CH2351 Chemical Engineering Thermodynamics II

Unit – V

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Refrigeration

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Contents

- Principles of refrigeration, methods of producing refrigeration, liquefaction process, coefficient of performance, evaluation of the performance of vapour compression and gas refrigeration cycles.

Introduction

- Refrigeration is the science of producing and maintaining temperatures below that of the surrounding atmosphere.

- Refrigeration is generally produced in one of the following three ways :

  (*i*) By melting a solid ; (*ii*) By sublimation of a solid ; (*iii*) By evaporation of a liquid.

History of Refrigeration

- Ice houses
- 1850s: Vapor compression refrigeration, and vapor absorption refrigeration systems based on ammonia
- 1920s: CFC refrigerants for household use
- 1970s: CFCs were found to react with ozone layer
- 1987: Montreal protocol to phase-out CFCs

Frederic Tudor
The "Ice King" of the World 1830

- The Tudor Ice Company harvested ice in a number of New England ponds for export and distribution throughout the Caribbean, Europe, and India from 1826 to 1892

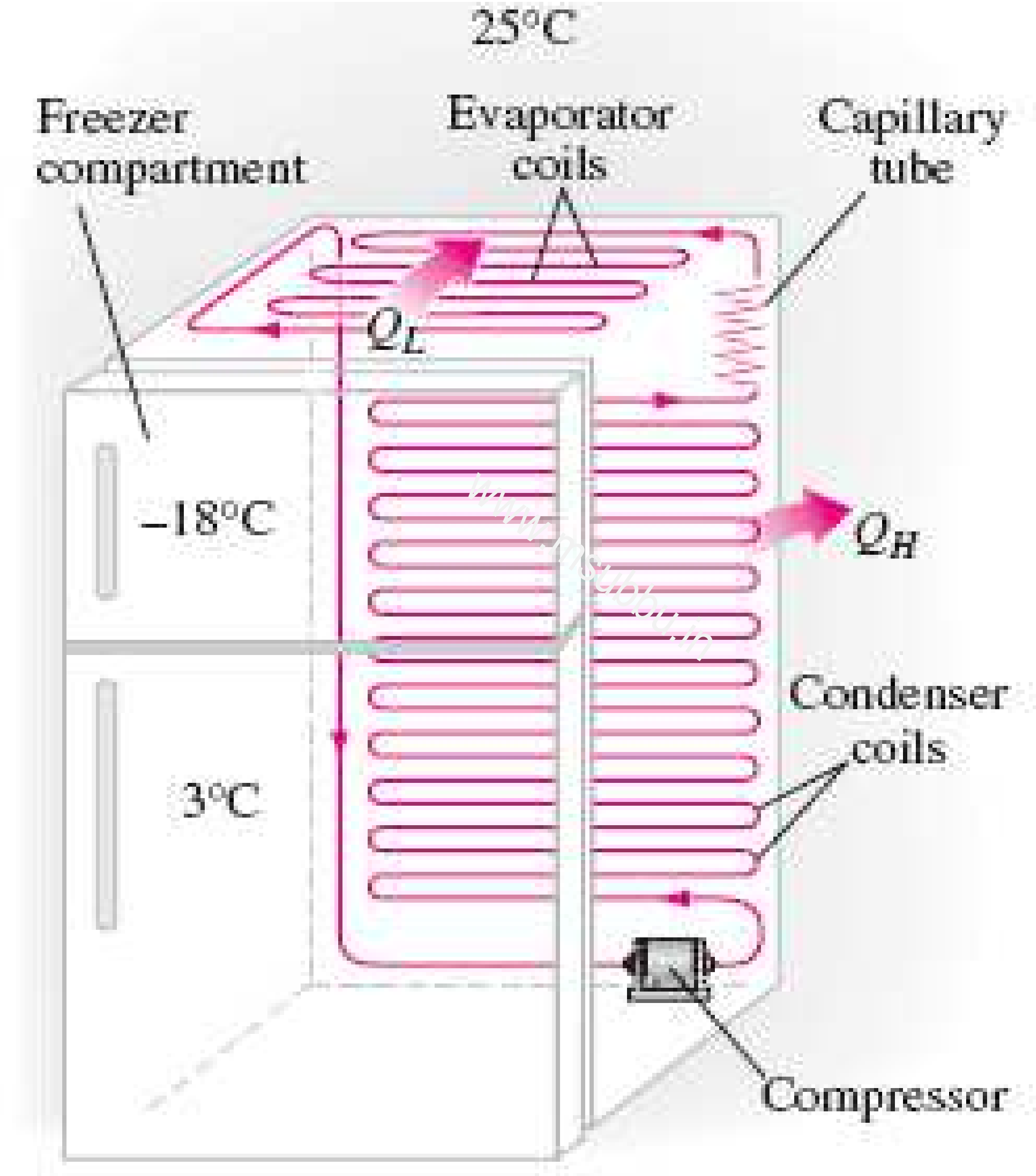
http://www.hindu.com/thehindu/mp/2003/01/02/stories/2003010200820300.htm

THE VIVEKANANDAR Illam, built more than 150 years ago, was popularly known as the Ice House. This was the very place where ice was stored in those days. In 1833, it was Fredric Tudor, an ice merchant of Boston, USA, who brought ice to India in a ship named *Clipper Tuscany*. That was the first time ice was brought into India from abroad. ..

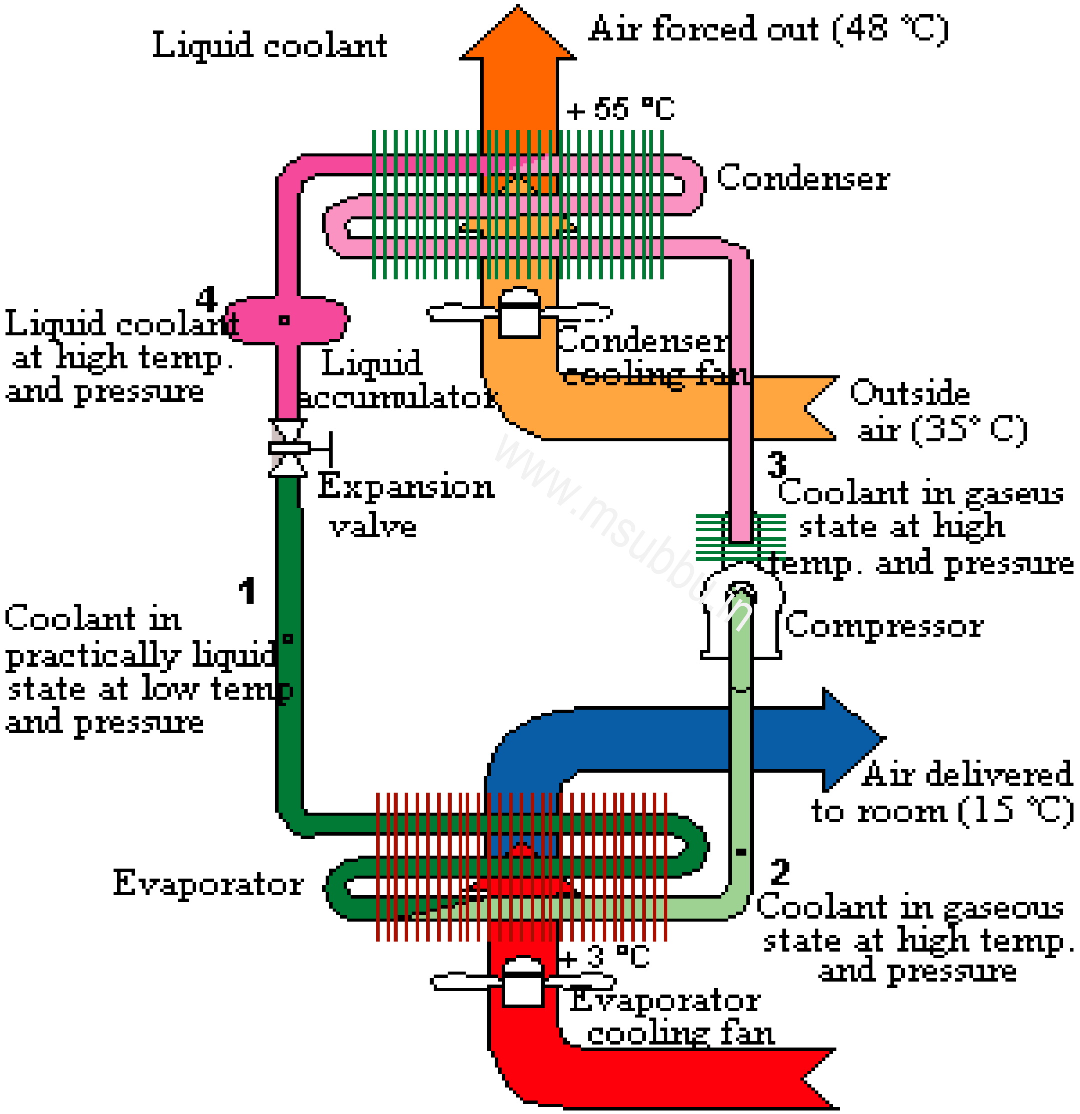
Data Collected by Student:
Ms.Sai Deepthi ASL: on 16th Jan 2013

Refrigerator:
Storage Capacity: 220 ltr
R-12, 100 gram refrigerant
Power consumption: 1/6 HP

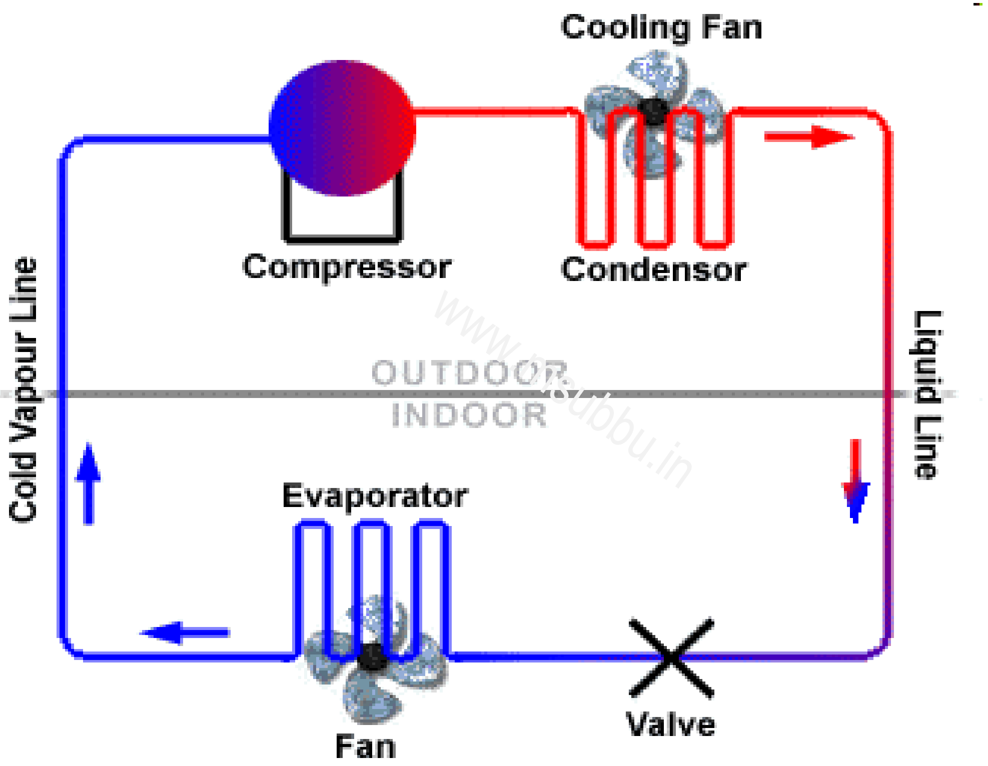
Household refrigerator

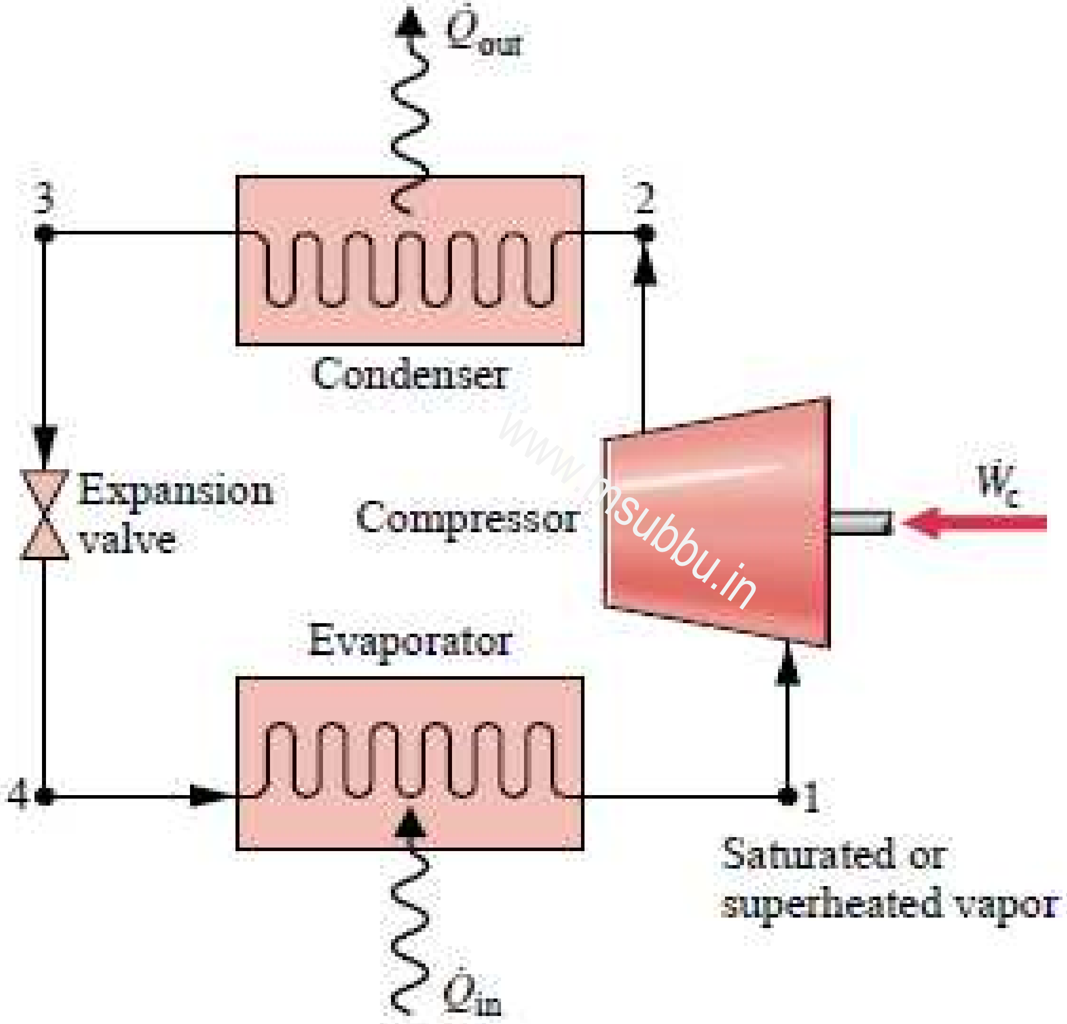


Air Conditioner



Air-conditioner




$\dot{Q}_{out}$
3
2
Condenser
Expansion valve
Compressor
$\dot{W}_c$
Evaporator
4
1
Saturated or superheated vapor
$\dot{Q}_{in}$

