Refrigeration and Liquefaction

- Refrigeration
  - Air conditioning of building
  - Preservation of foods and beverages
  - Manufacture of ice
  - Dehydration of gases
  - Purifications ,separations
  - Low temperature reactions
- Liquefaction
  - Propane gases in cylinders
  - Liquid oxygen for rockets
  - LNG (Liquid Natural Gas)
  - Separation of air

Carnot Refrigeration

- Reversed heat-engine cycle
  - Heat is absorbed at low T
  - Heat is rejected at high T
  - Requires external source of energy : W

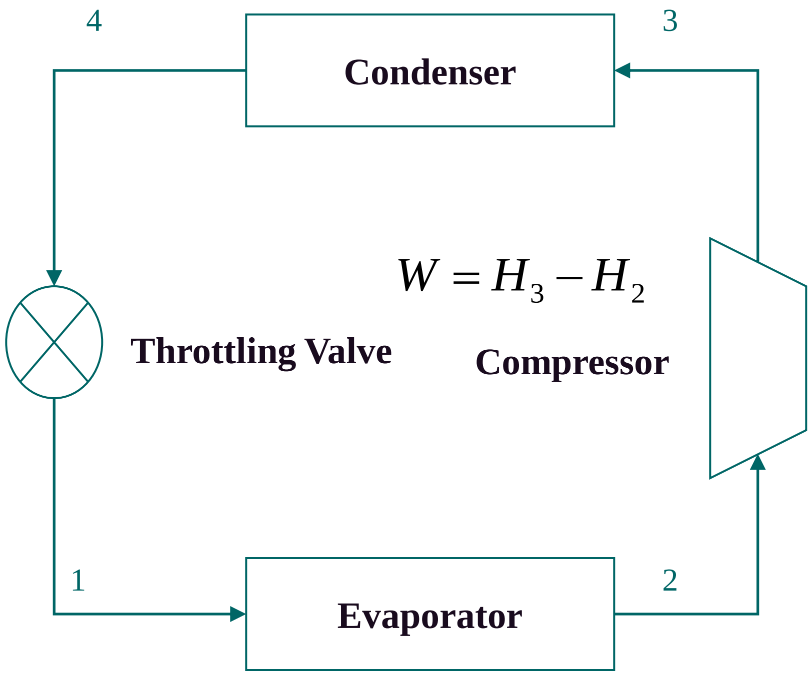
$$W = |Q_H| - |Q_C|$$

$$\omega \equiv \frac{|Q_C|}{W} = \frac{T_C}{T_H - T_C}$$

Where ω is a coefficient of Performance (COP)

