CHE654 – Plant Design Project #2
Semester 1, 2022

DESIGN OF A DIETHYL ETHER PRODUCTION PROCESS

(Courtesy of the Department of Chemical Engineering at West Virginia University)

Introduction

Diethyl ether (DEE) is a colorless, highly volatile, flammable liquid with a characteristic odor. It is an important solvent in the production of cellulose acetate and other cellulose-based polymers. Other uses for DEE are as a starter fluid for diesel and gasoline engines, and as a solvent for Grignard and other reactions involving organometallic reagents. Previously, it was used as a general anesthetic.

The common production method for DEE is as a by-product from the vapor-phase hydration of ethylene to make ethanol. However, we have an excess of ethanol in our facility. Therefore, the process of interest in this assignment uses the vapor-phase dehydration of ethanol.

We wish to manufacture 50,000 metric tons/year of a liquid containing at least 99.5 mol% DEE, subject to constraints which will be defined later in this document.

A suggested process flow diagram (PFD) of the unit, termed Unit 1200, is attached. You should use this as a starting point. However, any change that you can justify on economic grounds (and that does not violate the laws of nature) is not only allowed but encouraged. Your job is to analyze the simplified styrene production process, to suggest profitable operating conditions, and to write a final report summarizing your findings. Note that although you are to look for a "best" solution in your design, optimization is NOT required in this design project.

Process Description

See Figure 1. The fresh feed to the unit, Stream 1, consists of 70 mol% ethanol in water. This stream is pumped from storage and sent to an on-site feed vessel, V-1201, where it is mixed with recycled ethanol, Stream 29. The stream leaving V-1201, Stream 2, is vaporized and heated in heat exchanger E-1201. It is then fed to the packed bed reactor, R-1201. The reactor contains a packed bed of alumina catalyst. The main reaction:

$$\underset{ethanol}{2C_2H_5OH} \rightarrow \underset{DEE}{(C_2H_5)_2O} + H_2O \qquad (1)$$

is exothermic, reversible, and limited by equilibrium. The reaction occurs at medium temperatures (400-600 K) and high pressures (1000-1500 kPa). The alumina catalyst minimizes (but does not eliminate) side reactions at higher temperatures. For simplicity, assume that the only side reaction that occurs in R-1201 is the dehydration of DEE to form ethylene:

$$\underset{DEE}{(C_2H_5)_2O} \rightarrow H_2O + \underset{ethylene}{2C_2H_4} \tag{2}$$

