CHE 425

Engineering Economics and Design Principles

Prof. Adnan Alamer
Chemical Engineering Dept., KFUPM

CHAPTER 6

Estimation of Manufacturing Costs

Purpose of Chapter

- To introduce important factors that affect manufacturing cost
- To provide method for the estimation of each factor

Table 6.1 Factors Affecting the Cost of Manufacturing (COM), for a Chemical Product (from references [1, 2 and 3])

Factor	Description of Factor
1. Direct costs	**Factors that vary with the rate of production**
A. Raw materials	Costs of chemical feed stocks required by the process. Flowrates obtained from the PFD.
B. Waste treatment	Costs of waste treatment to protect environment.
C. Utilities	Costs of utility streams required by process. Includes but not limited to: a. Fuel gas, oil, and/or coal b. Electric power c. Steam (all pressures) d. Cooling water e. Process water f. Boiler feed water g. Instrument air h. Inert gas (nitrogen) etc. i. Refrigeration Flowrates for utilities found on the PFD/PIDs
D. Operating labor	Costs of personnel required for plant operations.
E. Direct supervisory and clerical labor	Cost of administrative/engineering and support personnel.
F. Maintenance and repairs	Costs of labor and materials associated with the maintenance.
G. Operating supplies	Costs of miscellaneous supplies that support daily operation not considered to be raw materials. Examples include chart paper, lubricants, miscellaneous chemicals, filters, respirators and protective clothing for operators, etc.
H. Laboratory charges	Costs of routine and special laboratory tests required for product quality control and troubleshooting.
I. Patents and royalties	Cost of using patented or licensed technology.

2. Fixed costs	**Factors not affected by the level of production**
A. Depreciation	Costs associated with the physical plant (buildings, equipment, etc.). Legal operating expense for tax purposes.
B. Local taxes and insurance	Costs associated with property taxes and liability insurance. Based on plant location and severity of the process.
C. Plant overhead costs (sometimes referred to as factory expenses)	Catch-all costs associated with operations of auxiliary facilities supporting the manufacturing process. Costs involve payroll and accounting services, fire protection and safety services, medical services, cafeteria and any recreation facilities, payroll overhead and employee benefits, general engineering, etc.
3. General expenses	**Costs associated with management level and administrative activities not directly related to the manufacturing process**
A. Administration costs	Costs for administration. Includes salaries, other administration, buildings, and other related activities.
B. Distribution and selling costs	Costs of sales and marketing required to sell chemical products. Includes salaries and other miscellaneous costs.
C. Research and development	Costs of research activities related to the process and product. Includes salaries and funds for research-related equipment and supplies, etc.

Estimation of Manufacturing Costs

- Direct Costs
  - Vary with production rate
- Fixed Costs
  - Do not vary with production rate
- General Expenses
  - Costs associated with management levels not directly related to the manufacturing process – overhead burden

Direct Costs

Factors that vary with the rate of production

- Raw Materials
- Waste Treatment
- Utilities
  - Examples: (a) Fuel gas and/or oil, (b) Electric power, (c) Steam (d) Cooling water, etc.
- Operating Labor
- Supervisory and Clerical Labor
- Maintenance and Repairs
- Operating Supplies
- Laboratory Charges
- Patents and Royalties

Fixed Costs

Factors not affected by the level of production

- Depreciation – cover as a separate topic in Chapter 7
- Local Taxes and Insurance
- Plant Overhead Costs

General Expenses

- Administration Costs
  - Salaries
  - Other administration
  - Building
- Distribution and Selling Costs
  - Costs of sales and marketing
  - Salaries
  - Miscellaneous costs
- Research and Development
  - Salaries and funds related to research equipments and supplies, etc.

Manufacturing Costs

- Table 6.1
  - Description of Items
- Table 6.2
  - Factors for Estimating Costs
- We relate (historically) the relationship between items in Table 6.1 to Direct Costs A (RM) , B (WT) , C (UT) , D (OL), and FCI of Plant

Manufacturing Costs - examples

Cost associated with management level and administrative activities not directly related to the manufacturing process.

- Maintenance and Repairs
  - 2 – 10 % FCI
  - Proportional to Size of Plant
- Supervisory and Clerical Labor
  - 10 – 25 % COL
  - Proportional to Op. Lab
- Depreciation
  - some % of FCI

Manufacturing Costs

Cost of Manufacture (*COM*) = Direct Manufacturing Costs (*DMC*) + Fixed Manufacturing Costs (*FMC*) + General Expenses (*GE*)

The cost of manufacturing, *COM*, can be determined when the following costs are known or can be estimated:

1. Fixed capital investment (*FCI*): (C_{TM} or C_{GR})
2. Cost of operating labor (C_{OL})
3. Cost of utilities (C_{UT})
4. Cost of waste treatment (C_{WT})
5. Cost of raw materials (C_{RM})

Table 6.2 Multiplication Factors Estimating Manufacturing Cost† (See also Table 6.1)

Cost Item from Table 6.1	Typical Range of Multiplying Factors	Value Used in Text
1. Direct manufacturing costs		
a. Raw materials	C_{RM}*	
b. Waste treatment	C_{WT}*	
c. Utilities	C_{UT}*	
d. Operating labor	C_{OL}	C_{OL}
e. Direct supervisory and clerical labor	$(0.1-0.25)C_{OL}$	$0.18C_{OL}$
f. Maintenance and repairs	$(0.02-0.1)FCI$	$0.06FCI$
g. Operating supplies	$(0.1-0.2)$(Line 1.F.)	$0.009FCI$
h. Laboratory charges	$(0.1-0.2)C_{OL}$	$0.15C_{OL}$
i. Patents and royalties	$(0-0.06)COM$	$0.03COM$
Total direct manufacturing costs	$C_{RM}+C_{WT}+C_{UT}+1.33C_{OL}$ $+0.03COM+0.069FCI$	

2. Fixed manufacturing costs		
a. Depreciation	$0.1FCI^{\ddagger}$	$0.1FCI^{\ddagger}$
b. Local taxes and insurance	$(0.014 - 0.05)FCI$	$0.032FCI$
c. Plant overhead costs	$(0.50 - 0.7)$(Line 1.D. + Line 1.E. + Line 1.F.)	$0.708C_{OL} + 0.036FCI$
Total fixed manufacturing costs	$\mathbf{0.708C_{OL} + 0.068FCI}$ **+ depreciation**	
3. General manufacturing expenses		
a. Administration costs	0.15(Line 1.D. + Line 1.E.+ Line 1.F.)	$0.177C_{OL} + 0.009FCI$
b. Distribution and selling costs	$(0.02 - 0.2)COM$	$0.11COM$
c. Research and development	$0.05COM$	$0.05COM$
Total general manufacturing costs	$\mathbf{0.177C_{OL} + 0.009FCI + 0.16COM}$	
TOTAL COSTS	$\mathbf{C_{RM} + C_{WT} + C_{UT} + 2.215C_{OL} + 0.190COM + 0.146FCI}$ **+ depreciation**	

*Costs are evaluated from information given on the PFD and the unit cost

†Costs are given in dollars per unit time (usually per year)

‡Depreciation costs are covered separately in Chapter 7. The use of 10% of *FCI* is a crude approximation at best.

from references [1], [2], and [3]

Manufacturing Costs

with depreciation as 10% FCI

$$COM = 0.280FCI + 2.73C_{OL} + 1.23\left(C_{UT} + C_{WT} + C_{RM}\right) \quad (6.1)$$

$$COM_d = 0.180FCI + 2.73C_{OL} + 1.23\left(C_{UT} + C_{WT} + C_{RM}\right) \quad (6.2)$$

COM without Depreciation – we use this since we calculate depreciation more accurately in Chapter 7

How Do We Get…..

