Chapter 9 Energy Balances

Problem 9.1

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. $$\frac{100 \text{ hp}}{} \left| \frac{0.7068 \text{ Btu/s}}{1 \text{ hp}} \right| \frac{3600 \text{ s}}{1 \text{ hr}} = \mathbf{2.544 \times 10^5 \text{ Btu/hr}}$$

b. $$\frac{100 \text{ hp}}{} \left| \frac{745.7 \text{ J/s}}{1 \text{ hp}} \right. = \mathbf{7.457 \times 10^4 \text{ J/s}}$$

c. $$\frac{100 \text{ hp}}{} \left| \frac{0.7457 \text{ kW}}{1 \text{ hp}} \right. = \mathbf{745.7 \text{ kW}}$$

Problem 9.2

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

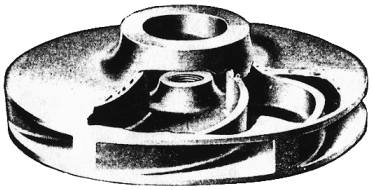


Fig 18a Cutaway view of two-vane impeller with open eye (courtesy of Nagle Pumps)

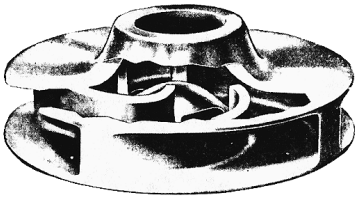


Fig 18b Semi-open impeller for handling fluids containing pulpy solids (courtesy of Nagle Pumps)

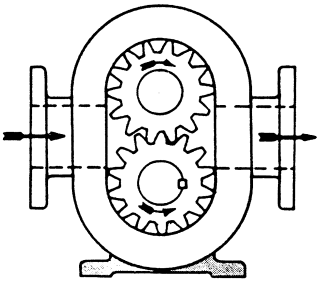


Fig. 18d Gear pump (courtesy of the Hydraulic Institute)

