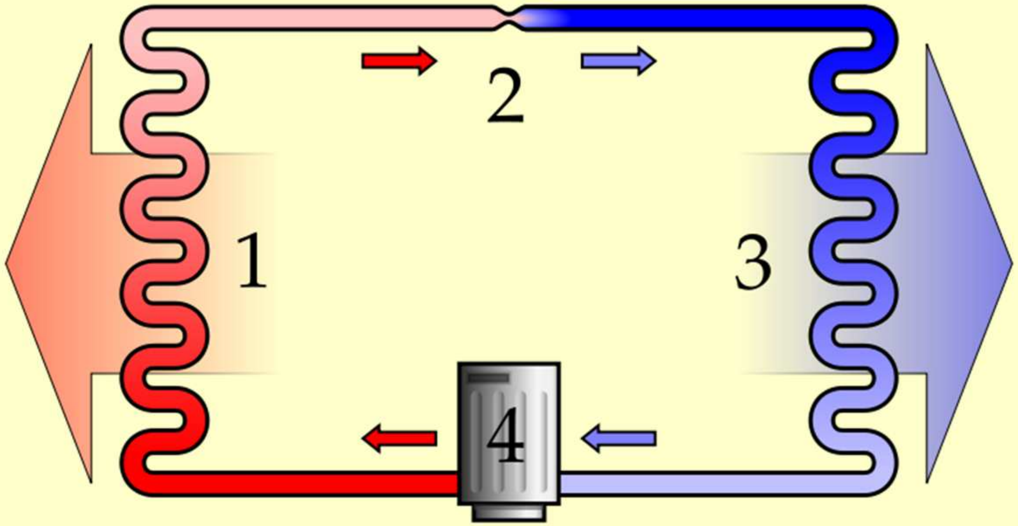
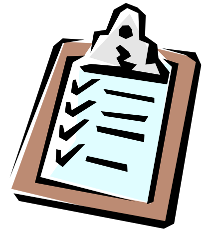


Principles of Refrigeration

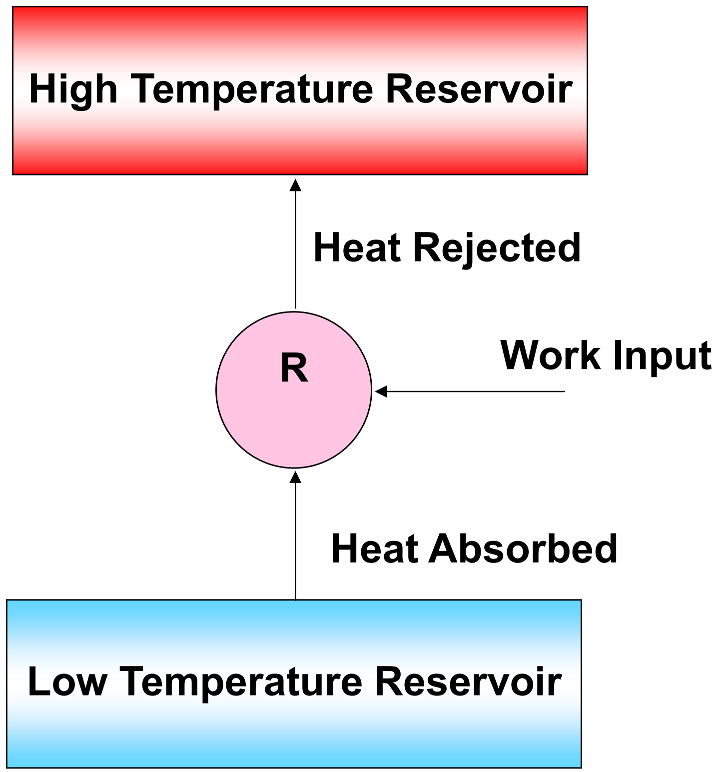
Ir. Dr. Sam C. M. Hui
Faculty of Science and Technology
E-mail: cmhui@vtc.edu.hk

Oct 2017

Contents



- Basic Concepts
- Refrigerants
- Selection of Refrigerants
- Refrigeration Cycles



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

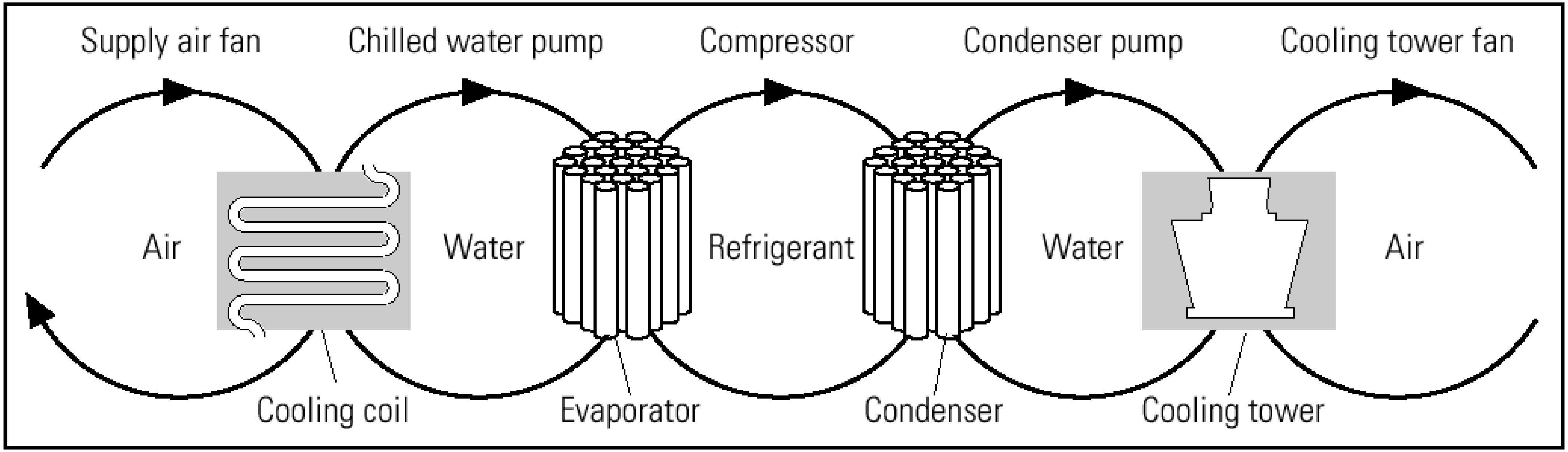
1) Indoor air loop

2) Chilled water loop

3) Refrigerant loop

4) Condenser water loop

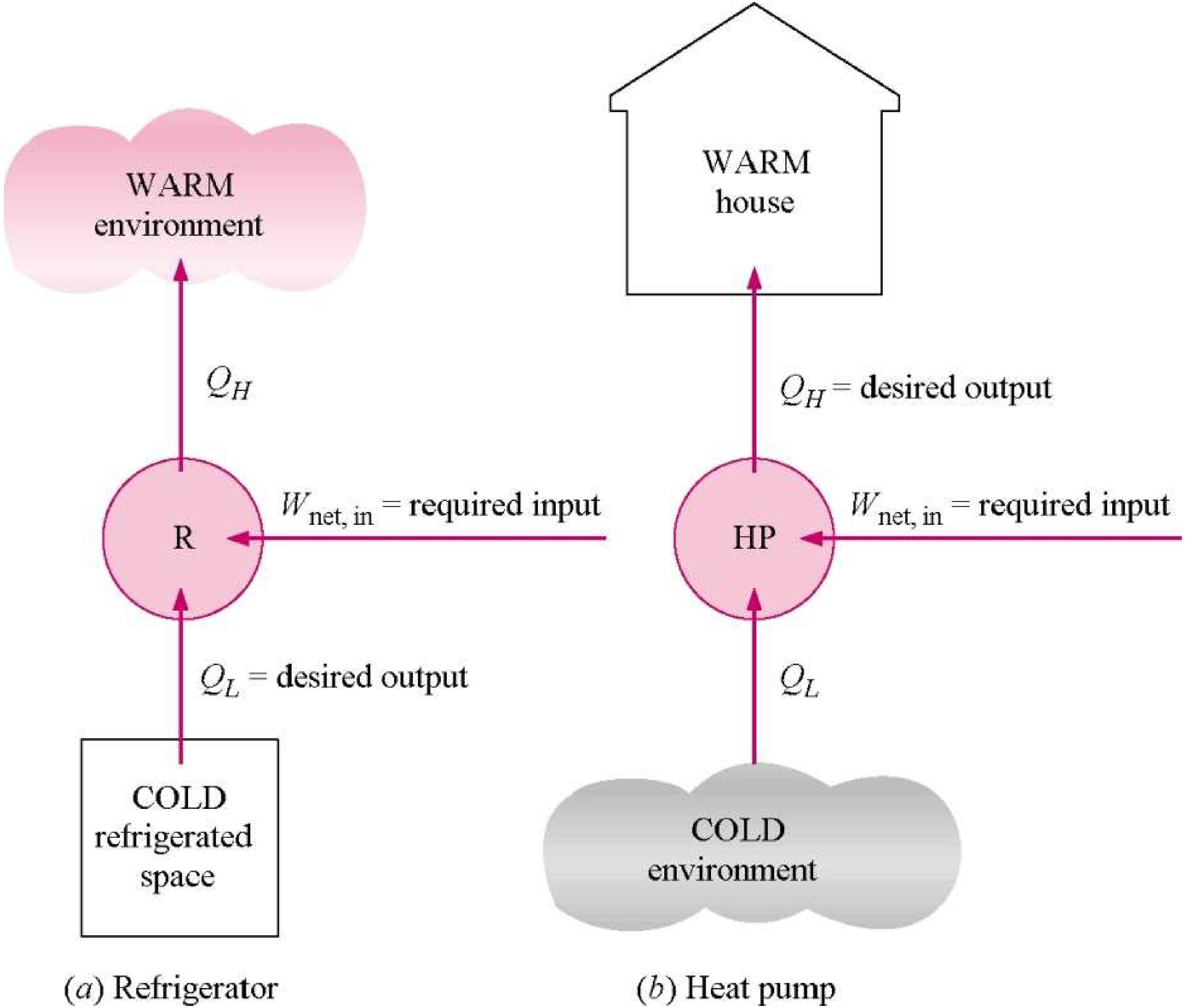
5) Cooling water loop



* 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



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

Basic Concepts

- 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

Basic Concepts

- 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

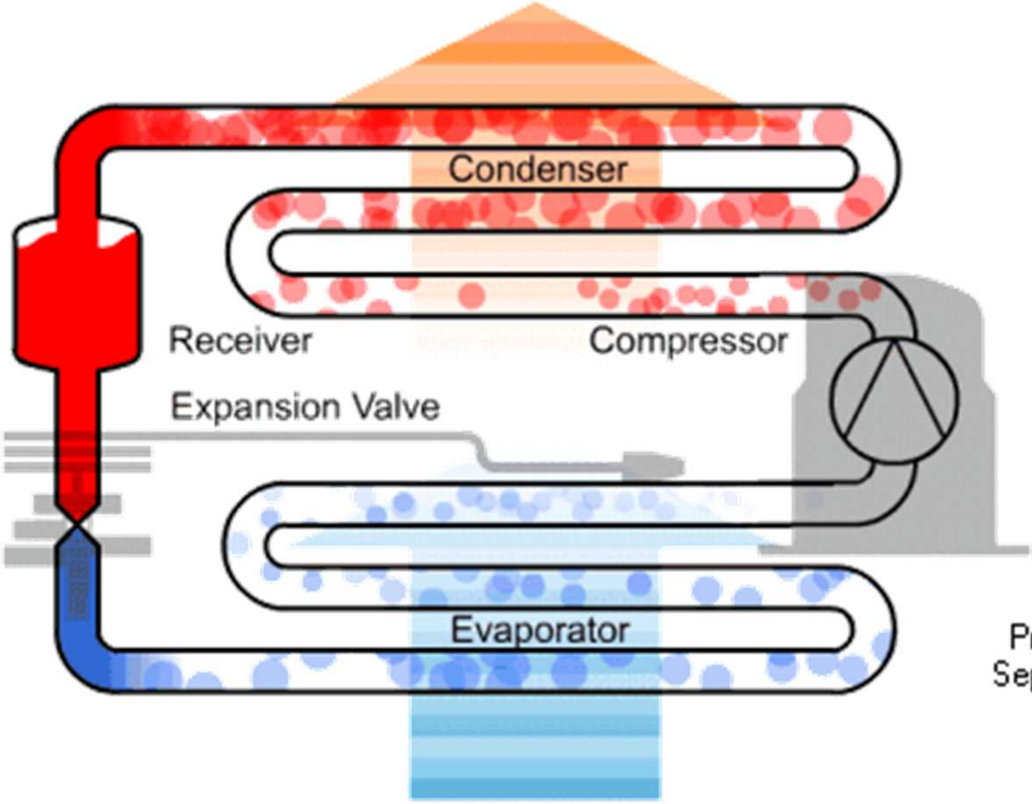
- Refrigeration systems
  - Combination of components, equipment & piping connected to produce the refrigeration effect

(* See also: The History of Refrigeration http://www.arca53.dsl.pipex.com/index_files/frig3.htm)

