Problem 5.1A

A 100-hp engine is used to pump ground water into an irrigation channel. Calculate the rate at which the pump is doing work in

(a) Btu/hr (b) J/s (c) kW.

Solution Basis: 100 hp

a.

$$\begin{array}{c|c|c} 100\text{ hp} & 0.7068\text{ Btu/s} & 3600\text{ s} \\ \hline & 1\text{ hp} & 1\text{ hr} \end{array} = \mathbf{2.544 \times 10^{5}\ Btu/hr}$$

b.

$$\begin{array}{c|c} 100\text{ hp} & 745.7\text{ J/s} \\ \hline & 1\text{ hp} \end{array} = \mathbf{7.457 \times 10^{4}\ J/s}$$

c.

$$\begin{array}{c|c} 100\text{ hp} & 0.7457\text{ kW} \\ \hline & 1\text{ hp} \end{array} = \mathbf{745.7\ kW}$$

Problem 5.1B

Classify the following variables as intense or extensive.

a) temperature
b) density
c) mass
d) specific heat capacity
e) refractive index

Solution

a. Temperature: **intensive property**

b. Density: **intensive property**

c. Mass: **extensive property**

d. Specific heat capacity: **intensive property**

e. Refractive index: **intensive property**

PUMPS AND BLOWERS

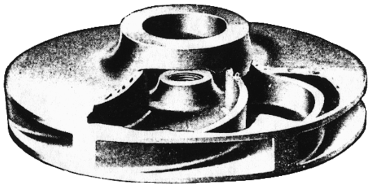


Fig 19a Cutaway view of two-vane impeller with open eye (courtesy of Nagle Pumps)

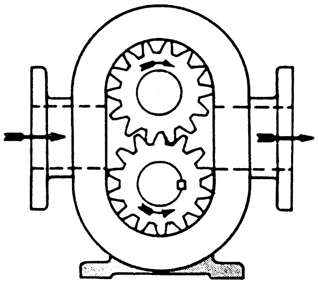


Fig. 19d Gear pump (courtesy of the Hydraulic Institute)

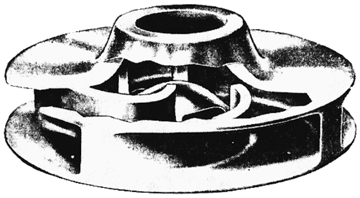


Fig 19b Semi-open impeller for handling fluids containing pulpy solids (courtesy of Nagle Pumps)

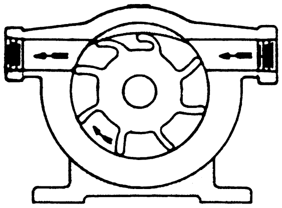


Fig. 19e Flexible impeller pump (courtesy of the Hydraulic Institute)

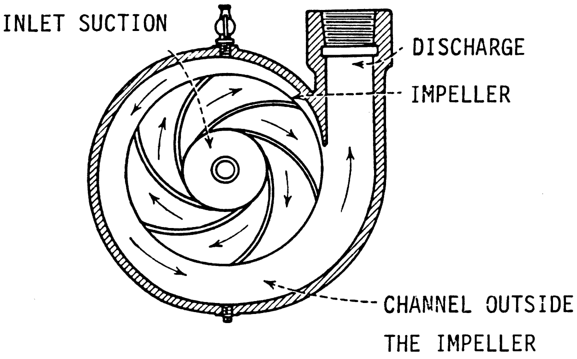


Fig 19c Volute pump

PUMPS

Numerous designs of pumps exist among which a few are illustrated in the figures above for pumping liquids. Centrifugal pumps have fixed impellers with fairly close clearance between the impeller and the casing. Flexible impeller pumps have rubber blades that are squeezed between the shell and the impeller hub. Gear pumps represent a class of positive displacement pumps whose teeth mesh and force liquid into the outlet. Reciprocating piston pumps operate much like the piston in an automobile except the latter pressurizes gases.

Problem 5.1C

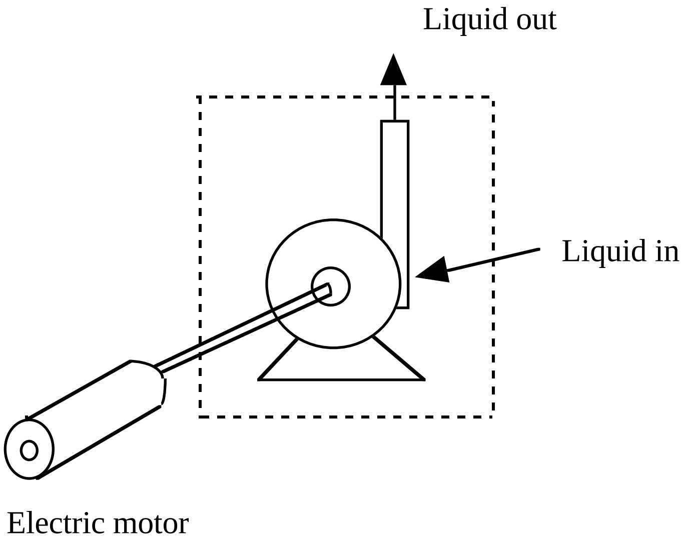
Make a rough sketch of each of the following processes. Show the system boundary, and classify the system as open or closed.

a) pump b) storage tank c) windmill d) internal combustion engine

Solution

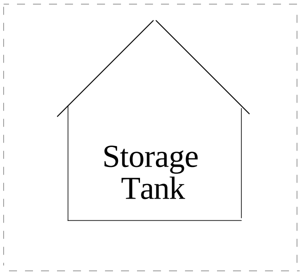
The dashed lines represent the respective system boundaries.

a. pump



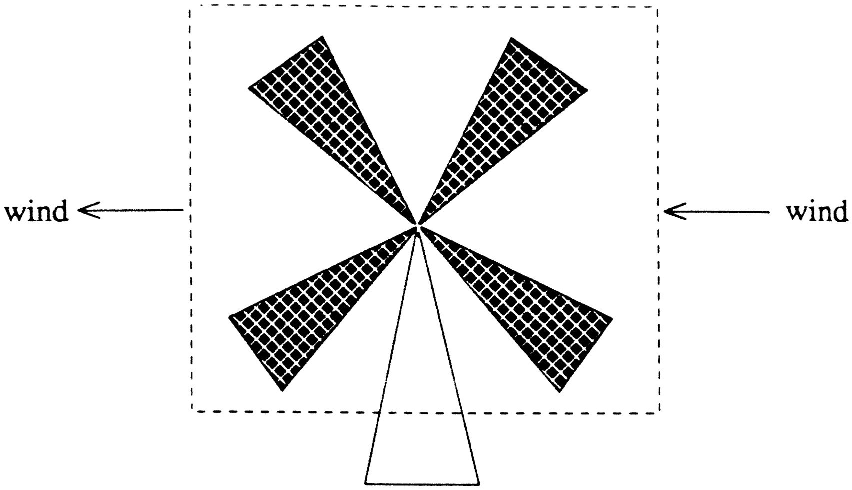
open system: mass is transferred across the system boundary

b. Storage tank



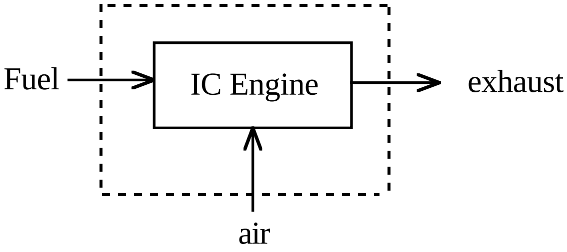
Closed system: the tank does not exchange mass or energy with surroundings (except when it is filled or emptied)

c. Windmill



Open System: wind moves in and out of the system

d.



Open System: fuel and air enter the engine, and exhaust gases leave the engine.

Problem 5.1D

Calculate the potential energy of 1 kg of water located at the surface of a lake that is 100 meters above a water turbine which is 200 meters away and used to generate electricity.

Solution

$$PE = mgh = \begin{array}{c|c|c|c} 1\ \text{kg} & 9.80\ \text{m} & 100\ \text{m} & 1\ \text{J} \\ \hline & \text{s}^2 & & \dfrac{1\ (\text{kg})(\text{m}^2)}{\text{s}^2} \end{array} = \mathbf{980J}$$

Problem 5.1E

An ideal gas in a tank at 500˚C and 100 kPa is compressed isothermally to 1000 kPa. What was the work (in J/g mol) of compression?

Solution

We have to assume that the work done on the gas represents energy transferred solely to the gas, and no work is done on the equipment containing the gas during the compression.

Basis: 1g mol gas

Isothermal compression

$$\widehat{W} = \int_{\hat{V}_1}^{\hat{V}_2} p\,d\widehat{V} = \int_{\hat{V}_1}^{\hat{V}_2} \frac{nRT}{\widehat{V}}\,d\widehat{V} = nRT \ln \frac{\widehat{V}_2}{\widehat{V}_1}$$

$$\frac{p_2V_2}{p_1V_1} = \frac{n_1RT_1}{n_2RT_2} \text{ so that } \frac{\hat{V}_2}{\hat{V}_1} = \frac{p_1}{p_2} = \frac{100}{1000} = 0.10$$

$$\widehat{W} = \frac{1 \text{ g mol}}{} \left| \frac{8.314\text{J}}{1 \text{ (g mol)(K)}} \right| \frac{(500 + 273.15)\text{ K}}{} \ln (0.10) = \mathbf{14{,}800J}$$

(the positive sign designates work done on the system)

Problem 5.1F

A wall of an annealing oven is made of 10 inch thick forebrick. If the interior of the wall is at 2550°F and the exterior of the wall is at 392°F, what is the heat loss per hour? The relation for heat transfer is $Q = kA (T_2 – T_1)/\Delta x$ where k is the thermal conductivity, T is the temperature in °F, and Δx is the wall thickness.

Solution

Basis: 1 hour

You have to look up the thermal conductivity in a handbook. It varies with temperature but assume an average value of 0.81 Btu/(hr)(ft^2)(°F)/ft.

$$\text{Thus,} \quad Q = \frac{0.81\text{(Btu)(ft)}}{\text{(hr)(ft}^2\text{)(°F)}} \left| \frac{(2550 - 392)\text{F}}{} \right| \frac{}{(10/12)\text{ft}}\ ) = \mathbf{2100}\ \frac{\mathbf{Btu}}{\mathbf{(hr)(ft^2)}}$$

ANNEALING OVENS

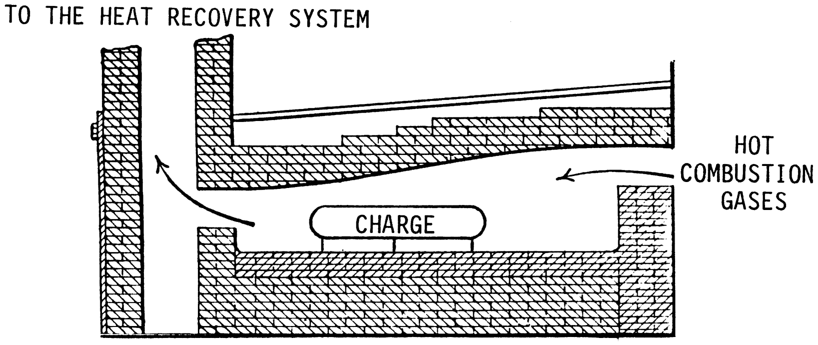


Fig 20 Reverbatory furnace

Ovens, kilns, retorts, and furnaces provide a way of heating a charge of material. Some ovens are fixed with the charge loaded and heated, and then cooled and unloaded as a batch. Others are tunnels in which the charge passes through on trolleys or conveyors with the heating occurring in the entrance region and the cooling taking place in an exit region. In both case the heat of combustion is transferred either by direct contact from the flame or combustion gases, or indirectly by transfer through a containing wall that separates the combustion products from the charge. The use of direct combustion offers cheaper construction, lower cost of operation and maintenance, and more rapid heating and cooling. The disadvantages are that the charge can be contaminated with the dust and components of the combustion gases, and that the charge can be oxidized/reduced depending on the oven conditions.

Problem 5.1G

An ideal gas at 50˚C and 1 atm is heated to 500˚C at constant pressure, and then isothermally compressed to 10 atm. It is then isobarically cooled to 50˚C, and finally is isothermally expanded to back to its initial state. For the overall process, determine ΔH and ΔU.

Solution

Enthalpy ΔH and internal energy ΔU are state functions and since the process returns to its initial state at the end

$$\mathbf{\Delta U = \Delta H = 0}$$

Problem 5.1H

A automobile weighing 2500 lb is traveling at 55 miles per hour when the brakes are suddenly applied bringing the vehicle to a stop. After the brakes have cooled to the ambient temperature, how much heat (in Btu) has been transferred from the brakes to the surroundings?

Solution

Let the system be the whole car. The accumulation term in the energy balance is not zero because the kinetic energy of the vehicle is initially not zero but after stopping is zero. Also, energy (heat) is transferred from the vehicle to the surroundings so that the energy transfer term in the energy balance is not zero. The rest of the terms presumably are zero. Consequently we get (in symbols)

$$Q = \Delta K = K_2 - K_1$$

Basis: 2500 lb automobile

$$K_2 = 0$$

$$K_1 = \left(\tfrac{1}{2}\right) mv^2 = \frac{1}{2}\left|\frac{2500\ \text{lb}_m}{}\right|\left(\frac{55\ \text{mile}}{\text{hr}}\right)^2\left|\left(\frac{1\ \text{hr}}{3600\ \text{S}}\right)^2\right|\left(\frac{5280\ \text{ft}}{1\ \text{mile}}\right)^2$$

$$\left|\frac{1\ (\text{s}^2)(\text{lb}_f)}{32.2(\text{ft})(\text{lb}_m)}\right|\frac{1\ \text{Btu}}{778(\text{ft})(\text{lb}_f)} = 325\ \text{Btu}$$

$Q = (0 - 325) =$ **–325 Btu** (the minus sign denotes heat transfer out of system)

Problem 5.1I

In Problem 5.1E, a gas was compressed isothermally. How much heat has to be transferred to or from the compression equipment to keep it isothermal. Was the transfer into or out of the equipment?

Solution

In the energy balance the accumulation term is zero because the internal energy of an ideal gas depends only on the temperature, and the temperature is constant. The energy transport terms involve heat and work

$$0 = Q + W \qquad \text{or here } Q = -W$$

$$Q = \mathbf{-14{,}800J}$$

In other words, the negative sign indicates heat is transferred from the system to the surroundings to keep the temperature constant in the system.

Problem 5.2A

A heat capacity equation for acetylene is given by

$$C_p = 9.89 + 0.8273 \times 10^{-2}T - 0.3783 \times 10^{-5}T^2 + 0.7457 \times 10^{-9}T^3$$

where T is in °F and C_p is in Btu/(lb mol) (°F).

a. Convert the C_p equation so that T can be inserted in the equation in °R, and the units of C_p will be Btu/(lb mol)(°R).

b. Convert the C_p equation so that T can be inserted in the equation in K and the units of C_p will be J/(g mol) (K).

