化工熱力學

Ch.5

Some Industrial Applications based on Pure Fluids

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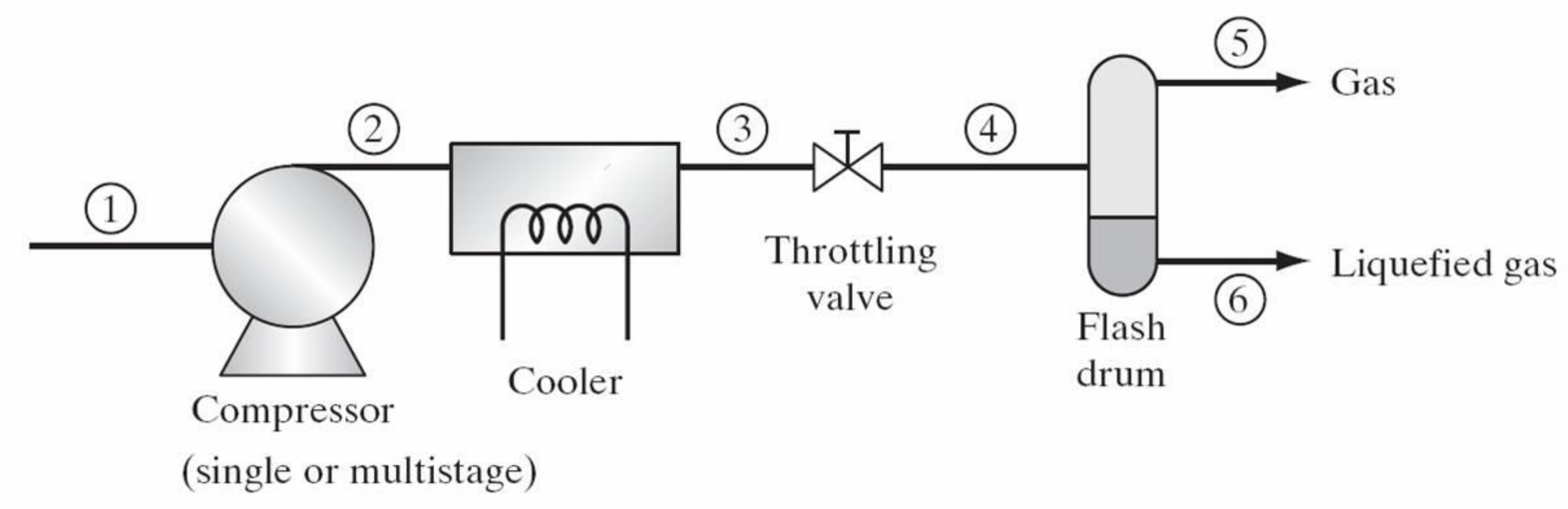
Outline

1. Liquefaction
2. Power Cycles
3. Refrigeration Cycles
4. Power and Refrigeration Cycles

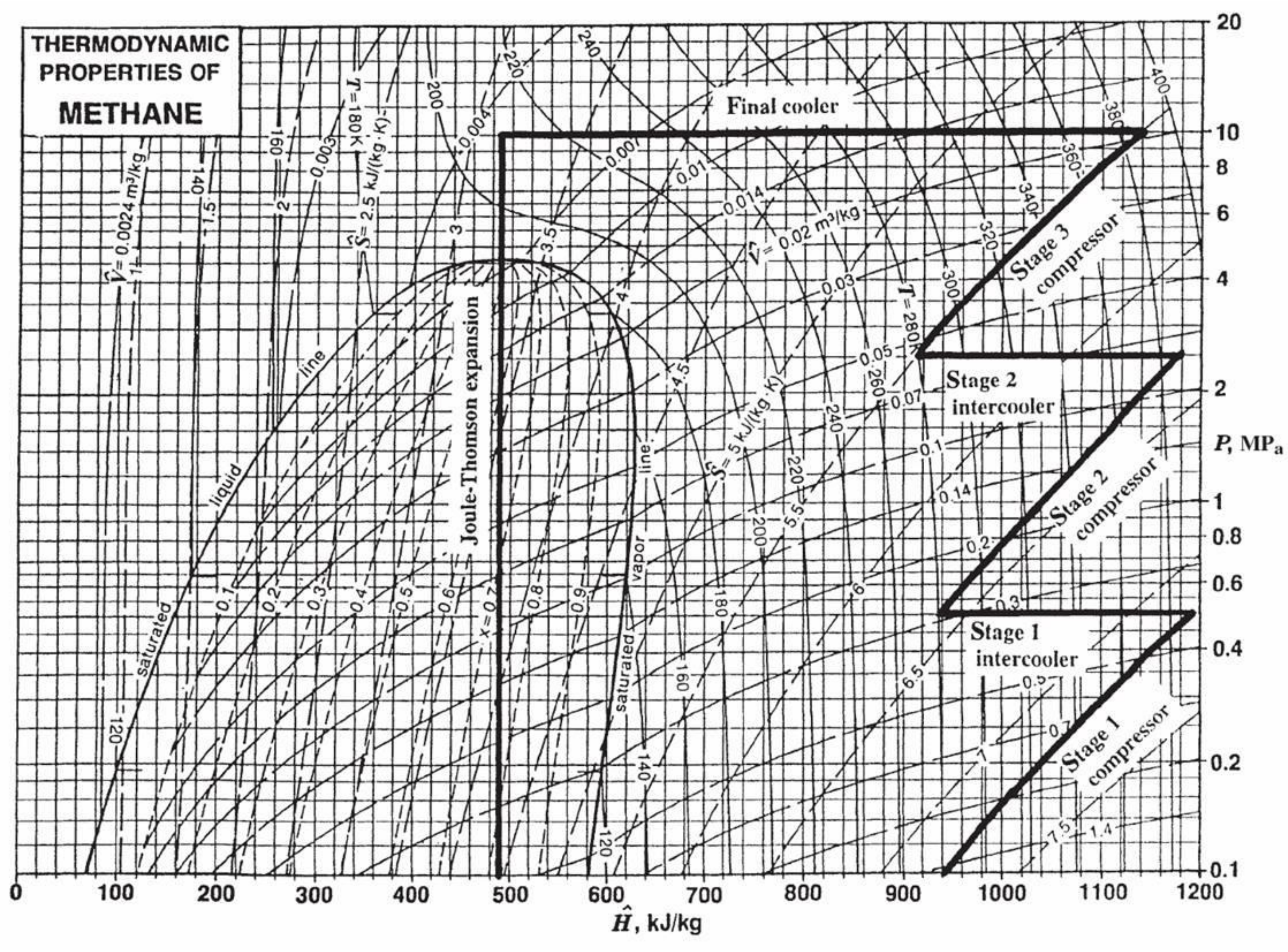
Liquefaction of Gases

- Industrial process for, e.g., natural gas (to LNG), petroleum gas (to LPG), refrigerant gases.
- The efficiency = the amount of liquefied gas produced per unit of work done in the compressor



NOTE: Compression usually results in an increase in T and expansion usually resulted in an decrease in T. The importance is how to increase the efficiency.

Liquefaction of Gases



Liquefaction of Gases

Industrial applications:

- natural gas (LNG)
- Propane
- refrigerant gases.

