EXAM

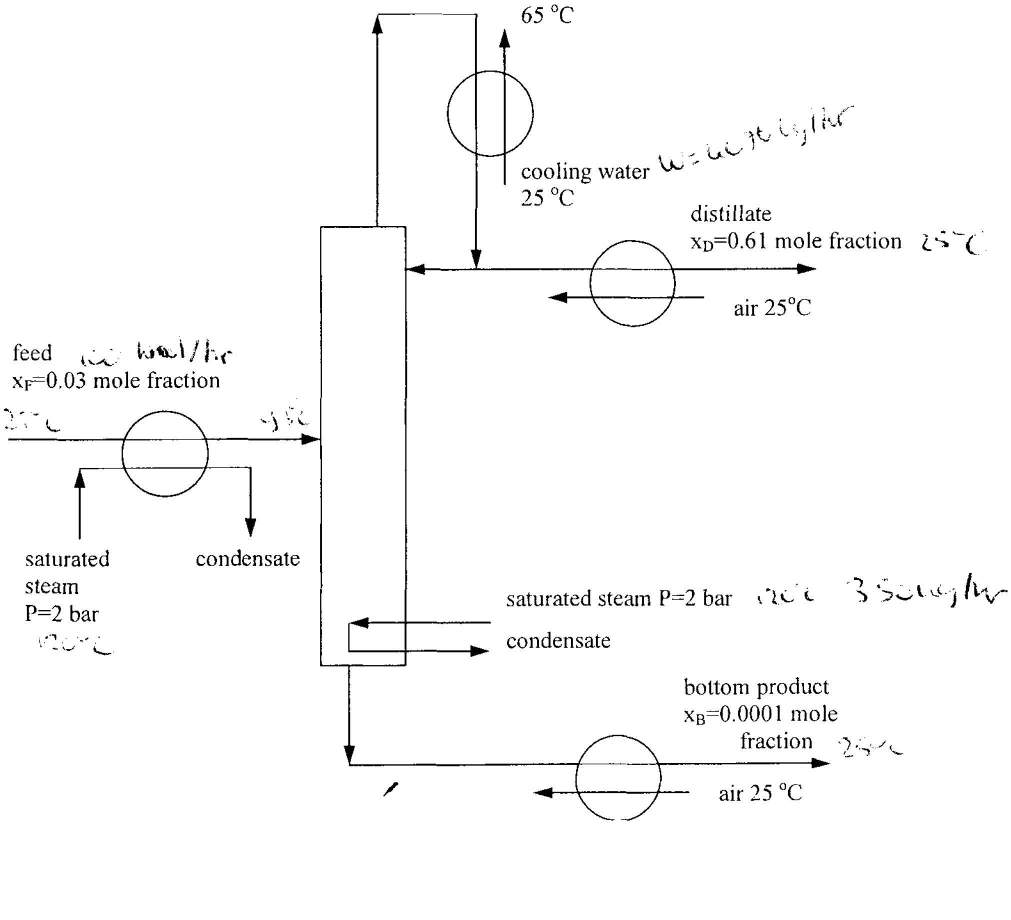
'EXERGY ROUTE TO SUSTAINABLE CHEMICAL ENGINEERING' 6KM21

October 27th 2009, 14.00 – 17.00

Grading: Problem 1: 10 points
Problem 2: 10 points
Problem 3: 10 points

Problem 1

A mixture of ethanol and water is separated in a continue distillation column. The feed F = 100 kmol/hr is introduced at the column top. The feed contains $x_F = 0.03$ mole fraction ethanol, the distillate: $x_D = 0.61$ mole fraction ethanol, and the bottom product: $x_B = 0.0001$ mole fraction ethanol.
The fresh feed is heated up in the heat exchanger from 25°C up to 93°C (boiling point) and subsequently it enters the distillation column. As a heating medium in this heat exchanger saturated steam is used which condenses at 2 bar at t_s = 120°C.
The top product which leaves the column is fully condensed in the condenser. In this condenser a stream of water W = 4076 kg/hr is used which is heated from the temperature 25°C till t_w = 65°C. This water stream is subsequently used as an useful warm water. The distillate which leaves the column is cooled down in a heat exchanger till 25°C using an air stream at 25°C.
The reboiler is heated using saturated steam which is fully condensed at 2 bar and t_s = 120°C. The flow rate of steam is S_R = 350 kg/hr. The bottom product leaves the column as a boiling liquid and is subsequently cooled down till 25°C in a heat exchanger using cooling air at 25°C.