Solution The units of C_p are already Btu/(lb mol) (°F) and since $\Delta°F = \Delta°R$, the units are also Btu/(lb mol) (°R). To change from $T_{\circ F}$, substitute $T_{\circ F} = T_{\circ R} - 460$ in the equation for C_p.

a. $$C_p = 9.89 + 0.8273 \times 10^{-2} \left(T_{\circ R} - 460\right) - 0.3783 \times 10^{-5} \left(T_{\circ R} - 460\right)^2 + 0.7457 \times 10^{-q} \left(T_{\circ R} - 460\right)^3$$

We will delete the cubic term for simplicity in the answer. The error is small.

$$\begin{aligned} C_p &= 9.89 + 0.8273 \times 10^{-2} (°R - 460) - 0.3783 \times 10^{-5} (°R - 920°R + 2.116 \times 10^5) \\ &= (9.89 - 0.8273 \times 10^{-2} (460) - 0.3783 \times 10^{-5} (2.116 \text{ x } 10^5)) + (0.8273 \times 10^{-2} + 0.3783 \times 10^{-5} \\ &\quad \times (920))°R - 0.3783 \times 10^{-5} °R^2 \end{aligned}$$

$$\mathbf{C_p = 5.284 + 0.1175 \times 10^{-2}\ T_{\circ R} - 0.3783 \times 10^{-5}\ T^2_{\circ R}\ \text{Btu/(lb mol) (°R)}}$$

b. First, multiply the entire equation by conversion factors to convert

$$\frac{\text{Btu}}{\text{(lb mol)(°F)}} \rightarrow \frac{\text{J}}{\text{(g mol)(K)}}$$

$$\frac{\text{Btu}}{\text{(lb mol)(°F)}}\left|\frac{\text{1 lb}}{\text{454g}}\right|\frac{\text{1.8°F}}{\text{1K}}\left|\frac{\text{1055 J}}{\text{1 Btu}}\right. \rightarrow 4.184 \text{ is the multiplier}$$

Then substitute in the equation for C_p the following expression for $T_{\circ F}$

$$T_{\circ F} = 1.8\ T_K - 460$$

$$C_p = [9.89 + 0.8273 \times 10^{-2} (1.8\ T_K - 460) - 0.3783 \times 10^{-5} (1.8T_K - 460)^2 + 0.7457 \times 10^{-9} \times (1.8T_K - 460)^3]\ [4.184]\ \text{J/(g mol) (K)}$$

$$\mathbf{C_p = 6.01 + 1.86 \times 10^{-2}\ T_K - 1.45 \times 10^{-5}\ T_K^2 + 1.34 \times 10^{-9}\ T_K^3}$$

Problem 5.2B

One of your coworkers has collected experimental values for the heat capacity of air from 0 to 1500°C as follows:

T(°C)	0	18	25	100	200	300	400	500	600	700
C_p (J/g mol) (°C)	29.062	29.075	29.075	29.142	29.292	29.514	29.782	30.083	30.401	30.711
T(°C)	800	900	1000	1100	1200	1300	1400	1500		
C_p(J/(g mol) (°C)	31.020	31.317	31.585	31.865	32.108	32.338	32.556	32.761		

Use the method of least square to estimate values of the coefficients in the following two functions that can be used to calculate C_p in the future.

$$\left.\begin{aligned} C_p &= a + bT + CT^2 \\ C_p &= a' + b'T + c'T^2 + d'T^3 \end{aligned}\right\} \text{where } T \text{ is in } {}^\circ\text{C}$$

Solution

From a computer program to carry out the least squares procedure you can find

a = 28.936 **a´ = 29.041**

b = 2.39×10^{-3} **b´ = 0.185×10^{-2}**

c = 1.62×10^{-7} **c´ = 0.339×10^{-5}**

d´ = -0.270×10^{-8}

Problem 5.2C

Two gram moles of carbon dioxide are heated from 400°C to 1100°C. Calculate ΔH by integrating the heat capacity equation for carbon dioxide. Compare your result with the value calculated from the enthalpy tables for the combustion gases.

Solution Basis: 2 g mol CO_2

a.

$$\Delta H = 2\left[\int_{400}^{1100} 36.11(1100-400) + \left(\frac{1}{2}\right)\left(4.233\times10^{-2}\right)\left(1100^2-400^2\right) - \frac{1}{3}\left(2.887\times10^{-5}\right)\left(1100^3-400^3\right) + \frac{1}{4}\left(7.464\times10^{-9}\right)\left(1100^4-400^4\right)\right] = \mathbf{7.598 \times 10^4\ J}$$

b. By use of the tables of enthalpies we find

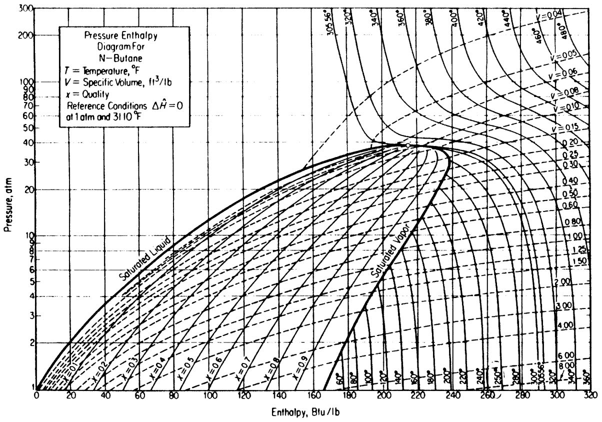
T°(C)	$\Delta\hat{H}$(J/(g mol)	
1100	55,310	
400	17,340	
	37,970	× 2 = **75,940 J**

Problem 5.2D

n-Butane is a common fuel used in locations where natural gas is not available. If 10 lb of n-butane are cooled from 10 atm and 260°F to saturated liquid at 2 atm, (a) determine the enthalpy change in Btu, and (b) if the 10 lb of n-butane were cooled isobarically (at constant pressure) to saturated liquid, determine the enthalpy change in Btu.

Solution

The easiest way to solve this problem is to use the pressure-enthalpy chart for n-butane found in the text. Basis: 10 lb n-butane.



Pressure enthalpy diagram for *n*-butane.

a. The pertinent data are

Initial state (260°F, 10 atm): $\Delta\hat{H} \cong 260$ Btu/lb

Final state (satd. liquid, 2 atm): $\Delta\hat{H} \cong 20$ Btu/lb

For the change

$$\Delta H = (20 - 260)\,10 = \mathbf{-2400\ Btu}$$

b. The initial specific enthalpy is still the same. The final specific enthalpy is $\Delta\hat{H}$(satd. liq., 10 atm) = 87 Btu/lb

For the change

$$\Delta H = 10\,(87 - 260) = \mathbf{-1730\ Btu}$$

Problem 5.2E

Use the SI data for water to calculate the change of enthalpy that occurs when 5 kg of water at 70°C in a closed vessel of 0.50m^3 in volume are heated to 453.1 K and 1000 kPa. Also determine the final quality of the steam in the vessel.

Solution

Even though the initial pressure of the water is not stated (remember, enthalpy is a function of temperature and pressure), the effect of pressure is negligible so that you can assume that the initial conditions are saturated water at 70°C (343K) where the specific liquid enthalpy is $\Delta\widehat{H}$ = 289.9 kJ/kg. The final conditions are 453.1K and 1000 kPa where the water is still saturated, hence at the final conditions the vessel contains a mixture of vapor and liquid. The fraction vapor has to be calculated first (the quality). Data at 453.1K and 1000 kPa are:

$\hat{V}_{liquid}$ = 0.001127 m^3/kg $\hat{V}_{vapor}$ = 0.1944 m^3/kg

$\Delta\hat{H}_{liquid}$ = 762.5 kJ/kg $\Delta\hat{H}_{vapor}$ = 2777.6 kJ/kg

The total volume is comprised of the volume of the liquid plus the volume of the vapor. Let x = fraction vapor.

Basis: 1 kg H_2O

b. $\frac{0.50}{5} = (1 - x)\,(0.001127) + x\,(0.1944)$ **x = 0.51**

The enthalpy of the wet steam is

a. $A\hat{H}$ = 0.49 (762.5) + 0.51 (2777.6) = 1794 kJ/kg so that the change in the enthalpy of the water is $\Delta H_{final} - \Delta H_{initial}$ = (1794 – 289.9) (5) = **7520 kJ**

Problem 5.2F

Use the steam tables in American Engineering units to calculate the quality of 15 lb of wet steam at 120 psia when the enthalpy of the wet steam has been calculated to be 12,000 Btu (relative to liquid water at 32°F which has a value of 0 Btu).

Solution

Basis: 1 lb wet steam at 120 psia

The enthalpy of the wet steam is 12,000/15 = 800 Btu/lb. From the steam tables for saturated steam at 120 psia the specific enthalpies of the liquid and vapor are

$\Delta\hat{H}_L$ = 312.46 Btu/lb $\Delta\hat{H}_V$ = 1190.6 Btu/lb

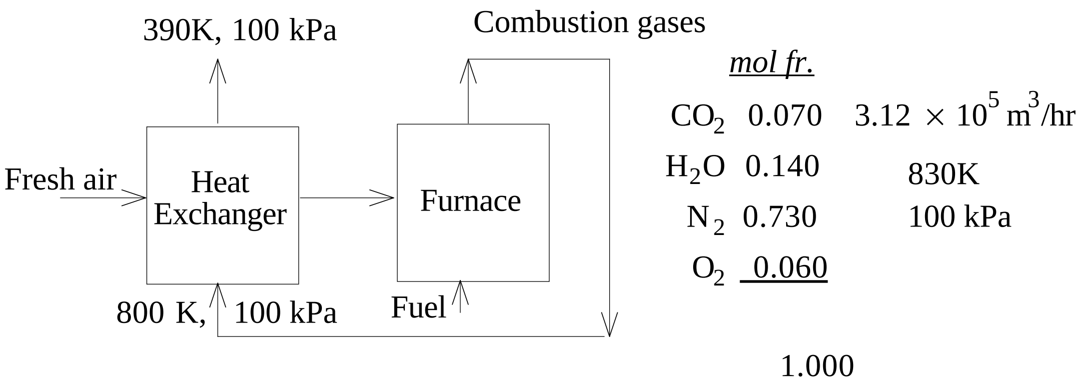
If we let x be the quality (vapor fraction) of the steam

$$312.46\,(1 - x) + 1190.6\,(x) = 800$$

x = 0.56

Problem 5.2G

Energy can be saved by passing the combustion gases from a furnace or boiler through a heat exchanger in which the air entering the furnace is preheated. Examine the figure.



The air does not contact the combustion gases directly in the heat exchanger; the streams are separated by tube walls. Calculate the enthalpy change in kJ that occurs for the combustion gases on passing through the heat exchanger.

Solution

The system is the heat exchanger. The process is steady state without reaction.

Step 5 Basis: 1 hr

HEAT EXCHANGERS

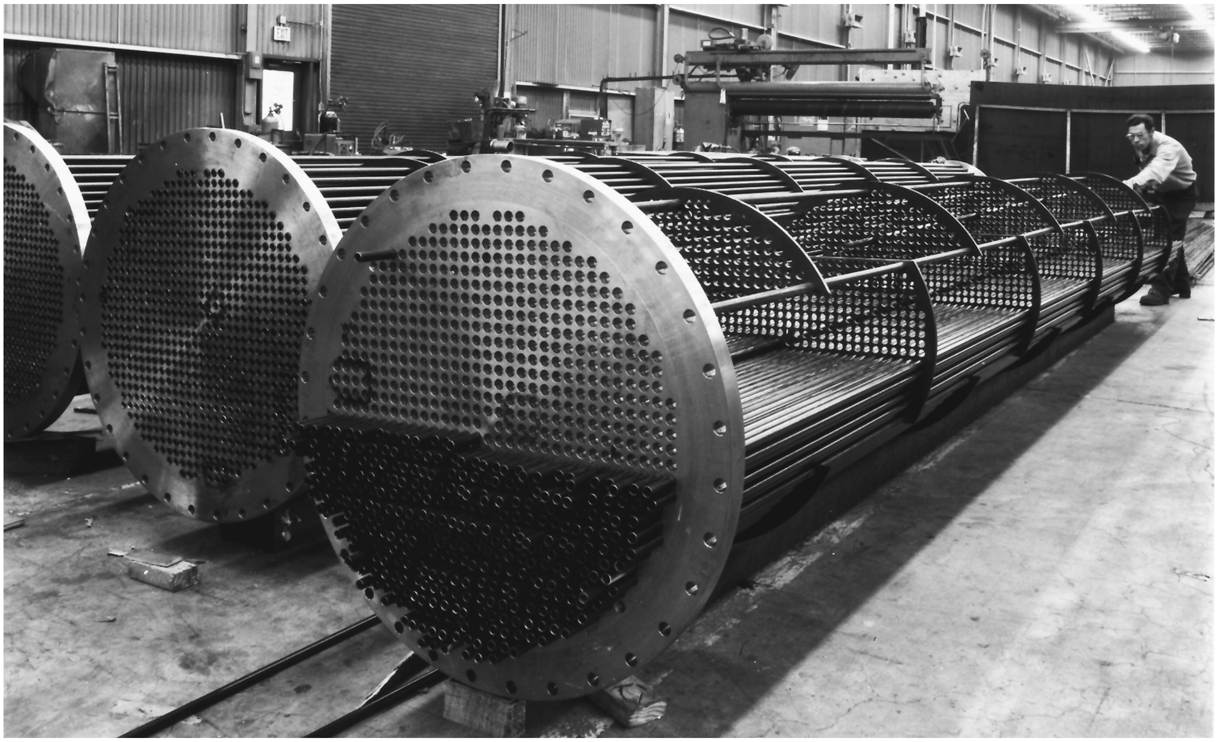


Fig 21a Shell and tube heat exchanger under construction (courtesy of Guston County Dyeing Machine Co.)

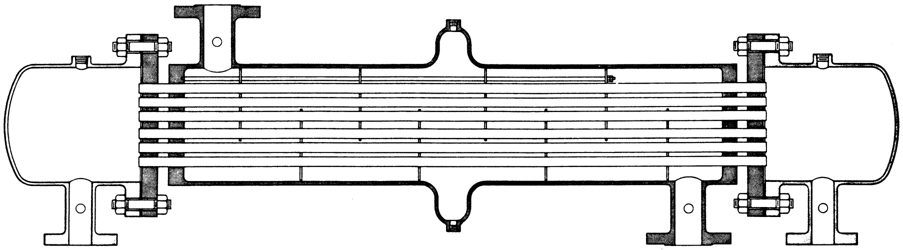


Fig 21b Line drawing of a standard type of shell and tube heat exchanger (courtesy of Patterson-Kelley Co.)

In these types of heat exchangers the two fluids are separated by the tube walls. As one fluid flows through the shell-- the region outside the tubes -- the other fluid flows through the tubes. Heat transfer occurs so as to cool, and perhaps even condense, the hotter fluid, and heat, and even vaporize, the cooler fluid. Heat exchangers are called by various names depending on their function such as chillers, condensers, coolers, heaters, reboilers, steam generators, vaporizes, waste heat boilers, and so on.

$$n = \frac{100 \text{ kPa}}{} \left| \frac{3.12 \times 10^5 \text{m}^3}{830\text{K}} \right| \frac{1 \text{ (kg mol)(K)}}{8.314 \text{ (kPa) (m}^3\text{)}} = 4.52 \times 10^3 \text{ kg mol}$$

Steps 1, 2, 3, and 4

All the data needed are in the figure except the specific enthalpy data which are in the third and fourth columns below. Interpolation in the tables in the text is needed to get $\Delta\hat{H}$ at 390K.

