American Institute of Chemical Engineers

STUDENT CONTEST PROBLEM

1980

345 East 47 Street • New York, New York 10017

CONTEST PROBLEM

1980

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS STUDENT CHAPTERS

Open Only to Undergraduates or Those
Without a Degree in Chemical Engineering

DEADLINE FOR MAILING

Solution must be postmarked not later than midnight, June 1, 1980.

RULES OF THE CONTEST

Solutions will be graded on (a) substantial correctness of results and soundness of conclusions, (b) ingenuity and logic employed, (c) accuracy of computations, and (d) form of presentation. Accuracy of computations is intended to mean primarily freedom from mistakes; extreme precision is not necessary.

It is to be assumed that the statement of the problem contains all the pertinent data except for those readily available in handbooks and similar reference works. The use of textbooks, handbooks, journal articles, and lecture notes is permitted. In cases where there is disagreement in the data reported in the literature, the values given in the statement of the problem have been chosen as being most nearly applicable.

The problem is not to be discussed with any person whatever until June 1, 1980. This is particularly important in cases where neighboring institutions may not begin the problem until after its completion by another chapter. Submission of a solution for the competition implies adherence to the foregoing condition.

A period of not more than thirty consecutive days is allowed for completion of the solution. This period may be selected at the discretion of the individual counselor, but in order to be eligible for an award a solution must be postmarked not later than midnight, June 1, 1980.

The finished report should be submitted to the chapter counselor within the thirty-day period. There should not be any variation in form or content between the solution submitted to the chapter counselor and that sent to the AIChE office. The report should be neat and legible, but no part need be typewritten.

The solution should be accompanied by a letter of transmittal giving only the contestant's name, school address, home address, and student chapter, lightly attached to the report. This letter will be retained for identification by the Secretary of the Institute. The solution itself must bear no reference to the student's name or institution by which it might be identified. In this connection, graph paper bearing the name of the institution should be avoided.

Each counselor should select the best solution or solutions, not to exceed two, from his chapter and send these by registered mail to

J. C. Forman, Secretary
American Institute of Chemical Engineers
345 East 47 Street
New York, New York 10017

AIChE STUDENT CONTEST PROBLEM

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Alkylation Unit Heat-Pump Fractionator

STATEMENT OF PROBLEM

An oil refiner requires additional *i*-butane feed for a new alkylation unit which produces gasoline from butylene and *i*-butane. To meet this need, he requires a system to produce an *i*-butane–rich stream containing 5,000 barrels (42 gallons per barrel measured at 60°F.) a day of *i*-butane. The propane content of this stream is acceptable since it will be removed in the alkylation unit facilities, but the *n*-butane content of this stream may not exceed 400 barrels a day. The refinery has available a maximum of 30,000 barrels a day of mixed butanes to supply this need at the following composition:

	Percentage of liquid volume at 60°F.
Propane	2.5
i-Butane	21.5
n-Butane	76.0
Total	100.0

There is an existing fractionation column with fifty actual trays and adequate diameter and design conditions (temperature and pressure) which the refiner wishes to use for this system. The alkylation-unit design has provided 30.0×10^6 Btu/hr of heat for reboiling this fractionation column from the exothermic alkylation reaction, which must be maintained at 105°F. It is expected that a vapor compression/condensation cycle (heat pump) can be economically utilized to provide the additional energy requirements for reboiling this system. All compressors, pumps, and heat exchange equipment will be purchased new.

You, as a design engineer for the engineering company licensing the alkylation process unit, are given the assignment of deciding the most profitable feed rate, operating conditions, and equipment configuration for this system. A preliminary flow diagram for a heat-pump fractionation column is shown in Figure 1.

OBJECTIVES OF THE PROBLEM

1. Select the optimum operating conditions and equipment configuration based upon the cost of utilities and the capital costs of new equipment. Capital costs for the alkylation-unit exchange, piping, instrumentation, and tray modifications (if required) may be considered a constant for all schemes; therefore, only the compressor, pumps, and fractionator heat exchange equipment need be considered for capital cost analysis.

2. Prepare a heat and material balance and process flow diagram for the selected processing scheme.

Your manager has given you the following guidelines for the design of the heat-pump fractionation column:

1. For the fractionation calculations all the propane in the feed may be assumed to go overhead, and the split between *i*-butane and *n*-butane may then be treated as a ***binary system.***

2. For this system constant molal overflow is a reasonable assumption; therefore, the use of a McCabe-Thiele diagram will give valid results.