- *FCI* – Chapter 5 C_{TM} or C_{GR}
- C_{RM}
- C_{UT}
- C_{WT}
- C_{OL}

(C_{RM}, C_{UT}, C_{WT}, C_{OL}) Look At These Separately

Example 6.1

The following cost information was obtained from a design for a 92,000 tonne/year nitric acid plant.

Fixed Capital Investment:	$11,000,000
Raw Material Cost	$ 7,950,000/yr
Waste Treatment Cost	$ 1,000,000/yr
Utilities	$ 356,000/yr
Direct Labor Cost	$ 300,000/yr
Fixed Costs	$ 1,500,000/yr

Determine:

a. the manufacturing cost in $/yr and $/tonne of nitric acid,

b. the percentage of manufacturing costs resulting from each cost category given in Table 6.1 and 6.2.

Using Equation 6.2:

$$COM_d = (0.180)(\$11{,}000{,}000) + (2.73)(\$300{,}000) + (1.23)(\$356{,}000 + \$1{,}000{,}000 + \$7{,}950{,}000) = \$14{,}245{,}000/\text{yr}$$

$$(\$14{,}245{,}000/\text{yr})/(92{,}000\ \text{tonne/yr}) = \$155/\text{tonne}$$

From the relationships given in Table 6.2:

Direct Manufacturing Costs = \$7,950,000 + \$1,000,000 + \$356,000 + (1.33)(\$300,000) + (0.069)(\$11,000,000) + (0.03)(\$14,245,000) = \$10,891,000

Percentage of manufacturing cost = (100)(10.891)/14.25 = 76%

Fixed Manufacturing Costs = (0.708)(\$300,000) + (0.068)(\$11,000,000) = \$960,000

Percentage of manufacturing cost = (100)(0.960)/14.25 = 7%

General Expenses = (0.177)(\$300,000) + (0.009)(\$11,000,000) + (0.16)(\$14,245,000) = \$2,431,000

Percentage of manufacturing cost = (100)(2.431)/14.25 = 17%

Cost of Operating Labor

$$N_{OL} = (6.29 + 31.7P^2 + 0.23N_{np})^{0.5}$$

N_{OL} = the number of operators per shift

P = particulate processing steps

N_{np} = non-particulate processing steps – compression, heating/cooling, mixing, separation, and reaction

$$N_{np} = \sum Equipment$$

compressors
towers
reactors
heaters
exchangers

Example 6.2

Estimate operating labor and cost of HDA facility shown in Fig 1.3 and 1.5

- $N_{OL} = [6.29 + (31.7)(0)^{0.1} + (0.23)(11)]^{0.5} = 2.97$
- Number of operators required for one operator per shift = 4.5

↓

= (49 wk/yr)(5 shifts/operator/wk)

= 245 shifts/year/operator

Total shifts per year = (365)(3 shifts per day)

= 1095 shifts/year

1095 / 245 = 4.5 operators (for a single shift)

Example 6.2 (cont.)

Equipment	Number of	N_{np}
Compressors	1	1
Exchangers	7	7
Heaters/Furnaces	1	1
Pumps	2	-
Reactors	1	1
Towers	1	1
Vessels	4	-
Total		11

Example 6.2 (cont.)

$$\text{Total Operators} = (2.97)(4.5) = 13.4 \Rightarrow 14$$

Salary = \$50,000/yr (2001 gulf coast average)

$$\boxed{C_{OL} = (50{,}000)(14) = \$700{,}000/\text{yr}}$$

Cost of Raw Materials, Utilities, and Waste Treatment

- Flow Rates
  - Get these from PFD – use stream factor
- Costs
  - Utilities and Waste Treatment - Table 6.3 – see Section 6.6 for Utilities Estimation
  - Common Chemicals – Table 6.4, Chemical Market Reporter, other sources

Stream Factor

- Operating hours per year divided by total hours per year
  - Typical 8000 Operating Hours
  - 0.9 – 0.95 Typical

    8000/8760 = 0.913

*Flows on PFD are kmol/operating hour

Utilities – Fuel and Electricity

- Fuel for Fired Heaters
  - PFD gives process load (energy balance) but total flow is more due to efficiency – 70-90% from Table 9.11 – item 13.
  - Fuel Costs may vary wildly – Figure 6.1
- Electricity for pumps and compressors – Figure 6.7
  - Shaft Power – Fluid Power/Efficiency
  - Power to Drive – Shaft Power/Drive Efficiency

* PFD usually gives Shaft Power – but be careful!