* Liquefy a gas ← cool it down to $T < T_b$

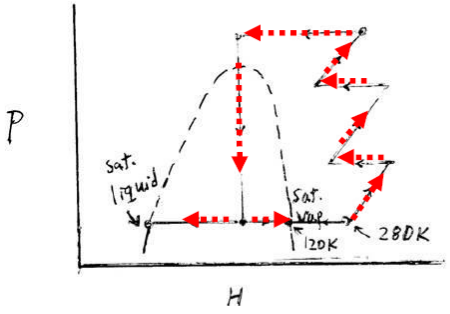
↑ refrigeration equipment is required

* Industrial processes

gas at low P $\xrightarrow{\text{compress}}$ high P gas

↓ Cooling at high P

Low T, P gas + liquid $\xleftarrow{\text{expansion}}$ Low T high P gas



Nitrogen can be liquefied using a Joule-Thomson expansion process. This is done by rapidly and adiabatically expanding cold nitrogen gas from high pressure to a low pressure. If nitrogen at 135 K and 20 MPa undergoes a Joule-Thomson expansion to 0.4 MPa, estimate the fraction of vapor and liquid present after the expansion, and the temperature of this mixture using the P-H diagram for nitrogen.

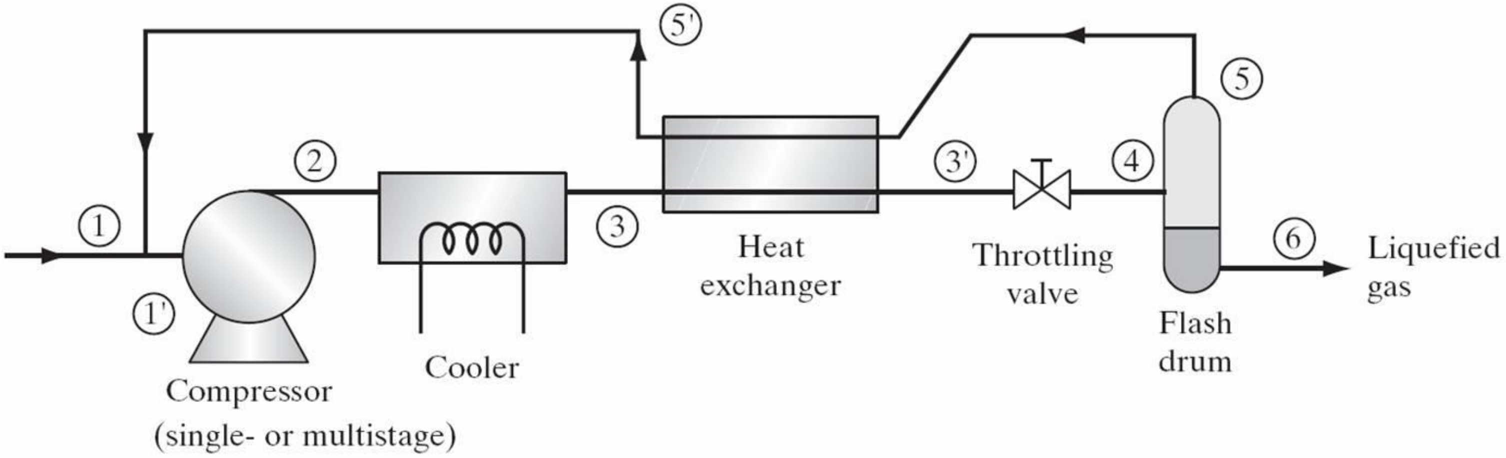
Liquefaction of Gases

- Ex. 5.1-1 Linde Liquefaction Process

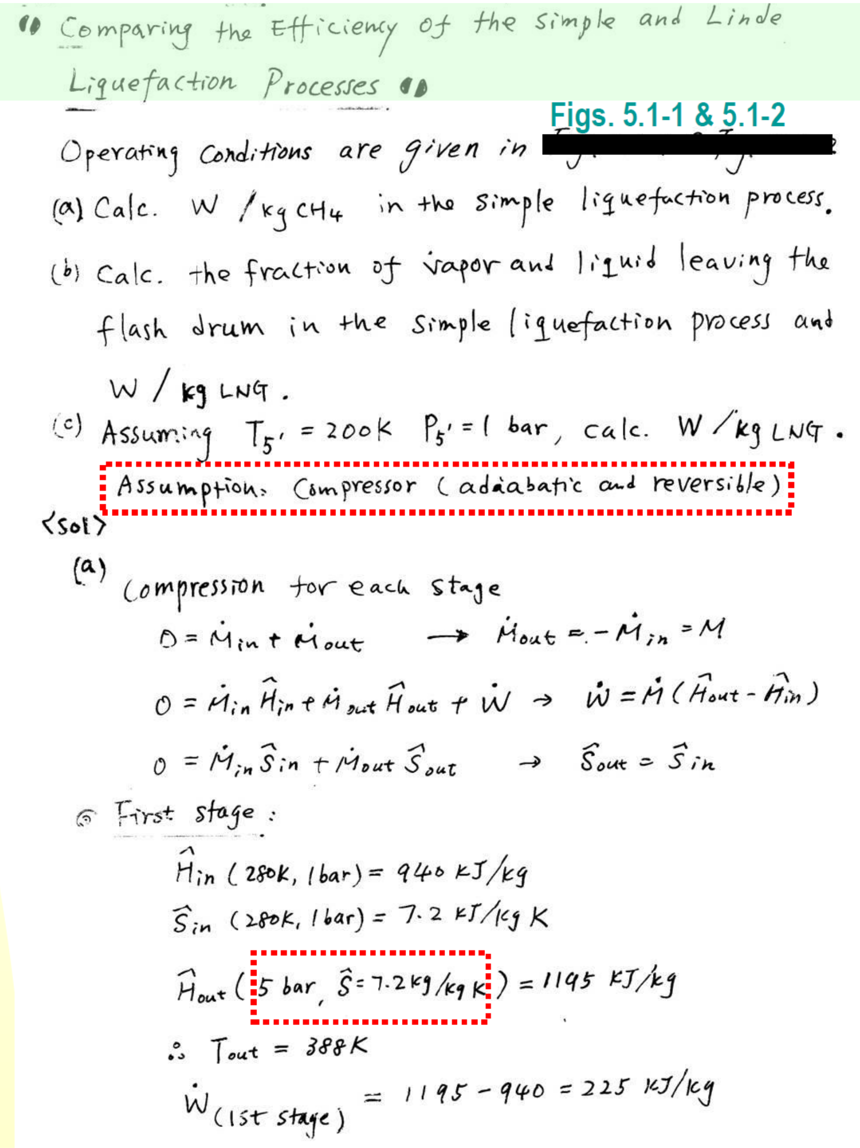
  Consider pure methane (natural gas) at 1 bar and 280 K is compressed and then cooled to 100 bar and 210 K. The flash drum is adiabatic and operates at 1 bar. The compressor is operated via 3-stage, from 1 to 5, 5 to 25, and 25 to 100 bar, with isobaric intercooling to 280 K.

  (a) Calculate the amount of work required per kg of methane.

  (b) Calculate the fraction of vapor and liquids leaving the flash drum.



Liquefaction of Gases



“ Comparing the Efficiency of the Simple and Linde Liquefaction Processes ”

Figs. 5.1-1 & 5.1-2

Operating Conditions are given in [redacted]

(a) Calc. W / kg CH_4 in the simple liquefaction process.

(b) Calc. the fraction of vapor and liquid leaving the flash drum in the simple liquefaction process and W / kg LNG.

(c) Assuming $T_{5'} = 200K$ $P_{5'} = 1$ bar, calc. W / kg LNG.