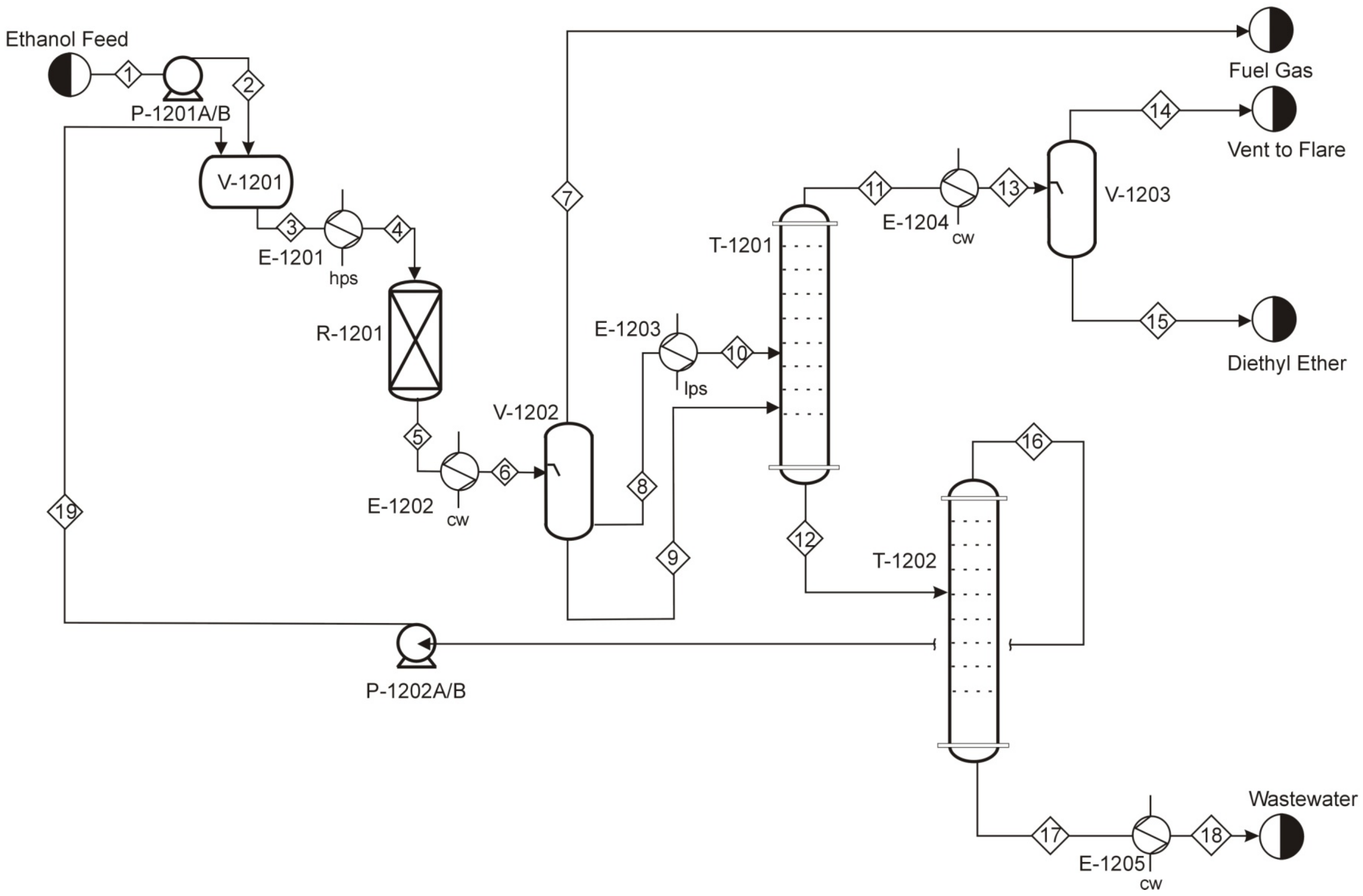
The primary reaction is limited by equilibrium, and is assumed to approach 80% of equilibrium. The selectivity of the ethylene side reaction is a function of reactor temperature and pressure.

The reactor effluent, Stream 4, is cooled in E-1202 using cooling water and enters a flash vessel, V-1202. The overhead stream from V-1202, Stream 7 (8), contains all of the ethylene that is formed in the undesirable side reaction, along with small amounts of DEE and ethanol. This stream is sent to another process to be used as fuel gas.

The liquid in V-1202 is sent to two distillation towers in series. The distillation columns operate at (different) constant pressures, the values of which are governed by the properties of the heating steam and cooling water used, and the composition of the top and bottom products, as described later. The liquid stream, Stream 6, enters the DEE purification column, T-1201, where the DEE is separated from the water and ethanol. The overhead product from this column, Stream 17, is then cooled in E-1205. The outlet, Stream 18, is the DEE 99.5+% product stream that is sent to storage.

The bottom product from T-1201, Stream 12, is sent to the second column, T-1202, where the ethanol is purified as the top product to a 70 mol% pure aqueous mixture. This mixture, Stream 28, is pumped back to the feed pressure using P-1203A/B and returned to the front end of the process. The bottom product stream from T-1202, Stream 22, is water with trace amounts of EtOH and DEE. This stream is cooled to 40°C in E-1208 and the wastewater stream is sent to be treated (not shown in Figure 1) prior to discharge to the environment.