	$n(\text{kg mol} \times 10^{-3})$	$\Delta\hat{H}(\text{kJ / kgmol})$ at 390K	$\Delta\hat{H}(\text{kJ / kgmol})$ at 800K	$\Delta H = n\left(\Delta\hat{H}_{390} - \Delta\hat{H}_{800}\right)(\text{kJ})$
$CO_2(g)$	0.316	3404	23,710	–6,420
$H_2O(g)$	0.633	3456	18,823	–9,730
$N_2(g)$	3.30	4511	15,756	–37,110
$O_2(g)$	0.27	3946	16,564	–3,410
				ΔH = –56,670 kJ

Problem 5.2H

The vapor pressure of benzene can be calculated from the Antoine equation.

$$\ln(p^*) = 15.9008 - \frac{2788.51}{-52.36 + T}$$

where p^* is in mm Hg and T is in K. Determine the heat of vaporization of benzene at its normal boiling point, and compare with the experimental value.

Solution

The normal boiling point of benzene = 353.26K. Use the Clausius Clapeyron equation to get ΔH_v

$$\frac{d \ln p^*}{dt} = \frac{\Delta\hat{H}_v}{RT^2}$$

Differentiate the Antoine equation with respect to T

$$\frac{d \ln p^*}{dT} = -2788.51 \left(-\frac{1}{(-52.36 + T)^2}\right)$$

$$\frac{d \ln p^*}{dT} = \frac{2788.51}{(-52.36 + T)^2} \qquad \text{(the units of the right hand side are K}^{-1}\text{)}$$

and equate the result with the right hand side of the Clausion Clapeyron equation to get

$$\frac{\Delta\hat{H}_v}{RT^2} = \frac{2788.51}{(-52.36 + T)^2}$$

Substitute T = 353.26 K and R = 8.314 J/(g mol) (K), and solve for $\Delta\hat{H}_v$

$$\Delta\hat{H}_v = \frac{8.314\text{J}}{(\text{g mol})\ (\text{K})}\left|\frac{(353.26\text{K})^2}{}\right|\frac{2788.51}{(-52.36 + 353.26)^2\text{K}} = \frac{3.195 \times 10^4\text{J}}{\text{g mol}}$$

or **31.95 kJ/g mol** compared with **30.76** from the Appendix in the text.

Problem 5.2I

Lead is used in a number of manufacturing industries. To prevent lead vapor from escaping from a molding unit, the vapors from the unit are passed through a chilling unit to condense the lead vapor. What is the enthalpy change per kg mol of lead if the lead vapor entering the chiller is at 1850°C and the product of the chiller is solid lead at 280°C.

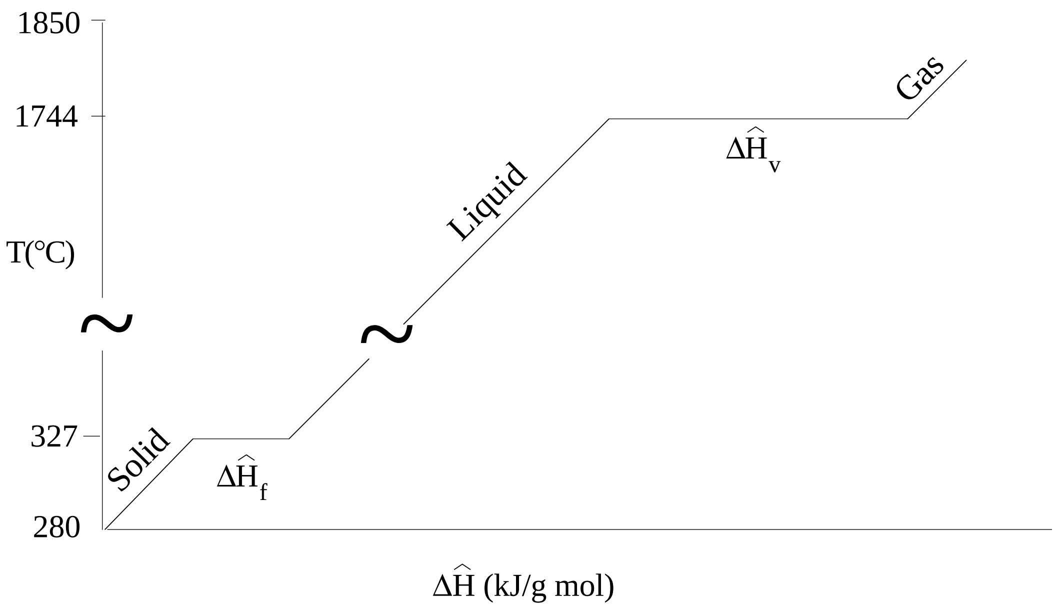
Data:

Melting point of lead: 327.4°C
Boiling point of lead: 1744°C
Heating capacity data: J/(g mol)(K) with T in K:
  Solid 24.1 + 0.049 T
  Liquid 6.8
  Vapor 20.8
Heat of fusion: 5.121 kJ/g mol
Heat of vaporization: 175.98 kJ/g mol

Solution

Basis: 1 g mol of lead

The diagram shows figuratively (not to scale) the successive calculations that must be carried out to get the overall enthalpy change.



$$\Delta\hat{H} = \int_{1850}^{1744} 20.8 \ dT - 175.98\times10^3 + \int_{1744}^{327.4} 6.8 \ dT - 5.121\times10^3$$

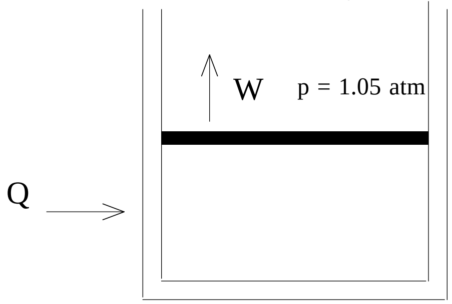
$$+\int_{327.4+273.15}^{280+273.15} (24.1 + 0.049T) \ dT = \mathbf{-195{,}400 \ kJ/gmol}$$

Problem 5.3A

Determine Q, W, ΔU and ΔH for the isothermal expansion of 1.31 mol of an ideal gas against a constant external pressure of 1.05 atm. This initial conditions are: T = 276 K and p_1 = 4.62 atm; the final pressure is p_2 = 2.21 atm for the gas.

Solution

Steps 1, 2, 3 and 4 This is an unsteady state closed process without reaction. The energy balance reduces to Q + W = ΔU. The system is the gas plus the sealing barrier.



	Initial	*Final*
p (atm)	4.62	2.21
T(K)	276	276

Assume that the work done by the gas is done only against the source of the external pressure, and none is done against the cylinder wall (frictionless piston assumption). We will assume that the surface enclosing the gas has no weight so that no change in potential energy is involved.

Step 5 Basis: 1.31 mol of ideal gas at 4.62 atm and 276 K

Step 6 The unknowns are Q, W, ΔU and ΔH

Steps 7, 8 and 9 Because the process is isothermal, **ΔH = ΔU = 0** since the gas is ideal. To calculate W we use

$$W = -\int_{V_1}^{V_2} p dV = -p\Delta V.$$

Use pV = nRT to calculate the initial and final volumes: V = n R T/p

$$V_{initial} = 6.42 \text{ L} \qquad V_{final} = 13.43 \text{ L}$$

$$\mathbf{W} = -p\Delta V = -1.05 \text{ atm } (13.43 - 6.42) \text{ L} = -7.36 \text{ (L) (atm)} = \mathbf{-745 \text{ J}}$$

$$\mathbf{Q = -W = 745 \text{ J}}$$

Note: The work being done by the system is negative and heat being supplied to the system is positive.

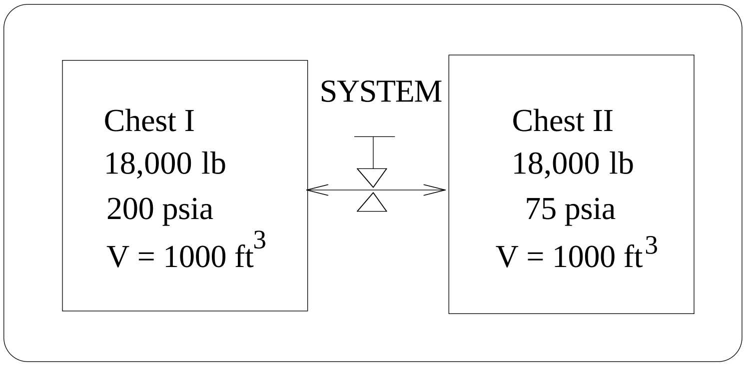
Problem 5.3B

In a paper mill two steam chests are to be operated in parallel. Each has a volumetric capacity of 1000 cu.ft and each contains 18,000 lb of steam and liquid water. The first chests registers a pressure of 200 psia, but owing to an error, it is connected to the second when the pressure in the latter is 75 psia. What will be the pressure in the system after equilibrium has been attained. It may be assumed that no heat is exchanged with the surroundings, and no water exits to the surroundings.

Solution This is a closed system for an unsteady state process without reaction.

Steps 1, 2, 3 and 4

The figure shows the initial conditions of the system.



Data from the steam tables are:

Data:	p_s (psia)	T_s (°F)	$V_{Liq.}$ (ft^3/lb)	V_{Gas} (ft^3/lb)	$\Delta H_{Liq.}$ (Btu/lb)	ΔH_{Gas} (Btu/lb)
	200	381.8	0.01839	2.288	355.4	1198.7
	75	307.6	0.01753	5.820	277.4	1181.9

The initial specific volumes show that the steam is a saturated mixture of liquid and vapor in each steam chest at the initial conditions.

Step 5 Basis: 18,000 lbs water + steam @ 200 psia, and 18,000 lbs water + steam @ 75 psia

Steps 6, 7, 8, and 9

The material balance is: the 36,000 lb of water present initially are present at the final state.

The energy balance is

$$\Delta E = \Delta U + \Delta P + \Delta K = -\Delta\left[\left(\hat{H} + \hat{P} + \hat{K}\right)\ m\right] + Q + W$$

STEAM CHEST

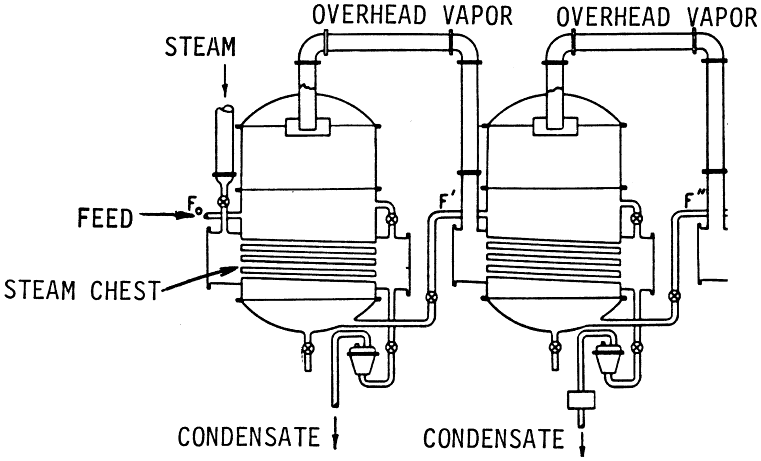


Fig 22 Steam chest in an evaporator

A steam chest is a heat exchanger placed inside another piece of equipment, such as an evaporator. In the figure steam is introduced into a set of tubular coils (or straight tubes) place inside the evaporator shell and submerged in the liquid. Steam condenses and is withdrawn as liquid condensate. A trap at the chest exit prevents the steam itself from escaping.

and the terms that are zero are:

ΔP	(no change from the reference plane)
ΔK	(no velocity)
$\Delta\left[\left(\widehat{H} + \widehat{P} + \widehat{K}\right) m\right]$	(no mass flow in or out)
Q	(assumed zero)
W	(no change in system boundary)

Thus, $\Delta U = 0$, or $\Delta U_{initial} = \Delta U_{final}$.

Step 6 The unknown is the final pressure which will be the equilibrium pressure at the final temperature of the system.

Step 4 Calculate the initial internal energy of the system. If the SI steam tables are used, $\Delta\widehat{U}$ can be read directly in the tables. If the American Engineering Tables are used

$$\Delta\hat{U} = \Delta\hat{H} - \Delta(p\hat{V})$$

hence both p and $\hat{V}$ as well as $\Delta\hat{H}$ are needed. Recall that at the reference conditions for the steam tables, p = 0.0886 psia and T = 32°F, $\Delta\hat{H} = 0$.

The specific volume of the water in both steam chests is $\dfrac{1000\ \text{ft}^3}{18{,}000\ \text{lb}} = 0.0556\ \text{ft}^3/\text{lb}$

Step 5 Basis: 1 lb steam

Step 4

<u>*The system is steam chest I*</u>. The initial fraction vapor comes from a volume balance. Let x_i = fraction vapor in steam chest I

$0.0556 = (1 - x_I)(0.01839) + (x_I)(2.288)$ $\qquad x_I = 0.0164$

$$\Delta\hat{U}_I = \{[0.9836\ (355.4) + 0.0164\ (1198.7)] - [0]\} - \Delta\left(p\widehat{V}\right)$$

(Note: $\Delta\hat{H}$ is 0 at 32°F and the vapor pressure of water so that the reference for the pV calculations is at the same conditions.)