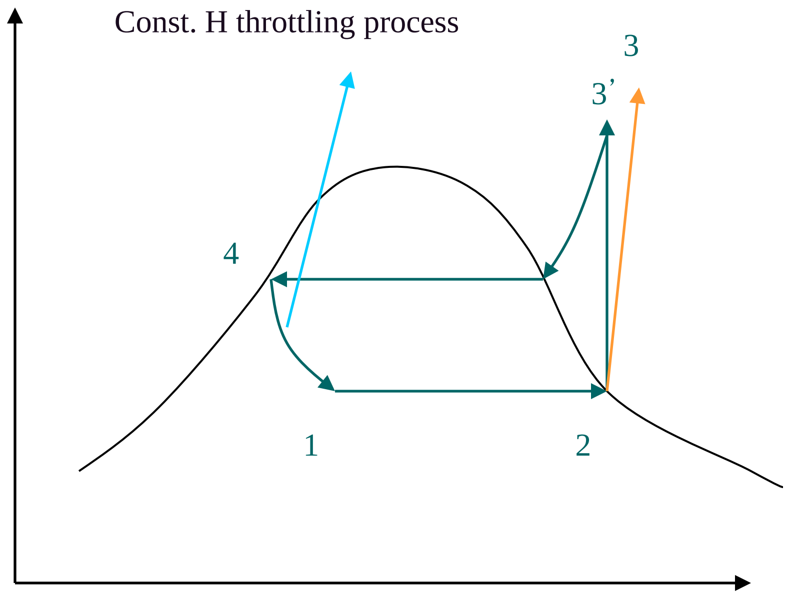
Vapor-Compression Cycle

$$|Q_H| = H_3 - H_4$$



$$W = H_3 - H_2$$

$$|Q_C| = H_2 - H_1$$



$$\omega = \frac{|Q_C|}{W} = \frac{H_2 - H_1}{H_3 - H_2}$$

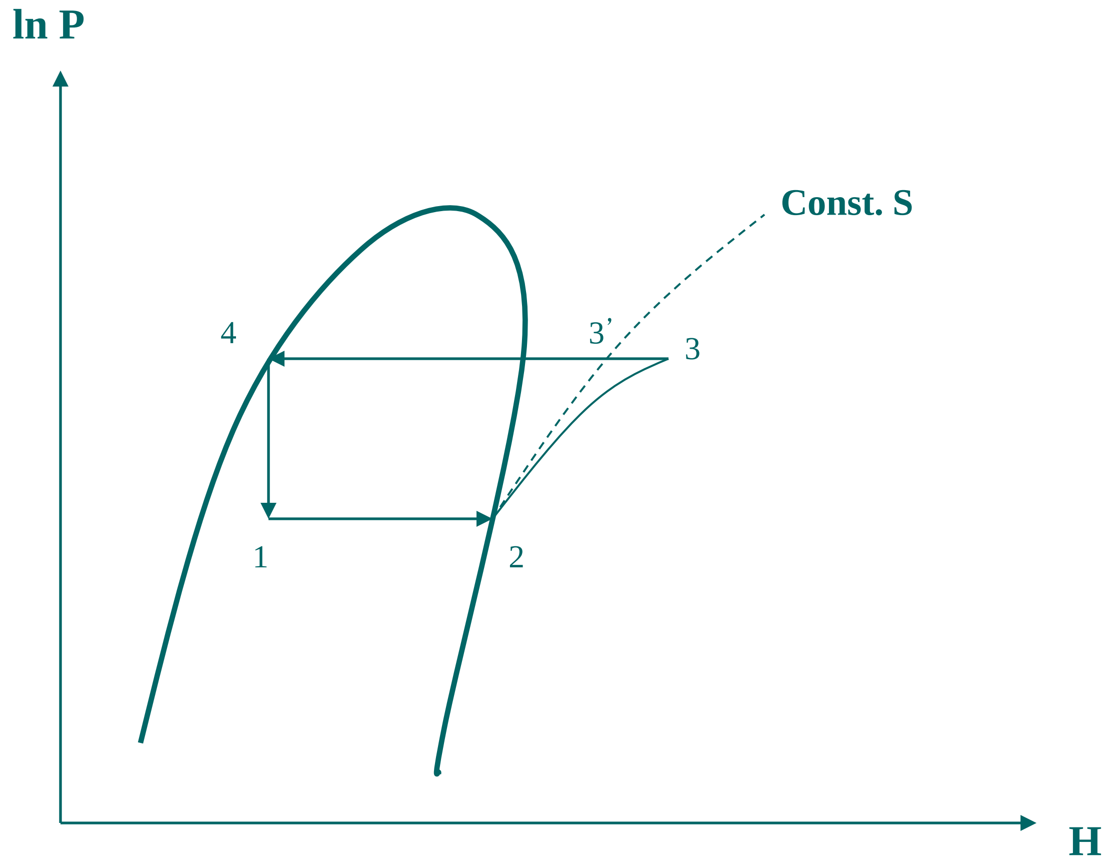
Coefficient of Performance

$$\dot{m} = \frac{|Q_C|}{H_2 - H_1}$$

Rate of circulation of refrigerant

Vapor-compression refrigeration cycle on P-H diagram

- **P-H diagrams are more commonly used in refrigeration cycle than TS diagrams.**
- **The evaporation and condensation processes are represented by constant-pressure paths.**



Example 9.1: A refrigerated space is maintained at 10 (^oF) and cooling water is available at 70 (^oF). Refrigeration capacity is 12,000 Btu/h. The evaporator condenser are of sufficient size that a 10 (^oF) minimum temperature difference for heat transfer can be realized in each. The refrigerant is tetrafluoroethane (HCF-134a), for which data are given in Table 9.1 and Fig.G.2 (App.G).

(a) Whate is the value of COP for a Carnot Refrigerator ?

(b) Cacluate COP and m for the vapor-compression cycle of Fig.9.1 if the compressor efficiency is 0.80 .