Cost of Fuel – Utility Costs

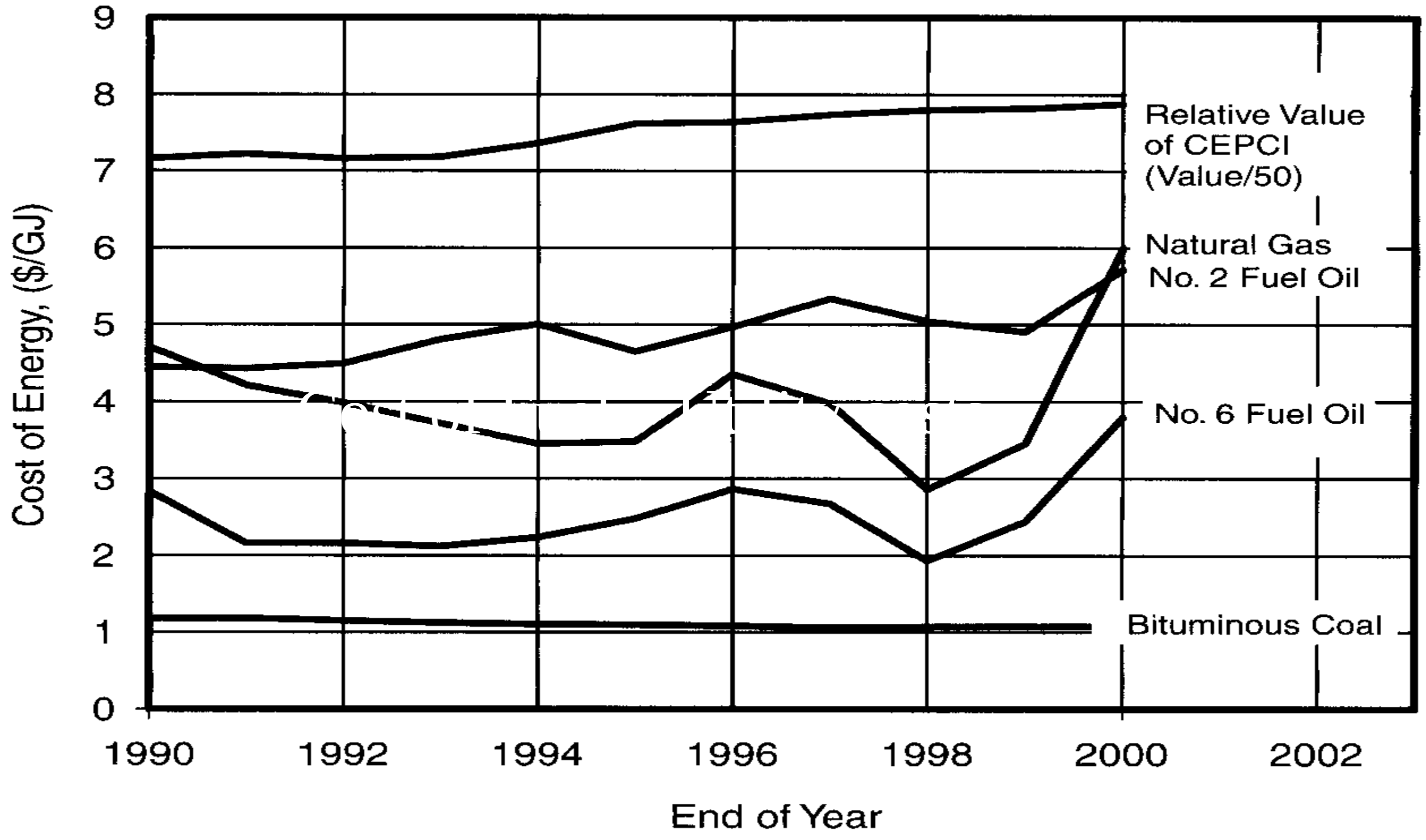


Figure 6.1 Changes in Fuel Prices from 1990 to 2000 (Information taken from Energy Information Administration [6])

Table 6.3 Utilities Provided by Off-sites for a Plant with Multiple Process Units (Costs Represent Charges for Utilities Delivered to the Battery Limit of a Process)

Utility	Description	Cost $/GJ	Cost $/Common Unit
Air supply	Pressurized and dried air (add 20% for instrument air)		
	a. 6 barg (90 psig)		\$0.49/100 std m^{3*}
	b. 3.3 barg (50 psig)		\$0.35/100 std m^{3*}
Steam from boilers	Process steam: latent heat only		
	a. Low pressure (5 barg, 160°C) from HP steam		
	with credit for power	6.08	\$12.68/1000 kg
	without credit for power	7.78	\$16.22/1000 kg
	b. Medium pressure (10 barg, 184°C) from HP steam		
	with credit for power	6.87	\$13.71/1000 kg
	without credit for power	8.22	\$16.40/1000 kg
	c. High pressure (41 barg, 254°C)	9.83	\$16.64/1000 kg
Steam generated from process	Estimate savings as avoided cost of burning natural gas in boiler	6.67	

Table 6.3 Utilities Provided by Off-sites for a Plant with Multiple Process Units (Costs Represent Charges for Utilities Delivered to the Battery Limit of a Process) (*continued*)

Utility	Description	Cost $/GJ	Cost $/Common Unit
Cooling tower water	Processes cooling water: 30°C to 40°C or 45°C	0.354	$14.8/1000 m³†
Other water	High purity water for		
	a. process use		$0.067/1000 kg
	b. boiler feed water (available at 115°C)‡		$2.45/1000 kg
	c. potable (drinking)		$0.26/1000 kg
	d. deionized water		$1.00/1000 kg
Electrical substation	Electric Distribution	16.8	$0.06/kWh
	a. 110 V		
	b. 220 V		
	c. 440 V		
Fuels	a. Fuel oil (no. 2)	6.0	$232/m³
	b. Natural gas	6.0§	$0.23/std m³*
	c. Coal (f.o.b. mine mouth)	1.07	$27.4/tonne

Table 6.3 Utilities Provided by Off-sites for a Plant with Multiple Process Units (Costs Represent Charges for Utilities Delivered to the Battery Limit of a Process) (*continued*)

Utility	Description	Cost $/GJ	Cost $/Common Unit
Refrigeration	a. Moderately low temperature Refrigerated water in at T = 5°C and returned at 15°C	4.43	$0.185/1000kg
	b. Low temperature Refrigerant available at T = −20°C	7.89	
	c. Very low temperature Refrigerant available at T = −50°C	13.11	Based on Process Cooling Duty
Thermal systems	Cost based on thermal efficiency of fired heater using natural gas		
	a. 90% efficient	6.67	Based on Process Heating Duty
	b. 80% efficient	7.5	
Waste disposal (solid and liquid)	a. Non-hazardous		$36/tonne
	b. Hazardous		$200–2000/tonne°
Waste water treatment	a. Primary (filtration)		$41/1000 m^3
	b. Secondary (filtration + activated sludge)		$43/1000 m^3
	c. Tertiary (filtration, activated sludge, and chemical processing)		$56/1000 m^3

Utilities - Steam

- Pressure Levels
  - Low (30 – 90 psi)
  - Medium (150 – 250 psi)
  - High (525 – 680 psi)
- Available saturated but sometimes superheated

Utilities - Steam

- Large chemical complexes generate high pressure steam and use excess pressure to generate electricity – Figure 6.6.
- Steam can be used as a drive medium for compressors and pumps
  - Thermodynamic efficiency - Table 6.5
  - Drive efficiency – Figure 6.7