Assumption: Compressor (adiabatic and reversible)

<sol>

(a) Compression for each stage

$$0 = \dot{M}_{in} + \dot{M}_{out} \rightarrow \dot{M}_{out} = -\dot{M}_{in} = M$$

$$0 = \dot{M}_{in}\hat{H}_{in} + \dot{M}_{out}\hat{H}_{out} + \dot{W} \rightarrow \dot{W} = \dot{M}(\hat{H}_{out} - \hat{H}_{in})$$

$$0 = \dot{M}_{in}\hat{S}_{in} + \dot{M}_{out}\hat{S}_{out} \rightarrow \hat{S}_{out} = \hat{S}_{in}$$

◎ First stage:

$\hat{H}_{in}$ (280K, 1bar) = 940 kJ/kg

$\hat{S}_{in}$ (280K, 1bar) = 7.2 kJ/kg K

$\hat{H}_{out}(\boxed{5\ \text{bar},\ \hat{S} = 7.2\ \text{kg/kg K}}) = 1195$ kJ/kg

$\therefore$ $T_{out} = 388K$

$\dot{W}_{(1st\ stage)} = 1195 - 940 = 225$ kJ/kg

Liquefaction of Gases

Fig. 5.1-1

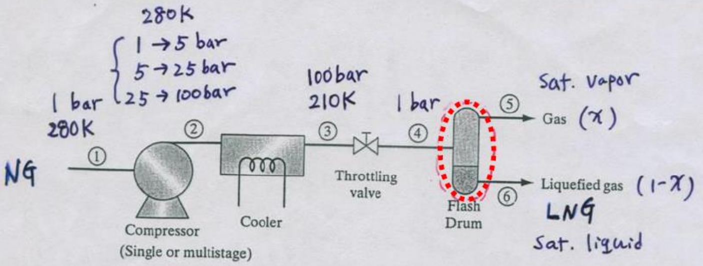


Figure [redacted] A simple liquefaction process without recycle.

[redacted]

Fig. 5.1-2

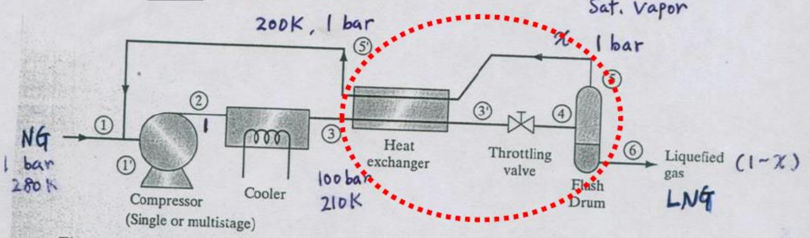
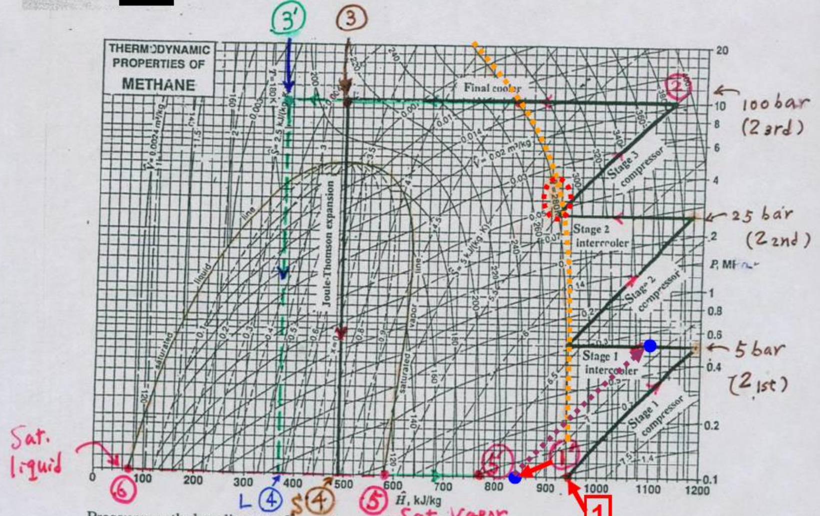


Figure [redacted] The more efficient Linde liquefaction process.

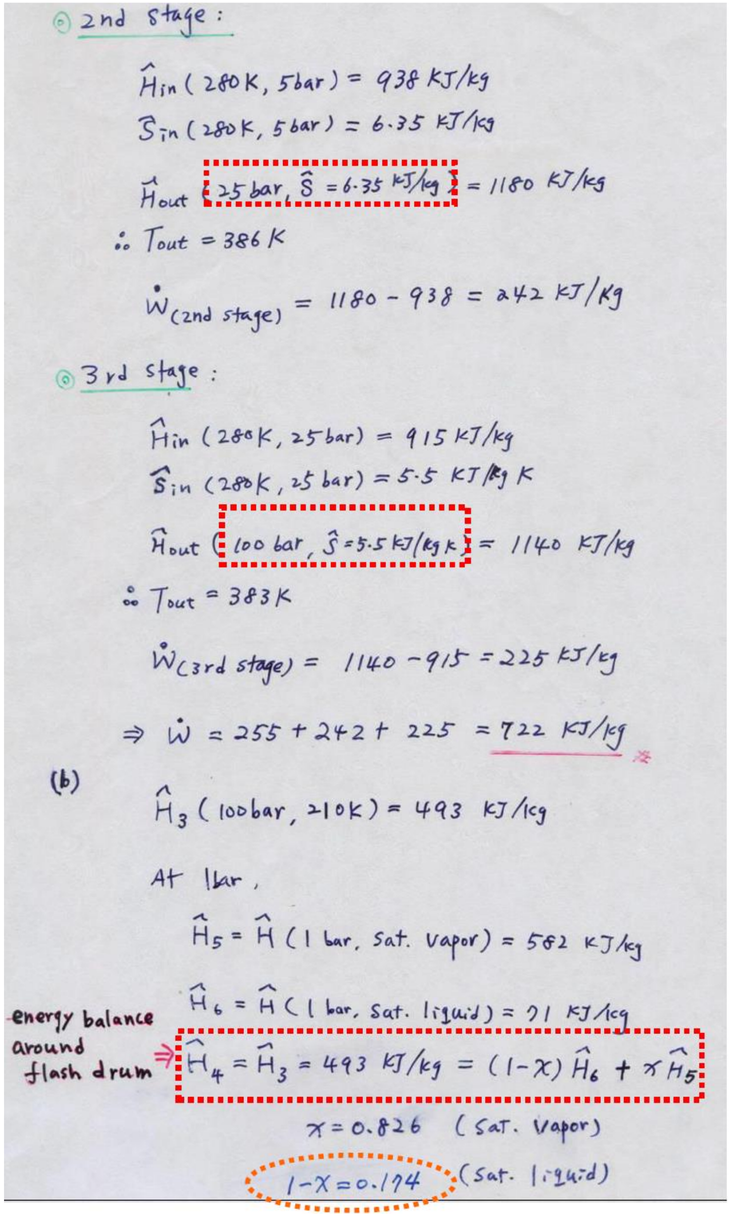
[redacted]

Fig. 5.1-3



Pressure–enthalpy diagram for methane. (*Source:* Thermodynamic Properties in SI by W. C. Reynolds, Department of Mechanical Engineering, Stanford University, Stanford, CA, 1979. Used with permission.)