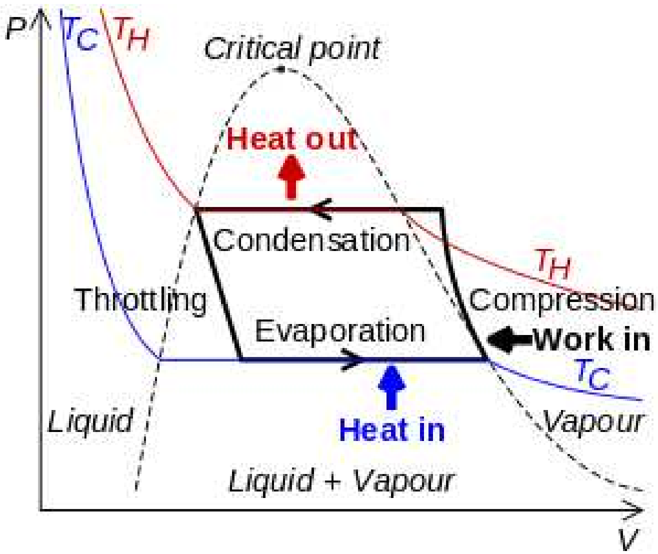
Basic Concepts

- 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

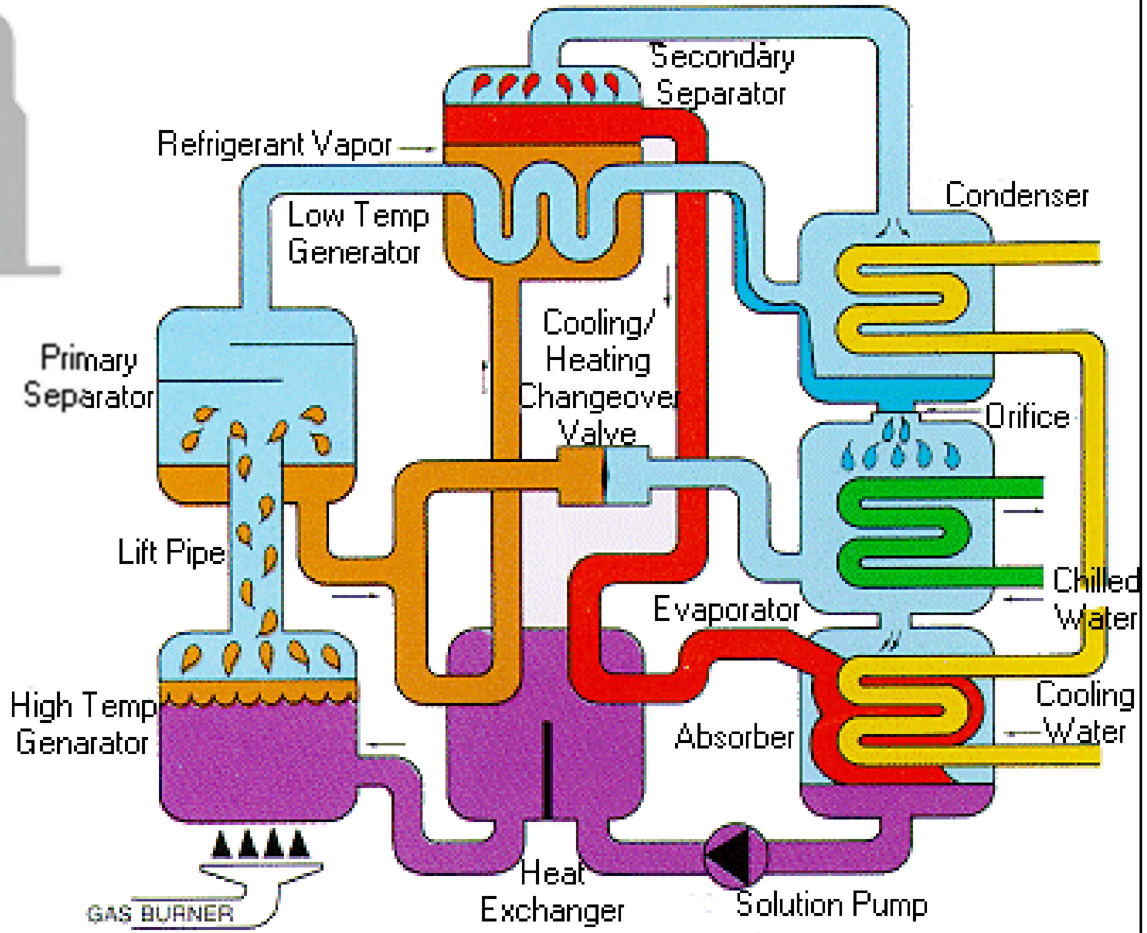
Vapour compression system



Refrigeration Cycle



Vapour absorption system

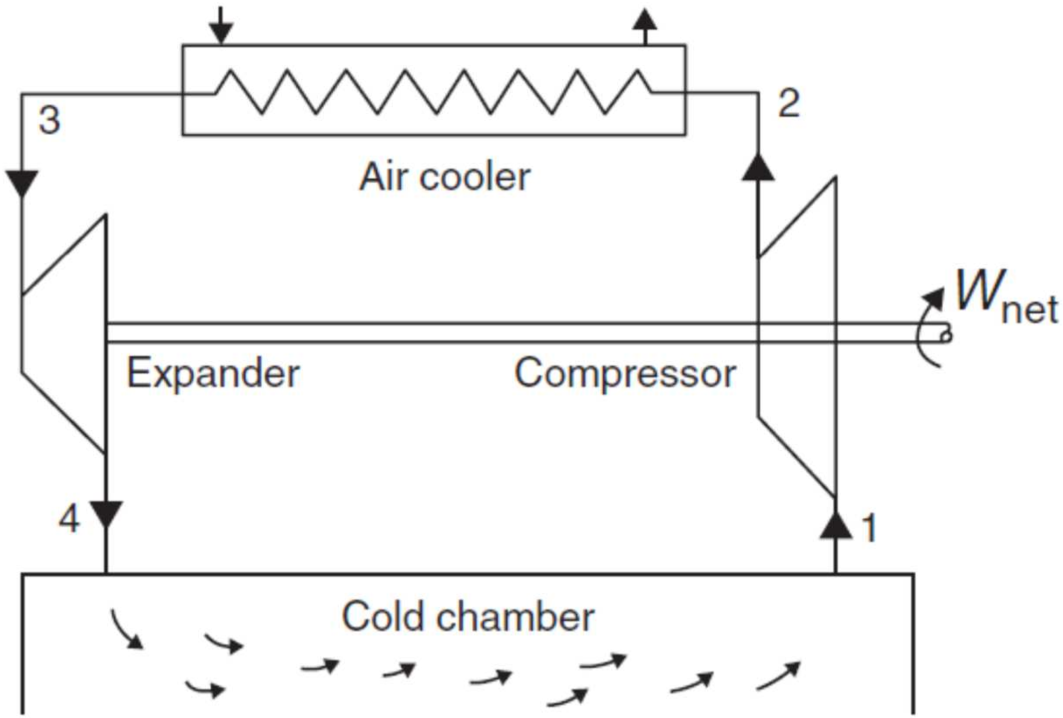


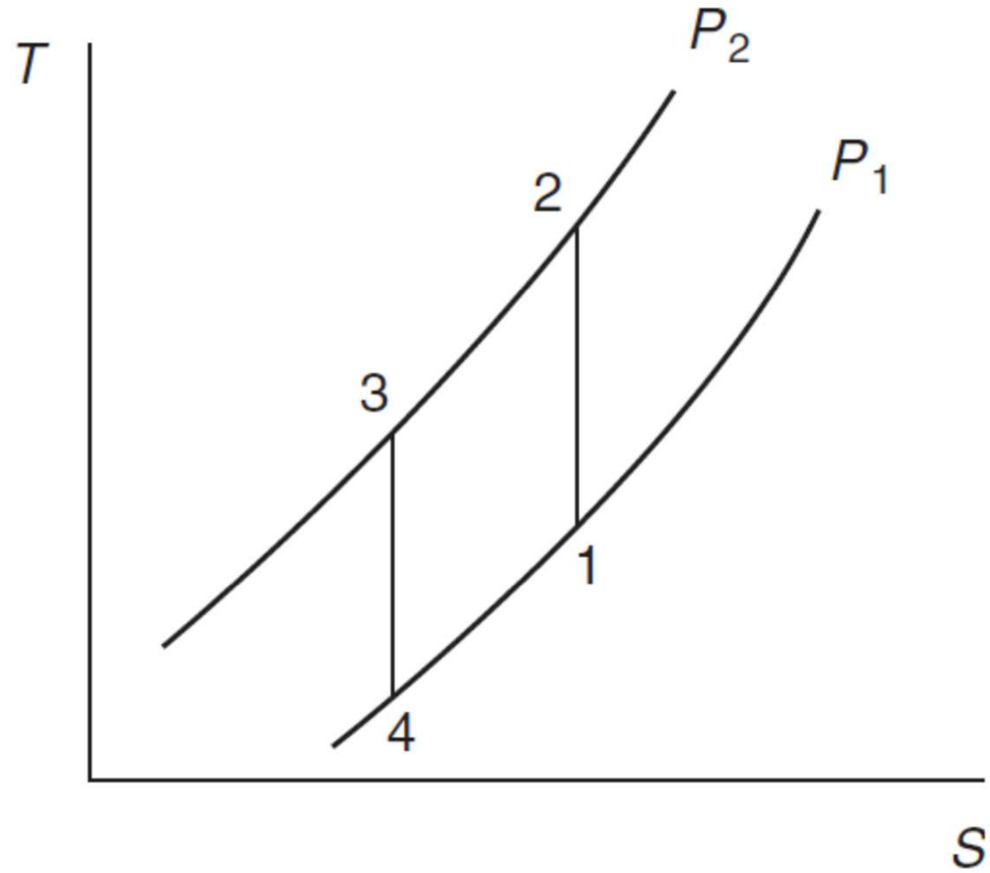
Videos:

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.

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

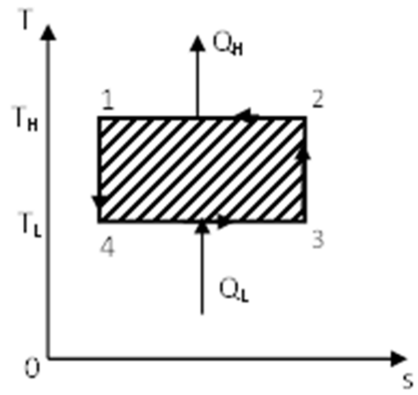
(* See also: Air cycle machine - Wikipedia http://en.wikipedia.org/wiki/Air_cycle_machine)

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

Basic Concepts

- 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

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

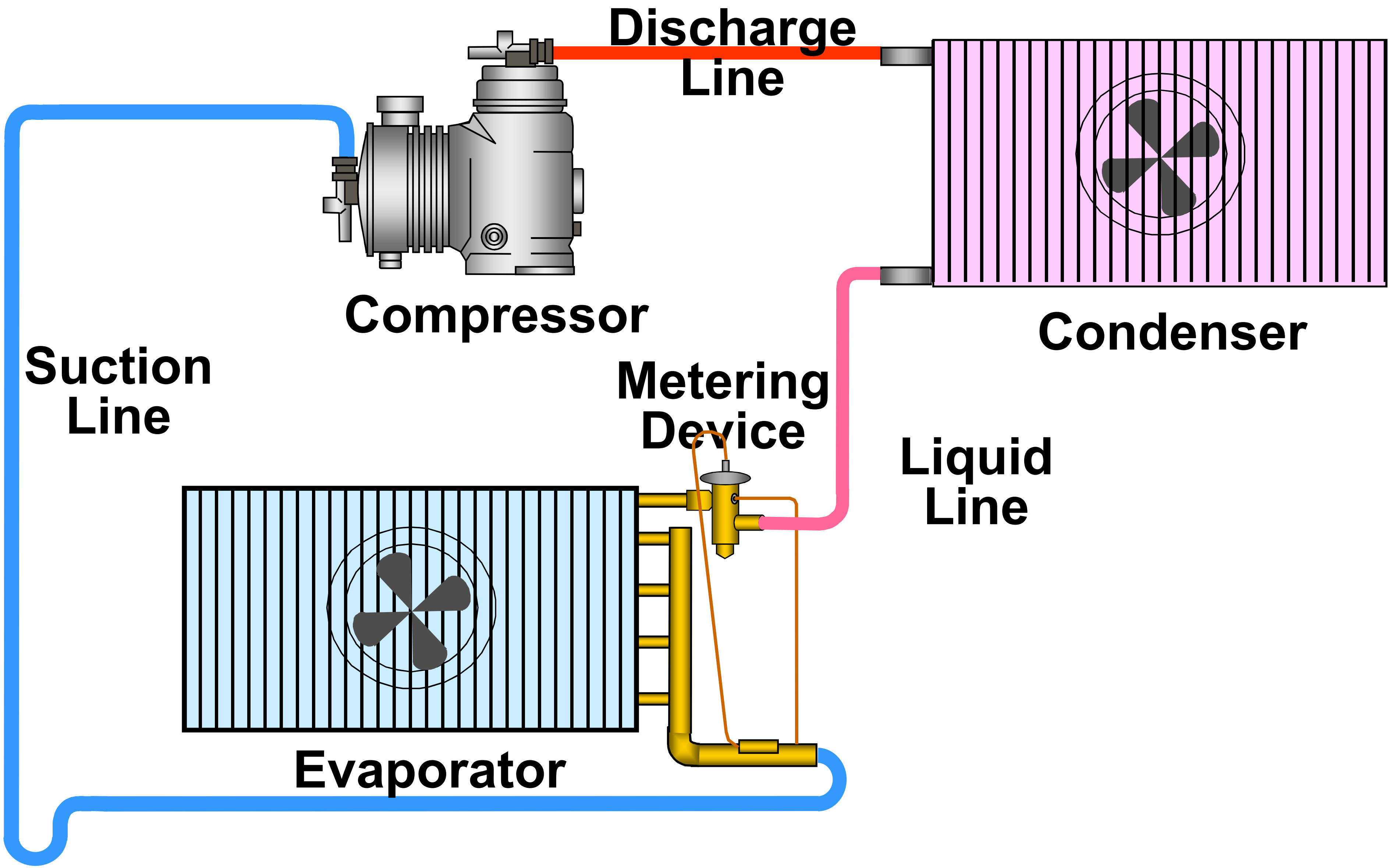


(* See also: The Reversed Carnot Cycle http://thermodynamics-engineer.com/429-2/)

Basic Concepts

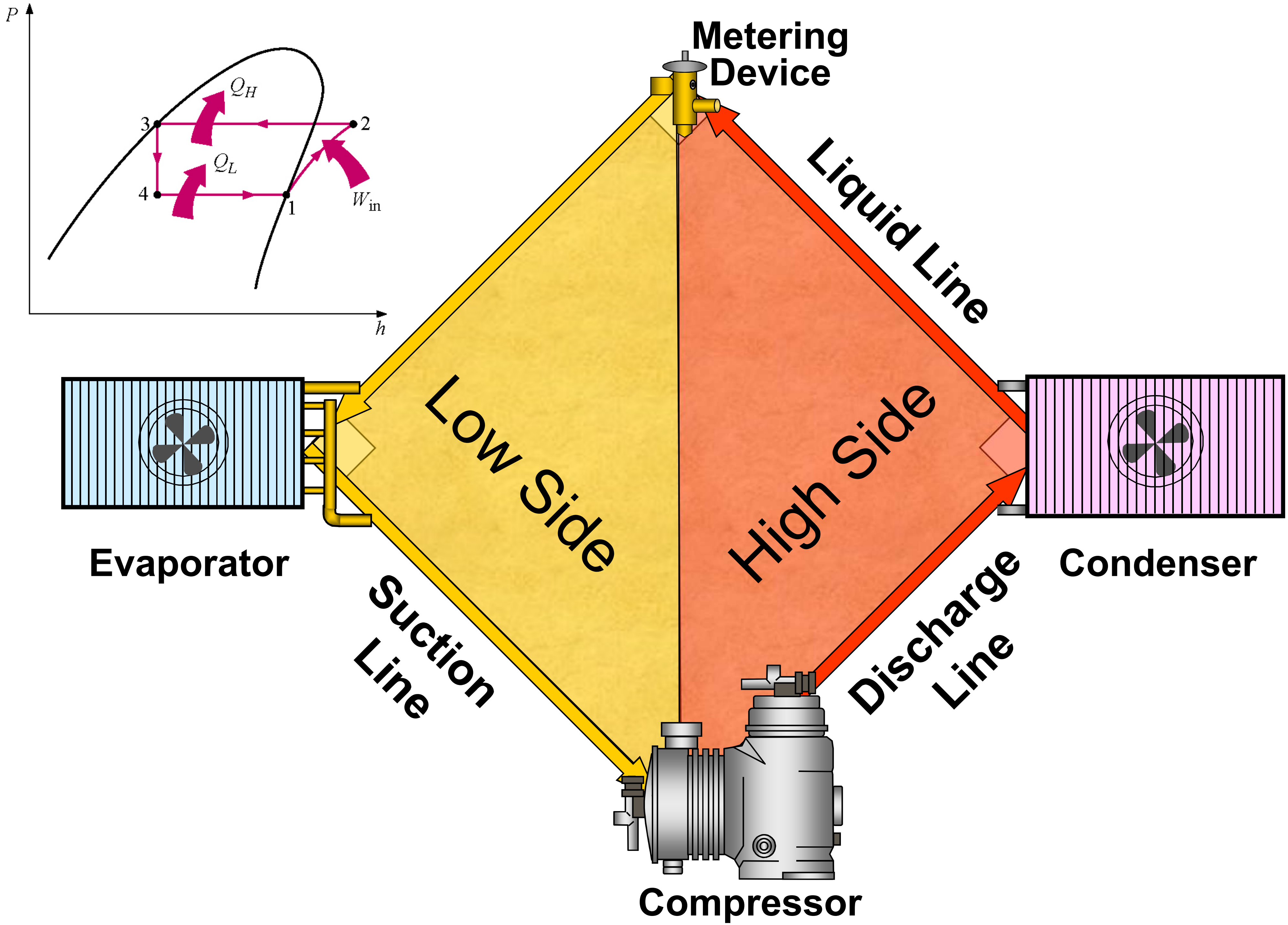
- Four basic components of vapour compression refrigeration systems
  - Compressor – raises the temperature and pressure of the refrigerant
  - Condenser – removes heat that was added to the system by the evaporator and compressor
  - Metering device – controls refrigerant flow to the evaporator
  -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

Basic Concepts

- 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 (e.g. chilled water, brine, and glycol)
  - Liquid absorbent:
    - Working fluid (e.g. lithium bromide and ammonia) to absorb vaporised refrigerant (water) after evaporation in an absorption refrigeration system

Refrigerants

製冷劑、冷媒、雪種

- Refrigerants absorb heat at a low temperature and low pressure and release heat at a higher temperature and pressure
  - Most refrigerants undergo phase changes during heat absorption (evaporation) and heat releasing (condensation)
  - A refrigerant can either be a single chemical compound or a mixture (blend) of multiple compounds

(Video: Refrigerants How they work in HVAC systems (8:53) http://www.youtube.com/watch?v=lMqoKLli0Y4)

(* See also: http://en.wikipedia.org/wiki/Refrigerant)

Classification of fluids used as refrigerants

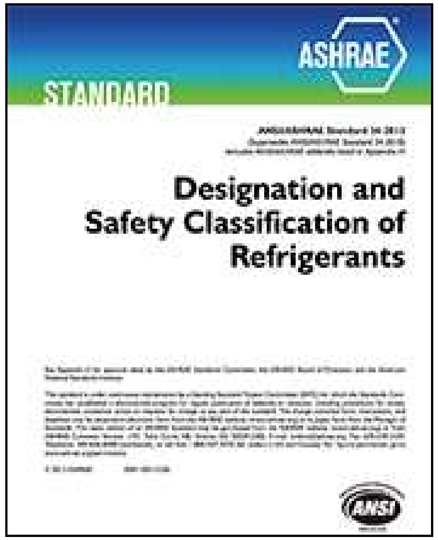
Refrigerants

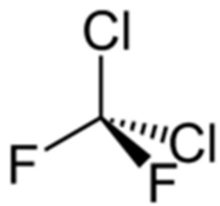
- **Pure fluids**
  - **Synthetic**
    - CFCs
    - HCFCs
    - HFCs
  - **Natural**
    - Organic (HCs)
    - Inorganic
      - NH_3
      - CO_2
      - H_2O
- **Mixtures**
  - Azeotropic
  - Zeotropic

(Source: NPTEL E-learning course -- Refrigeration and Air Conditioning, Lesson 26 Refrigerants http://nptel.ac.in/courses/112105129/26)

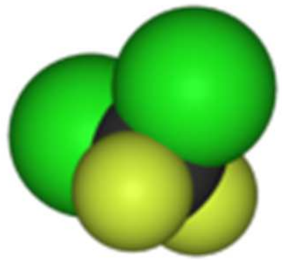
Refrigerants

- 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 = $CHCl_2CF_3$





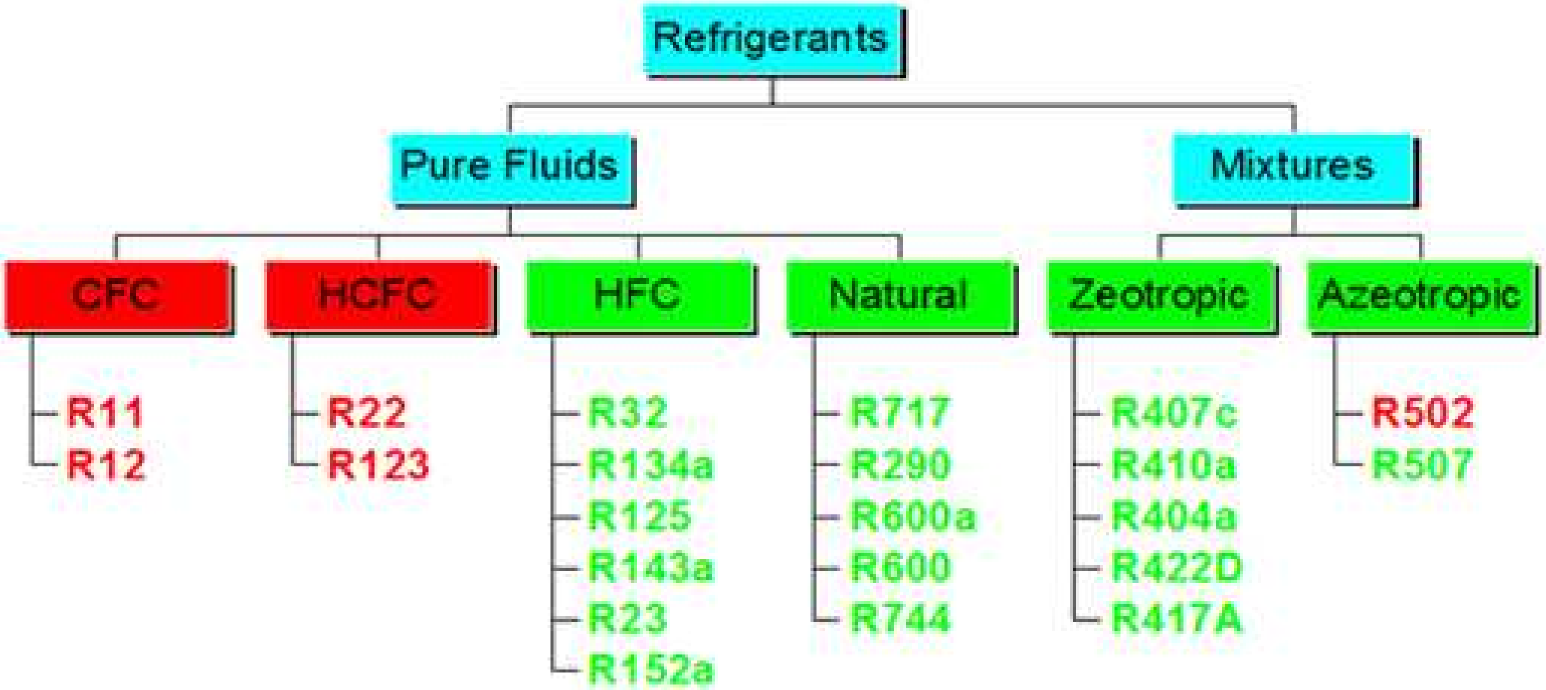
- Today's refrigerants are predominantly from a group of compounds called halocarbons (halogenated hydrocarbons) or specifically fluorocarbons



(* "*Halogen*", from the Greek roots *hal*- ("salt") and -*gen* ("to produce"), i.e. produce sodium salts.)

