Material Balance Project
Ethanol Production

A new ethanol production facility within a refinery complex is designed to produce 5,000,000 gallons per year of chemical grade ethanol which is 95 vol% pure. The ethanol is made by reacting ethylene with steam over a catalyst. The ethylene feed is 99% pure, with a 1.0% ethane impurity that does not react. High-purity steam, suitable for the process, is available within the refinery. The reactor in the chemical plant is designed to operate at 227°C and produce an equilibrium mixture of ethanol, ethylene and water.

The reaction is

$$C_2H_4 + H_2O \rightarrow C_2H_5OH$$

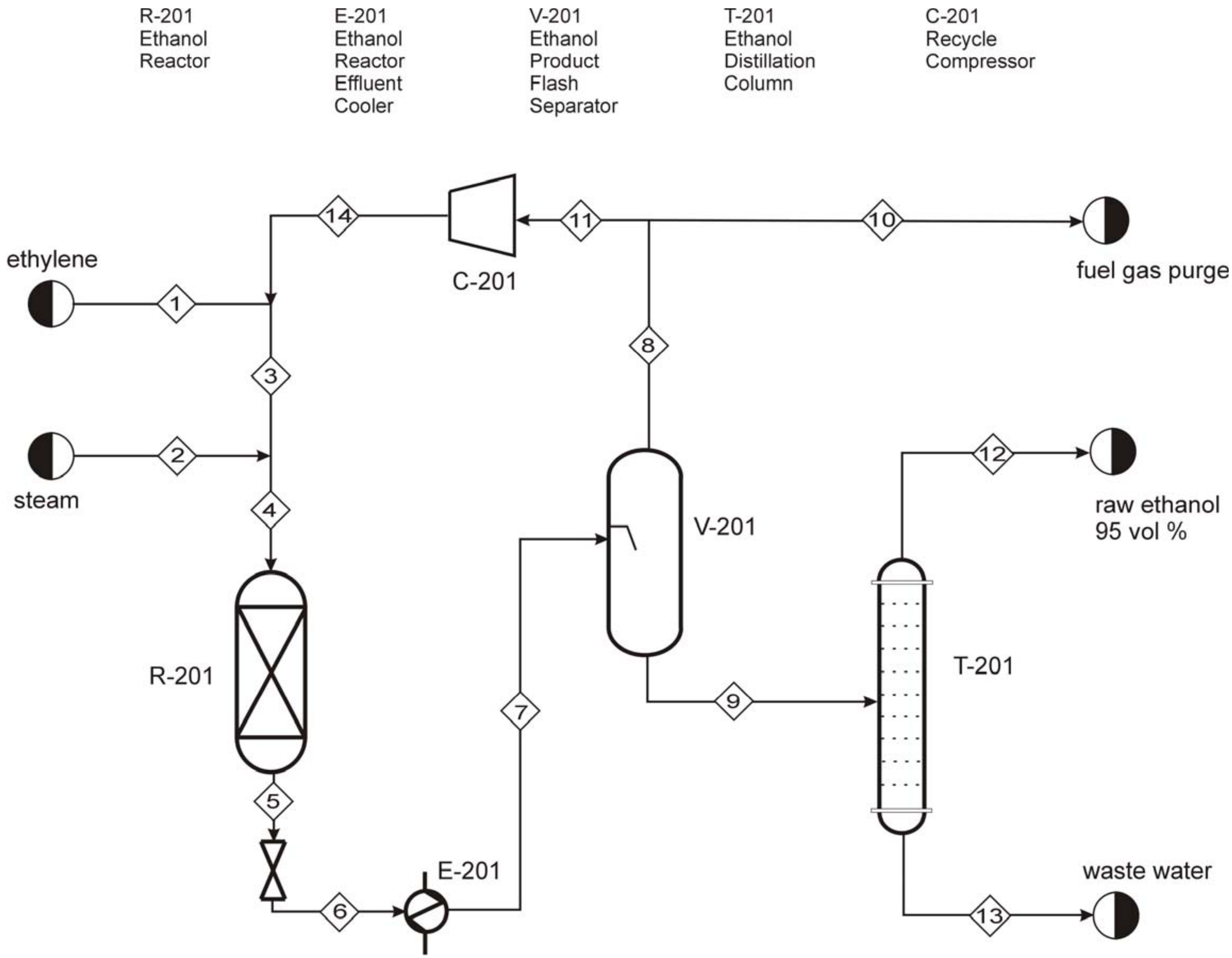
In the temperature range of normal operations, there are no side reactions.

Process Description

A simplified process flow diagram for the ethanol facility is shown in Figure 1. The fresh ethylene and steam are mixed with a recycle stream and sent to a reactor. The reactor operates at 227°C and 40 atm pressure. The reactants and products are at chemical equilibrium within the reactor. The effluent in Stream 5 is at the same composition as the reactor. The effluent pressure is reduced to 5 atm and is cooled to condense ethanol and water. The liquid and vapor phases are separated in the flash unit. For simplicity, it is assumed that all of the ethanol and water are condensed, and that all of the ethylene and the ethane impurity are in the vapor phase. The liquid product is sent to a distillation column for purification. The overhead stream produces a liquid containing 95 volume% ethanol. The bottoms stream, containing a negligible amount of ethanol, is sent to a wastewater treatment facility. The vapor phase from the separator is recycled to the reactor. To prevent impurities from building up in the recycle loop, a portion of the recycle stream is purged. This purge stream is used as fuel gas and is sold to the refinery. A compressor increases the pressure of the recycle stream from 5 atm to 40 atm before it is mixed with fresh feed.