Liquefaction of Gases



◎ 2nd stage :

$\hat{H}_{in}(280K, 5bar) = 938$ KJ/kg

$\hat{S}_{in}(280K, 5bar) = 6.35$ KJ/kg

$\hat{H}_{out}\boxed{(25bar, \hat{S} = 6.35 \text{ KJ/kg})} = 1180$ KJ/kg

∴ $T_{out} = 386K$

$\dot{W}_{(2nd\ stage)} = 1180 - 938 = 242$ KJ/Kg

◎ 3rd stage :

$\hat{H}_{in}(280K, 25bar) = 915$ KJ/kg

$\hat{S}_{in}(280K, 25bar) = 5.5$ KJ/kg K

$\hat{H}_{out}\boxed{(100bar, \hat{S} = 5.5 \text{ KJ/(kg K)})} = 1140$ KJ/kg

∴ $T_{out} = 383K$

$\dot{W}_{(3rd\ stage)} = 1140 - 915 = 225$ KJ/kg

⇒ $\dot{W} = 255 + 242 + 225 = \underline{722 \text{ KJ/kg}}$ ※

(b)

$\hat{H}_3(100bar, 210K) = 493$ KJ/kg

At 1bar,

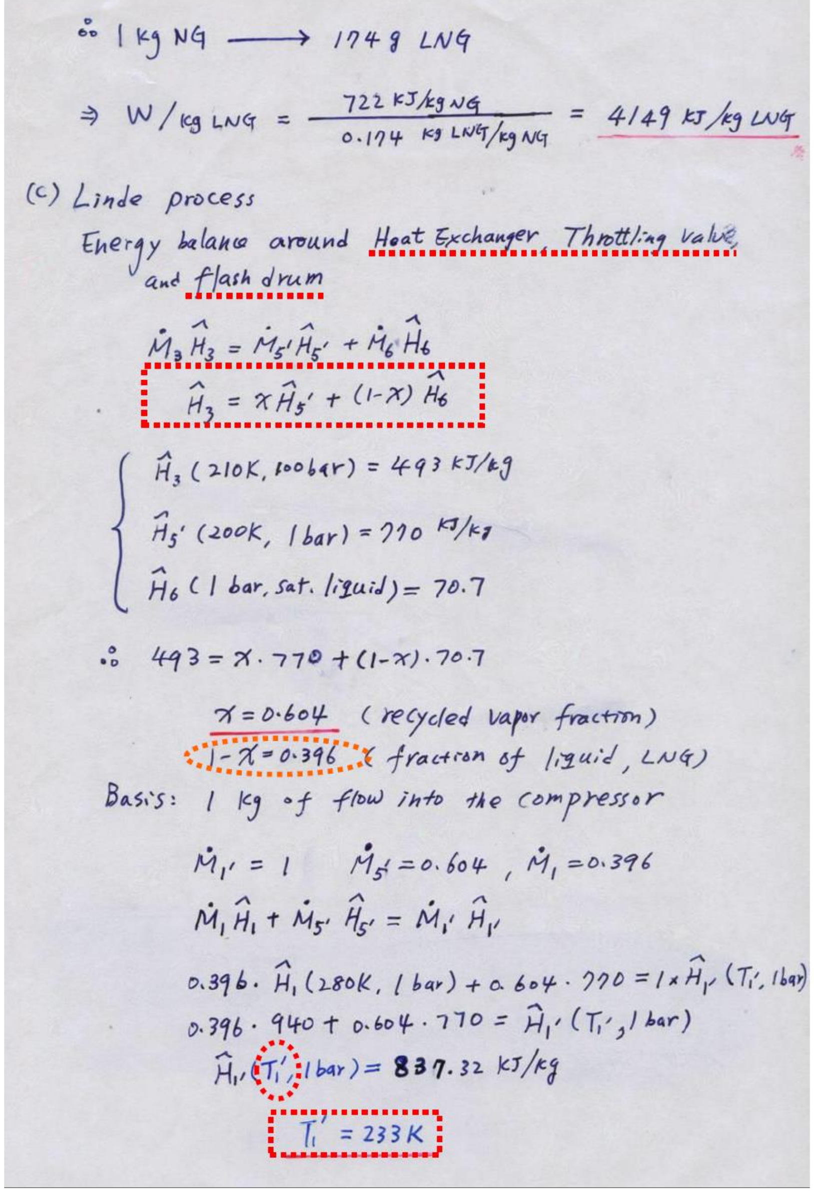
$\hat{H}_5 = \hat{H}(1 \text{ bar, Sat. vapor}) = 582$ KJ/kg

$\hat{H}_6 = \hat{H}(1 \text{ bar, Sat. liquid}) = 71$ KJ/kg

energy balance around flash drum ⇒ $\boxed{\hat{H}_4 = \hat{H}_3 = 493 \text{ KJ/kg} = (1-x)\hat{H}_6 + x\hat{H}_5}$

$x = 0.826$ (Sat. vapor)

$1 - x = 0.174$ (Sat. liquid)



∴ 1 kg NG ⟶ 174 g LNG

⇒ $W/\text{kg LNG} = \dfrac{722 \text{ KJ/kg NG}}{0.174 \text{ kg LNG/kg NG}} = \underline{4149 \text{ KJ/kg LNG}}$

(c) Linde process

Energy balance around Heat Exchanger, Throttling valve, and flash drum

$\dot{M}_3\hat{H}_3 = \dot{M}_{5'}\hat{H}_{5'} + \dot{M}_6\hat{H}_6$

$\boxed{\hat{H}_3 = x\hat{H}_{5'} + (1-x)\hat{H}_6}$

$\hat{H}_3(210K, 100bar) = 493$ KJ/kg

$\hat{H}_{5'}(200K, 1bar) = 770$ KJ/kg

$\hat{H}_6(1 \text{ bar, sat. liquid}) = 70.7$

∴ $493 = x \cdot 770 + (1-x) \cdot 70.7$

$\underline{x = 0.604}$ (recycled vapor fraction)

$1 - x = 0.396$ (fraction of liquid, LNG)

Basis: 1 kg of flow into the compressor

$\dot{M}_{1'} = 1 \quad \dot{M}_{5'} = 0.604, \ \dot{M}_1 = 0.396$

$\dot{M}_1\hat{H}_1 + \dot{M}_{5'}\hat{H}_{5'} = \dot{M}_{1'}\hat{H}_{1'}$

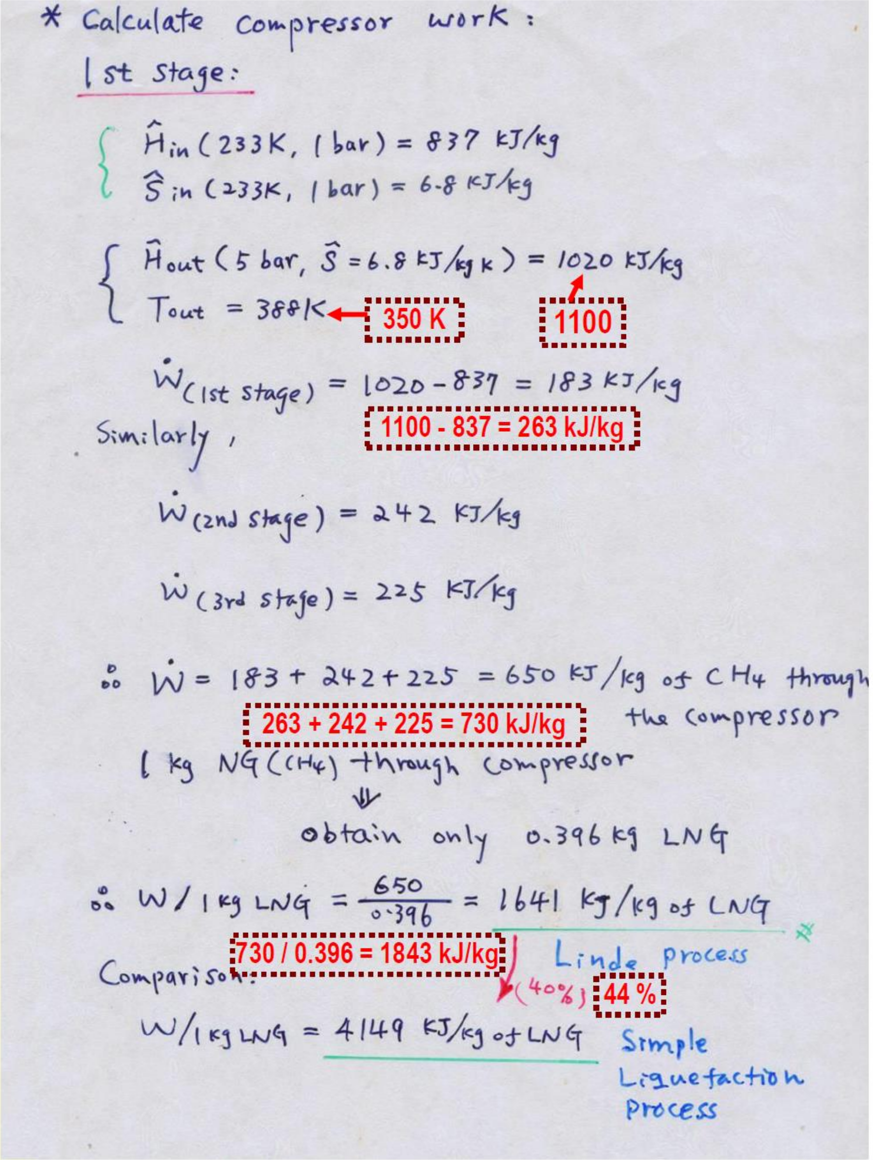
$0.396 \cdot \hat{H}_1(280K, 1bar) + 0.604 \cdot 770 = 1 \times \hat{H}_{1'}(T_1', 1bar)$