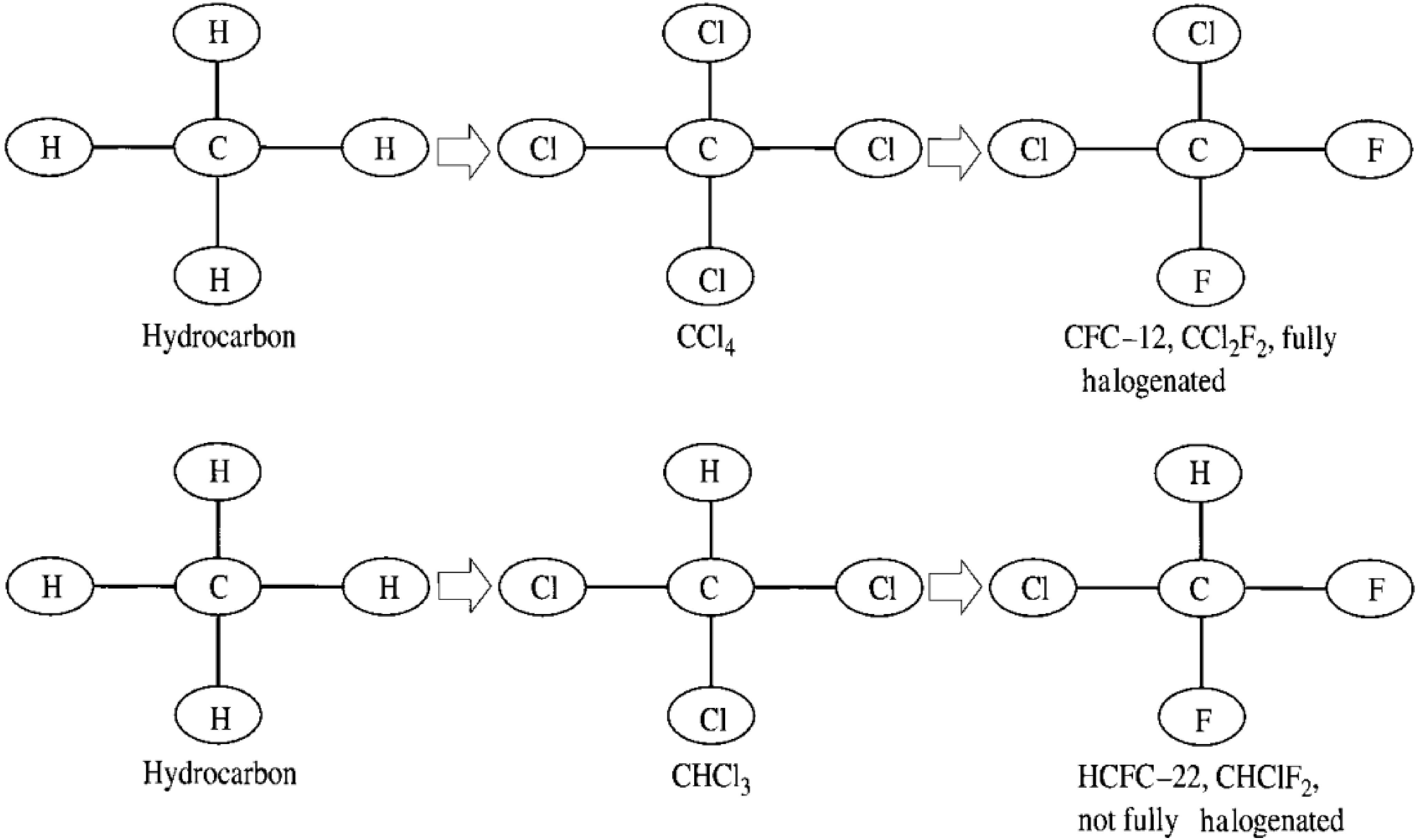
Numbering system and types of refrigerants

Series	Description
000	Methane Based
100	Ethane Based
200	Propane Based
300	Cyclic Organic Compounds
400	Zeotropes
500	Azeotropes
600	Organic Compounds
700	Inorganic Compounds
1000	Unsaturated Organic Compounds



(Source: http://www.fwdengineers.com/2017/01/17/refrigerant-history-and-nomenclature-part-2/)

Fully halogenated CFCs and not fully halogenated HCFCs

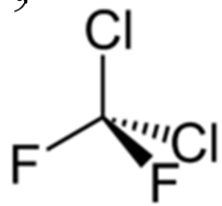


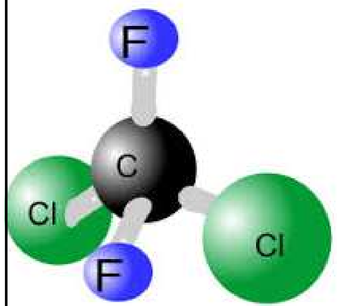
C Carbon atom H Hydrogen atom Cl Chlorine atom F Fluorine atom

(Source: *Wang, S. K., 2001. Handbook of Air Conditioning and Refrigeration*)

Refrigerants

- Chlorofluorocarbons (CFCs) 氟氯化碳
  - Contains only chlorine, fluorine & carbon atoms; fully halogenated



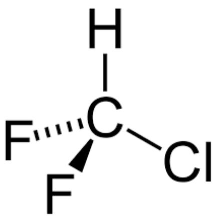


    - CFCs were first developed by General Motor's researchers in the 1920's and commercialized by Dupont as "Freons" family of refrigerants, such as R-11, R-12, R-113, R-114, R-115
    - Inert, colourless, odourless, low toxicity, low flammability and low reactivity
    - Also used in aerosol cans, blowing agents, solvents, degreasing, cleaning, fire extinguishers, asthma inhalers

(* See also: http://en.wikipedia.org/wiki/Chlorofluorocarbon)

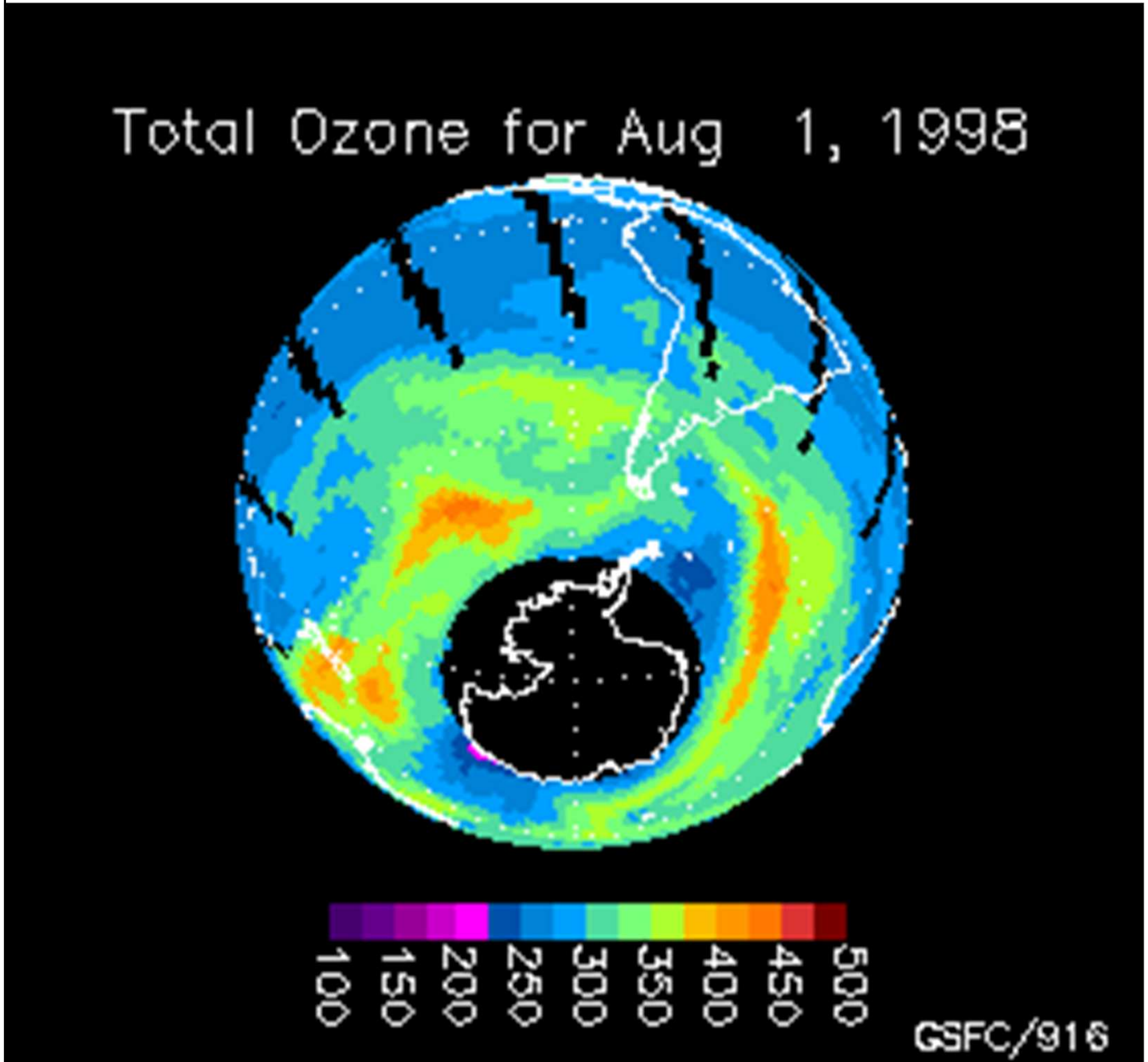
Refrigerants

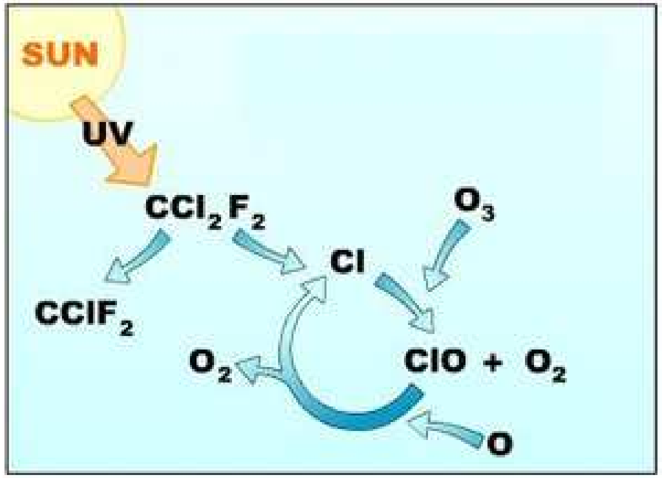
- Hydrochlorofluorocarbons (HCFCs) 氟氯烴



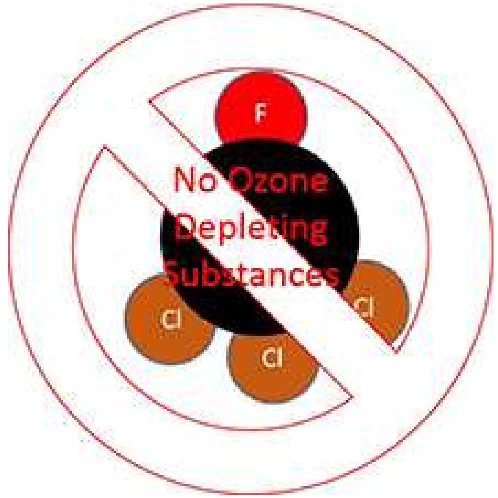
  - Contain hydrogen, chlorine, fluorine & carbon atoms and are not fully halogenated
  - Smaller lifetime in atmosphere than CFCs & cause far less ozone depletion (ODP = 0.02 to 0.1)
  - Such as R-22, R-123, R-124
- Hydrofluorocarbons (HFCs) 氫氟碳化物
  - Contains only hydrogen, fluorine, and carbon atoms; cause less ozone depletion, but high GWP
  - Such as R-134a, R-410a, R-407c, R-404a

Ozone depletion in the atmosphere





DESTRUCTION OF OZONE BY CFC



(Video: Refrigerant types and their future (12:40) http://www.youtube.com/watch?v=J77a0keM2Yk)

(* See also: CFCs (The Ozone Hole) http://www.theozonehole.com/cfc.htm)

Environmental impacts of common refrigerants

Refrigeration	Type[1]	ODP[2]	GWP[3]
R-744 (CO_2)	Natural	0	1
R-134A	HFC	0	1,430
R-410A	HFC	0	2,088
R-407C	HFC	0	1,774
R-404A	HFC	0	3,922
R-22	HCFC	0.055	1,810
R-12	CFC	1	10,900
R-717 (Ammonia)	Natural	0	0

[1] Natural = Naturally occurring; HFC = hydrofluorocarbon; HCFC = hydrochlorofluorocarbons; CFC = chlorofluorocarbon

[2] ODP = Ozone depletion potential, 0 to 1 scale with R-12 = 1

[3] GWP = Global warming potential, scale based on CO_2 = 1

(Source: http://www.zondits.com/article/14037/brief-history-co2-refrigerant)

Refrigerants

- Assess environmental impacts of refrigerants
  - Ozone depletion potential (ODP) 臭氧破壞潛勢
    - Ratio of ozone depletion rate compared with R-11
  - Global warming potential (GWP) 全球暖化潛勢
    - Global warming effect compared with R-11 or CO_2
- HCFC's near azeotropic & HCFC's zeotropic
  - Blends of HCFCs with HFCs
  - Transitional or interim refrigerants, scheduled for restricted production starting in 2004

(* See also: CFCs (The Ozone Hole) http://www.theozonehole.com/cfc.htm)

Refrigerants

- HFC’s azeotropic blends or azeotropic (共沸)
  - Azeotropic = mixture of multiple refrigerants that evaporate & condense as a single substance and do not change in volumetric composition or saturation temperature when evaporate or condense
    - ASHRAE assign numbers R-500 to 599 for azeotropic
  - Such as R-507 (blend of R-125/R-143)
- HFC’s near azeotropic (近共沸)
  - Mixture of refrigerants whose characteristics are near those of an azeotropic
    - ASHRAE assign numbers R-400 to 499 for zeotropic
  - Such as R-404A (R-125/R-134a/R-143a) and R-407B (R-32/R-125/R-134a)

Refrigerants

- Zeotropic or non-azeotropic (非共沸)
  - Including near azeotropic
  - Show a change in composition due to the difference between liquid & vapour phases, leaks, and the difference between charge & circulation
  - A shift in composition causes change in evaporating & condensing temperature/pressure
  - Middle between dew point & bubble point is often taken as evap. & cond. temp. for the blends

Refrigerants

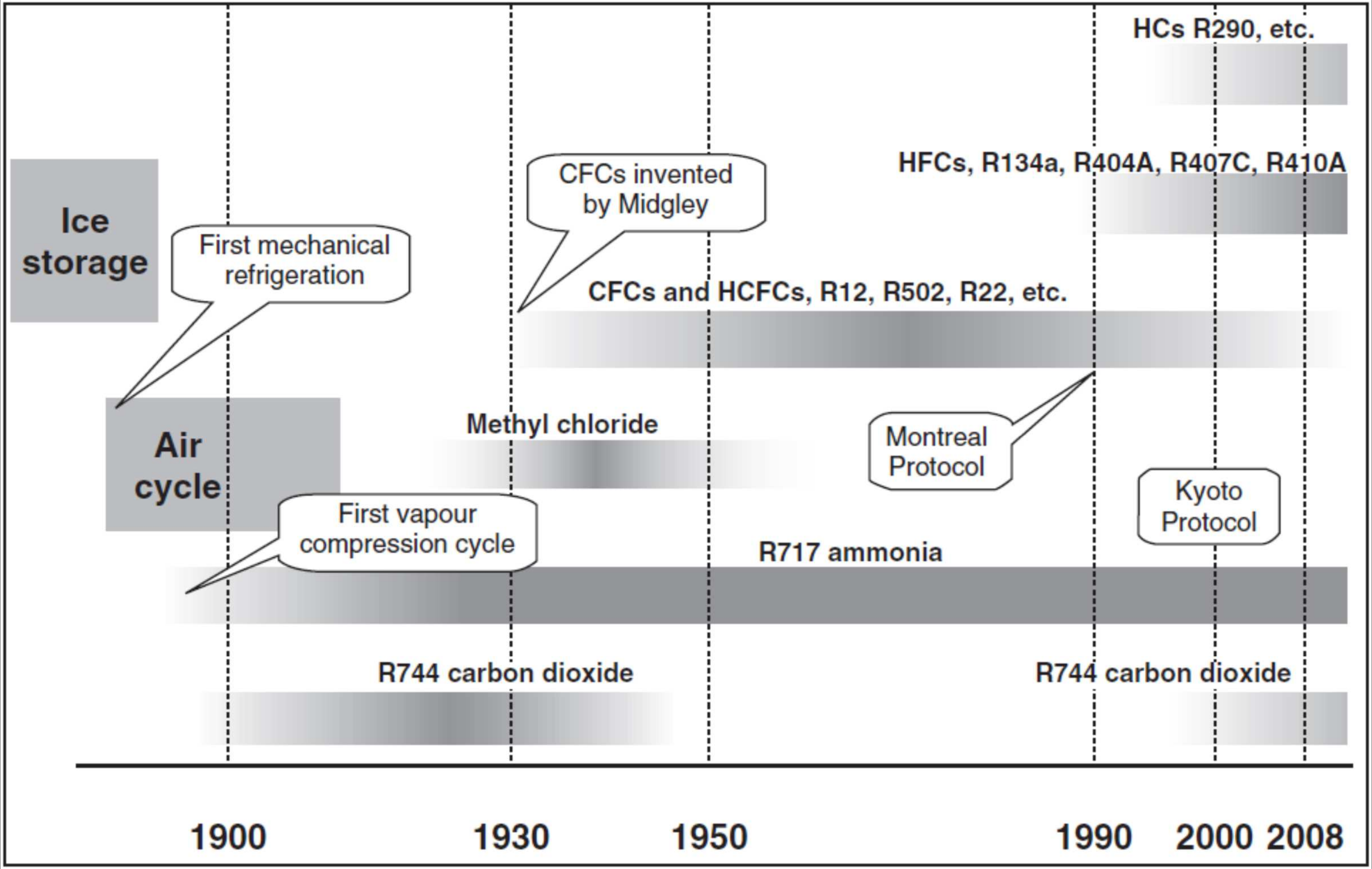
- Inorganic compounds
  - ASHRAE assign numbers R-700 to -799
    - Ammonia (NH_3) R-717, carbon dioxide (CO_2) R-744, air R-729, water (H_2O) R-718, sulphur dioxide (SO_2) R-764
  - Natural refrigerant, do not deplete ozone layer
- CFCs
  - Long lifetime (centuries)
  - Cause ozone depletion (ODP = 0.6 – 1)
  - Such as R-11, R-12, R-113, R-114, R-115