$\Delta\left(p\hat{V}\right)$ is a very small quantity as can be seen from the following calculations:

$$\left(p\hat{V}\right)_{32°F}{}^{32°F} = \frac{0.0886\ \text{lb}_f}{\text{in}^2}\left|\frac{144\ \text{in}^2}{1\ \text{ft}^2}\right|\frac{0.01602\ \text{ft}^3}{1\ \text{lb}_m}\left|\frac{1\ \text{Btu}}{778.16\ (\text{ft})(\text{lb}_f)}\right. = 0.00026\ \text{Btu}$$

$$\Delta\hat{U}_I = 369.2 - 2.06 = 367.2\ \text{Btu} \qquad \overline{\Delta(pV) = 2.06\ \text{Btu}}$$

Next, the system is steam chest II.

$$0.0556 = (1 - x_{II})\,(0.01753) + (x_{II})\,(5.820)$$

$$x_{II} = 0.00656 \qquad \Delta\left(p\hat{V}\right) = 0.77 \text{ Btu}$$

$$\Delta\hat{U}_{II} = \{\,[0.99346\,(277.4) + 0.00656\,(1181.9)] - [0]\,\} - 0.77 = 282.6 \text{ Btu}$$

Steps 7, 8, and 9

Thus, ΔU_{final} = 367.2 (18,000) + 282.6 (18,000) = 1.170×10^7 Btu

After equilibrium is reached, to get the pressure we need to find two intensive properties to fix the state of the system (from among $\hat{V}$, $\Delta\hat{U}$, T, and x). One is

$$\hat{V} = \frac{2000\text{ft}^3}{36{,}000 \text{ lb}} = 0.0556 \text{ ft}^3/\text{lb}$$

We can get an approximate answer by estimating the $\Delta\left(p\hat{V}\right)$ term as about 1 Btu in calculating $\Delta\hat{H}$

$$\Delta\hat{U}_{final} = \frac{1.170 \times 10^7 \text{Btu}}{36{,}000 \text{ lb}} = 325.25 \text{ Btu/lb}$$

$$\Delta\hat{H} = 326 \text{ Btu/lb}$$

Assume a final pressure of 120 psia so that $\Delta\hat{H}_L$ = 312.46 Btu/lb and $\Delta\hat{H}_G$ = 1190.6 But/lb; T = 341.26°F; $\hat{V}_L$ = 0.0179 ft^3/lb and $\hat{V}_G$ = 3.728 ft^3/lb; the fraction vapor is

$$0.0556 = (1 - x)\,(0.0179) + (x)\,(3.728)$$
$$x = 0.01016$$

To check the assumption calculate $\Delta\hat{H}$

$$0.98984\,(312.46) + 0.01016\,(1190.6) = 309.3 \neq 326 \qquad \text{Too low.}$$

Assume a final pressure of 130 psia so that $\Delta\hat{H}_L$ = 318.81, and $\Delta\hat{H}_G$ = 1192.0; T = 347.31°F; $\hat{V}_L$ = 0.0180 and $\hat{V}_G$ = 3.455.

$$0.0556 = (1 - x)\,(0.0180) + (x)\,(3.455)$$
$$x = 0.01094$$

Check $\Delta\hat{H}$ again.

$$0.98905\,(318.81) + 0.01094\,(1192.0) = 328.4 \qquad \text{Too high.}$$

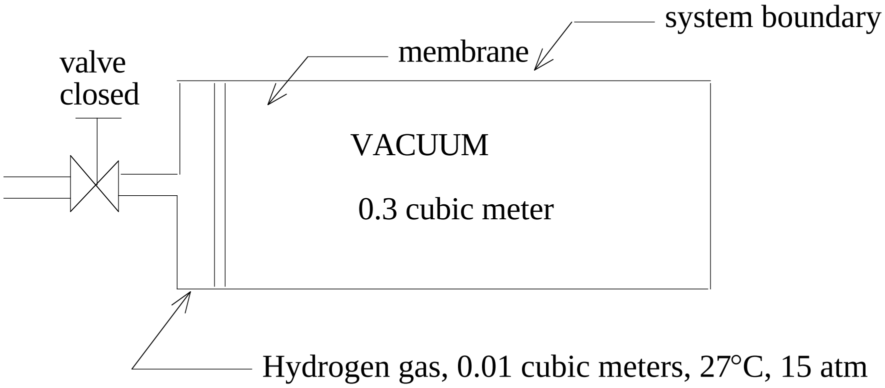
The pressure is about **129 psia.**

Problem 5.3C

A shock tunnel uses hydrogen as its driving gas. The hydrogen at high pressure is restrained by a metallic membrane. When the membrane is ruptured, the hydrogen bursts into the evacuated section and a researcher can study high intensity shock waves. Given the data on the schematic diagram of the tunnel, determine the final temperature and pressure of the gas. The process occurs quickly, before any appreciable heat transfer can occur between the gas and the walls of the chamber.

Solution

Steps 1, 2, 3 and 4 This is an unsteady state process without reaction. The system will be entire chamber, both the high pressure side and the vacuum side. All of the known data have been placed on the figure.



Step 5 Basis: 0.01 m^3 of H_2 at 27°C, 15 atm

Steps 6, 7, and 8

The unknowns are the final temperature and pressure. The mass balance is just the initial mass of H_2 equals the final mass of H_2. The energy balance

$$\Delta E = \Delta U + \Delta P + \Delta K = -\Delta\left[\left(\hat{H} + \hat{P} + \hat{K}\right)\ m\right] + Q + W$$

reduces to $\Delta U = 0$ because $\Delta P = \Delta K = 0$ and all the terms on the right hand side of the equation are zero (no mass flow, no heat transfer, and fixed system boundary.)

Let us check to see if the H_2 can be treated as an ideal gas because we know if $\Delta U = 0$, the final temperature equals the initial temperature for an ideal gas.

$p_c = 12.8$ atm $\qquad T_c = 33.3\text{K}$

use $\quad p_c' = 12.8 + 8 = 20.8$ atm $\qquad T_c' = 33.8 + 8 = 41.8\text{K}$

$$p_r' = \frac{15}{20.8} = 0.72 \qquad T_r' = \frac{300}{41.8} = 7.18$$

From the compressibility charts $z \cong 1.01$ so that the assumption of an ideal gas holds, and $\Delta U = 0$ so the final temperature = 300K = T. At constant temperature.

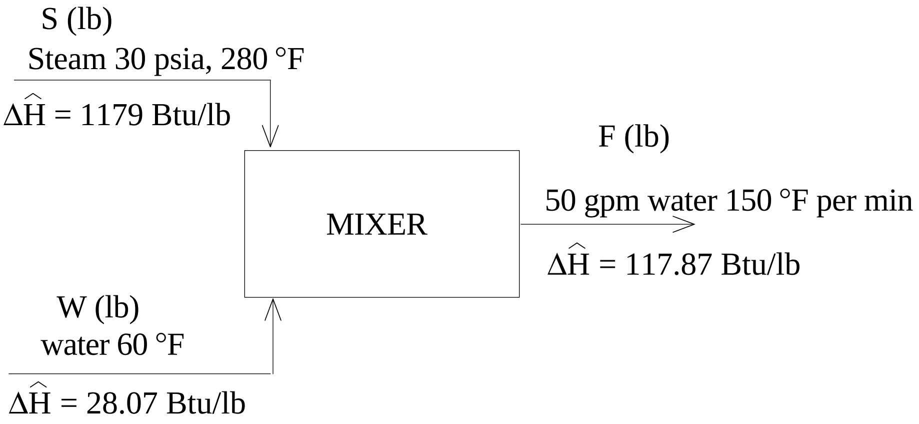
$$p_2 = p_1\left(\frac{V_1}{V_2}\right) = 15\left(\frac{0.01}{0.31}\right) = \mathbf{0.48\ atm}$$

Problem 5.3D

A stream of hot water at 150 °F flowing at a rate of 50 gal/min is to be produced by mixing water at 60 °F and steam at 30 psia and 280 °F in a suitable mixer. What are the required flow rates of steam and cold water. Assume Q = 0.

Solution

Steps 1, 2, 3 and 4 This is a steady state problem. The system is open. No reaction occurs. The stream properties are placed in the figure



$$\frac{50\text{ gal}}{\text{min}}\bigg|\frac{1\text{ ft}^3}{7.48\text{ gal}}\bigg|\frac{1\text{ lb}_m}{0.01634\text{ ft}^3} = 409\,\frac{\text{lb}_m}{\text{min}}$$

Step 5 Basis: 50 gpm of hot water at 150 °F (equivalent to 1 min)

Steps 6 and 7 Unknowns are m_W, m_S.

Balances (2): Energy balance and overall mass balance. The mass balance is

$$S + W = F = 409$$

There is no heat exchange with the surroundings, so that Q = 0. The work W = 0, the kinetic and potential energies are constant, hence $\Delta K = \Delta P = 0$, and there is no accumulation in the system so that $\Delta E = 0$. The overall energy balance reduces to

$$\Delta H = 0 = F\,\Delta\hat{H}_F + S\,\Delta\hat{H}_S + W\,\Delta\hat{H}_W$$

Steps 7, 8 and 9

Substitute the enthalpy data from steam tables:

$$28.07\ (W) + 1179\ (S) = 409\ (117.87)$$

Solve the energy balance with the material balance to get

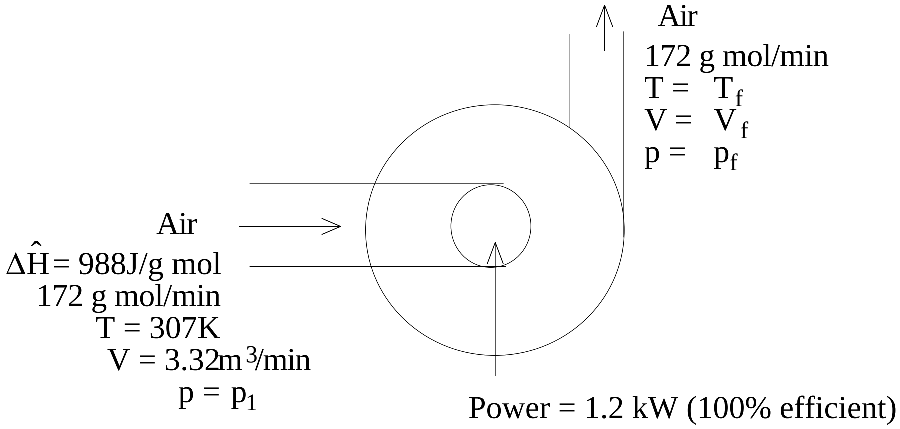
W = 377 lb/min; S = 32 lb/min

Problem 5.3E

In a waste treatment plant, hazardous chemicals are oxidized to less toxic chemicals by bubbling air through the waste solution. This process is known as aeration. The rate of aeration is governed by the COD (chemical oxygen demand). In a pilot unit, an air blower supplies 172 g mol of air/min to the aerator. The blower uses 1.2 kW. The inlet gas flow rate is 3.32 m^3/min at a temperature of 307 K and a pressure of p_1. Determine the final temperature of the gas assuming the process is adiabatic, and that the blower is 100% efficient.

Solution

Steps 1, 2, 3 and 4 This is a steady state flow problem without reaction. The known properties of the air are shown in the figure.



Step 5 Basis: 1 min (172 g mol/air)

Steps 6, 7, 8 and 9

The kinetic and potential energy effects can be neglected (= 0). There is no exchange of heat with the surroundings (Q = 0). The general energy balance reduces to: $\Delta H = W$

Note that the value of W is positive (work done on the system) .

$$W = \frac{1.2\ \text{kW}}{} \left| \frac{1000\ \frac{\text{J}}{\text{s}}}{1\ \text{kW}} \right| \frac{60\ \text{s}}{1\text{min}} = 7.2 \times 10^4\ \text{J/min}$$

$$\Delta H = \Delta H_{\text{final}} - \Delta H_{\text{initial}} = \left(\Delta\hat{H}_f\right) 172 - 988\,(172) = 7.2 \times 10^4$$

$\Delta\hat{H}_f$ = 1407 J/g mol which from tables for the thermodynamic properties air with the same reference state (273K) corresponds to about **321K**

If you assume air is an ideal gas, you can calculate T_1 by

$$\Delta H = n\int_{307}^{T_1} C_p\, dT = 172\left(\frac{7}{2}\right)(8.314)\,(T - 307) = +7.2 \times 10^4$$

$$T = 321\text{K}$$

Problem 5.4A

Calculate the heat of reaction at standard conditions (T = 25°C and p = 101.3kPa) for 1 mol of HCl(g) for the following reaction:

$$4HCl(g) + O_2\ (g) \leftrightarrows 2\ H_2O(g) + 2Cl_2(g)$$

Solution

The assumption is that stoichiometric amounts of the reactants react completely to form the products shown in the equation at 25°C and 1 atm.

Data	$\Delta\hat{H}_f^\circ(\text{kJ / gmol})$
$HCl(g)$	-92.311
$O_2(g)$	0
$H_2O(g)$	-241.826
$Cl_2(g)$	0

Basis: 4 g mol HCl(g)

$$\Delta H^\circ_{rxn} = \sum_{\text{products}} \Delta H^\circ_{f,i} - \sum_{\text{reactants}} \Delta H^\circ_{f,i}$$

$$\Delta H^\circ_{rxn} = 2(-241.826) -4(-92.311) = 114.4 \text{ kJ}$$

$$\Delta\hat{H}^\circ_{rxn} = -\frac{114.4}{4} = \mathbf{-28.6\ kJ/g\ mol\ HCl(g)}$$

Problem 5.4B

Find the standard (25°C and 1 atm) heat of reaction for the following reaction:

$$C_3H_6(g) + 9/2\ O_2(g) \rightarrow 3\ CO_2(g) + 3H_2O(l)$$

Solution

Data	$\Delta\hat{H}_f^\circ(\text{kJ / g mol})$
$C_3H_6(g)$	20.41
$O_2(g)$	0
$CO_2(g)$	-393.51
$H_2O(l)$	-285.840

Basis: 1 g mol $C_3H_6(g)$

$$\Delta H^\circ_{rxn} = \sum_{\text{products}} \Delta H^\circ_{f,i} - \sum_{\text{reactants}} \Delta H^\circ_{f,i}$$

$$\Delta H^\circ_{rxn} = 3(-393.51) + 3\,(-285.840) - 1(20.41)$$

$$\Delta H^\circ_{rxn} = \mathbf{-2058.46\ kJ/g\ mol\ C_3H_6(g)}$$

Problem 5.4C

The corrosion of aluminum in water is normally prevented by the tightly adhering oxide layer that forms on the aluminum. If this layer were absent, as when aluminum is amalgamated with mercury in an anaerobic atmosphere, the following reaction occurs.

$$2Al(s) + 6H_2O(l) \rightarrow 2A1(0H)_3(s) + 3H_2(g)$$

To get the heat of formation of $A1(OH)_3(s)$, the reaction is carried out with stoichiometric quantities of reactants, and after complete reaction occurs you find that heat was liberated. After applying the energy balance, you calculate $\left(\Delta H^\circ_{rxn}\right)$ at standard conditions per 2 moles of A1) was –837.0 kJ. What is the heat of formation of $A1(OH)_3$ (s)?

Solution

Basis: 2g mol Al(s)

Data	ΔH°_f(kJ/g mol)
Al(s)	0
$H_2O(l)$	-285.841
$A1(OH)_3(s)$	?
$H_2(g)$	0

$$\Delta H^\circ_{rxn} = \sum_{\text{products}} \Delta H^\circ_{f,i} - \sum_{\text{reactants}} \Delta H^\circ_{f,i} = -837.0$$

$$2\left(\Delta \hat{H}^\circ_f\right) - 6(-285.841) = -837.0$$

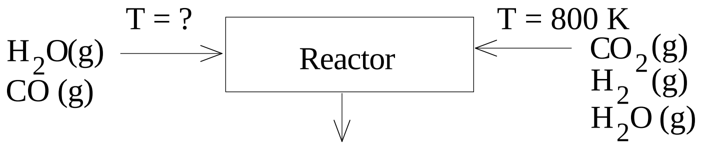
$$\mathbf{\Delta \hat{H}^\circ_f = -1276\ kJ / g\ mol\ A1(OH)_3}(s)$$

Problem 5.4D

Carbon monoxide and 100% excess water are reacted to form hydrogen and carbon dioxide. The heat loss from the reactor is 120.2 kJ per kg mole of CO entering. If the exit temperature is 800K, what is the entering temperature? The pressure is 1.0 atm. Assume complete combustion.