P-1201 A/B	V-1201	E-1201	R-1201	P-1202-A/B	E-1202	V-1202	E-1203	T-1201	E-1204	V-1203	T-1202	E-1205
Ethanol Feed Pumps	Feed Drum	Feed Heater	Reactor	Ethanol Recycle Pumps	Reactor Effluent Cooler	Three-Phase Flash Drum	DEE Column Prehater	DEE Column	DEE Cooler	Knockout Drum	Ethanol Column	Wastewater Cooler



Process Details

Feed Stream

Stream 1: Feed: liquid solution of 70 mol% EtOH in water at 30°C and 1500 kPa.

Effluent Streams

Stream 8: Fuel Gas: light-gas stream of ethylene with traces of water vapor, DEE and EtOH in the vapor phase at 40°C and 1100 kPa. Take credit for this stream as a fuel, using the lower heating values of the components of the stream.

Stream 18: Product Liquid: contains at least 99.5 mol% DEE, with the balance being EtOH and water, at 37°C.

Stream 23: Wastewater: contains water with traces of EtOH and DEE, at 40°C. Stream 23 must be processed at the associated waste-water treatment cost given below. For this design project, assume the properties of this stream to be those of pure water.

Recycle Stream.

Stream 29: top product of the EtOH column, T-1202, an aqueous solution of 70 mol% EtOH. Assume that it is pumped back to the feed drum, V-1201, at 1500 kPa and the temperature at the top of T-1202.

Equipment

Heat Exchangers: Heat exchanger E-1201 heats the feed, Stream 2. The temperature of the exit stream, Stream 3, may not exceed a value that is 5°C lower than the inlet temperature of the appropriate type of steam used for heating.

Heat exchanger E-1202 may be used to cool (or heat) the reactor outlet, Stream 4. If E-1202 is used for cooling, then the temperature of the exit stream, Stream 5, should be at least 5°C greater than the temperature of the outlet cooling water. If E-1202 is used for heating, then the Stream-5 temperature may not exceed a value that is 5°C lower than the inlet temperature of the appropriate type of steam used for heating. The temperature of Stream 5 should be such that the temperatures of Streams 6 and 7 correspond to an optimum separation in the Flash Vessel V-1202 operating adiabatically at the optimum separation pressure.

Heat exchangers E-1205 and E-1208 are used respectively to cool the product liquid, Stream 17, to 37°C and the wastewater, Stream 22, to 40°C. For each of these heat exchangers, the exit temperatures should be at least 5°C greater than the temperature of the outlet cooling water.

Temperature constraints of heat exchangers, condensers and reboilers associated with other pieces of equipment are provided separately below.

Catalytic Reactor, R-1201: This may be either an isothermal fixed-bed reactor with a heat-transfer jacket, or two (or more) adiabatic fixed-bed reactor stages with a heat exchanger between stages. (Figure 1 shows only the isothermal option but you should consider both in your optimization.)

Only the reactions in Equations (1) and (2) are assumed to occur. The ranges of parameters that can be used are: temperature between 400-600 K and pressure between 1000-1500 kPa. The selectivity S for DEE formation in R-1201 (relative to ethylene) is dependent on temperature and pressure, and is given by the following:

$$S = S_o \left(\frac{P}{1250} \right)^n \exp\left[A \left(\frac{1}{T} - \frac{1}{1500} \right) \right] \tag{3}$$

with T in [K] and P in [kPa]. S_o, A and n must be obtained by regression of data provided in Table 1 by the company laboratory. These data are approximate and are to be used only for this design project this semester, not for more complex versions to be completed in subsequent semesters. The regression should not be extrapolated outside the range 400-600 K.

Table 1. Selectivity Data for DEE

Temperature, T [K]	400	400	450	450	500	500	550	550	600	600
Pressure, P [kPa]	1000	1500	1000	1500	1000	1500	1000	1500	1000	1500
Selectivity	24.87	21.48	12.60	10.84	7.43	6.38	4.94	4.23	3.59	3.08

$$S = \frac{\text{change in the molar flow rate of DEE}}{\text{change in the molar flow rate of ethylene}}$$

The catalyst cost in R-1201 may be significant and must be taken into account in the economics and optimization.