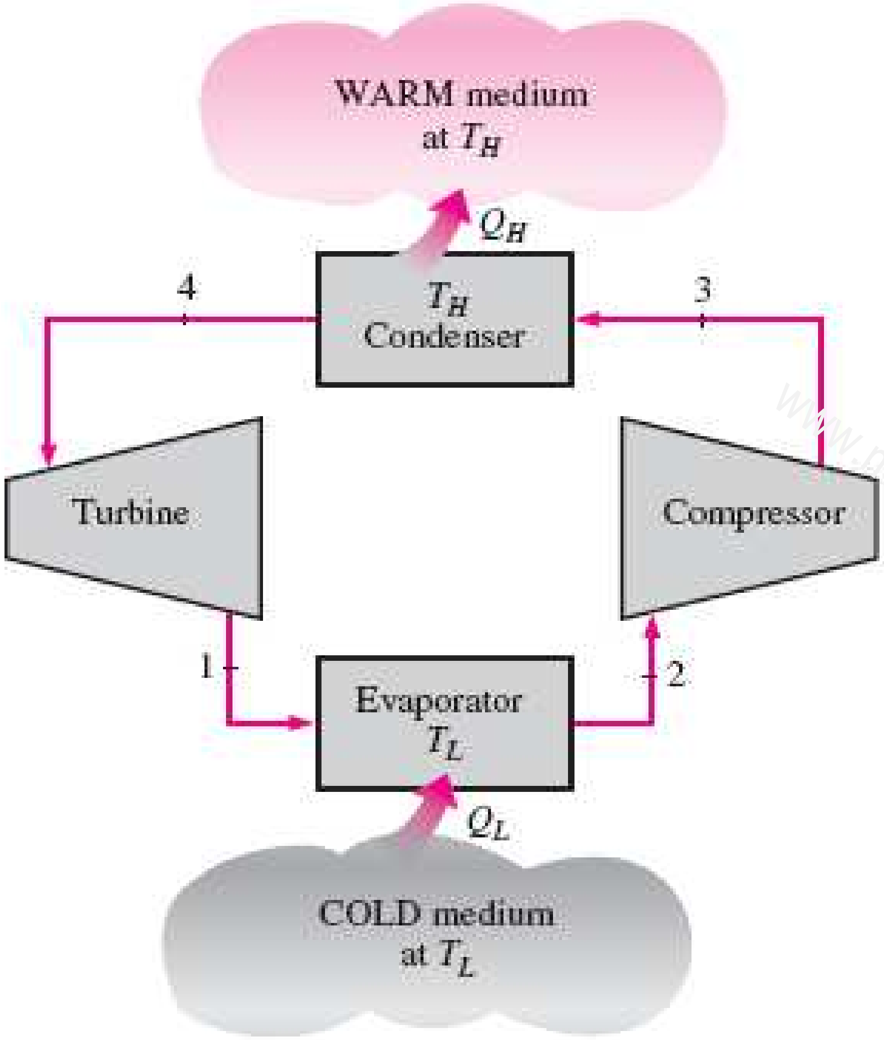
Cooling Capacity

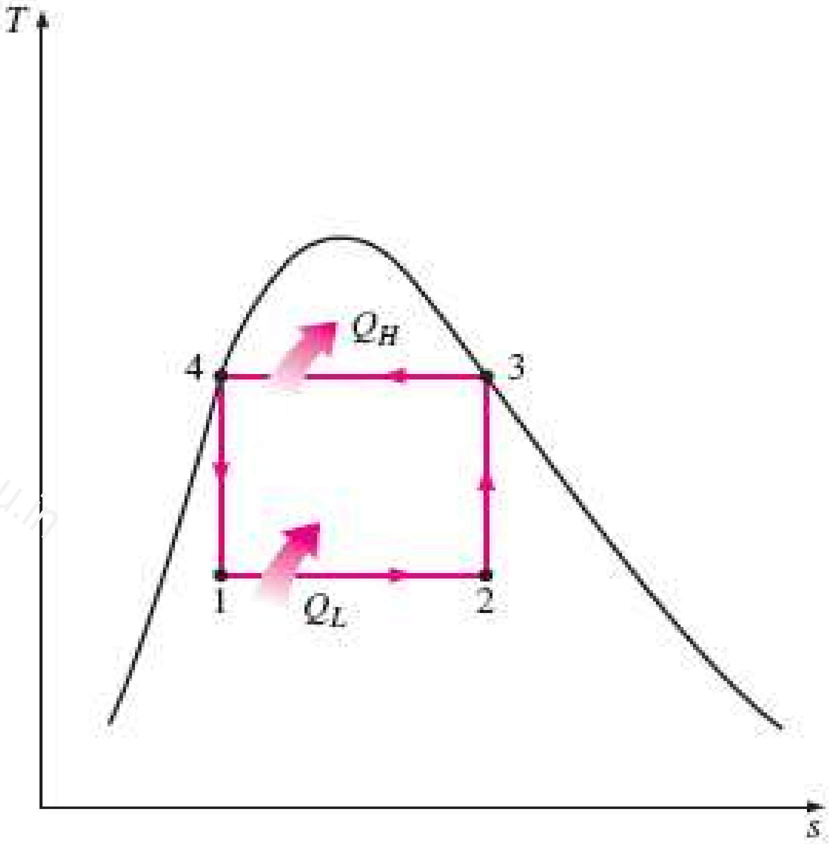
- The *cooling capacity of a refrigeration system—that is, the rate of heat* removal from the refrigerated space—is often expressed in terms of **tons of refrigeration. The capacity of a refrigeration system that can freeze 1 ton** (2000 lb, short ton) of liquid water at 0°C (32°F) into ice at 0°C in 24 h is said to be 1 ton.

- One ton of refrigeration is equivalent to 50 kCal/min or 211 kJ/min or 200 Btu/min (~ 3500 W).

- The cooling load of a typical 200-m^2 residence is in the 3-ton (10-kW) range.

Carnot Refrigerator





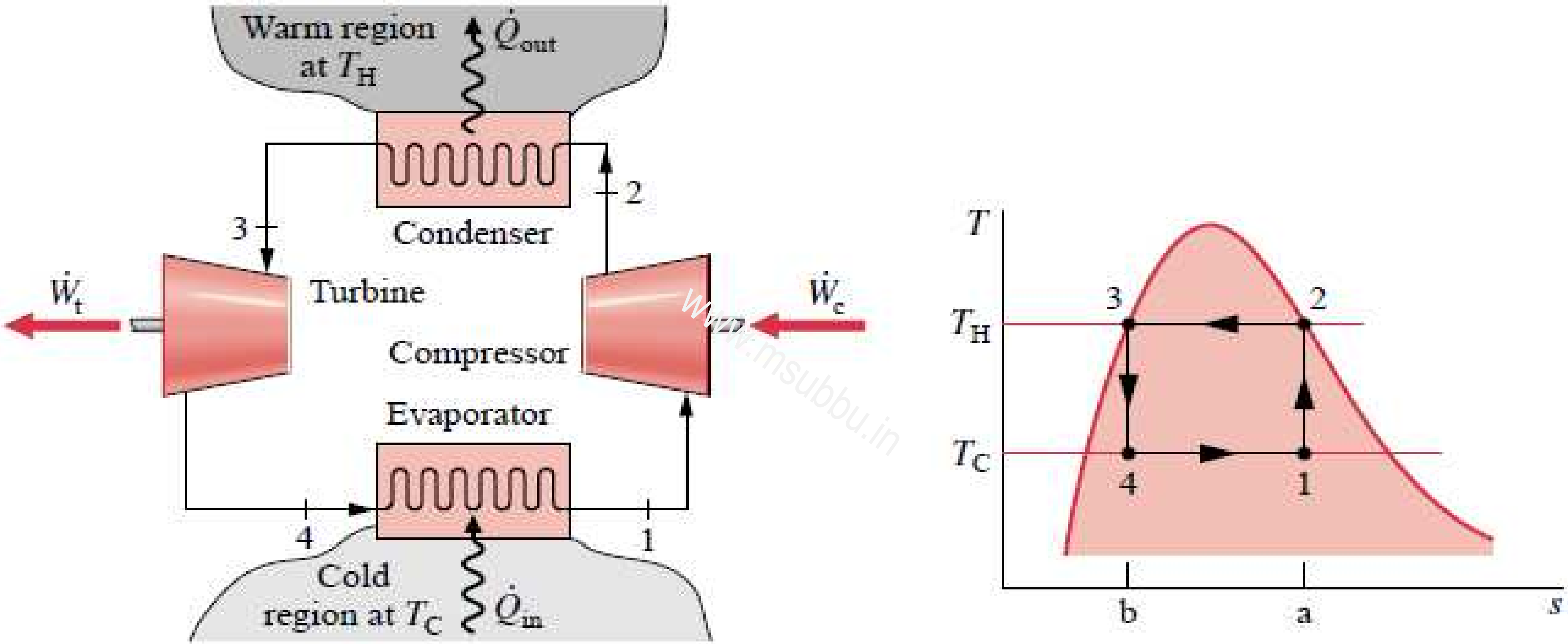
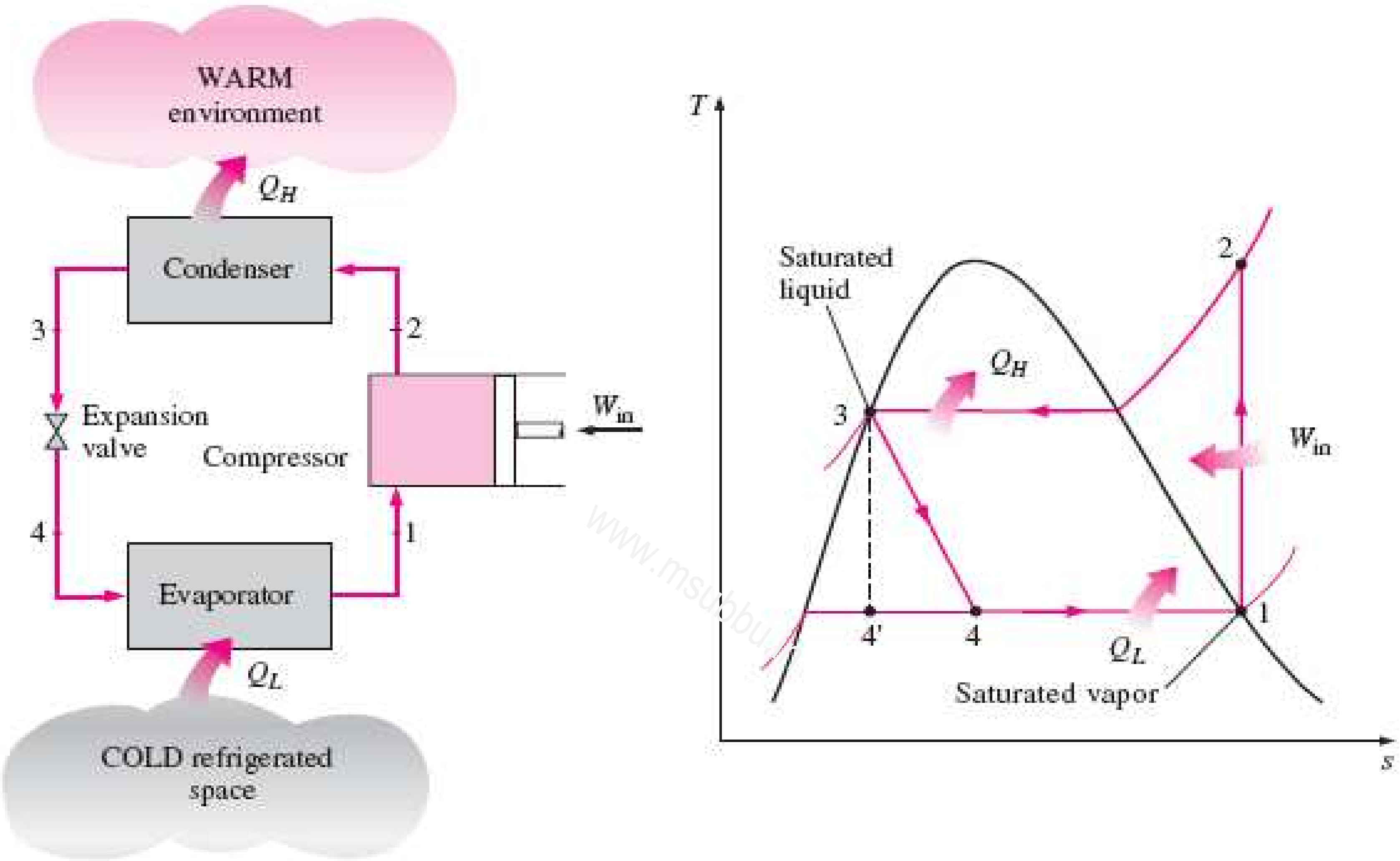
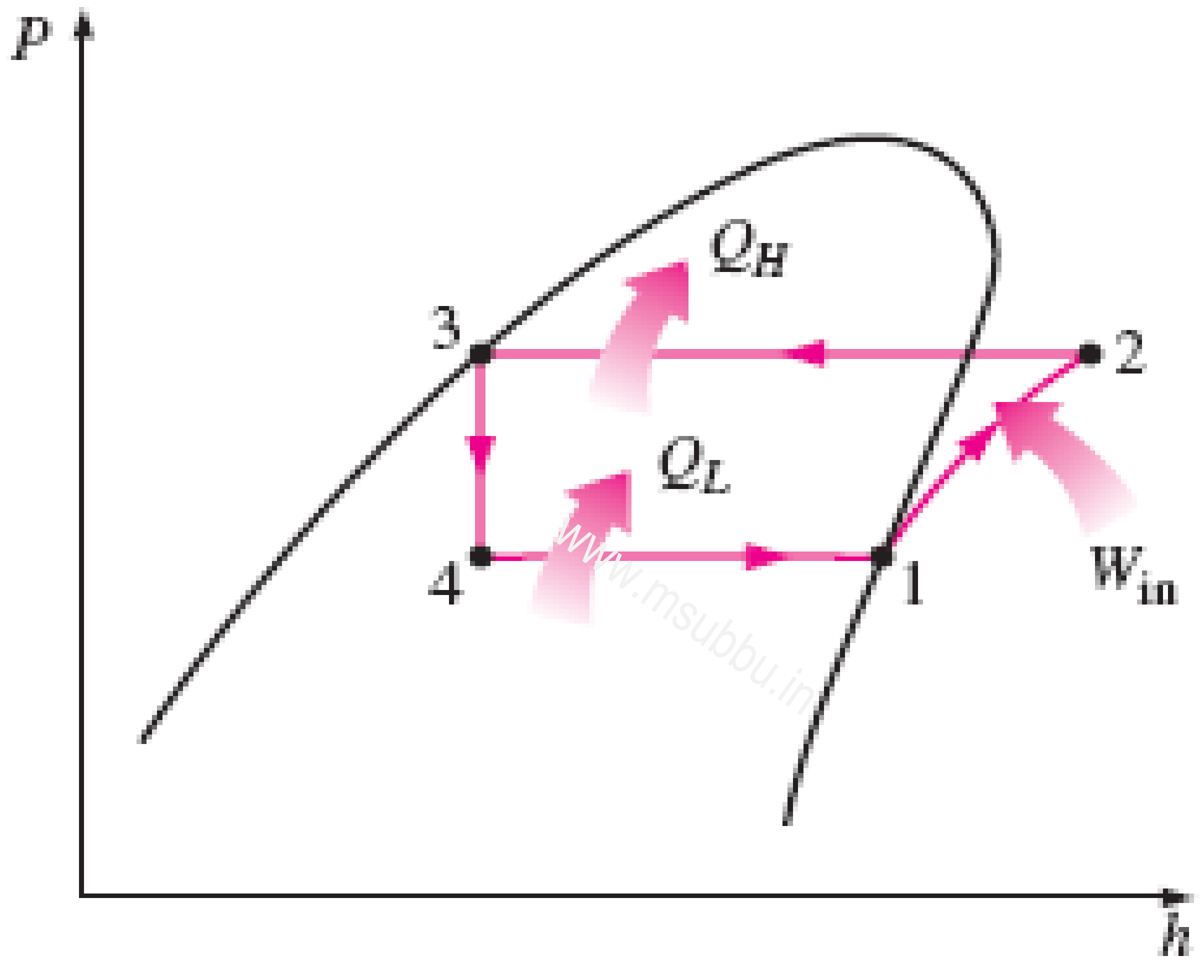


Figure 8.10 Carnot vapor refrigeration cycle.

