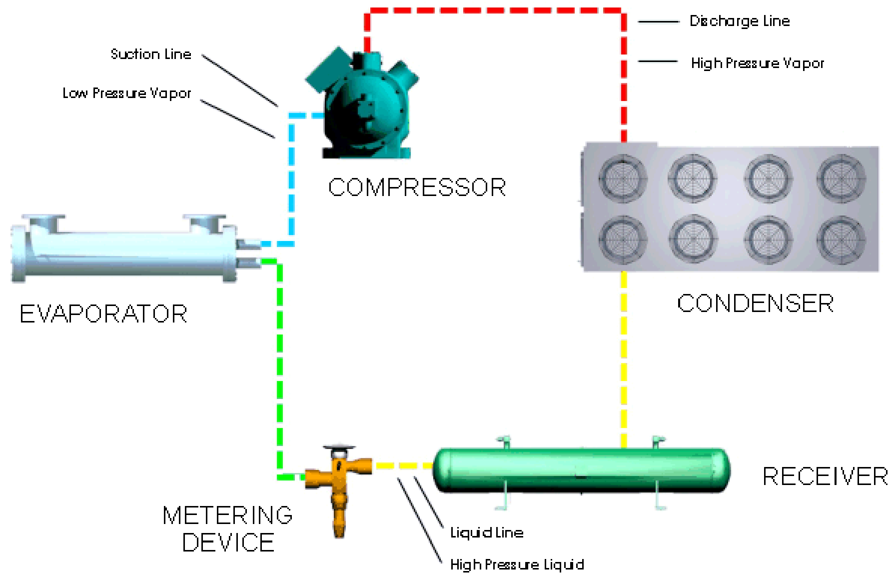
(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

2. Basic principles

- Ideal single-stage cycle
  - Isentropic compression, pressure losses neglected
  - q_{rf} = refrigeration capacity
  - W_{in} = work input to compressor
- Coefficient of performance (COP)
  - COP = q_{rf} / W_{in}
    - Refrigerator: produce refrigeration effect
    - Heat pump: produce heating effect
- Subcooling and superheating

Refrigeration cycle -- vapour compression cycle

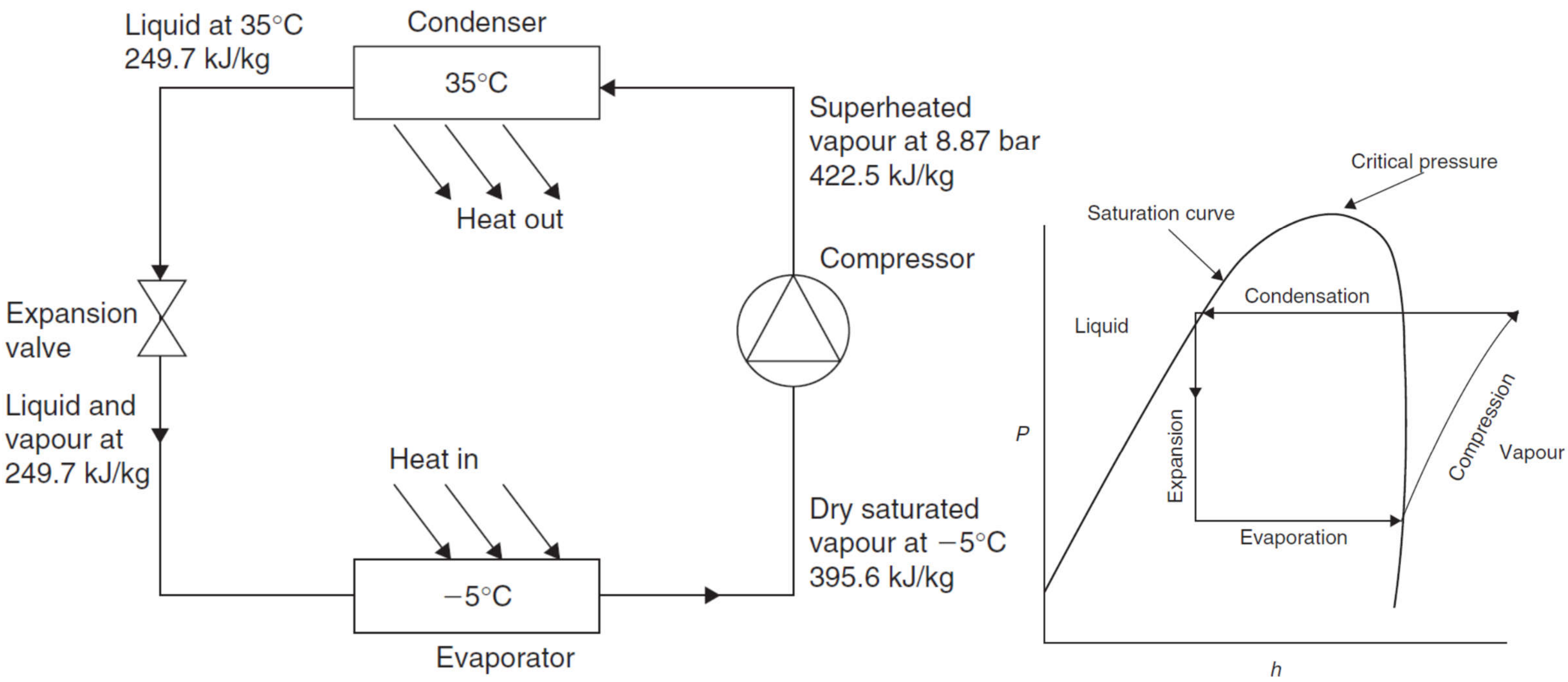




System COP normally includes all the power inputs associated with the system, i.e. fans and pumps in addition to compressor power.

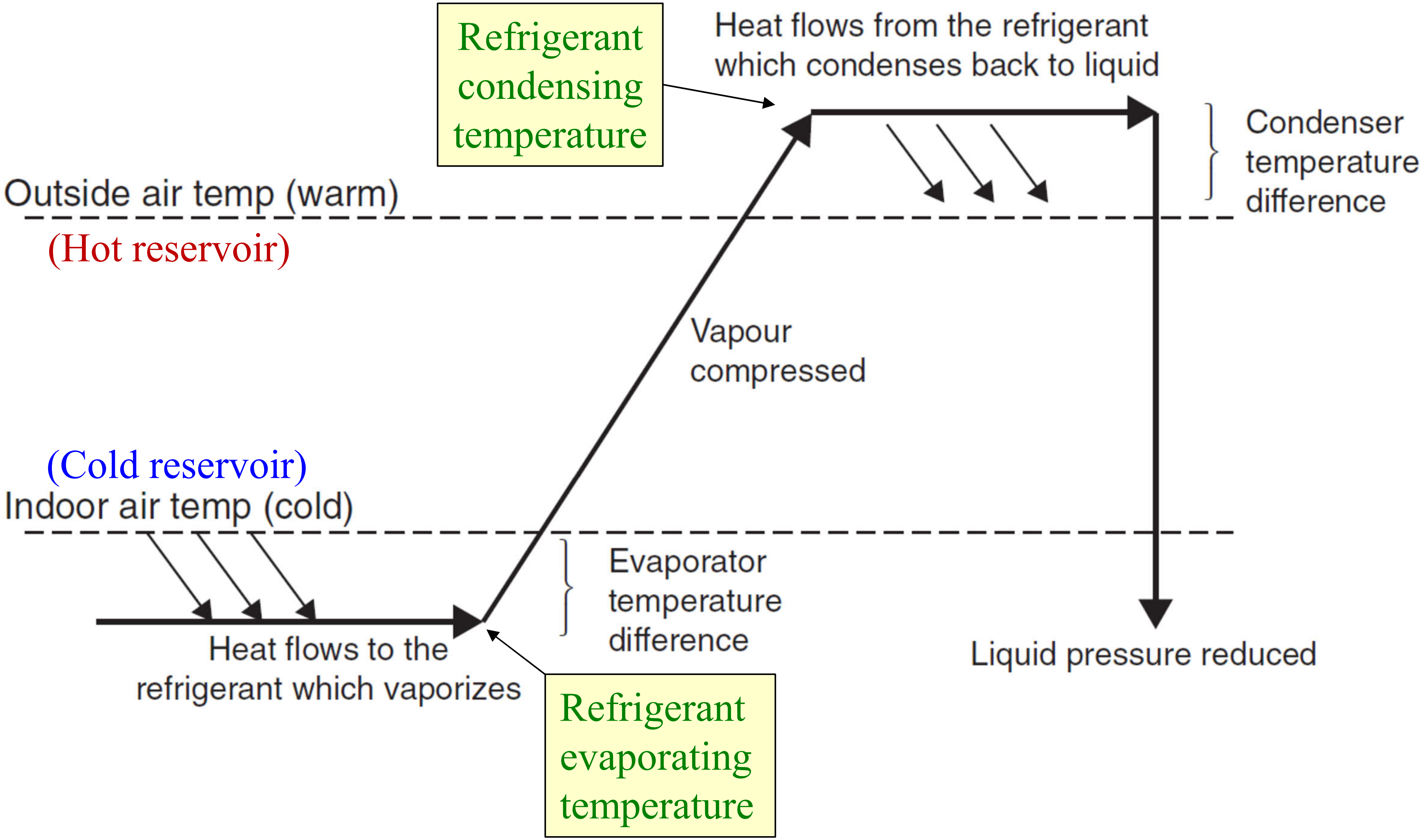
A ratio of System COP to Carnot COP (for the process) is termed *system efficiency index*, SEI.

Simple vapour compression cycle with pressure and enthalpy values for R134a



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

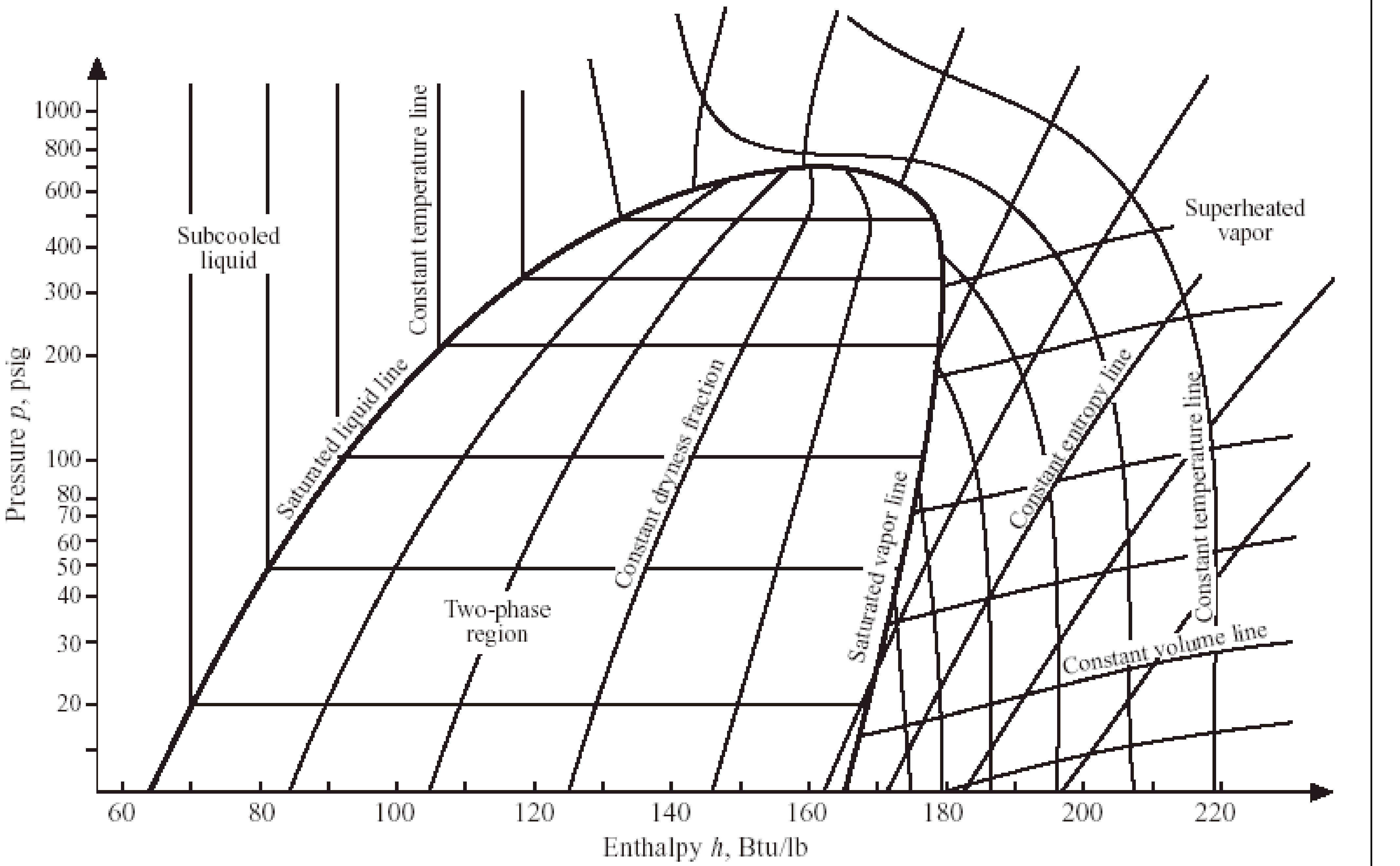
The temperature rise or ‘ lift ’ of the refrigeration cycle is increased by temperature differences in the evaporator and condenser

