Problem 1

A furnace for a high temperature reactor is fueled by natural gas, and the hot exhaust gases leave the furnace at a temperature of 1050 °C. You want to recover as much heat as possible from the gases by producing high pressure steam, but due to some uplift in the chimney is required you decide not to cool the gases below 150 °C. The produced steam should have a pressure of 70 bar at the outlet, and it should be superheated to 600 °C. The temperature of the feed water is 20 °C.

a) Draw an T-H diagram for the process.

b) Calculate the amount of steam produced from 1 tonne (1000 kg) of exhaust gas. What is the minimum temperature approach of the process.

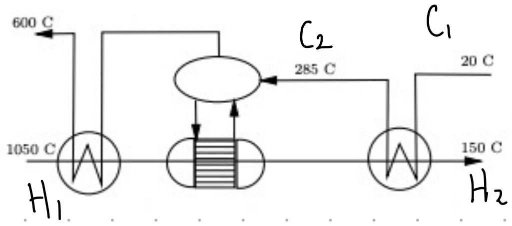
c) If the hot exhaust gas has a temperature of 650 °C, draw T-H diagram and locate where the pinch temperature is. How much steam can be produced from 1 tonne of exhaust gas in this case.

d) Calculate the heat exchanger areas of the feed water heater, the evaporator and the superheater at conditions as under b) when you burn 2 tonnes/h of natural gas (calculated as pure methane) per hour with 10% surplus of air.

Some data provided

- An enthalpy-entropy diagram for steam is attached
- Specific heat capacity for the exhaust gas may be set constant to $c_{p,gas} = 1.113$ kJ/(kg K) (The real values for gases are indeed increasing with temperature)
- Enthalpy of water:
  - Enthalpy in the feed water: $H_0 = 83.8$ kJ/kg.
  - Enthalpy in the water at the evaporation temperature: $H_1 = 1267$ kJ/kg
  - Enthalpy of evaporation for the water at bp.(70 bar, 285 °C): $\Delta H_{vap} = 1506$ kJ/kg
- The overall heat transfer coefficients:
  - In the feed water heater: $U = 60$ W/(m^{2}K)
  - In the evaporator: $U = 50$ W/(m^{2}K)
  - In the steam superheater: $U = 40$ W/(m^{2}K)

a)



$H_{C_1} = 0$

$H_{C_2} = 1183{,}2$ kJ/kg

(285°C) $H_{C_3} = H_{C_2} + 1506$ kJ/kg $= 2689{,}2$ kJ/kg

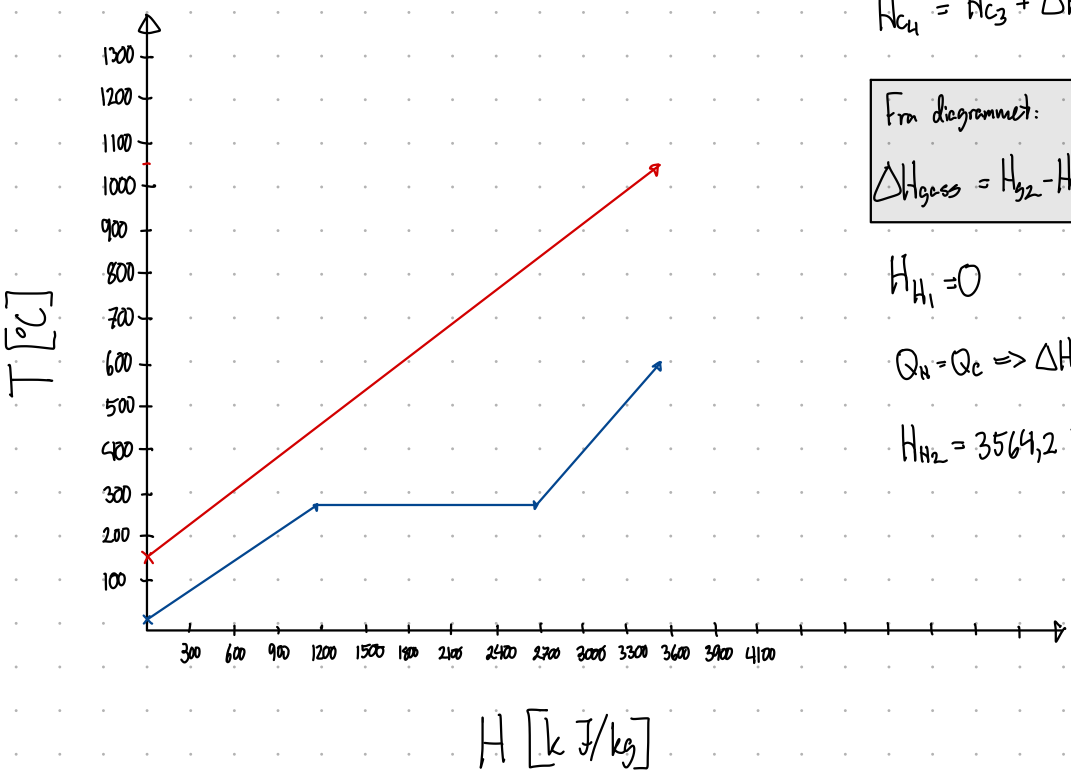
$H_{C_4} = H_{C_3} + \Delta H_{gass} = 3564{,}2$ kJ/kg

