Energy Balances and Numerical Methods
Design Project

Production of Cumene

Process Description

Figure 1 is a preliminary process flow diagram (PFD) for the cumene production process. The raw materials are benzene and propylene. The propylene feed contains 5 wt% propane as an impurity, It is a saturated liquid at 25°C. The benzene feed, which may be considered pure, is liquid at 1 atm and 25°C. Both feeds are pumped to about 3000 kPa by pumps P-201 and P-202, are then vaporized and superheated to 350°C in a fired heater (H-201). The fired heater outlet stream is sent to a packed bed reactor (R-201) in which cumene is formed. There are no side-reactions or by-products. The reactor effluent is sent to a flash unit (V-201) in which light gases (mostly propane and propylene, some benzene and cumene) are separated as vapor in Stream 9. Stream 10, containing mostly cumene and benzene is sent to a distillation column (T-201) to separate benzene for recycle from cumene product. The desired cumene production rate is 100,000 metric tons/yr.

Process Details

Feed Streams

Stream 1: benzene, pure liquid, 25°C and 1 atm

Stream 2: propylene with 5 wt% propane impurity, saturated liquid at 25°C

Effluent Streams

Stream 9: fuel gas stream, credit may be taken for LHV of fuel

Stream 12: cumene product, assumed pure

Equipment

Pump (P-201):

The pump increases pressure of the benzene feed from 1 atm to about 3000 kPa. Pump operation may be assumed isothermal, and the cost of energy may be neglected. (Both of these assumptions are valid for this semester's design only.)

Pump (P-202):

The pump increases the pressure of the propylene feed to about 3000 kPa.. Pump operation may be assumed isothermal, and the cost of energy may be neglected. (Both of these assumptions are valid for this semester's design only.)

Fired Heater (H-201):

The fired heater desubcools, vaporizes, and superheats the mixed feed up to 350°C. Air and natural gas must be fed to the fired heater. Natural gas is priced at its lower heating value. The fired heater is 75% efficient.

Reactor (R-201):

The reactor feed must be between 300°C - 400°C and between 2800 kPa - 3200 kPa. Benzene must be present in at least 50% excess. Conversion of the limiting reactant is 92%. The reactor may be assumed isothermal, and the exothermic heat of reaction is removed by vaporizing boiler feed water to make high-pressure steam. Credit may be taken for the high-pressure steam.

The following reaction occurs:

$$C_3H_6 \quad + \quad C_6H_6 \quad \rightarrow \quad C_9H_{12}$$

propylene benzene cumene

There are no side reactions.

Flash Vessel (V-201):

This is actually a combination of a heat exchanger and a flash drum. The temperature and pressure are lowered in order to separate the propane and propylene from the cumene and benzene. Cooling water is used to lower the temperature.

Distillation Column (T-201):

Here all cumene in Stream 10 goes into Stream 12 (may be assumed pure cumene), and is in the liquid phase. All benzene, propylene and propane goes to Stream 11, and is also in the liquid phase. A distillation column requires both heat addition and heat removal. Heat removal is accomplished in a condenser (not shown), which requires an amount of cooling water necessary to condense the contents of Stream 11. Heat addition is accomplished in a reboiler (not shown), which requires an amount of high-pressure steam necessary to vaporize the cumene in Stream 12.

Utility Costs

Low-Pressure Steam (446 kPa, saturated) $3.00/1000 kg

Medium-Pressure Steam (1135 kPa, saturated) $6.50/1000 kg

High-Pressure Steam (4237 kPa, saturated) $8.00/1000 kg

Natural Gas (446 kPa, 25°C) $3.00/$10^6$ kJ

Electricity $0.05/kW hr

Boiler Feed Water (at 549 kPa, 90°C) $300.00/1000 m^3

Cooling Water $20.00/1000 m^3
available at 516 kPa and 30°C
return pressure ≥ 308 kPa
return temperature should be no more than 15°C above the inlet temperature, otherwise there is an additional cost of $0.35/$10^6$ kJ

Refrigerated Water $200.00/1000 m^3
available at 516 kPa and 10°C
return pressure ≥ 308 kPa
return temperature is no higher than 20°C
if return temperature is above 20°C, there is an additional cost of $7.00/$10^6$ kJ

Data

Use data from References [1] or from any handbook (such as Reference [2]). The following data are not readily available in these references.