Utilities - Steam

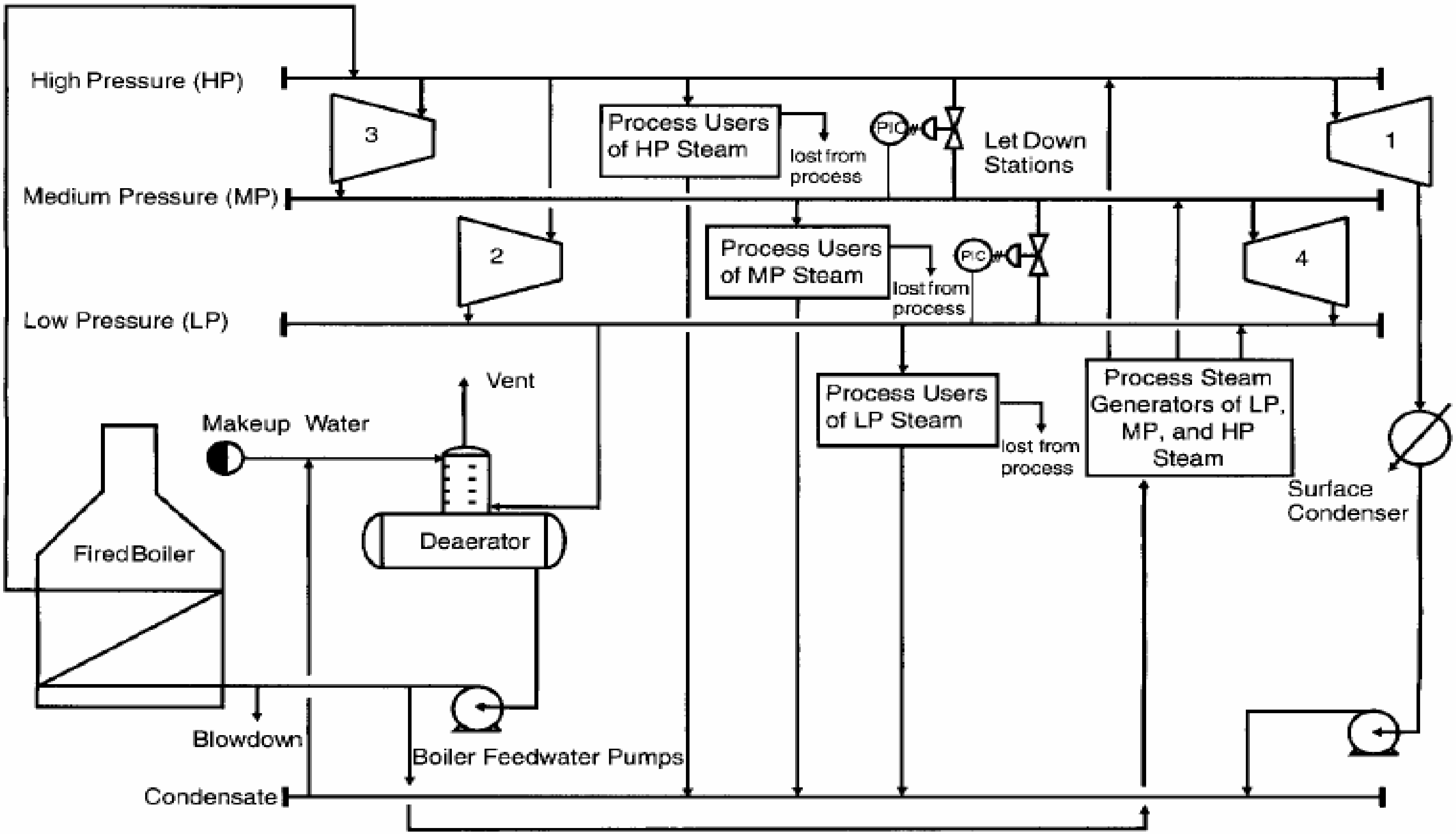
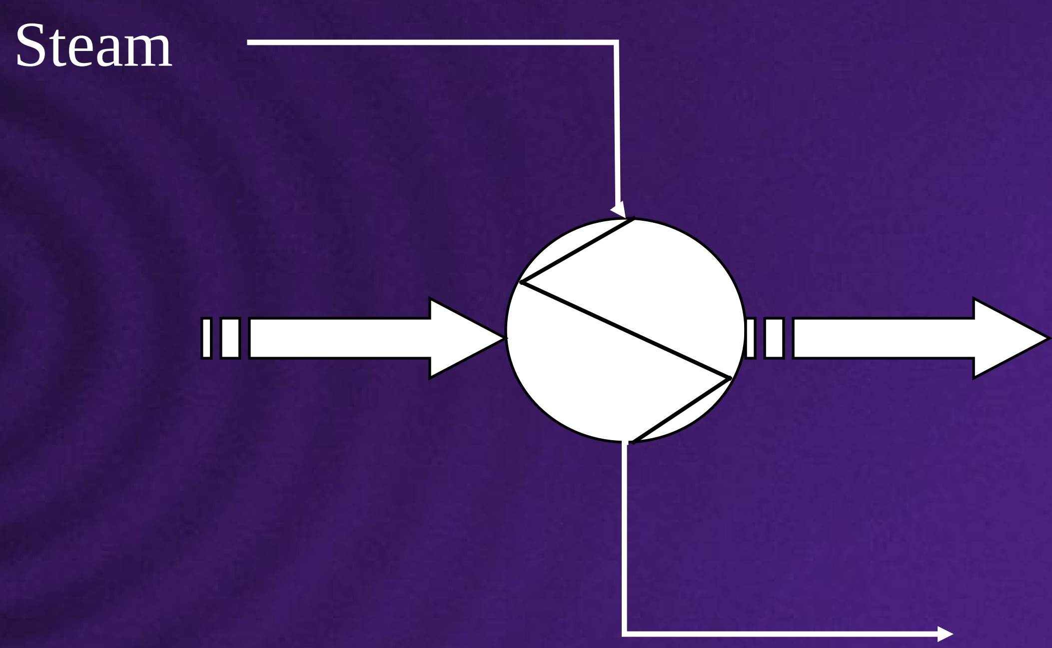