(See also: List of refrigerants - Wikidpedia http://en.wikipedia.org/wiki/List_of_refrigerants)

Refrigerants

- Halons (or BFCs)
  - Contain bromide, fluorine & carbon atoms
  - R-13B1, R-12B1 (used in very low temp. systems)
  - Very high ozone depletion (ODP for R-13B1 =10)
- Montreal Protocol (1987) & Vienna Convention (1985)
  - Restrict the production & consumption of CFCs & BFCs
  - Phase-out of CFCs, BFCs, HCFCs and their blends

Time line for refrigerants



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

Selection of Refrigerants

- Concerns of each application are different, e.g. transport, large chiller, small air-conditioner, industrial plant, refrigerator/freezer
  - Important practical issues e.g. system design, size, initial and operating costs, safety, reliability, and serviceability etc. depend very much on the type of refrigerant selected
- Environmental issues such as ODP and GWP and their relation to the refrigerants used

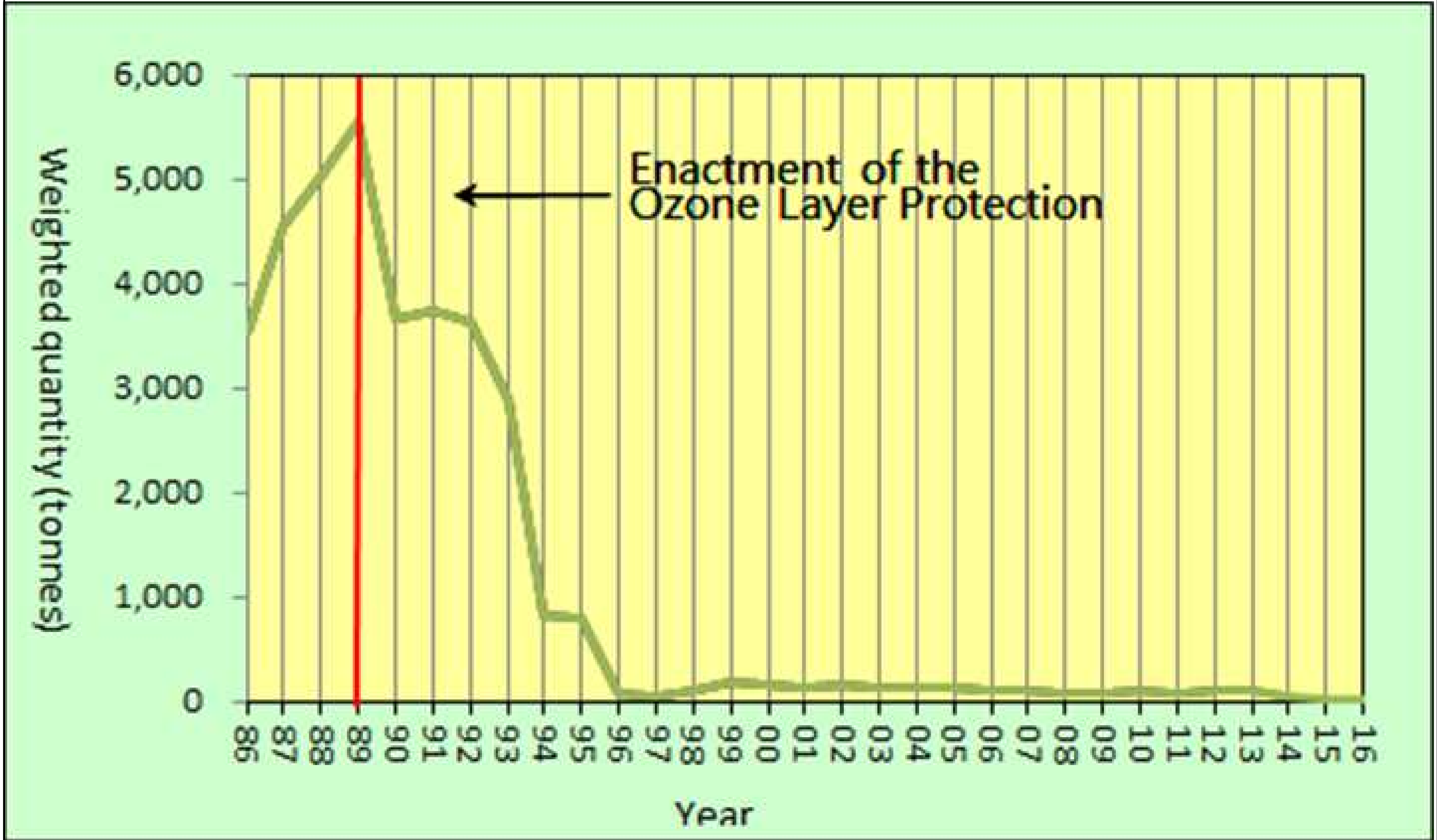
Selection of Refrigerants

- Selection of refrigerant for a particular application is based on the following requirements:
  - 1. Thermodynamic and thermo-physical properties
    - Such as suction/discharge pressure, isentropic index
  - 2. Environmental and safety properties
    - Such as ODP, GWP, toxicity, flammability
  - 3. Economics
    - Inexpensive and easily available

Selection of Refrigerants

- In early 1990s
  - R-11: widely used for centrifugal chillers
  - R-12: for small & medium systems
  - R-22: for all vapour compression systems
  - R-502 (CFC/HCFC blend) for low-temp. systems
- Hong Kong
  - Ozone Layer Protection Ordinance
    - See website of Environmental Protection Dept. http://www.epd.gov.hk/epd/english/environmentinhk/air/ozone_layer_protection/wn6_info.html

Import of ozone depleting substances in Hong Kong



(Source: http://www.epd.gov.hk/epd/english/environmentinhk/air/air_maincontent.html)

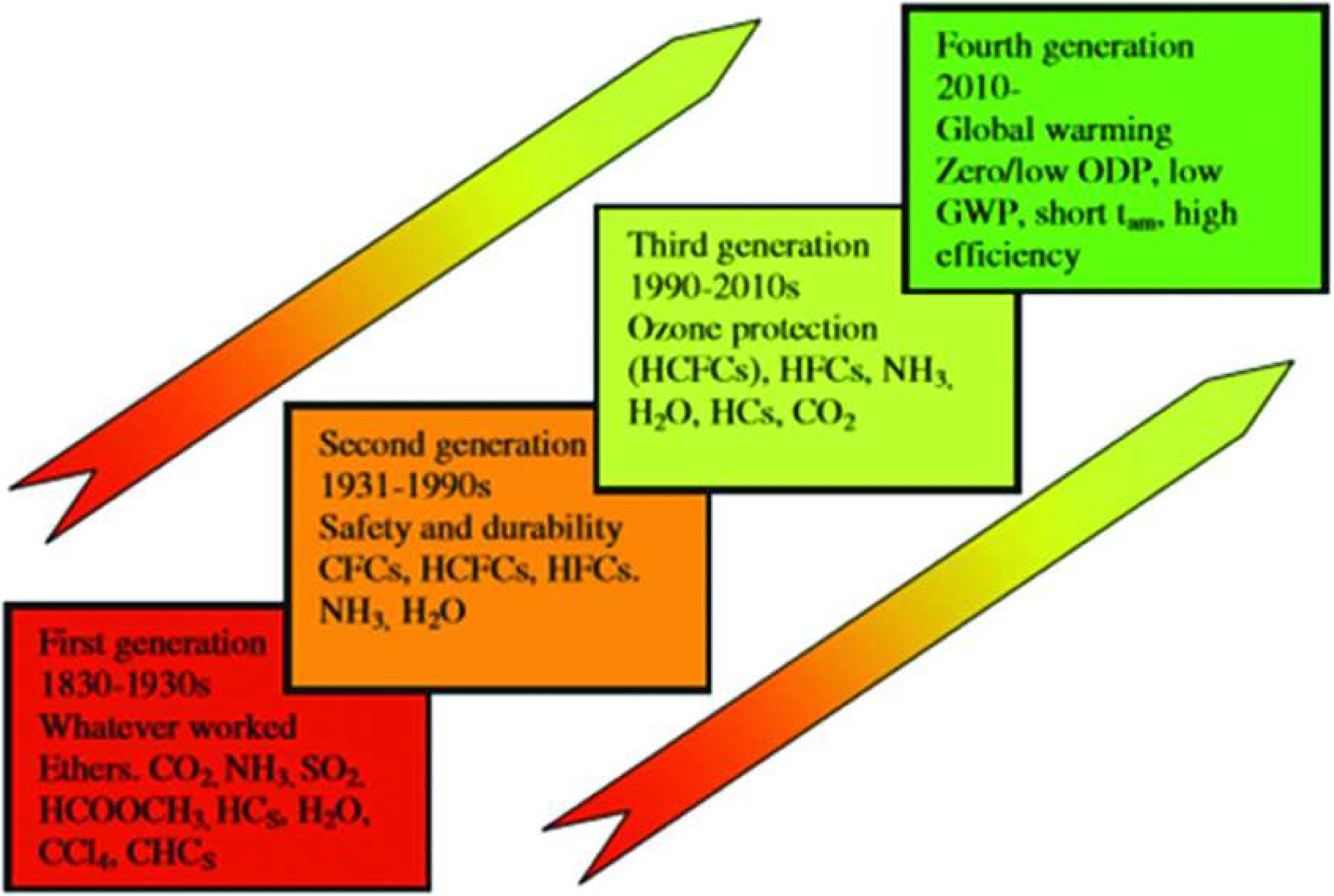
Import banning of products containing HCFCs in phases in Hong Kong

(Source: http://www.epd.gov.hk/epd/english/environmentinhk/air/ozone_layer_protection/wn6_info.html)

Selection of Refrigerants

- Alternative refrigerants (transitional)
  - R-123 (HCFC, ODP = 0.02), replace R-11
    - R-245a (ODP = 0), replace R-11 (longer term?); high GWP
  - R-134a (HFC, ODP = 0), replace R-12
    - Not miscible with mineral oil, synthetic lubricant is used; high GWP
  - R-404A (R-125/R-134a/143a) and R-407C
    - HFCs near azeotropic, ODP = 0; long-term alternatives to R-22
  - R-507 (R-125/R-134a)
    - HFC's azeotropic, ODP = 0; long-term alternatives to R-502
    - Synthetic lubricant oil is used
    - R-402A (R-22/R-125/R-290) as short-term drop-in replacement

Different generations of refrigerants



(Source: http://coolingindia.in/blog/post/id/13925/refrigerants-past-present--future)

Properties of second and third generation refrigerants

Table 2: Properties of second generation refrigerants

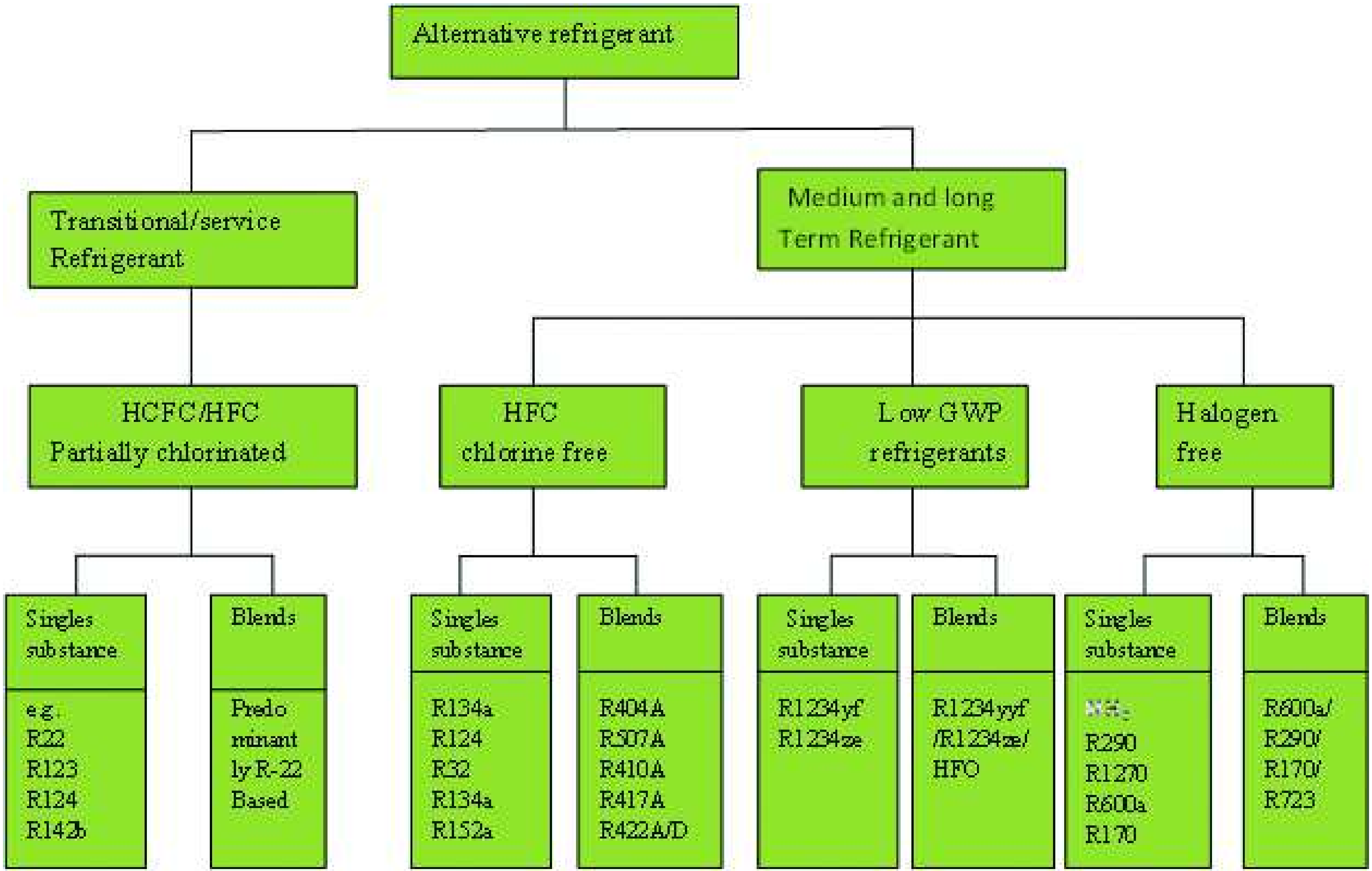
Substance	R Number	M Kg/kmol	NBP (°C)	CRT (°C)	CRP Bar	Safety Group	ODP	GWP
Trichlorofluoromethane	R-11	137.4	23.71	197.96	44.1	A1	1	4000
Dichlorodifluoromethane	R-12	120.91	-29.75	111.97	41.4	A1	1	8500
Chlorotrifluoromthane	R-13	104.5	-81.3	29.2	39.2	A1	1	11700
Chlorodifluoromethane	R-22	86.47	-40.8	96.15	49.9	A1	0.055	1700
R-22/R115	R-502	111.6	-45.3	80.73	40.2	A1	0.33	5600

Table 3: Properties of third generation refrigerants

R number	M Kg/kmol	NBP (°C)	CT (°C)	CP Bar	Temp. glide (°C)	Safety Group	GWP
R-32	-52.02	-51.65	78.11	57.8	0	A2L1	580
R-134A	102.03	-26.07	101.06	40.6	0	A1	1300
R-404A	97.6	-46.6	72.14	37.4	0.46	A1	3800
R-407C	86.2	-43.8	86.05	46.3	5.59	A1	1600
R-410A	72.59	-51.6	70.17	47.7	0.1	A1	1900
R-507	98.86	-47.1	70.75	37.2	0	A1	4000
R-508A	100.1	-87.4	11.01	37.0	0	A1	13000

(Source: http://coolingindia.in/blog/post/id/13925/refrigerants-past-present--future)

Classification of alternative refrigerants

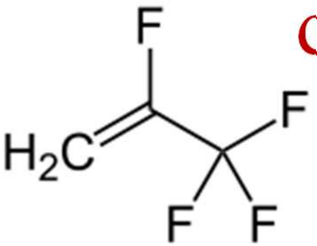


(Source: http://coolingindia.in/blog/post/id/13925/refrigerants-past-present--future)

Selection of Refrigerants

氫氟烯烴

- Hydrofluoroolefins (HFOs) + HFO blends
  - The fourth generation refrigerants; the molecules are named olefins or alkenes
  - Unsaturated HFCs, with at least one carbon-carbon double bond, such as:
    - R-1234yf: for automotive air conditioning (replace R-134a)
    - R-1234ze: for large chillers (replace R-134a, R-404a)
    - R-1233zd: for industrial HVAC & buildings (replace R-123)
  - Zero OZP, low GWP that reduce environmental impact while offering energy efficiency