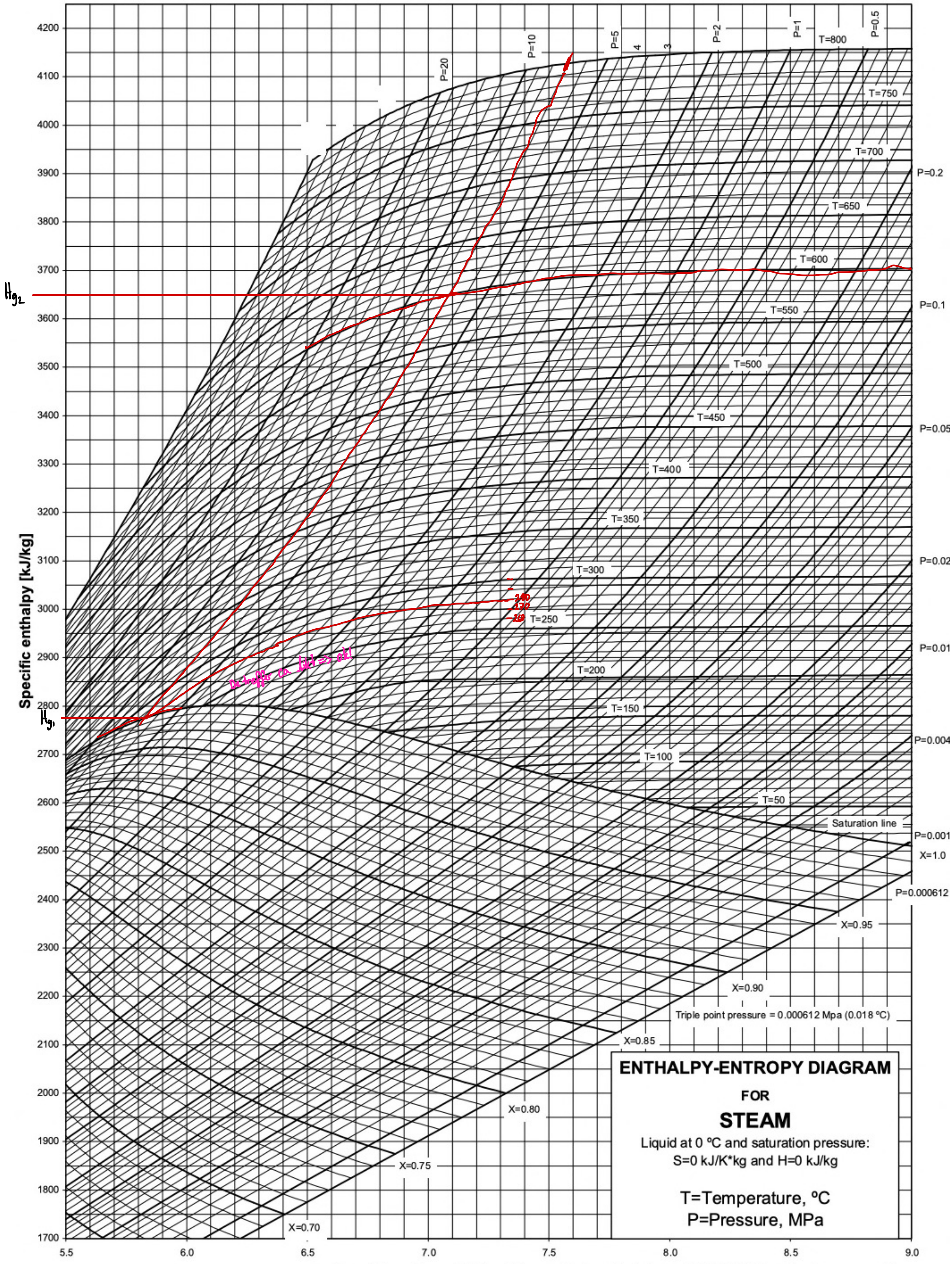
$$\boxed{\begin{array}{l}\text{Fra diagrammet: (neste side)} \\ \Delta H_{gass} = H_{g_2} - H_{g_1} = 3650 - 2775 = 875 \text{ kJ/kg}\end{array}}$$