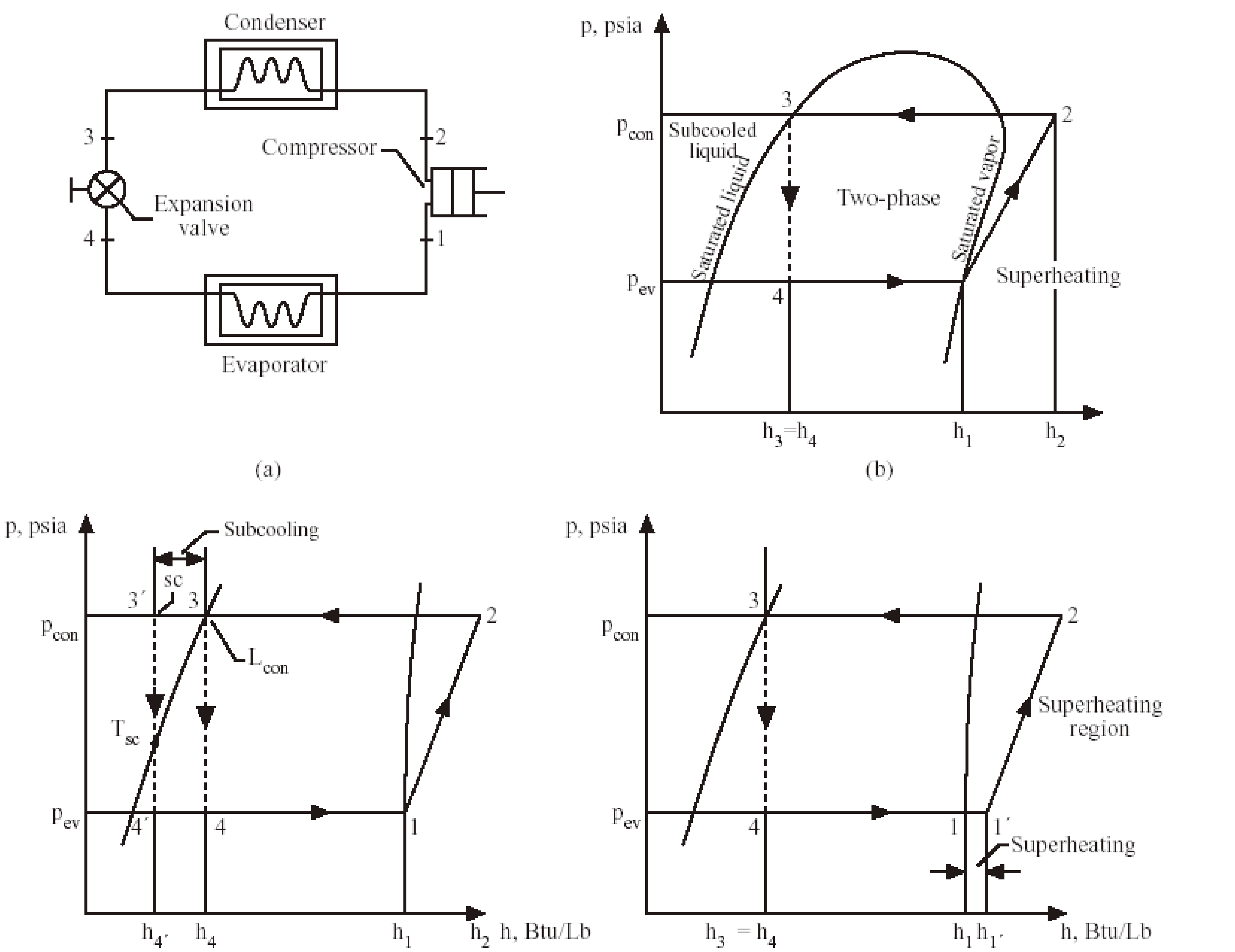


(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

2. Basic principles

- Energy efficiency of a refrigeration system
  - Minimize the required heat extraction
    - Insulate the refrigerated room and low-temperature parts of the refrigeration system, minimize ambient air infiltration (e.g. door openings and leakage) and reducing energy use in refrigerated applications (e.g. fans and forklifts)
  - Reduce the difference between T_C (condensing temperature) and T_0 (evaporating temperature)
    - Maximize condenser and evaporator heat transfer performance and minimize refrigerant pressure drops in suction and discharge pipelines


1000
800
600
400
300
200
100
80
70
60
50
40
30
20
Pressure p, psig
60
80
100
120
140
160
180
200
220
Enthalpy h, Btu/lb
Subcooled liquid
Constant temperature line
Saturated liquid line
Two-phase region
Constant dryness fraction
Saturated vapor line
Constant entropy line
Constant temperature line
Constant volume line
Superheated vapor



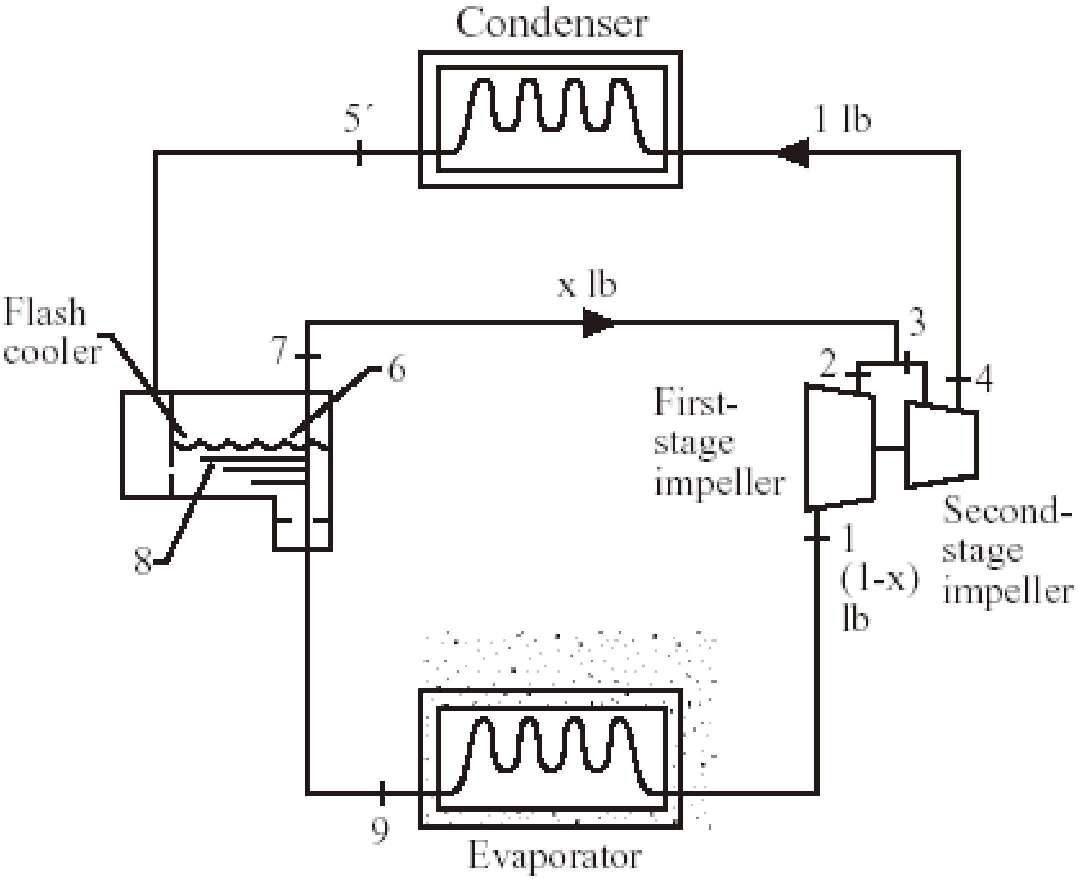
Condenser
Compressor
Expansion valve
Evaporator
3
2
4
1
(a)
p, psia
p_{con}
p_{ev}
Subcooled liquid
Saturated liquid
Two-phase
Saturated vapor
Superheating
$h_3 = h_4$
h_1
h_2
(b)
Subcooling
sc
3′
L_{con}
T_{sc}
4′
$h_{4'}$
h_4
h, Btu/Lb
Superheating region
1′
Superheating
$h_{1'}$

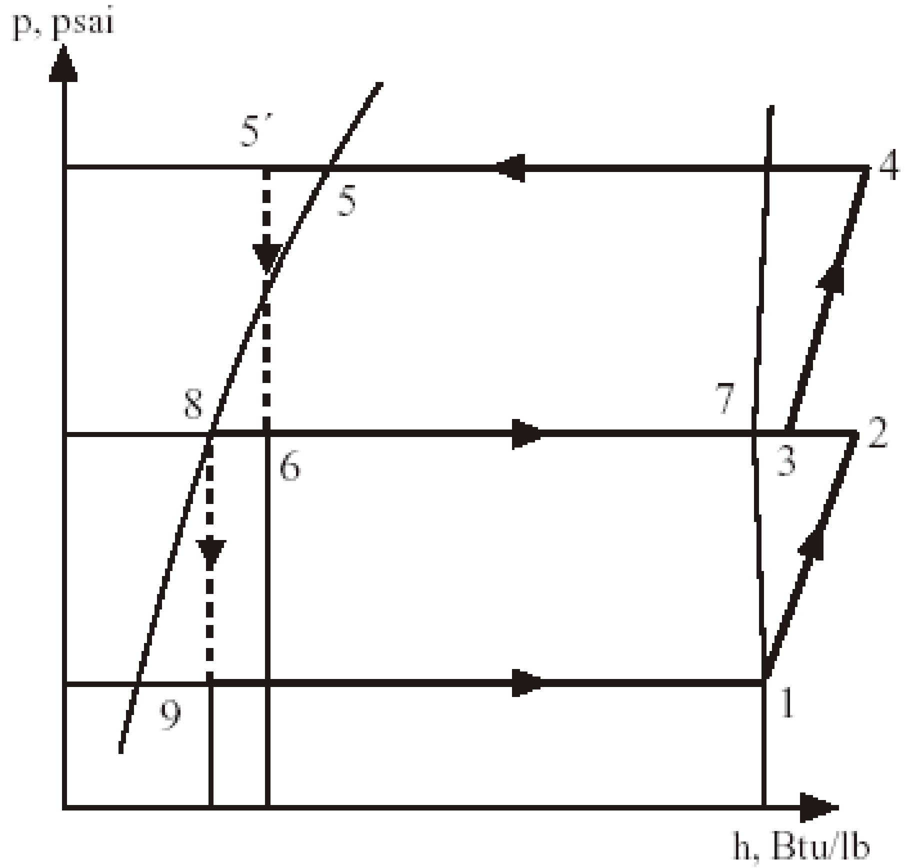
2. Basic principles

- Two-stage compound systems w/ flash cooler
  - Multi-stage compression connected in series
    - Higher compression efficiency, greater refrig. effect
  - Compressor ratio
  - Flash cooler: an economizer to subcool liquid refrigerant to saturated temperature

$$COP_{ref} = \frac{q_{ref}}{W_{in}} = \frac{(1-x)(h_1 - h_9)}{(1-x)(h_2 - h_1) + (h_4 - h_3)}$$

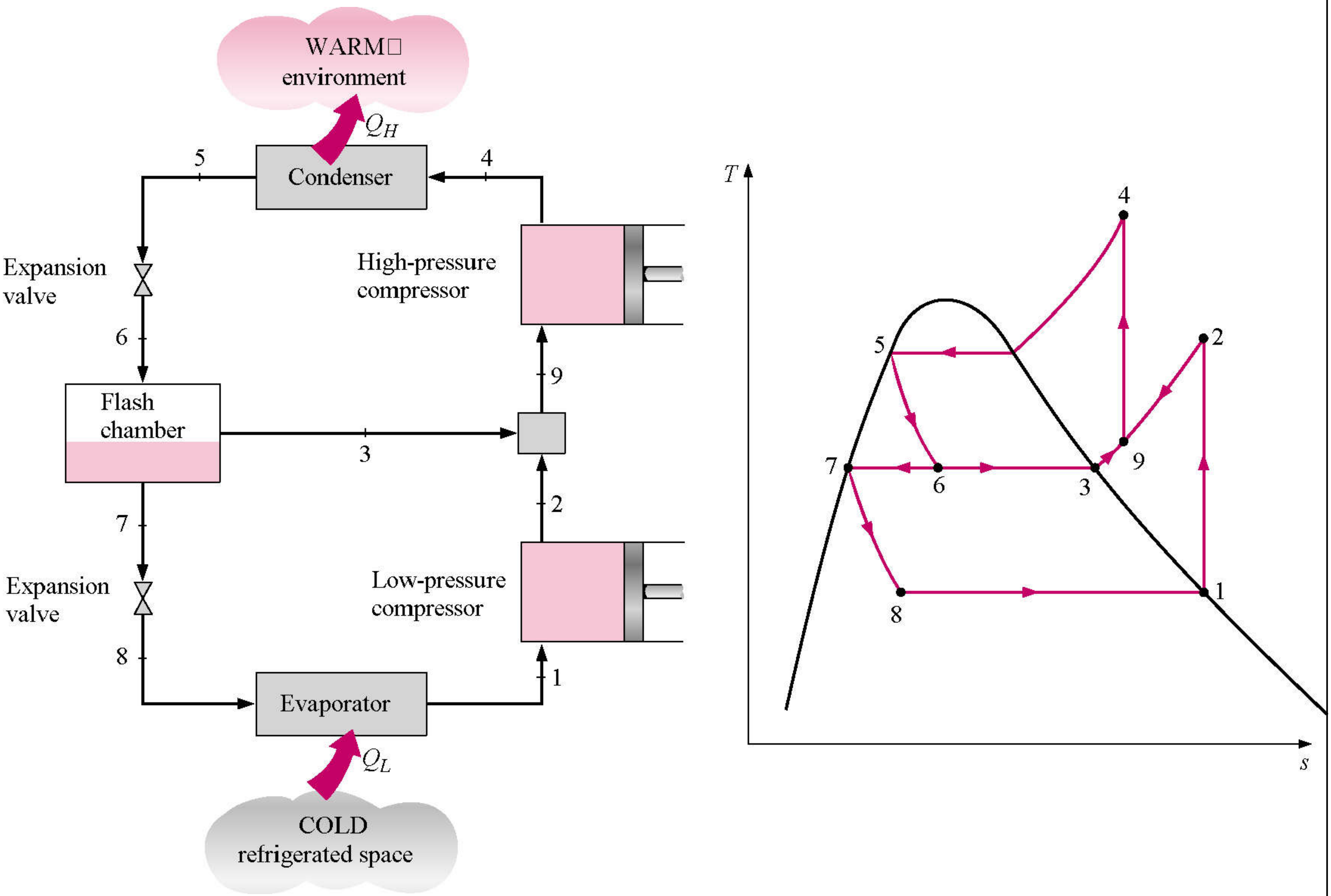
Two-stage compound systems w/ flash cooler





* Where the ratio of suction to discharge pressure is high enough to cause a serious drop in volumetric efficiency or an unacceptably high discharge temperature, vapour compression must be carried out in two or more stages.