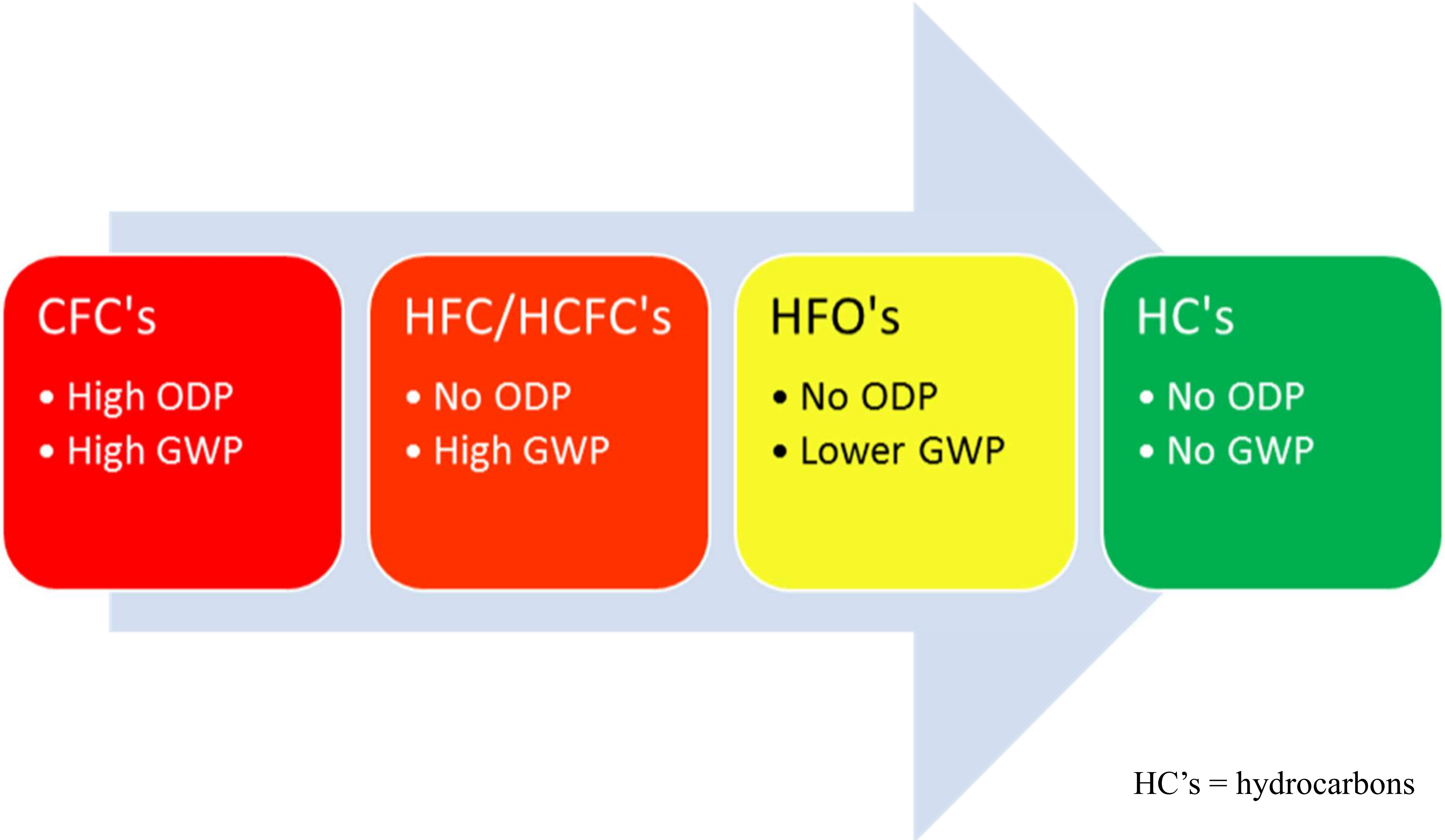


(* See also: HFO refrigerants explained - KTH http://www.kth.se/en/itm/inst/energiteknik/forskning/ett/projekt/koldmedier-med-lag-gwp/low-gwp-news/nagot-om-hfo-koldmedier-1.602602)

Selection of Refrigerants

- Natural refrigerants
  - Such as ammonia (NH_3, R-717) carbon dioxide (CO_2, R-744), and propane (R-290)
  - Advantages:
    - Environmentally friendly, high volumetric efficiency
  - Drawbacks:
    - Danger of suffocation, high pressure, toxicity, flammability, explosion risk
  - High safety standard is needed
    - Safety standards can differ between regions and countries

Evolution of alternative refrigerants



HC's = hydrocarbons

(Source: http://www.vtechonline.com/r448a-r449a-r513a-refrigerant-charging.html)

Selection of Refrigerants

- Required properties of refrigerants
  - Safety (ANSI/ASHRAE Standard 34)
    - Toxicity: Class A (lower) and Class B (higher)
    - Flammability:
      - Class 1 – no flame propagation
      - Class 2 – lower flammability
      - Class 3 – higher flammability
    - Such as “A1” Group: R-134a & R-22; “B2”: ammonia
  - Effectiveness of refrigeration cycle (kW/TR)
  - Lubricant oil miscibility
  - Compressor displacement

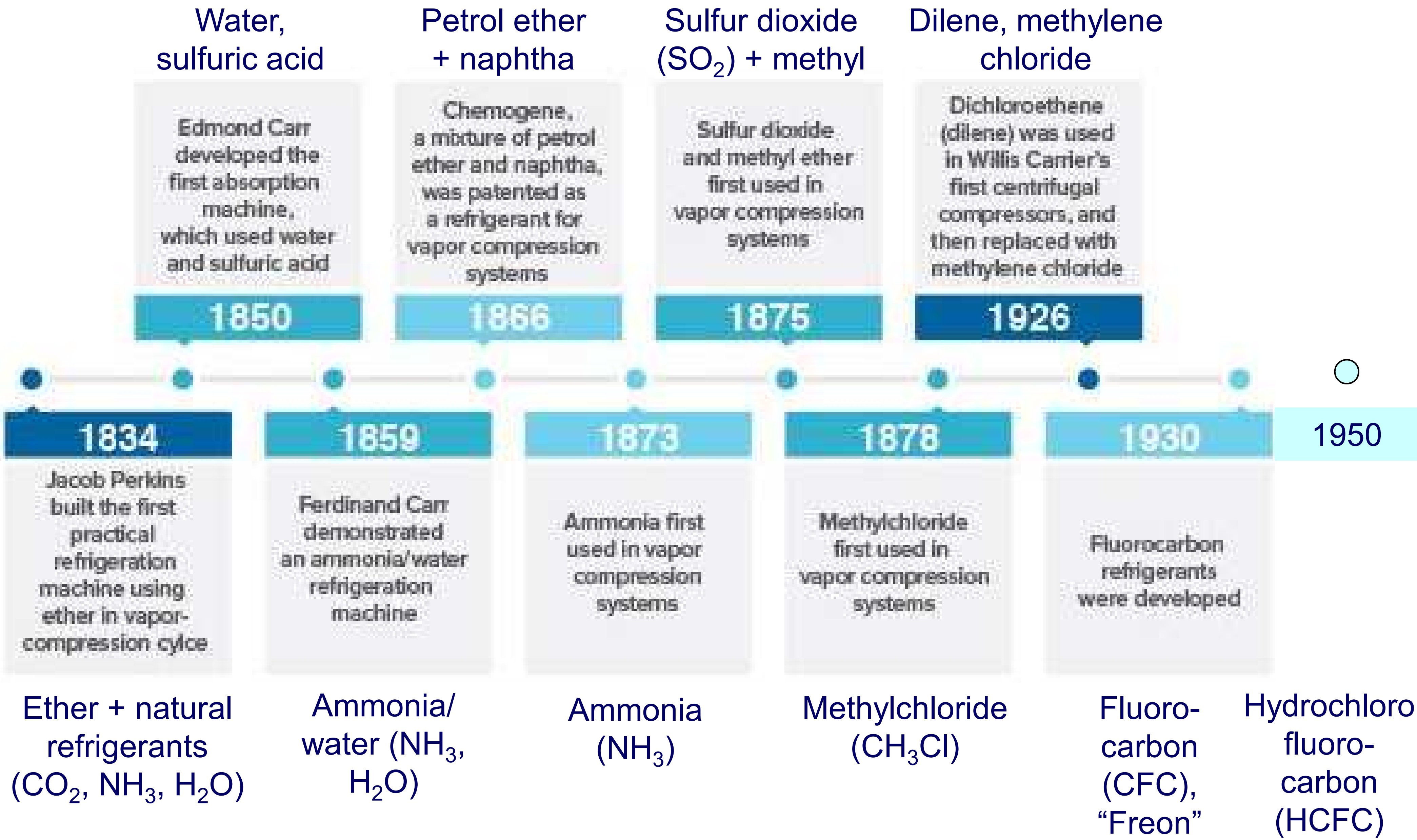
Selection of Refrigerants

- Desired properties:
  - Evaporative pressure > atmospheric
    - Non-condensable gas will not enter the system
  - Lower condensing pressure (lighter construction)
  - High thermal conductivity (better heat transfer)
  - Dielectric constant compatible w/ air
  - An inert refrigerant (avoid corrosion, erosion)
  - Refrigerant leakage can be detected

HVAC refrigerant cylinders: All refrigerant canisters are expected to sport a uniform colour by 2020. *Do you know why?*

(Source: http://www.achrnews.com/articles/133531-hvac-refrigerant-cylinders-are-over-the-rainbow)

Timeline of refrigerant history (nearly all of the historically used refrigerants were flammable, toxic, or both)



(Source: Refrigerant Safety (US-EPA) http://www.epa.gov/snap/refrigerant-safety)

Refrigerant safety classification from ASHRAE Standard 34

	lower toxicity	higher toxicity	
higher flammability	A3	B3	LFL ≤ 0.10 kg/m³ or heat of combustion ≥19 000kj/kg
lower flammability	A2	B2	LFL ≤ 0.10 kg/m³ and heat of combustion ≥19 000kj/kg
	A2L*	B2L*	
no flame propagation	A1	B1	no LFL based on modified ASTM E681-85 test
	no identified toxicity at concentrations ≤400 ppm	evidence of toxicity below 400 ppm (based on data for TLV-TWA or consistent indices)	

*A2L and B2L are lower flammability refrigerants with a maximum burning velocity of < 10 cm/s.

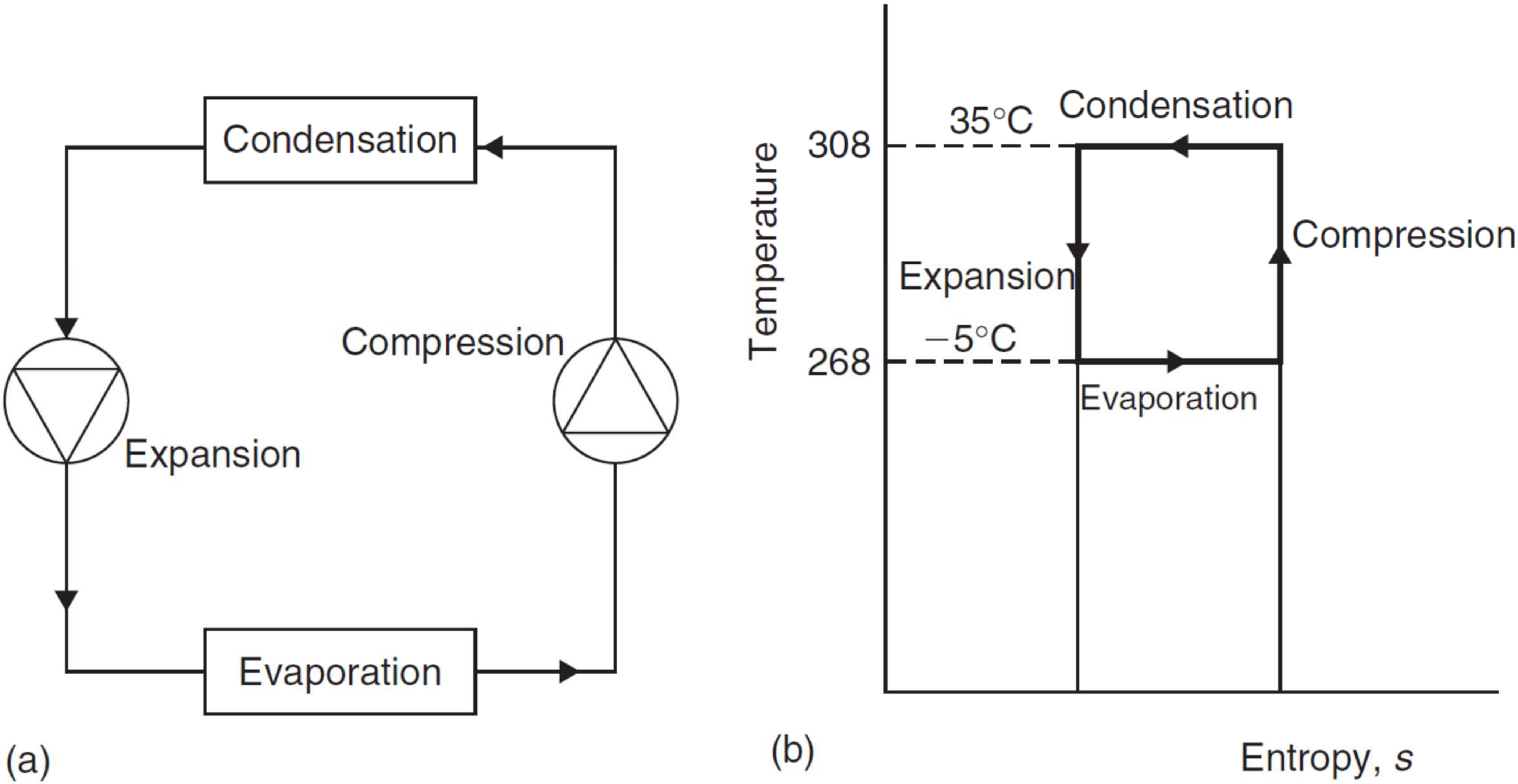
LFL = lower flammability limit; UFL = upper flammability limit; TLV-TWA = threshold limit value-time weighted average

(Source: Refrigerant Safety (US-EPA) http://www.epa.gov/snap/refrigerant-safety)

Refrigeration Cycles

- 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

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

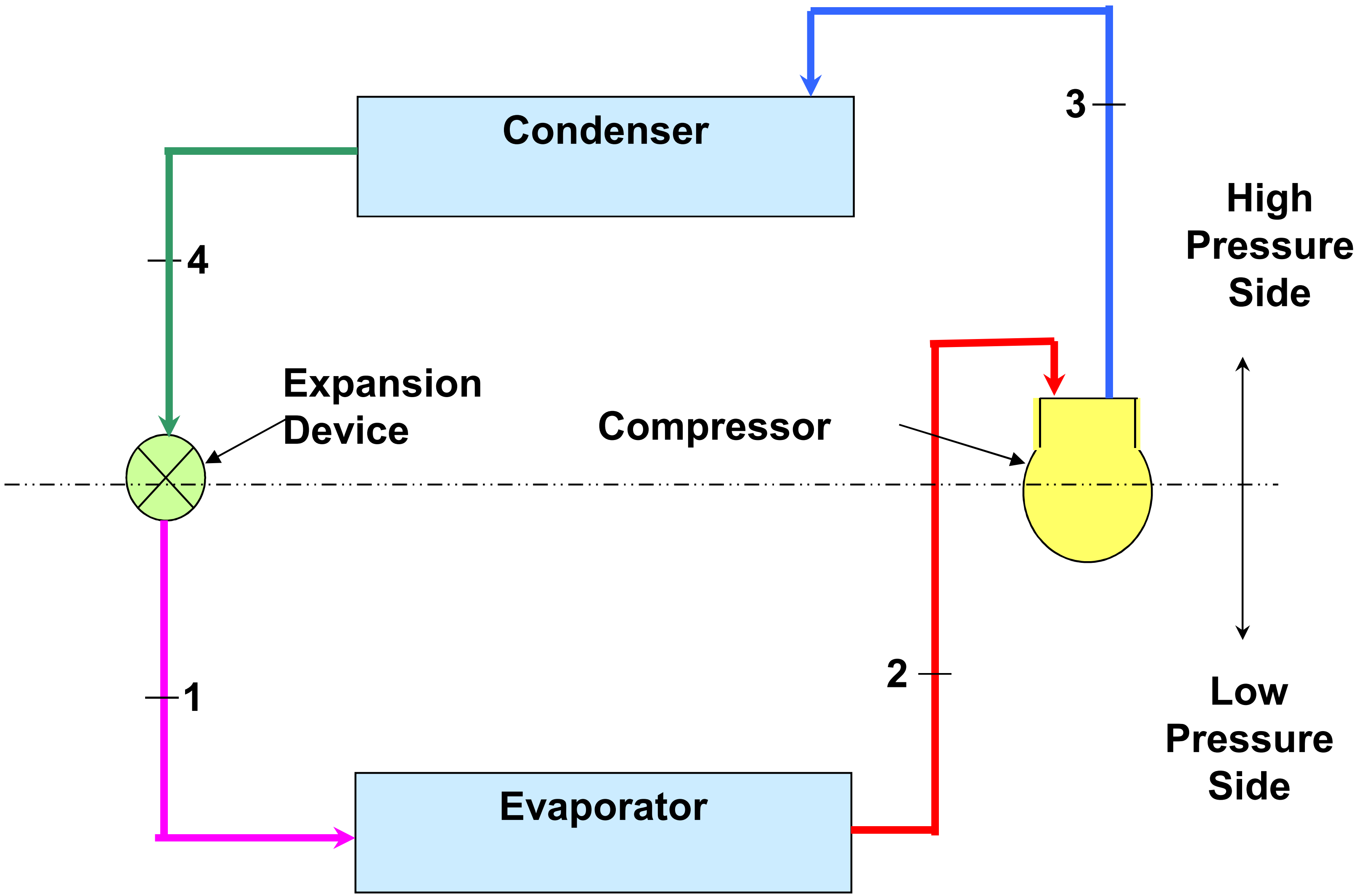


(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

Refrigeration Cycles

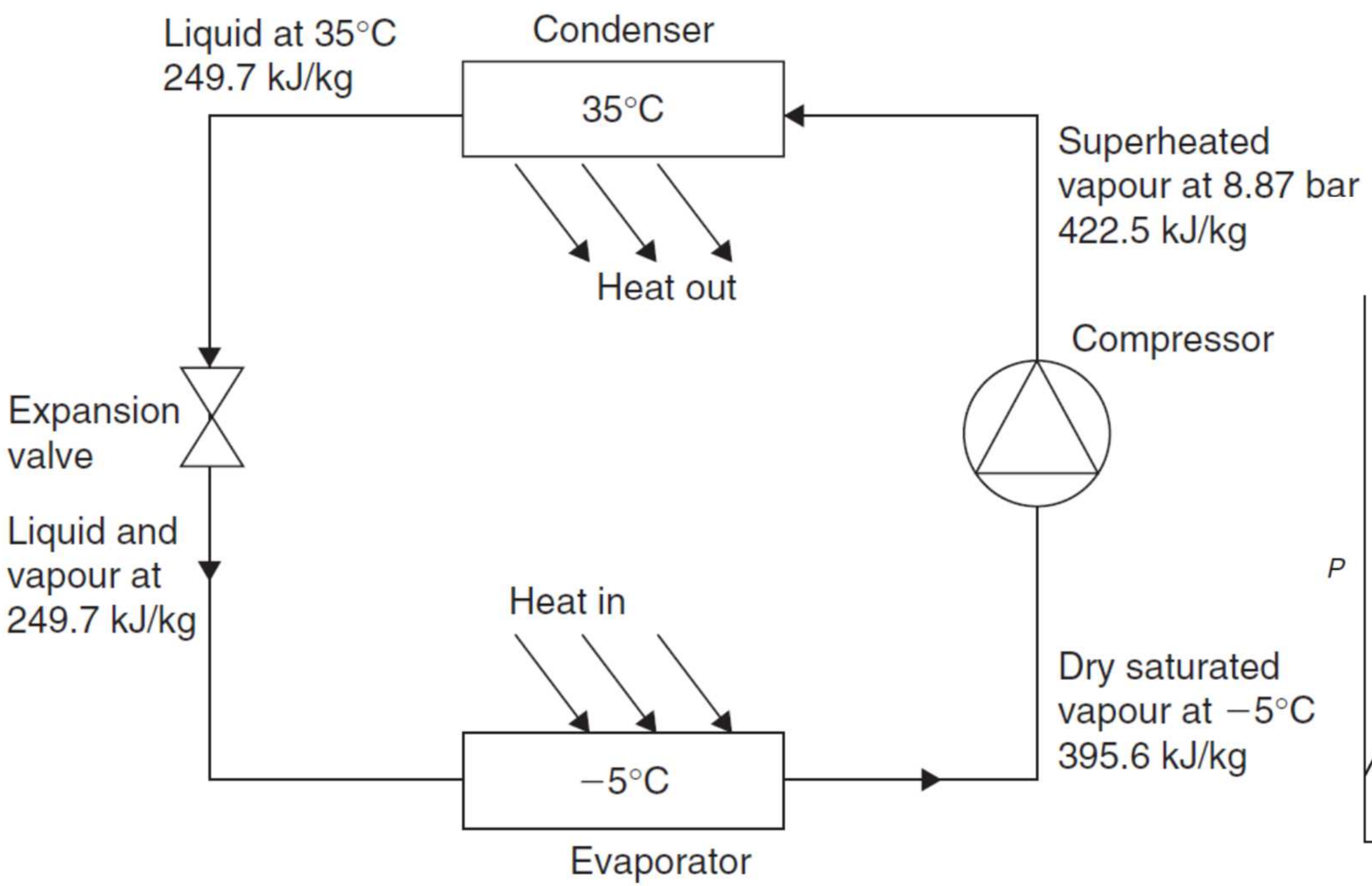
- Ideal single-stage cycle
  - Isentropic compression, pressure losses neglected
  - q_{rf} = refrigeration capacity
  - W_{in} = work input to compressor
- Coefficient of performance (COP)
  - $\text{COP} = q_{rf} / W_{\text{in}}$
    - Refrigerator: produce refrigeration effect
    - Heat pump: produce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