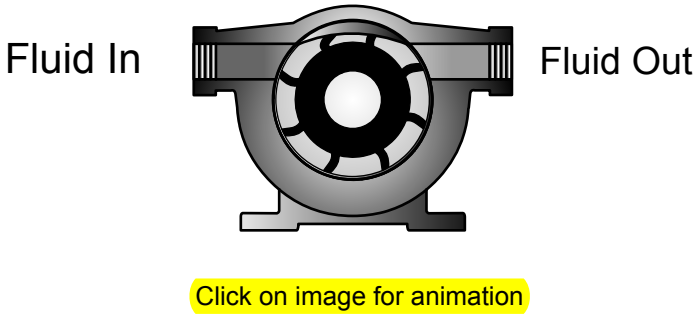


Fig. 18e Flexible impeller pump

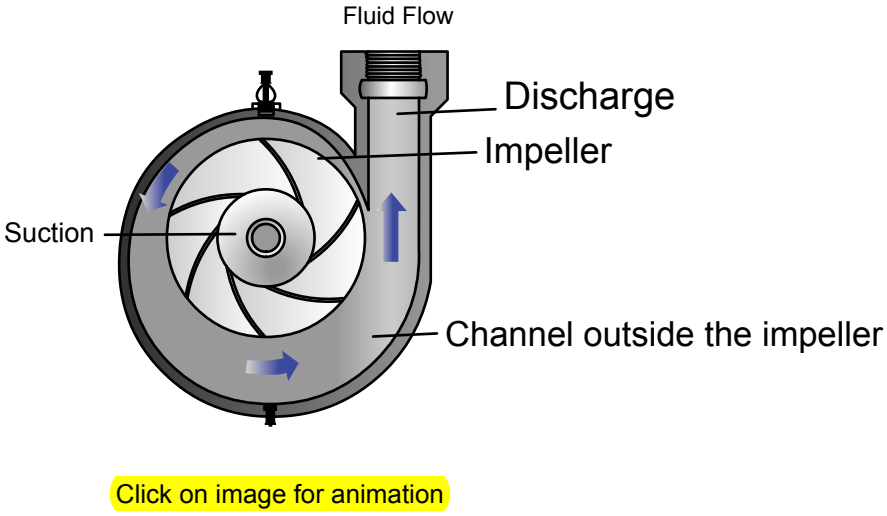


Fig 18c Volute pump

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 9.3

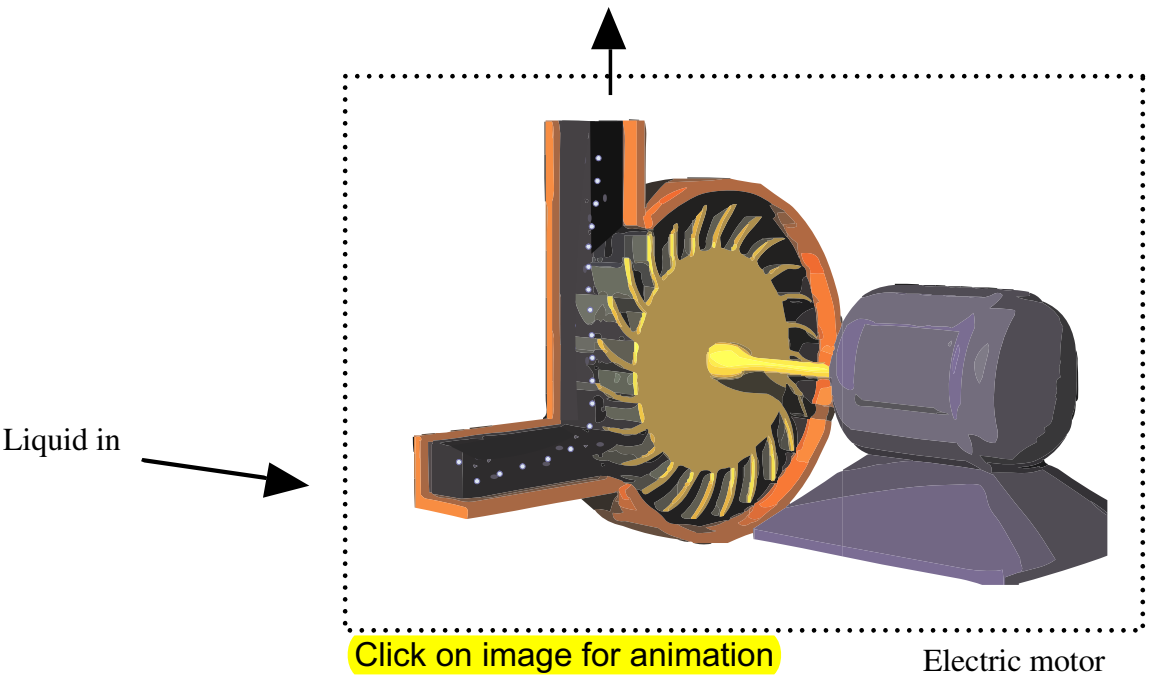
Make a rough sketch of each of the following processes. Show the system boundary, and classify the system as open or closed.

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)

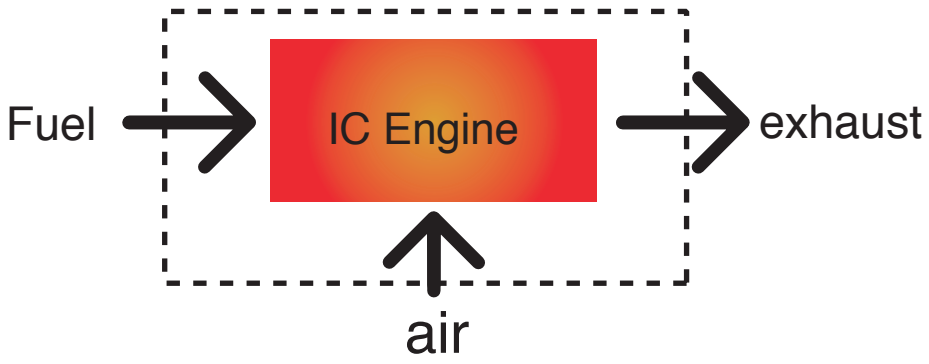
c. Windmill



Open System: wind moves in and out of the system

Click on image for animation

d.



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

Problem 9.4

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

$$PE = mgh = \frac{1\,kg}{}\left|\frac{9.80\ m}{s^2}\right|\left|\frac{100\ m}{}\right|\frac{1\ J}{\frac{1(kg)(m^2)}{s^2}} = \mathbf{980J}$$

Problem 9.5

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

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

$$\frac{p_2 V_2}{p_1 V_1} = \frac{n_1 R T_1}{n_2 R T_2} \text{ so that } \frac{\hat{V}_2}{\hat{V}_1} = \frac{p_1}{p_2} = \frac{100}{1000} = 0.10$$

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

(the positive sign designates work done on the system)

Problem 9.6

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.