$H_{H_1} = 0$

$Q_H = Q_C \Rightarrow \Delta H_C = \Delta H_H \Rightarrow H_{H_2} = H_{C_4}$

$H_{H_2} = 3564{,}2$ kJ/kg





Produced by I. Aartun, NTNU 2001. Based on the program Allprops, Center for Applied Thermodynamic Studies, University of Idaho

b) Per kg H_2O: kreves 3564,2 kJ/kg H_2O

For 1000 kg eksos overføres $\Delta H_H = 1000\ kg \cdot 1{,}133\ kJ/kg \cdot K \cdot (1050 - 150) = 1019700\ kJ$

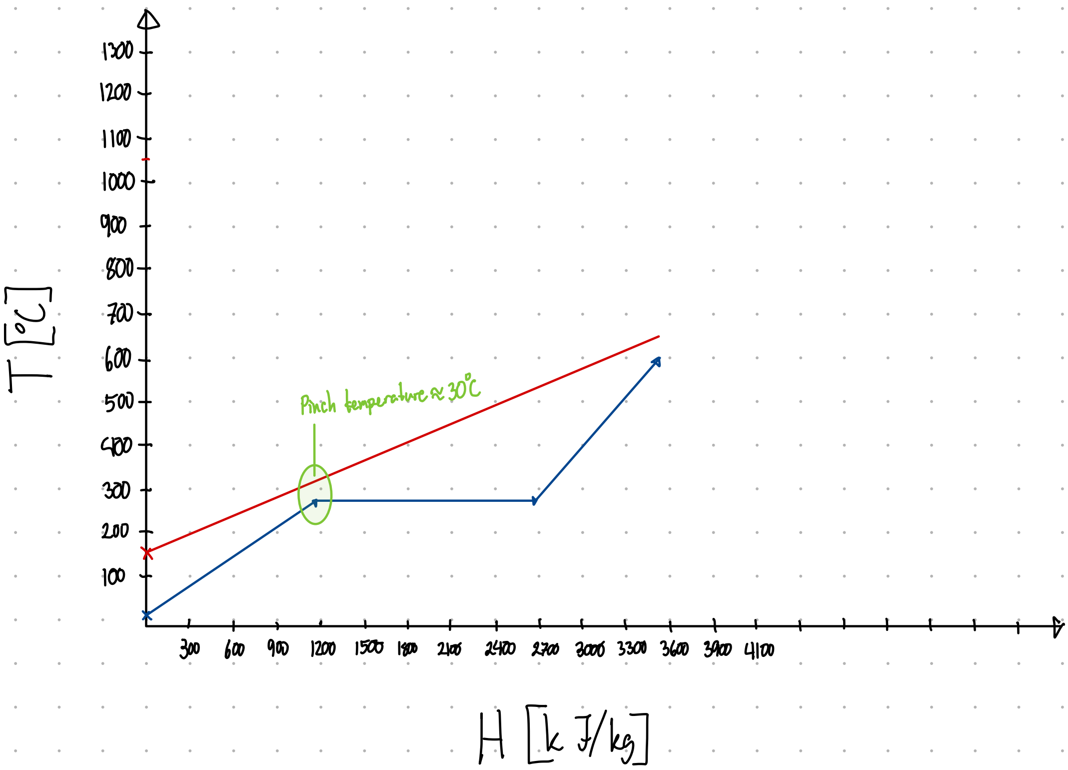
Da blir $\dot{m} = \frac{1019700}{3564{,}2}\ kg\ H_2O$

