The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and that elucidate difficult concepts. Manuscripts should not exceed ten double-spaced pages if possible and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

APPLICATION OF A HEAT PUMP

A Feasibility Study

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Distillation is one of the most widely used separation processes in the chemical and allied industries. Among possible distillation schemes with energy saving, incorporation of a heat pump can be very efficient—but any decision in a particular distillation problem should be very carefully considered. First and foremost, a separation process must be feasible; *i.e.,* it must have the potential of giving desired results. The decision of whether to use a heat pump or not depends on the economics of the process. An established practice is to make a preliminary design or feasibility study to decide whether to proceed with detailed calculations.

Before digital computers, the economic design of multicomponent fractionating towers and other vapor-liquid contacting devices was a tedious, difficult, and time-consuming job. Various "short-cut" methods were developed to simplify the task of designing multicomponent columns, and those methods are still useful in preliminary design work, where they can greatly reduce the number of calculations to be made. With the advent of large-capacity, high-speed digital computers and sophisticated calculation techniques, however, many new and powerful programs for process design have been developed.[1] One of them is ChemCAD III,[2] —a powerful and comprehensive chemical-plant simulation program.

THEORY

The initial design includes a prelimary flow diagram, material and energy balances, determination of the equipment size, and estimation of equipment costs and utility energy.

The preliminary flow diagram shows the arrangement of basic individual units of equipment. The flowsheet commands of ChemCAD III allow for a very simple creation of the flowsheet. The flowsheet menu has two basic purposes:

1. *To define the flowsheet; i.e., the unit operations and their connectivity*

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2. *To establish the calculation order of the flowsheet simulation*

The full simulation program is capable of carrying out rigorous simultaneous heat and material balances and preliminary equipment design. Our example will describe the techniques for solving multicomponent distillation problems of an interconnected flowsheet.

Distillation with Vapor Recompression

Three arrangements of heat pumps are possible.[3-5] In each case, compression work is normally used to overcome the adverse temperature difference, which precludes having the condenser serve as the heat source for the reboiler in an ordinary distillation column. If conditions are suitable, the process fluid can be used as the working fluid for the heat pump. In alternative arrangements, the process vapor is taken from the top of the column, compressed, and fed to the reboiler to provide heating. In distillation systems where the heat pump is applicable,[4] the heat pump with direct overhead vapor recompression proves to be the most economic solution. The compressor is the "heart" of the system. The ratio of compression is crucial to the power requirements, and depends on

$$\Delta p_{com} = \Delta p_{col} + \Delta p_b + \Delta p_c + \Delta p_{eq} \tag{1}$$

Relations between pressures and temperatures are given on the p/T diagram shown in Figure 1.

The ratio of compression is

$$r = \frac{p_2}{p_1} = \frac{\left(p_t + \Delta p_{com}\right)}{p_t} \tag{2}$$

A vapor compression heat pump applied to a distillation column is shown in Figure 2.