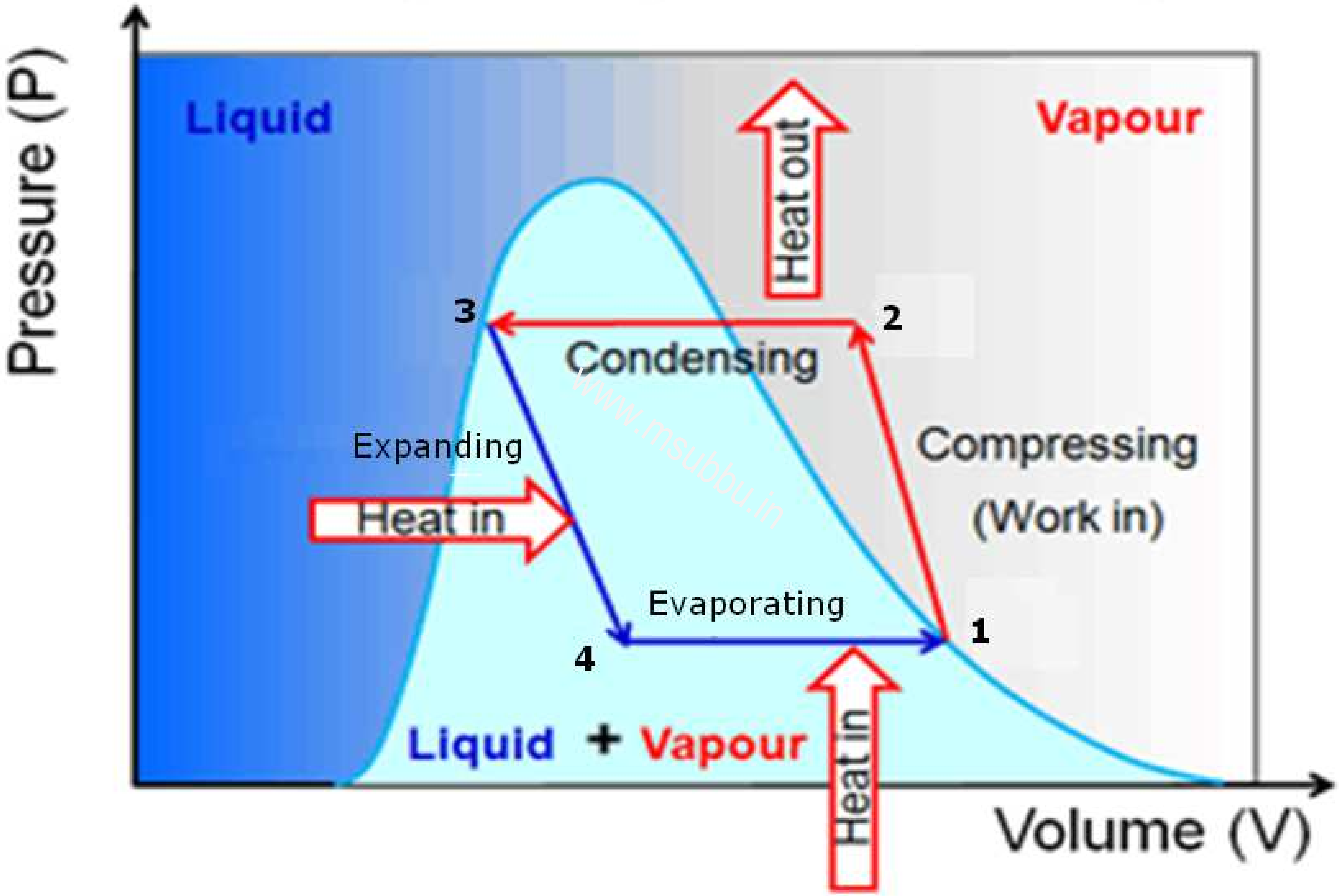


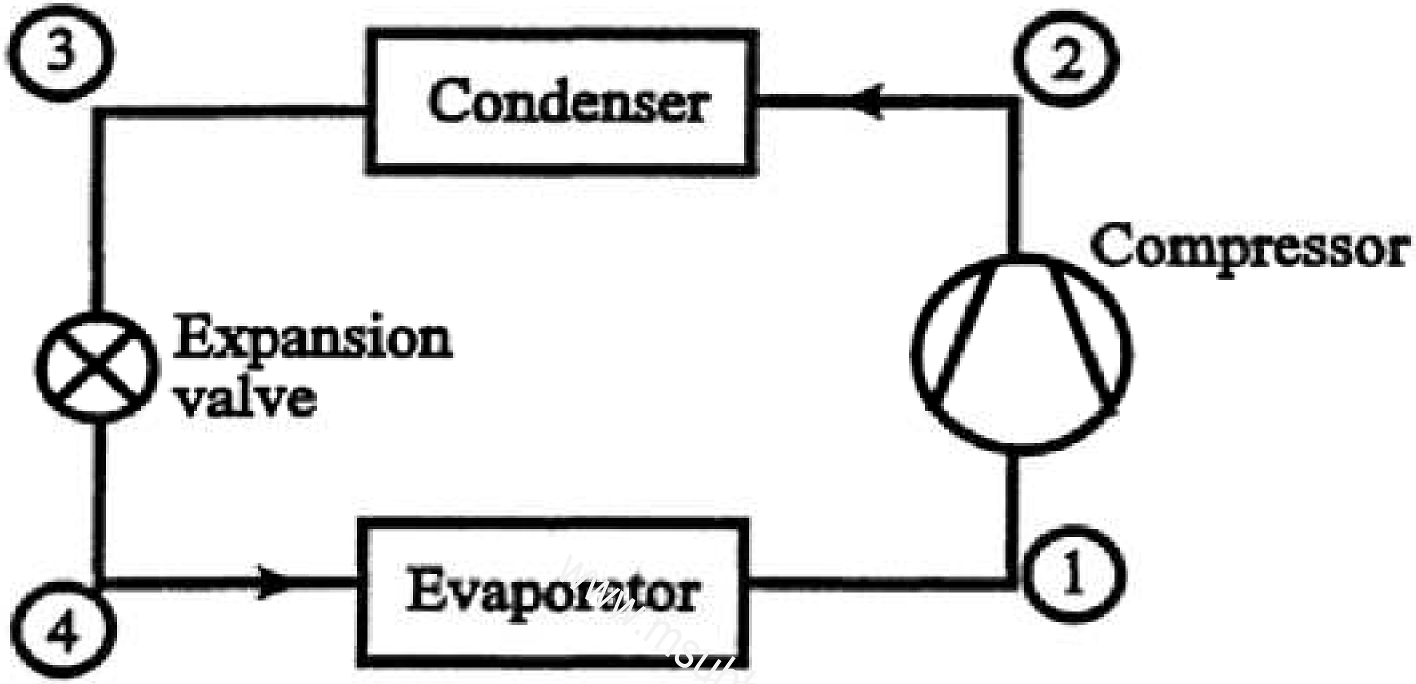
Schematic and *T-s diagram for the ideal vapor-compression refrigeration cycle*

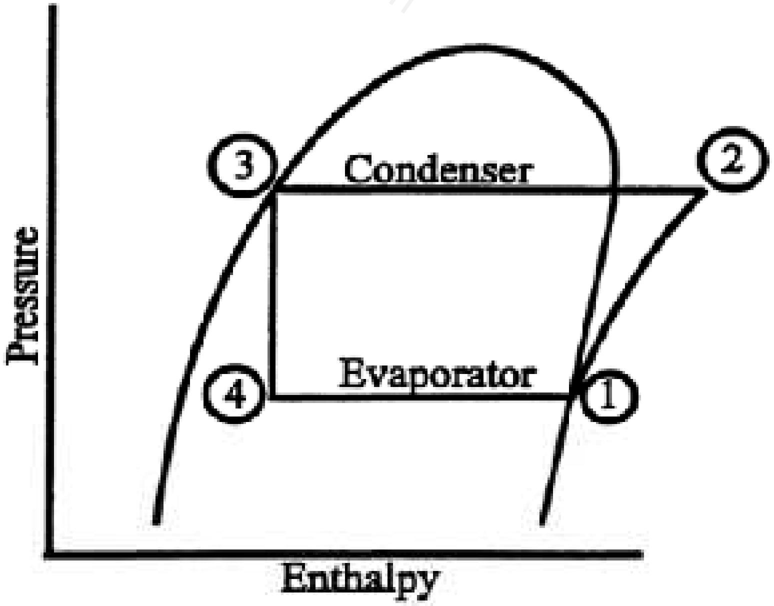


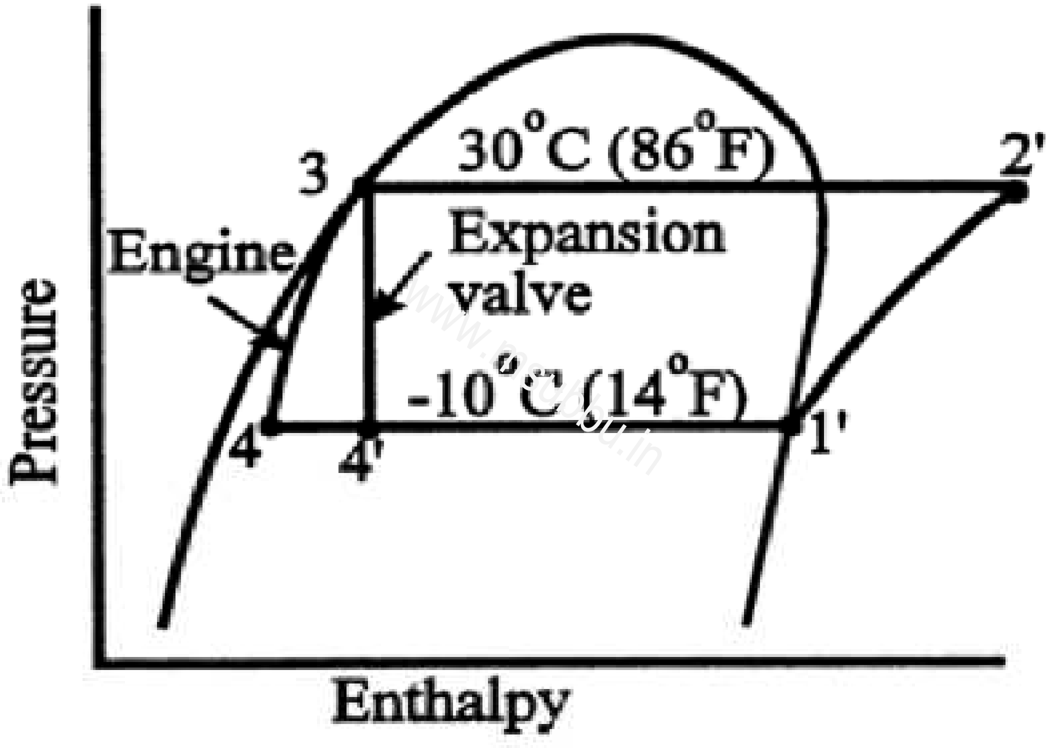
$$\text{COP}_\text{R} = \frac{q_L}{w_\text{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

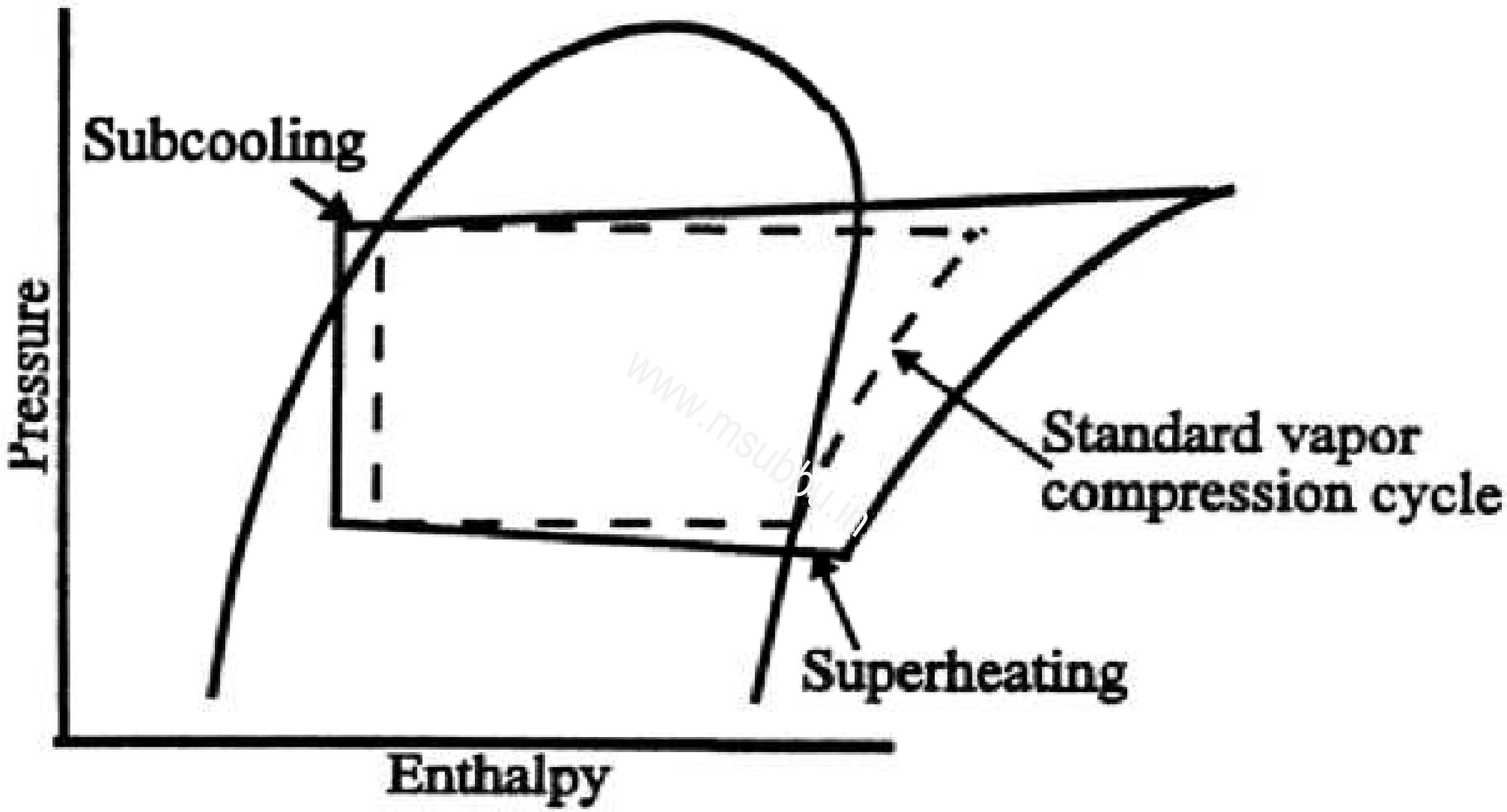
Heat Pump/ Refrigeration P-V Diagram




③
Condenser
②
Compressor
Expansion valve
④
Evaporator
①


③
Condenser
②
Pressure
Evaporator
④
①
Enthalpy


30°C (86°F)
3
2'
Engine
Expansion valve
-10°C (14°F)
4
4'
1'
Pressure
Enthalpy



Deviations of the real cycle from the standard vapor-compression cycle.