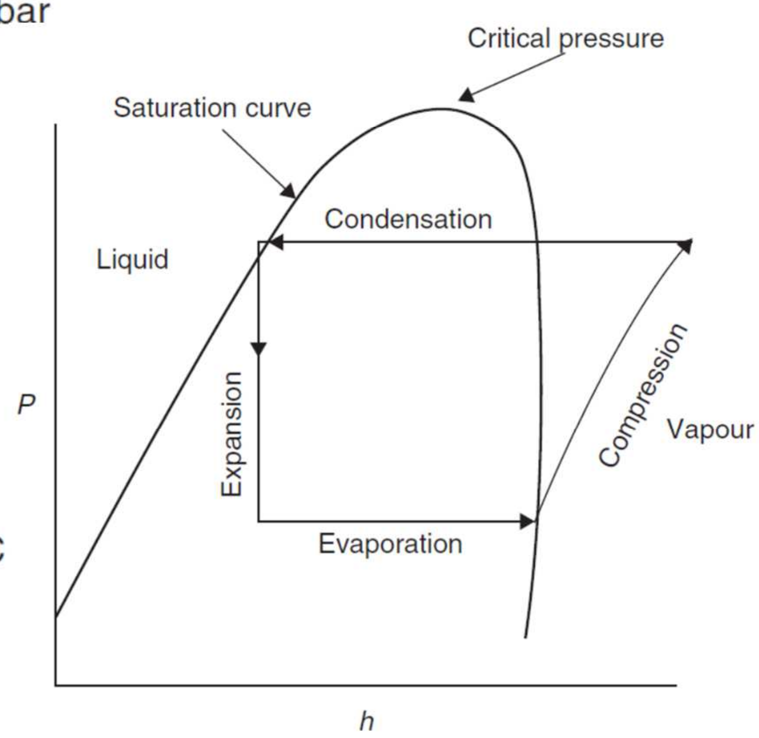
Refrigeration cycle -- vapour compression cycle



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

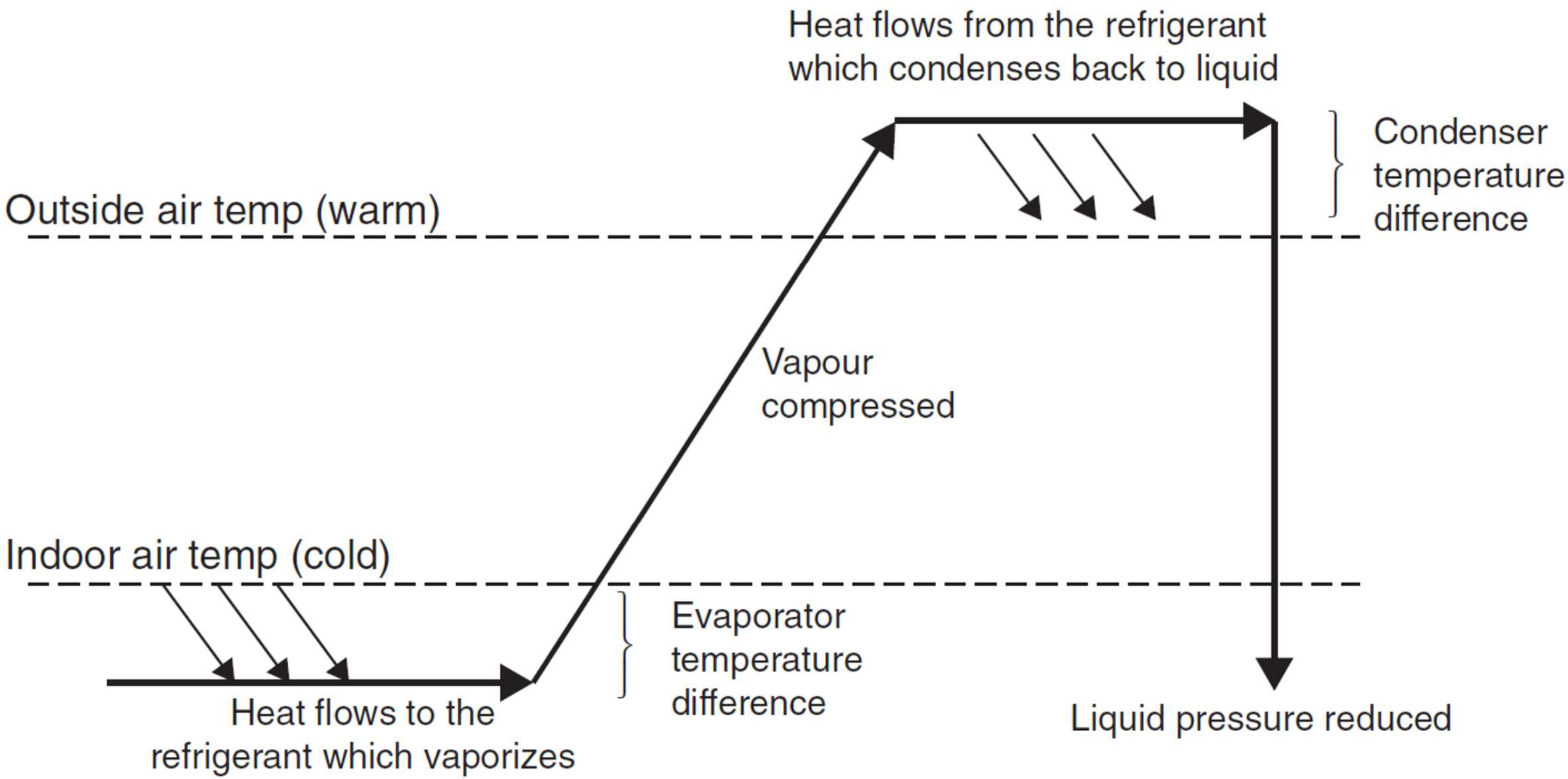
Simple vapour compression cycle with pressure and enthalpy values for R134a





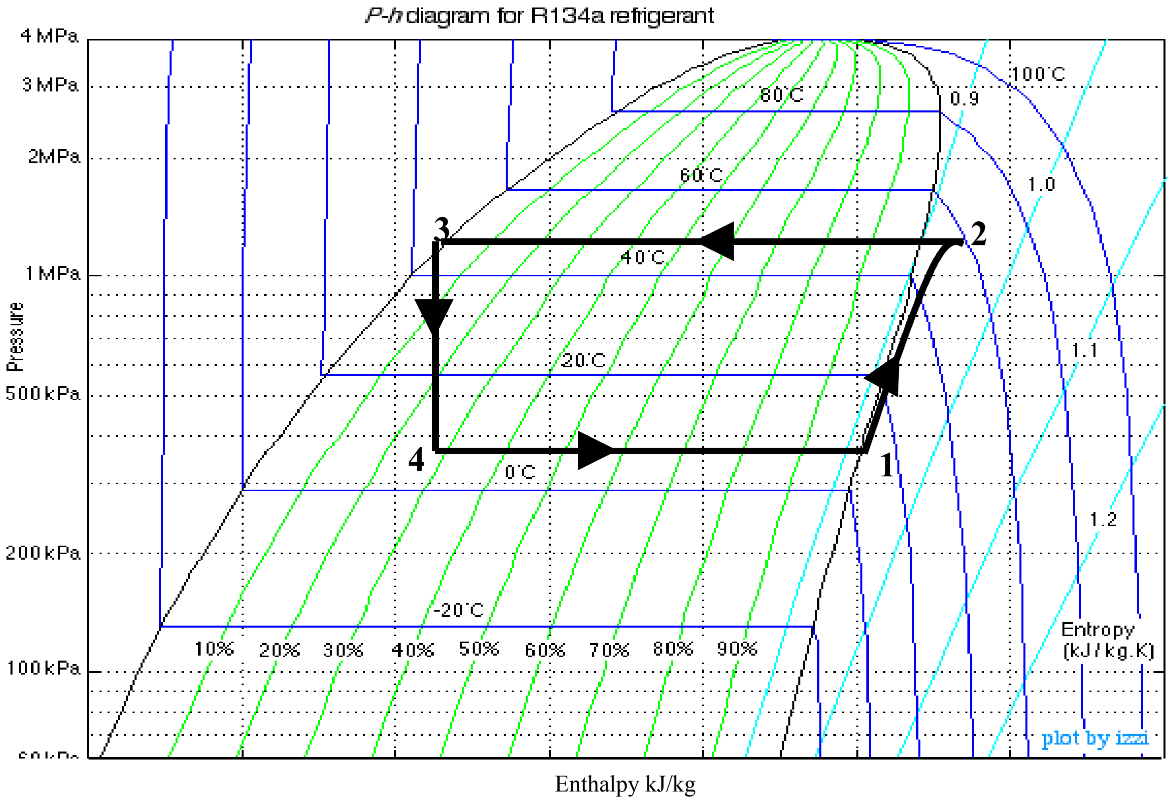
(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

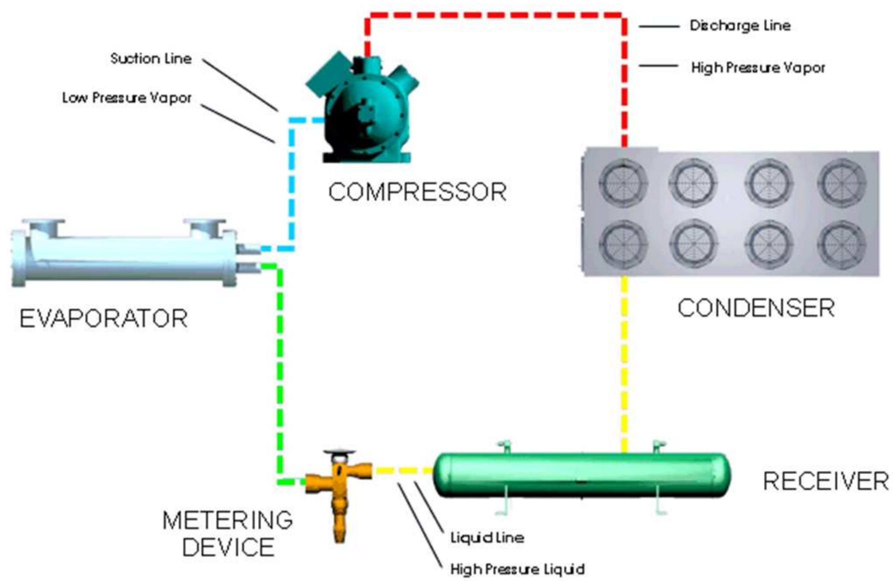
The temperature rise or ' lift ' of the refrigeration cycle is increased by temperature differences in the evaporator and condenser



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

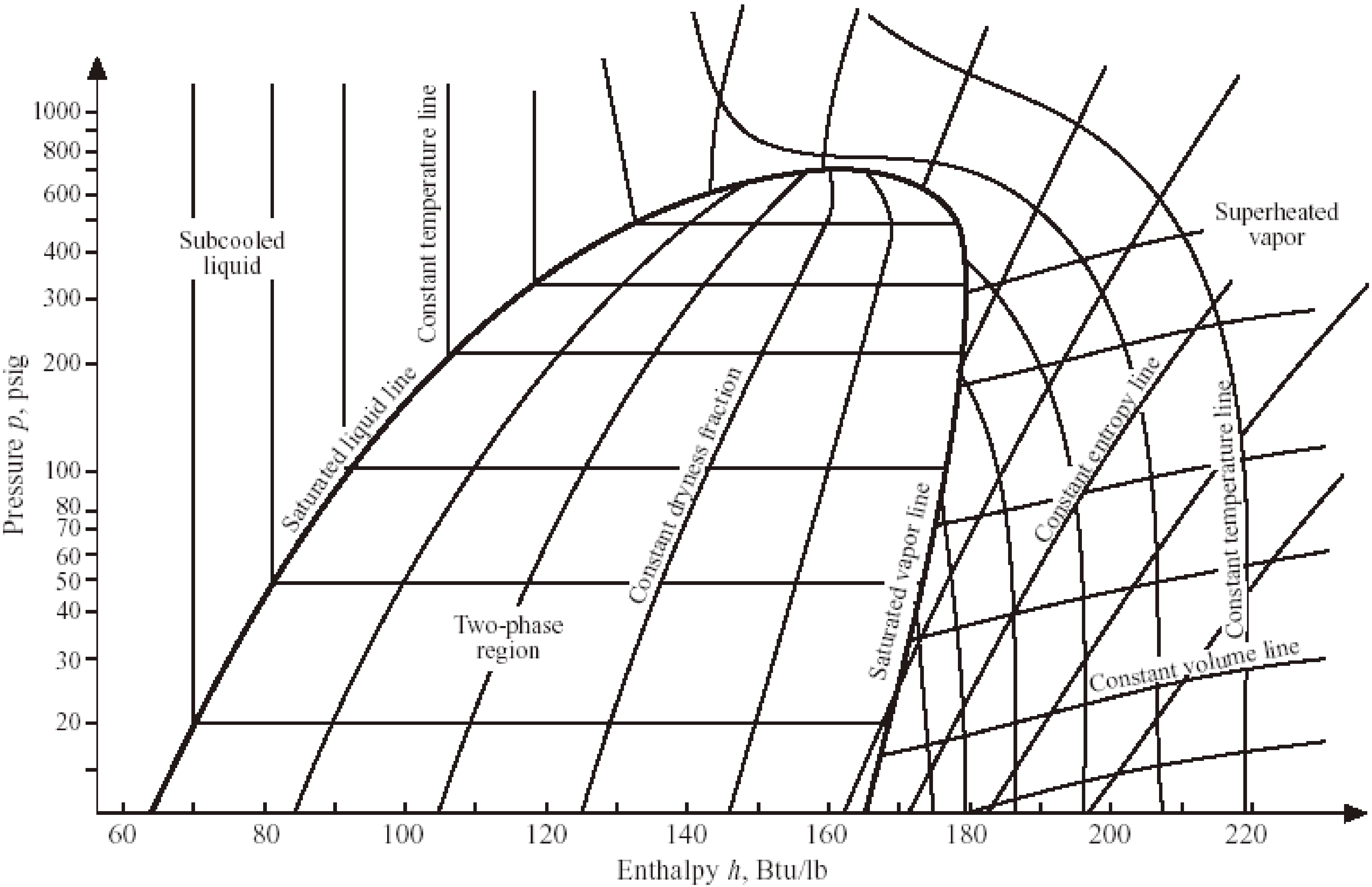
Refrigeration cycle -- vapour compression cycle



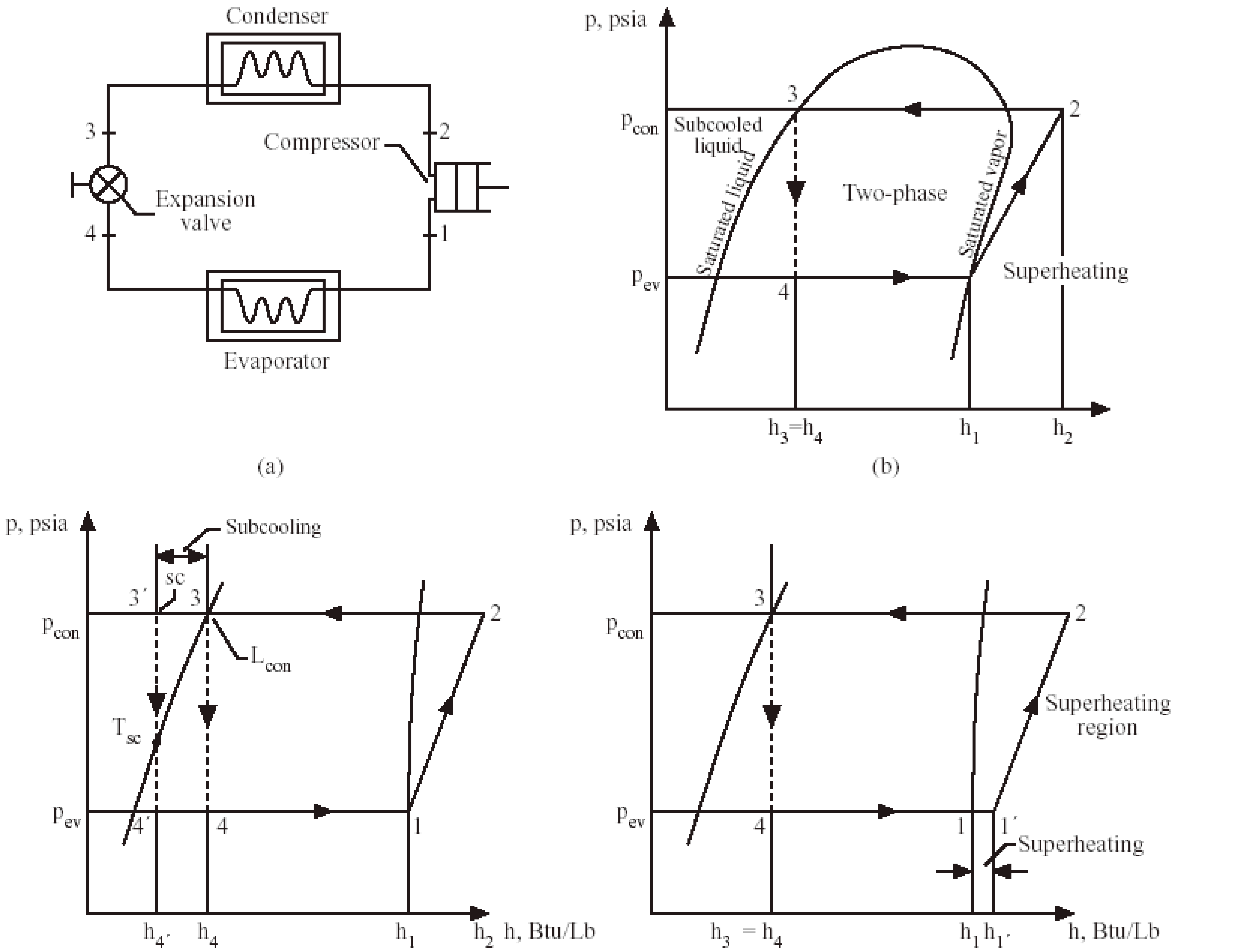


System COP normally includes all the power inputs associated with the system, i.e. fans and pumps in addition to compressor power.
A ratio of System COP to Carnot COP (for the process) is termed *system efficiency index*, SEI.