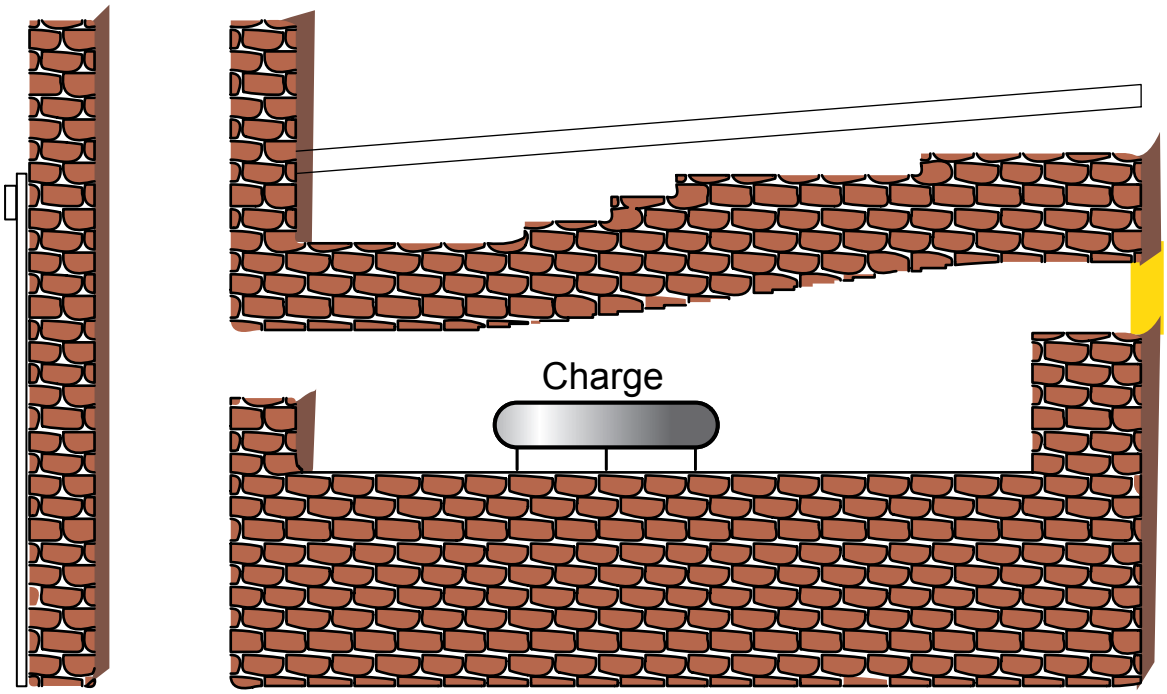
Solution

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.

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

ANNEALING OVENS



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Fig 19 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 9.7

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 9.8

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

$K_2 = 0$

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

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

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

Problem 9.9

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 9.10

Ethyl ether has a normal melting point at 116.3°C. If it is frozen from a liquid at 116.3°C in a container of fixed volume, to what equation could the general energy balance be reduced:

Solution

The general energy balance for a *closed* system is

$$\Delta U + \Delta P + \Delta K = Q + W$$

$\Delta P = \Delta K = W = 0$ so that $\Delta U = Q$.

Problem 9.11

Water flows through a horizontal hose nozzle from a pressure of 40 psig to 15 psig. Neglect the initial velocity of the water and any heat transfer. What would be the simplest energy balance to use in calculating the exit velocity of the water?

Solution

The general energy balance for an open system is

$$\Delta E = Q + W - \Delta(H + K + P)$$

If we assume steady state flow, $\Delta E = 0$. $Q = 0$ by specification. Assumes $\Delta P = 0$. $W = O$ because no mechanical or electrical work is done. Consequently,

$$-\Delta H = \Delta K = \frac{1}{2} m V_{final}^2$$

Problem 9.12

Water boils from an open pot. In the steady state, what terms in the general energy balance would be retained:

Solution

The general energy balance for an open system is

$$\Delta E = Q + W - \Delta(H + K + P)$$

Because of the steady state assumption, $\Delta E = 0$. No mechanical or electrical work is done, hence $W = 0$. By assumption, $\Delta K = \Delta P = 0$. Thus, the balance reduces to

$$Q = \Delta H$$

Problem 9.13

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 $T_{°F}$, substitute $T_{°F} = T_{°R} - 460$ in the equation for C_p.

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

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

$$C_p = 9.89 + 0.8273 \times 10^{-2}\,(°R - 460) - 0.3783 \times 10^{-5}\,(°R - 920°R + 2.116 \times 10^{5})$$
$$= (9.89 - 0.8273 \times 10^{-2}\,(460) - 0.3783 \times 10^{-5}\,(2.116 \times 10^{5})) + (0.8273 \times 10^{-2} + 0.3783 \times 10^{-5} \times (920))°R - 0.3783 \times 10^{-5}°R^2$$

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

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

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

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

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

$$T_{°F} = 1.8\ T_K - 460$$

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

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

Problem 9.14

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.