Two-stage compound systems and T-s diagram



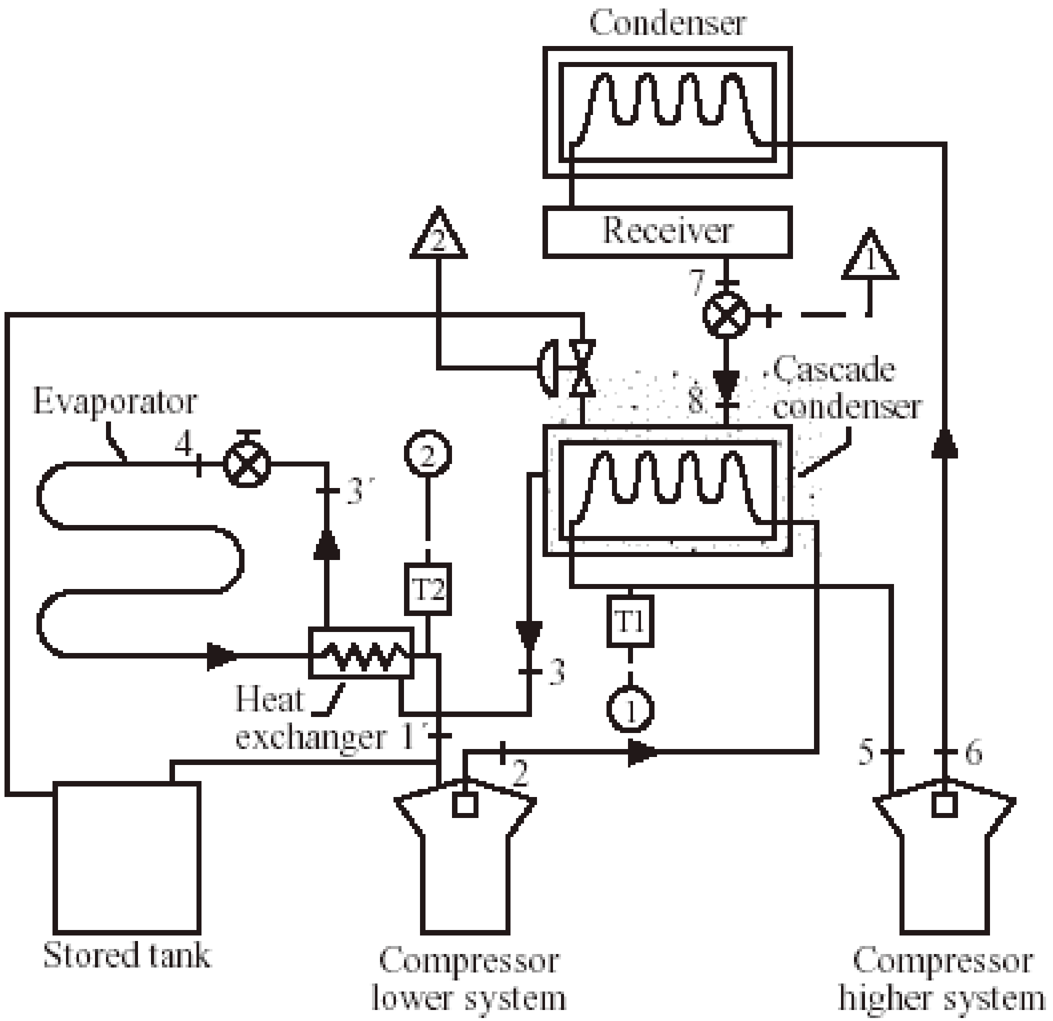
(Source: *Thermodynamics: An Engineering Approach*, 8th edition, by Yunus A. Çengel and Michael A. Boles)

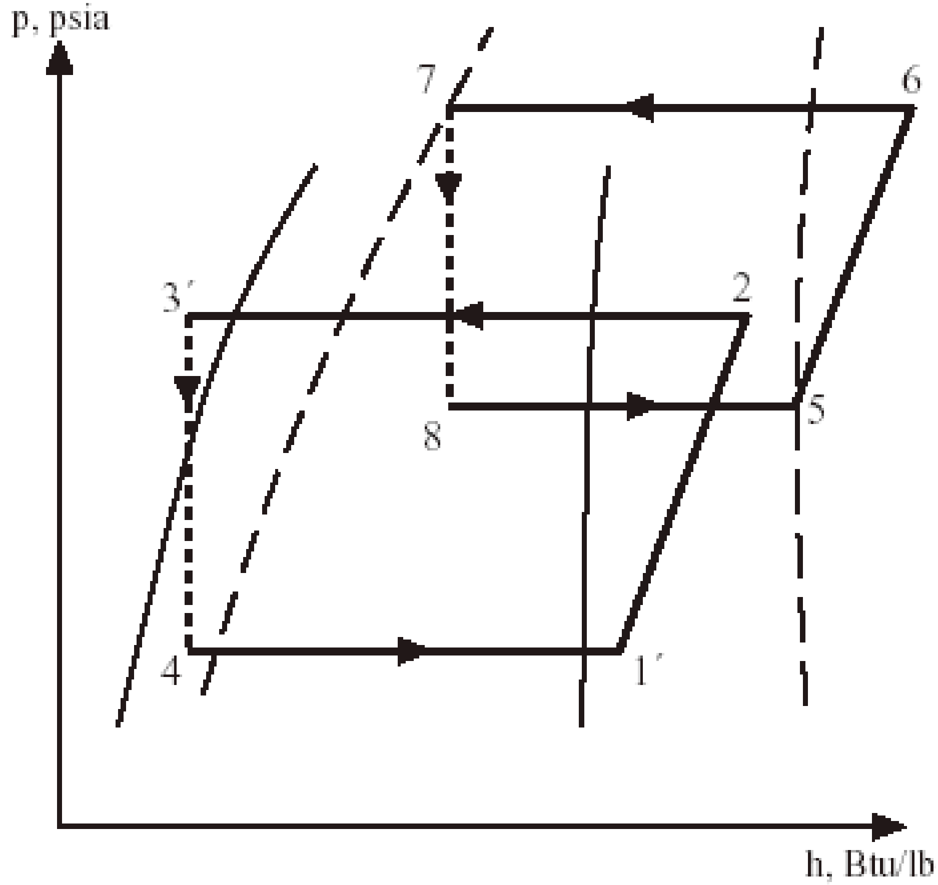
2. Basic principles

- Casade system characteristics
  - Two independently operated single-stage systems
    - Connected by a cascade condenser
  - Main advantages
    - Different refrigerants, oils and equipment can be used
  - Disadvantages: more complicated

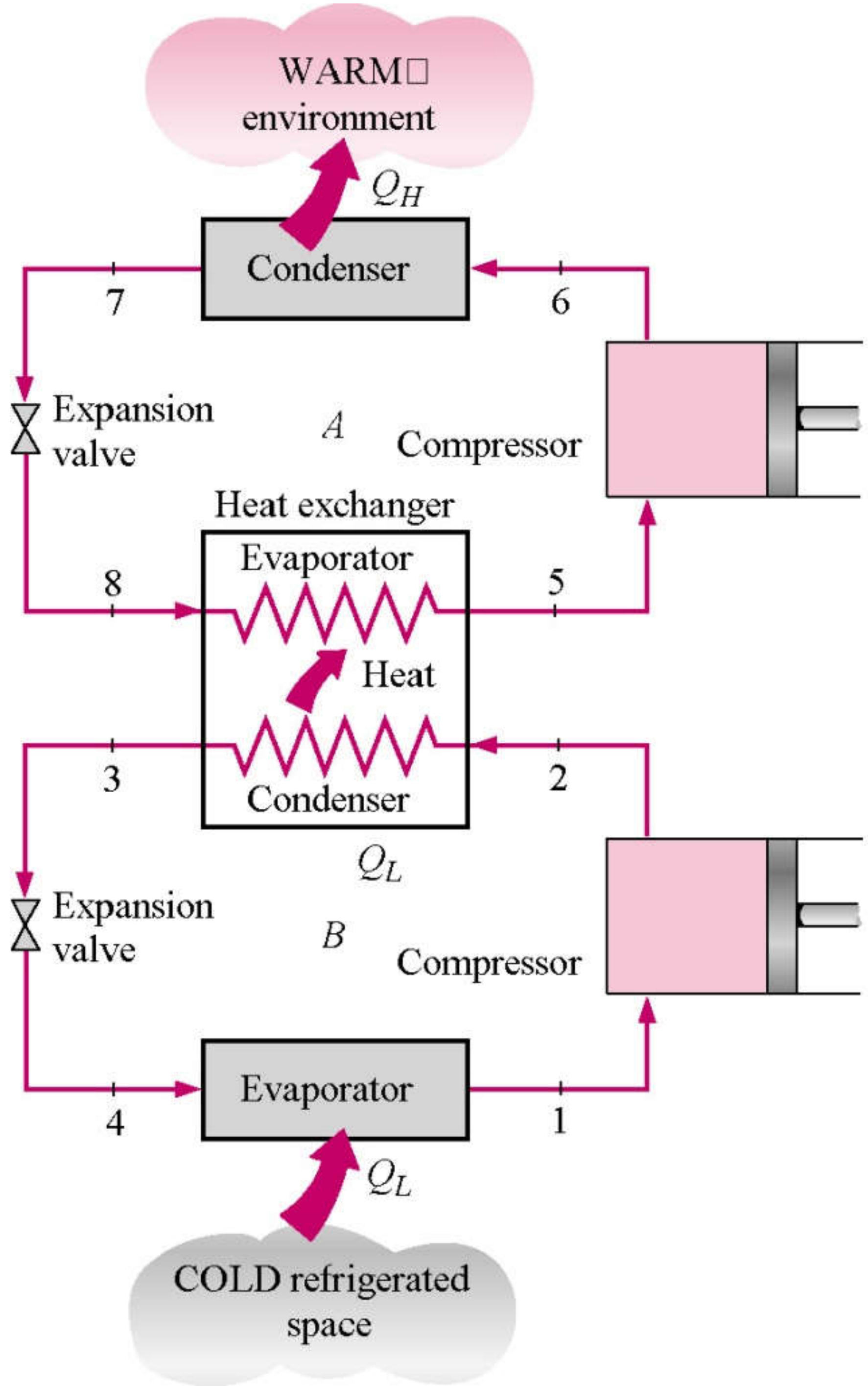
$$\mathrm{COP}_{ref} = \frac{q_{ref}}{W_{\mathrm{in}}} = \frac{\dot{m}_l(h_1 - h_4)}{\dot{m}_l(h_2 - h_{1'}) + \dot{m}_h(h_6 - h_5)}$$

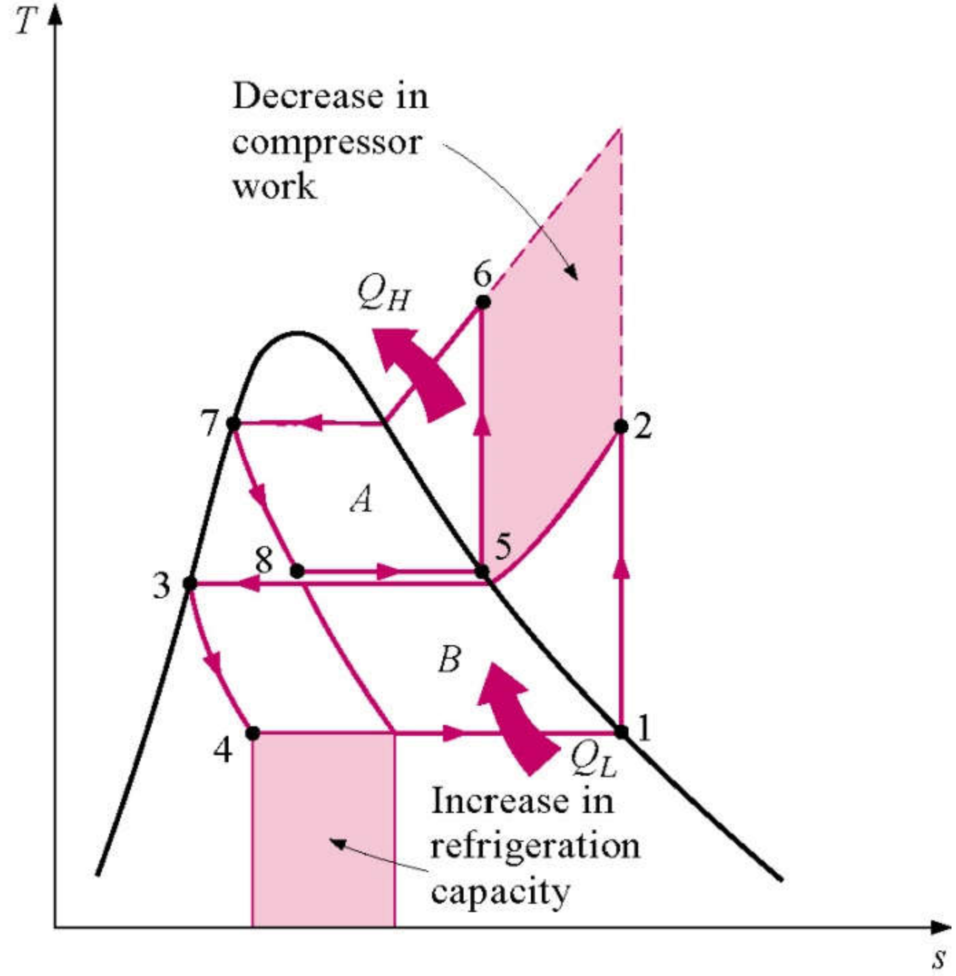
Cascade system





Cascade system and T-s diagram



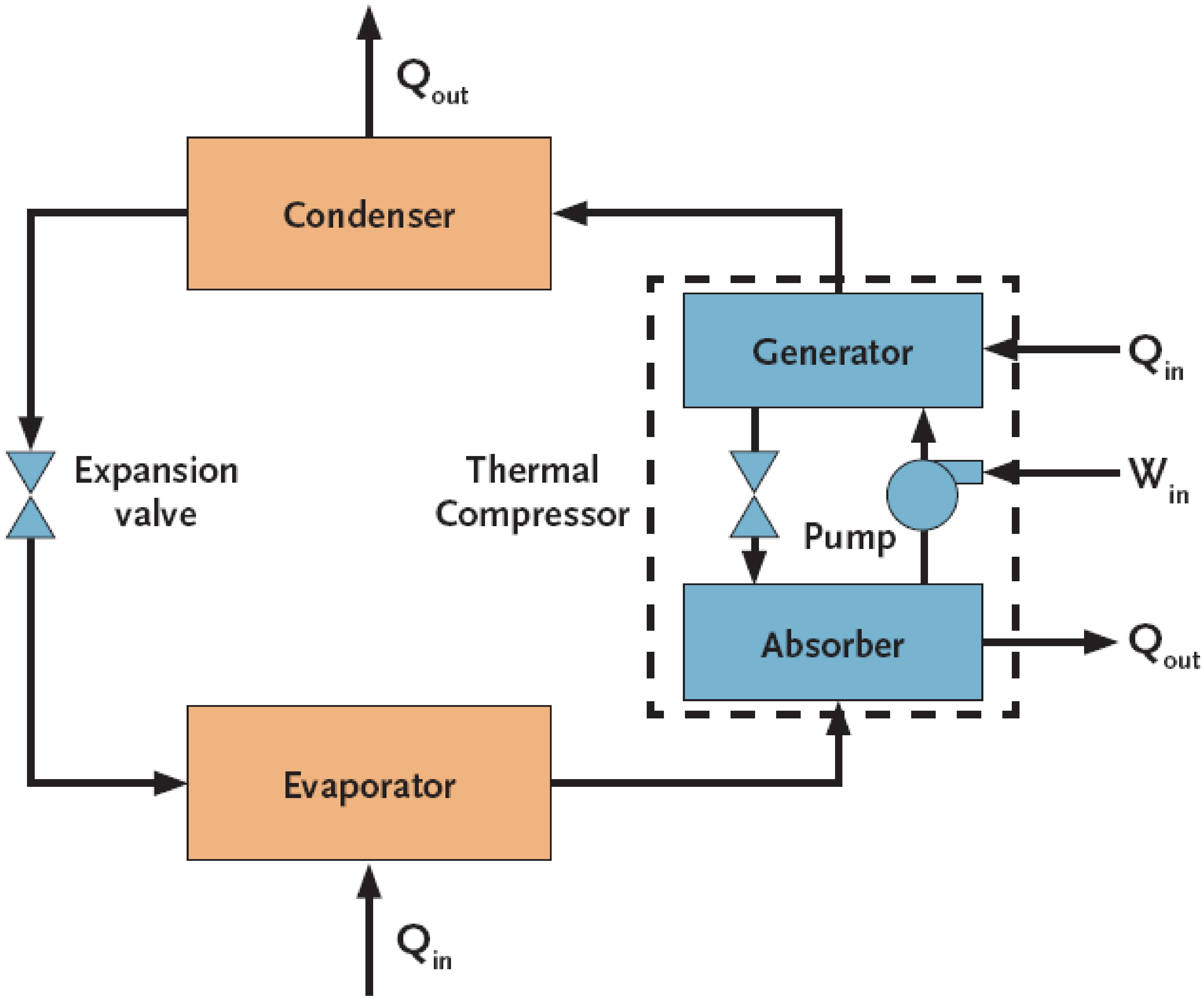


(Source: *Thermodynamics: An Engineering Approach*, 8th edition, by Yunus A. Çengel and Michael A. Boles)