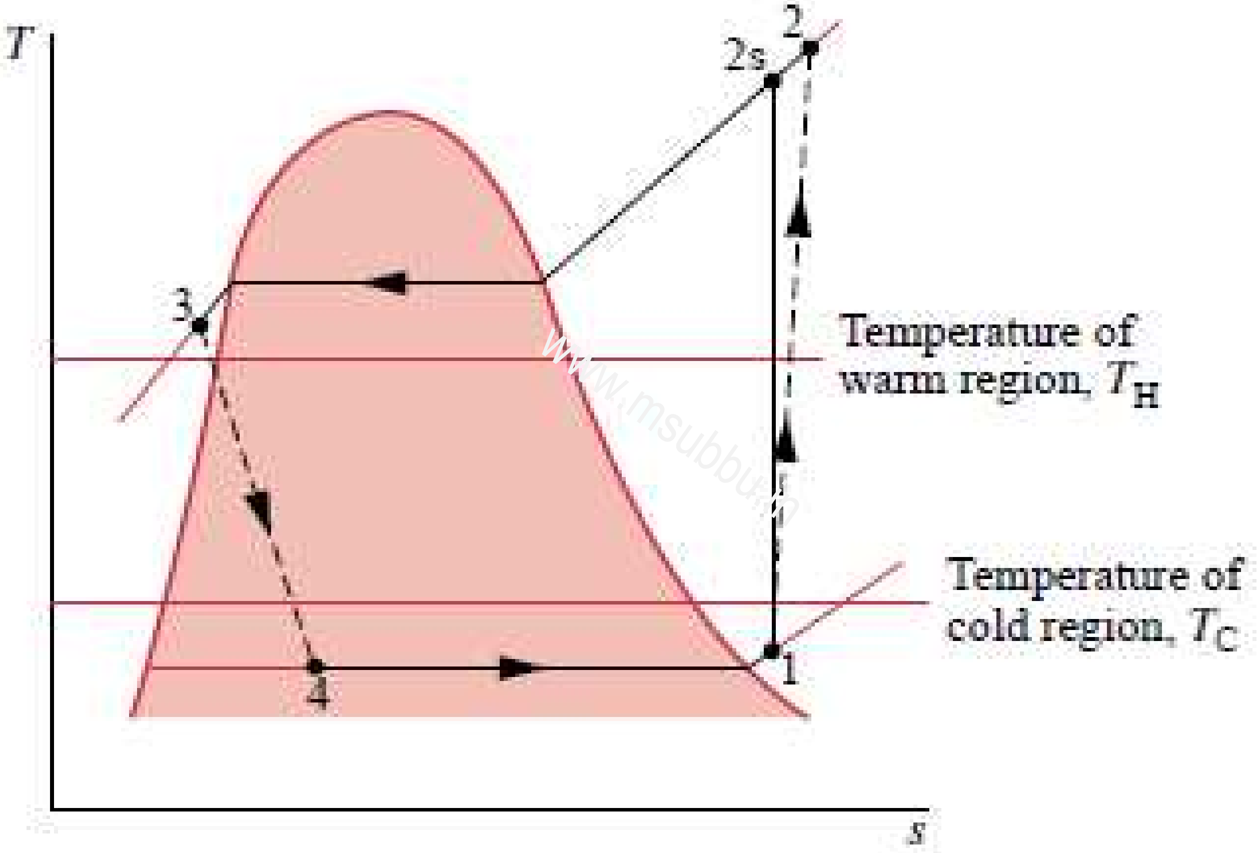


Figure 8.14 T–s diagram of an actual vapor-compression cycle.

Required Properties of Ideal Refrigerant

1. The refrigerant should have low boiling point and low freezing point.

2. It must have low specific heat and high latent heat. Because high specific heat decreases the refrigerating effect per kg of refrigerant and high latent heat at low temperature increases the refrigerating effect per kg of refrigerant.

3. The pressures required to be maintained in the evaporator and condenser should be low enough to reduce the material cost and must be positive to avoid leakage of air into the system.

4. It must have high critical pressure and temperature to avoid large power requirements.

5. It should have low specific volume to reduce the size of the compressor.

6. It must have high thermal conductivity to reduce the area of heat transfer in evaporator and condenser.

Required Properties of Ideal Refrigerant

7. It should be non-flammable, non-explosive, non-toxic and non-corrosive.

8. It should not have any bad effects on the stored material or food, when any leak develops in the system.

9. It must have high miscibility with lubricating oil and it should not have reacting property with lubricating oil in the temperature range of the system.

10. It should give high COP in the working temperature range. This is necessary to reduce the running cost of the system.

11. It must be readily available and it must be cheap also.

Important Refrigerants

Properties at **-15^{o}C**

(1) Ammonia (NH_3)(R-717)

Latent heat = 1312.75 kJ/kg

Specific volume = 0.509 m^3/kg

(2) Dichloro–Difluoro methane (Freon–12) (R-12) [$C\,Cl_2\,F_2$]

Latent heat = 162 kJ/kg

Specific volume = 0.093 m^3/kg

(3) Difluoro monochloro methane – or Freon-22 (R-22) [$CH\,Cl\,F_2$]

Latent heat = 131 kJ/kg

Specific Volume = 0.15 m^3/kg.

(4) **Tetrafluoro ethane – Freon-134a (R-134a) [CH_2FCF_3]**

Methods of Producing Refrigeration

- Non-cyclic refrigeration – using melting ice, sublimation of dry ice
- Cyclic refrigeration
  - Vapor cycles
    - Vapor compression
    - Vapor absorption
  - Gas cycles: for the same cooling load, a gas refrigeration cycle needs a large mass flow rate and is bulky.
- Peltier effect

Ammonia as Refrigerant

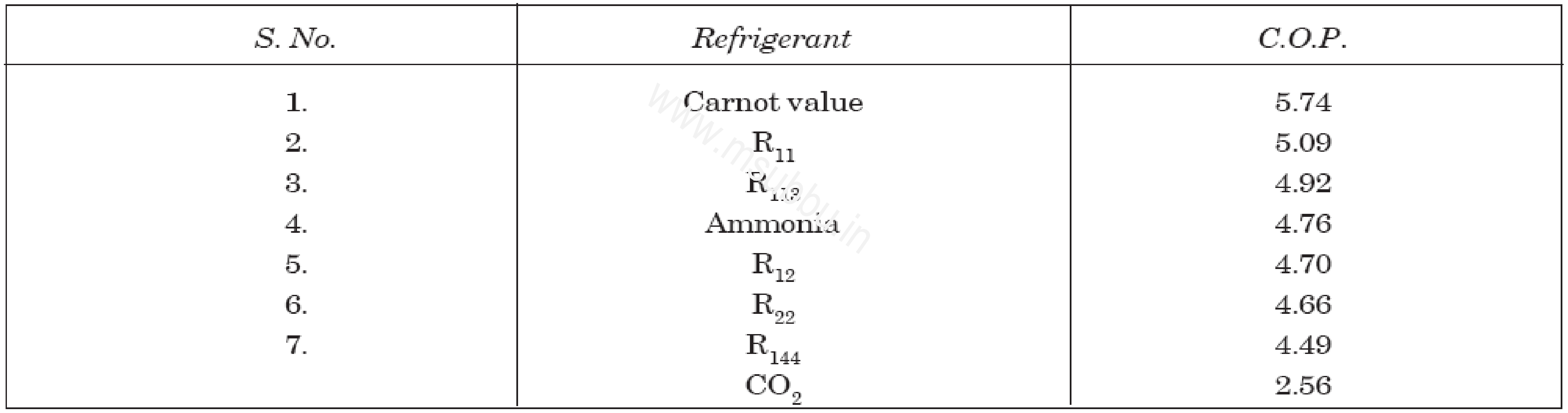
- With increased regulation being placed upon the use of chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) based refrigerants, and the pending phaseout of CFCs and HCFCs altogether, alternative refrigerants for use in existing refrigeration systems are actively being investigated. These alternative refrigerants must have thermodynamic characteristics similar to those of halocarbons and be safe for humans and the environment.

- Ammonia has a low boiling point (-28°F @ 0 psig), an ozone depletion potential (ODP) of 0.00 when released to atmosphere, and a high latent heat of vaporization (9 times greater than R-12). In addition, ammonia in the atmosphere does not directly contribute to global warming. These characteristics result in a highly energy-efficient refrigerant with minimal environmental problems

- **Capacity of refrigerator in liters** refers to the total storage volume i.e. the storage space available in refrigerator. This unit is used because refrigerators are used for domestic purpose.

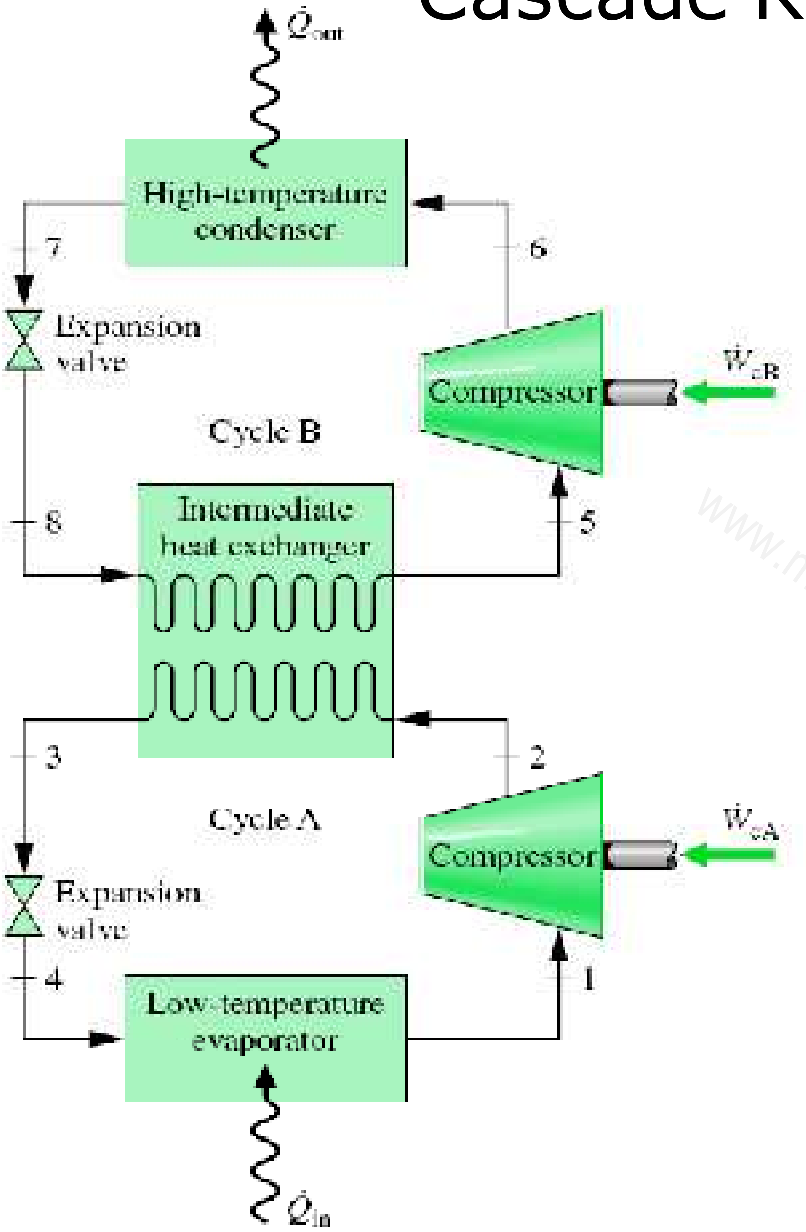
- **Freon:** Dupont’s trade name for CFCs

Table 14.1. C.O.P. of some important refrigerants



S. No.	*Refrigerant*	*C.O.P.*
1.	Carnot value	5.74
2.	R_{11}	5.09
3.	R_{113}	4.92
4.	Ammonia	4.76
5.	R_{12}	4.70
6.	R_{22}	4.66
7.	R_{144}	4.49
	CO_2	2.56

Cascade Refrigeration



Example:

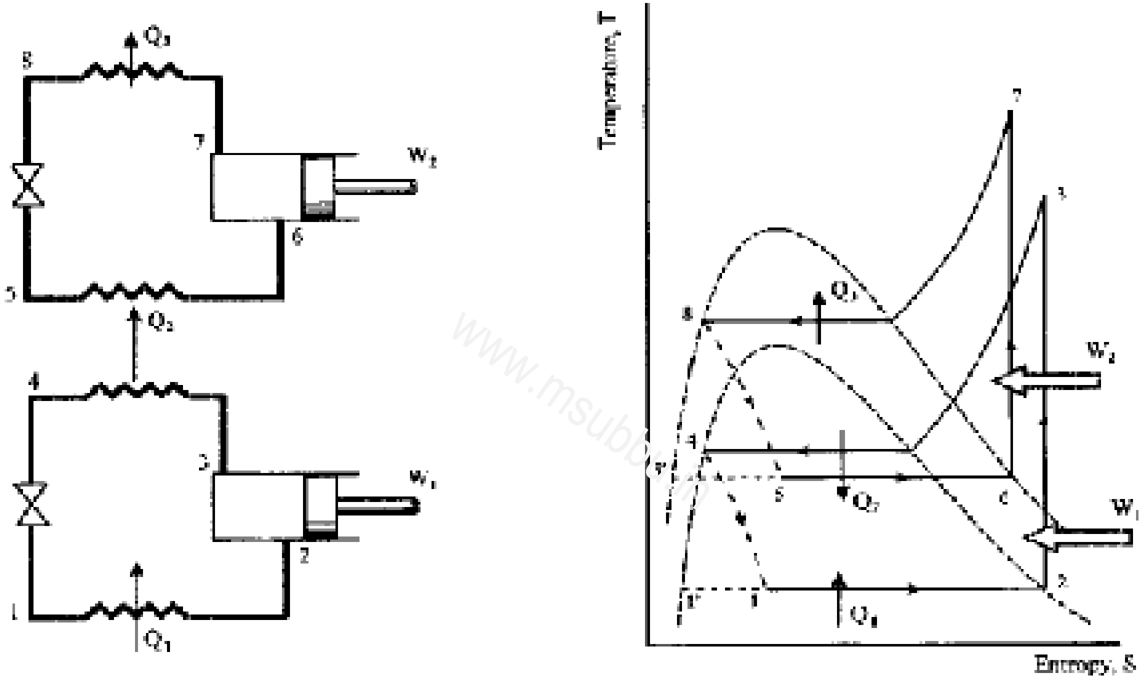
Cycle A: Propylene

227 K to 261 K (1.1 bar to 4 bar)

Cycle B: Tetrafluoroethane(HFC-134a)