Solution

a) 10 ^{o} F Minimum temperature difference :

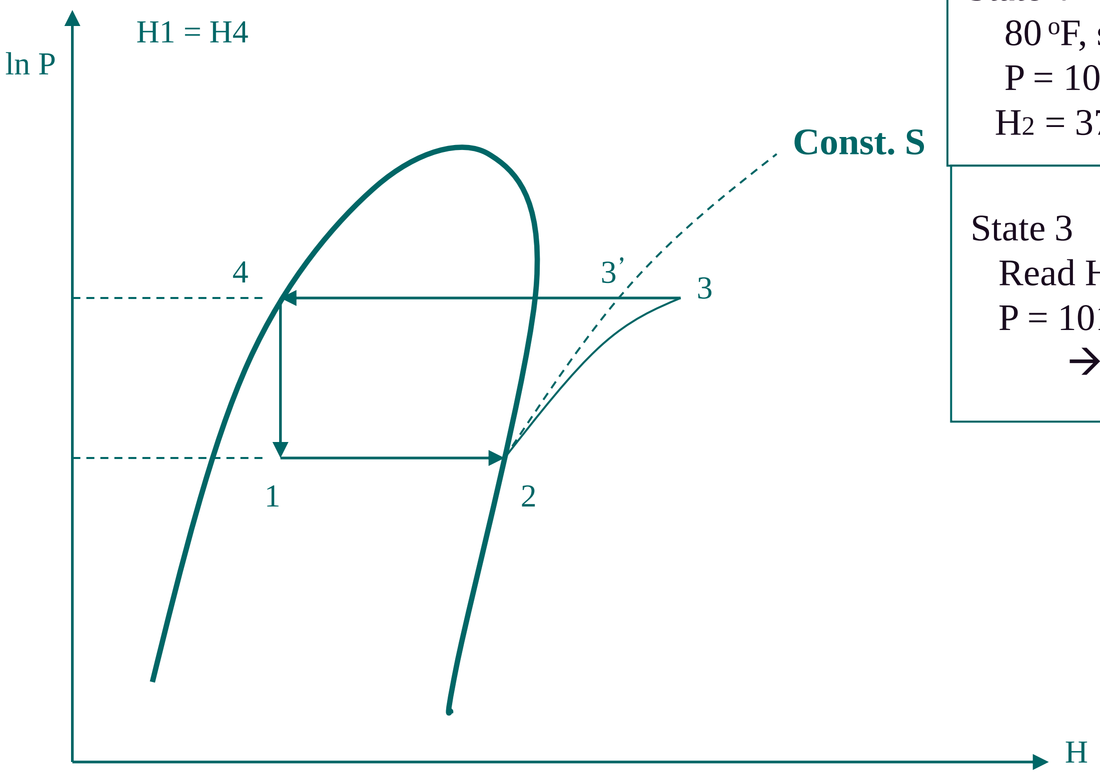
Tc = 0 ^{o}F

Th = 80 ^{o}F

$$\omega = \frac{|Q_C|}{W} = \frac{T_C}{T_H - T_C} = \frac{(0+459.67)}{(80+459.67)-(0+459.67)} = 5.75$$

(b)

H_1, H_2, H_3, H_4



State 2
0 °F, saturation condition (V)
P = 21.162 psia
H_2 = 103.015 Btu/lbm
S_2 = 0.22525 Btu/lbm.F

State 4
80 °F, saturation condition (L)
P = 101.37 psia
H_2 = 37.987 Btu/lbm

State 3
Read H from Fig.G.2.
P = 101.37 psia, S=0.22525
→ H_3' = 117 Btu /lbm

$$\left(\Delta H\right)_S = H_{3'} - H_2 = 117 - 103.015 = 13.98$$

$$\eta = 0.8 = \frac{\left(\Delta H\right)_S}{\Delta H}$$

$$\Delta H = \frac{\left(\Delta H\right)_S}{\eta} = \frac{13.98}{0.8} = 17.48$$

- **COP**

$$\omega = \frac{H_2 - H_1}{H_3 - H_2} = \frac{103.015 - 37.978}{17.48} = 3.72$$

- **Refrigerant Circulation Rate**

$$\dot{m} = \frac{\left|Q_C\right|}{H_2 - H_1} = \frac{120{,}000}{103.105 - 37.978} = 1{,}845 lb_m / hr$$

The Choice of Refrigerant

- ✓ In principle, COP of Carnot refrigerator is independent of the refrigerant.
- ✓ Irreversibility in the refrigerator cause the COP to depend on the choice of refrigerant .