Flash Vessel, V-1202: For the purposes of this design project, assume the flash vessel operates adiabatically. Assume that ethylene is insoluble in Stream 6; therefore, all the ethylene present in Stream 5 is present only in Stream 7. Also, assume that water, DEE and EtOH are partitioned between Streams 6 and 7 according to Raoult's Law. You should optimize V-1202 (using vapor-liquid equilibrium equations developed in class) for the best temperature and pressure to operate this unit in order to maximize the recovery of DEE in Stream 6.

Pumps: Pumps increase the pressure of liquids. Figure 1 contains one pair of pumps, P-1201A/B. When you revise Figure 1, you need to add pumps as appropriate, even if they are not currently present in Figure 1. For all pumps, the cost of energy may be neglected for this project.

Compressors: Compressors increase the pressure of vapor phases. If you use one or more compressors, they may be assumed to be adiabatic. In that case, the compressor power may be calculated as:

$$\dot{W}_s[\text{kW}] = 20{,}000\dot{m}[\text{kmol/s}]\left[\left(\frac{P_{out}}{P_{in}} \right)^{0.286} - 1 \right] \tag{4}$$

where $\dot{m}$ [kmol/s] is the total molar flow rate of the inlet stream. Equation (4) includes the compressor efficiency. In general, the ratio of outlet to inlet pressure (compression ratio) in a compressor is between 3 and 5. If a compression ratio greater than 5 is needed, compressors are usually staged, with cooling between the compressor stages ("intercooling"), but not after the last stage. If you choose to do this, the compression ratio for each stage should be identical, and the intercooling should be to 50°C. The PFD that you draw should accurately represent the chosen compressor configuration.

The compressor increases the temperature of the stream being compressed according to:

$$\frac{T_{out}}{T_{in}} = \left(\frac{P_{out}}{P_{in}}\right)^{0.286} \tag{5}$$

where T is absolute temperature. The cost of electricity to run the compressor is a utility cost.

Distillation Columns T-1201 and T-1202: From V-1202, the liquid product stream (Stream 6) enters the distillation section, columns T-1201 and T-1202.

Stream 17, the top product from the DEE column T-1201, must contain all of the DEE entering the distillation train, and must contain 99.5 mol% DEE, with the rest of Stream 17 being water and ethanol. Note that the compositions of Streams 14-18 must be the same, although temperatures and phases differ. Stream 14, which goes to condenser E-1203, must be a saturated vapor, while Streams 15-17 are saturated liquids. The molar flow rate of Stream 14 must be 10 times that of Stream 17. Stream 17 is cooled to 37°C by E-1205, as noted earlier. Also, the compositions of Streams 9-13 must be the same, although temperatures and phases vary. Streams 9, 10 and 12 must be saturated liquids and Stream 11 must be a saturated vapor. The molar flow rate of Stream 11 must be one-third that of Stream 12. T-1201 must operate at a pressure low enough to make Stream 9 vaporize at a temperature that has a value no higher than 5°C lower than the temperature of the steam used as the heat source for E-1204. Stream 13, the bottoms product from the DEE column (T-1201), is further distilled in the EtOH column (T-1202).

In T-1202, note that the compositions of Streams 24-28 must be the same, although temperatures and phases differ. Stream 24, which goes to condenser E-1206, must be a saturated vapor, while Streams 25-27 are saturated liquids. The molar flow rate of Stream 24 must be 10 times that of Stream 28. The overhead product, Stream 28, contains 70 mol% EtOH in water, and is recycled to mix with Stream 1 in V-1201 before the reactor R-1201. Also, the compositions of Streams 19-23 must be the same, although temperatures and phases vary. Streams 19, 20 and 22 must be saturated liquids and Stream 21 must be a saturated vapor. The bottoms product of T-1202, Stream 22, must be water with a small amount of EtOH, and goes to a wastewater treatment facility after being cooled to 40°C in E-1208. The molar flow rate of Stream 21 must be one-third that of Stream 22. T-1202 must operate at a pressure low enough to make Stream 19 vaporize at a temperature that has a value no higher than 5°C lower than the temperature of the steam used as the heat source for E-1206.