Figure 6.6 Typical Steam Producing System for a Large Chemical Facility

Utilities - Condensate Return and Boiler Feed Water

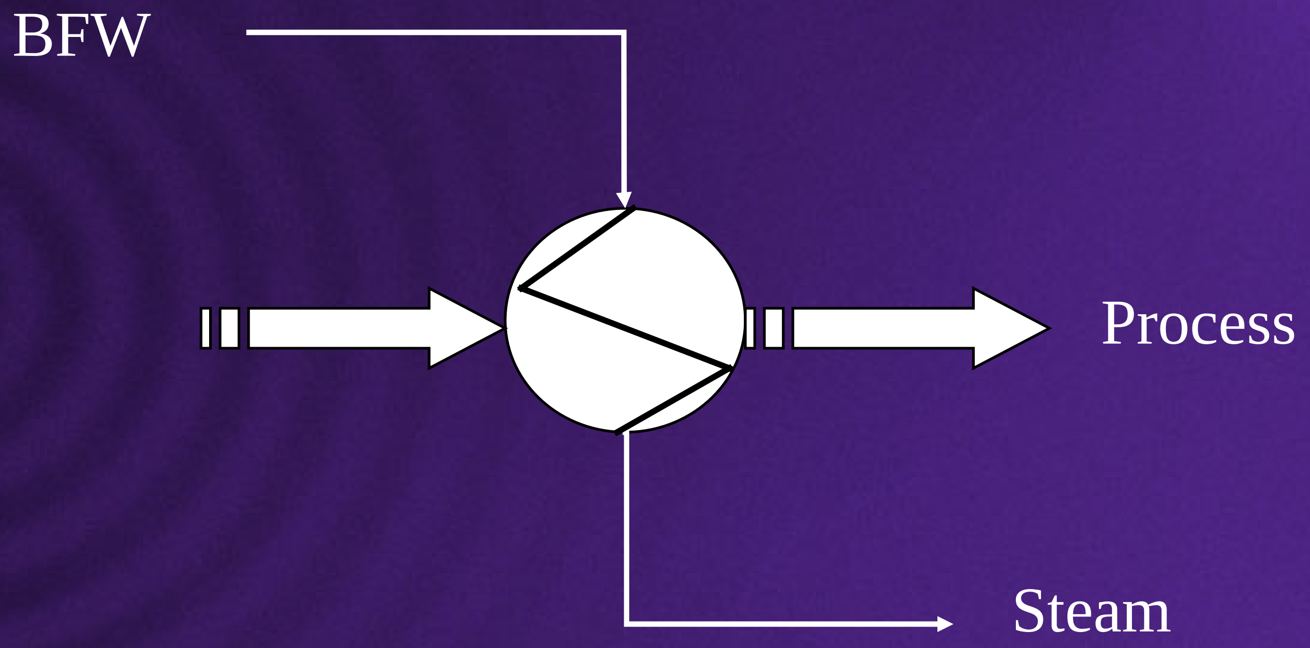


* Just use Steam Costs

If Steam Lost in Process

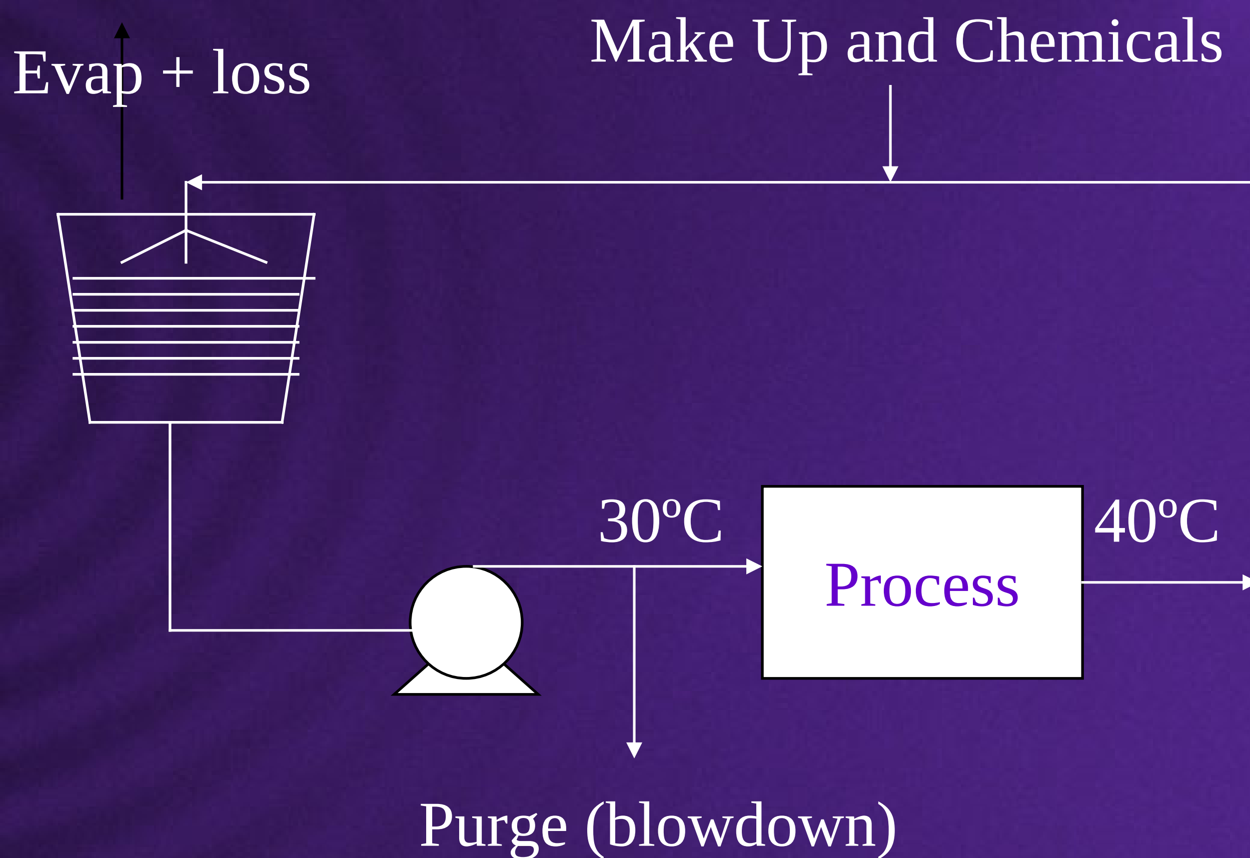
Use Steam Cost + BFW
since Condensate is not returned

Steam Generated in Process



* Just Take Credit for Steam – unless Steam is lost in Process

Utilities - Cooling Water



Example 6.3

Estimate the utility cost for producing a circulating cooling water stream using a mechanical draft cooling tower. Consider a basis of 1 GJ/h of energy removal from the process units. Flow of cooling water required to remove this energy = $\dot{m}$ kg/h.

An energy balance gives

$$\dot{m}c_p\Delta T = 1 \times 10^9 \Rightarrow (\dot{m})(4180)(40 - 30) = 41{,}800\,\dot{m} = 1 \times 10^9 \text{ J/h}$$

Therefore, $\dot{m} = \dfrac{1 \times 10^9}{41{,}800} = 23{,}923$ kg/h

Latent heat of water at average temperature of 35°C = 2417 kJ/kg
Amount of water evaporated from tower, W_{tower}

$$W_{tower} = \frac{Heat\ Load}{\Delta H_{vap}} = \frac{1 \times 10^9}{2417 \times 10^3} = 413.7 \text{ kg/h}$$

This is (413.7)(100)/(23,923) = 1.73% of the circulating water flowrate.

Typical windage losses from mechanical draft towers are between 0.1 and 0.3% [9, 10], use 0.3%.

To calculate the blowdown, we must know the maximum allowable salt (inorganics) concentration factor, S, of the circulating water compared with the makeup water. Where S is defined as

$$S = \frac{\text{concentration salts in cooling water loop}}{\text{concentration salts in make-up water}} = \frac{S_{loop}}{S_{in}}$$

Typical values are between 3 to 7 [9]. Here a value of 5 is assumed. By performing a water and salt balance on the loop shown in Figure 6.3, the following results are obtained:

$$W_{MU} = W_{tower} + W_{wind} + W_{BD}$$

$$s_{in}W_{MU} = s_{loop}W_{wind} + s_{loop}W_{BD}$$

Because $s_{loop} = 5s_{in}$, it follows that

$$s_{in}(W_{tower} + W_{wind} + W_{BD}) = s_{loop}W_{wind} + s_{loop}W_{BD}$$

$$W_{BD} = \frac{s_{in}W_{tower} + W_{wind}(s_{in} - s_{loop})}{s_{loop} - s_{in}} = \frac{s_{in}W_{tower}}{s_{loop} - s_{in}} - W_{wind} = \frac{W_{tower}}{4} - W_{wind} = \frac{1.73\%}{4} - 0.3\% = 0.133\%$$

$$W_{MU} = 1.73 + 0.3 + 0.133 = 2.163\% = 517 \text{kg/h}$$

Pressure drop around cooling water loop is estimated as follows, ΔP_{loop} = 15 psi (pipe losses) + 5 psi (exchanger losses) + 10 psi (control valve loss) + 8.7 psi of static head (because water must be pumped to top of cooling water tower estimated to be 20 ft above pump inlet) = 38.7 psi =266.7 kPa.