❖ Main characteristics

- Vapor pressure of the refrigerant at evaporation T should be greater than 1 atm.
- Vapor pressure condenser T should not be high.

❖ Additional characteristics

- Toxicity
- Flammability
- Cost
- Corrosion properties
- Environmental consideration

Choice of Refrigerant

- **Ammonia, Methyl chloride, Carbon Dioxide, Propane and other hydrocarbons.**
- **Halogenated Hydrogcarons (CFC,HCFC)**
  - **CCl_3F (CFC-11), CCl_2F_2 (CFC-12)**
  - **Replacement**
    - **$CHCl_2CF_3$ (HCF-123), CF_3CH_2F(HCF-134a), CHF_2CF_3 (HCF-125)**

Cascade refrigeration systems

- To overcome the limit of operation…
  - Tc fixed : environments
  - Two or more refrigeration cycle employing different refrigerant

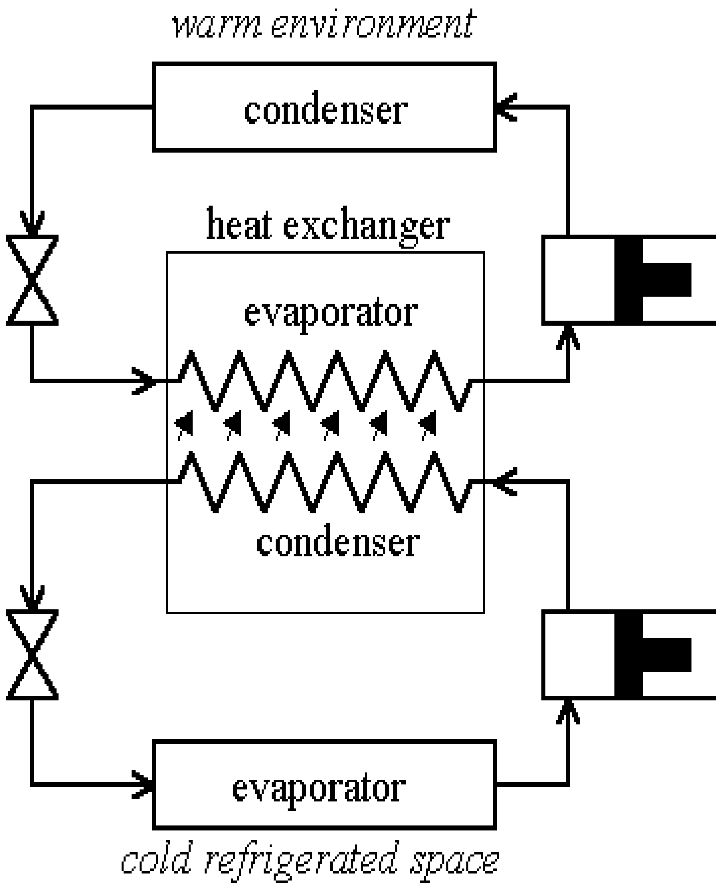
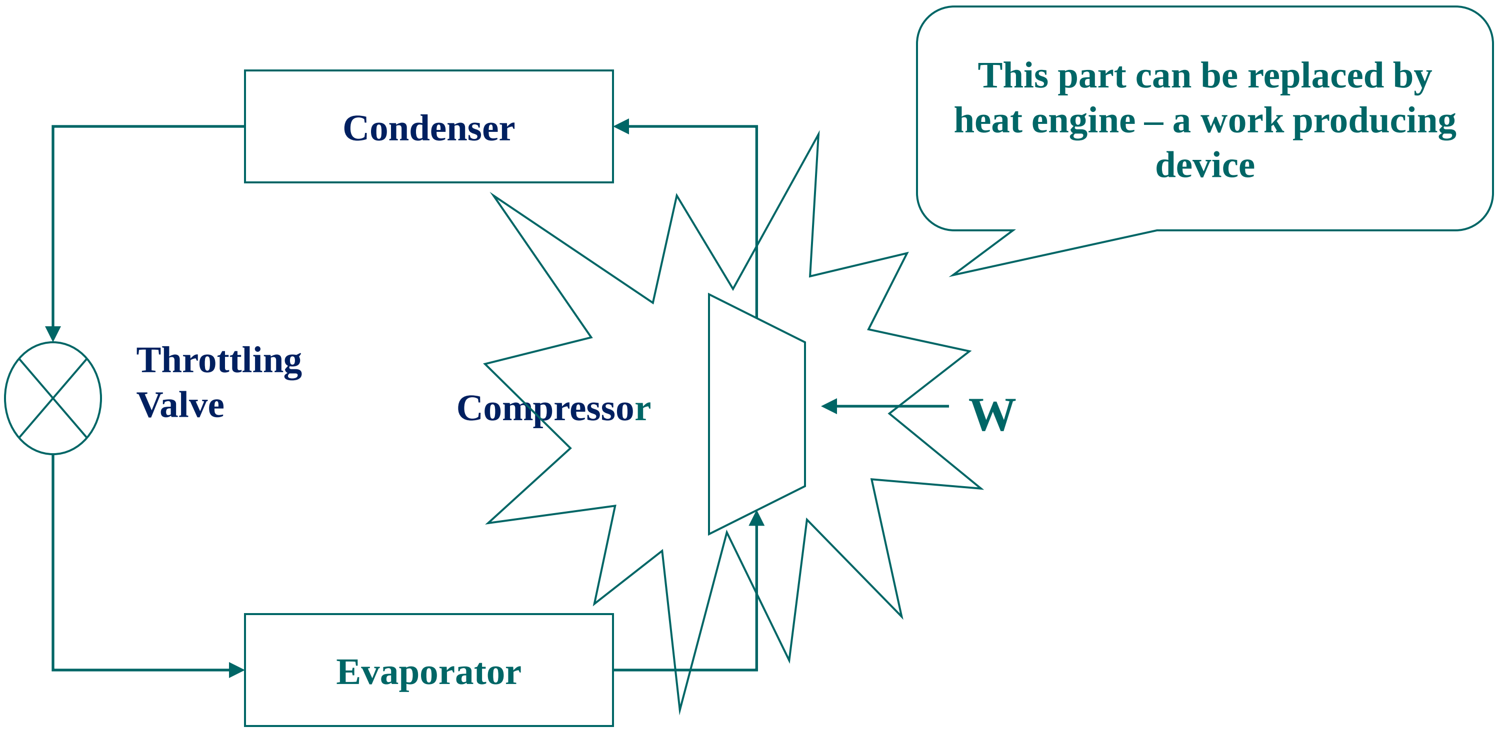
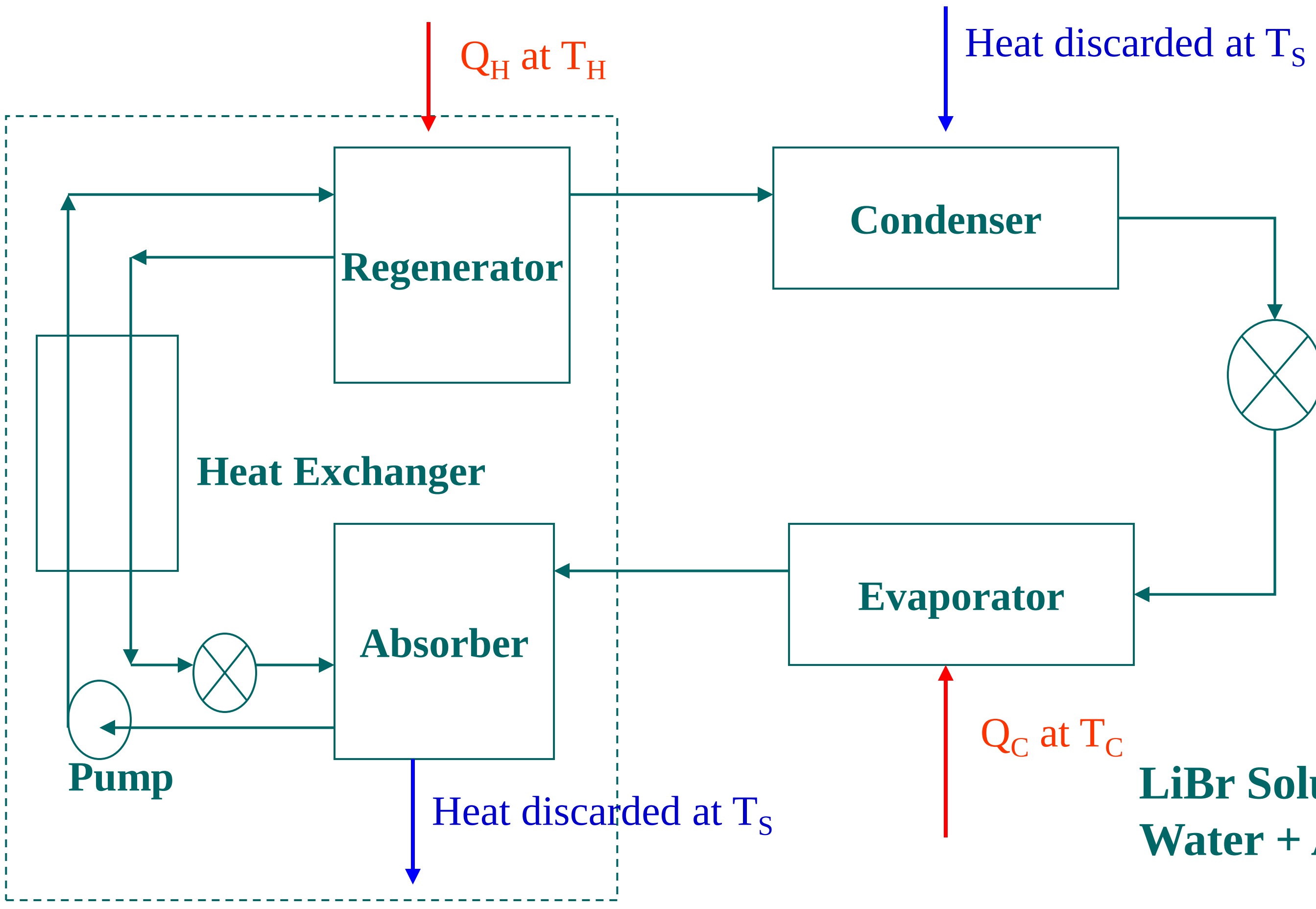