Other Equipment Considerations:

- Flow must occur from a higher pressure to a lower pressure.
- Two streams that are to be mixed are required to be at identical pressures.

- Pressure reduction is accomplished by adding a valve.
- Pumps increase the pressure of liquid streams, and compressors are used to increase the pressure of gaseous streams. For example, locations where pumps are needed are in the liquid streams exiting V-1201, T-1201, and T-1202, and to remove material from any towers operating under vacuum conditions.
- A distillation column operates at constant pressure, *i.e.*, the two (or more) streams leaving the column are at the same pressure. The stream(s) entering the column may be at the column pressure, or above. For this design, column pressure is determined by the temperature of the heating source for the bottom product and the composition of the bottom product; see the instructions in the Equipment section. The temperatures of streams entering and leaving the column generally decrease with height up the column, *i.e.*, the temperature of the top product is the lowest and the temperature of the bottom product is the highest.
- For this design, it is assumed that valves are available as needed at no cost. For this project, assume that pumps and compressors are available as needed at no cost, and that there is no cost associated with any pressure increases. However, based on your design, the report should indicate placement of pumps, compressors and valves on the PFD.

Design of Heat Exchangers E-1201 and E-1202

A detailed design of E-1201 and E-1202 is required for base-case conditions. It should be assumed that cooling water and other utilities are available at the conditions specified in the Appendix of this problem statement. For this heat exchanger design, the following information should be provided:

- Diameter of shell
- Number of tube and shell passes
- Number of tubes per pass
- Tube pitch and arrangement (triangular/square/..)
- Number of shell-side baffles, if any, and their arrangement (spacing, pitch, type)
- Diameter, tube-wall thickness, shell-wall thickness, and length of tubes
- Calculation of both shell- and tube-side film heat transfer coefficients
- Calculation of overall heat transfer coefficient (you may assume that there is no fouling on either side of the exchanger)
- Heat transfer area of the exchanger
- Shell-side and tube-side pressure drops (calculated, not estimated)
- Materials of construction
- Approximate cost of the exchanger

A detailed sketch of the two exchangers should be included along with a set of comprehensive calculations in an appendix for the design of the heat exchangers. You should use ASPEN Exchanger Design & Rating (EDR) in the ASPEN Plus simulator to carry out the detailed design.

Physical Property Data

Most data can be found in Reference [1]. Use:

$$C_{p\ DEE}^{(liq)}[\text{kJ/kmol K}] = 0.147 \tag{6}$$

$$C_{p\ DEE}^{(vap)}[\text{kJ/kmol K}] = 0.02149 + 3.369\times10^{-4}T - 1.039\times10^{-7}T^2 - 9.387\times10^{-12}T^3 \tag{7}$$

with T in [K] for this year's project only. Any other data can be found from any handbook, *e.g.*, Reference [2].

Raw Material Cost, Product Value

These are provided in Table 2. When using these numbers, you should be aware that they may be modified later, so write programs, spreadsheets, etc. with this in mind.

Table 2. Material Prices [3]

Component	DEE	Ethanol
Price [$/kg]	1.51	0.98

Equipment Costs

Preliminary equipment costs for the plant are given in Table 3. More up-to-date costs may be provided later. Each cost is for an individual piece of equipment, including installation.