255 K to 303 K (1.45 bar to 7.72 bar)

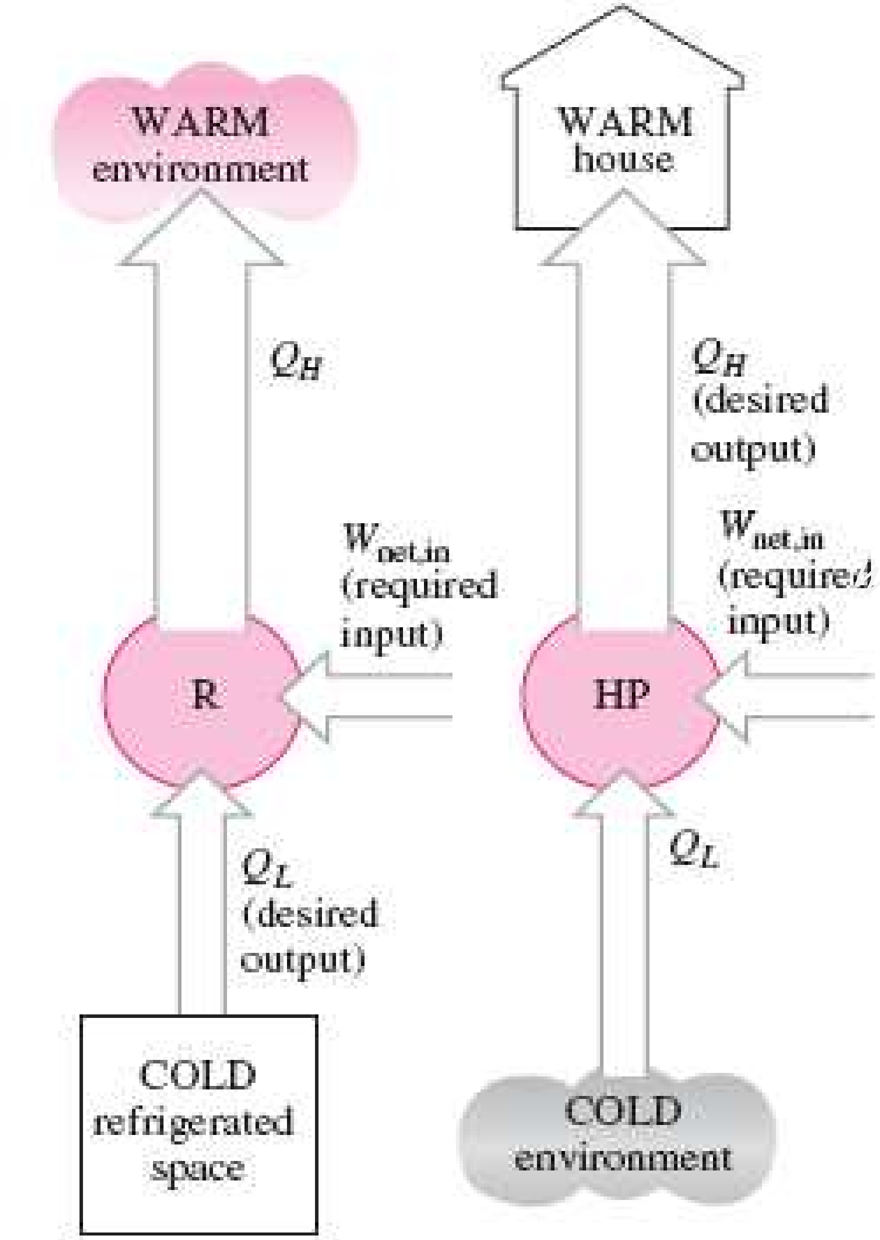
For a single cycle, with HFC-134a:
227 K to 303 K (0.4 bar to 7.72 bar)
Pressure ratio: 19.3



(a)

(b)

Fig. 8.3 Cascade refrigeration cycle



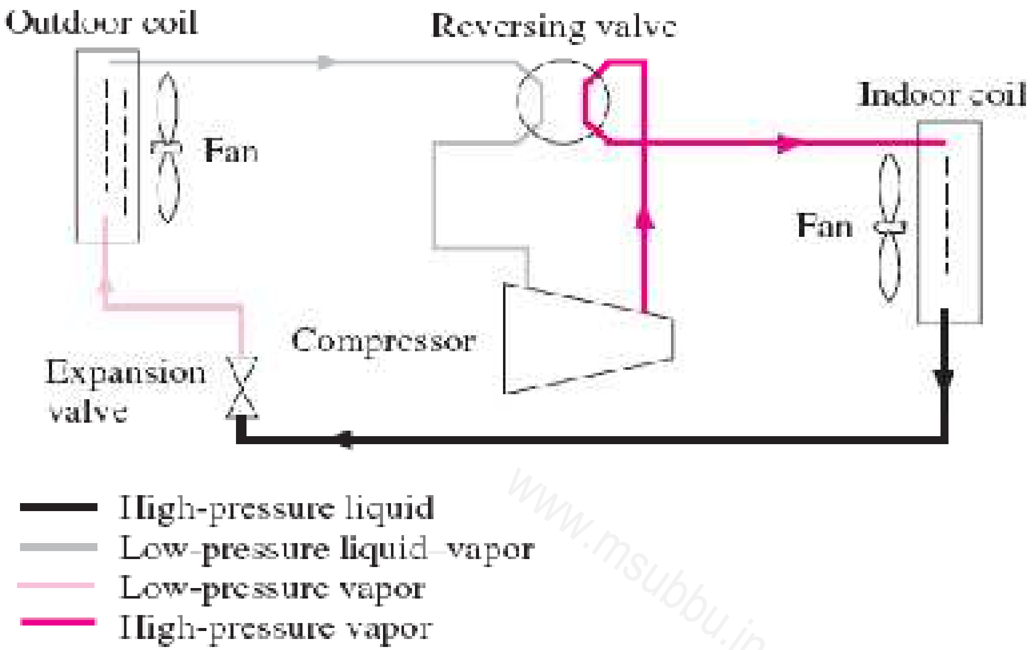
(*a*) Refrigerator (*b*) Heat pump

$$\text{COP}_\text{R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{\text{net,in}}}$$

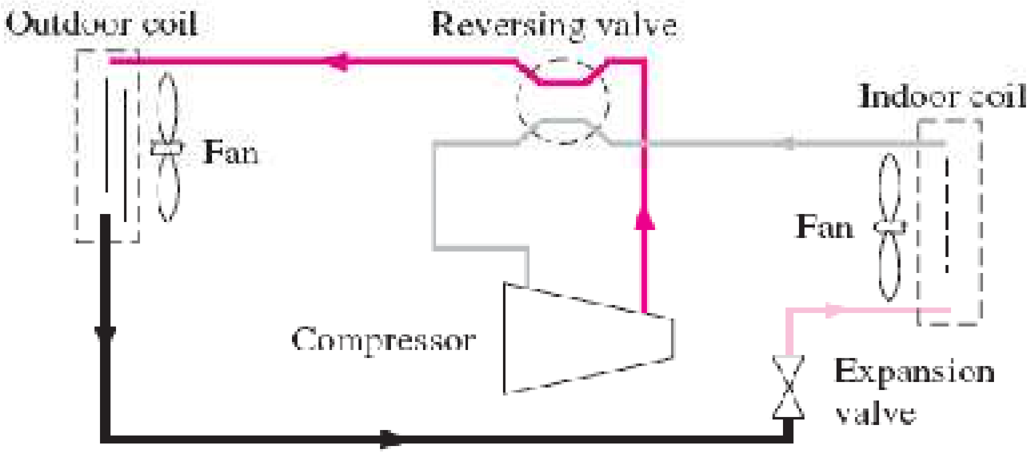
$$\text{COP}_\text{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{\text{net,in}}}$$

$$\text{COP}_\text{HP} = \text{COP}_\text{R} + 1$$

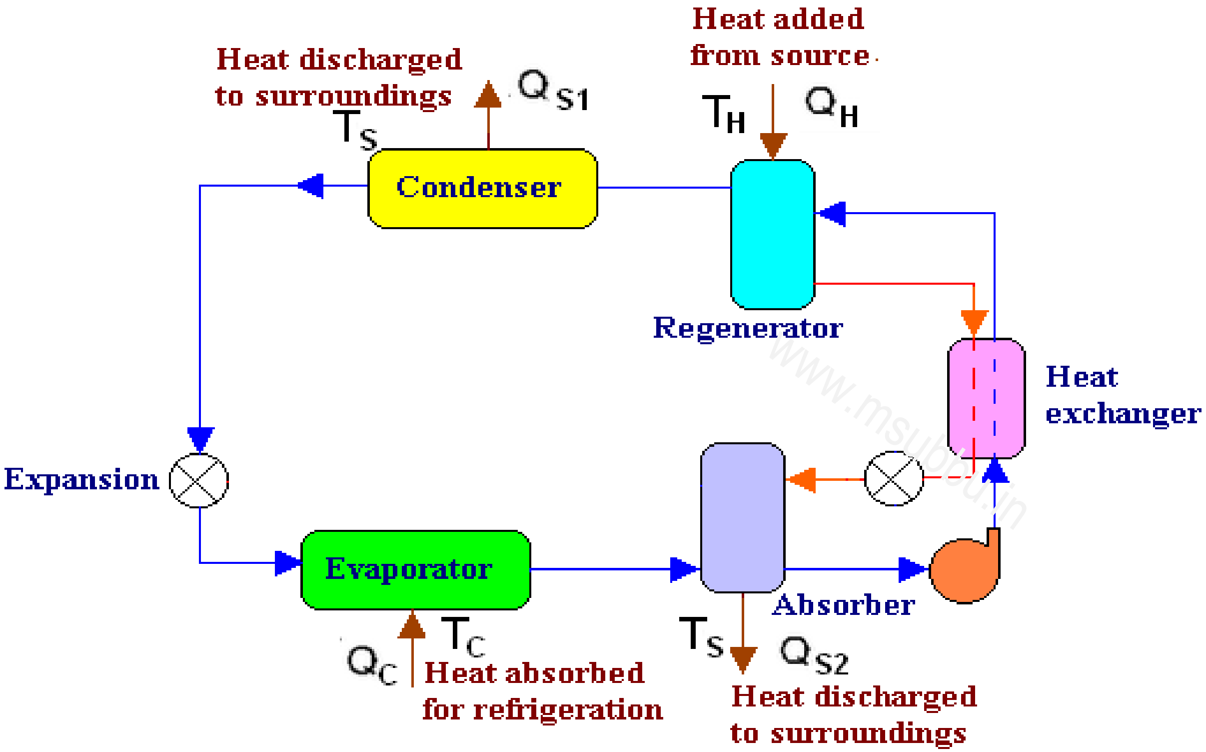
HEAT PUMP OPERATION—HEATING MODE



HEAT PUMP OPERATION—COOLING MODE



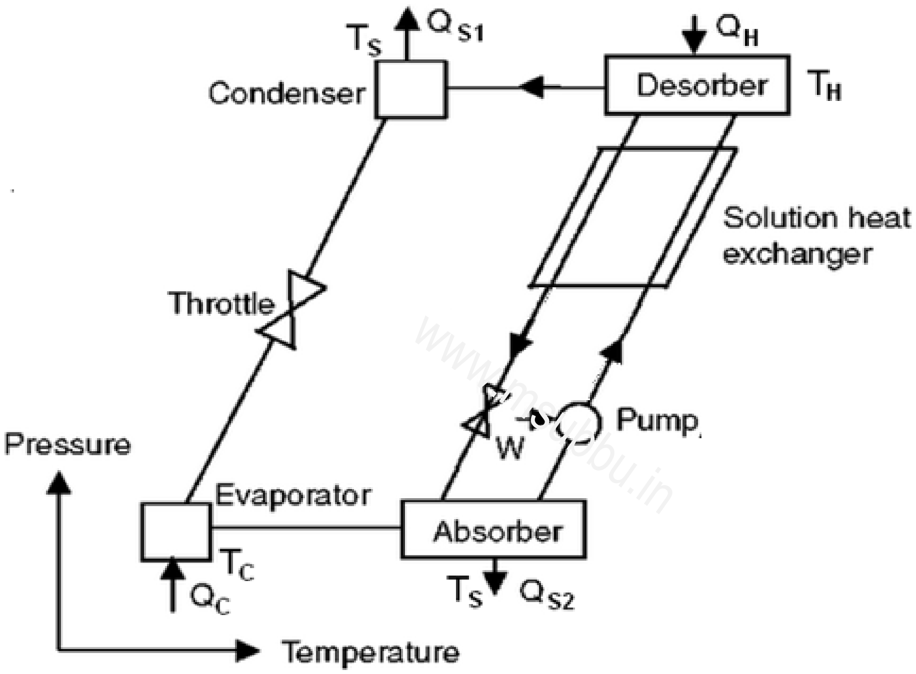
Vapor Absorption Refrigeration

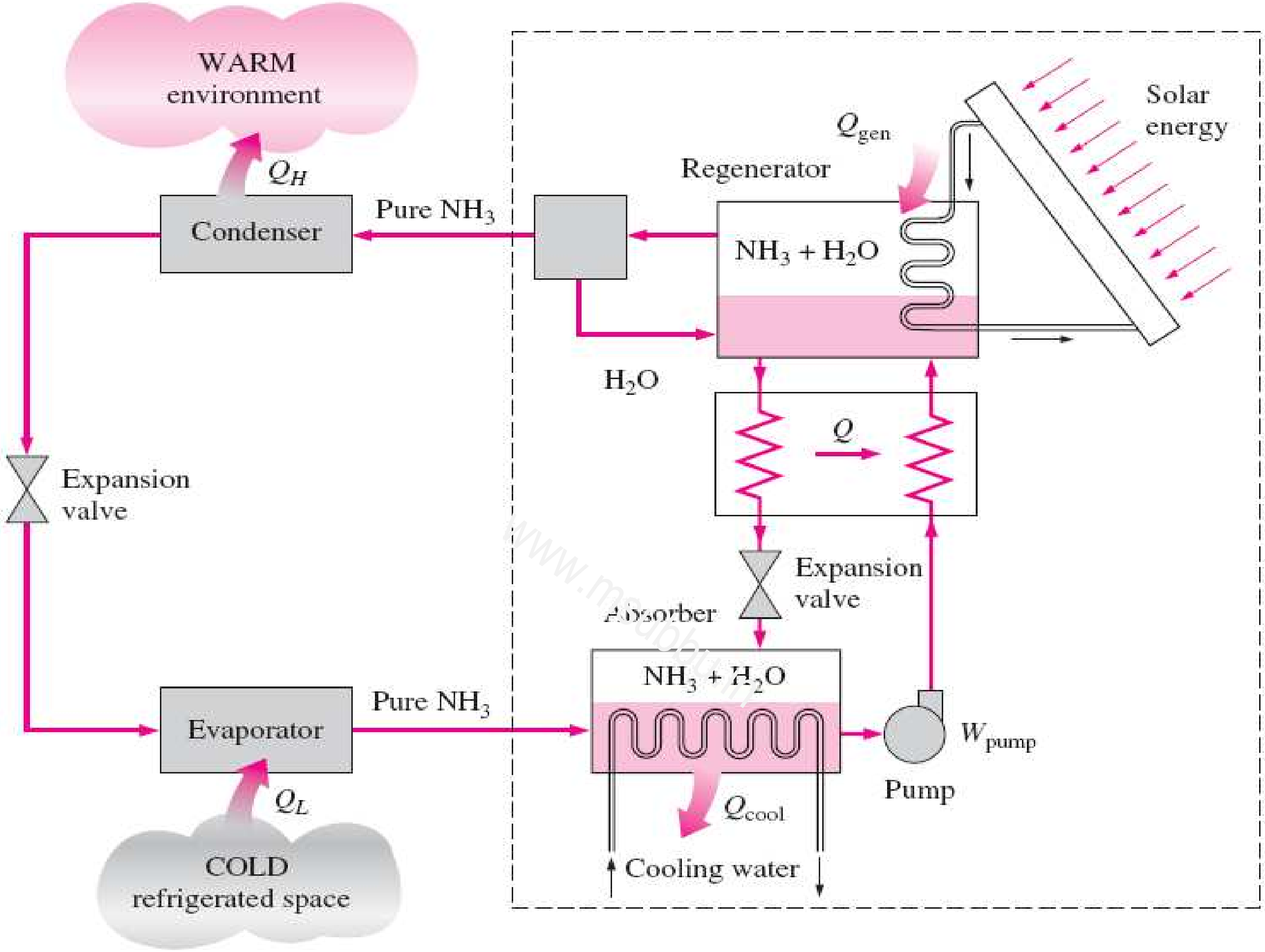


Examples:

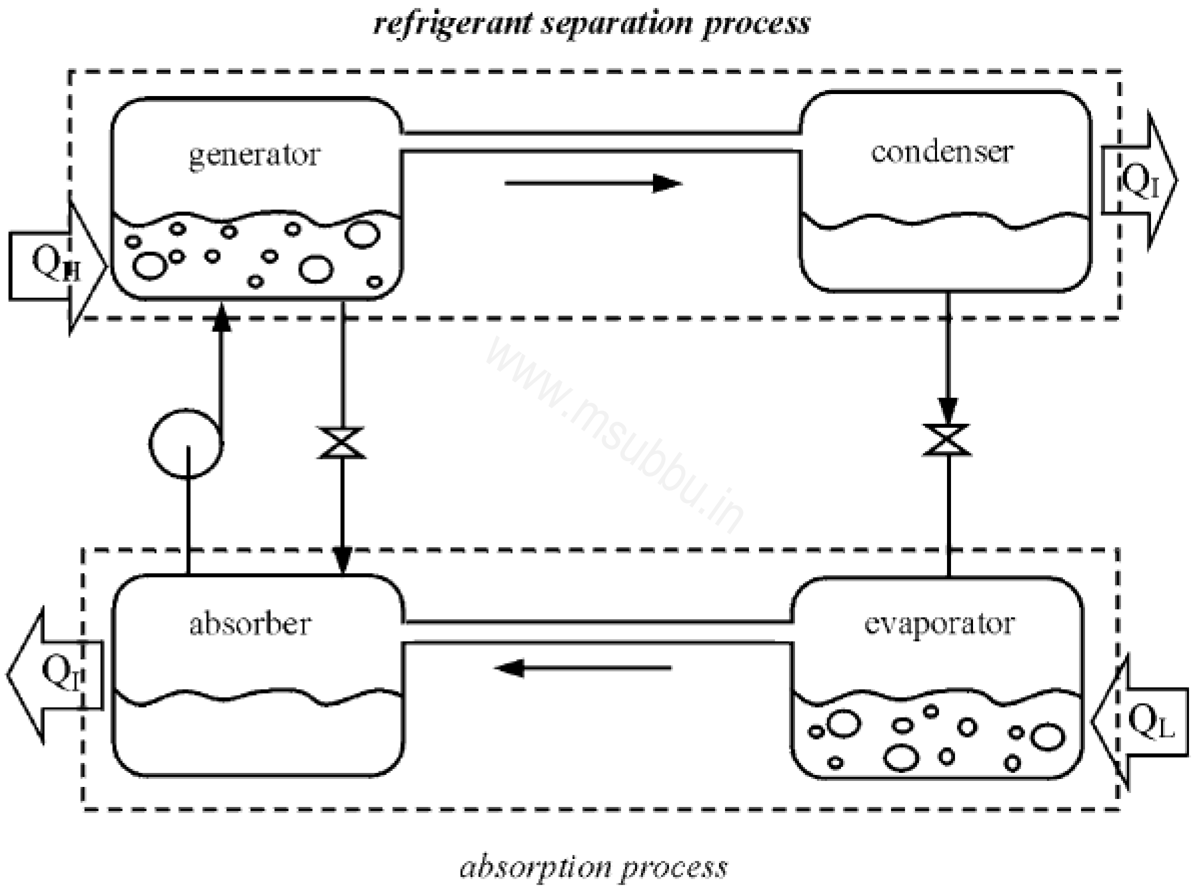
Water - Lithium Bromide

Ammonia - Water

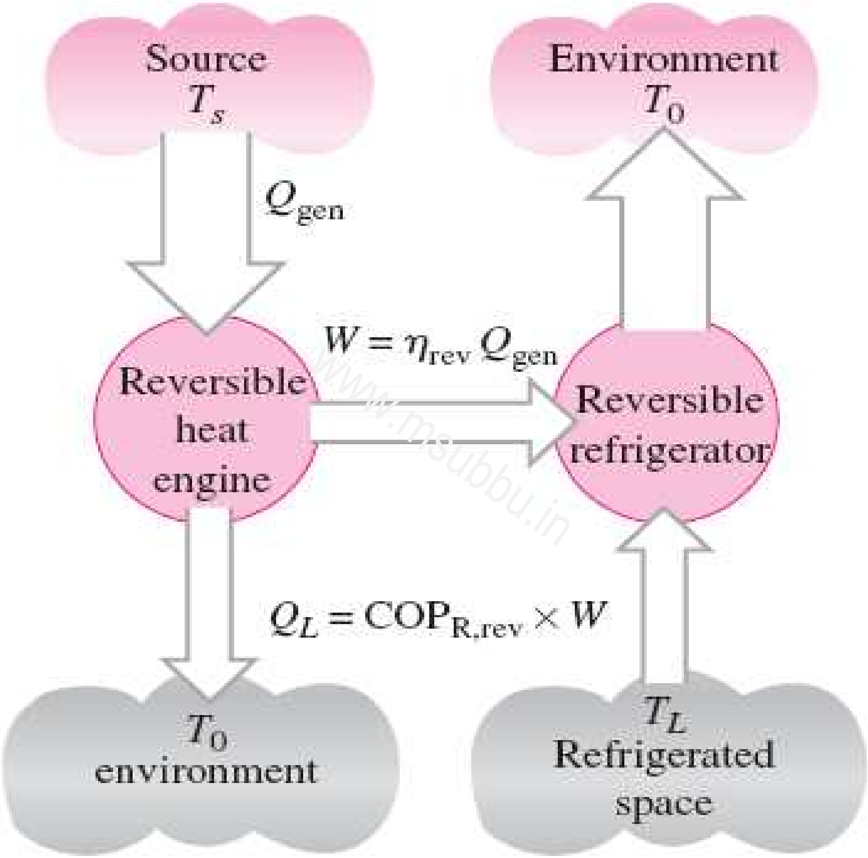

T_S
Q_{S1}
Q_H
Condenser
Desorber
T_H
Solution heat exchanger
Throttle
Pump
W
Pressure
Evaporator
Absorber
T_C
Q_C
T_S
Q_{S2}
Temperature



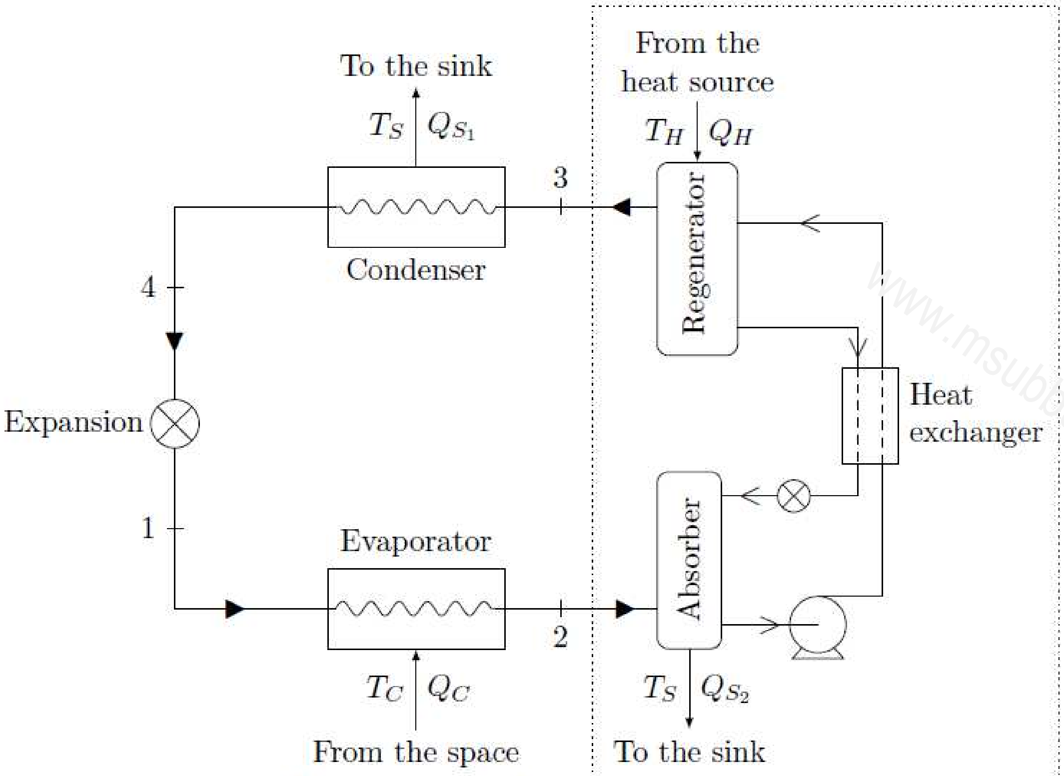
$$\text{COP}_{\text{absorption}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{Q_{gen} + W_{pump,in}} \cong \frac{Q_L}{Q_{gen}}$$


refrigerant separation process
generator
condenser
Q_H
Q_I
absorber
evaporator
Q_I
Q_L
absorption process

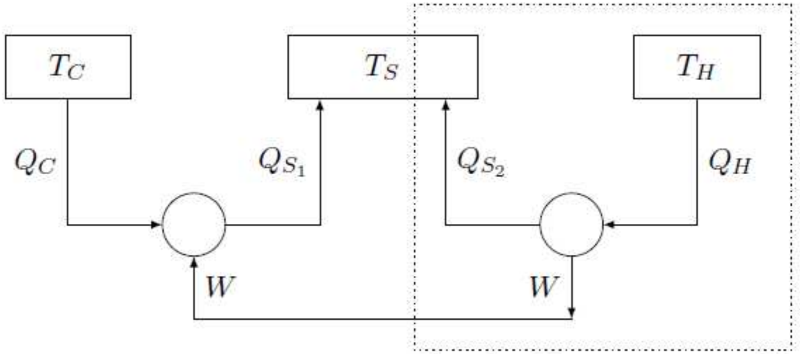
Vapor Absorption Refrigeration



Carnot Cycle Analysis of Vapor Absorption Refrigeration



Absorber-Regenerator combination replaces the compressor



Absorber-Regenerator combination replaces the compressor

$$
\begin{aligned}
\text{COP} &= \frac{\text{useful output}}{\text{input}} \\
&= \frac{\text{cooling effect produced}}{\text{heat input to the regenerator} + \text{work input to the pump}} \\
&= \frac{Q_C}{Q_H + W_{\text{pump}}}
\end{aligned}
$$

W_{pump} is negligible in comparison to Q_H. Therefore,

$$\text{COP} = \frac{Q_C}{Q_H} \tag{7.1}$$

For the Carnot refrigerator acting between T_C and T_S, from the definition of COP, we have

$$\frac{Q_C}{W} = \frac{Q_C}{Q_{S_1} - Q_C} = \frac{T_C}{T_S - T_C} \tag{7.2}$$

For the Carnot engine acting between T_H and T_S, from the definition of efficiency, we have

$$\frac{W}{Q_H} = \frac{Q_H - Q_{S_2}}{Q_H} = \frac{T_H - T_S}{T_H} \tag{7.3}$$

Multiplying Eqns.(7.3) and (7.2), we get

$$\frac{Q_C}{Q_H} = \left(\frac{T_C}{T_S - T_C}\right)\left(\frac{T_H - T_S}{T_H}\right) \tag{7.4}$$

From Eqns.(7.1) and (7.4) we can write the maximum possible COP of vapor compression refrigeration as

$$COP = \left(\frac{T_C}{T_S - T_C}\right)\left(\frac{T_H - T_S}{T_H}\right) \tag{7.5}$$

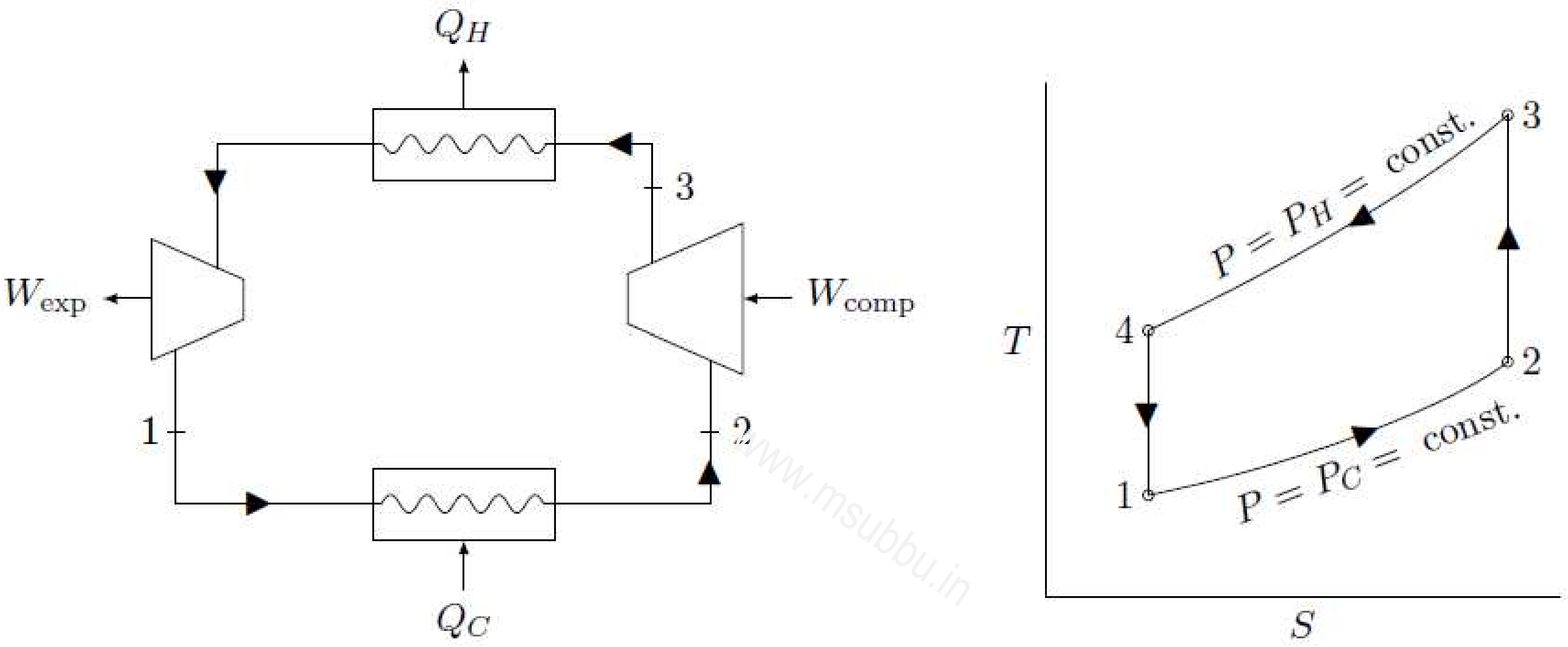
14.4.4. Comparison between Vapour Compression and Vapour Absorption Systems

S. No.	*Particulars*	*Vapour compression system*	*Vapour absorption system*
1.	*Type of energy supplied*	Mechanical—a high grade energy	Mainly heat—a low grade energy
2.	*Energy supply*	Low	High
3.	*Wear and tear*	More	Less
4.	*Performance at part loads*	Poor	System not affected by variations of loads.
5.	*Suitability*	Used where high grade mechanical energy is available	Can also be used at remote places as it can work even with a simple kerosene lamp (of course in small capacities)
6.	*Charging of refrigerant*	Simple	Difficult
7.	*Leakage of refrigerant*	More chances	No chance as there is no compressor or any reciprocating component to cause leakage.
8.	*Damage*	Liquid traces in suction line may damage the compressor	Liquid traces of refregerant present in piping at the exit of evaporator constitute no danger.

Gas cycle Refrigeration

- Air is used as working fluid.
- No change of phase through out.
- Heat carrying capacity/kg of air is very small compared with other refrigerant systems.
- As the air is easily available compared with the other refrigerant, it is cheap.
- The air used is non-flammable, so there is no danger of fire as in NH_3 machine.