Additional Process Information

Stream 1 – The ethylene feed is 99% pure and contains 1.0% ethane impurity. The ethane does not react and should be treated as an inert.
Stream 2 – Pure water vapor. This stream is saturated steam at 600 psig.
Stream 4 – The water/ethylene feed ratio can be adjusted from 1:1 to 5:1.
R-201 – The reactor operates at 227°C and in the 10-40 atm pressure range. The contents are mixed and are always at equilibrium in this model. Heat for the process comes from the steam and from the heat of the exothermic reaction. At steady state, heat has to be removed from the reactor to maintain constant temperature. This detail is not considered in this project. The equilibrium constant at 227°C is K_{eq} = 0.01306
Stream 5 – Contents are at the same temperature, pressure and concentrations as in the reactor.
Stream 6 – Pressure is reduced to 5 atm.
Stream 7 – Stream is cooled to separator temperature.
Stream 8 – Ethylene and ethane only.



Unit 200 Ethanol Production

Stream 9 – Ethanol and water only.
Stream 10 – Purge stream: purge-to-recycle ratio can be adjusted from 1:10 to 1:50.
Stream 11 – Recycle stream: recycle-to-purge ratio can be adjusted from 10:1 to 50:1.
Stream 12 – Ethanol product containing 95 volume% liquid ethanol.
Stream 13 – Waste water stream sent to treatment plant assumed to contain negligible ethanol (read as no ethanol).
Stream 14– Recycled ethylene and ethane.

Problem

You, the engineering team, are to plan the operation of the ethanol production unit in order to produce 5,000,000 gallon per year. Your goal is to minimize operating costs and maximize profit. You have some flexibility in the operation of this unit in that the reactor pressure can be varied from 10-to-40 atm, the steam-to-ethylene ratio can be adjusted from 1:1 to 5:1, and the recycle-to-purge ratio can be changed from 10:1 to 50:1. Each of these variable parameters involves trade-offs. Increasing the reactor pressure increases equilibrium conversion but also increases compression costs for the recycle loop. Increasing the steam-to-ethylene ratio increases equilibrium conversion, but increases the costs of effluent cooling and the costs of distillation. Increasing the recycle-to-purge ratio reduces the amount of ethylene lost to the purge stream but increases the costs of compression.

You may not use CAD software, but you are encouraged to use spreadsheet calculations since variables may be changed and operating profit or loss calculated immediately. Prior to setting up a spreadsheet, you must turn in hand calculations for two cases to demonstrate that the spreadsheet is set up correctly. The first case will be done as a problem set for class and will be due Monday, November 26. Conditions for the first hand calculation are: P(reactants) = 10 atm; steam-to-ethylene ratio = 2; recycle-to-purge ratio = 10. The second set of hand calculations, due Wednesday, November 28, are for P(reactants) = 40 atm; steam-to-ethylene ratio = 1; recycle-to-purge ratio = 40.

Operating Costs

Value of Feeds and Products

Ethylene fresh feed	\$0.35/lb
High purity steam at 600 psig	\$0.03/lb
Fuel gas	\$0.18/lb
95 vol% ethanol (SG = 0.807)	\$2.90/gal

Variable Operating Costs

Distillation	\$0.47/lb-mol
Cooling after reactor	\$0.03/lb-mol
Recycle compressor	\$0.003(ΔP in atm)/lb-mol
Wastewater treatment	\$100/1000 m^3

Fixed Operating Costs

Operating the ethanol production unit involves additional costs such as labor, maintenance and debt service which should remain nearly constant as operating parameters change. Assume that these fixed costs are $0.30/gal of ethanol produced.

Profit (Loss) on Unit

At a selling price of $2.90/gal, the value of 5-million gallons of ethanol is $14.5 million. In estimating profit or loss for various operating conditions, the significant figure for profit or loss should be $0.01 million.

Group Formation

A student design group will consist of 3 or 4 group members. You are encouraged to choose a partner for this project to form a pair. When you have formed a pair, please write your names on the chart provided in class. Dr. Kugler will combine pairs to form groups of three or four. Group assignments will be made on November 12.

Reports

Each group will be expected to prepare a written report recommending the best operating procedures for the ethanol production process. This report is due at 3:00 PM, Wednesday, December 5. The report should follow the department's design-report guidelines. Data should be in the form of graphs and tables since this serves to both condense results and make them easily understandable. The appendix should include your spreadsheet and a hand calculation of one representative case. Hand calculations should be made using a pencil.

Report Authors

Although work on a group report can never be divided equally, only those members making substantial contributions to the final report should be listed as authors.