$\underline{\underline{\dot{m} = 286{,}1\ kg\ H_2O}}$

Den minste $\Delta T_{ch} = 150 - 20 = 130°C$

$\underline{\underline{\text{Minimum temperature approach: } 130°C}}$

c) Tallene blir de samme, utenom at H_{H_2} skal tegnes lavere.



Per kg H_2O: kreves 3564,2 kJ/kg H_2O

For 1000 kg eksos overføres $\Delta H_H = 1000\ kg \cdot 1{,}133\ kJ/kg \cdot K \cdot (650 - 150) = 566500\ kJ$

Da blir $\dot{m} = \frac{566500}{3564{,}2}\ kg\ H_2O$

$\underline{\underline{\dot{m} = 158{,}9\ kg\ H_2O}}$

d) Forbrenningsreaksjon for metan:

$$CH_4 + 2O_2 \rightleftharpoons CO_2 + 2H_2O$$

Ser at det kreves $1 \text{ mol } CH_4 \Leftrightarrow 2 \text{ mol } O_2$

Vi skal ha 10% excess O_2

$\Rightarrow 2{,}2 \text{ mol } O_2$

Antar kun O_2 og N_2 i luft, da får vi også

$N_2 = 4 \cdot n_{O_2} = 8{,}8 \text{ mol } N_2$

Finner så der molare vekten av innstrømmen (per kmol metan)

$$M_m = \underbrace{1 \cdot 16}_{CH_4} + \underbrace{2{,}2 \cdot 32}_{O_2} + \underbrace{8{,}8 \cdot 28}_{N_2} = 332{,}8 \text{ kg/kmol Methane}$$

Gitt: Vi brenner 2000 kg CH_4 per h

Omregnet til mol: $\dot{n}_{CH_4} = \dfrac{2000 \text{ kg/h}}{16 \text{ kg/kmol}} = 125 \text{ kmol/h}$

Massebalanse (0 massetap) gir følgende vekt av eksosen:

$$\dot{m} = n_{CH_4} \cdot 332{,}8 \text{ kg eksos / kg } CH_4 = 41600 \text{ kg eksos/h} = 11{,}556 \text{ kg eksos/s}$$

I b) fant vi at for 1000 kg eksos, kan vi lage 286,1 kg H_2O damp

I dette tilfellet kan vi da produsere

$$\dot{m}_{H_2O} = \frac{11{,}556 \text{ kg eksos/s} \cdot 286{,}1 \text{ kg } H_2O}{1000 \text{ kg eksos}} = 3{,}306 \text{ kg } H_2O/s$$

Ønsker å bruke $Q = UA \cdot \Delta T_{lm} \Rightarrow A = \dfrac{Q}{U \cdot \Delta T_{lm}}$ for å beregne arealet, trenger Q og mellomtemperaturene for å beregne disse.

La 1 være feed water heater, 2 være evaporator og 3 være steam superheater

$$\dot{Q}_1 = \Delta H_1 \cdot \dot{m}_{H_2O} = (H_{c_2} - H_{c_1}) \cdot \dot{m}_{H_2O} = 1183{,}2 \text{ kJ/kg} \cdot 3{,}306 \text{ kg/s} = 3911{,}66 \text{ kW}$$

$$\dot{Q}_2 = \Delta H_2 \cdot \dot{m}_{H_2O} = (H_{c_3} - H_{c_2}) \cdot \dot{m}_{H_2O} = \Delta H_{vap} \cdot \dot{m}_{H_2O} = 1506 \text{ kJ/kg} \cdot 3{,}306 \text{ kg/s} = 4978{,}84 \text{ kW}$$

$$\dot{Q}_3 = \Delta H_3 \cdot \dot{m}_{H_2O} = (H_{c_4} - H_{c_3}) \cdot \dot{m}_{H_2O} = \Delta H_{gas} \cdot \dot{m}_{H_2O} = 875 \text{ kJ/kg} \cdot 3{,}306 \text{ kg/s} = 2892{,}75 \text{ kW}$$