Liquid Heat Capacity (range 25°C - 300°C)
Assume that the liquid heat capacity for benzene given in Reference [1] is valid for all organic liquids.

Vapor Pressures
Vapor pressures may be interpolated or extrapolated from the following data:

	normal boiling point	additional vapor pressure point	
	T (K)	T (K)	10^{-6} P (kPa)
benzene	353	562	4.87
propylene	225	365	4.59
propane	231	370	4.14
cumene	425	631	3.21

Normal heat of vaporization
for cumene: 3.81×10^7 J/kmole

Heat of formation
for cumene: 3.933×10^6 J/kmole

Economic Analysis

When evaluating alternative cases, the following objective function should be used. It is the equivalent annual operating cost (EAOC), and is defined as

EAOC = -(product value - feed cost - other operating costs - capital cost annuity)

A negative EAOC means there is a profit. It is desirable to minimize the EAOC; i.e., a large negative EAOC is very desirable.

The costs for cumene (the product) and benzene (the feed) should be obtained from the *Chemical Marketing Reporter*, which is in the Evansdale Library. The "impure" propylene feed is $0.095/lb.

Other operating costs are utilities, such as steam, cooling water, natural gas, and electricity.

The capital cost annuity is an ***annual*** cost (like a car payment) associated with the ***one-time***, fixed cost of plant construction. A list of capital costs for each piece of equipment will be provided by Spring Break. You will learn to calculate the annuity value in ChE 38.

Other Information

You should assume that a year equals 8000 hours. This is about 330 days, which allows for periodic shut-down and maintenance.

You should assume that two streams that mix must be at identical pressures. Pressure reduction may be accomplished by adding a valve. These valves are not shown on the attached flowsheet, and it may be assumed that additional valves can be added as needed.

Deliverables

Each group must deliver a report written using a word processor. The report should be clear and concise. The format is explained in a separate document. Any report not containing a labeled PFD and a stream table will be considered unacceptable. When presenting results for different cases, graphs are greatly superior to tables. The report appendix should contain, for the optimal case, details of calculations that are easy to follow. These calculations may be (neatly) hand-written. Calculations which can not be followed easily will lose credit.

Each group will give an oral report in which the results of this project are presented in a concise manner. The oral report should be no more than 15 minutes, and each group member must speak. A five-minute question-and-answer session will follow. Instructions for presentation of oral reports will be provided in a separate document. However, the best way to learn how to present an oral report, other than actually presenting one, is to make time to see some of the oral reports presented by the juniors the week before you are to present your report.

As mentioned in the cover memo, the written project report is due upon presentation of the oral report. The oral reports will be Monday, April 22, 1995 (ChE 38 class) and Wednesday, April 24, 1995 (ChE 41 class). There will be a project review on Friday, April 26, 1995 (ChE 41 class). In addition, everyone must attend at least one (and preferably both) of the senior design presentations, either on Tuesday, April 23, 1995, or on Thursday, April 25, 1995 (substitutes for Thursday ChE 38 class). Furthermore, attendance is required of all students during their classmates' presentations (this means in the room, not in the hall or the lounge). Failure to attend any of the above required sessions will result in a decrease in one letter grade (per occurrence) from your project grade in both ChE 38 and ChE 41.

Anyone not participating in this project will automatically receive an F for ChE 38, regardless of other grades earned in this classes.