2. Basic principles

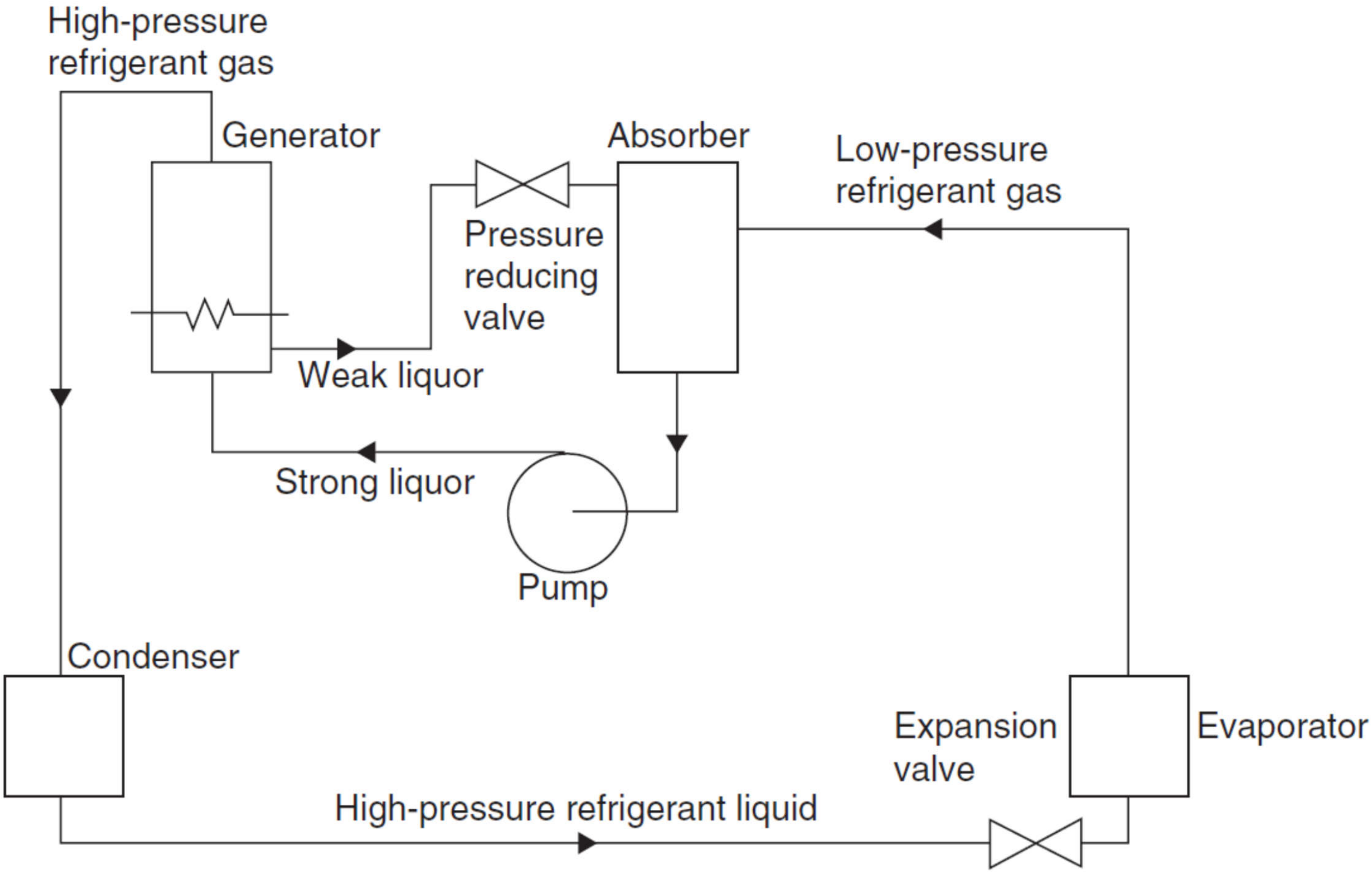
- Absorption cycle
  - Such as ammonia and lithium bromide systems
    - Absorption of ammonia gas into water, and of water vapour into lithium bromide
    - Refrigerant vapour from the evaporator is drawn into the absorber by the liquid absorbant. The liquor is then pumped up to condenser pressure and 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

Basic absorption cycle



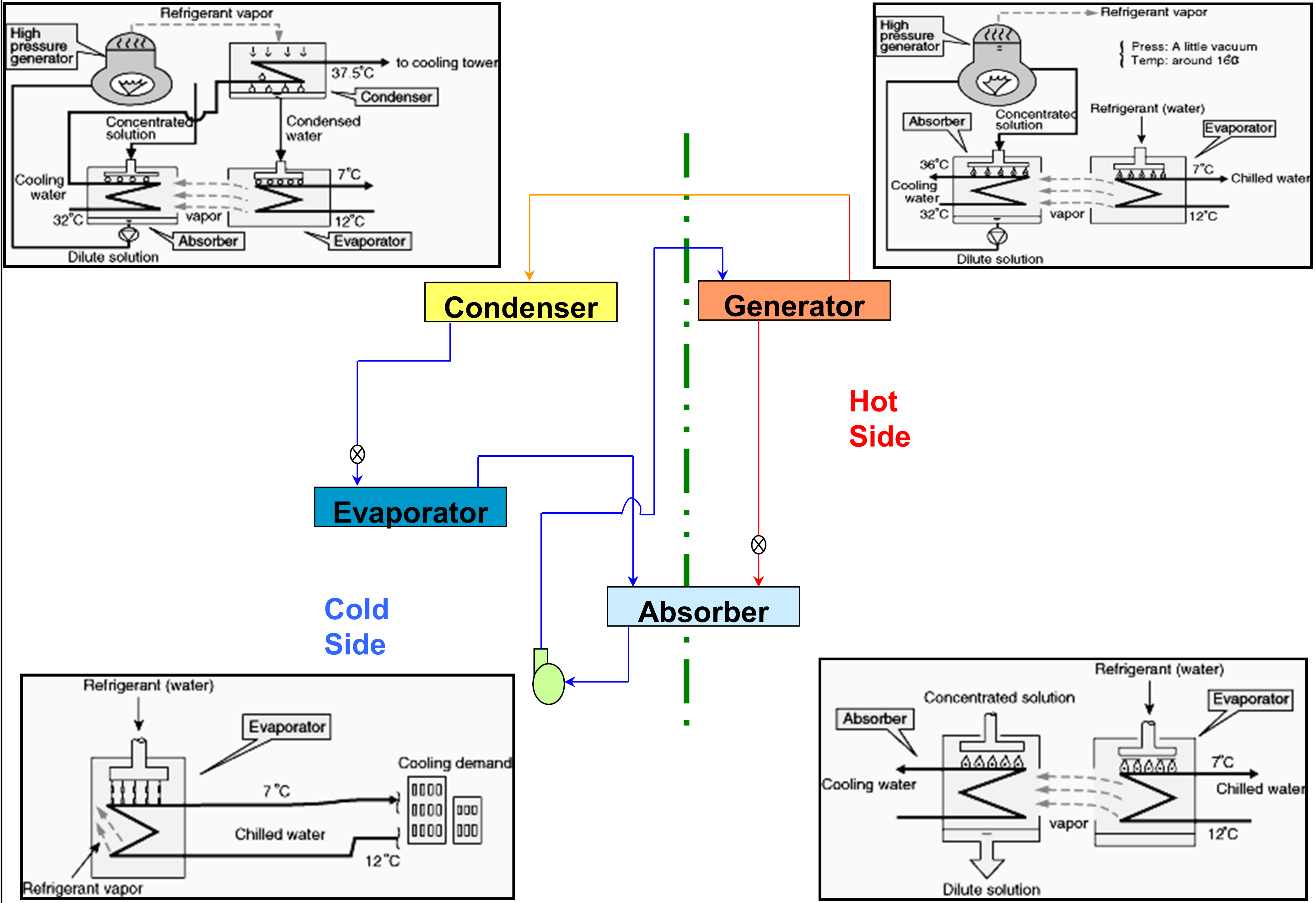
(Source: https://www.cibsejournal.com/cpd/modules/2009-11/)

Absorption cycle: basic circuit

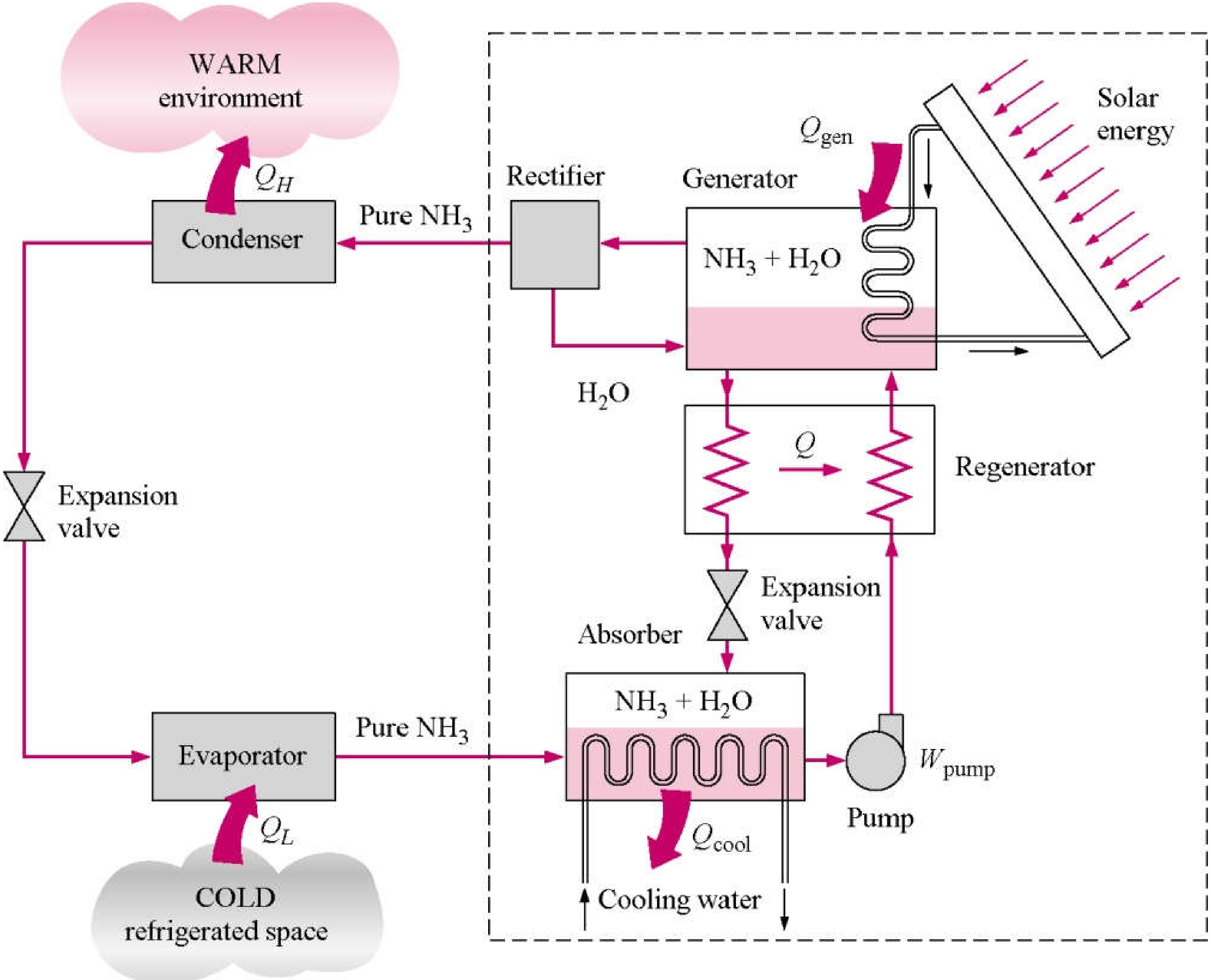


(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

Vapour absorption refrigeration



Absorption refrigeration system with solar energy at generator

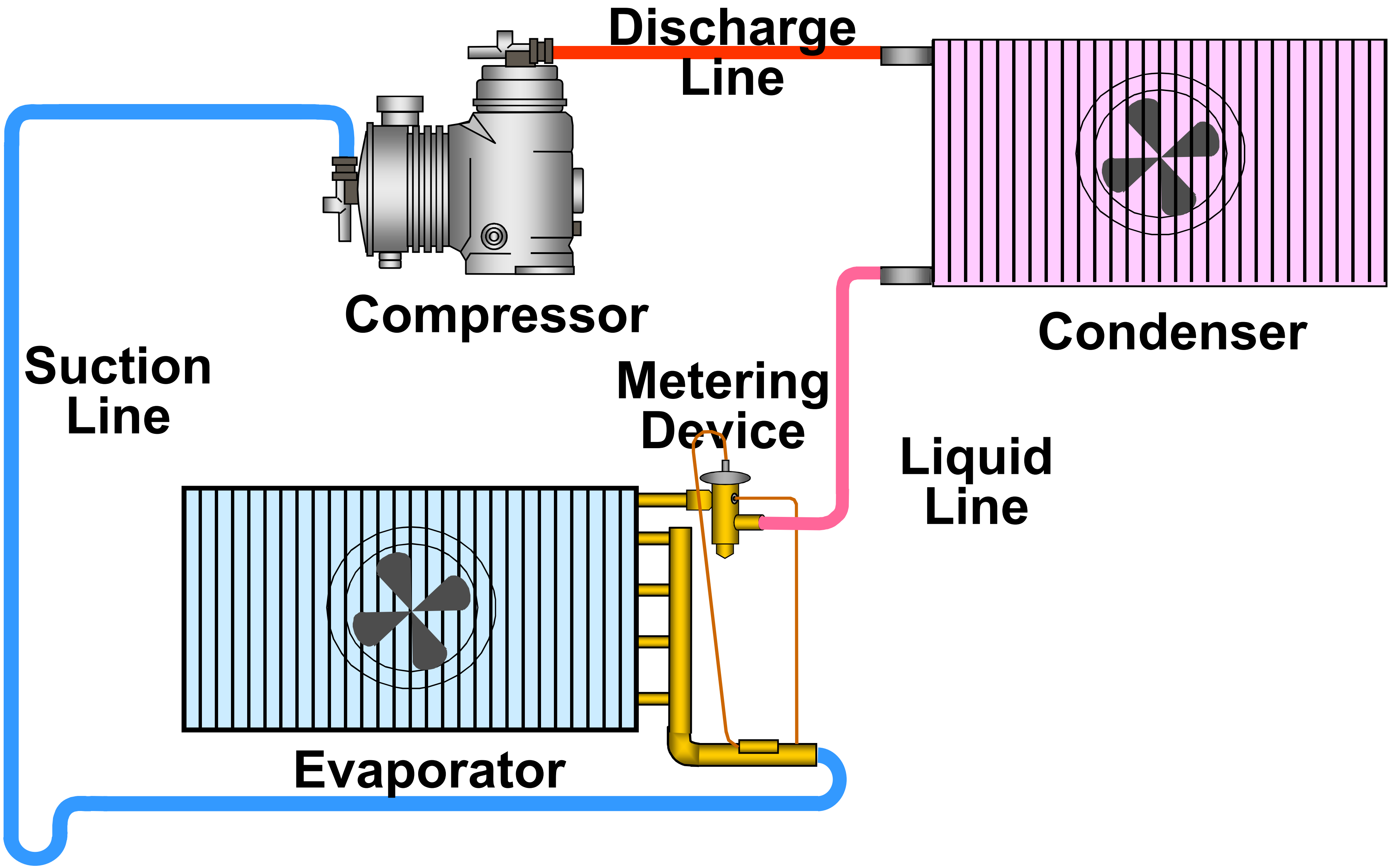


(Source: *Thermodynamics: An Engineering Approach*, 8th edition, by Yunus A. Çengel and Michael A. Boles)

