

Aug. 24, 2017 - ANSWERS

$$\text{Ex 1 a) } dh = T ds + v dp \Rightarrow \frac{dh}{dp} = T \frac{ds}{dp} + v$$

$$\left(\frac{\partial h}{\partial p}\right)_T \Leftrightarrow \frac{dh}{dp}, \quad \left(\frac{\partial s}{\partial p}\right)_T \Leftrightarrow \frac{ds}{dp}$$

$$\Rightarrow \underline{\underline{\left(\frac{\partial h}{\partial p}\right)_T = T \left(\frac{\partial s}{\partial p}\right)_T + v}} \quad \text{QED}$$

$$\text{b) } h(T, p) \Rightarrow dh = \left(\frac{\partial h}{\partial T}\right)_p dT + \left(\frac{\partial h}{\partial p}\right)_T dp = 0$$

$$\left(\frac{\partial T}{\partial p}\right)_h \Leftrightarrow \frac{dT}{dp} = - \frac{\left(\frac{\partial h}{\partial p}\right)_T}{\left(\frac{\partial h}{\partial T}\right)_p} \quad (h = \text{const.})$$

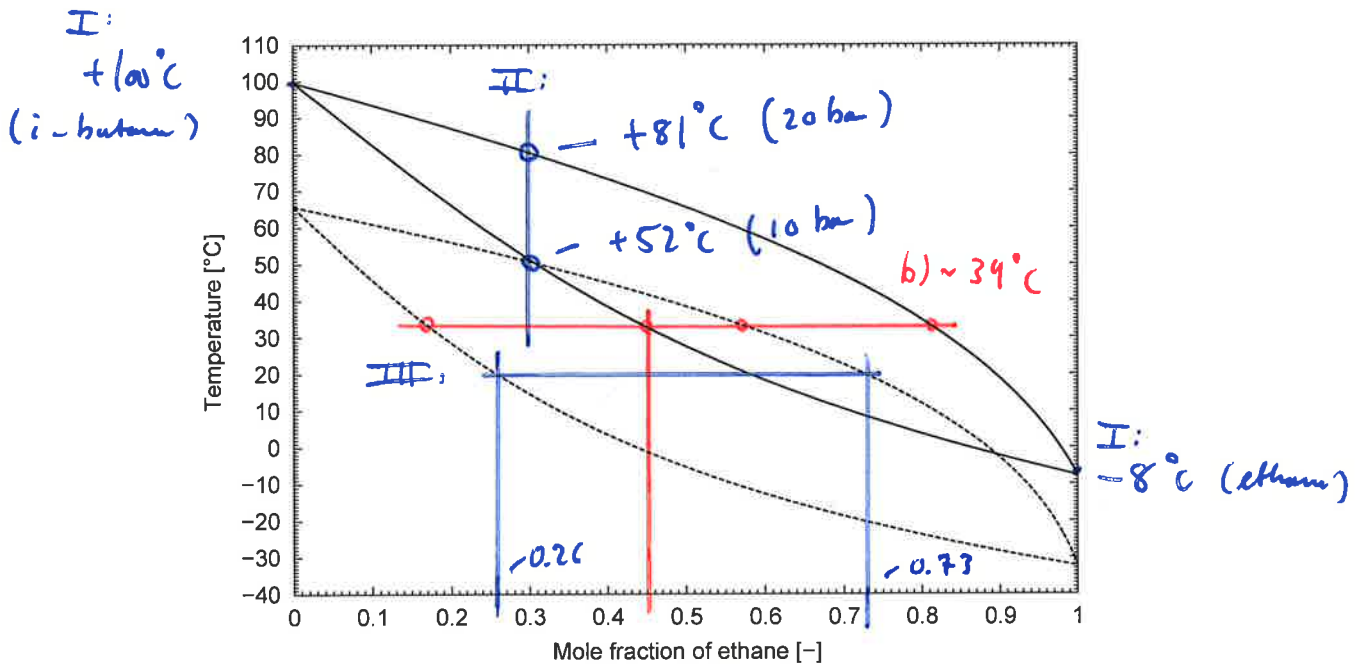
$$\Rightarrow \mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h = - \frac{T \left(\frac{\partial s}{\partial p}\right)_T + v}{c_p}$$