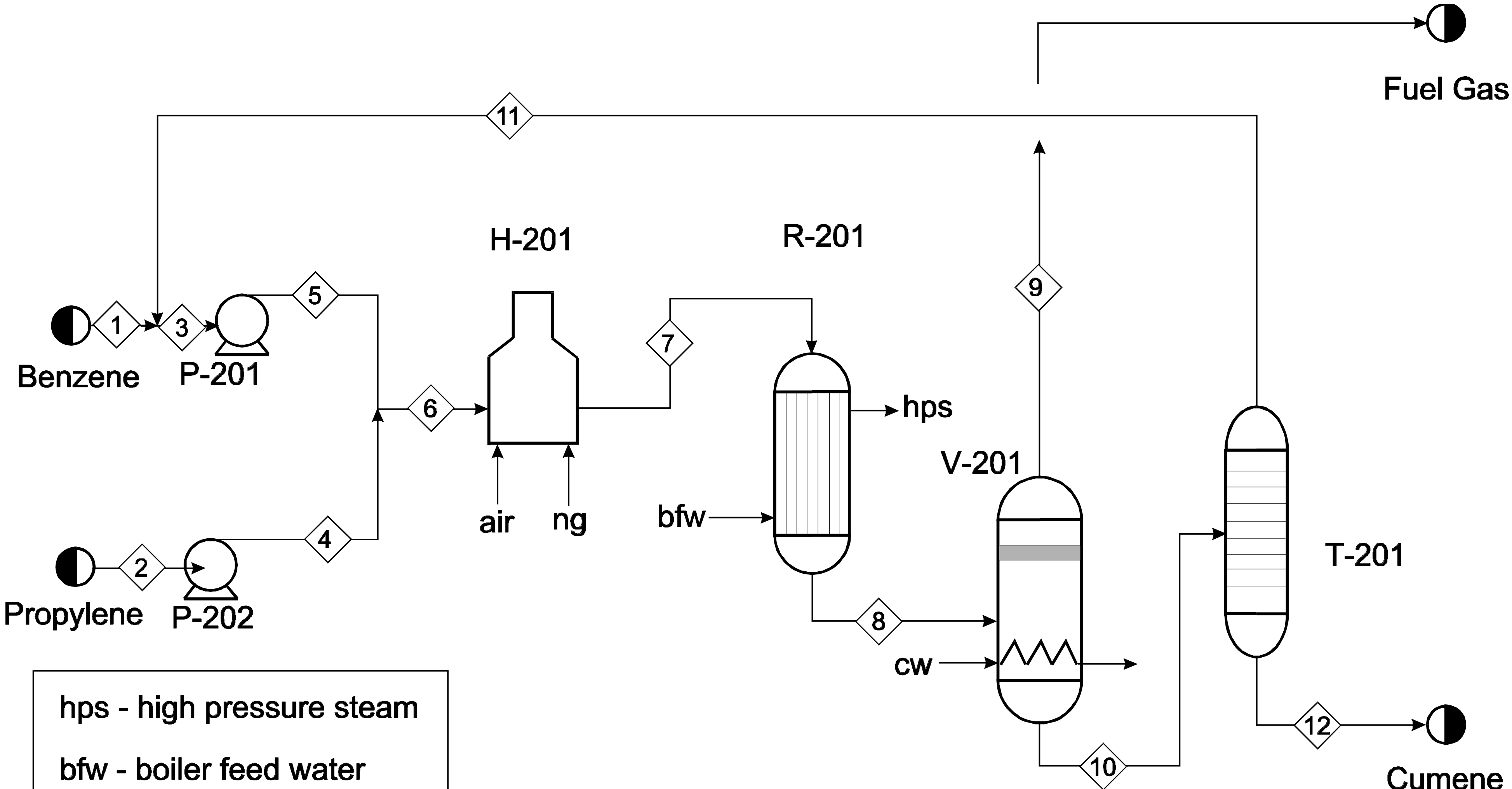
Revisions

As with any open-ended problem; i.e., a problem with no single correct answer, the problem statement above is deliberately vague. The possibility exists that as you work on this problem, your questions will require revisions and/or clarifications of the problem statement. You should be aware that these revisions/clarifications may be forthcoming.

References

1. Felder, R.M. and R.W. Rousseau, *Elementary Principles of Chemical Processes (2nd ed.)*, Wiley, New York, 1986.

2. Perry, R.H. and D. Green, eds., *Perry's Chemical Engineering Handbook (6th ed.)*, McGraw-Hill, New York, 1984, p. 9-74.



hps - high pressure steam

bfw - boiler feed water

cw - cooling water

ng - natural gas

Figure 1: Preliminary Process Flow Diagram for Cumene Production