Table 3. Equipment Costs

Equipment	**Installed Cost [in thousands of dollars]**
Isothermal packed-bed reactor	5,000
Adiabatic packed-bed reactor, per stage	100
Vessel	100
Distillation column	500
Heat exchanger	300
Compressor	Larger of [4,000 and 0.0189 ($\dot{W}_S$ [W])$^{0.8}$[
Fired Heater	11×10^{A} where $A = 0.8 \log_{10}[Q] - 0.5$ and Q is the heat duty [kW]

Utility Costs/Credits

Low-Pressure Steam (618 kPa, saturated, cost or credit)	\$13.28/GJ
Medium-Pressure Steam (1135 kPa, saturated, cost or credit)	\$14.19/GJ
High-Pressure Steam (4237 kPa, saturated, cost or credit)	\$17.70/GJ
Natural Gas (446 kPa, 25°C, cost)	\$11.00/GJ
Waste Stream 8 used as a fuel source (credit)	\$9.00/GJ
Electricity	\$0.06/kWh
Boiler Feed Water (at 549 kPa, 90°C) There is a cost for boiler feed water only if the steam produced enters process streams. If, on the other hand, the steam produced does not enter a process stream and is subsequently condensed, then it can be made into steam again. In that case, there is no net cost for boiler feed water.	\$2.45/1000 kg
Cooling Water Available at 516 kPa and 30°C Return pressure ≥ 308 kPa Return temperature should be no more than 15°C above the inlet temperature	\$0.354/GJ
Refrigerated Water Available at 516 kPa and 5°C Return pressure ≥ 308 kPa Return temperature should be no higher than 15°C	\$4.43/GJ

Waste treatment

For Stream 23	\$5.00/1000 kg

Catalyst

Cost	\$1.00/kg
Load	40 metric ton
Replacement Time	21 months

Other Information

You should assume that a year equals 8,000 hours. This is about 330 days, which allows for periodic shut-down and maintenance.

During the actual process, the liquid formed in V-1202 separates into two phases, which must be added as two streams separately to T-1201. Further, DEE and water could form an azeotrope, a mixture which is difficult to separate by distillation. Finally, a peroxide inhibitor is generally added to the product DEE for safety reasons. These issues are not considered in this design project. Additionally, the selectivity data used may not correspond to the actual kinetics and equilibrium.

Economic Analysis

When evaluating alternative cases, you should carry out an economic evaluation and profitability analysis based on a number of economic criteria such as payback period, internal rate of return, and cash flow analysis. In addition, 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, although you are **not** being asked to carry out optimization.

Other operating costs are for utilities (steam, cooling water, natural gas, electricity, etc.), for catalyst replacement, and for waste treatment. The power needed for compression is provided in Equation (4). The costs of utilities, catalysts and waste treatment are provided below.

Operating credits are for streams sold for their fuel content (if they are not used within Unit 1200). These credits are also provided below.

The capital cost annuity is an ***annual*** cost (like a car payment) associated with the ***one-time***, fixed cost of plant construction. The capital cost annuity is defined as follows:

$$capital\ cost\ annuity = FCI\frac{i(1+i)^n}{(1+i)^n - 1}$$

where FCI is the installed cost of all equipment; i is the interest rate, $i = 0.15$; and n is the plant life for accounting purposes, $n = 10$.

For detailed sizing, costing, and economic evaluation including profitability analysis, you may use the Aspen Process Economic Analyzer (formerly Aspen Icarus Process Evaluator) in Aspen Plus Version 8. However, it is also a good idea to independently verify the final numbers based on other sources such as cost data given below.

Final Comments

As with any open-ended problem; i.e., a problem with no single correct answer, the problem statement above is deliberately vague. You may need to fill in some missing data by doing a literature search, Internets search, or making assumptions. 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.

Moreover, in some areas (e.g. sizing/costing) you are given more data and information than what is needed. You must exercise engineering judgment and decide what data to use. Also you should also seek additional data from the literature or Internet to verify some of the data, e.g. the prices of products and raw materials.

Reference

1. Himmelblau, D. M. and J. B. Riggs, *Basic Principles and Calculations in Chemical Engineering (7th ed.)*, Prentice Hall, Englewood Cliffs, NJ, 2004.