3. Key components

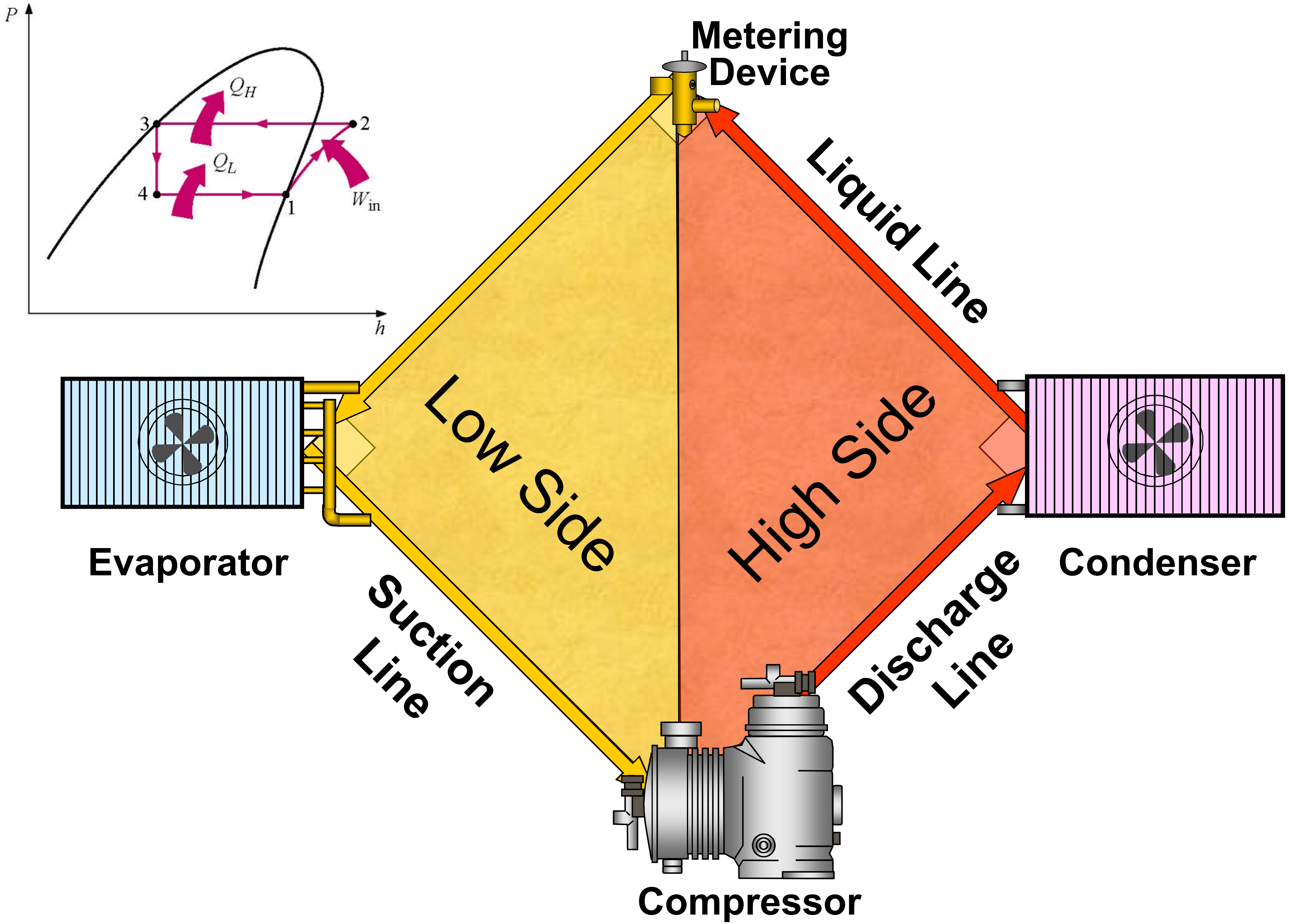
- Four basic components of vapour compression refrigeration systems
  - Compressor – raises the temperature and pressure of the refrigerant
  - Condenser – removes heat that was added to the system by the evaporator and compressor
  - Metering device – controls refrigerant flow to the evaporator
  - Evaporator – heat is absorbed from the space

Basic components and piping of a refrigeration system



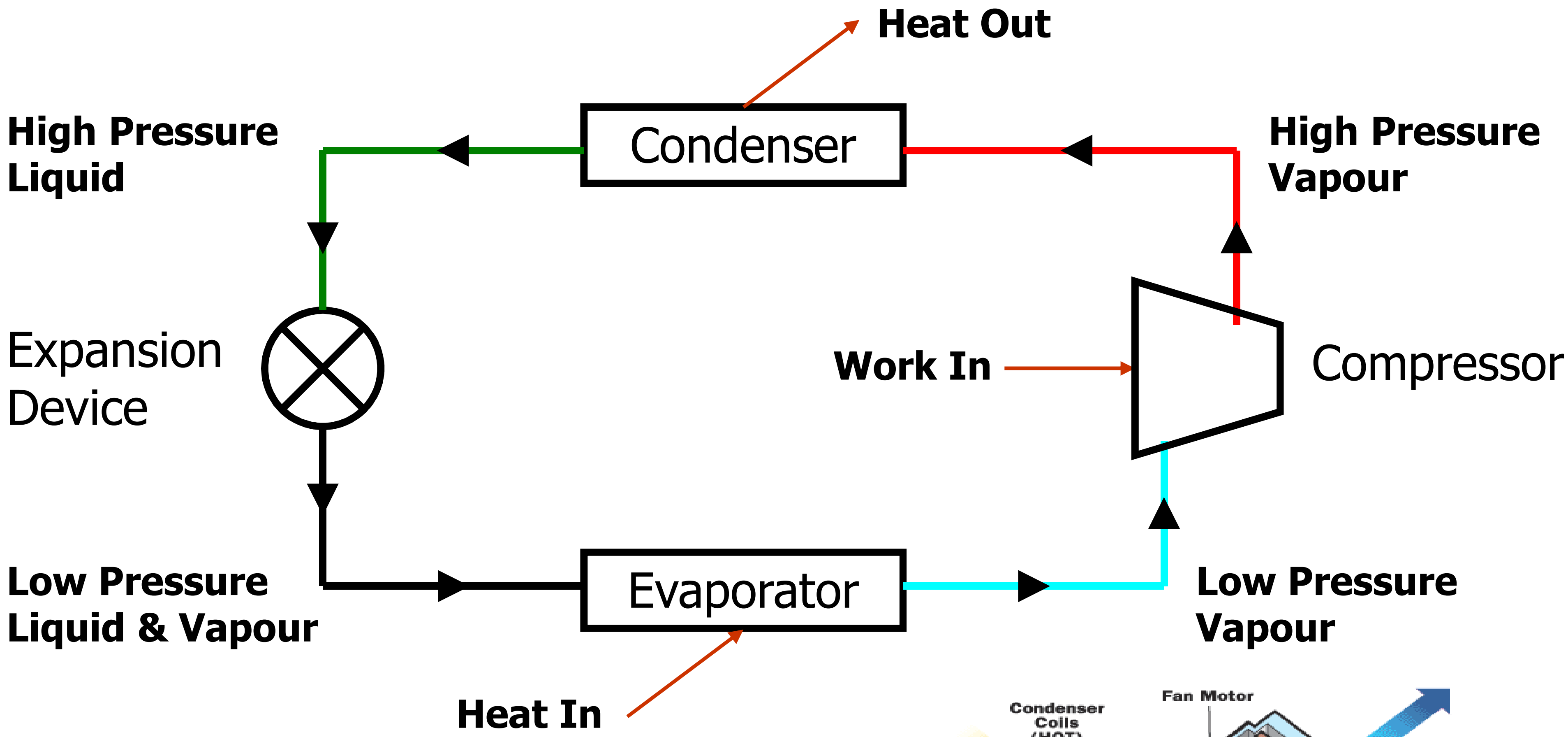
(Source: Thomson Delmar Learning)

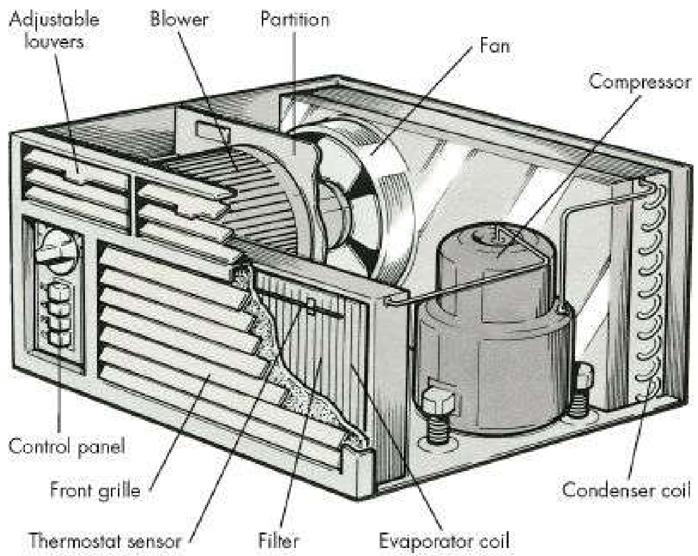
Basic components illustrated in the shape of a "baseball diamond"

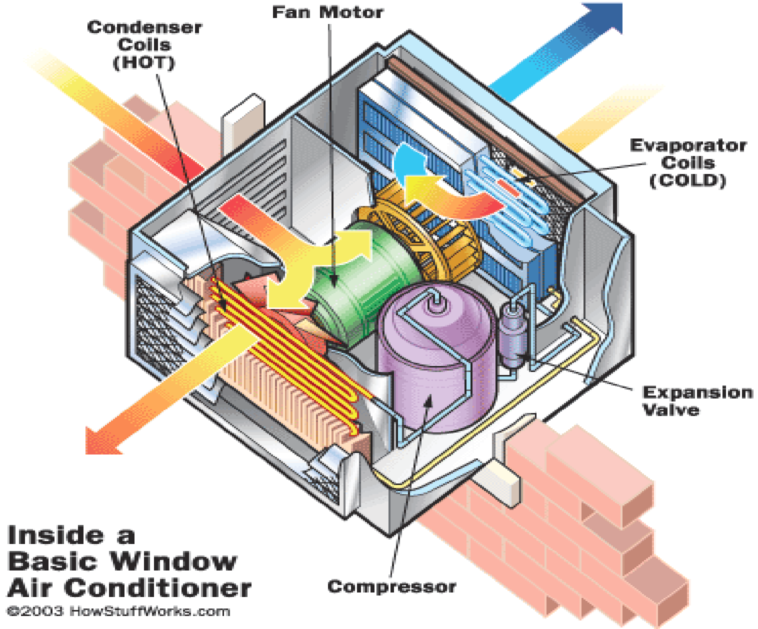


(Source: Thomson Delmar Learning)

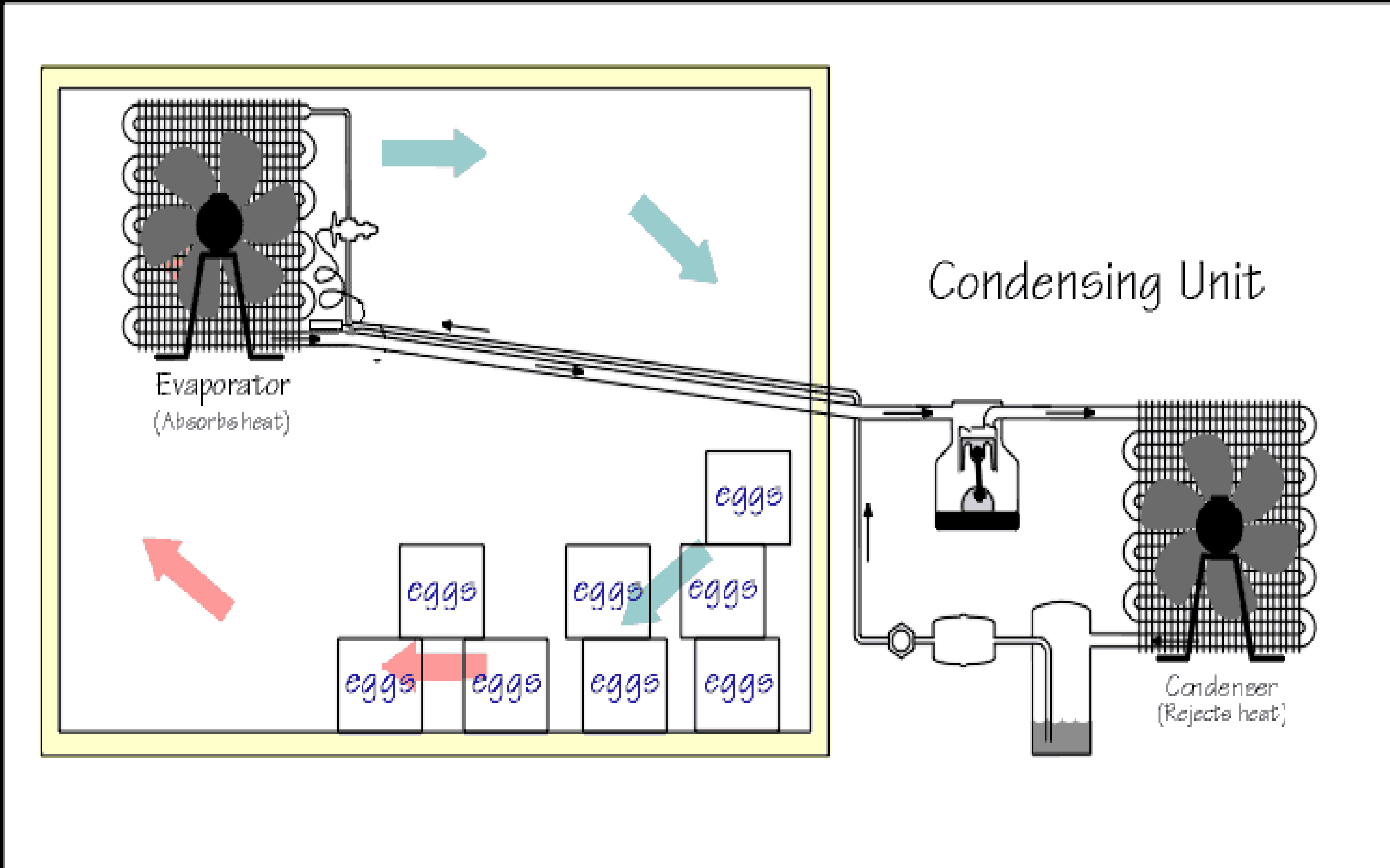
Simple refrigeration system (e.g. in a window-type air conditioner)