Gas Refrigeration Cycle



Reversed Brayton Cycle (**Bell Coleman cycle)**

$1-2$: constant pressure process; energy is taken away from the space to be cooled by the circulating gas (gas is getting heated up by taking the heat)
$2-3$: isentropic compression of gas from state 2 to state 3
$3-4$: energy exchange with the surrounding (gas is cooled)
$4-1$: isentropic expansion in a turbine to state 1

Heat removed from the refrigerated space:

$$Q_C = H_2 - H_1 = C_P(T_2 - T_1)$$

Work done on the compressor:

$$W_{\text{comp}} = H_3 - H_2 = C_P(T_3 - T_2)$$

Work delivered by the turbine by expansion of the gas:

$$W_{\text{exp}} = H_4 - H_1 = C_P(T_4 - T_1)$$

The net work required (W_{net})= $W_{\text{comp}} - W_{\text{exp}}$. The COP of this refrigeration system is given by:

$$\text{COP} = \frac{Q_C}{W_{\text{net}}} = \frac{T_2 - T_1}{(T_3 - T_2) - (T_4 - T_1)} \tag{7.6}$$

i.e.,

$$\text{COP} = \frac{T_2 - T_1}{(T_3 - T_4) - (T_2 - T_1)} = \frac{1}{\left(\frac{T_3 - T_4}{T_2 - T_1}\right) - 1} \tag{7.7}$$

In the refrigeration cycle, $2-3$ and $4-1$ are isentropic processes. For an isentropic process $PV^{\gamma} =$ constant; from which we can get the following relationships (for an ideal gas):

$$\frac{T_4}{T_1} = \frac{T_3}{T_2} = \left(\frac{P_H}{P_C}\right)^{\frac{\gamma-1}{\gamma}} \tag{7.8}$$

From the following algebraic rule,

$$\frac{a}{b} = \frac{c}{d} = \frac{a-c}{b-d} = \frac{a+c}{b+d}$$

and from Eqn.(7.8), it can be written that

$$\frac{T_3 - T_4}{T_2 - T_1} = \frac{T_3}{T_2} \tag{7.9}$$

Using Eqn.(7.9) in Eqn.(7.7), we get

$$\text{COP} = \frac{1}{(T_3/T_2) - 1} = \frac{T_2}{T_3 - T_2} \tag{7.10}$$

i.e., COP is written in terms of entry and exit temperatures of compression.

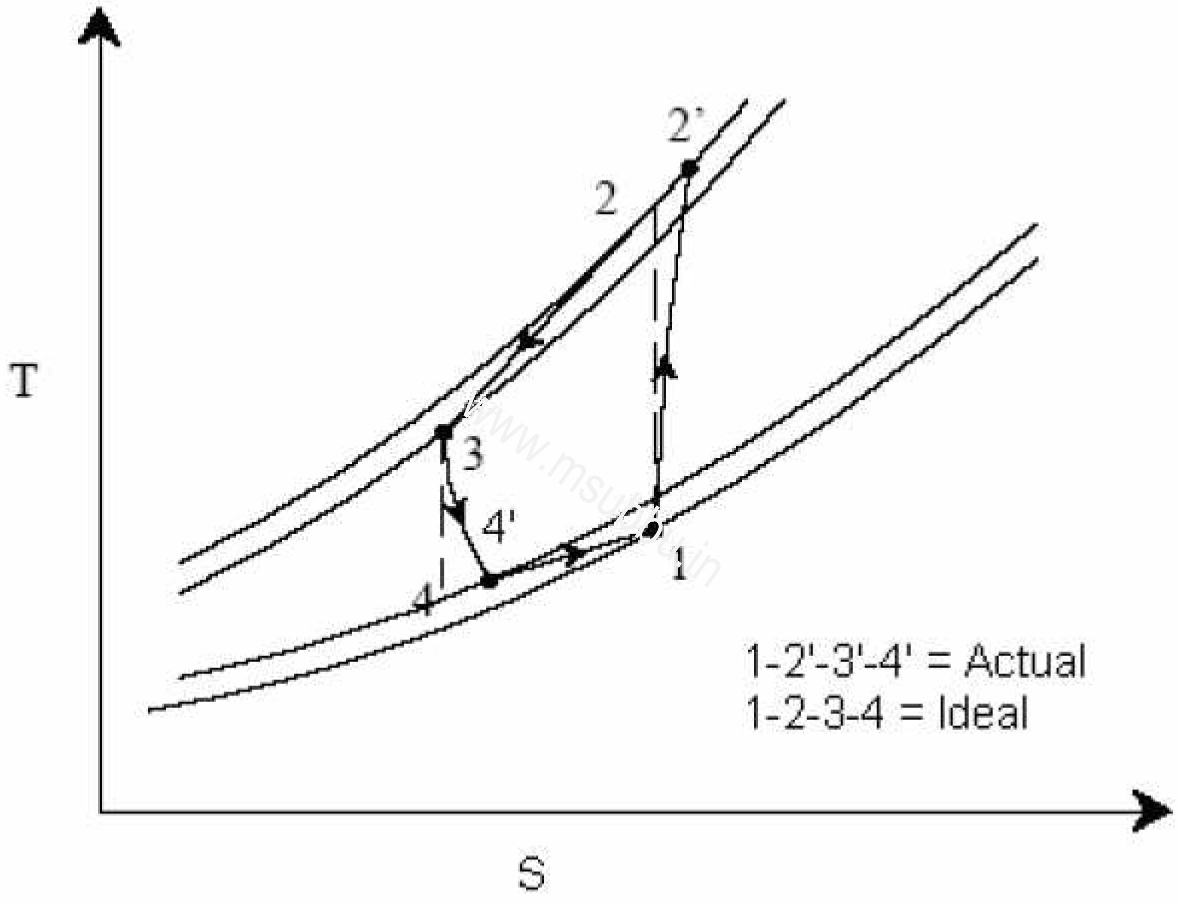
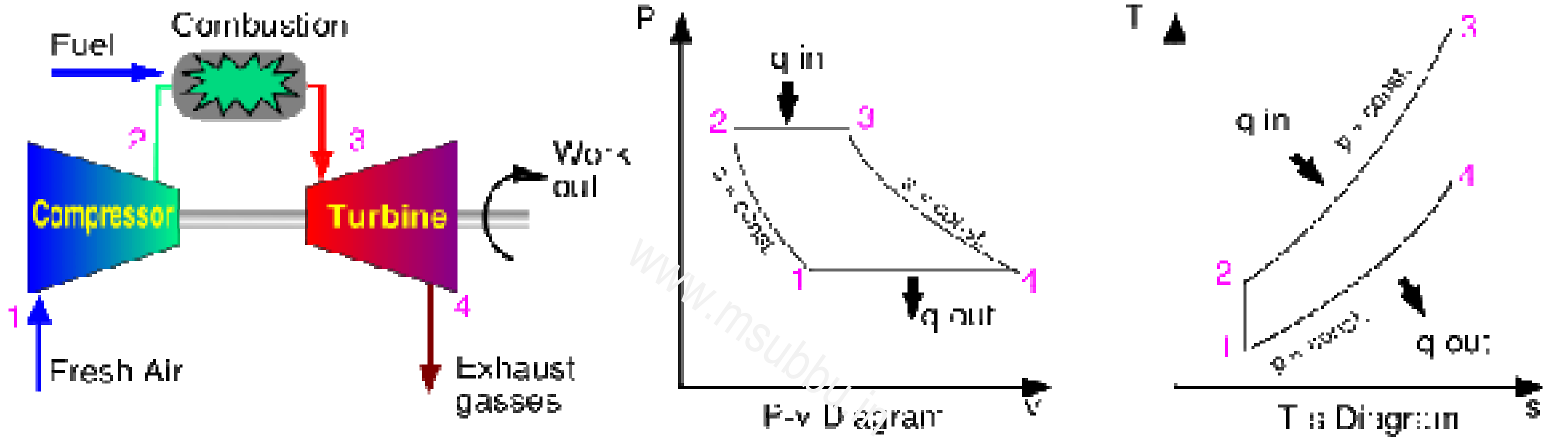
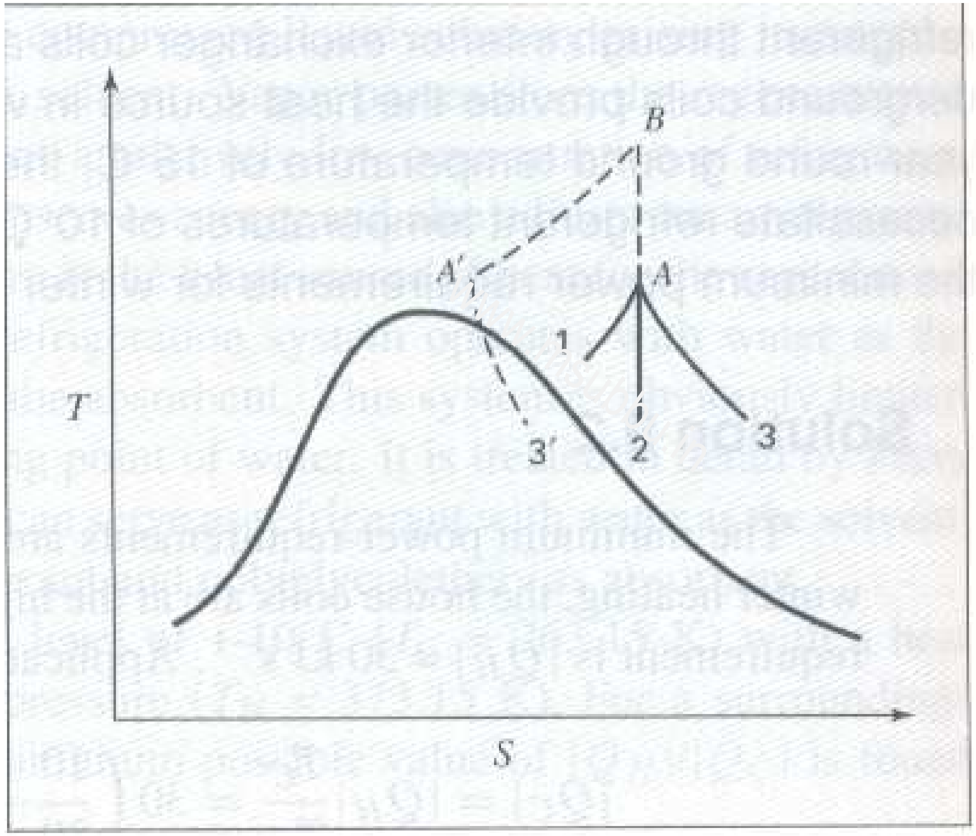


***Fig. 9.4**. Comparison of ideal and actual Brayton cycles T-s plane*



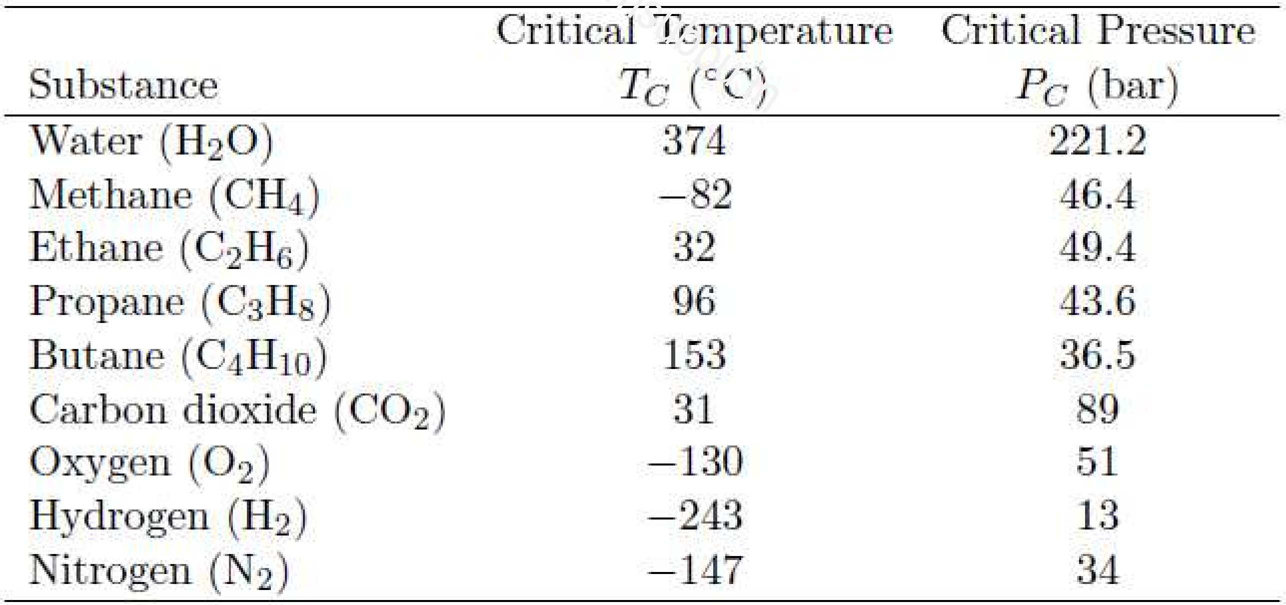
Idealized Brayton Cycle

Liquefaction



Liquefaction of Gases

- If the temperature and pressure of a gas can be brought into the region between the saturated liquid and saturated vapour lines then the gas will become ‘wet’ and this ‘wetness’ will condense giving a liquid.
- *Most gases existing in the atmosphere are extremely superheated, but are at pressures well below their critical pressures.*



Substance	Critical Temperature T_C (°C)	Critical Pressure P_C (bar)
Water (H_2O)	374	221.2
Methane (CH_4)	−82	46.4
Ethane (C_2H_6)	32	49.4
Propane (C_3H_8)	96	43.6
Butane (C_4H_{10})	153	36.5
Carbon dioxide (CO_2)	31	89
Oxygen (O_2)	−130	51
Hydrogen (H_2)	−243	13
Nitrogen (N_2)	−147	34