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

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 9.15

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

b. By use of the tables of enthalpies we find

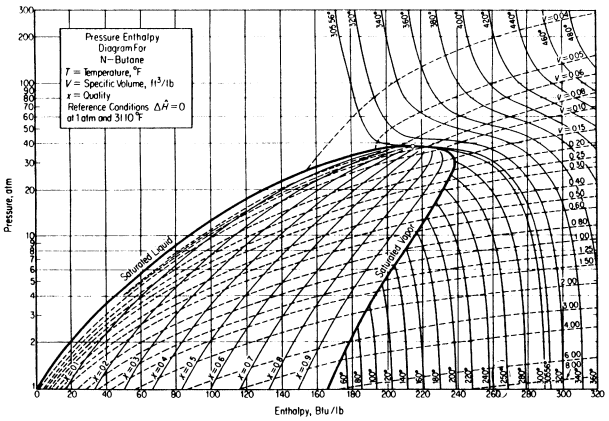
T°(C)	$\Delta\hat{H}$(J/(g mol)	
1100	55,310	
400	17,340	
	37,970	× 2 = **75,940 J**

Problem 9.16

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.

Click image for animation

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 9.17

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

$\Delta\hat{H}_{liquid}$ = 762.5 kJ/kg $\quad\quad$ $\Delta\hat{H}_{vapor}$ = 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. $\frac{0.50}{5} = (1 - x)\,(0.001127) + x\,(0.1944)$ $\quad\quad$ **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 9.18

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

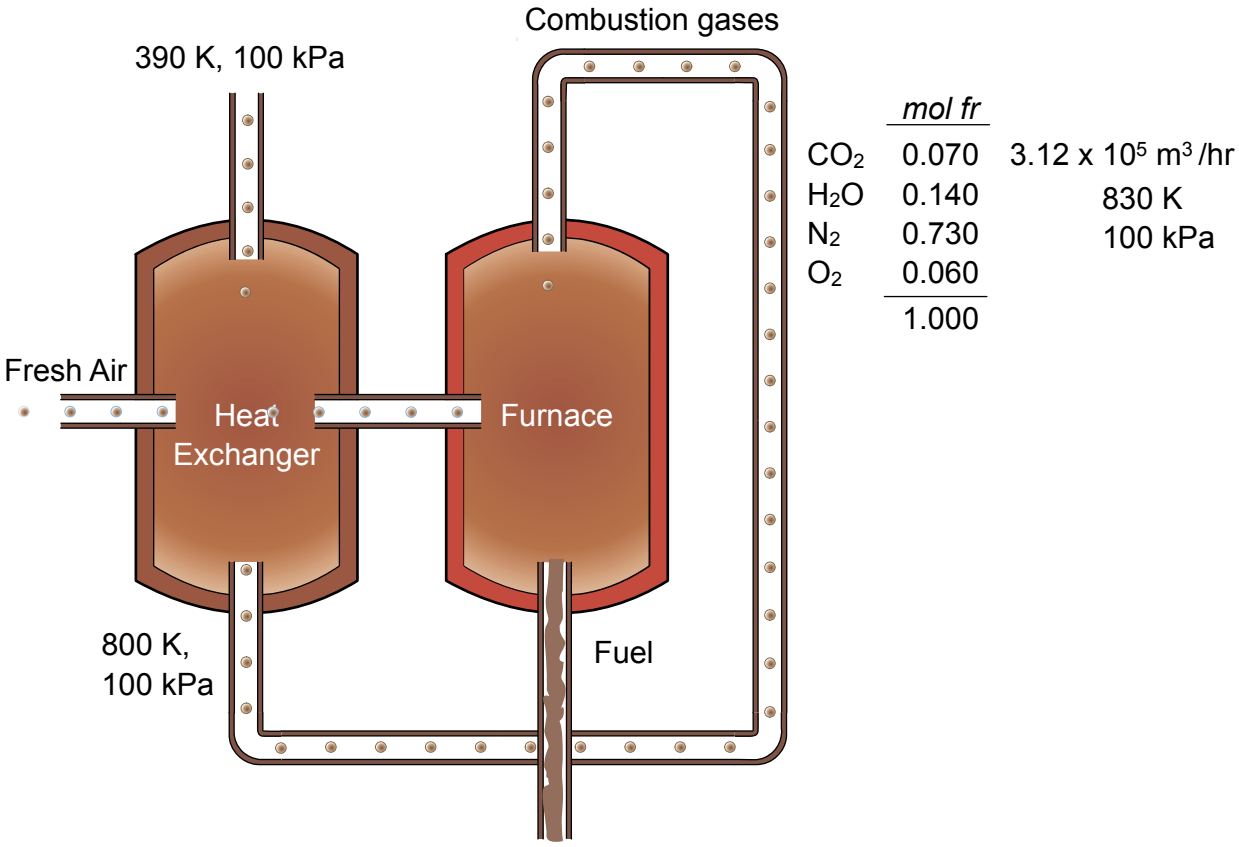
If we let x be the quality (vapor fraction) of the steam

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

x = 0.56

Problem 9.19

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.