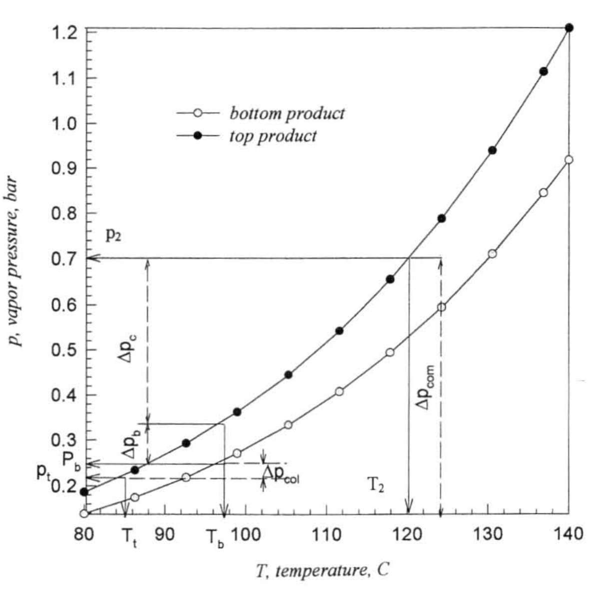

Figure 1. *Diagram of p/T for overhead vapor recompression.*

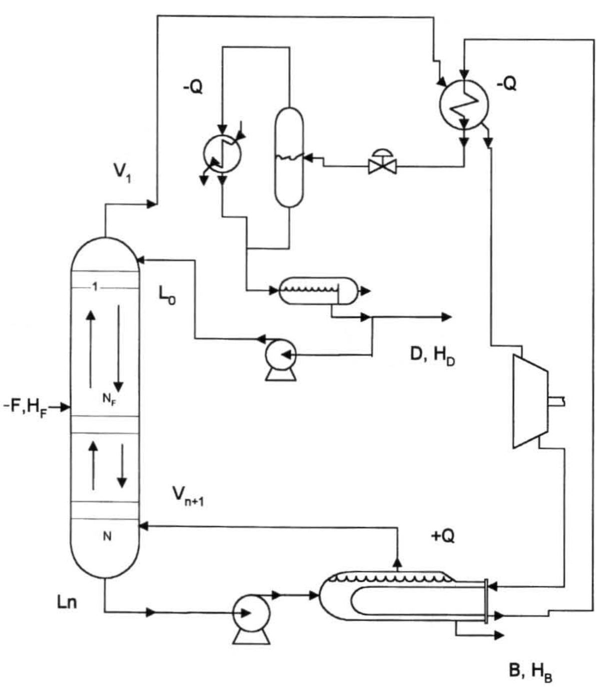

Figure 2. *Distillation column with heat pump.*

ESTIMATION OF PURCHASED EQUIPMENT COSTS

Capital cost estimates for chemical process plants are often based on the purchased cost of the major equipment items required for the process, the other costs being estimated as factors of the equipment cost. Costs are correlated against sizes of individual units. The relationship between size and cost is given by Eqs. 3 through 14.[6,8] The equipment-sizing facility inside ChemCAD III can be found under the command describing each equipment type. The following correlations for the base cost in carbon steel are given in SI units and US dollars.

Pressure vessels

$$C_{pv} = C^0_{pv} F_m F_p \frac{I}{336.2} \tag{3}$$

$$C^0_{pv} = (a + bL)d^{1.1} \tag{4}$$

In the following two correlations, column cost represents the sum of the costs of the shell and internals, either trays or packing.

$$C_{co} = C_{pv.vert} + C_{pack} \tag{5}$$

$$C_{pack} = C^0_{pack} d^n V_{pack} \frac{I}{336.2} \tag{6}$$

Heat Exchangers

$$C_{exc} = C^0_{exc} F_p F_{tex} \frac{I}{336.2} \tag{7}$$

$$C^0_{exc} = \exp(a + b\,\ell nA) \tag{8}$$

Pumps

$$C_{pu} = C^0_{pu} F_m F_p \frac{I}{418.3} \tag{9}$$

$$C^0_{pu} = \exp\{a + \ell n P[b + \ell n P(c + d\,\ell n P)]\} \tag{10}$$

Compressors

$$C_{com} = C^0_{com} F_m \frac{I}{418.3} \tag{11}$$

$$C^0_{com} = \exp(a + b\,\ell n P) \tag{12}$$

$$C_{em} = C^0_{em} F_{tem} F_{na} \frac{I}{331.2} \tag{13}$$

$$C^0_{em} = \exp\{5.33 + \ell n P[0.3 + \ell n P(0.162 - 0.014\,\ell n P)]\} \tag{14}$$

ESTIMATION OF UTILITY ENERGY

The word "utilities" is generally used for the ancillary services needed in the operation of any production process.[8] The services in this example include electricity, steam for process heating, and cooling water. The quantities required can be obtained from the energy balances and the flowsheets. The prices will depend on the primary energy sources and the plant location.

Cooling water

Mass flow rate of water

$$Q_{mass(H_2O_{liq})} = \frac{Q_{HD}}{C_p \Delta T} \tag{15}$$

Price of cooling water: \$0.02/m³

$$\text{Cost} = 0.02 \frac{Q_{mass(H_2O_{liq})}}{\rho_{water}}$$

Steam

Mass flow rate:

$$Q_{mass(H_2Og)} = \frac{Q_{TD}}{Hp} \tag{16}$$

Price of steam: \$10/t

$$\text{Cost} = 10\ Q_{mass}$$

Electric power

$$\text{Cost} = \$0.07 / \text{kWh}$$

All costs of utilities are based on one year or 8,000 hours. The base date for utilities energy is the start of 1987.[3]

PROCESS PROJECT

A flow rate of 22,000 kg/h of liquid has the composition shown in Table 1. The mixture has to be distilled to give an overhead product with 0.15 mole percent styrene and a bottom product with 0.3 mole percent ethyl benzene. The necessary information for using the ChemCAD III program includes working pressures and temperatures along the column and preliminary material balances. The column will operate at a pressure of 0.23 bar at the top and a temperature of 97 °C at the bottom. The pressure drop along the column is 0.02 bar.