Refrigeration system for a walk-in cooler



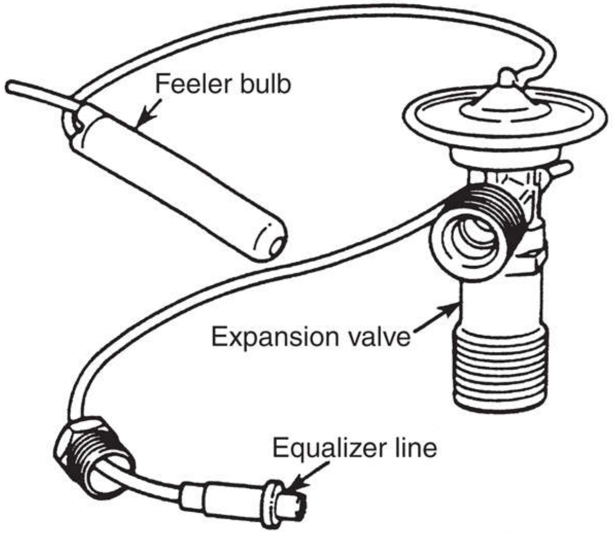
(Source: http://www.refrigerationbasics.com/RB2/rb3.htm)

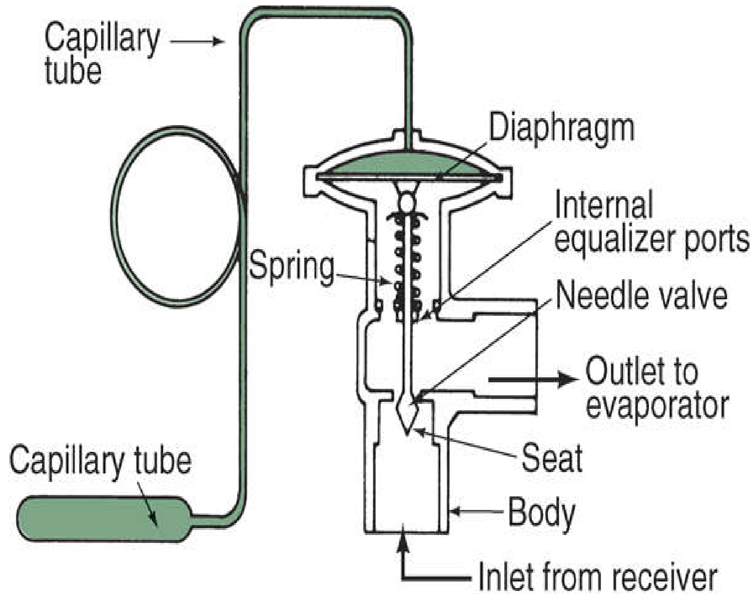
3. Key components

- Evaporator
  - It is where the heat is removed
  - It blows cold air
  - It removes heat
  - It can collect frost
  - The refrigerant goes in as a liquid and comes off as a gas
  - Usually, a fan will move warm air from the space across the evaporator finned coils

3. Key components

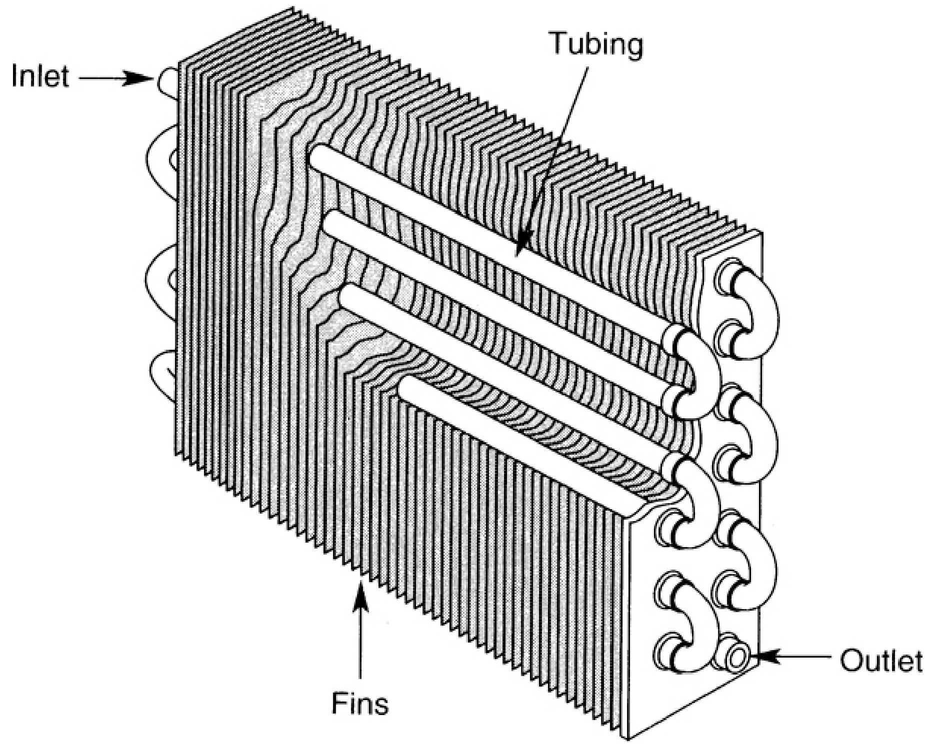
- Expansion device
  - Such as thermostatic expansion valve (TXV)
  - Changes the refrigerant from high temperature high pressure to low pressure low temperature
  - Controlling the refrigerant flow





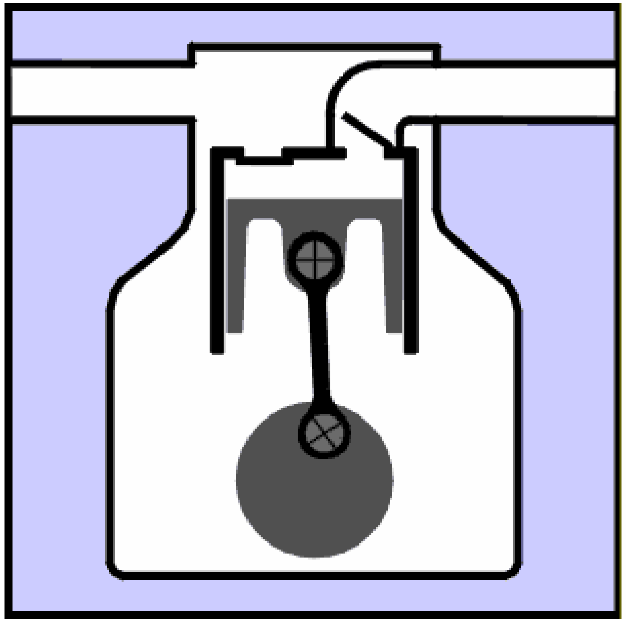
3. Key components

- Condenser
  - Heat is rejected
  - The heat can be reclaimed
  - Various types:
    - Air-cooled
    - Water-cooled
    - Evaporative



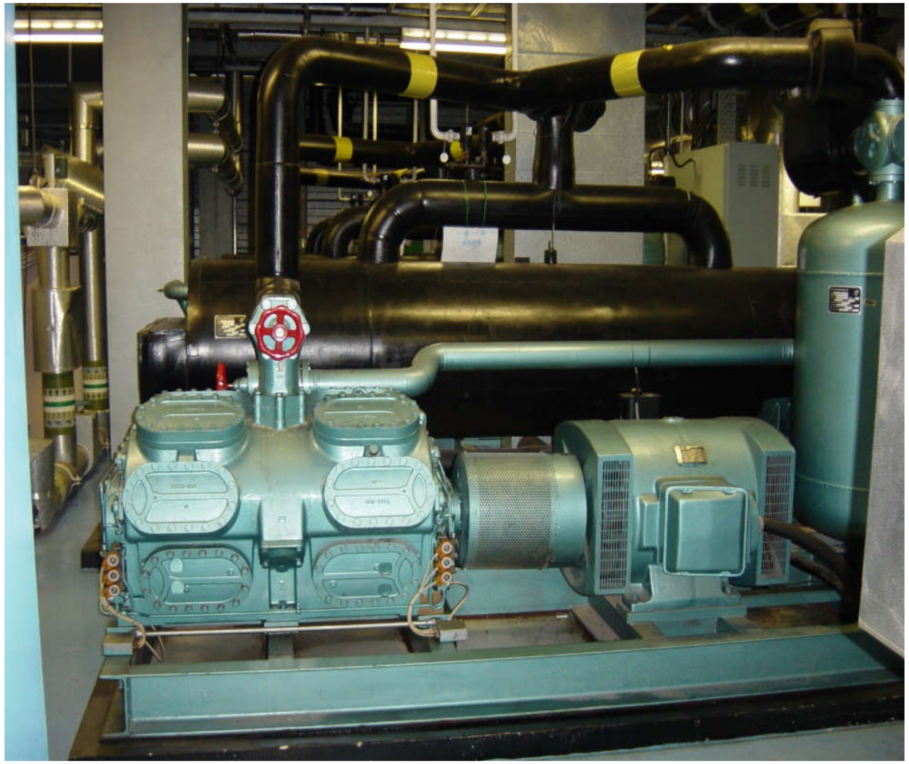
3. Key components

- Compressor
  - The engine
  - The pump
  - Sucks and blows
  - Driven by a motor
  - Various types & sizes
  - It generates heat
  - It compresses the gas



3. Key components

- Electric drive motor
  - Used to drive the compressor
  - Generates heat
  - Various types
  - Different speeds
  - Various sizes



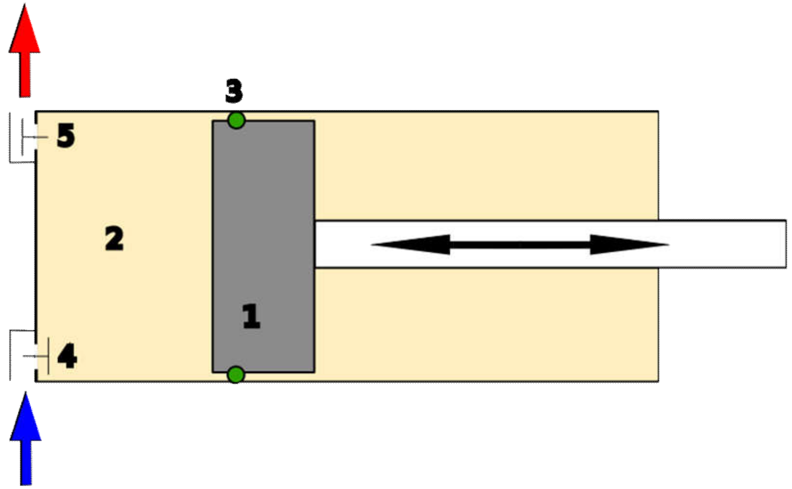
3. Key components

- Interconnecting piping
  - Efficiency can be reduced if interconnecting piping is of the wrong size or is arranged in ways that cause unnecessary pressure drop or inhibit oil return (e.g. excessive bends and fitting)
- Importance of controls
  - The components are correctly matched and controlled to maximize energy efficiency

4. Refrigeration systems

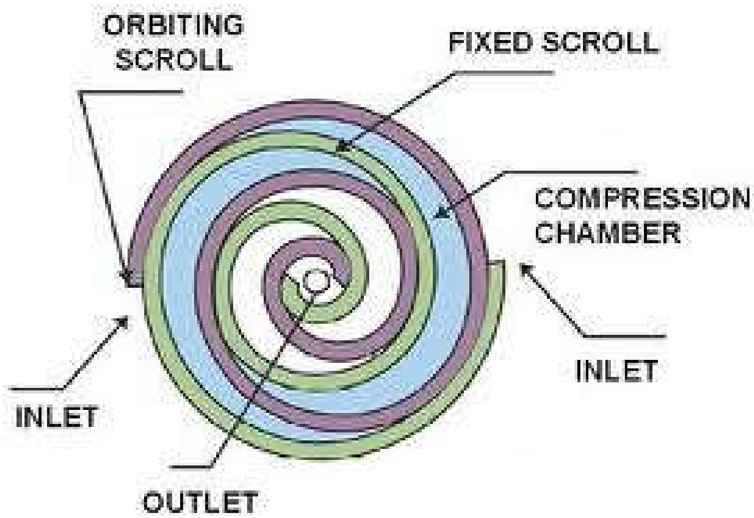
- Common types of compressors used in chillers (HVAC refrigeration plant):
  - Reciprocating -- piston-style, positive displacement
  - Rotary screw -- positive displacement; 2 meshing screw-rotors rotate in opposite directions
  - Scroll -- positive displacement; one spiral orbits around a second stationary 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