Data:

- chemical exergy feed $\varepsilon_F^o = 43\,760$ kJ/kmol
- physical exergy heated feed (93°C): $\varepsilon_F^{ph} = 507$ kJ/kmol
- chemical exergy distillate: $\varepsilon_D^o = 832\,593$ kJ/kmol
- chemical exergy bottom product: $\varepsilon_B^o = 3\,254$ kJ/kmol
- heat capacity feed: $C_{P,F} = 82$ kJ/kmol * K
- physical exergy warm water (65°C) $\varepsilon_W^f = 10.3$ kJ/kg
- saturated steam (2 bar, $t_s = 120°C$): enthalpy $H_s = 2706.3$ kJ/kg, entropy $S_s = 7.1268$ kJ/kg *K
- condensate (2 bar, $t_s = 120°C$): enthalpy $h_c = 504.7$ kJ/kg, entropy $s_s = 1.5301$ kJ/kg *K
- the standard temperature $T_o = 298K$

a. Calculate the flow rate of the distillate D [kmol/hr] and bottom product B [kmol/hr].

b. How much steam S [kg/hr] is needed in the heat exchanger to heat up the feed?

c. How much exergy [MJ/hr] is delivered in this heat exchanger from steam condensation?

d. Calculate exergy increase of the feed [MJ/hr] during heating up in the heat exchanger.

e. Calculate the irreversibility [MJ/hr] in this heat exchanger and its rational efficiency.

f. Set up the overall exergy balance for the whole distillation plant and calculate the overall exergy losses [MJ/hr].

g. Make a short proposal to reduce the exergy losses of the distillation plant.

$F = D + B$

$F \cdot x_F = D \cdot x_D + B \cdot x_B$

$\Downarrow$

D, B

F = 100 kmol/hr

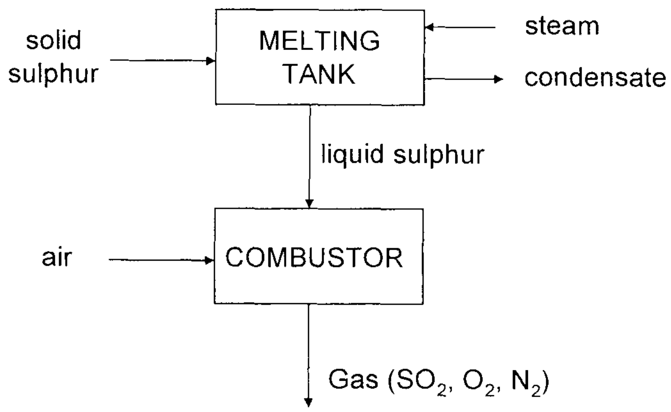
overall

Problem 2

The main process steps of the sulphuric acid plant are: sulphur combustion, catalytic oxidation of SO_2 to SO_3 and absorption of SO_3 in water to H_2SO_4. In these processes a lot of heat is also produced and exergy analysis can help in more efficient use of the heat.

In this problem the exergy analysis is applied for an evaluation of sulphur combustion (see the scheme below). Solid sulphur (W_s = 0.015 kmol/s, temperature 25°C) is first introduced into the melting tank. Saturated steam is used in the melting tank as a heating medium. The steam fully condenses at 50 bar and t_w = 264°C. The heat losses in the melting tank are 10% of the total amount of heat which is needed for sulphur melting.

Liquid sulphur (temperature t_S^l = 180°C) and air (W_A = 0.18 kmol/s, temperature 25°C) are subsequently introduced to the sulphur combustor. In the combustor sulphur is completely oxidized to SO_2. The product gas (SO_2, O_2, N_2) leaves the combustor at the temperature t_G = 764°C.



Data:

- chemical exergy solid sulphur: ε_S^o = 598 850 kJ/kmol
- physical exergy liquid sulphur (180 °C): ε_S^{ph} = 4 258 kJ/kmol
- melting point sulphur: t_S^m = 119 °C
- heat capacity solid sulphur: $C_{P,S}^s$ = 21.8 kJ/kmol · K
- heat capacity liquid sulphur: $C_{P,S}^l$ = 31.5 kJ/kmol · K
- melting enthalpy sulphur: ΔH_S = 14 200 kJ/kmol
- condensation enthalpy steam at 50 bar: ΔH_W = 1 639 kJ/kg
- chemical exergy combustion gas: ε_G^o = 24 620 kJ/kmol
- physical exergy combustion gas (794 °C): ε_G^{ph} = 12 970 kJ/kmol

The standard conditions: $P_0 = 1$ bar, $t_0 = 25\ ^{o}C$

a. How much steam W_W [kg/s] is needed in the melting tank?

b. How much exergy [kJ/s] is delivered by steam in the melting tank?

c. Calculate exergy increase [kJ/s] of sulphur in the melting tank.

d. Calculate irreversibilty [kJ/s] and rational efficiency [%] for the melting tank.

e. Calculate irreversibilty [kJ/s] in the sulphur combustor.