The preliminary flow diagram and preliminary material balances are shown in Figure 3 and Table 2. Figure 3 shows a standard column configuration, *i.e.*, conventional distillation that was modified to use a heat pump with the stream transfer modules (STM). These modules serve as an abstract block in the flowsheet, and their output stream is exactly the same as their input stream.

TABLE 1
Feed Composition

	mol%
Benzene	0.8
Toluene	1.2
Ethyl benzene	40.0
Styrene	58.0

RESULTS

The feed rate is 22,000 kg/h. The mean molecular weight

TABLE 2
Preliminary Material Balance

	Feed		*Top*		*Bottom*	
Comp	*kmol/h*	*fraction*	*kmol/h*	*fraction*	*kmol/h*	*fraction*
Benzene	1.680	0.008	1.680	0.019	0	0
Toluene	2.520	0.012	2.520	0.029	0	0
Etbenzene	84.000	0.400	83.750	0.950	0.250	0.002
Styrene	121.800	0.580	0.190	0.002	121.610	0.980
Total	**210.000**	**1.000**	**88.140**	**1.000**	**121.860**	**1.000**

of the liquid mixture is

$$M = \sum x_i M_i = 0.008 \times 78.114 + 0.012 \times 92.141 + 0.40 \times 106.168 + 0.58 \times 104.52 = 104.61$$

Thus, the molar flow rate of feed is 22,000/104.61 = 210.3 kmol/h.

EQUIPMENT SIZES OBTAINED BY CHEM CAD III SIMULATION

► *Distillation Column*

- Type and size of packing: Intalox ceramic saddle (3 inch)
- Height required for the specified separation: 86 m
- Column diameter (capacity): 7.5 m

► *Distillation Storage Tank*

	Conventional Distillation	*Heat Pump*
Height (width), m	*8.23*	*8.23*
Diameter, m	*2.74*	*2.74*

► *Vapor-Liquid Separator*

	Heat Pump
Height (width), m	*13.26*
Diameter, m	*4.42*

► *Heat Exchanger: Heat duty and area*

	Conventional Distillation	*Heat Pump*
Heat duty Q, kJ/h (E01, E05)	-1.4×10^8	-1.74×10^7
Heat duty Q, kJ/h (E02, E04)	1.4×10^8	3.73×10^6
Heat duty Q, kJ/h (E03)	-	1.41×10^8
Area, m^2 (E01, E05)	*213.0*	*165.1*
Area, m^2 (E02, E04)	*690.2*	*261.4*
Area, m^2 (E03)	-	*5,549.0*

► *Pumps: Pumping power*

	Conventional Distillation	*Heat Pump*
Power, kW (P01, P03)	*100.7*	*2.5*
Power, kW (P02, P04)	*1.9*	*1.9*

► *Compressor*

Compressor power: P=4,205 kW

EQUIPMENT COSTS

► *Conventional Distillation: Purchased equipment cost*

Equipment Items		*Price: \$*
Tower	*T01*	*\$2,315,000*
Pump	*P01*	*15,470*
Pump	*P02*	*760*
Vessel	*D01*	*25,660*
Condenser	*E01*	*39,440*
Reboiler	*E02*	*140,000*
	Total	***\$2,536.330***

► *Utilities Cost*

Utilities	*Cost: \$/year*
Steam	*\$4,467,200*
Cooling water	*1,457,600*
Electrical power	*62,400*
Total	***\$5,987,200***