(See also: Vapour Compression Refrigeration Cycle Calculator http://engr.usask.ca/classes/ME/227/Refrigeration/js/)



Pressure p, psig
1000
800
600
400
300
200
100
80
70
60
50
40
30
20
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
Superheated vapor
Constant entropy line
Constant temperature line
Constant volume line



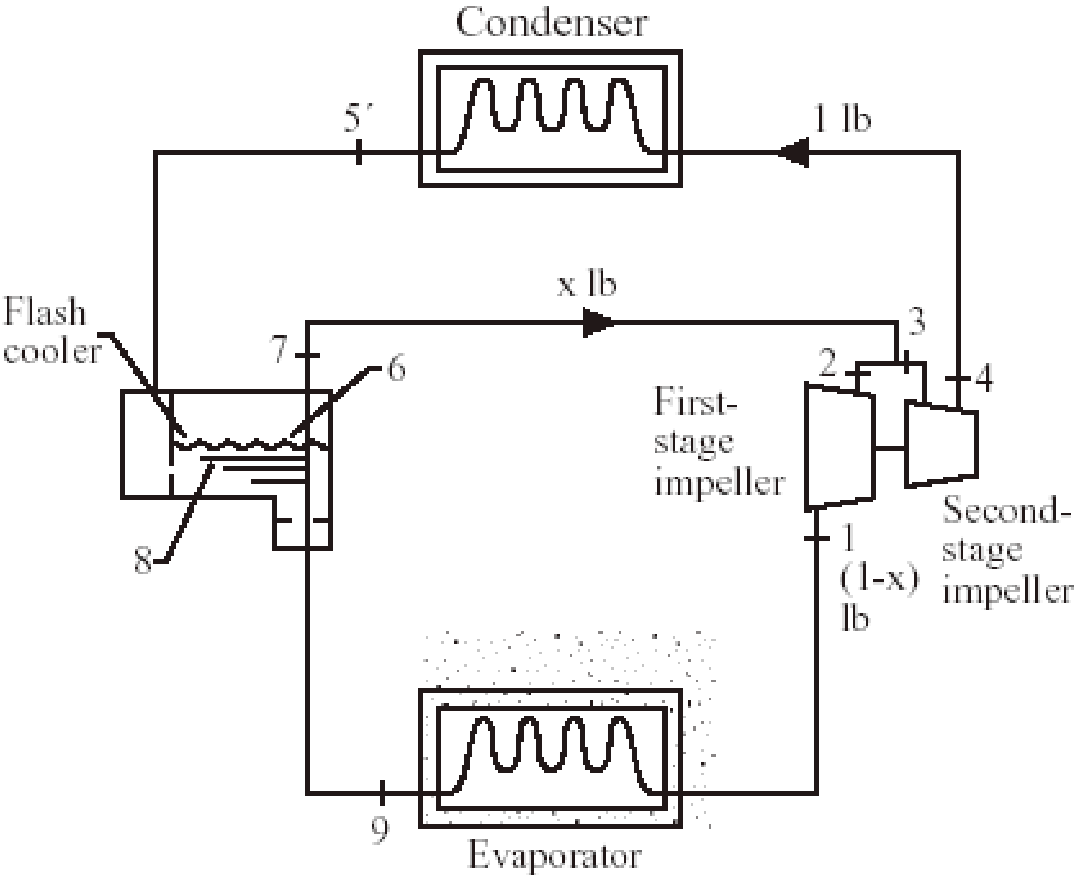
Condenser
Compressor
Expansion valve
Evaporator
3
2
4
1
(a)
p, psia
p_con
p_ev
Subcooled liquid
Saturated liquid
Two-phase
Saturated vapor
Superheating
h_3=h_4
h_1
h_2
(b)
Subcooling
sc
3´
L_con
T_sc
4´
h_4´
h_4
h_1
h_2
h, Btu/Lb
Superheating region
1´
Superheating
h_3 = h_4
h_1 h_1´

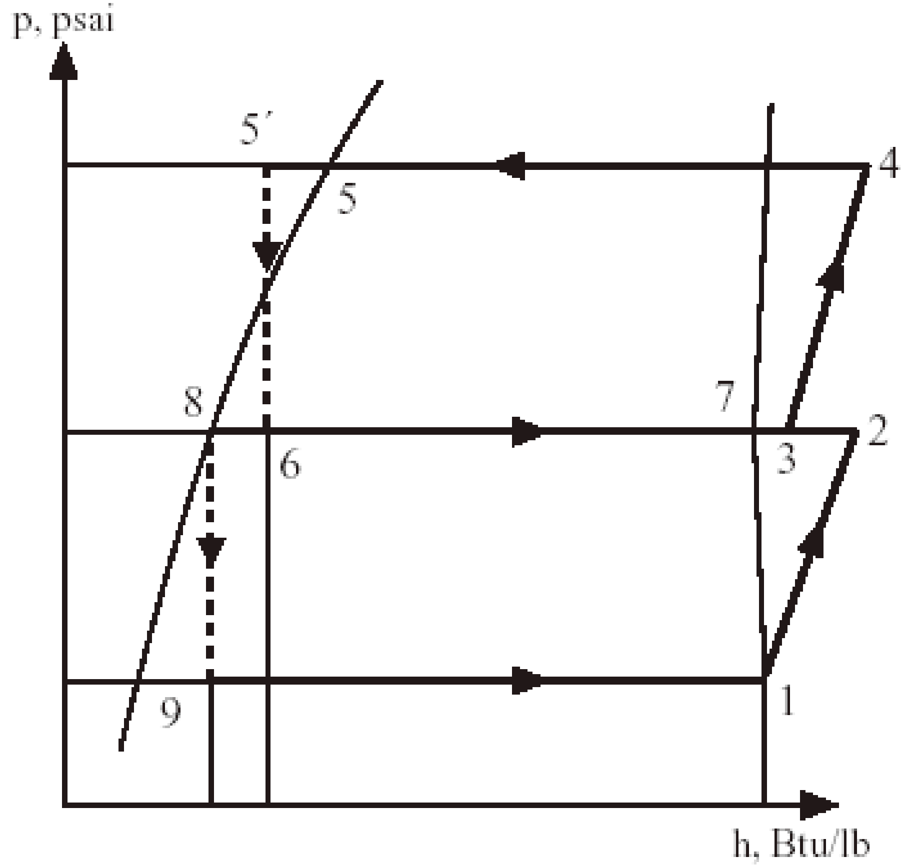
Refrigeration Cycles

- 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

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

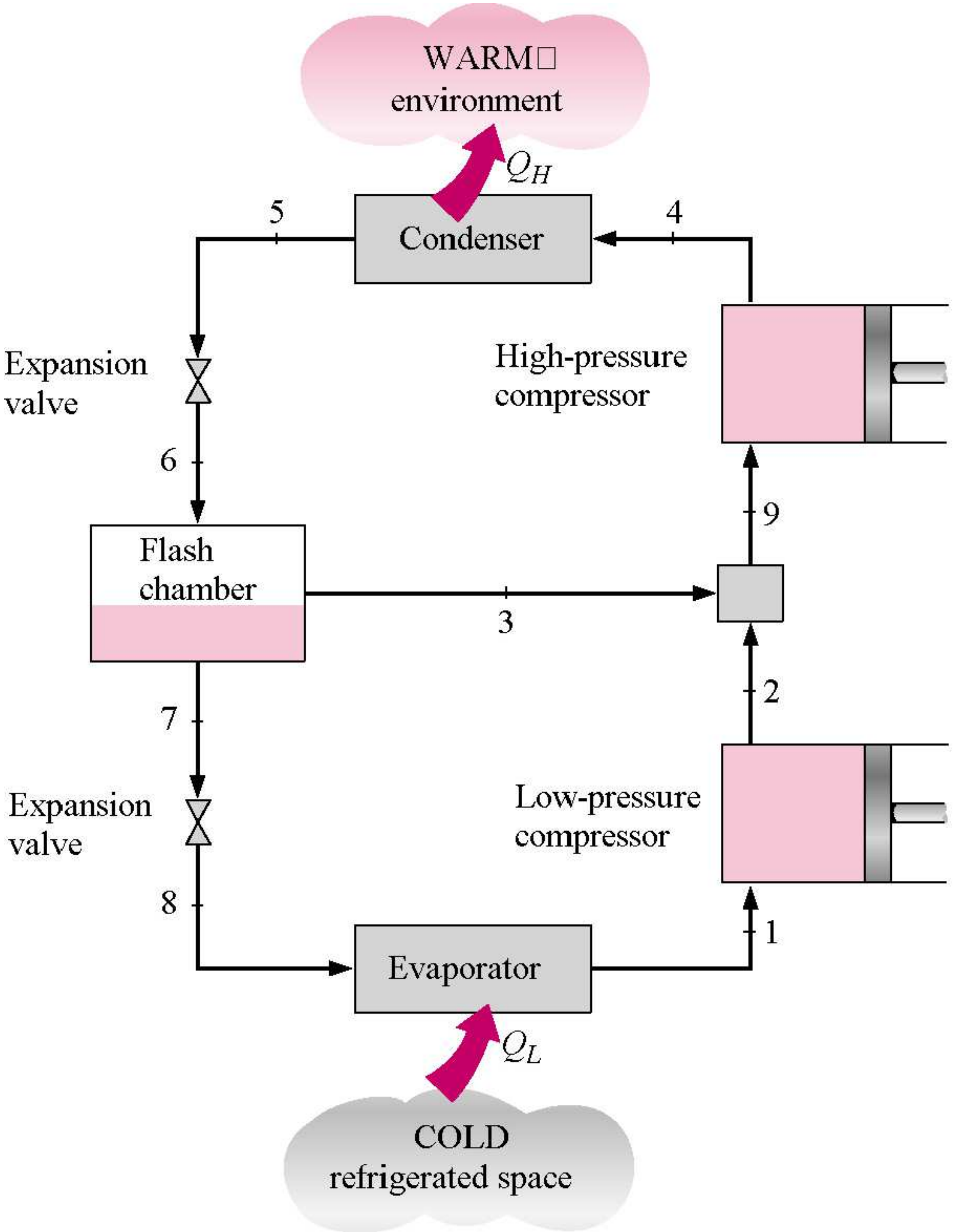
Two-stage compound systems w/ flash cooler

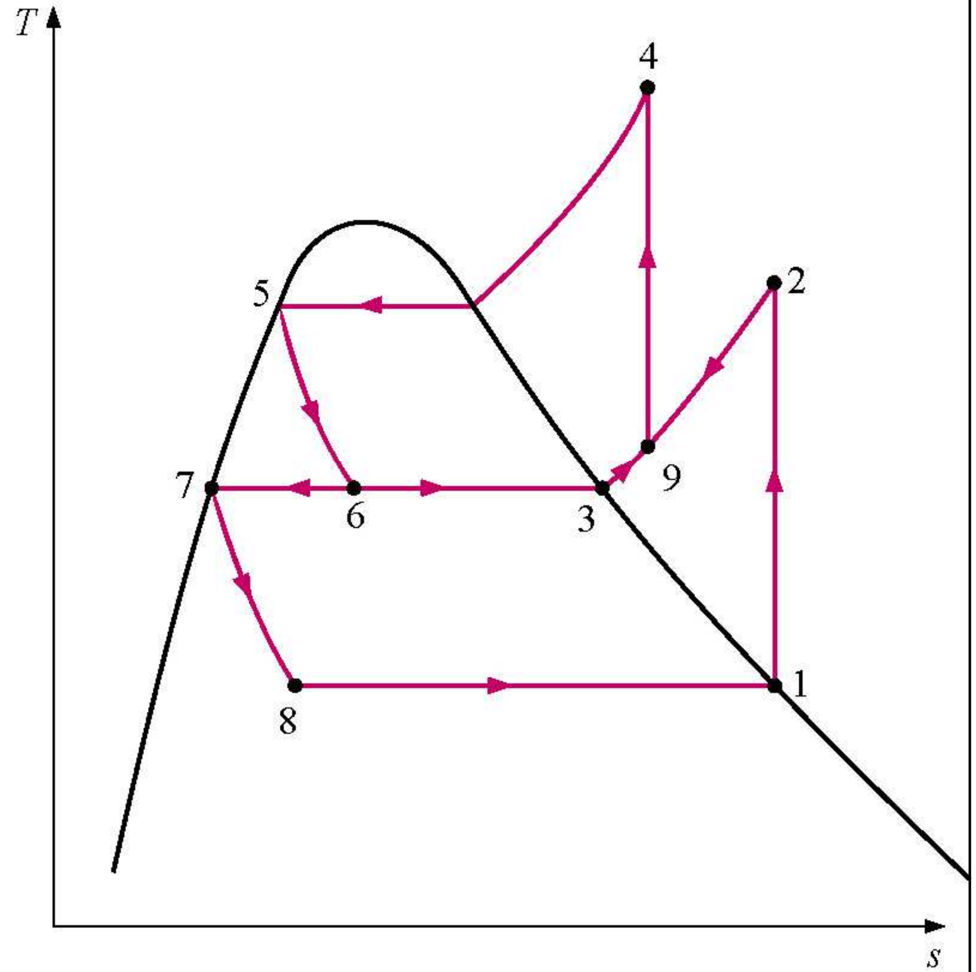




* Where the ratio of suction to discharge pressure is high enough to cause a serious drop in volumetric efficiency or an unacceptably high discharge temperature, vapour compression must be carried out in two or more stages.

Two-stage compound systems and T-s diagram





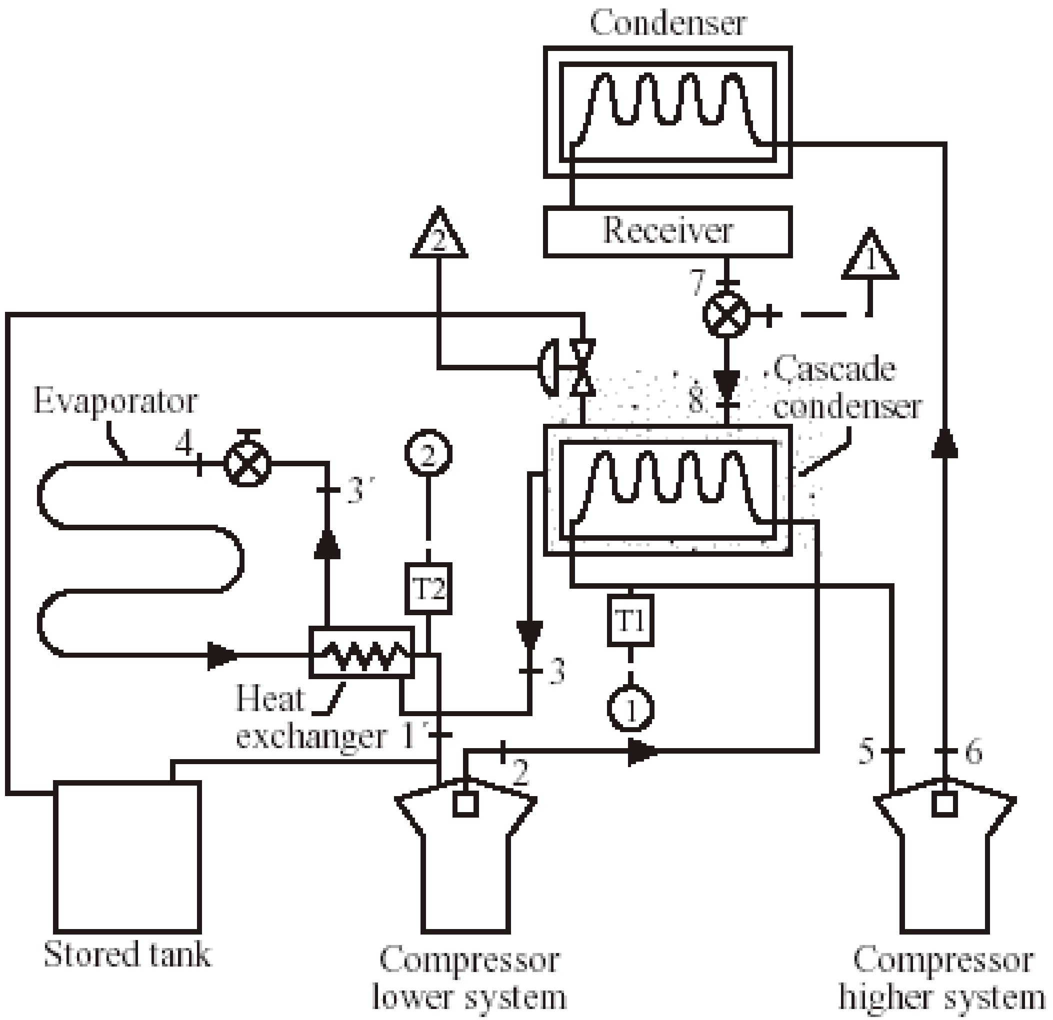
(Source: *Thermodynamics: An Engineering Approach*, 8th edition, by Yunus A. Çengel and Michael A. Boles)