Power required for cooling water pumps with a volumetric flow rate $\dot{V}$, assuming an overall efficiency of 75%, is

$$\text{Pump Power} = \frac{1}{\varepsilon}\dot{V}\Delta P = \frac{1}{(0.75)}\frac{(23{,}923)}{(1000)(3600)}(266.7) = 2.36 \text{ kW}$$

Power required for fans:

From reference [11], the required surface area in the tower = 0.5 ft^2/gpm (this assumes that the design wet-bulb air temperature is 26.7°C [80°F]). From the same reference, the fan horsepower per square foot of tower area is 0.041 hp/ft^2.

$$\text{Power for fan} = \frac{(23{,}923)(2.2048)}{(60)(8.337)}(0.5)(0.041) = (2.16)(0.746) = 1.61 \text{ kW}$$

From a survey of vendors, the cost of chemicals is \$0.156/1000 kg of makeup water.

Using an electricity cost of \$0.06/kWh and a process water cost of \$0.067/1000 kg, the overall cost of the cooling water is given by:

Cost of cooling water = cost of electricity + cost of chemicals for make-up water + cost of make-up water

Using the cost values for electricity and process water given in Table 6.3:

$$\text{Cooling water cost} = (0.06)(2.36 + 1.61) + \frac{(517.3)(0.156)}{1000} + \frac{(517.3)(0.067)}{1000}$$

$$= \$0.354/\text{hr} = \$0.354/\text{GJ}$$

Utilities - Cooling Water

- Make – up based on Δ*T* (40 - 30) !
- Should charge cw based on energy used
  - Table 6.3
- Does not matter (much) if cw returned at 40ºC or 45ºC – same energy
- 45ºC is absolute max – due to fouling

Utilities - Refrigerated Water

- Same as Previous Slide in that Energy Costs are not ΔT Dependent – but cost based on 5ºC supply temperature.
- Figure 6.4 shows cost of refrigeration as a function of temperature.

Utilities - Refrigerated Water

The Carnot efficiency of a mechanical refrigeration system can be expressed by the reversible coefficient of performance, COP_{REV}:

$$COP_{REV} = \frac{\text{evaporator temperature } (T_1)}{\text{temperature difference between condenser and evaporator } (T_2 - T_1)}$$

$$COP \cong \frac{\text{evaporator heat load}}{\text{work required}} \quad \text{or} \quad \text{work required} = \frac{\text{evaporator heat load}}{\text{COP}}$$

Utilities - Refrigerated Water

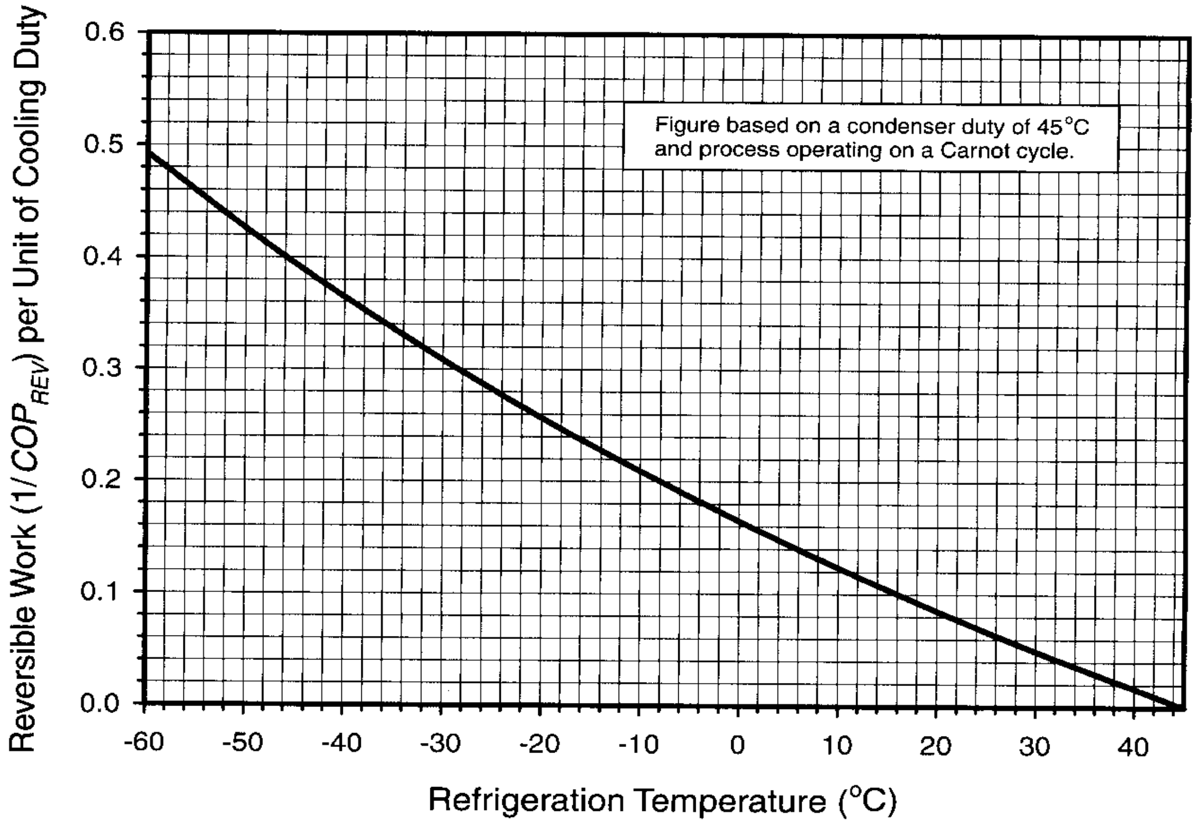


Figure 6.4 Ideal Work for Refrigeration Cycles as a Function of Refrigeration Temperature

Utilities - Refrigerated Water

Example 6.4

Using Figure 6.4, calculate the relative costs of providing refrigeration at 5°C, –20°C, and –50°C. From the figure, the ordinate values are given as

Temperature	$1/COP_{REV}$
5°C	0.144
–20°C	0.257
–50°C	0.426

Therefore, compared with cooling at 5°C, cooling to –20°C is 0.257/0.144 times more expensive and cooling to –50°C is 0.426/0.144 times more expensive. This analysis assumes that the two refrigeration systems operate equally efficiently with respect to the reversible limit and that the major cost is the power to run the compressors.