Click on image for animation

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

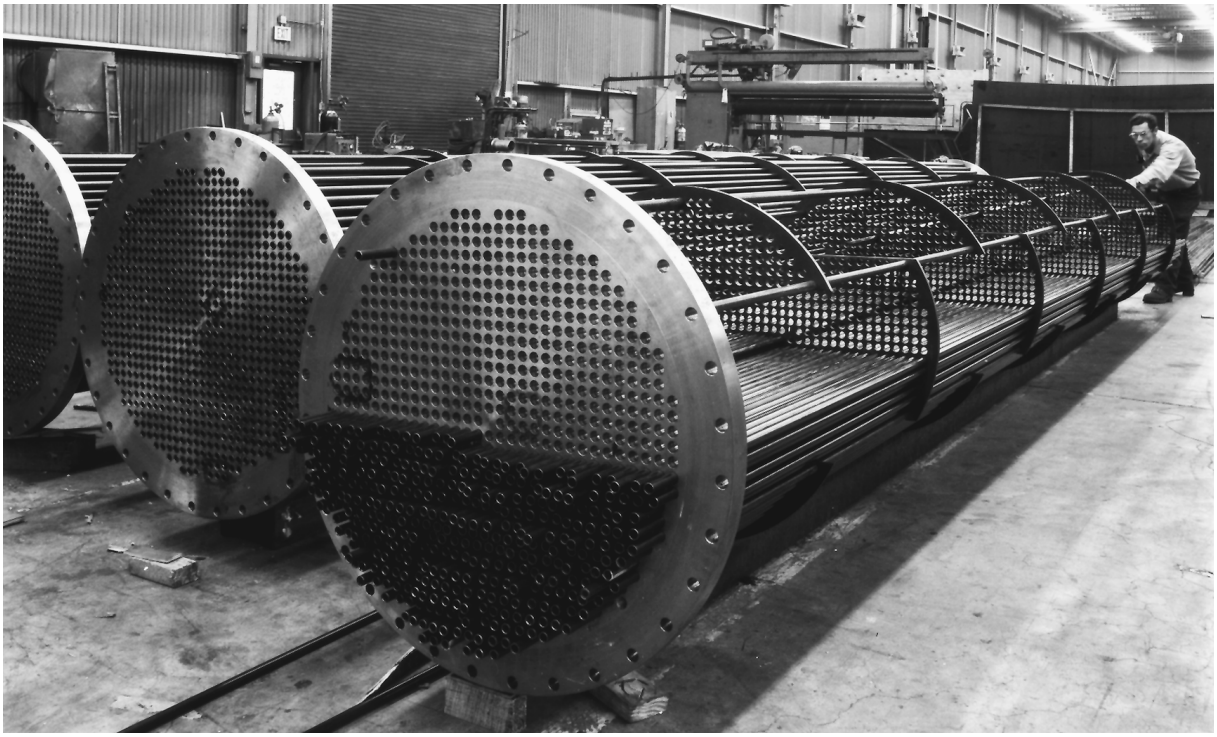


Fig 20a Shell and tube heat exchanger under construction (courtesy of Guston County Dyeing Machine Co.)

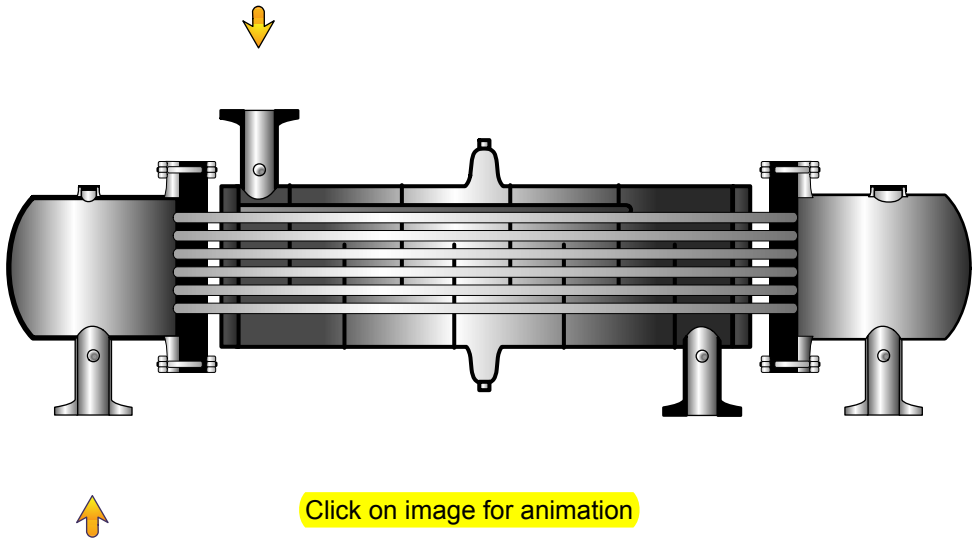


Fig 20b Line drawing of a standard type of shell and tube heat exchanger (courtesy of Patterson-Kelley Co.)