$$\text{Maxwell: } \left(\frac{\partial v}{\partial T}\right)_p = - \left(\frac{\partial s}{\partial p}\right)_T$$

$$\Rightarrow \underline{\underline{\mu_{JT} = \frac{1}{c_p} \left(T \left(\frac{\partial v}{\partial T}\right)_p - v \right)}}$$

$$\text{c) Ideal gas: } pv = RT \rightarrow v = \frac{RT}{p}$$

$$\Rightarrow \left(\frac{\partial}{\partial T} \left(\frac{RT}{p}\right)\right)_p = \frac{R}{p} \Rightarrow \mu_{JT} = \frac{1}{c_p} \cdot \left(T \cdot \frac{R}{p} - v \right) = \underline{\underline{0}}$$



EX 2. a) I: -8°C for ethane, +100°C for i-butane
 II: +52°C (10 bar), +81 (20 bar)
 III: X = 0.26, Y = 0.73

b) Approximately 34°C. At 10 bar the mixture is 2-phase with $X \approx 0.17$ and $Y \approx 0.57$.
 $Y = Z = 0.57$ becomes the total composition for the new situation at 20 bar, with $X \approx 0.45$ and $Y \approx 0.81$

c) I: $\mu_{JT} \equiv \left(\frac{\partial T}{\partial P} \right)_h \approx \left(\frac{\Delta T}{\Delta P} \right)_h$

Pressure drop of 10 bar $\Rightarrow \Delta P = -10$ bar

$\rightarrow \Delta T = (T_2 - T_1) = \mu_{JT} \cdot \Delta P = 2.6 \frac{\text{K}}{\text{bar}} \cdot -10 \text{ bar}$

(3)

$$= -26 \text{ K} \Rightarrow T_2 = -26 \text{ K} + 60^\circ\text{C} = \underline{\underline{34^\circ\text{C}}}$$

(Using K for temperature differences, and $^\circ\text{C}$ for absolute temperatures)

$$\text{II} \quad X = 0.17, \quad Y = 0.57 \quad (\text{same as in b}) \quad \text{☺}$$

$$\text{III} \quad Z = \alpha \cdot Y + (1 - \alpha) \cdot X \quad (\text{"Lever rule"})$$

$$\Rightarrow Z - X = \alpha(Y - X) \Rightarrow \alpha = \frac{Z - X}{Y - X} = \frac{0.4 - 0.17}{0.57 - 0.17}$$

$$= \underline{\underline{0.575}}$$

Ex. 3 a)

1: Heat exch. / ext. refrigeration: + No pressure drop
 ÷ More equipment units

2: JT-value: + Simple
 ÷ Large pressure drop
 Compared to temp. drop.