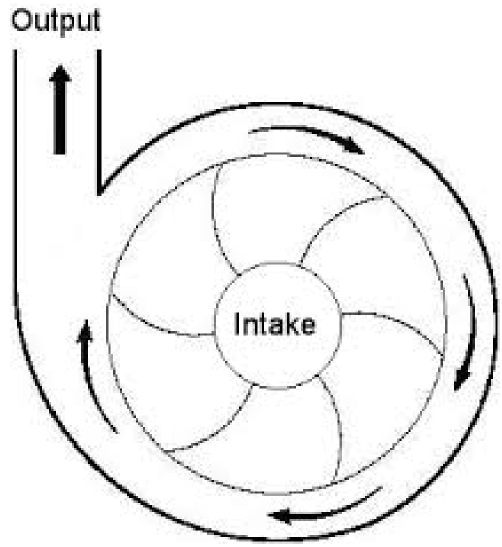


Reciprocating

Rotary screw



Scroll

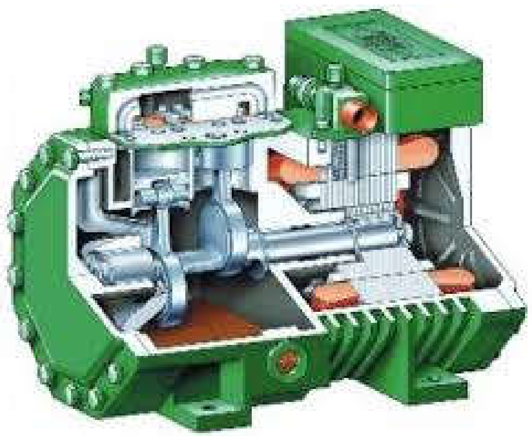


Centrifugal

4. Refrigeration systems

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





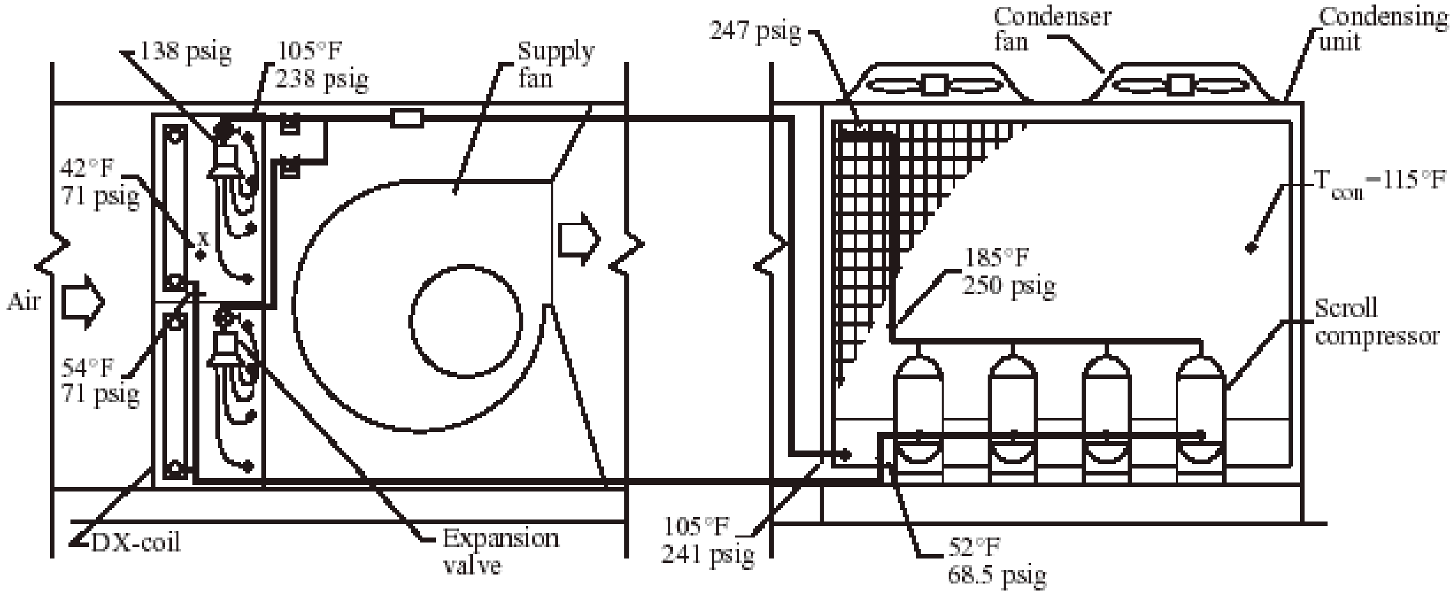
4. Refrigeration systems

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

4. Refrigeration systems

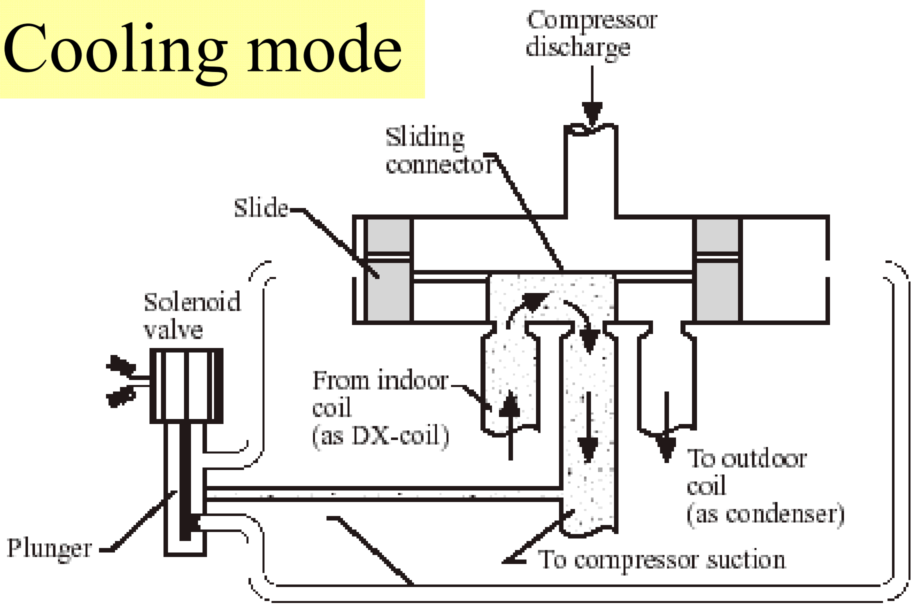
- Direct expansion (DX) systems
  - Part of the packaged air-conditioning system
  - R-22 and R-134a widely used
  - Range 3-100 TR
  - Components & accessories
    - Compressor(s): reciprocating and scroll
    - Condensers
    - Refrigeration feed
    - Oil lubrication
    - Refrigerant piping

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



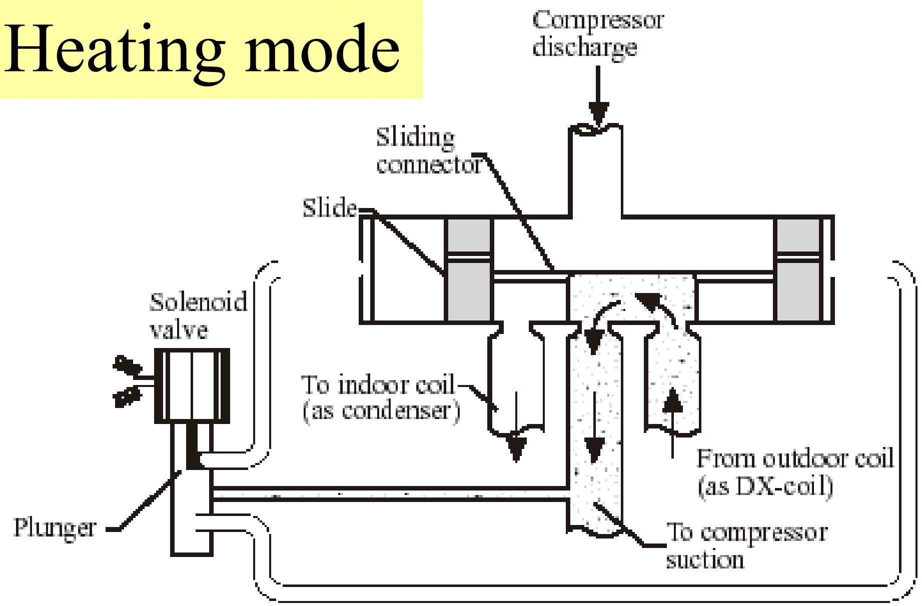
(a)

Cooling mode



(b)

Heating mode

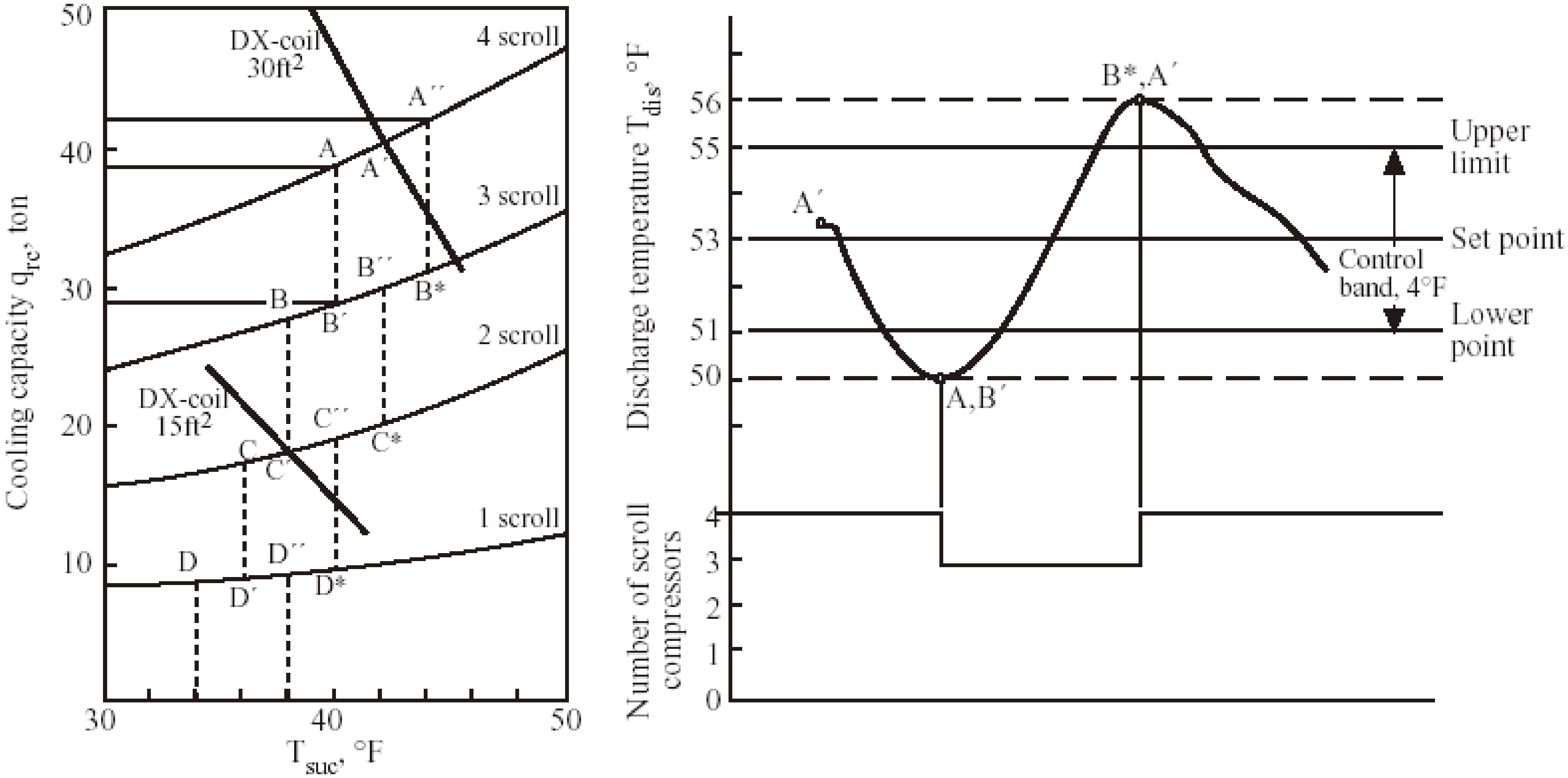


(c)

4. Refrigeration systems

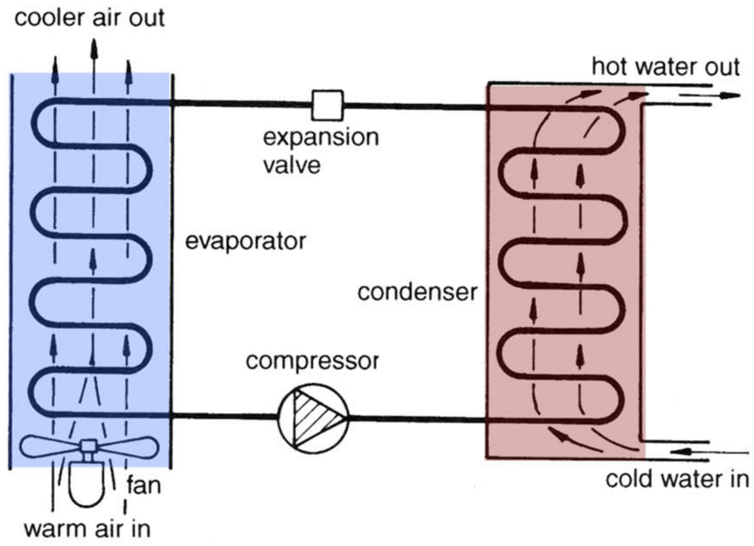
- Direct expansion (DX) systems (cont’d)
  - Capacity control
    - On-off control
    - Cylinder unloader
    - Speed modulation
  - Safety control
    - Low- & high-pressure control
    - Low-temperature control
    - Motor overload control
    - Pump-down control
  - Full- and part-load operation

Capacity control of a DX system



4. 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)