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.

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

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.

		$\Delta\hat{H}(\text{kJ / kgmol})$		
	$n(\text{kg mol} \times 10^{-3})$	at 390K	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 9.20

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

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

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

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 $\Delta\hat{H}_v$

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

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

Problem 9.21

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.

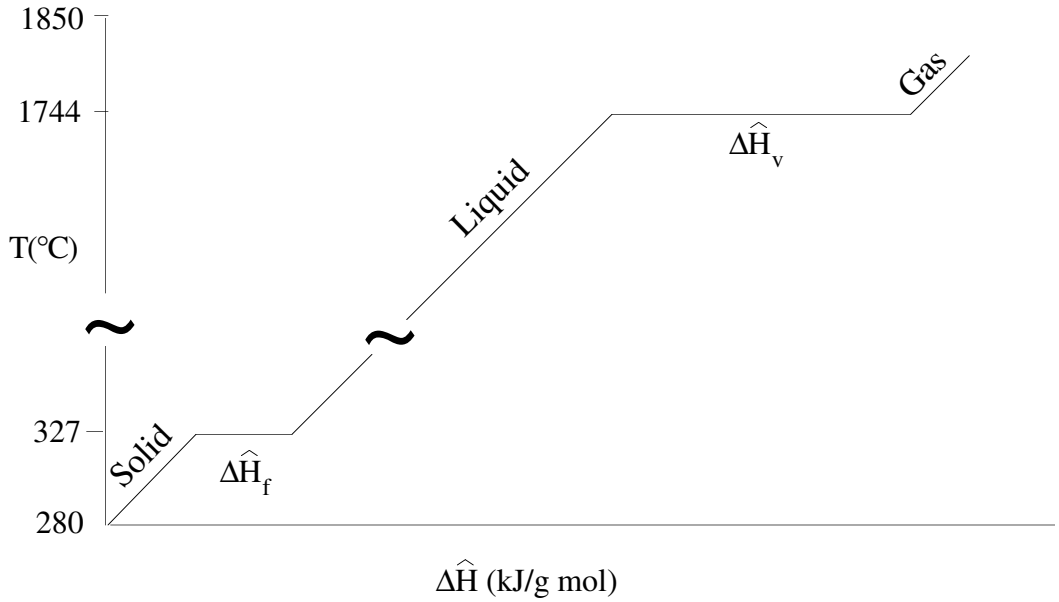
Data:

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.



$$\Delta\hat{H} = \int_{1850}^{1744} 20.8 \; dT - 175.98 \times 10^3 + \int_{1744}^{327.4} 6.8 \; dT - 5.121 \times 10^3$$

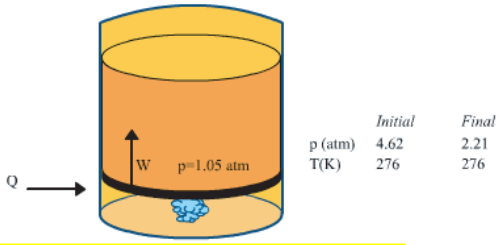
$$+ \int_{327.4+273.15}^{280+273.15} (24.1 + 0.049T) \; dT = \textbf{–195,400 kJ/gmol}$$

Problem 9.22

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.



Click on image to open animation

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.

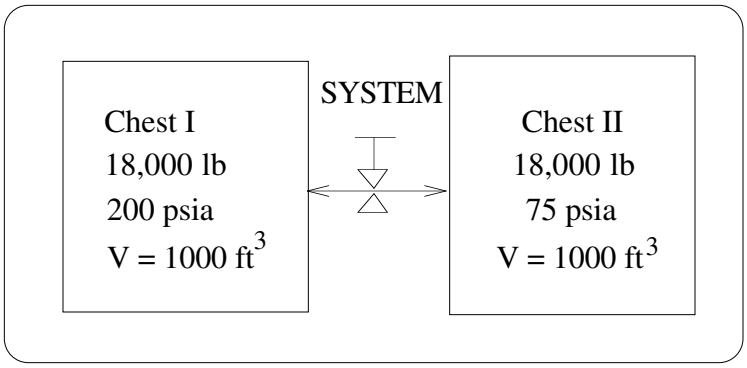
Problem 9.23

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)	$V_{Liq.}$ (ft³/lb)	V_{Gas} (ft³/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