Appendix 1
Other Data

Heat Exchangers

For heat exchangers that do not have to be designed in detail, the following approximations may be used for heat transfer coefficients to calculate the heat transfer area and heat exchanger cost.

situation	*h* (W/m²°C)
condensing steam	6000
condensing organic	1000
boiling water	7500
boiling organic	2000
flowing liquid	600
flowing gas	60

The equations for the log-mean-temperature-difference correction factor, *F*, for a 1-2, shell-and-tube heat exchanger are:

For $R \neq 1$

$$F = \frac{\sqrt{R^2+1}\ln\left[\dfrac{1-P}{1-RP}\right]}{(R-1)\ln\left[\dfrac{2-P\left(R+1-\sqrt{R^2+1}\right)}{2-P\left(R+1+\sqrt{R^2+1}\right)}\right]} \tag{5}$$

and for $R = 1$

$$F = \frac{P\sqrt{2}}{(1-P)\ln\left[\dfrac{2-2P+P\sqrt{2}}{2-2P-P\sqrt{2}}\right]} \tag{6}$$

where

$$P = \frac{t_{out}-t_{in}}{T_{in}-t_{in}} \tag{7}$$

$$R = \frac{\dot{m}_{tube}C_{p,tube}}{\dot{m}_{shell}C_{p,shell}} = \frac{T_{in}-T_{out}}{t_{out}-t_{in}} \tag{8}$$

the upper-case T is for the tube side and the lower-case t is for the shell side. It is understood that it does not matter which fluid is placed on which side, since the same value for F results for either configuration.

For a 2-4 shell-and-tube heat exchanger, the equations are

For $R \neq 1$

$$F = \frac{\sqrt{R^2+1}\ln\left[\dfrac{1-P}{1-RP}\right]}{2(R-1)\ln\left[\dfrac{2-P-PR+2\sqrt{(1-P)(1-PR)}+P\sqrt{R^2+1}}{2-P-PR+2\sqrt{(1-P)(1-PR)}-P\sqrt{R^2+1}}\right]} \tag{9}$$

and for $R = 1$

$$F = \frac{P\sqrt{2}}{2(1-P)\ln\left[\dfrac{4(1-P)+P\sqrt{2}}{4(1-P)-P\sqrt{2}}\right]} \tag{10}$$

For a 3-6 shell-and-tube heat exchanger, the equations are

For $R \neq 1$

$$F = \frac{\sqrt{R^2+1}\ln\left[\dfrac{1-P^*}{1-RP^*}\right]}{(R-1)\ln\left[\dfrac{2-P^*\left(R+1-\sqrt{R^2+1}\right)}{2-P^*\left(R+1+\sqrt{R^2+1}\right)}\right]} \tag{11}$$

and for $R = 1$

$$F = \frac{P^*\sqrt{2}}{(P^*-1)\ln\left[\dfrac{2-2P^*-P^*\sqrt{2}}{2-2P^*+P^*\sqrt{2}}\right]} \tag{12}$$

where

$$P^* = \frac{1-\dfrac{1-RP}{\sqrt[3]{1-P}}}{R-\dfrac{1-RP}{\sqrt[3]{1-P}}} \tag{13}$$

Appendix 2
Economic Data

Equipment Costs (Purchased)

Note: The numbers following the attribute are the minimum and maximum values for that attribute. For a piece of equipment with a lower attribute value than the minimum, the minimum attribute value should be used to compute the cost. For a piece of equipment with a larger attribute value, extrapolation is possible, but inaccurate. To err on the side of caution, the price for multiple, identical, smaller pieces of equipment should be used.

Pumps

$$\log_{10}(\text{purchased cost}) = 3.4 + 0.05\log_{10} W + 0.15[\log_{10} W]^2$$

W = power (kW, 1, 300)
assume 80% efficiency

Heat Exchangers

$$\log_{10}(\text{purchased cost}) = 4.6 - 0.8\log_{10} A + 0.3[\log_{10} A]^2$$

A = heat exchange area (m^2, 20, 1000)
add 25% to the purchased cost for finned tubes