Figure A two-stage cascade refrigeration system

Absorption Refrigeration



Schematic Diagram of an Absorption-Refrigeration Unit



LiBr Solution + Water

Water + Ammonia

Analysis

Work required for
the refrigeration cycle

$$W = \frac{T_S - T_C}{T_C}\left|Q_C\right|$$

Heat required for
the production of
the work.

$$\eta = \frac{\left|W\right|}{\left|Q_H\right|} = 1 - \frac{T_S}{T_H}$$

$$\left|Q_H\right| = \left|W\right|\frac{T_H}{T_H - T_S}$$

$$\left|Q_H\right| = \left|Q_C\right|\frac{T_H}{T_H - T_S}\frac{T_S - T_C}{T_C}$$

The Heat Pump

- Dual-purpose reversed heat engine
  - Winter : Heating
  - Summer : Cooling
- If COP = 4, five times work has to be done to the compressor.
- Economic advantage depends on the cost of electricity vs. oil and natural gases.

Liquefaction Processes

- **Liquefaction processes**
  - By heat exchange at const. P
  - By an expansion process from which work is obtained (Adiabatic expansion)
  - By a throttling process

- For small-scale commercial liquefaction plant, throttling process is commonly employed.
- Sufficiently low T and high P desired.

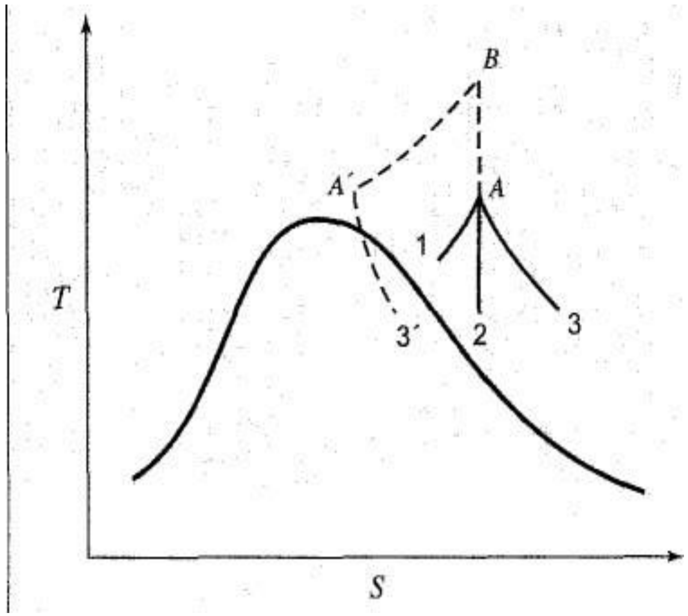


Figure Cooling processes on a TS diagram

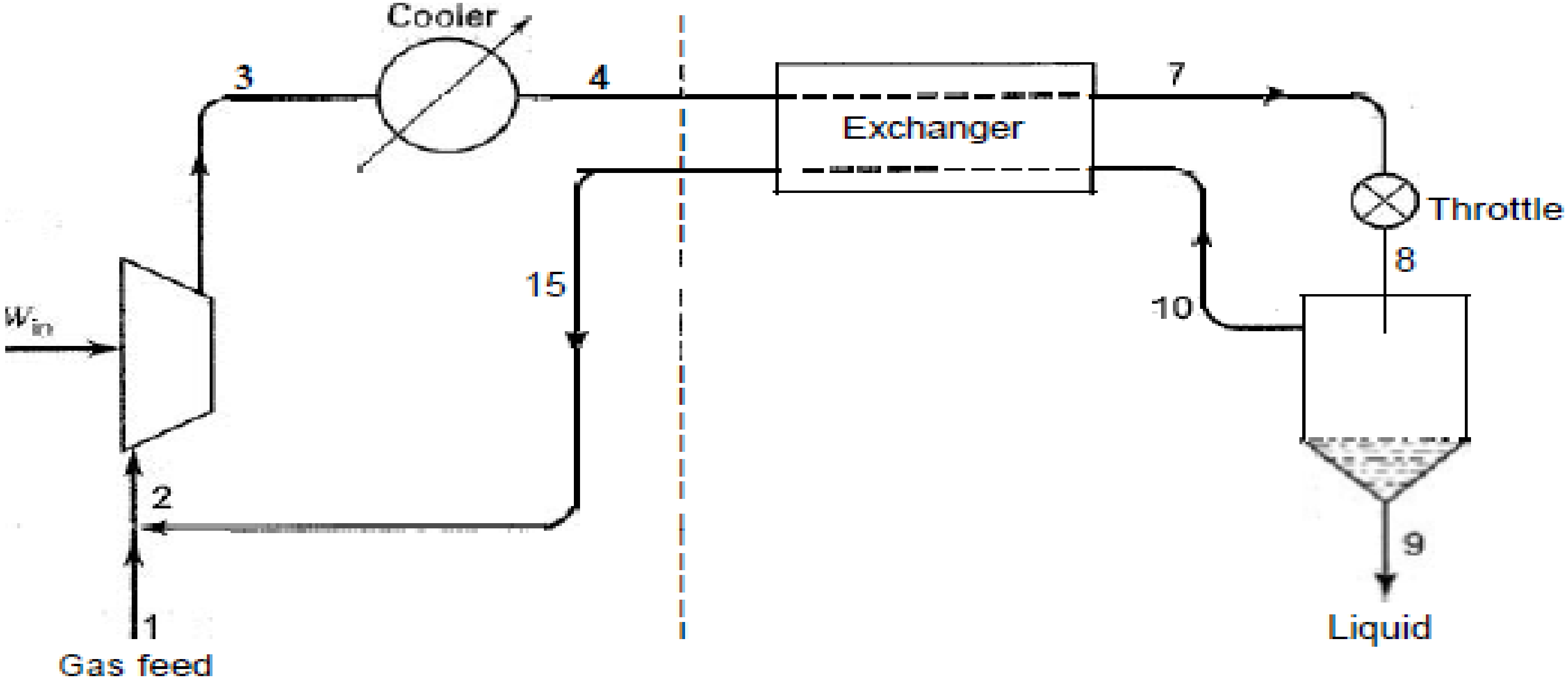


Figure . Linde liquefaction process