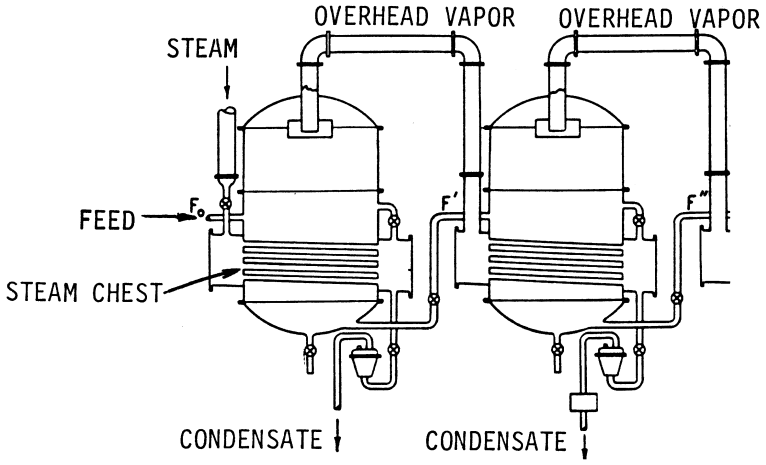


Fig 20 Steam chest in an evaporator

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)
$\Delta\left[\left(\hat{H} + \hat{P} + \hat{K}\right)m\right]$	(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, $\Delta\hat{U}$ 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 $\dfrac{1000\ ft^3}{18{,}000\ lb} = 0.0556\ ft^3/lb$

Step 5 Basis: 1 lb steam

Step 4

The system is steam chest I. The initial fraction vapor comes from a volume balance. Let x_i = fraction vapor in steam chest I

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

$$\Delta\hat{U}_I = \{[0.9836\ (355.4) + 0.0164\ (1198.7)] - [0]\} - \Delta(\hat{pV})$$

(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.)

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

$$(\hat{pV})_{32°F}{}^{32°F} = \frac{0.0886\ lb_f}{in^2}\left|\frac{144\ in^2}{1\ ft^2}\right|\frac{0.01602\ ft^3}{1\ lb_m}\left|\frac{1\ Btu}{778.16\ (ft)(lb_f)}\right. = 0.00026\ Btu$$

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

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, $\Delta U_{final} = 367.2\ (18{,}000) + 282.6\ (18{,}000) = 1.170 \times 10^7$ 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.**

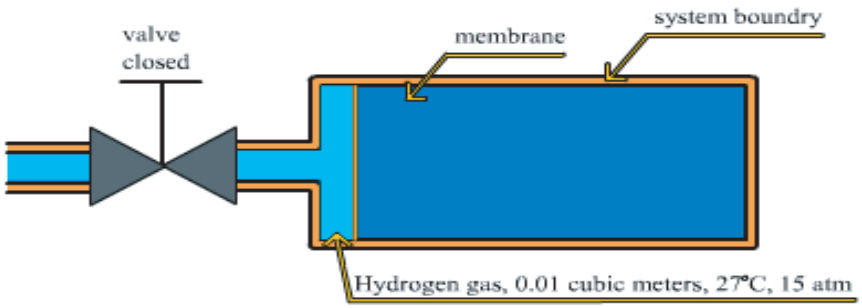
Problem 9.24

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.

Click on image to open animation



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

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

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 $\qquad T_c = 33.3K$

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

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

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.

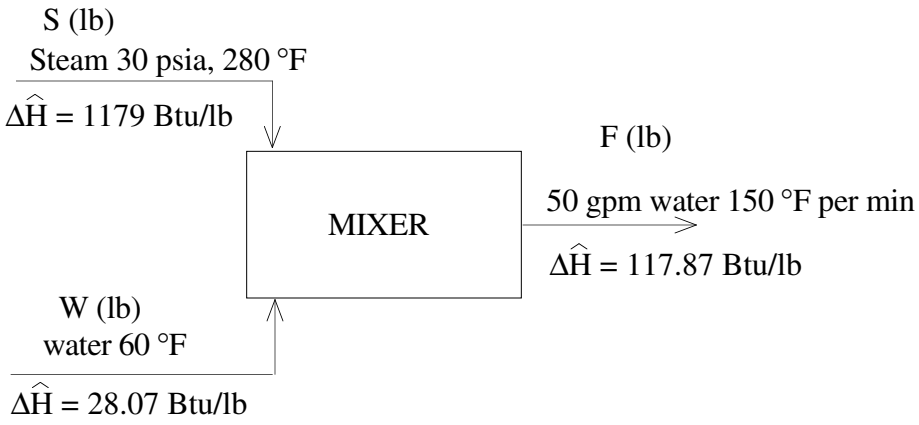
$$p_2 = p_1\left(\frac{V_1}{V_2}\right) = 15\left(\frac{0.01}{0.31}\right) = \mathbf{0.48\ atm}$$