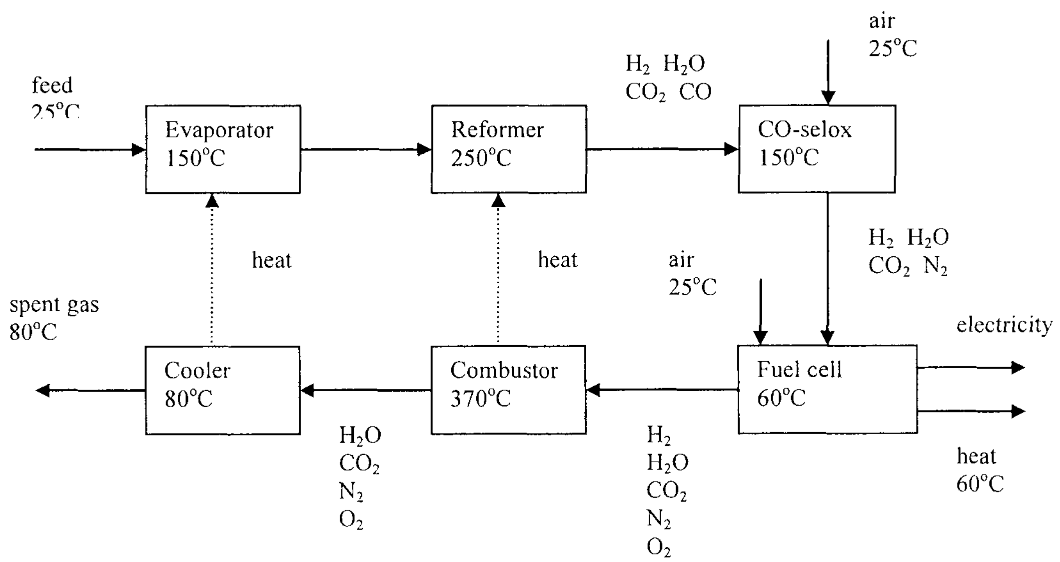
f. What is the main reason of irreversibilities in the melting tank? And in the sulphur combustor?

g. Make a short proposal to reduce the exergy losses in both processes.

Problem 3

For many electrical devices (e.g. laptops, cell phones) electricity is supplied by (rechargeable) batteries. However, batteries have low capacity and need some time to be fully recharged. Fuel cells are an interesting future alternative. Present fuel cells use mainly hydrogen as a fuel but hydrogen is very difficult to be stored. A solution of this problem could be an on-site production of hydrogen from a liquid fuel, such as methanol. Due to the micro-reactor technology hydrogen production and fuel cell units can be miniaturized.

In this problem exergy analysis is applied for evaluation of methanol conversion unit coupled with a fuel cell. The feed consists of solution of methanol in water. The feed ($W_F = 2.54.10^{-5}$ kg/s) at temperature 25°C is introduced into methanol evaporator. In the reformer methanol reacts with water to produce hydrogen, but also some amounts of CO and CO_2. In the CO-selox reactor CO, which is a poison for the fuel cell, is removed by oxidation with air. In the fuel cell a part of produced hydrogen is electrochemically oxidized into water in order to produce electrical energy (E = 100 J/s) and also some heat (Q = 96.8 J/s). The heat produced in the fuel cell is removed to the environment and can be assumed as a waste. The heat needed for the reformer and evaporator is obtained by combustion and cooling down of remaining hydrogen. Combustion gas from the methanol-hydrogen conversion unit ($W_{SG} = 1.47.10^{-4}$ kg/s, temperature 80°C) is removed to the environment.



Data:

- chemical exergy feed $\varepsilon_F^o = 10\,500$ kJ/kg
- chemical exergy spent gas $\varepsilon_{SG}^o = 80.1$ kJ/kg
- enthalpy spent gas at 80°C (reference temperature $T_o = 298$ K) $h_{SG} = 68.2$ kJ/kg
- entropy spent gas at 80°C (reference temperature $T_o = 298$ K) $s_{SG} = 0.216$ kJ/kg.K

a. Calculate the exergy flow rate for the following streams:

a1. feed at 25°C
a2. air at 25°C in the CO-selox reactor
a3. air at 25°C in the fuel cell
a4. electricity produced by the fuel cell at 60°C
a5. heat produced by the fuel cell at 60°C
a6. spent gas from the cooler at 80°C

b. Set up the exergy balance for the overall process. Calculate the overall irreversibility and rational efficiency. What are the internal and external exergy losses in this process?

c. How can you reduce the internal end external exergy losses in this process?

d. Suppose that methanol and water would be introduced into evaporator at the same amounts but as two separate streams. Is chemical exergy of these streams lower, higher, or equal than the chemical exergy of the mixed feed? Explain why.

e. For your laptop you are considering as the energy source:

e1. electricity from methanol according to the process as described in this problem
e2. electricity from a rechargeable battery.

Which energy source has higher exergetic efficiency for conversion of chemical exergy into electricity?
The exergetic efficiency of a rechargeable battery is 70% when calculated as a ratio between electrical output and electricity input needed to charge the battery. The exergetic efficiency of the power plant is 40%.