Solution

Steps 1, 2, 3, and 4 This is a steady state process with reaction. The system is the reactor.



heat loss: Q = –120.2 kJ/kg mol CO

$$CO(g) + H_2O(g) \rightleftarrows CO_2(g) + H_2(g)$$

$\Delta\hat{H}_f^\circ$ (kJ/g mol): –110.52 –241.826 –393.51 0

Step 5 Basis: 1.0 g mol CO entering

Steps 6, 7, 8, and 9 The material balance summary is (in g mol)

Compound	In	Out
CO	1	0
H_2O	2	1
CO_2	0	1
H_2	0	1

The enthalpies with respect to 25°C and 1 atm can calculate from the tables of the combustion gases:

Compounds In	g mol	Enthalpies (kJ/g mol)		ΔH(kJ)
		$\Delta\hat{H}_f^\circ$	$\Delta\hat{H}^T_{298K}$	
CO(g)	1	–110.52	$\left(\Delta\hat{H}^T_{CO} - 0.728\right)$	$-110.52(1) + \Delta\hat{H}^T_{CO}(1) - 0.728(1)$
$H_2O(g)$	2	–241.826	$\left(\Delta\hat{H}^T_{H_2O} - 0.837\right)$	$-241.826(2) + \Delta\hat{H}^T_{H_2O}(2) - 0.837(2)$
			Total	$-596.574 + \Delta\hat{H}_{CO} + 2\Delta\hat{H}_{H_2O}$

Compounds Out	g mol	$\Delta\hat{H}_f^\circ$	ΔH^{800K}_{298K}	ΔH(kJ)	
$CO_2(g)$	1	–393.51	(23.710 – 0.912)1	–393.51 + 22.798	= –370.71
$H_2(g)$	1	0	(15.413 – 0.718)1	0 + 14.695	= 14.695
$H_2O(g)$	1	–241.826	(18.823 – 0.837)1	–241.826 + 17.986	= –223.840
			Total		–579.867

The energy balance reduces to

$$Q = -0.1202 \text{ kJ} = \Delta H = \underset{\text{products}}{\Sigma\Delta H_i} - \underset{\text{reactants}}{\Sigma\Delta H_i}$$

so that

$$(-579.867) - \left(-596.574 + \Delta\widehat{H}^{T}_{CO_2} + 2\Delta\widehat{H}^{T}_{H_2O}\right) + 0.1202 = 0$$

By choosing successive temperatures, the energy balance can be made to balance at the desired temperature.

Let T = 500K. Then $\Delta\widehat{H}^{T}_{CO}$ = 6,652J/g mol and $\Delta\widehat{H}^{T}_{H_2O}$ = 7,752J/g mol from the tables.

$$-579.867 + 596.574 - 6.652 - 15.504 + 0.1202 = -5.329 \neq 0 \qquad \text{Too low.}$$

Let T = 400K. Then $\Delta\widehat{H}^{T}_{H_2O}$ = 3,696 J/g mol and $\Delta\widehat{H}^{T}_{H_2O}$ = 4,284 J/g mol.

$$-579.867 + 596.574 - 3.696 - 8.568 + 0.1202 = 4.563 \neq 0 \qquad \text{Too High}$$

However the temperature has been bracketed and linear interpolation gives

$$400 + \frac{4.563 - 0}{4.563-(-5.329)}(100) = \mathbf{446K}$$

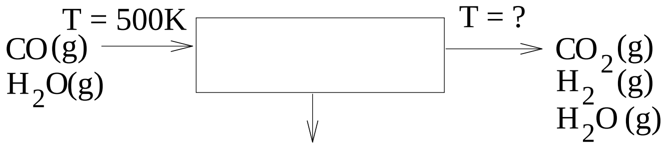
You could use the heat capacity equations to get the enthalpy changes for the gases, $\Delta\widehat{H}^{T}_{i,\ 298}$, i.e., use the sensible heats, but the calculations would take longer than using the tables. However, you would get an equation (fourth order) containing only one variable, the desired temperature T. By dropping terms higher than second order (which contribute little to ΔH), you can solve a quadratic equation for T.

Problem 5.4E

Carbon monoxide is reacts with 100% excess water to form carbon dioxide and hydrogen. The reactants enter the reactor at 500K and 1.0 atm. Because of poor insulation, the heat loss from the reactor is 71.21kJ per g/mol of carbon monoxide entering. Find the temperature of the outlet gas stream from the reactor.

Solution

Steps 1, 2, 3 and 4 This is a steady state problem with reaction. The system is the reactor.



heat loss: Q = –71.21 kJ/g mol CO

$$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$$

$\Delta\hat{H}^\circ_f$(kJ/g mol): –110.52 –241.826 –393.51 0

Step 5 Basis: 1 g mol CO entering

Steps 6, 7, 8 and 9

Material Balance	*In*	*Out*
CO(g)	1	0
$H_2O(g)$	2	2 – 1 = 1
$CO_2(g)$	0	1
$H_2(g)$	0	1

Energy Balance

The energy balance reduces to Q = ΔH, and

$$\Delta H = n \sum_{\text{products}} n_i\left(\Delta\hat{H}^\circ_{f,i} + \Delta\hat{H}^T_{298,i}\right) - \sum_{\text{reactants}} n_i\left(\Delta\hat{H}^\circ_{f,i} + \Delta\hat{H}^{500}_{298,\,i}\right).$$

Let T = 298K be the reference temperature.

Heat capacity equations can be used to calculate the "sensible heats", $\Delta\hat{H}^T_{298}$ instead of tables, but use of the tables is quicker.

In

Compound	g mol	$\Delta\hat{H}^\circ_f$ (kJ/g mol)	$\Delta\hat{H}^{500}_{298}$ (kJ/g mol)	ΔH(kJ)
CO(g)	1	–110.52	(6.652 – 0.728)	–104.596
$H_2O(g)$	2	–241.826	(7.752 – 0.837)	–469.822
				–574.418

<u>Out</u>

Compound	g mol	$\Delta\widehat{H}^{\circ}_f$ (kJ/g mol)	$\Delta\widehat{H}^{T}_{298}$ (kJ/g mol)	ΔH(kJ)
CO_2(g)	1	–393.51	$\left(\Delta\widehat{H}^{T}_{CO_2} - 0.912\right)$	$\Delta\widehat{H}^{T}_{CO_2} - 394.422$
H_2(g)	1	0	$\left(\Delta\widehat{H}^{T}_{H_2} - 0.718\right)$	$\Delta\widehat{H}^{T}_{H_2} - 0.718$
H_2O(g)	1	–241.826	$\left(\Delta\widehat{H}^{T}_{H_2O} - 0.837\right)$	$\Delta\widehat{H}^{T}_{H_2O} - 242.663$
				$\Sigma\Delta\widehat{H}^{T}_{i} - 637.803$

We need to assume temperatures until we find the temperature that yields $\Delta\widehat{H}^{T}_{i}$ values that cause the energy balance to balance:

$$\Delta H - Q = 0 \text{ or}$$

$$\left[(1)\left(\Delta\widehat{H}^{T}_{CO_2}\right) + (1)\left(\Delta\widehat{H}^{T}_{H_2}\right) + (1)\left(\Delta\widehat{H}^{T}_{H_2O}\right) - 637.803 - (-469.822)\right] + 71.21 = 0$$

Let T = 1000K. Then

$(1)\quad \Delta\widehat{H}^{T}_{CO_2} = 34.308$

$(1)\quad \Delta\widehat{H}^{T}_{H_2} = 21.388$

$(1)\quad \Delta\widehat{H}^{T}_{H_2O} = \underline{26.823}$

Total 82.519

Substitute 82.519 in the energy balance and get for the sum of the terms –14.252 kJ. Too low.

Increase the temperature to 1200K:

$$(1)\,\Delta\widehat{H}^{T}_{CO_2} + (1)\,\Delta\widehat{H}^{T}_{H_2} + (1)\,\Delta\widehat{H}^{T}_{H_2O} = 45.404 + 27.509 + 35.312 = 108.225$$

and the energy balance sums to 11.454 kJ: Too high. The temperature is bracketed, however.
Use T = 1100K

$$(1)\,\Delta\widehat{H}^{T}_{CO_2} + (1)\,\Delta\widehat{H}^{T}_{H_2} + (1)\,\Delta\widehat{H}^{T}_{H_2O} = 39.802 + 24.426 + 31.011 = 95.239$$

and the energy balance sums to –1.53kJ.

The temperature is $1100 + 100\,\dfrac{0 - (-1.53)}{11.454 - (-1.53)}$ = **1112K**

FURNACE

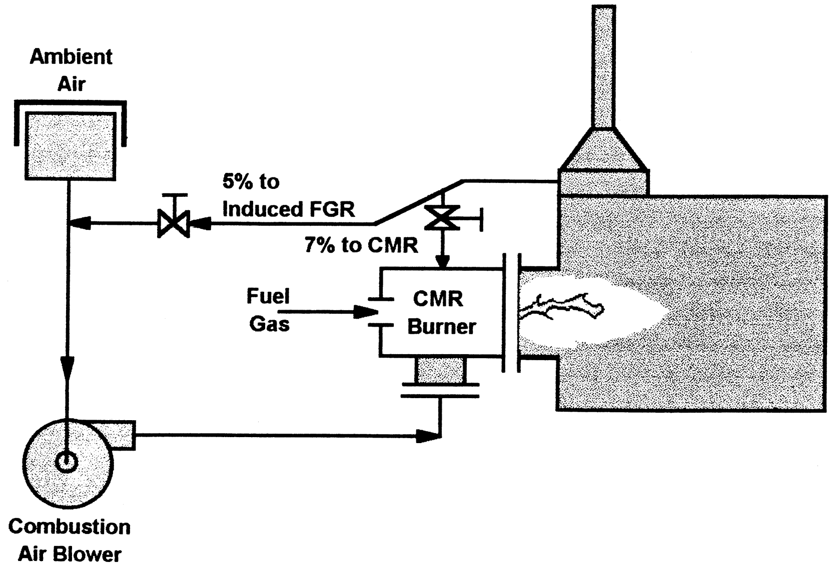


Fig 23 Furnace (with recirculated combustion products)

Combustion of fuel focuses on the production of CO_2 and H_2O, but a small amount of N_2 also oxidizes to form various nitrogen oxides, NO_x, that are pollutants. Increasingly stringent federal and local regulations for the permitted NO_x emmissions in flue gas discharge have led to various technologies for NO_x reduction. A combination of combustion staging, premix combustion, and recirculation make it possible to achieve low NO_x levels.

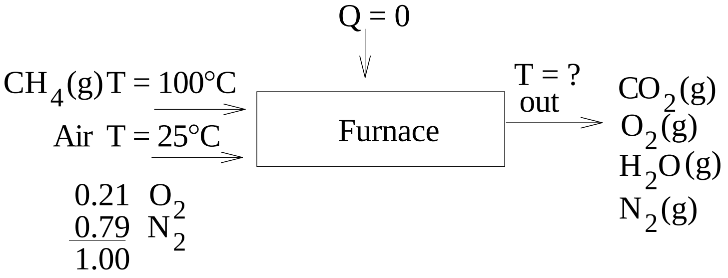
Problem 5.4F

Methane at 100°C is burned with 100% excess air which is at 25°C in an insulated furnace. From the data given, calculate the adiabatic flame temperature.

Solution

Steps 1, 2, 3 and 4

The system is the reactor.



This is a steady state process with reaction

	$CH_4(g)$ +	$2O_2(g) \rightarrow$	$CO_2(g)$ +	$2H_2O(g)$
$\Delta\hat{H}_f^\circ$(kJ/g mol):	–74.84	0	–393.51	–241.826

Step 5 Basis: 1 g mol CH_4 entering

Steps 6, 7, 8 and 9

Material Balance Summary

Component	*g mol in*	*g mol out*
$CH_4(g)$	1.0	0
$O_2(g)$	2 reqd + 2xs = 4	2.0
$N_2(g)$	15.05	15.05
$CO_2(g)$	0	1.0
$H_2O(g)$	0	2.0

The energy balance reduces to $\Delta H = 0$. Let T = 25°C be the reference temperature. The sensible heats will be taken from the tables of enthalpies of gases so that a trial and error solution procedure will be needed. (If heat capacity equations are used to calculate the "sensible heats," i.e., $\Delta\hat{H}_{298}^{T}$, then the energy balance reduces to a cubic or quadratic equation in T_{out} that must be solved for T_{out}.

Components In	T(K)	g mol	$\Delta\hat{H}_f^\circ$(kJ/g mol)	$\Delta\hat{H}_{298}^{T}$(kJ/g mol)	ΔH(kJ)
$CH_4(g)$	373	1.0	–74.84	(3.717 – 0.879)	–72.00
$O_2(g)$	298	4.0	0	(0.732 – 0.732)	0
$N_2(g)$	298	15.05	0	(0.728 – 0.728)	0
				Total	–72.00

Components Out	g mol	$\Delta\hat{H}_f^\circ$(kJ/g mol)	$\Delta\hat{H}_{298}^T$(kJ/g mol)	ΔH(kJ)
CO_2(g)	1.0	–393.51	$\left(\Delta\hat{H}_{CO_2}^T - 0.912\right)$	$\Delta\hat{H}_{CO_2}^T - 394.422$
H_2O(g)	2.0	–241.826	$\left(\Delta\hat{H}_{H_2O}^T - 0.837\right)$	$2\Delta\hat{H}_{H_2O}^T - 485.326$
O_2(g)	2.0	0	$\left(\Delta\hat{H}_{O_2}^T - 0.732\right)$	$2\Delta\hat{H}_{O_2}^T - 1.464$
N_2(g)	15.05	0	$\left(\Delta\hat{H}_{N_2}^T - 0.728\right)$	$15.05\Delta\hat{H}_{N_2}^T - 10.956$
			Total	$\Sigma\Delta\hat{H}_i^T - 892.168$

Substitution of the above quantities into the energy balance ($\Delta H = 0$) gives ($\Delta H_{out} - \Delta H_{in}$) = 0 or

$$\left[\Delta\hat{H}_{CO_2}^T + 2\Delta\hat{H}_{H_2O}^T + 2\Delta\hat{H}_{O_2}^T + 15.05\,\Delta\hat{H}_{N_2}^T - 892.168\right] - [-72.00] = 0$$

We assume a series of temperatures to bracket the solution, and introduce the corresponding $\Delta\hat{H}_i^T$ values from the enthalpy tables into the equation.

Let T = 1500 K

$$62.676 + 2\,(48.848) + 2\,(41.337) + 15.05\,(39.145) - 820.168 = 12.010$$

Let T = 1400K

$$56.860 + 2(44.237) + 2(37.693) + 15.05\,(35.639) - 820.168 = -63.081$$

$$T = 1500 - \frac{(12.010 - 0)}{(12.010 - (-63.081))}\,(100) = \mathbf{1484\ K}$$

Problem 5.5A

Nitrogen at 500K and 200kPa absolute is enclosed in a cylinder fitted with a frictionless piston. The weight of the piston exerts a force of 50.1 kPa on the gas, and the barometer reads 99.0 kPa. The gas moves the piston up expanding the gas volume from 0.50m^3 to 0.63m^3. Calculate the work done by nitrogen for two cases:

(a) The expansion is isobaric (constant pressure)
(b) The expansion is isothermal (constant temperature)

Assume the N_2 behaves as an ideal gas.