Ved å anta null varmetap, kan vi nå anta null varmetap $\rightarrow \dot{Q}_{H_2O} = -\dot{Q}_{eksos} = \dot{m}_{eksos} \cdot c_{p,eksos} \cdot \underbrace{\Delta T}_{= T_i - T_{i-1}} \Rightarrow T_i = T_{i-1} - \dfrac{\dot{Q}_{H_2O}}{\dot{m}_{eksos} \cdot c_{p,eksos}}$

$$T_1 = T_0 - \frac{\dot{Q}_1}{\dot{m}_{eksos} \cdot c_{p,eksos}} = 1050°C - \frac{3911{,}66 \text{ kW}}{11{,}556 \text{ kg/s} \cdot 1{,}113 \text{ kJ/kg K}} = 745{,}87 °C$$

$$T_2 = T_1 - \frac{\dot{Q}_2}{\dot{m}_{eksos} \cdot c_{p,eksos}} = 745{,}87°C - \frac{4978{,}84 \text{ kW}}{11{,}556 \text{ kg/s} \cdot 1{,}113 \text{ kJ/kg K}} = 358{,}77 °C$$

$$T_3 = T_2 - \frac{\dot{Q}_3}{\dot{m}_{eksos} \cdot c_{p,eksos}} = 745{,}87°C - \frac{2892{,}75 \text{ kW}}{11{,}556 \text{ kg/s} \cdot 1{,}113 \text{ kJ/kg K}} = 133{,}86 °C$$

Denne verdien avviker noe fra ut-verdien gitt i oppgaven, høyst sannsynlig på grunn av mange avrundinger underveis i beregningene. Den er mest representativ for de beregnede verdiene, så jeg bruker den allikevel.

Kan nå beregne A (antar motstrøms varmeveksler)

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}, \quad \Delta T_2 = T_{eksos,inn} - T_{H_2O,ut}, \quad \Delta T_1 = T_{eksos,ut} - T_{H_2O,inn}$$

A_1:

$\Delta T_2 = 1050 - 600 = 450$

$\Delta T_1 = 745{,}87 - 285 = 460{,}87$

$\Rightarrow \Delta T_{lm,1} = 455{,}41 \text{ K}$

$$A_1 = \frac{Q_1}{U_1 \cdot \Delta T_{lm,1}} = \frac{3911{,}66 \cdot 10^3 \cancel{\text{W}}}{60 \frac{\cancel{\text{W}}}{\text{m}^2 \cancel{\text{K}}} \cdot 455{,}41 \cancel{\text{K}}}$$

$$\boxed{A_1 = 143{,}15 \text{ m}^2}$$

A_2:

$\Delta T_2 = 745{,}87 - 285 = 460{,}87$

$\Delta T_1 = 358{,}77 - 285 = 73{,}77$

$\Rightarrow \Delta T_{lm,2} = 211{,}28 \text{ K}$

$$A_2 = \frac{Q_2}{U_2 \cdot \Delta T_{lm,2}} = \frac{4978{,}84 \cdot 10^3 \cancel{\text{W}}}{50 \frac{\cancel{\text{W}}}{\text{m}^2 \cancel{\text{K}}} \cdot 211{,}28 \cancel{\text{K}}}$$

$$\boxed{A_2 = 471{,}30 \text{ m}^2}$$

A_3:

$\Delta T_2 = 358{,}77 - 285 = 73{,}77$

$\Delta T_1 = 133{,}86 - 20 = 113{,}86$

$\Rightarrow \Delta T_{lm,3} = 92{,}37 \text{ K}$

$$A_3 = \frac{Q_3}{U_3 \cdot \Delta T_{lm,3}} = \frac{2892{,}75 \cdot 10^3 \cancel{\text{W}}}{40 \frac{\cancel{\text{W}}}{\text{m}^2 \cancel{\text{K}}} \cdot 92{,}37 \cancel{\text{K}}}$$

$$\boxed{A_3 = 782{,}92 \text{ m}^2}$$

Syns jeg har litt høye verdier her, men men...