3. Turbine

+ Large temp. drop,
 possible to reclaim expansion work

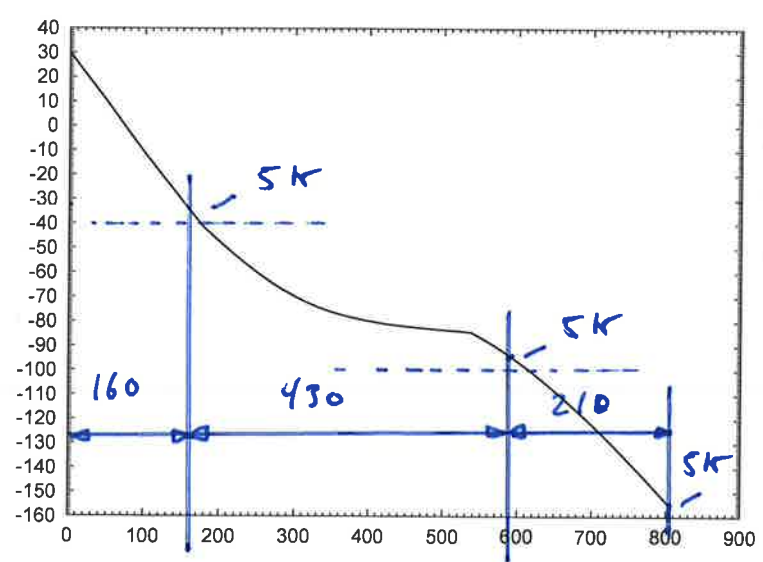
÷ More complex, must
 be design to handle condensing
 vapour.

b) Both streams are gases, so C_p -values are of comparable magnitude. The flow in the cold stream (II) will necessarily be smaller than in the warm stream (I) since condensate is removed. ΔT increase in II is therefore larger than ΔT decrease in I.

c) Down. More of the heates will thereby go to liquid.

d) Warm side, i.e. after stream II exits the HX. - Because temperature will go up after compression the low temperature wouldn't be exploited.

Ex. 4



(a) Cooldown curve for natural gas

(5)

a) From the cooldown curve:

Appr. 800 kJ/kg are distributed with

160 kJ/kg for the propane circuit, 430 kJ/kg for the ethylene circuit and 210 kJ/kg for the methan circuit.

b) Cold duty for the methan circuit:

$$Q_c = \dot{m} \cdot \Delta h$$

Need \dot{m} in kg/s:

$$1.5 \text{ mtpa} = 1.5 \cdot 10^6 \frac{\text{t}}{\text{y}} \cdot 1000 \frac{\text{kg}}{\text{t}} \cdot \frac{1}{365 \text{ d/y} \cdot 24 \text{ h/d} \cdot 3600 \text{ s/h}}$$

$$= 47.56 \text{ kg/s}$$

$$\Rightarrow Q_c = 47.56 \frac{\text{kg}}{\text{s}} \cdot 210 \frac{\text{kJ}}{\text{kg}} = \underline{\underline{9988.6 \text{ kW}}}$$

($\approx 10000 \text{ kW}$)

c) From log p - h - diagram:

* Condensed methan at -95°C $h_1 = 280 \text{ kJ/kg}$

* Evaporated methan at -160°C $h_2 = 560 \text{ "}$

* Compressed methan at 30 bar $h_3 = 800 \text{ kJ/kg}$

Enthalpy difference of metham evaporating from

$$1 - 2 : \quad \Delta h = 520 - 280 = \underline{240 \text{ kJ/kg}}$$

To provide the prescribed cold duty of ~10000 kW calculated amount of metham must be :

$$\dot{m}_{c1} = \frac{10000 \text{ kW}}{240 \text{ kJ/kg}} = \underline{41.67 \text{ kg/s}}$$

Enthalpy difference of isentropic compression from

$$2 - 3_s : \quad \Delta h_{is} = 800 - 520 = \underline{280 \text{ kJ/kg}}$$

Enthalpy difference considering $\eta_{is} = 0.91$:

$$\eta_{is} = \frac{h_{3s} - h_2}{h_3 - h_2} \rightarrow h_3 = \left(\frac{280}{0.91} \right) + 520 = \underline{827.7 \text{ kJ/kg}}$$

(Directly)

$$\Delta h = 827.7 - 520 = \underline{307.7 \text{ kJ/kg}}$$

Compression work: $W_c = \dot{m}_{c1} \cdot \Delta h = 41.67 \frac{\text{kg}}{\text{s}} \cdot 307.7 \frac{\text{kJ}}{\text{kg}}$
 $= \underline{\underline{12821.5 \text{ kW}}}$

Attachment 2: $\log(p)$ - h diagram for methane (for Exercise 4)