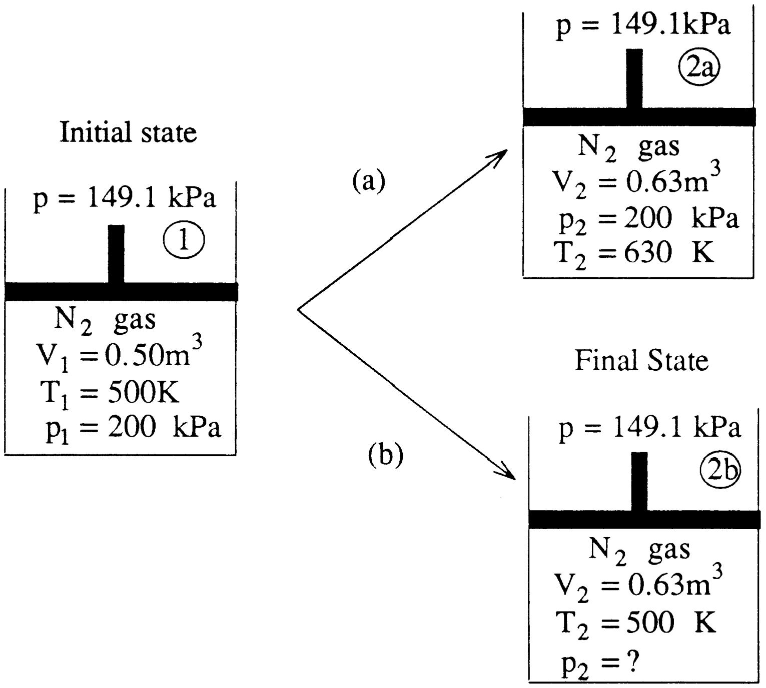
Solution

Note that the piston has to be frictionless because otherwise work will be done in an unknown amount against the cylinder wall. The force of the gas in the bottom of the piston is 200 kPa, and the force on the top exerted by the atmosphere and the weight of the piston is 149.1 kPa so that the system is not at equilibrium and the piston must be held in place initially by a lock. If the piston is released, the gas will expand until the gas pressure reaches some new value at a new volume (the piston has to be stopped by a lock), but the expansion will not be a reversible process -- quite the contrary. The system is the gas.

What we will calculate is the upper limit obtainable for the work if the gas expanded reversibly. The idea of maintaining reversibility during expansion is itself contradicted by the need for a pressure difference (absence of equilibrium) for expansion to take place! Heat has to be added to the cylinder to maintain a constant pressure or temperature in the gas.

Steps 1, 2, 3 and 4

The figure shows the two cases, a and b, and the calculated data has been placed on the figure.



Step 5 Basis: 0.50m^3 of N_2 at 500K and 200 kPa

Steps 6, 7, 8 and 9

The unknown is the work done by the gas, W. Assume that N_2 is an ideal gas so that $pV = nRT$.

$$n_{N_2} = \frac{pV}{RT} = \left.\frac{200\text{kPa}}{\dfrac{8.314(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})}}\right|\frac{0.5\text{m}^3}{500\text{K}} = 0.024 \text{ kg mol}$$

Isobaric Process

$$\frac{p_2V_2}{p_1V_1} = \frac{n_2RT_2}{n_1RT_1} \text{ or } T_2 = 500\left(\frac{0.63}{0.50}\right) = 630\text{K}$$

$$\lim W = -\int_{0.50}^{0.63} pdV = \left.\frac{200 \text{ kPa}}{}\right|\left.\frac{(0.63-0.50)\text{m}^3}{}\right|\left.\frac{1000 \text{ Pa}}{1 \text{ kPa}}\right|$$

$$\left.\frac{1\dfrac{\text{N}}{\text{m}^2}}{1 \text{ Pa}}\right|\left.\frac{1\dfrac{\text{J}}{\text{m}}}{1 \text{ N}}\right|\frac{1 \text{ kJ}}{1000 \text{ J}} = -26 \text{ kJ}$$

Isothermal Process

$$p_2 = p_1\frac{V_1}{V_2} = 200\left(\frac{0.50}{0.63}\right) = 159 \text{ kPa}$$

$$\lim W = -\int_{0.50}^{0.63} pdV = \int_{0.50}^{0.63}\frac{nRT}{V}\ Vd = nRT\,ln\left(\frac{0.63}{0.50}\right)$$

$$= \left.\frac{0.024 \text{ kg mol}}{}\right|\left.\frac{8.314(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})}\right|\left.\frac{500 \text{ K}}{}\right|\left.\frac{ln(1.26)}{}\right|$$

$$\times\frac{1 \text{ kJ}}{1(\text{kPa})(\text{m}^3)} = -23 \text{ kJ}$$

Note that the work done by the gas is the sum of the work done is pushing back the atmosphere by 0.13 m^3 plus the gain in the potential energy of the piston relative to a reference plane.

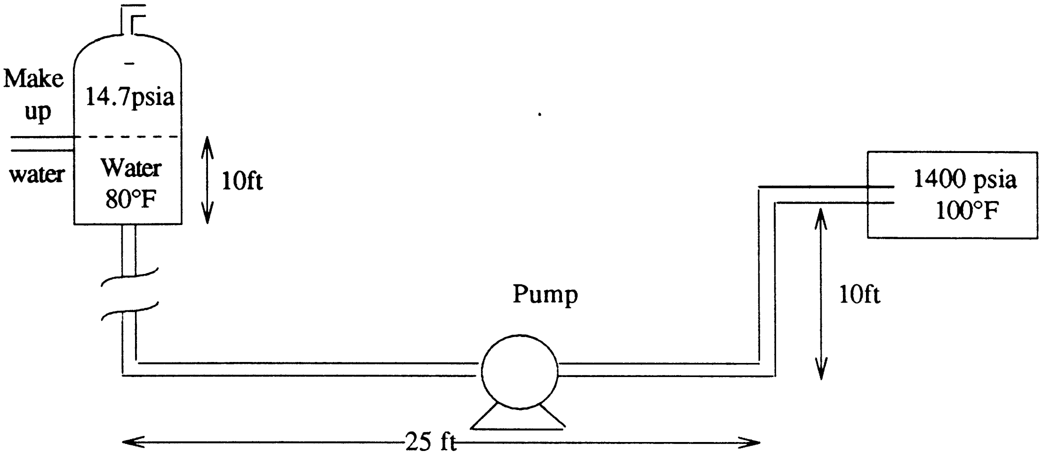
Problem 5.5B

A pump delivers water from the bottom of a storage tank (open to the atmosphere) containing water at 80°F. The bottom of the tank is 100 ft from the ground, and the water is maintained at a level 10 ft deep in the tank. The pump delivers 100°F water at 1400 psia to a chamber at a level 10ft off the ground and 25ft away from the storage tank. From a handbook you can find that the losses of energy in the transit of the fluid because of friction, etc. are estimated to be 320(ft)(lb_f)/lb_m, and for the normal flow rate of 10,000 lb/hr the pump efficiency is 76.2 percent. What horsepower pump is required to deliver 10,000 lb of water per hour to the chamber?

Solution

Steps 1, 2, 3, and 4

All the data have been placed on the figure. This is a steady state flow process. The system is the water.



From the steam tables for saturated liquid

$$\hat{V}(80°F) = 0.01607 \text{ ft}^3/\text{lb}_m \qquad \hat{V}(100°F) = 0.01613 \text{ ft}^3/\text{lb}_m$$

so that we can assume water is incompressible at 0.0161 ft^3/lb_m

Step 5 Basis: 1 hr (10,000 lb water)

Step 6 The unknown is the work, W, done by the pump.

Steps 7, 8, and 9

Since we know the frictional losses, E_v, we can use the steady state mechanical energy balance to solve for W.

$$\Delta(\hat{K} + \hat{P}) + \int_{p_1}^{p_2} \hat{V}dp - \hat{W} + \hat{E}_v = 0$$

$$E_V = \frac{10{,}000\ \text{lb}_m}{} \left| \frac{320(\text{ft})(\text{lb}_f)}{\text{lb}_m} \right. = 3.20 \times 10^6 (\text{ft})(\text{lb}_f)$$

$\Delta K =$ 0 (no information on the water velocity, but the value will be very small)

$$\Delta P = \frac{10{,}000\ \text{lb}_m}{} \left| \frac{(10\ \text{ft} - 110\ \text{ft})}{} \right| \frac{32.2\ \text{ft}}{\text{s}^2} \left| \frac{(\text{s}^2)(\text{lb}_f)}{32.2(\text{ft})(\text{lb}_m)} \right.$$

$$= -1.00 \times 10^6 (\text{ft})(\text{lb}_f)$$

$$m \int_{14.7}^{1400} \hat{V} dp = \frac{10{,}000\ \text{lb}_m}{} \left| \frac{0.0161\ \text{ft}^3}{\text{lb}_m} \right| \frac{(1400 - 14.7)}{\text{in.}^2} \left| \frac{(12\text{in.})^2}{(1\ \text{ft}^2)} \right. = 32.1 \times 10^6 (\text{ft})(\text{lb}_f)$$

$$W = 3.20 \times 10^6 + 32.1 \times 10^6 - 1.00 \times 10^6 = 34.3 \times 10^6 (\text{ft})(\text{lb}_f) \text{ or}$$

$$W = \frac{34.3 \times 10^6 (\text{ft})(\text{lb}_f)}{\text{hr}} \left| \frac{1(\text{hp})(\text{hr})}{1.98 \times 10^6 (\text{ft})(\text{lb}_f)} \right. = 17.3\ \text{hp (work done on the water)}$$

If the motor and pump is 75% efficient, the size needed is $\mathbf{\frac{17.3}{0.75} = 23\ hp}$

Problem 5.6A

Ammonium dihydrogen phosphate ($NH_4H_2PO_4$) is used in both the chemical and fertilizer industries. Given the experimental data below for the integral heat of formation of $NH_4H_2PO_4$ in water

a. Plot the standard integral heat of solution curve for $NH_4H_2PO_4$ in water;

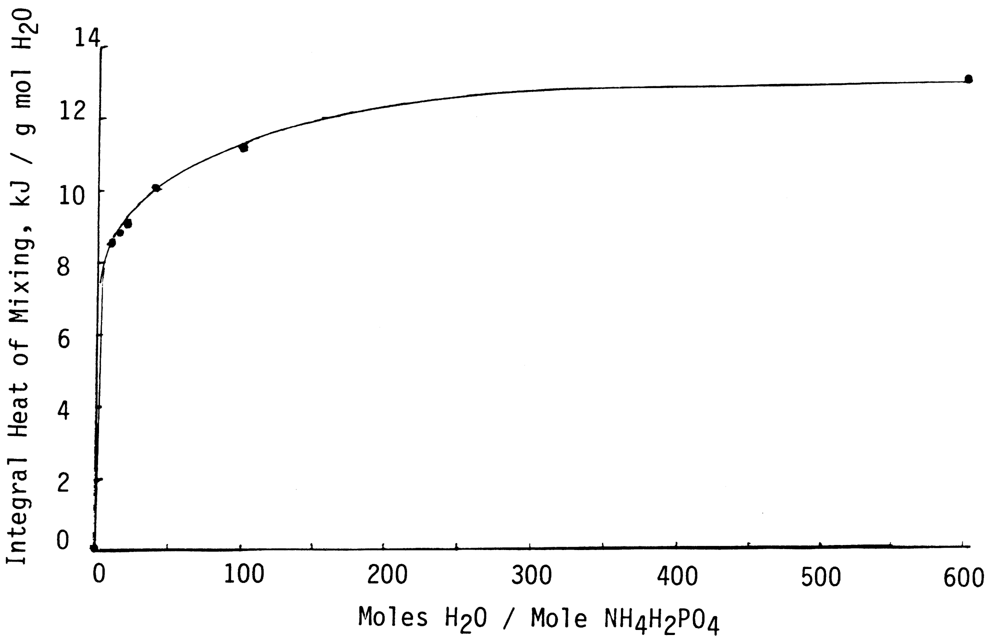
b. What would be the approximate final temperature of the solution if you mix $NH_4H_2PO_4$ and H_2O each at 25°C to form a 15% solution of $NH_4H_2PO_4$? The C_p^o of $NH_4H_2PO_4$ (crystal) is 182 J/g mol.

Heat of formation$\left(\Delta\hat{H}_f^o, \text{kJ / g mol } H_2O \text{ in solution}\right)$

Mole H_2O:	0	11	13	15
$\Delta\hat{H}^o$:	−1573.7	−1565.1	−1565.0	−1564.9
Mole H_2O:	20	40	100	600
$\Delta\hat{H}^o$:	−1564.6	−1563.6	−1562.3	−1560.6

Solution

a. The plot is as follows



b. To get the final temperature of the solution, make an energy balance. Assume a flow process for the mixing, or assume $\Delta H = \Delta U$ for a batch process ($\Delta pV \cong 0$). Then $\Delta H_{in} = \Delta H_{out}$, and on the basis of 100 g of a 15% solution of $NH_4H_2PO_4$ (MW = 115)

$$\frac{\text{mol } H_2O}{\text{mol } NH_4H_2PO_4} = \frac{\frac{(100)(0.85)}{18}}{\frac{(100)(0.15)}{115}} = 36.2$$

From the graph, $\Delta \hat{H}_{\text{soln}} \cong 9.8$. At 25°C

$$\Delta \hat{H}_f^\circ(\text{soln}) = 9.8 + (-1573.7) = -1563.9 \text{ kJ / g mol } NH_4H_2PO_4$$

To make the energy balance, we have to know the enthalpy of the 15% solution as a function of temperature. What value should be used for C_p? Usually, for not too concentrated solutions, we can assume the C_p of the solution is the C_p of water multiplied by the mass fraction of water in the solution.

ΔH_{in}		ΔH_{out}
$NH_4H_2PO_4$	H_2O	Solution
$\left(\frac{(100)(0.15)}{115}\right)\left(-1573.7\times10^3\right) +$	$\left(\frac{0.85}{18}\right)(0)$	$= \left(\frac{(100)(0.15)}{115}\right)\left(-1563.9\times10^3\right) + \int_{25}^{T}(0.85)(100)(4.184)dT$

$T - 25 = -3.6$ so that **T = 21.4°C**

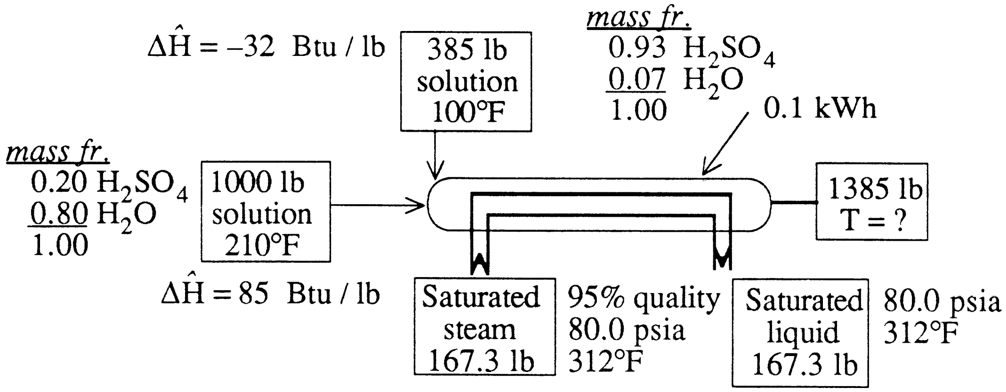
Problem 5.6B

A stainless steel mixing tank contains a steam coil and agitator. One thousand lb of 20% H_2SO_4 solution at 210°F is initially in the tank, and steam at 65.3 psig, 95% quality, is turned on into the coil. The agitator starts and 385 lb of 93% H_2SO_4 solution at 100°F added to the tank. Measurements from the steam trap attached to the coil should that 167.3 lb condensate at 312°F was removed from the coil. It is estimated that the agitator transmitted 0.10 kWh of energy to the liquid. What is the final temperature, weight, and composition of the solution in the tank?

Solution

Steps 1, 2, 3, and 4

Data required for the solution of this problem are the enthalpies of the steam and the H_2SO_4 solutions (see Appendices C and I in the textbook). The reference states are identical. The data have been entered on the figure below. Treat the process as a flow process.