Example 6.5

Obtain a cost estimate for a refrigerated cooling utility operating at 5°C.

Consider a single-stage refrigeration system to provide refrigeration at 5°C, using 1,1 difluoroethane (R-152a) as the refrigerant. The process flow diagram and operating conditions are given in Figure E6.5 and Table E6.5, respectively.

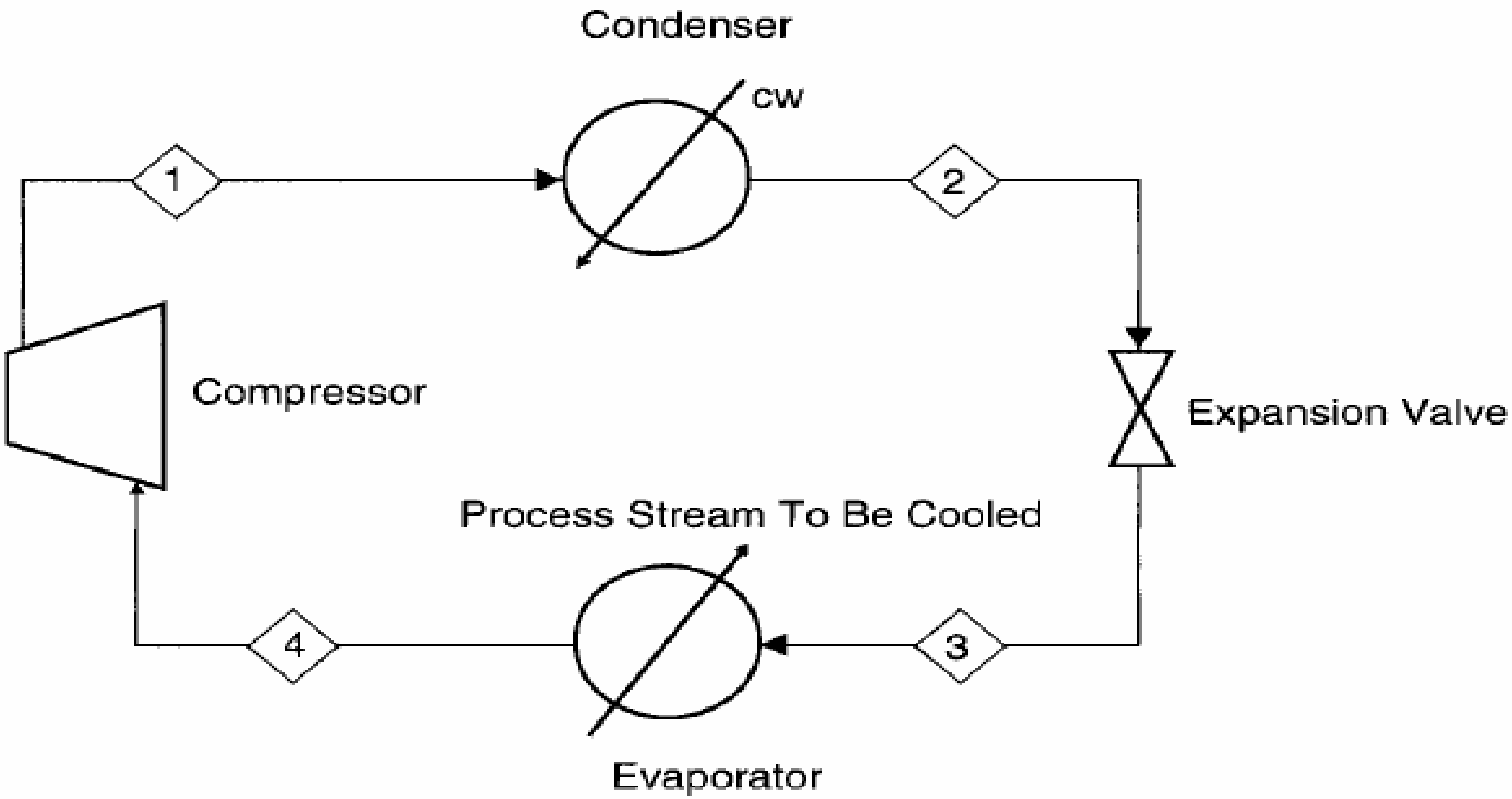


Figure E6.5 Process Flow Diagram for Simple Refrigeration Cycle of Example 6.5

Table E6.5 Stream Conditions for Figure E6.5

Stream number	1	2	3	4
Pressure (bar)	10.9	10.9	3.21	3.21
Temperature (°C)	68.7	45.0	5.0	5.0
Vapor fraction	1.0	0.0	0.2492	1.0

Compressor Power = 66.5 kW (at 75% efficiency)

Condenser Duty = 1.24 GJ/h

Evaporator Duty = 1.00 GJ/h

$$\text{Compressor work per unit of cooling} = (66.5)/(1{,}000{,}000/3600) = 0.2394$$

This value compares with 0.144 for the Carnot cycle. The main differences are due to the inefficiencies in the compressor and the use of a throttling valve instead of a turbine.

$$\text{The cost of refrigeration at } 5^{\circ}\text{C} = (66.5)(0.06) + (1.24)(0.354) = 3.99 + 0.44$$
$$= 4.43\ \$/\text{h} = 4.43\ \$/\text{GJ}$$

Using the results of Example 6.4, we can predict the cost of refrigeration at −20°C and −50°C as

$$\text{The cost of refrigeration at } -20^{\circ}\text{C} = (4.43)(1.78) = \$7.89/\text{GJ}$$

$$\text{The cost of refrigeration at } -50^{\circ}\text{C} = (4.43)(2.96) = \$13.11/\text{GJ}$$

Summary

- FCI
- C_{OL}
- C_{UT}
- C_{WT}
- C_{RM}

From these get COM_d

Example 6.9

Estimate the quantities and yearly costs of the appropriate utilities for the following pieces of equipment on the toluene hydrodealkylation PFD (Figure 1.5). It is assumed that the stream factor is 0.95 and that all the numbers on the PFD are on a stream time basis. The duty on all of the units can be found in Table 1.7.

a. E-101, Feed Preheater
b. E-102, Reactor Effluent Cooler
c. H-101, Heater
d. C-101, Recycle Gas Compressor, assuming electric drive
e. C-101, Recycle Gas Compressor, assuming steam drive using 10 barg steam discharging to atmospheric pressure.
f. P-101, Toluene Feed Pump

a. E-101: Duty is 15.19 GJ/h. From Table 6.3: Cost of High Pressure Steam = \$9.83/GJ

$$\text{Energy Balance: } Q = 15.19 \text{ GJ/h} = (\dot{m}_{steam})(\Delta H_{vap}) = (\dot{m}_{steam})(1699.3) \text{ kJ/kg}$$

$$\dot{m}_{steam} = 8939 \text{ kg/h} = 2.48 \text{ kg/s}$$

$$\text{Yearly Cost} = (Q)(C_{steam})(t) = (15.19 \text{ GJ/h})(\$9.83/\text{GJ})(24)(365)(0.95) = \$\,1{,}242{,}000/\text{yr}$$

