Introduction to Chemical Engineering

Problem Sheet 9 – Week 12 – Friday 06 December 2024

Problem 1: Chemical Engineering for Biological Process (Energy Balance – Reactive)

Citric acid is a well-known compound that occurs in living cells for both plants and animals. The citric acid cycle is a series of chemical reactions occurring in a living cell that is essential for the oxidation of glucose, a major source of energy for the cells.

The reaction scheme is far too complicated to show here, but from a macroscopic (overall) viewpoint, for the commercial production of citric acid in a batch process, three different phases occur for which the stoichiometries are slightly different:

Early idophase (occurs between 80 and 120 hours), the initial reaction:

1g mol glucose + 1.5 g mol O_2(g) → 3.81 g mol biomass + 0.62 g mol citric acid + 0.76 g mol CO_2(g)

Medium idophase (occurs between 120 and 180 hours), additional glucose consumed

1g mol glucose + 2.4 g mol O_2(g) → 1.54 g mol biomass + 0.74 g mol citric acid + 1.33 g mol CO_2(g)

Late idophase (occurs between 180 and 220 hours), additional glucose consumed

1g mol glucose + 3.91 g mol O_2(g) → 0.86 g mol biomass + 0.74 g mol citric acid + 2.41 g mol CO_2(g)

In an aerobic (the presence of air) batch process, a 30% glucose solution at 25°C is introduced into a fermenter. Citric acid is to be produced by using the fungus *Aspergillus niger*. Stochiometric sterile air is mixed with the culture solution by a 100-horsepower aerator. Only 60% overall of the glucose supplied is expected to be converted to citric acid. The early phase is run at 32°C, the middle phase at 35°C, and the late phase at 25°C.

Based on the given data, how much heat must be added or removed from the fermenter during the production of a batch of 10,000 kg of citric acid? Ignore any slight effects of solution on the value of the heat of formation.

Data

	MW (g/mol)	$-\Delta\widehat{H}^{\circ}_{f}$ (kJ/g mol)
Glucose	180.16	1266
Citric acid	192.12	1544.8
Dry cells (biomass)	28.6	91.4

Problem 2: Heat of Solution (Energy Balance – Reactive)

Hydrochloric acid is produced by absorbing gaseous HCl in water. Calculate the heat that must be transferred to or from an absorption unit if HCl(g) at 100°C and water at 25°C are fed to produce 1000kg/h of 20.0 wt% HCl(aq) at 40°C)?

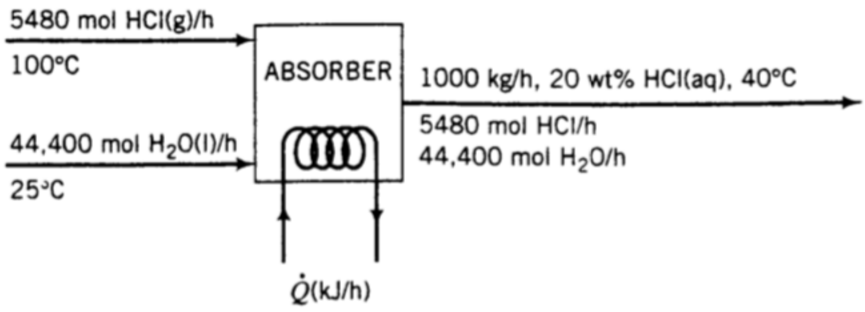


Table B.11 Integral Heats of Solution and Mixing at 25°C

r(mol H_2O/mol solute)	$(\Delta\hat{H}_s)_{HCl(g)}$ kJ/mol HCl	$(\Delta\hat{H}_s)_{NaOH(s)}$ kJ/mol NaOH	$(\Delta\hat{H}_m)_{H_2SO_4}$ kJ/mol H_2SO_4
0.5	—	—	−15.73
1	−26.22	—	−28.07
1.5	—	—	−36.90
2	−48.82	—	−41.92
3	−56.85	−28.87	−48.99
4	−61.20	−34.43	−54.06
5	−64.05	−37.74	−58.03
10	−69.49	−42.51	−67.03
20	−71.78	−42.84	—
25	—	—	−72.30
30	−72.59	−42.72	—
40	−73.00	−42.59	—
50	−73.26	−42.51	−73.34
100	−73.85	−42.34	−73.97
200	−74.20	−42.26	—
500	−74.52	−42.38	−76.73
1 000	−74.68	−42.47	−78.57
2 000	−74.82	−42.55	—
5 000	−74.93	−42.68	−84.43
10 000	−74.99	−42.72	−87.07
50 000	−75.08	−42.80	—
100 000	−75.10	—	−93.64
500 000	—	—	−95.31
∞	−75.14	−42.89	−96.19

[a]From J. C. Whitwell and R. K. Toner, *Conservation of Mass and Energy*, pp. 344–346.

Problem 3: El Classico (Energy Balance – Reactive)

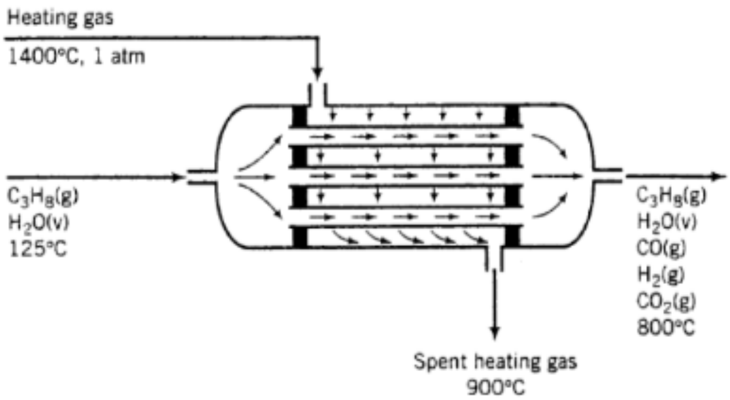
Hydrogen is produced in the steam reforming of propane:

$$C_3H_8(g) + 3\ H_2O(v) \rightarrow 3\ CO(g) + 7\ H_2(g)$$

The water-gas shift reaction also takes place in the reactor, leading to the formation of additional hydrogen:

$$CO(g) + H_2O(v) \rightarrow CO_2(g) + H_2(g)$$

The reaction is carried out over a nickel catalyst in the tubes of a shell-and-tube reactor. The feed to the reactor contains steam and propane in a 6:1 molar ratio at 125°C, and the products emerge at 800°C. The excess steam in the feed assures essentially complete consumption of the propane. Heat is added to the reaction mixture by passing a hot gas over the outside of the tubes that contain the catalyst. The gas is fed at 4.94 m^3/mol C_3H_8, entering the unit at 1400°C and 1 atm and leaving at 900°C. The unit may be considered adiabatic.



Calculate the molar composition of the product gas, assuming that the heat capacity of the heating gas is 0.040 kJ/(mol·°C).