Step 5 Basis: Data in diagram

Steps 6, 7, 8, and 9

The *material balance* is simple:

Total balance: 1000 + 385 = **1385 lb H_2SO_4 solution leave**
H_2SO_4 balance: 1000 (.20) + 385(.93) = 558 lb H_2SO_4

$$\frac{558}{1385}(100) = 40.3\% \text{ H}_2\text{SO}_4 \text{ overall}$$

However, some of the water vaporizes (40% is in the two phase region of the enthalpy concentration chart).

The *energy balance* is $\Delta H_{in} + 0.1 \text{ kWh}\left(\frac{3.413\times10^3 \text{ Btu}}{1 \text{ kWh}}\right) = \Delta H_{out}$ if $Q = 0$.

Flow	$\%H_2SO_4$	T(°F)	$\Delta\hat{H}$ (Btu/lb)	ΔH(Btu)
1000 lb and	20	210	85	85,000
385 lb and	93	100	-32	-12,320
(0.95) 167.3 lb steam	0	312	1183	188,020
167.3 lb water	0	312	282	41,179
1385 lb and	40.3	?	?	?

$$(1385)\Delta\hat{H}_{out} + 41{,}179 = 341 + 85{,}000 - 12{,}320 + 188{,}020 + (0.05)167.3(282)$$
$$\Delta\hat{H}_{out} = 159 \text{ Btu / lb}$$

From the enthalpy concentration chart at 40.3% H_2SO_4 solution and $\Delta\hat{H} = 159$ Btu / lb, we find the solution is in the two phase region at ~249°F. The liquid concentration is ~46% H_2SO_4 solution $(\Delta\hat{H} = 17 \text{ Btu / lb})$, the vapor is steam at 249°F $(\Delta\hat{H} = 1163.2)$, and the weight of the solution (x) is

$$1385(159) \cong 220{,}000 = x(17) + (1385 - x)1163.8$$

x = 1213 lb of 46% H_2SO_4 solution

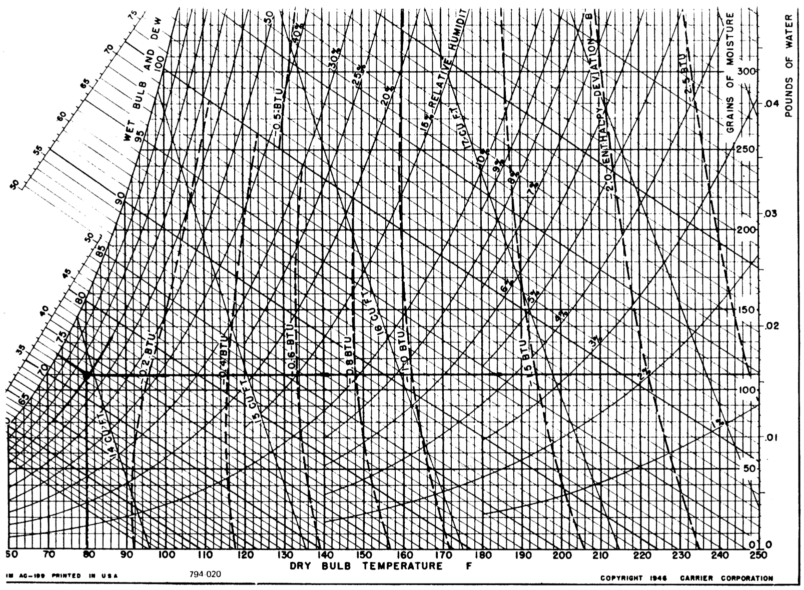
Problem 5.7A

Given t_{DB} = 80°F and t_{WB} = 73°F, from the psychrometric chart find the

a. percentage relative humidity
b. dewpoint
c. specific enthalpy
d. specific volume
e. humidity

Solution

The two given conditions completely specify the state of the air-water vapor mixture on the chart, and consequently the other conditions may be read directly from the chart.

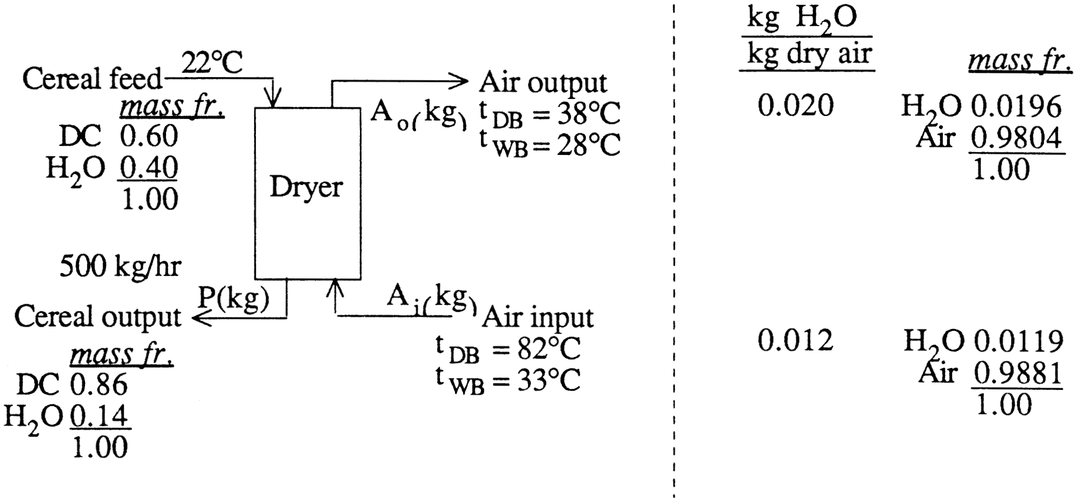


They are

a. **70% relative humidity** read from the curve sloping at 45°.
b. **70°F** (read left at constant humidity).
c. $\Delta\hat{H}$(saturated) = 36.8 Btu/lb. Subtract about 0.1 Btu/lb for less than saturated (interpolating between the dashed curves) to get **36.7 Btu/lb.**
d. Interpolating between the solid line, $\hat{V} \cong \mathbf{13.95\ ft^3 / lb}$.
e. Read the value of the humidity from the far right hand axis as about **0.0158 lb H_2O/lb air.**

Problem 5.7B

Breakfast cereal is being dried in a fluidized bed dryer in which the cereal moves roughly countercurrent to the air flow. The figure below shows the process with the data placed on the respective stream flows. Determine the required inlet moist air flowrate in m^3/hr if the cereal must have a water content of no more than 14.0 percent. (DC = dry cereal).



Solution

Steps 1, 2, 3, and 4 All the data is in the figure above. The data on concentrations comes from the SI psychometric chart. Assume p = 1 atm.

Step 5 Basis: 1 hr

Steps 6, 7, 8, and 9

Dry cereal balance

$$500\,(0.60) = P\,(0.86) \qquad P = 348.8 \text{ kg}$$

Dry air balance

$$A_i(0.9881) = A_o(0.9804)$$

Water balance

$$500\,(0.40) + A_i\,(0.019) = 348.8\,(0.14) + A_o\,(0.0196) \qquad A_i = 193 \times 10^4 \text{ kg}$$

From the psychrometric chart the specific volume is approximately 1.025 m^3/kg dry air

$$\frac{1.025\ \text{m}^3}{\text{kg dry air}} \left| \frac{1.93\times10^4\ \text{kg wet air}}{\text{hr}} \right| \frac{0.9881\ \text{kg dry air}}{1\ \text{kg wet air}} = \mathbf{1.96\times10^4\ m^3\ /\ hr\ at\ 82°C\ and\ 1\ atm}$$

DRYERS

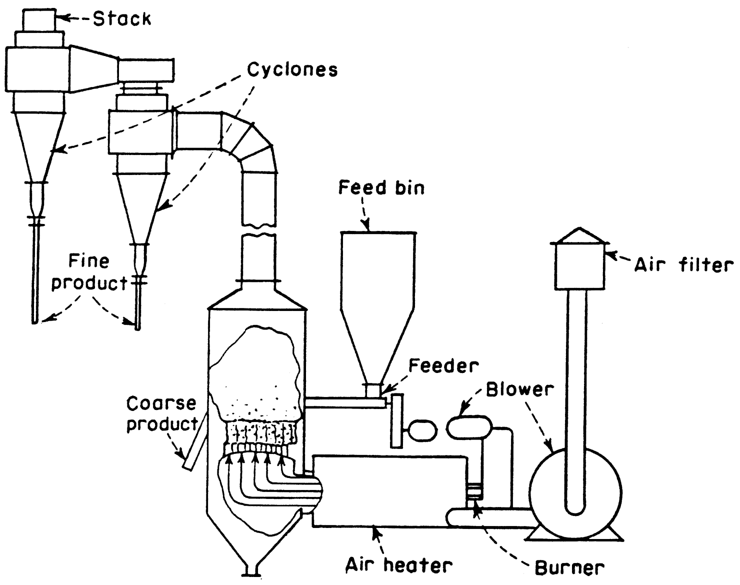


Fig. 24a. Fluidized bed dryer used for materials with high moisture content

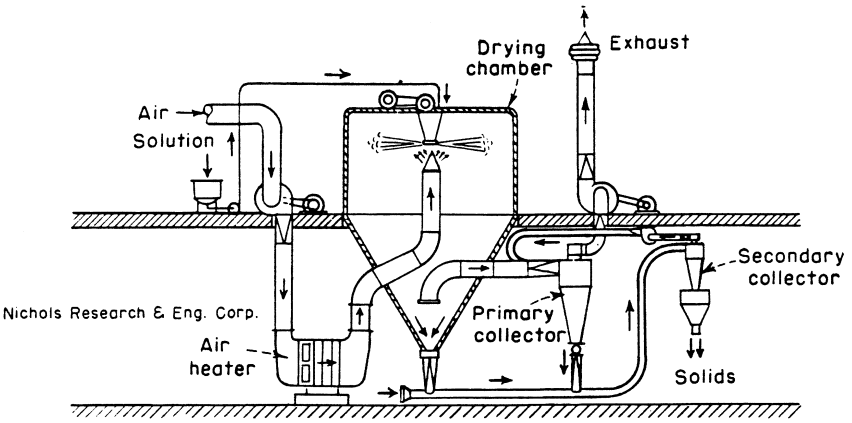


Fig. 24b. Spray dryer used for solutions

Drying is understood as a technology for removing a liquid from a solid by vaporization of the liquid. The solid product does not have to be entirely dry because any material will reach equilibrium with the water in the surrounding atmosphere. Two basic types of dryers are (1) directly heated and (2) indirectly heated. In the former the heat is applied to the wet solid by the heating medium, usually a hot gas which carries away the vaporized liquid. In freeze drying the liquid sublimates. In indirect dryers, heat is applied by conduction from the heat source through an intermediate wall. If a gas is used, its purpose is just to carry away the vapor produced in the process. Other types of dryers uses infrared heat or microwave heating.

Problem 5.7C

Air enters a drier at 200°F with a dew point of 80°F. The total pressure is 1 atm.

a. What is the humidity?
b. What is the wet bulb temperature?
c. What is the relative humidity?

The drier operates adiabatically and the air is cooled to 110°F. At 110°F

d. What is the humidity?
e. What is the dew point?

Finally the air is heated at constant humidity to 180°F. At 180°F

f. What is the adiabatic saturation temperature?
g. What is the dew point?
h. What is the relative humidity?
i. How much energy is used per lb of dry air?

Solution

Steps 1, 2, 3, and 4 Refer to the psychrometric chart.

Step 5 Basis: a fixed amount of air at 200°F, 1 atm, and a dew point of 80°F

Steps 6, 7, 8, and 9

a. Read on the right hand axis **0.022 lb H_2O/lb BDA.**

b. Read up along the adiabatic cooling line to **102°F.**

c. Read along the curved line **4.3% relative humidity.**

d. Read along the adiabatic cooling line **to 110°F and then to the right axis to get 0.044 lb H_2O/lb BDA.**

e. Read back along the constant humidity line to get **100.7°F.**

f. The adiabatic saturation temperature is the wet bulb temperature or **111°F.**

g. Dew point is **100.7°F.**

h. Relative humidity is **13%.**

i. $\Delta\hat{H}$ before = 75 – 0.15 = 74.85 Btu/lb BDA

$\Delta\hat{H}$ after = 95 – 1.35 = 93.65 Btu/lb BDA

Heat added = $\Delta\hat{H}$ = 93.65 – 74.85 = **18.8 Btu/lb BDA.**

CHAPTER 5 – ADDITIONAL PROBLEMS
(Answers will be found in Appendix A)

Section 5.1

5.1A Explain specifically what the system is for each of the following processes; also indicate which of the two modes of energy transfer, heat and work (Q and W), are involved.

(a) A liquid inside a well insulated metal can is shaken very rapidly in a vibrating shaker.
(b) Hydrogen is exploded in a calometric bomb, and the water layer outside the bomb rises in temperature by 1°C.
(c) A motor boat is driven by an outboard-motor propeller.
(d) Water flows through a pipe at 10 ft/min, and the temperature of the water and the air surrounding the pipe are the same.

5.1B Are the following variables intensive or extensive variables? Explain for each.

(a) Pressure.
(b) Volume.
(c) Specific volume.
(d) Refractive index.
(e) Surface tension.

5.1C Suppose that a constant force of 40.0 N is exerted to move an object for 6.00 m. What is the work accomplished (on an ideal system) expressed in the following:

(a) joules
(b) $(\text{ft})(\text{lb}_f)$
(c) Btu

5.1D If a pail weighting 1/2 lb is dropped into a well 50 ft deep, what is the kinetic and potential energy of the pail (a) just before it hits the water, and (b) after it hits the water surface (at 50 ft)?

5.1E A chart for carbon dioxide (see Appendix) shows that the enthalpy of saturated CO_2 liquid is zero at —40°F. Can this be true? Explain your answer.

Section 5.2

5.2A Experimental values of the heat capacity C_p have been determined in the laboratory as follows; fit a second-order polynomial in temperature (determine values for a, b, and c in the relation $C_p = 1 + bT + CT^2$):

T,°C	C_p cal/(g mol)(°C)
100	9.69
200	10.47
300	11.23
400	11.79
500	12.25
600	12.63
700	12.94

(The data are for carbon dioxide; if a computer is used in the data-fitting process, also calculate the confidence limits for the predicted value of C_p.)

5.2B Your assistant has developed the following equation, to represent the heat capacity of air (with C_p in J/(g mol) (K) and T in K):

$$C_p = 26.7 + 7.36 \times 10^{-3}T - 1.09 \times 10^{-6}T^2$$

Derive an equation giving C_p but with the temperature expressed in °C.

5.2C Given that the heat capacity C_p for mercury at —20°C is 0.140 J/g, while at 100°C the value of C_p is 0.137, compute the change of enthalpy of 10 g of mercury from —20°C to 100°C. Given that the heat capacity at constant volume, C_v, is 0.123 at —20°C and 0.116 J/g at 100°C, compute the change in internal energy for the same temperature range. Then compute ΔpV for mercury for the same temperature range. Assume C_p and C_v change linearly with T.

5.2D Calculate the enthalpy change in raising 1 g mole of CO_2 from 50° to 100°C at 1 atm. Do this problem by three different methods.