$0.396 \cdot 940 + 0.604 \cdot 770 = \hat{H}_{1'}(T_1', 1bar)$

$\hat{H}_{1'}(T_1', 1bar) = 837.32$ KJ/kg

$\boxed{T_1' = 233K}$

Liquefaction of Gases



* Calculate compressor work :

1st stage:

$\hat{H}_{in}$ (233K, 1 bar) = 837 kJ/kg
$\hat{S}_{in}$ (233K, 1 bar) = 6.8 kJ/kg

$\hat{H}_{out}$ (5 bar, $\hat{S}$ = 6.8 kJ/kg K) = 1020 kJ/kg
T_{out} = 388K

350 K

1100

$\dot{W}_{(1st\ stage)}$ = 1020 − 837 = 183 kJ/kg

1100 - 837 = 263 kJ/kg

Similarly ,

$\dot{W}_{(2nd\ stage)}$ = 242 kJ/kg

$\dot{W}_{(3rd\ stage)}$ = 225 kJ/kg

∴ $\dot{W}$ = 183 + 242 + 225 = 650 kJ/kg of CH_4 through the compressor

263 + 242 + 225 = 730 kJ/kg

1 kg NG (CH_4) through compressor

⇓

obtain only 0.396 kg LNG

∴ W / 1 kg LNG = $\frac{650}{0.396}$ = 1641 kg/kg of LNG

730 / 0.396 = 1843 kJ/kg

Linde process

(40%) 44 %

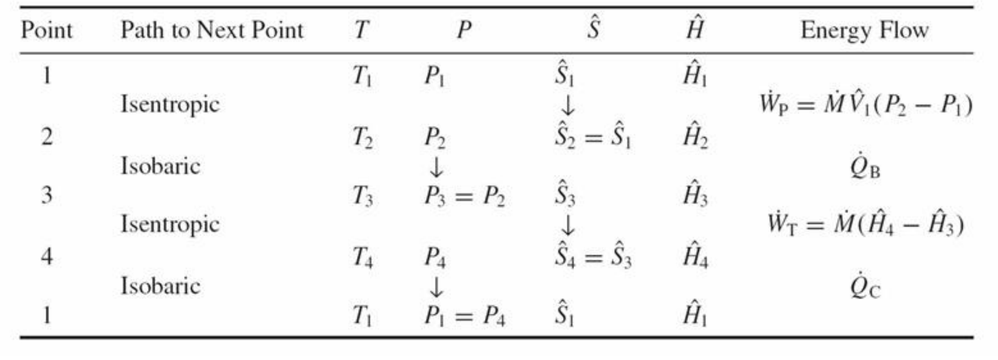
Comparison:

W/1 kg LNG = 4149 kJ/kg of LNG

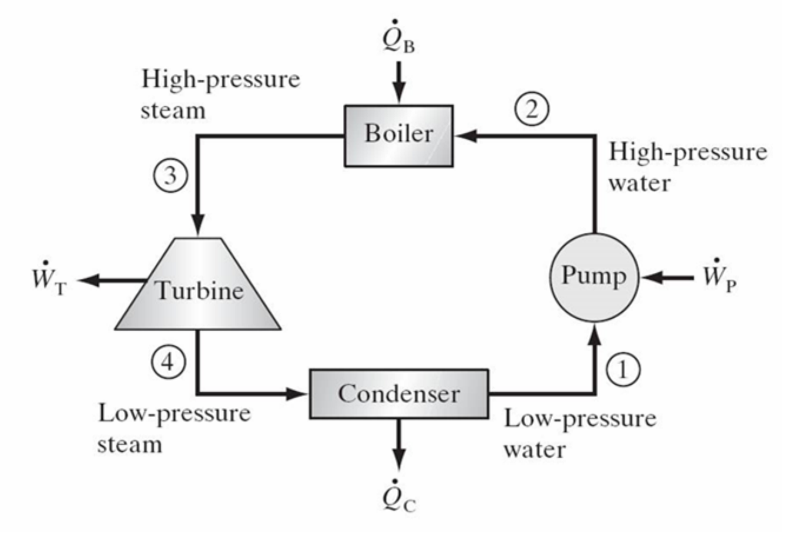
Simple Liquefaction process

Power cycles

- Canot cycle: ideal gas as the fluid in heat engine; the isothermal compression step usually requires large amount of work.
- Rankine cycle: use steam as the working fluid to run heat engine; both turbine and pump are considered to operate isentropically, the condenser operates isobarically, the heating in boiler is at constant P.



Point	Path to Next Point	T	P	$\hat{S}$	$\hat{H}$	Energy Flow
1		T_1	P_1	$\hat{S}_1$	$\hat{H}_1$	
	Isentropic			$\downarrow$		$\dot{W}_P = \dot{M}\hat{V}_1(P_2 - P_1)$
2		T_2	P_2	$\hat{S}_2 = \hat{S}_1$	$\hat{H}_2$	
	Isobaric		$\downarrow$			$\dot{Q}_B$
3		T_3	$P_3 = P_2$	$\hat{S}_3$	$\hat{H}_3$	
	Isentropic			$\downarrow$		$\dot{W}_T = \dot{M}(\hat{H}_4 - \hat{H}_3)$
4		T_4	P_4	$\hat{S}_4 = \hat{S}_3$	$\hat{H}_4$	
	Isobaric		$\downarrow$			$\dot{Q}_C$
1		T_1	$P_1 = P_4$	$\hat{S}_1$	$\hat{H}_1$	