Compressors

$$\log_{10}(\text{purchased cost}) = 2.3 + 1.4\log_{10} W - 0.1[\log_{10} W]^2$$

W = power (kW, 450, no limit)
assume 65% efficiency

Compressor Drive

$$\log_{10}(\text{purchased cost}) = 2.5 + 1.4\log_{10} W - 0.18[\log_{10} W]^2$$

W = power (kW, 75, 2600)
all compressors require a drive in addition to the compressor

Turbine

$$\log_{10}(\text{purchased cost}) = 2.5 + 1.45\log_{10} W - 0.17[\log_{10} W]^2$$

W = power (kW, 100, 4000)
assume 65% efficiency

Fired Heater

$$\log_{10}(\text{purchased cost}) = 3.0 + 0.66\log_{10} Q + 0.02[\log_{10} Q]^2$$

Q = duty (kW, 3000, 100,000)
assume 80% thermal efficiency
assume can be designed to use any organic compound as a fuel

Vertical Vessel

$$\log_{10}(\text{purchased cost}) = 3.5 + 0.45\log_{10} V + 0.11[\log_{10} V]^2$$

V = volume of vessel (m^3, 0.3, 520)

Horizontal Vessel

$$\log_{10}(\text{purchased cost}) = 3.5 + 0.38\log_{10} V + 0.09[\log_{10} V]^2$$

V = volume of vessel (m^3, 0.1, 628)

Storage Tanks

$$\log_{10}(\text{purchased cost}) = 4.85 - 0.397\log_{10} V + 0.145[\log_{10} V]^2$$

V = volume of tank (m^3, 90, 30000)

Additional Cost Information

Piping straight pipe: $\$/\text{m} = 5.0\ (\text{nominal pipe diameter, in})(1+(\text{sch }\#)/20)^{0.25}$
sch= schedule number for pipe
use the same schedule number for fittings and valves

Fittings (except valves) $\$/\text{fitting} = 50.0\ (\text{nominal pipe diameter, in})(1+(\text{sch }\#)/20)^{0.25}$

Valves
for gate (isolation) valves $\$100\ (\text{nominal pipe diameter, in})^{0.8}\ (1+(\text{sch }\#)/20)^{0.25}$
for control valve use $\$1000\ (\text{nominal pipe diameter, in})^{0.8}(1+(\text{sch }\#)/20)^{0.25}$

Utility Costs

Low-Pressure Steam (618 kPa saturated)	\$13.28/GJ
Medium-Pressure Steam (1135 kPa saturated)	\$14.19/GJ
High-Pressure Steam (4237 kPa saturated)	\$17.70/GJ
Natural Gas (446 kPa, 25°C)	\$11.00/GJ
Fuel-gas/Off-gas Credit	at LHV
Electricity	\$0.06/kWh
Boiler Feed Water (at 549 kPa, 90°C)	\$2.45/1000 kg
Cooling Water available at 516 kPa and 30°C return pressure ≥ 308 kPa return temperature is no more than 15°C above the inlet temperature	\$0.354/GJ
Refrigerated Water available at 516 kPa and 10°C return pressure ≥ 308 kPa return temperature is no higher than 20°C	\$4.43/GJ
Deionized Water available at 5 bar and 30°C	\$1.00/1000 kg
Low-temperature Refrigerant available at -20°C	\$7.89/GJ
Very low-temperature Refrigerant available at -50°C	\$13.11/GJ
Wastewater Treatment	\$56/1000 m^3

Equipment Cost Factors

Total Installed Cost = Purchased Cost (4 + material factor (MF) + pressure factor (PF))

Pressure (absolute)
< 10 atm, PF = 0.0
10 - 20 atm, PF = 0.6
20 - 40 atm, PF = 3.0
40 - 50 atm, PR = 5.0
50 - 100 atm, PF = 10
100 - 200 atm, PF = 25

does not apply to turbines, compressors, vessels, packing, trays, or catalyst, since their cost equations include pressure effects

Carbon Steel MF = 0.0
Stainless Steel MF = 4.0

Raw Material Costs/Product Value

Raw Material or Product	price
ethanol	1.15/kg
diethyl ether	1.70/kg