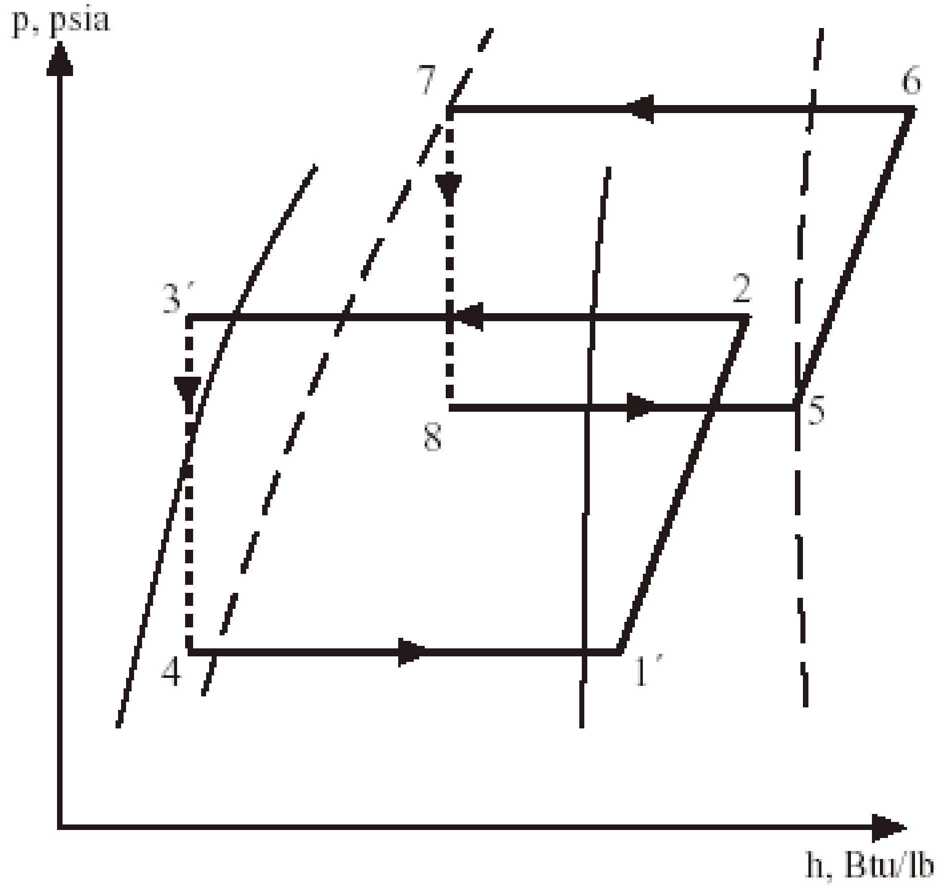
Refrigeration Cycles

- 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

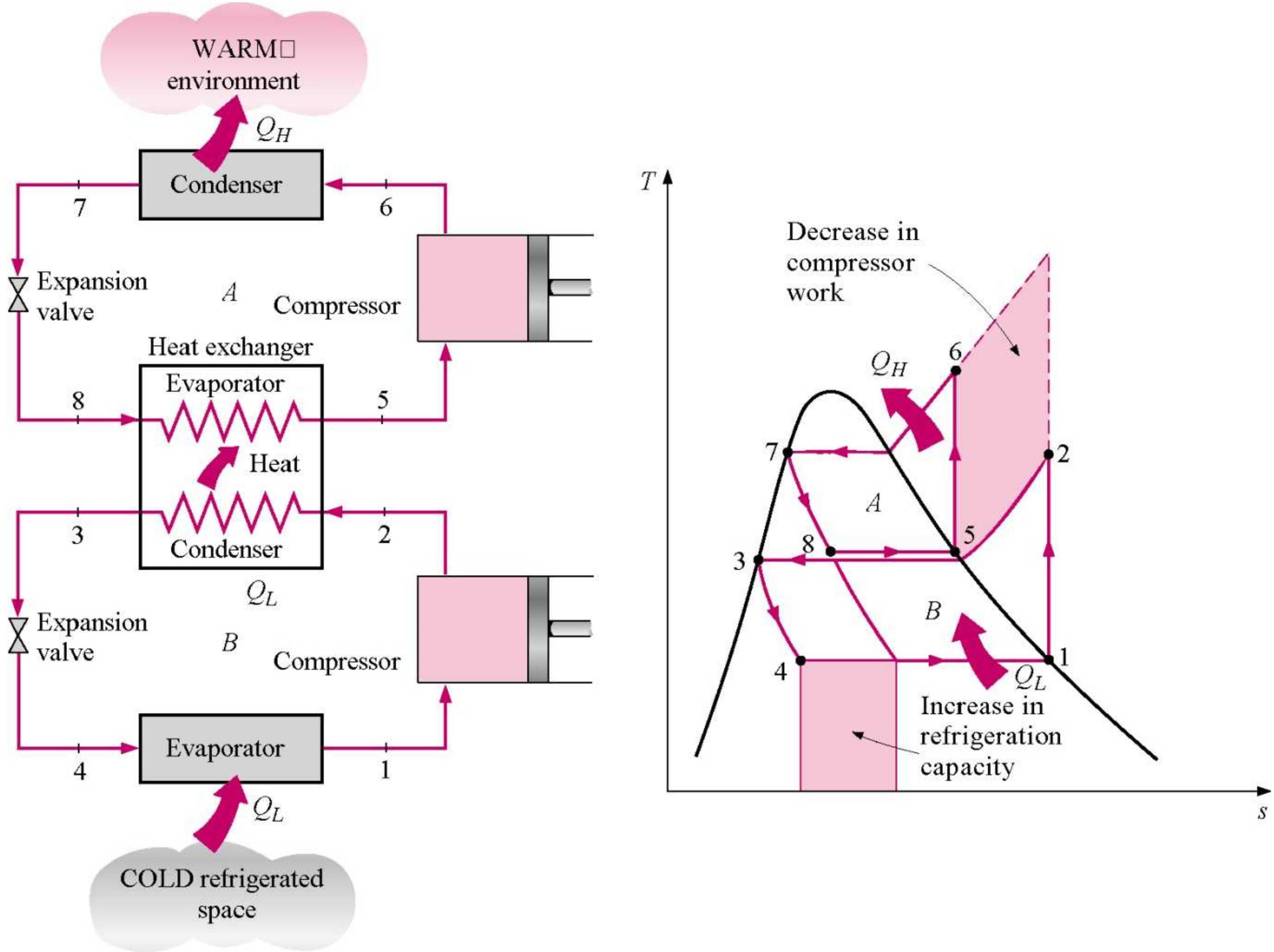
$$\text{COP}_{ref} = \frac{q_{ref}}{W_{\text{in}}} = \frac{\dot{m}_l (h_1 - h_4)}{\dot{m}_l (h_2 - h_{1'}) + \dot{m}_h (h_6 - h_5)}$$

Cascade system and p-h diagram





Cascade system and T-s diagram

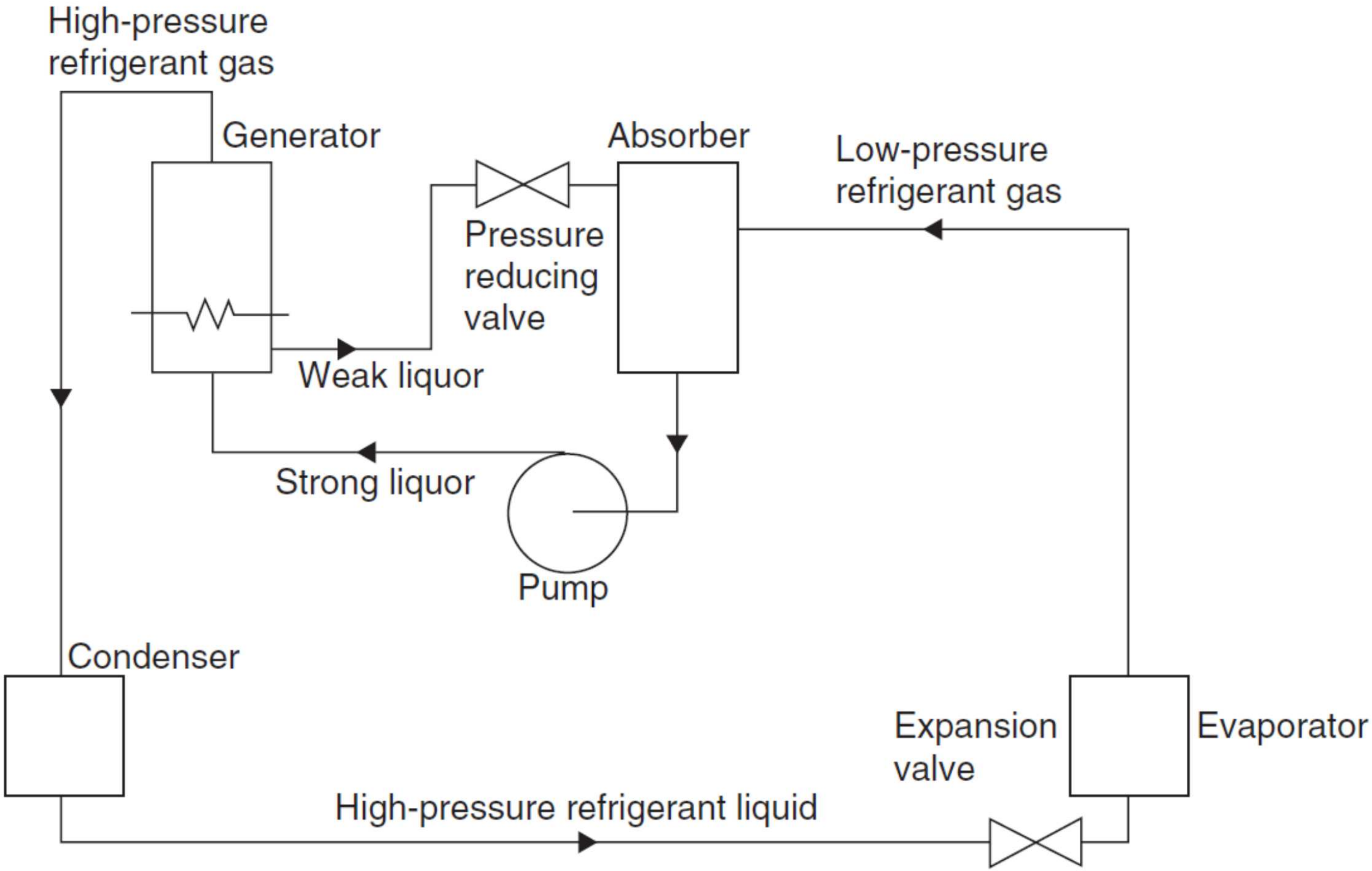


(Source: *Thermodynamics: An Engineering Approach*, 8th edition, by Yunus A. Çengel and Michael A. Boles)

Refrigeration Cycles

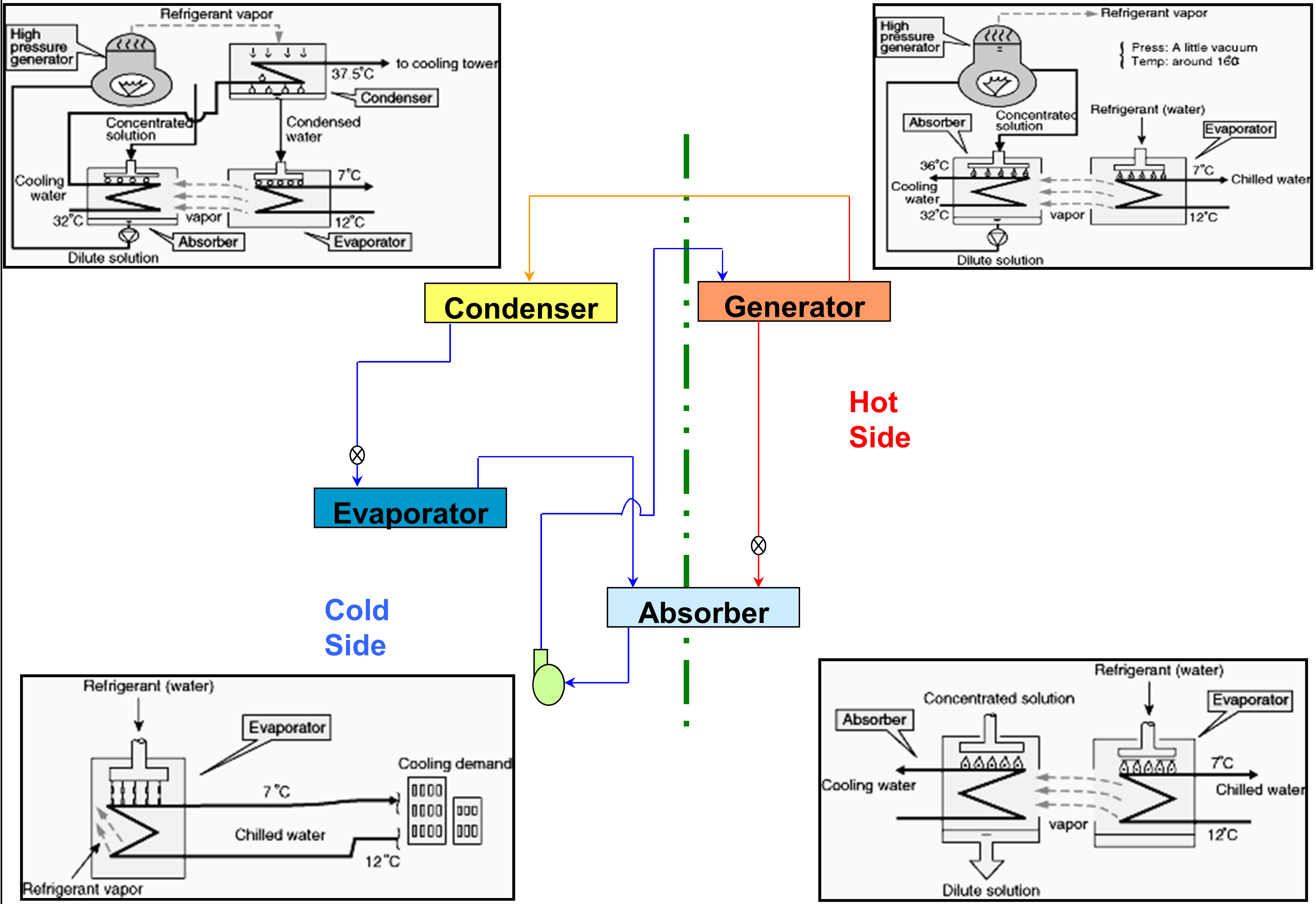
- Absorption cycle
  - Such as ammonia and lithium bromide systems
    - Absorption of ammonia gas into water, and of water vapour into lithium bromide
    - Refrigerant vapour from the evaporator is drawn into the absorber by the liquid absorbant. The liquor is then pumped up to condenser pressure and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

Absorption cycle: basic circuit

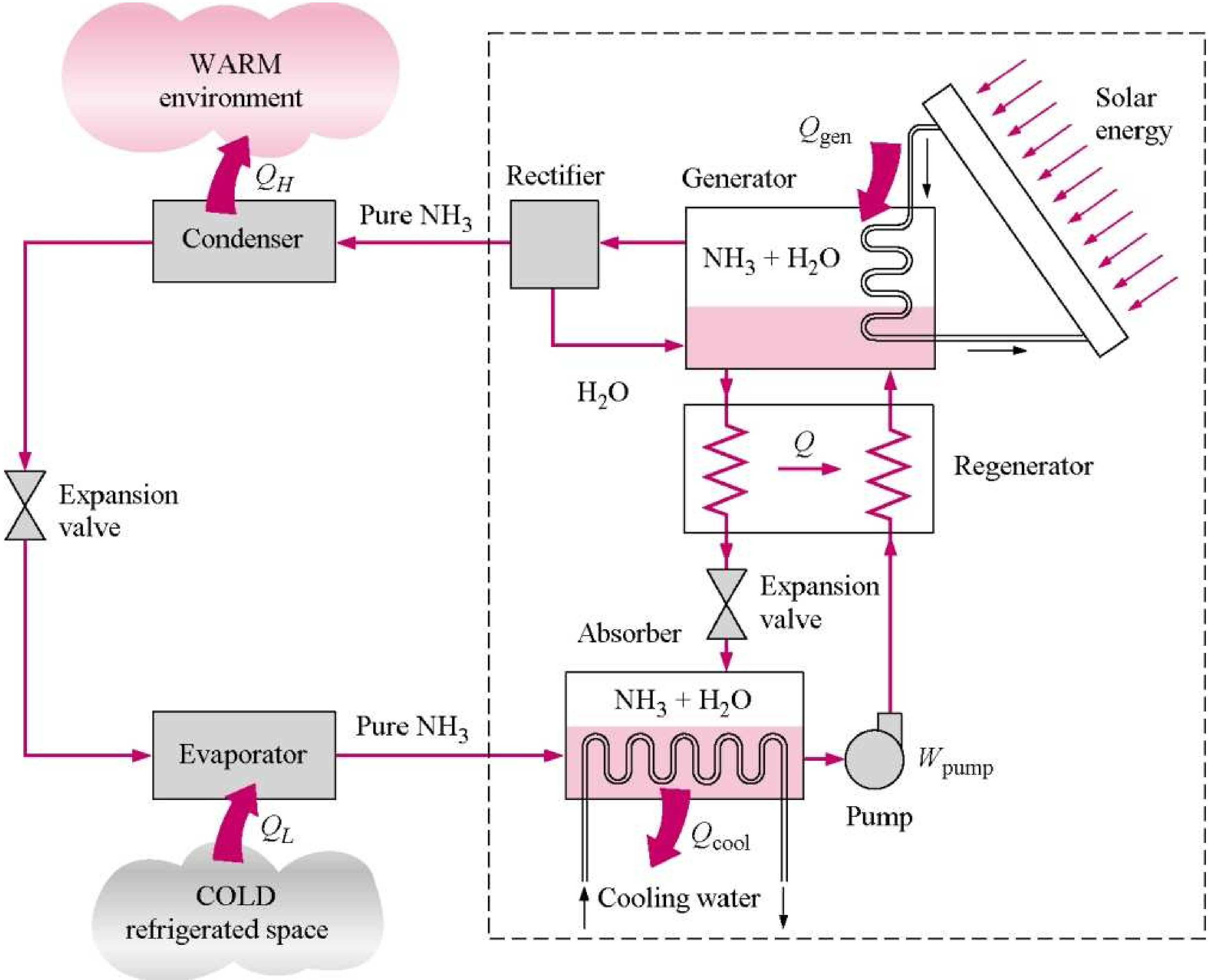


(Source: Hundy, G. F., Trott, A. R. and Welch, T. C., 2008. *Refrigeration and Air-conditioning*, 4th ed.)

Vapour absorption refrigeration

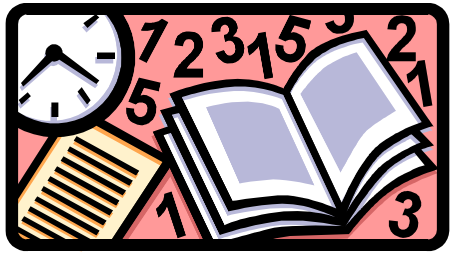


Absorption refrigeration system with solar energy at generator



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

Further Reading



- 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