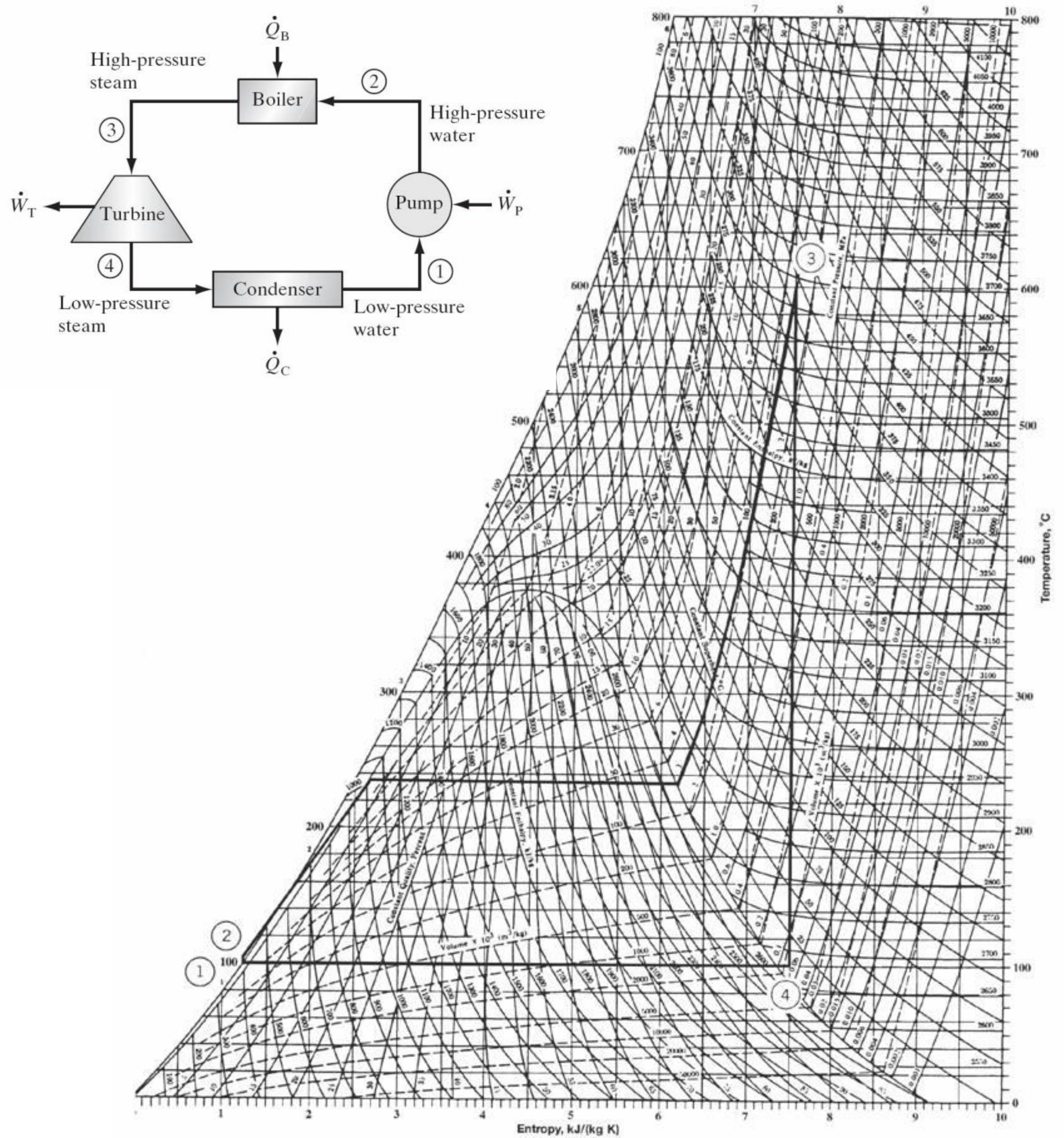


Power Cycles

- Ex.5.2-1

A Rankine power generation cycle using steam operates at 100 ºC in the condenser, a pressure of 1 MPa in the evaporator, and a max temperature of 600 ºC. Assuming both turbine and pump operate reversibly, plot the cycle on a T-S diagram and calculate the efficiency of the cycle.

$$\eta = \frac{-(\dot{W}_T + \dot{W}_P)}{\dot{Q}_B}$$

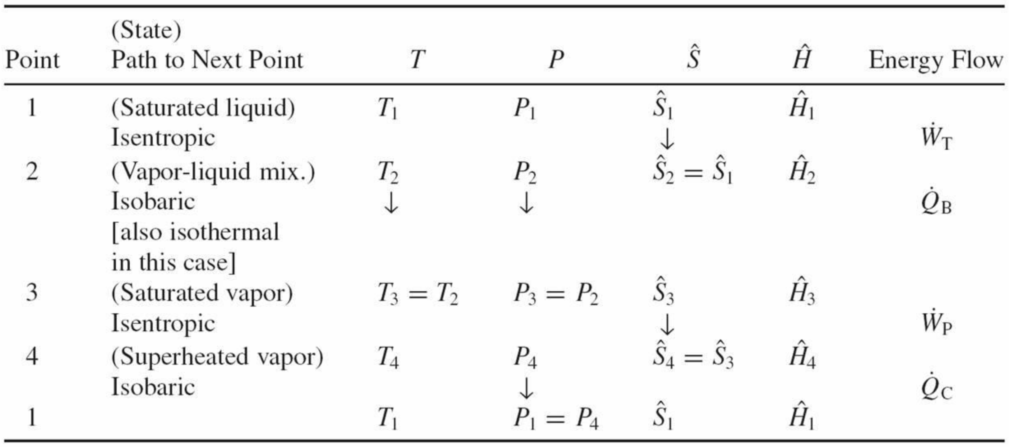


Refrigeration Cycles

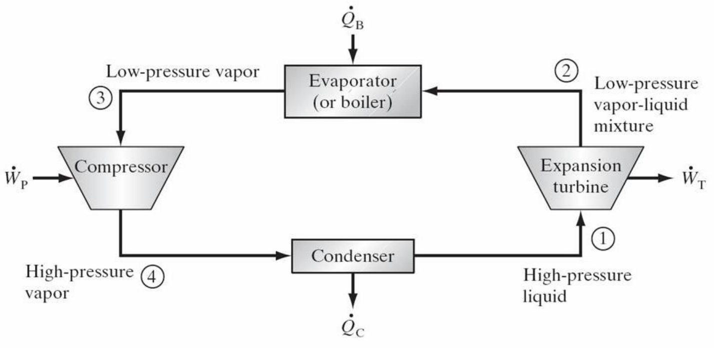
- Refrigeration (and cooling): heat is removed from low-temperature body and is directed to high-temperature body (e.g., surrounding).
- Refrigeration is not a naturally occurring process and it requires work consumption.
- This results in using work to pump heat from a low-T region to a high-T region. Therefore, it is also called a heat pump.
- This can be carried out conceptually by reversing the operation of a power cycle.

Refrigeration Cycles

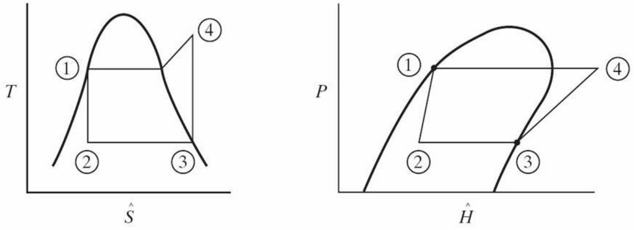
- Rankine refrigeration cycle: a similar cycle as the Rankine cycle operates essentially in reverse.