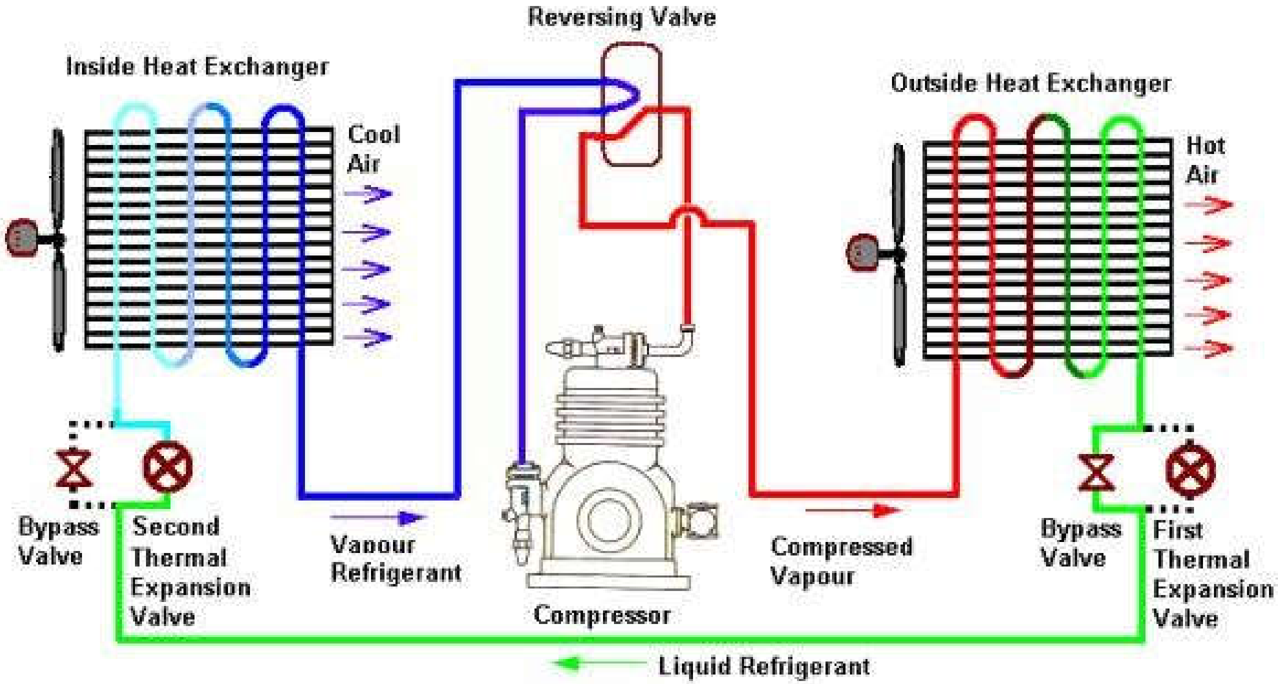


Fig. 1 - Heat Pump in Cooling Mode

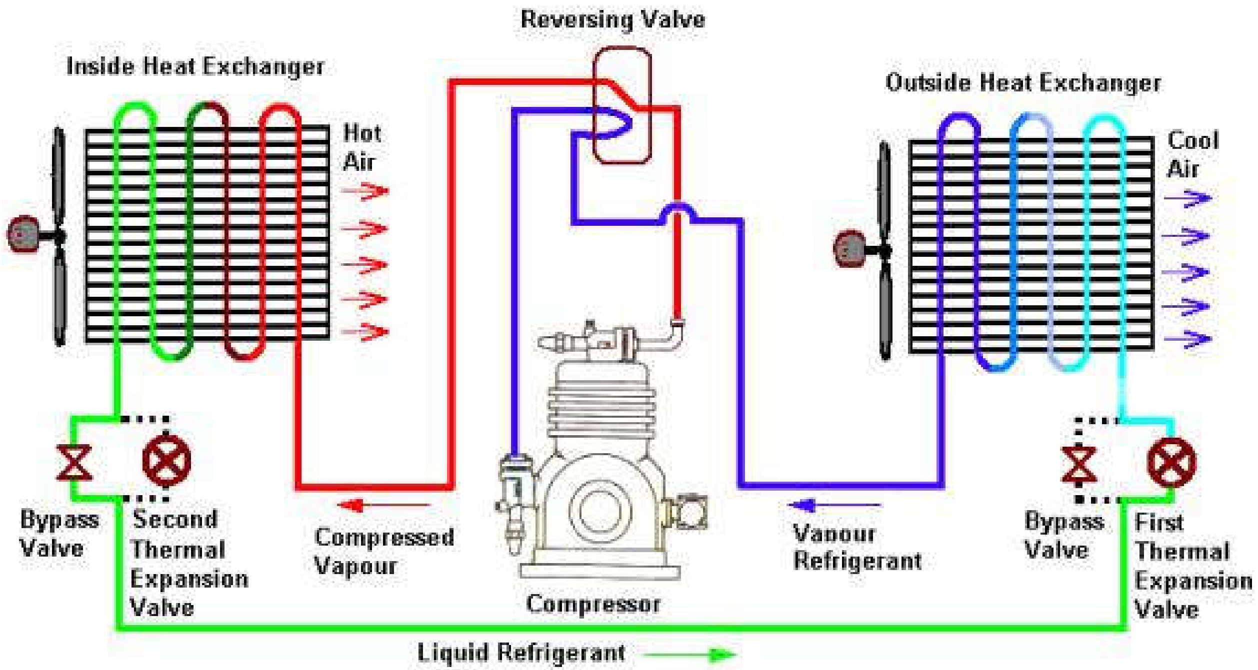
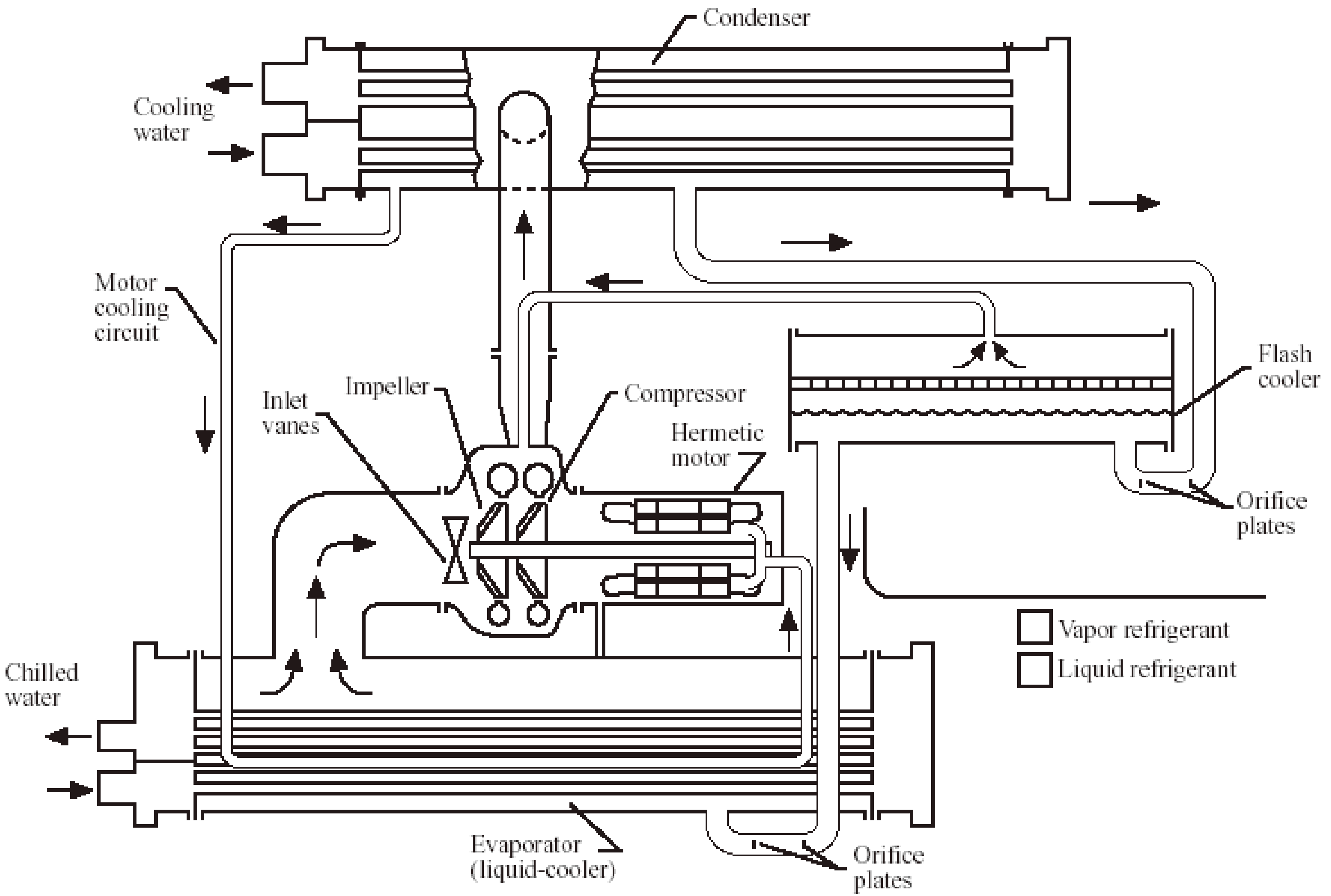


Fig. 2 - Heat Pump in Heating Mode

4. 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



4. Refrigeration systems

- Centrifugal chillers (cont'd)
  - Performance rating: ARI Standard 550
    - 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

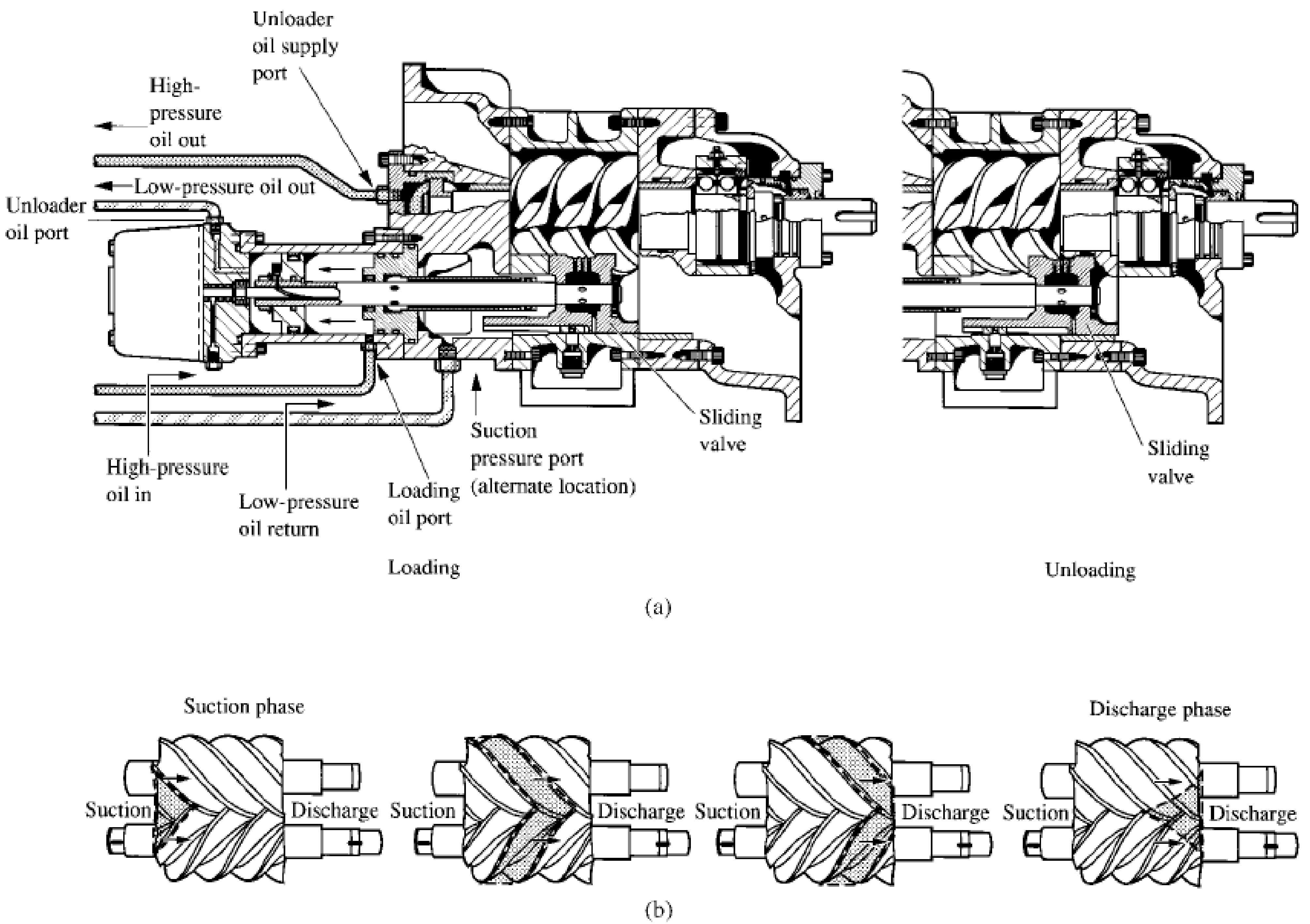
4. Refrigeration systems

- 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

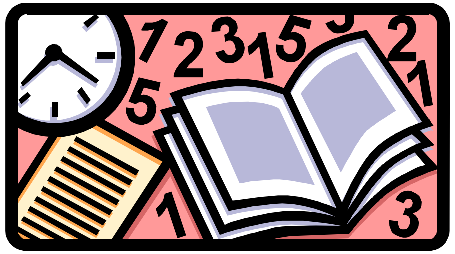
4. Refrigeration systems

- 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



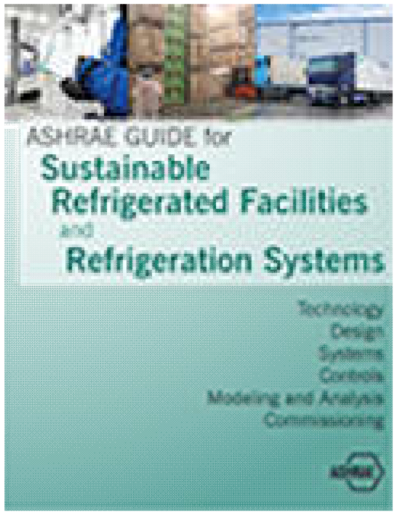
Useful E-learning

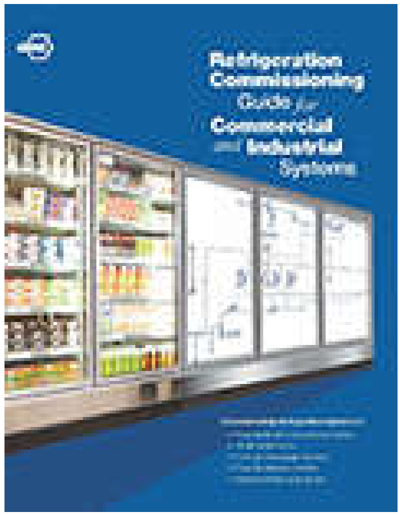


- NPTEL E-learning course -- Refrigeration and Air Conditioning http://nptel.ac.in/courses/112105129/
  - Lesson 10 Vapour Compression Refrigeration Systems
  - Lesson 11 Vapour Compression Refrigeration Systems: Performance Aspects And Cycle Modifications
  - Lesson 12 Multi-Stage Vapour Compression Refrigeration
  - Lesson 13 Multi-Evaporator And Cascade Systems
  - Lesson 14 Vapour Absorption Refrigeration Systems
  - Lesson 25 Analysis Of Complete Vapour Compression Refrigeration Systems
  - Lesson 26 Refrigerants

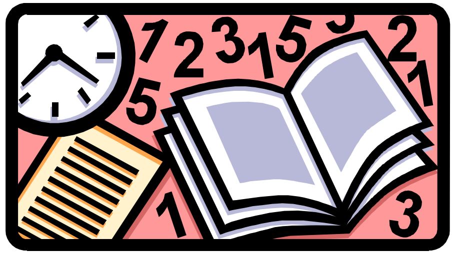
Useful References

- ASHRAE Guide for Sustainable Refrigerated Facilities and Refrigeration Systems (2018)
- Refrigeration Commissioning Guide for Commercial and Industrial Systems (2013)





Relevant Standards



- ANSI/ASHRAE Standard 15-2016, Safety Standard for Refrigeration Systems
- ANSI/ASHRAE Standard 34-3016, Designation and Safety Classification of Refrigerants
- ANSI/ASHRAE Standard 147-2013, Reducing Release of Halogenated Refrigerants from Refrigerating and Air-Conditioning Equipment and Systems.