Alternatively: Yearly Cost = (Yearly flowrate)(Cost per unit mass)

Yearly Cost = (2.48)(3600)(24)(365)(0.95)(16.64/1000) = \$1,236,000/yr
(same as above within round-off error)

b. E-102: Duty is 46.66 GJ/h. From Table 6.3 Cost of Cooling Water = \$0.354/GJ

$$Q = 46.66 \text{ GJ/h} = (\dot{m}_{cw})(C_{pcw})(\Delta T_{cw}) = (\dot{m}_{cw})(4.18)(10) = 41.8\,\dot{m}_{cw}$$

$$\dot{m}_{cw} = (46.66)(10^9/41.8)(10^3) = 1{,}116{,}270 \text{ kg/h} = 310 \text{ kg/s}$$

$$\text{Yearly Cost} = (46.66 \text{ GJ/h})(24)(365)(0.95)(\$0.354/\text{GJ}) = \$137{,}000/\text{yr}$$

c. H-101: Duty is 27 GJ/h (7510 kW). Assume that an indirect, nonreactive process heater has a thermal efficiency (ξ_{th}) of 90%. From Table 6.3, natural gas cost \$6/GJ, and the heating value is 0.0377 GJ/m³.

$$Q = 27\ \text{GJ/h} = (\dot{v}_{gas})(\Delta H_{natural\ gas})(\text{efficiency}) = (\dot{v}_{gas})(0.0377)(0.9)$$

$$\dot{v}_{gas} = 796\ \text{std m}^3/\text{h}\ (0.22\ \text{std m}^3/\text{sec})$$

$$\text{Yearly Cost} = (27)(6.0)(24)(365)(0.95)/(0.90) = \$1{,}498{,}000/\text{yr}$$

d. C-101: Shaft power is 49.1 kW and from Figure 6.7 the efficiency of an electric drive (ξ_{dr}) is 90 %.

$$\text{Electric Power} = P_{dr} = \text{Output power}/\xi_{dr} = (49.1)/(0.90) = 54.6\ \text{kW}$$

$$\text{Yearly Cost} = (54.6)(0.06)(24)(365)(0.95) = \$27{,}300/\text{yr}$$

e. Same as Part d with steam driven compressor. For 10 barg steam with exhaust at 0 barg Table 6.5 provides a steam requirement of 8.79 kg-steam/kWh of power. The shaft efficiency is about 35% (extrapolating from Figure 6.7).

$$\text{Steam required by drive} = (49.1)(8.79/0.35) = 1233 \text{ kg/h } (0.34 \text{ kg/s})$$

$$\text{Cost of Steam} = (1233)(24)(365)(0.95)(13.71 \times 10^{-3}) = \$140{,}700/\text{yr}$$

f. P-101: Shaft Power is 14.2 kW. From Figure 6.7 the efficiency of an electric drive is about 86%.

$$\text{Electric Power} = 14.2/0.86 = 16.5 \text{ kW}$$

$$\text{Yearly Cost} = (16.5)(0.06)(24)(365)(0.95) = \$8240/\text{yr}$$

Note: The cost of using steam to power the compressor is much greater than the cost of electricity even though the cost per unit energy is much lower for the steam. The reasons for this are (1) the thermodynamic efficiency is low, and (2) the efficiency of the drive is low for a small compressor. Usually steam drives are only used for compressor duties greater than 100 kW.

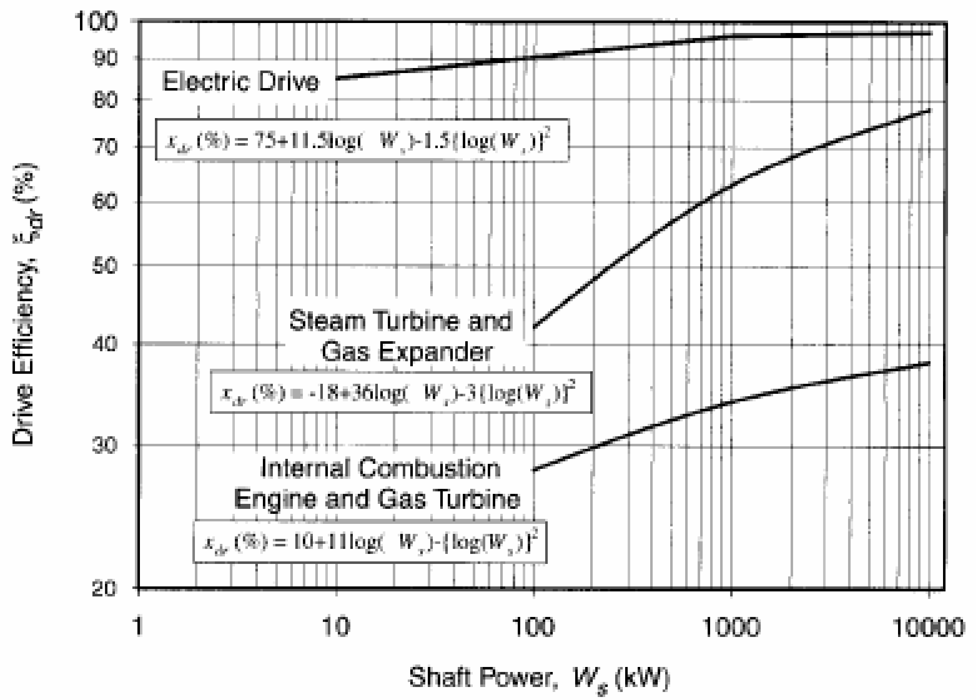


Figure 6.7 Efficiencies for Pumps and Compressor Drives (Data from Walas [9], Chapter 4)

Table 6.5 Theoretical Steam Requirements (kg steam/kWh)

Theoretical Steam Requirements	Inlet Condition of Steam (barg) (Superheat in °C)							
Exhaust Pressure	10.0	13.8	17.2	27.6	41.4	41.4	58.6	58.6
	sat'd	sat'd	50	170	145	185	165	205
2" Hg abs	4.77	4.54	4.11	3.34	3.22	3.07	2.98	2.85
4" Hg abs	5.33	5.04	4.54	3.62	3.47	3.30	3.20	3.05
0 barg	8.79	7.94	6.88	5.08	4.72	4.45	4.22	4.00
0.69 barg	10.87	9.57	8.11	5.77	5.28	4.97	4.67	4.40
2.07 barg	15.24	12.72	10.40	6.91	6.18	5.78	5.35	5.02
3.45 barg	20.86	16.32	12.79	7.97	6.97	6.49	5.93	5.54
4.14 barg	24.45	18.32	14.11	8.50	7.34	6.83	6.20	5.78
4.82 barg	28.80	20.68	15.47	9.05	7.71	7.16	6.45	6.01