Point	(State) Path to Next Point	T	P	$\hat{S}$	$\hat{H}$	Energy Flow
1	(Saturated liquid)	T_1	P_1	$\hat{S}_1$	$\hat{H}_1$	
	Isentropic			↓		$\dot{W}_T$
2	(Vapor-liquid mix.)	T_2	P_2	$\hat{S}_2 = \hat{S}_1$	$\hat{H}_2$	
	Isobaric [also isothermal in this case]	↓	↓			$\dot{Q}_B$
3	(Saturated vapor)	$T_3 = T_2$	$P_3 = P_2$	$\hat{S}_3$	$\hat{H}_3$	
	Isentropic			↓		$\dot{W}_P$
4	(Superheated vapor)	T_4	P_4	$\hat{S}_4 = \hat{S}_3$	$\hat{H}_4$	
	Isobaric		↓			$\dot{Q}_C$
1		T_1	$P_1 = P_4$	$\hat{S}_1$	$\hat{H}_1$	



(a)



(b)

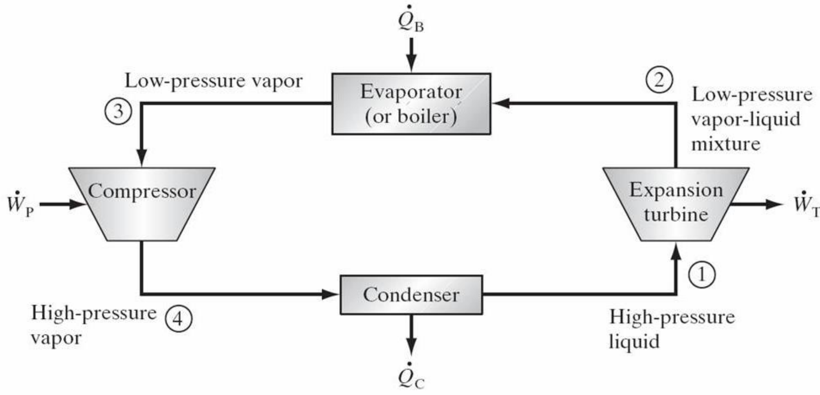
Refrigeration Cycles

- Ex.5.2-2

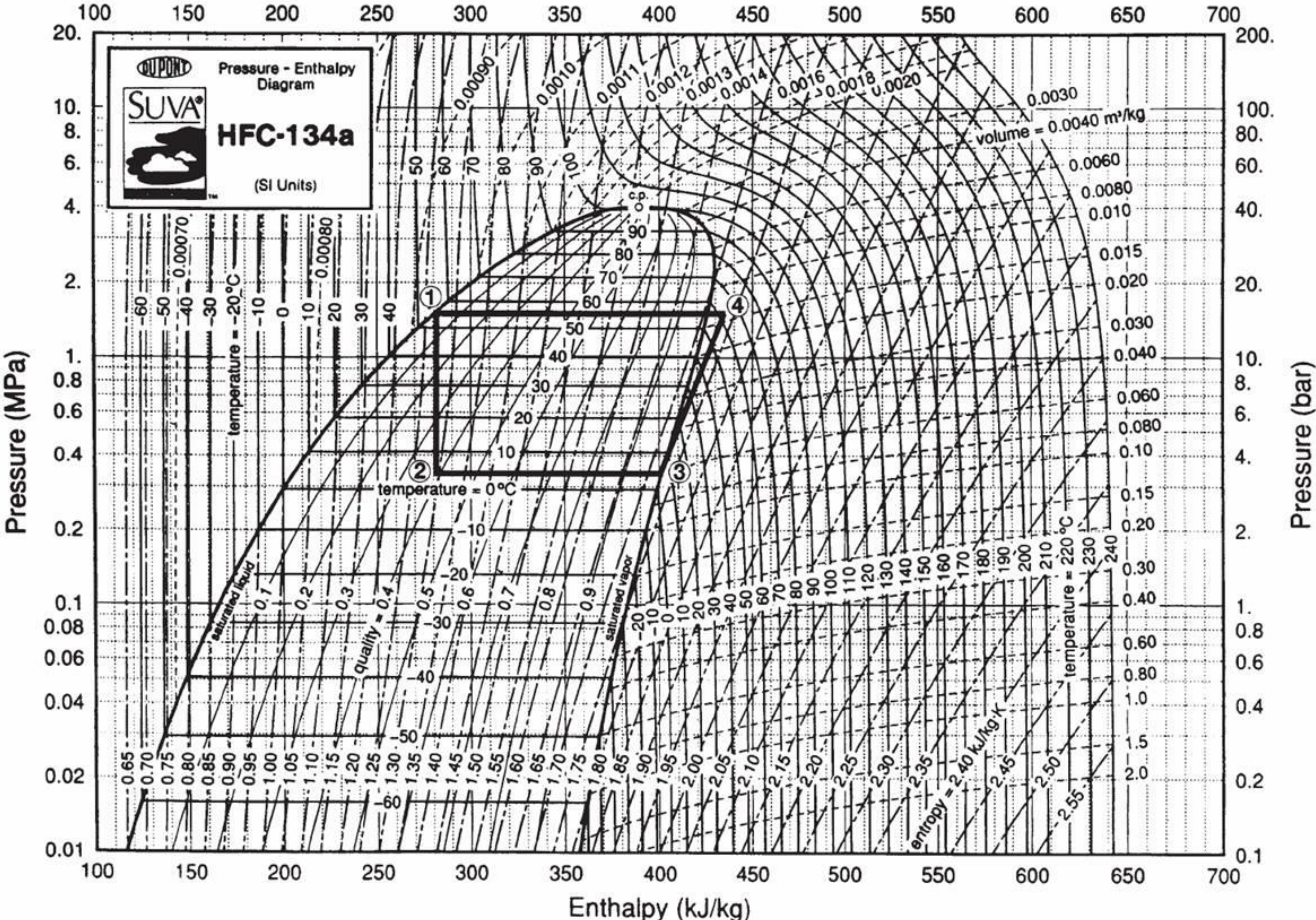
  An automobile air conditioner uses a vapor-compression refrigeration cycle with the environmentally friendly refrigerant HFC-134a as the working fluid. (a) Calculate the missing temperature and pressures in the table. (b) Evaluate the coefficient of performance (C.O.P.).

Point	Fluid State	Temperature
1	Saturated liquid	55°C
2	Vapor-liquid mixture	
3	Saturated vapor	5°C
4	Superheated vapor	

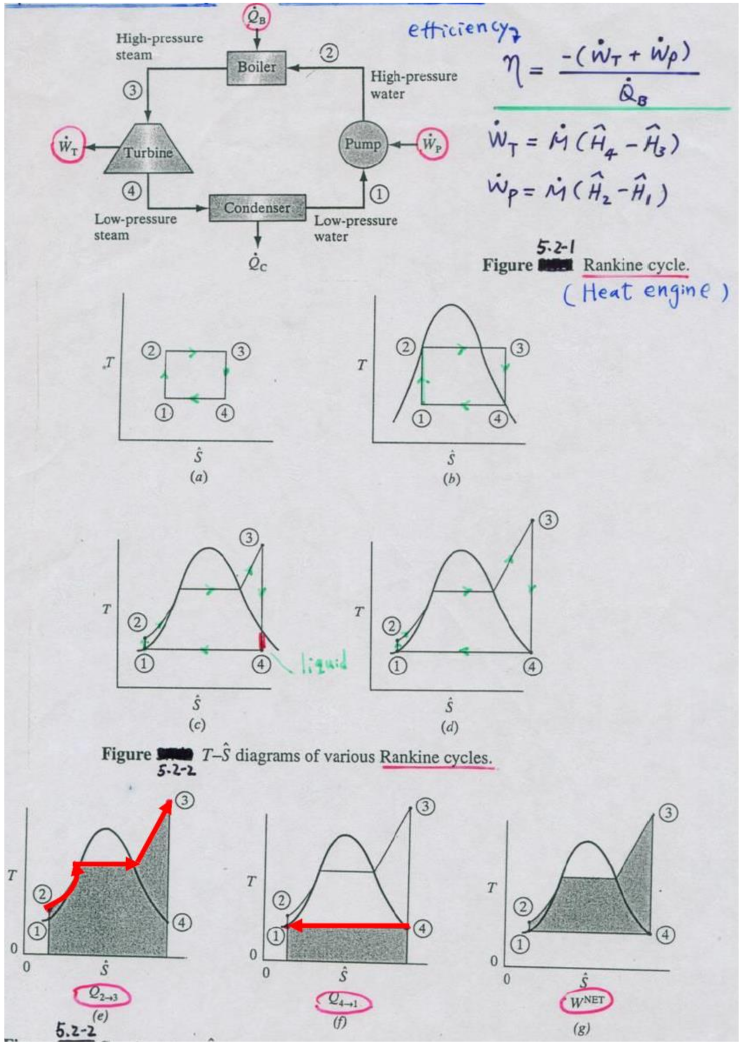
$$C.O.P. = -\frac{\dot{Q}_B}{\dot{W}_T + \dot{W}_P}$$