3. The overall tray efficiency for systems of this type has been approximately 80%.

4. The optimum cold-end approach temperatures for the heat-pump reboiler should fall somewhere between 10° and 40°F. Assume that the temperatures on the hot sides of the reboiler and trim condenser vary linearly with the amount of heat transferred. The terminal temperatures will be the dew points at the inlet pressures and the bubble points at the outlet pressures.

5. The exchange with alkylation unit (30×10^6 Btu/hr.) is attractive because the LMTD was based upon the fractionator bottoms, of which the temperature rise upon vaporization is minimal; hence, 90°F. is used as the inlet and outlet temperature of this stream to and from the reactor exchanger. This temperature will set the operating pressure of the fractionation column.

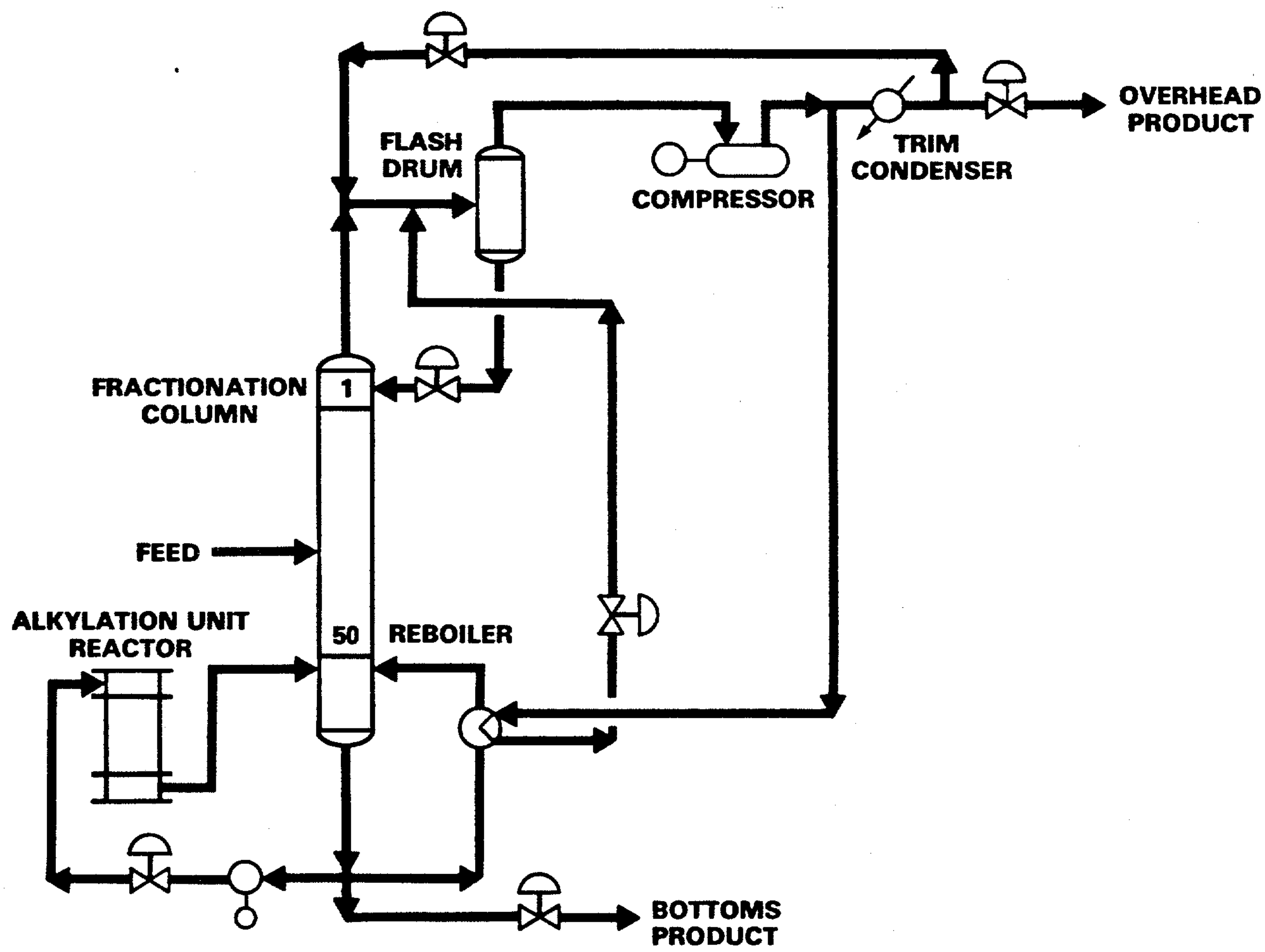


Fig. 1. Heat-pump fractionation column.