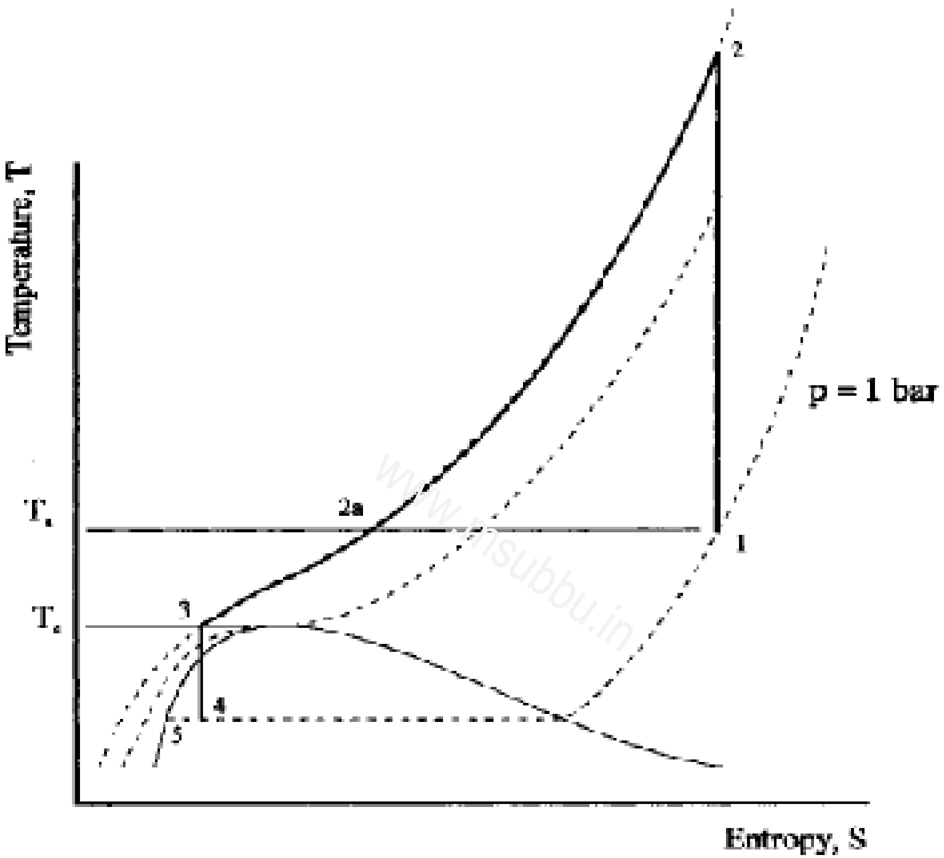
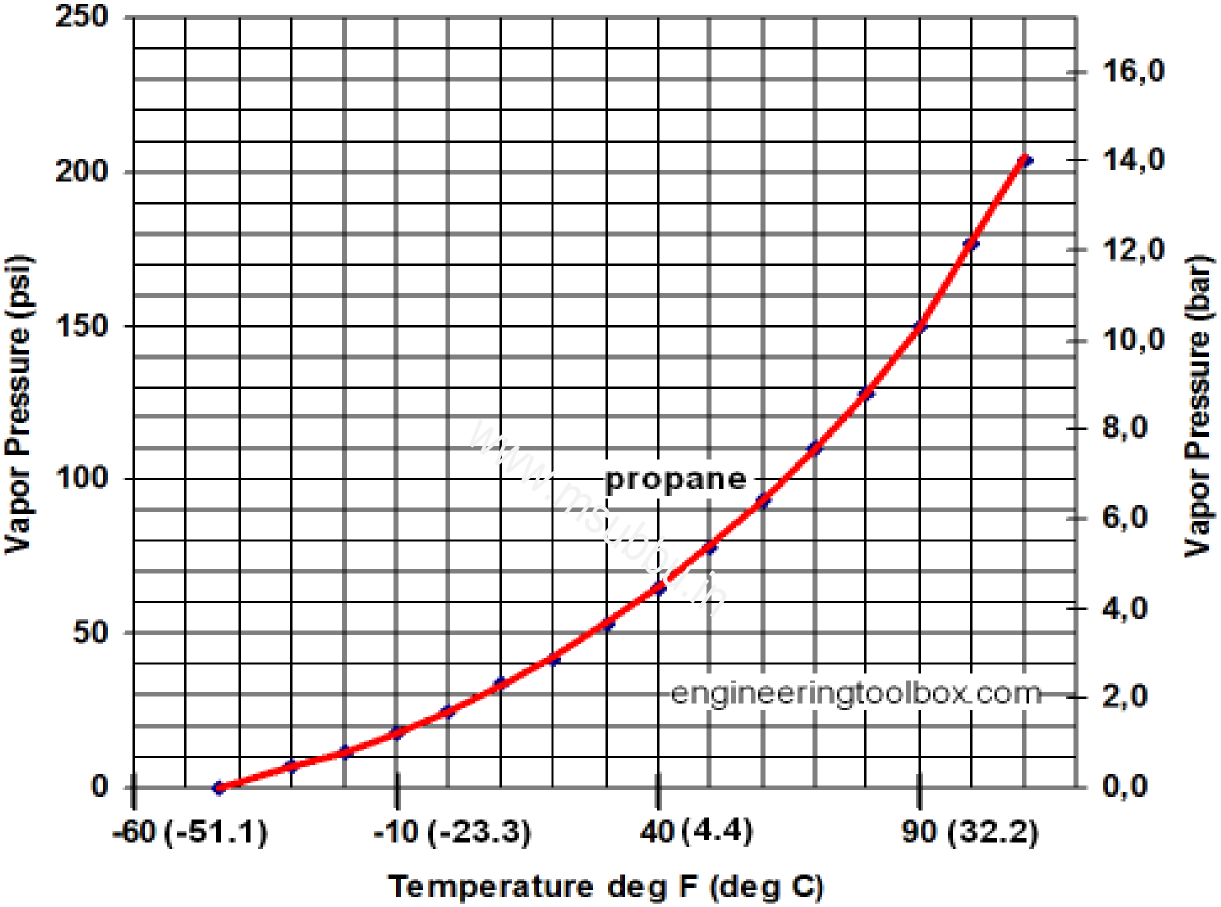


Fig. 8.6 A method for liquefying a gas



LPG in India: 60%Butane, 40%Propane Mix

Liquefaction Process

- The essence of liquefaction is to cool the gas until it passes into the two-phase region. This cooling may be accomplished in several ways:
  1. Cooling at constant pressure, as in a heat exchanger (using refrigeration)
  2. Cooling by expansion in a turbine
  3. Cooling by expansion in a throttle vale

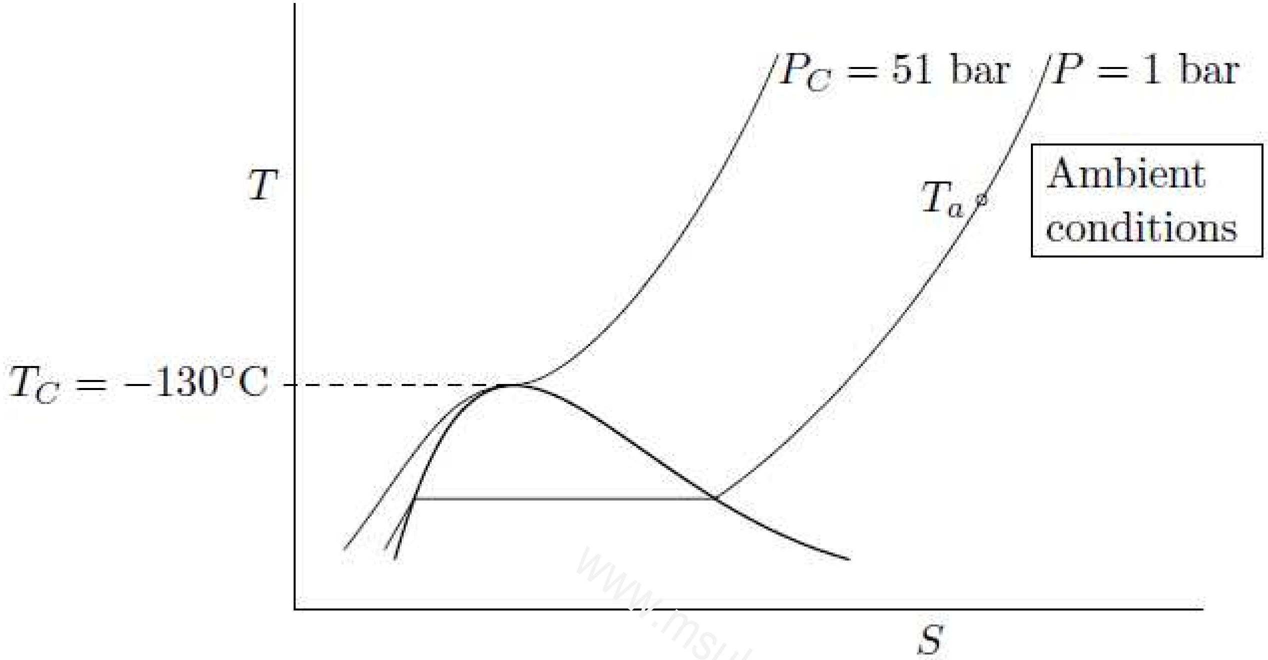


Figure 7.4: State point of oxygen at ambient temperature and pressure

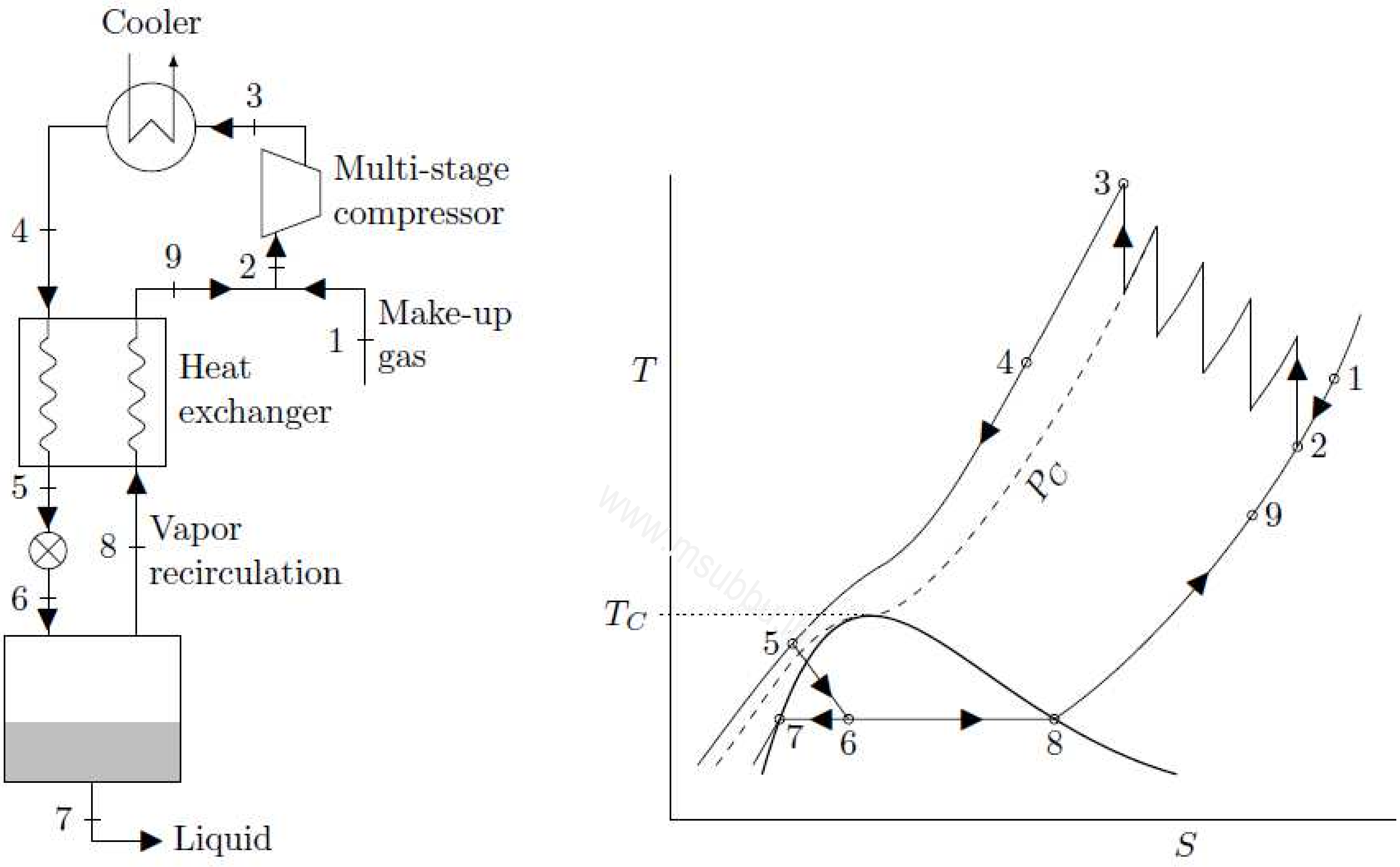


Figure 7.5: Linde-Hampson cycle for liquefying gases

Claude's process: Isentropic expansion

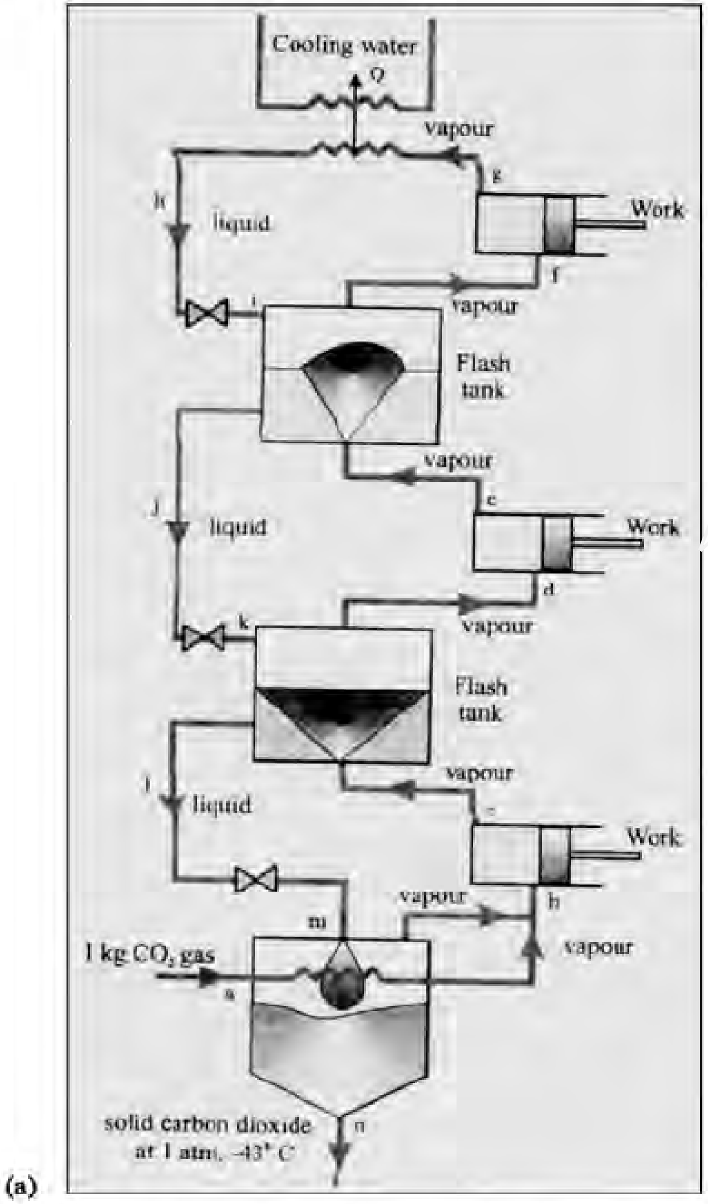


Fig. 8.5 Plant for manufacture of dry ice (solid carbon dioxide)

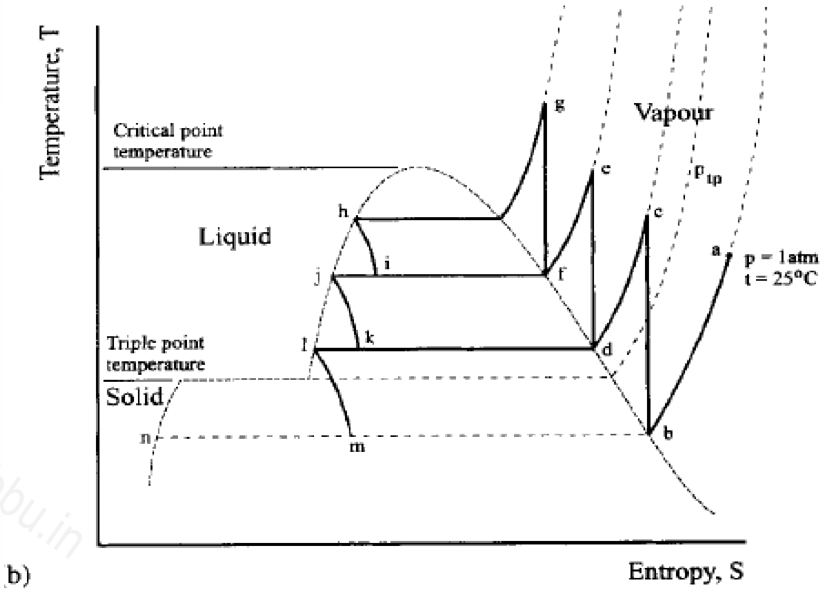


Fig. 8.5 *Continued*