(a) Use the heat capacity equation from the Appendix;
(b) Use the CO_2 chart in the Appendix;
(c) Use the data in the Table of Enthalpies of the Combustion Gases.

5.2E Use the chart for n-butane to calculate the enthalpy change for 10 lb of butane from a volume of 2.5 ft^3 at 360F to saturated liquid at 10 psia.

5.2F The vapor pressure of n-pentane is given by the equation.

$$\ln p^* = A - \frac{B}{(C+T)}$$

where p^* = vapor pressure in mm Hg and T is in K. The values of the coefficients are

A = 15.8333
B = 2477.07
C = −39.94

Calculate the heat of vaporization of n-pentane at the normal boiling point in J/g. Compare with experimental value.

5.2G Use the steam tables to answer the following questions.

(a) What is the enthalpy change needed to change 1 lb of a water-steam mixture of 60 percent quality to one of 80 percent quality if the mixture is at 300°F?
(b) Calculate the ΔH value for an isobaric (constant pressure) change of steam from 120 psia and 500°F to saturated liquid.
(c) Do the same for an isothermal change to saturated liquid.
(d) Does an enthalpy change from saturated vapor at 450°C to 210°F and 7 psia represent an enthalpy increase or decrease? A volume increase or decrease?
(e) In what state is water at 40 psia and 267.24°F? At 70 psia and 302°F? At 70 psia and 304°F?

Section 5.3

5.3A One pound mole of an *ideal* gas whose C_p is 7 Btu/(lb mole)(°R) is confined in a reservoir with a floating top such that the pressure on the gas is 60 psig no matter what its volume is. In the morning the gas is at 50°F, but late in the afternoon its temperature rises to 90°F.

(a) Determine how much heat has been transferred into the tank, the work done by the gas, and the internal energy change for the gas from the morning to afternoon.
(b) If the system returns to its original state in the evening, again find Q, W, and the internal energy and enthalpy changes for the cooling process.
(c) What are Q, W, and the internal energy and enthalpy changes for the overall process of heating and cooling?

5.3B Write the simplified energy balance for the following processes. List and number each assumption or decision made in the simplification.

(a) A fluid flows steadily through a poorly designed coil in which it is heated from 170° to 250°F. The pressure at the coil inlet is 120 psia, and at the coil outlet is 70 psia. The coil is of uniform cross section, and the fluid enters with a velocity of 2 ft/sec.

(b) A fluid is allowed to flow through a cracked (slightly opened) valve from a region where its pressure is 200 psia and 670°F to a region where its pressure is 40 psia, the whole operation being adiabatic.

5.3C In one stage of a process for the manufacture of liquid air, air as a gas at 4 atm abs and 250K is passed through a long, insulated 3-in. ID pipe in which the pressure drops 3 psi because of frictional resistance to flow. Near the end of the line, the air is expanded through a valve to 2 atm abs. State all assumptions.

(a) Compute the temperature of the air just downstream of the valve.
(b) If the air enters the pipe at the rate of 100 lb/hr, compute the velocity just downstream of the valve.

5.3D Your company produces small power plants that generate electricity by expanding a waste process steam in a turbine. You are asked to study the turbine to determine if it is operating as efficiently as possible. One way to ensure good efficiency is to have the turbine operate adiabatically. Measurements show that for steam at 500°F and 250 psia.

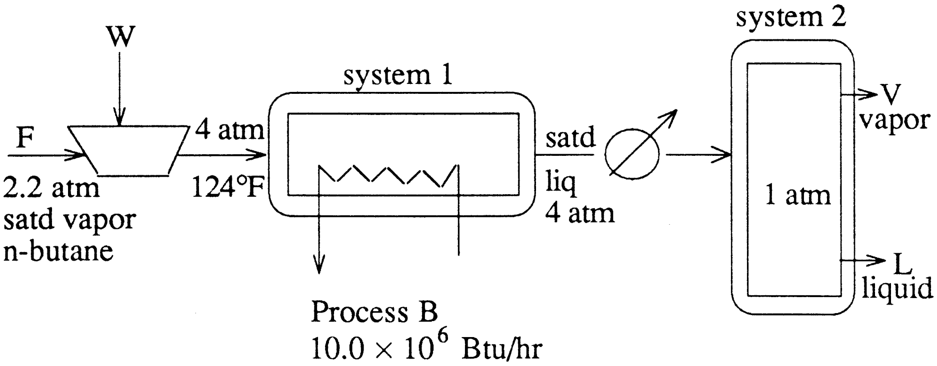
(a) The work output of the turbine is 86.5 hp.
(b) The rate of steam usage is 1000 lb/hr.
(c) The steam leaves the turbine at 14.7 psia and consists of 15 percent moisture (i.e., liquid H_2O).

Is the turbine operating adiabatically? Support your answer with calculations.

5.3E In a waste treatment plant, wet sludge containing 50 wt% moisture is fed into a rotary, countercurrent (sludge and air flow in opposite directions through the vessel) dryer at the rate of 300 lb/minute. The air enters at 220°F and has an absolute humidity of 0.007 lb H_2O/lb BDA, and leaves at 100°F and a RH of 100%. The sludge enters the dryer at 70°F and leaves at 97°F with 3 wt% moisture. Assuming adiabatic operation of the dryer so that the heat loss from dryer to the surroundings can be neglected, calculate:

(a) Pounds per hour of dry air passing through the dryer.
(b) Humidity of the air leaving the dryer in lb H_2O/lb BDA.

5.3F A saturated vapor stream of n-butane is available at 2.2 atm for a heat pump application. The vapor is compressed to 4 atm and 124°F. The heat released when it is condensed to a saturated liquid at 4 atm is used to heat process B, which requires 10.0×10^6 Btu/hr. The butane pressure is then reduced to 1 atm where the vapor and liquid streams are sent separately to another area in the plant. Calculate:
(a) The n-butane flow rate (lb/hr) required to provide heat to process B.
(b) The vapor flowrate lb/hr.
(c) The liquid flow rate lb/hr.
(d) If the n-butane flow rate and all the pressures are maintained constant, but the process B heat load drops to 7.5×10^6 Btu/hr, what are the new vapor and liquid flow rates?



Section 5.4

5.4A Calculate the heat of reaction of the following reaction at 25°C.

$$\underset{\text{methyl alcohol}}{CH_3OH(g)} + \tfrac{1}{2}O_2 \rightarrow \underset{\text{formaldehyde}}{H_2CO(g)} + H_2O(g)$$

5.4B When water is formed from $H_2(g)$ and $O_2(g)$, the reaction is exothermic. How much steam at 100°C has to be condensed per mole of $H_2(g)$ to maintain the vessel in which the reaction takes place at 25°C?

5.4C Calculate the heat of reaction for the synthesis of methanol

$$CO(g) + 2H_2(g) \rightarrow CH_3OH(g)$$

when the gases enter and leaves the reaction at 400°C and 200 atm.

5.4D In a heat treating plant, 10 tons of steel plate are being processed per hour by being heated from 80°F to 1500°F before quenching. The furnace atmosphere is required to be a reducing atmosphere to prevent excessive oxidation of the steel surface. Therefore it is necessary to burn the fuel oil (whose composition is approximately $C_{16}H_{34}$ incompletely with dry air to produce a stack gas containing a ratio of CO_2 to CO of 2 to 1. Assume that all of the hydrogen in the oil is burned to water and there is no O_2 in the stack gas and that 60% of the heat generated from the combustion is lost by radiation and stack losses. What quantities of oil (in lb) and air in standard cubic feet (32°F, 760 mm Hg) are needed per hour?

5.4E The reaction $SO_2 + \frac{1}{2}O_2 \rightarrow SO_3$ would seem to offer a simple method of making sulfur trioxide. However, both the reaction rate and equilibrium considerations are unfavorable for this reaction; the reaction is only about 70 percent complete. If the products leave the reactor at 900K and the reactants enter at 25°C, what is the heat evolved or absorbed from the system under these conditions (per mol of SO_2)?

5.4F Propane, butane, or liquefied petroleum gas (LPG) has seen practical service in passenger automobiles for 30 years or more. Because LPG is used in the vapor phase, it pollutes less than gasoline but more than natural gas. A number of cars in the Clean Air Car Race ran on LPG. The table below lists the results and those for natural gas. It must be kept in mind that these vehicles were generally equipped with platinum catalyst reactors and with exhaust-gas recycle. Therefore the gains in emission control did not come entirely from the fuels.

	Natural gas, avg 6 cars	*LPC, avg 13 cars*	*Fed. Std.*
HC (g/mile)	1.3	0.49	0.22
CO (g/mile)	3.7	4.55	2.3
NO_x (g/mile)	0.55	1.26	0.6

Suppose that in a test butane gas at 100°F is burned completely with the stoichiometric amount of air which is at 400°F and a dew point of 77°F in an engine. To cool the engine, 12.5 lb of steam at 100 psia and 95 percent quality were generated from water at 77°F per pound of butane burned. It may be assumed that 7 percent of the gross heating value of the butane is lost as radiation from the engine. Will the exhaust gases leaving the engine exceed the temperature limit of the catalyst of 1500°F?

5.4G A power plant burns natural gas (90 percent CH_4, 10 percent C_2H_6) at 25°C and 100kPa with 70 percent excess air at the same conditions. Calculate the theoretical maximum temperature (in K) in the boiler if all the products are in the gaseous state.

5.4H If CO at constant pressure is burned with excess air and the theoretical flame temperature is 981°C, what was the percentage of excess air used ? The reactants enter at 93°C.

Section 5.5

5.5A Water is being pumped from a pond through a long fire hose. A 50-hp motor drives the pump, and the overall efficiency of the motor pump is 75 percent i.e. 75 percent of the energy supplied by the motor is transferred to the water. The nozzle of the hose is 25 ft above and 250 ft from the pond; 100 gpm are being pumped, and the water velocity at the nozzle exit is 50 ft/sec. Estimate the temperature change in the water between the pond and the nozzle exit.

5.5B A system consists of 5 kg of water vapor at the dew point. The system is compressed isothermally at 400K, and 400kJ of work are done on the system by the surroundings. What volume of liquid was present in the system before and after compression?

5.5C Solid carbon dioxide (dry ice) has innumerable uses in industry and in research. Because it is easy to manufacture, the competition is severe, and it is necessary to make dry ice very cheaply to be successful in selling it. In a proposed plant to make dry ice, the gaseous CO_2 is compressed isothermally and essentially reversibly from 6 psia and 40°F to a specific volume of 0.05 ft^3/lb_m.

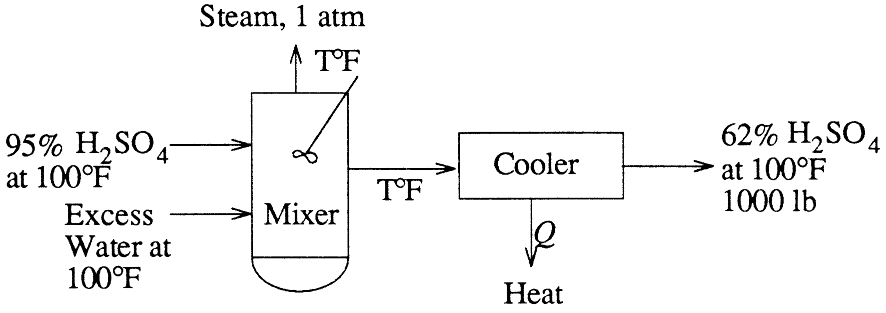
(a) What is the final state of the compressed CO_2?
(b) Compute the work of compression.
(c) What is the heat removed ?
(d) If the actual efficiency of the compressor (relative to a reversible compressor) is 85 percent and the electricity to run the compressor motor costs $0.02/kWh, what is the cost of compression of the solid CO_2 in dollars per pound of dry ice?

Section 5.6

5.6A A 10 percent (by weight) sulfuric acid solution at 70°F is placed in an open kettle evaporator and evaporated at atmospheric pressure to a 60 percent solution. If the steam leaving the kettle contains no sulfuric acid and is considered as leaving at the average temperature of the boiling range (arithmetic mean temperature)

(a) What are the initial and final boiling temperatures?
(b) How much heat must be supplied per pound of 60 percent acid produced?

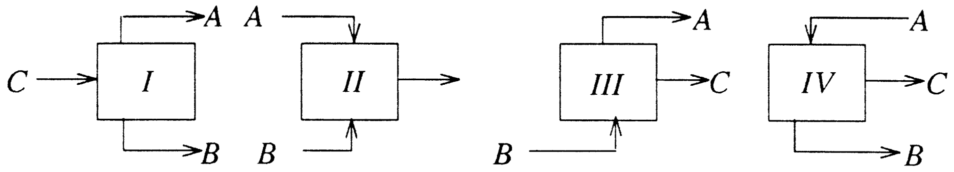
5.6B A dilute sulfuric acid (62 percent by weight) is to be made by diluting concentrated acid (95 percent) with water; however, due to the highly exothermic nature of the mixing, some provision is necessary to hold down the temperature of the fluid during mixing. The scheme shown in Fig. P5.6B is to be used. The concentrated acid is mixed with an excess of water and the mixture boils, driving off steam (no H_2SO_4 evaporates). Hot acid of the desired concentration leaves the mixer (both the steam and hot acid leave at the same temperature) and is finally cooled to 100°F. Determine the following:



(a) The amount of concentrated acid required per 1000 Ib of dilute acid produced.
(b) The amount of steam that leaves.
(c) The amount of water added to mixer.
(d) The temperature of the contents of the mixer.
(e) The amount of heat removed from the acid by the cooler.

5.6C In each of the four cases diagrammed in the figure below, the following data apply:

stream	*wt % EtOH*	*condition*	*amount*
A	80	Unknown	Unknown
B	10	70°F	Unknown
C	60	Superheated vapor at 800 Btu/lb	100 lb



Making the necessary material and energy balances for each diagram, and find the mass flows, compositions, and specific enthalpies of each stream.

Section 5.7

5.7A Moist air at 1 atm, a dry-bulb temperature of 195°F, and a wet-bulb temperature of 115°F is enclosed in a rigid container. The container and its contents are cooled to 110°F.

(a) What is the molar humidity of the cooled moist air?
(b) What is the final total pressure in atm in the container?
(c) What is the dew point in °F of the cooled moist air?
(d) What is the final wet-bulb temperature in °F?

5.7B A humidifier is conditioning air to 120°F dry-bulb and 90°F wet-bulb by heating outside air and then passing it through a spray chamber in which it reaches 90 percent humidity, and then reheating it to the desired temperature. The outside air is foggy at 40°F, carrying as liquid water 0.0004 lb water/ft^3 wet air. What temperature (of the air) must be reached in each heating operation, and how many Btu are required in each heating stage per 100 lb of dry air entering from the outside ?

5.7C In one of the hotter regions of the country a home owner decides to keep her home at an average temperature of 80°F and 40 percent humidity. On a typical day the outside conditions are as follows: dry-bulb temperature = 95°F and wet-bulb = 85°F. The city water supply is at 70°F and scarce. She therefore decides to use an electric refrigeration unit to cool the air entering the ventilating ducts. Summary of conditions:

Size of home: 50,000 ft^3.
Recirculation rate: one complete change every 3 min.
Average outlet temperature of the air: 82°F.
The increase in humidity in the house may be considered as zero.
Makeup air may be considered at 15 percent of the inlet air.

Give a complete flow sheet of the process and determine the amount of refrigeration and reheating necessary to maintain the above conditions.