TECHNICAL DATA

1. Physical Properties

	Propane	*i*-Butane	*n*-Butane
Molecular formula	C_3H_8	C_4H_{10}	C_4H_{10}
Molecular weight	44.094	58.120	58.120
Normal boiling point, °F.	−43.7	10.9	31.1
Critical temperature, °R.	666.0	734.7	765.3
Critical pressure, lb./sq. in. abs.	617.4	529.1	550.7
Density, lb./gal. at 60°F.	4.233	4.695	4.872

2. Equilibrium Vaporization Constants

For *equilibrium vaporization constants* assume that Raoult's and Dalton's laws are valid.

3. Vapor Pressure

Vapor pressure may be calculated from the Antoine equation:

$$\mathrm{Log}_{10} P = A - \left(\frac{B}{C + T}\right)$$

P is in lb./sq.in.abs.
T is in °F.
A, B, C are constants.

Antoine Constants:

	Propane	*i*-Butane	*n*-Butane
A	5.11612	5.03447	5.11668
B	1463.76	1589.04	1702.62
C	414.40	400.0	400.0

4. Liquid Solution Volumes

Assume ideal liquid solutions; for example, component volumes are additive.

5. Enthalpy

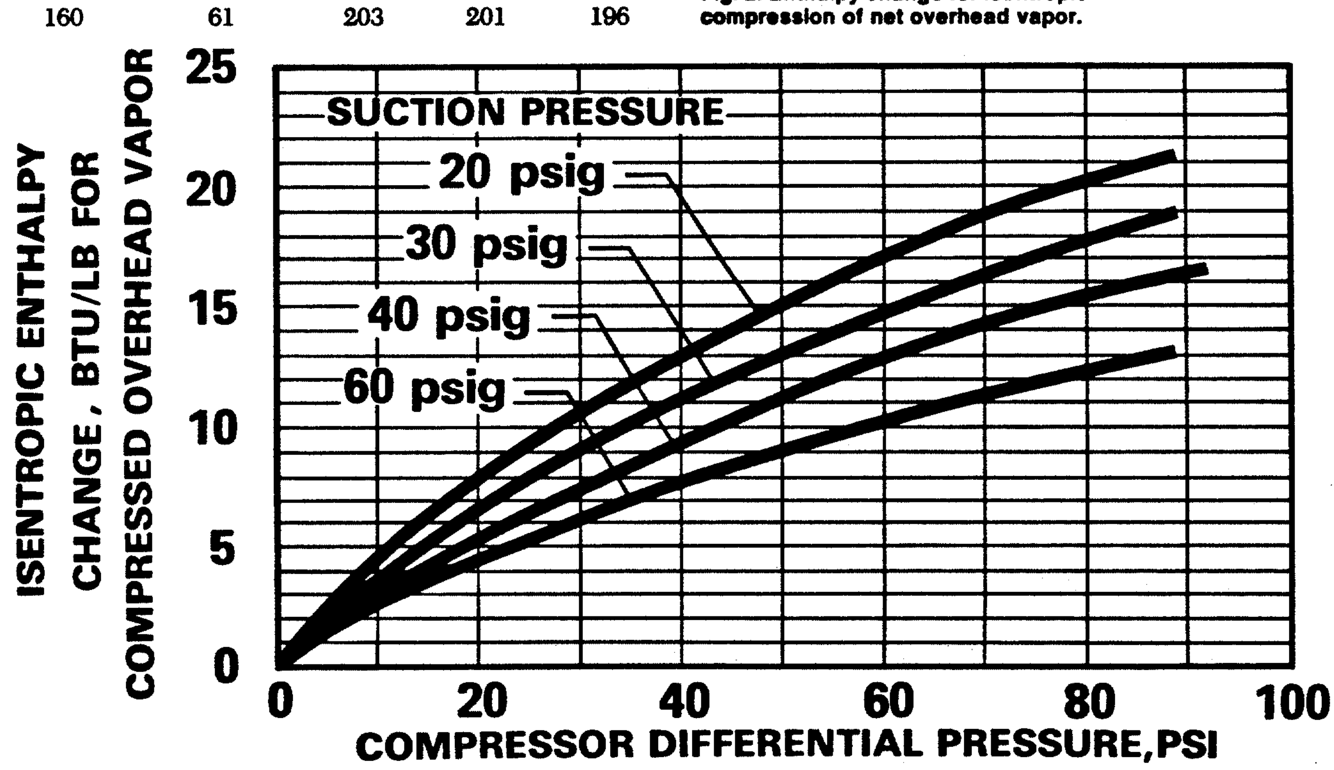
The enthalpy of a mixture in either the vapor or liquid phase may be obtained by summing the weight fraction of each individual component times its enthalpy at total system pressure. This is a consequence of the assumption of an ideal solution and will be sufficiently accurate for the purpose of this problem. The enthalpy of the three components is shown in the following table:

Temperature, °F.	Liquid enthalpy, B.t.u./lb.	Vapor enthalpy, B.t.u./lb. 25 lb./sq. in.abs.	50 lb./sq. in.abs.	100 lb./sq. in.abs.
		PROPANE		
60	0	161	158	153
80	13	169	167	162
100	27	177	175	171
120	41	186	184	180
140	57	195	193	189
160	74	204	202	199
		i-BUTANE		
60	0	149	145	137
80	11	157	154	147
100	23	165	163	157
120	36	174	171	166
140	49	183	181	176
160	62	192	190	185
		n-BUTANE		
60	0	160	156	147
80	11	168	165	157
100	23	176	174	167
120	36	185	182	176
140	48	194	192	186
160	61	203	201	196

6. Isentropic Compression
From a Mollier diagram of overhead vapor, Figure 2 was prepared to show the enthalpy change for isentropic compression for various suction pressures from 20 to 60 lb./sq.in.abs.

7. Thermal Expansion
The thermal expansion of the liquid feed stream is shown in Figure 3. When the volume of the overhead and bottom streams from the fractionation column is required, the expansion factors from Figure 3 should be utilized.

Fig. 2. Enthalpy change for isentropic compression of net overhead vapor.



BASIC DESIGN ENGINEERING DATA

1. Battery Limit Condition

	Temperature, °F.	Pressure, lb./sq.in.gauge
Feed	80	Adequate (no feed pump required)
Net overhead product	110 maximum	100 minimum
Net bottoms product	110 maximum	100 minimum

2. Utility Information

	Temperature, °F.	Pressure, lb./sq.in. gauge	Cost, $/1,000 lb.
High-pressure steam	750	600	2.30
Exhaust steam	297	50	1.80
Electricity	$0.022/kw.-hr.		
Cooling water (sea)	$0.03/1,000 gal. Use 90°F. inlet with 20°F. maximum rise		
Ambient air for cooling	Use 108°F. and assume 1.4 hp. will move 1,000 lb./min. of air through air fan. The specific heat of air is 0.24 B.t.u./lb. –°F.		