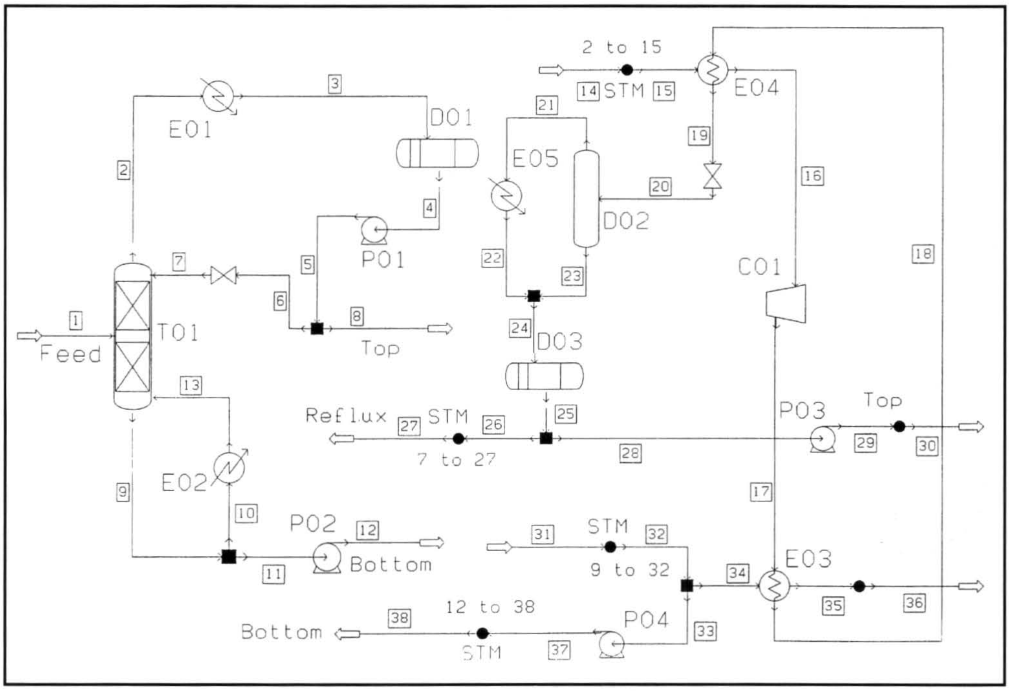

Figure 3.

Process flow diagram

▶ *Distillation with Heat Pump: Purchased Equipment Cost*

Equipment Items		***Price: $***
Tower	*T01*	*$2,315,000*
Pump	*P03*	*3,360*
Pump	*P04*	*770*
Condenser	*E04*	*45,090*
Condenser	*E05*	*33,210*
Heater	*E03*	*334,750*
Compressor	*C01*	*3,683,000*
Separator	*D02*	*68,000*
Storage tank	*D03*	*25,670*
	Total	***$6,508,850***

▶ *Utilities Cost*

Utilities	***Cost: $/year***
Cooling water	*182,400*
Electrical power	*2,572,000*
Total	***$2,754,400***

▶ *Summary of Annual Costs*

	Conventional Distillation: $/year	***Heat Pump:$/year***
Equipment (amortized over ten years)	*$253,630*	*$650,890*
Utilities	*$5,987,200*	*$2,754,400*
Total	***$6,240,830***	***$3,405,290***

CONCLUSION

The purpose of this example is not to obtain a detailed calculation, but to illustrate the methodology of a preliminary design of equipment and obtain a feasibility study. The preliminary design includes shortcuts in calculations so that the cost estimates of equipment probably contain moderate errors. There are two alternative designs for the distillation and the aim of this work is to find which of them is more attractive economically. Both designs are feasible.

The results show that the application of the heat pump with vapor recompression is more economically justified. The purchased cost of the major equipment items required for the process with the heat pump is 2.5 times higher than for conventional distillation, but the energy costs saved easily justifies the investment after one year's operation of the equipment.

The above example shows the benefits of making a preliminary calculation to prove whether or not to proceed with detailed calculations.

NOMENCLATURE

a,b,c,d,	coefficients in Eqs. (4) and (8)
A	heat transfer area, m^2
C_{co}	cost of column, $
C_{com}	cost of compressor, $
C^0_{com}	base cost of compressor, $
C_{em}	cost of electromotor, $
C^0_{em}	base cost of electromotor, $
C_{exc}	cost of exchanger, $
C^0_{exc}	base cost of exchanger, $
C_{pack}	cost of packing per unit volume, $/$m^3$
C^0_{pack}	base cost of packing per unit volume, $/$m^3$
C_{pu}	cost of pump, $
C^0_{pu}	base cost of pump, $
C_{pv}	cost of pressure vessel, $
$C_{pv,vert}$	cost of vertical vessel, $
C^0_{pv}	base cost of pressure vessel, $
d	diameter, m
Δp_b	vapor pressure difference between overhead and bottom product at column bottom temperature, bar
Δp_c	pressure difference between hot and cold side in evaporator/condenser, bar
Δp_{col}	column pressure drop, bar
Δp_{eq}	equipment and pipes pressure drop, bar
Δp_{com}	growth pressure in compressor, bar
F_m	material cost factor
F_{na}	electromotor purpose cost factor
F_p	pressure cost factor
F_{tem}	electromotor type cost factor
F_{tex}	exchanger type cost factor
I	inflation index
L	length of column, m
P	power, kWh
p_1	compressor suction pressure, bar
p_2	compressor discharge pressure, bar
p_b	column bottom pressure, bar
p_t	column top pressure, bar
Q	heat transferred per unit time, kJ/h
Qv	flowrate, m^3/h
r	compression ratio
U	overall heat transfer coefficient, kJ/m^2K
V_{pack}	volume of packing, m^3
ΔTm	mean temperature difference, the temperature driving force, K
η_p	pump efficiency

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