Refrigeration Cycles

- 

Power regeneration & Refrigeration cycles



efficiency η

$$\eta = \frac{-(\dot{W}_T + \dot{W}_P)}{\dot{Q}_B}$$

$$\dot{W}_T = \dot{M}(\hat{H}_4 - \hat{H}_3)$$

$$\dot{W}_P = \dot{M}(\hat{H}_2 - \hat{H}_1)$$

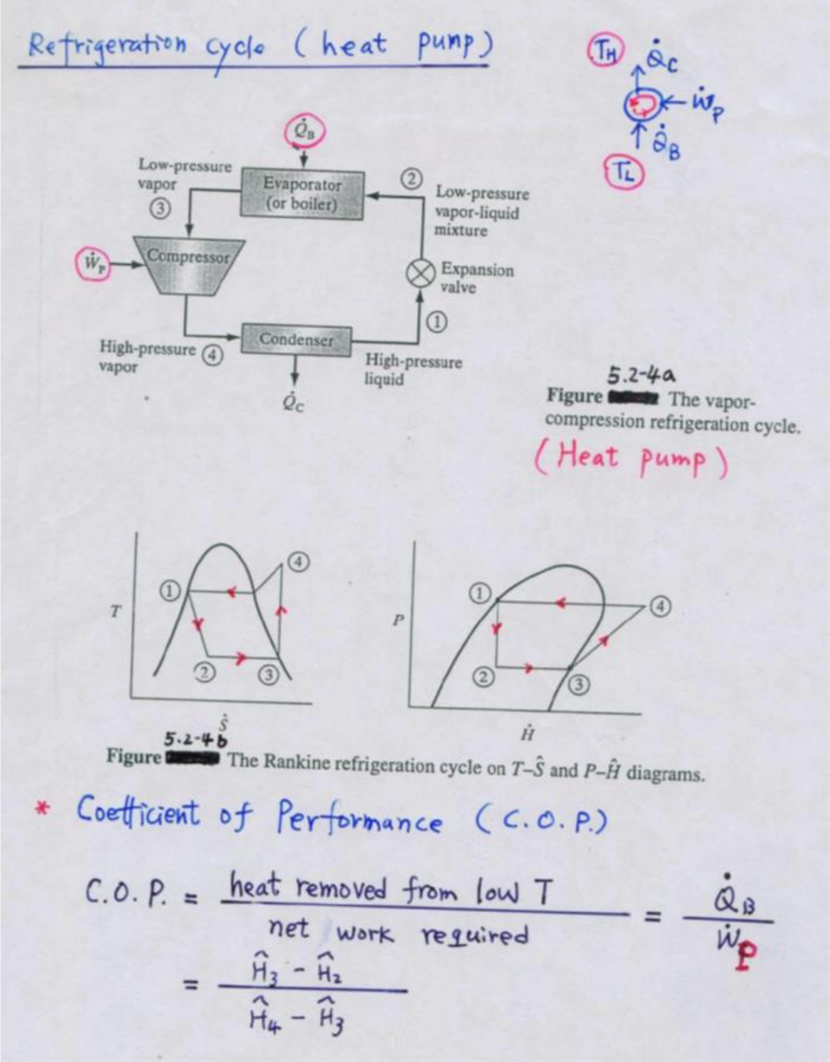
5.2-1
Figure [redacted] Rankine cycle.
(Heat engine)

(*a*) (*b*) (*c*) (*d*)

Figure [redacted] T–$\hat{S}$ diagrams of various Rankine cycles.
5.2-2

$Q_{2\to3}$ (*e*) $Q_{4\to1}$ (*f*) W^{NET} (*g*)

5.2-2



Refrigeration cycle (heat pump)

5.2-4a
Figure [redacted] The vapor-compression refrigeration cycle.
(Heat pump)

5.2-4b
Figure [redacted] The Rankine refrigeration cycle on T–$\hat{S}$ and P–$\hat{H}$ diagrams.

* Coefficient of Performance (C.O.P.)

$$\text{C.O.P.} = \frac{\text{heat removed from low T}}{\text{net work required}} = \frac{\dot{Q}_B}{\dot{W}_P}$$

$$= \frac{\hat{H}_3 - \hat{H}_2}{\hat{H}_4 - \hat{H}_3}$$

Power regeneration & Refrigeration cycles

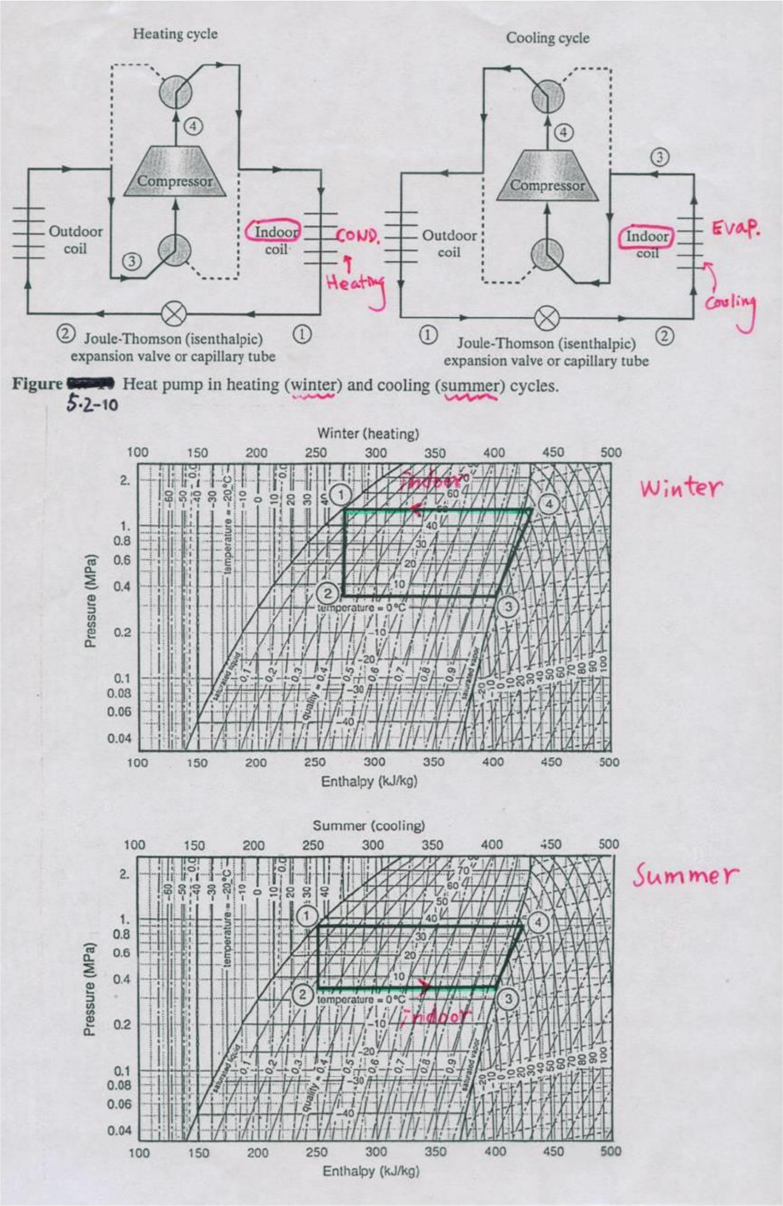


Figure [redacted] Heat pump in heating (winter) and cooling (summer) cycles.
5.2-10