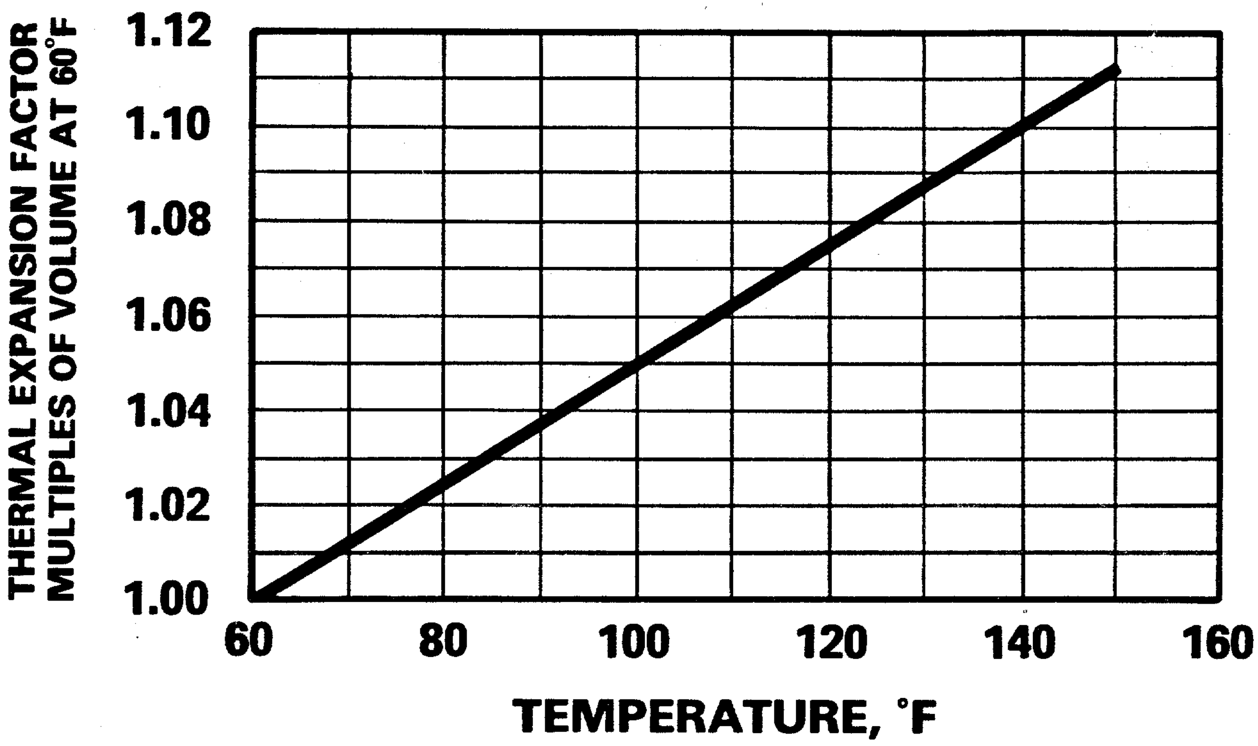


Fig. 3. Thermal expansion factor.

3. Equipment Costs

Rotating equipment:	Installed cost
Pump and driver	$150/B.hp.(turbine or motor)
Compressor and motor driver	$200/B.hp.
Compressor and turbine driver	$250/B.hp.
Exchangers:	
Water cooled	$40/sq.ft.
Air cooled	$25/sq.ft.(based upon bare tube surface)
Other (tube and shell type)	$25/sq.ft.

Do not include any costs for spare equipment.

4. Exchanger Heat Transfer Coefficients

Tube and shell:	B.t.u./hr.-sq.ft.-°F.
Reboiler using condensing vapors	120
Liquid/liquid exchanger	110
Water cooled	70
Air fin:	
Cooler/condensers	90 (based upon bare tube surface)

5. Equipment Pressure Drop

Exchanger:	
Tube side (tube and shell type)	3 lb./sq.in. per unit
Tube side (air fin type)	3 lb./sq.in. per unit
Shell side	2 lb./sq.in. per unit
Fractionator tray	0.06 lb./sq.in. per actual tray
Piping	negligible

6. Equipment Efficiency

Compressors	Use 74% for the isentropic efficiency of the centrifugal compressor.
Compressor driver	Since 50 lb./sq.in.gauge steam may be used in downstream processing facilities, a topping turbine exhausting to 50 lb./sq.in.gauge may be used. The steam rate for a turbine of this type is 15 lb./hr. of 600 lb./sq.in. steam per brake horsepower.
Pumps	All pumps will have motor drivers. Use 75% for overall pump and driver efficiency.

7. Economic Guidelines

The refiner uses the following guidelines: A $1/day reduction in operating utilities will be equivalent to a $1,300 capital outlay. The value per barrel of the fractionation-column bottoms product is equal to that of the fractionation-column feed.

REPORT FORMAT

The final report of your studies should include the following:

1. Cover letter
2. Introduction
   A concise statement of the problem covering background and objectives.
3. Summary
   a. A brief description of the work involved in the study.
   b. The conclusions of the study.
4. Technical information
   a. Heat and material balance for the selected scheme.
   b. Process flow diagram.
   c. Tabulation of optimization studies.
5. Appendix
   Calculations, explanation of assumptions made, and details not included elsewhere.

REFERENCES

1. Null, H. R., "Heat Pumps in Distillation," *CEP*, **72**, 7, 58-64 (1976).
2. Finelt, S., "Better C_3 Distillation Pressure," *Hydrocarbon Processing*, **58**, 2, 95-98 (1979).
3. Shinskey, F. G., "Distillation Control," p. 191-195, McGraw-Hill, New York (1977).