Problem 9.25

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



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

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 ΔK = ΔP = 0, and there is no accumulation in the system so that ΔE = 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

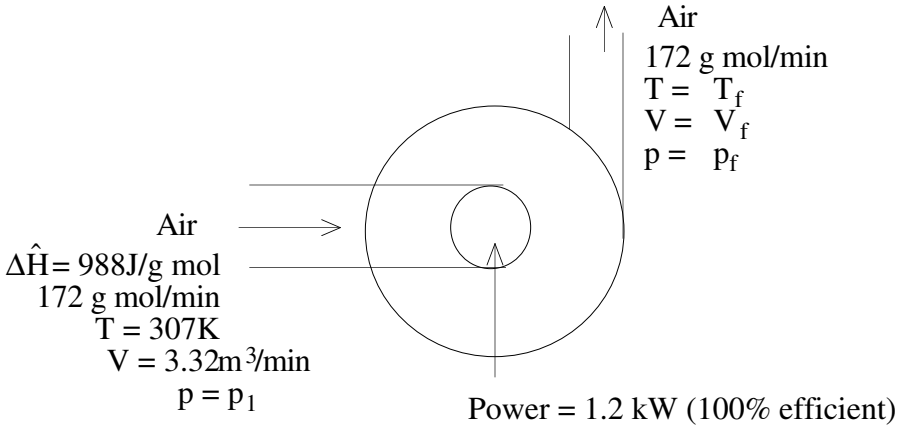
W = 377 lb/min; S = 32 lb/min

Problem 9.26

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) .

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

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

$\Delta\hat{H}_f$ = 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

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

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

Chapter 10 Energy Balances: How to Account for Chemical Reaction

Problem 10.1

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

Basis: 4 g mol HCl(g)

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

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

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

Problem 10.2

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	$\Delta\hat{H}_f^\circ(kJ/g\ mol)$
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 10.3

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

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

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

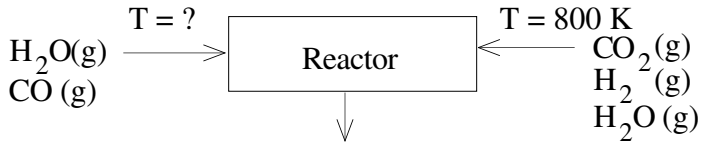
$$\Delta \hat{\mathbf{H}}^\circ_{\mathbf{f}} = \mathbf{-1276\ kJ/g\ mol\ A1(OH)_3(s)}$$

Problem 10.4

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

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

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

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

Compounds Out	g mol	$\Delta\hat{H}_f^\circ$	ΔH_{298K}^{800K}	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

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

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

Let T = 500K. Then $\Delta \hat{H}^T_{CO} = 6{,}652$J/g mol and $\Delta \hat{H}^T_{H_2O} = 7{,}752$J/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 $\Delta \hat{H}^T_{H_2O} = 3{,}696$ J/g mol and $\Delta \hat{H}^T_{H_2O} = 4{,}284$ 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

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

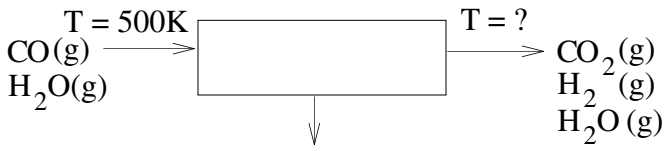
You could use the heat capacity equations to get the enthalpy changes for the gases, $\Delta \hat{H}^T_{i,\ 298}$, i.e., use the sensible heats, but the calculations would take longer than using the tables. However, you would get an equation (fourth order) containing only one variable, the desired temperature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

Problem 10.5

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

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

$\Delta\hat{H}_f^\circ$(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 $\Delta H = n \sum_{\text{products}} n_i \left(\Delta\hat{H}_{f,i}^\circ + \Delta\hat{H}_{298,i}^T\right) - \sum_{\text{reactants}} n_i \left(\Delta\hat{H}_{f,i}^\circ + \Delta\hat{H}_{298,\,i}^{500}\right)$. Let T = 298K be the reference temperature.

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

In

Compound	g mol	$\Delta\hat{H}_f^\circ$ (kJ/g mol)	$\Delta\hat{H}_{298}^{500}$ (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

Out

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

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

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

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

Let T = 1000K. Then

(1)	$\Delta\hat{H}_{CO_2}^T$	=	34.308
(1)	$\Delta\hat{H}_{H_2}^T$	=	21.388
(1)	$\Delta\hat{H}_{H_2O}^T$	=	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:

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

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

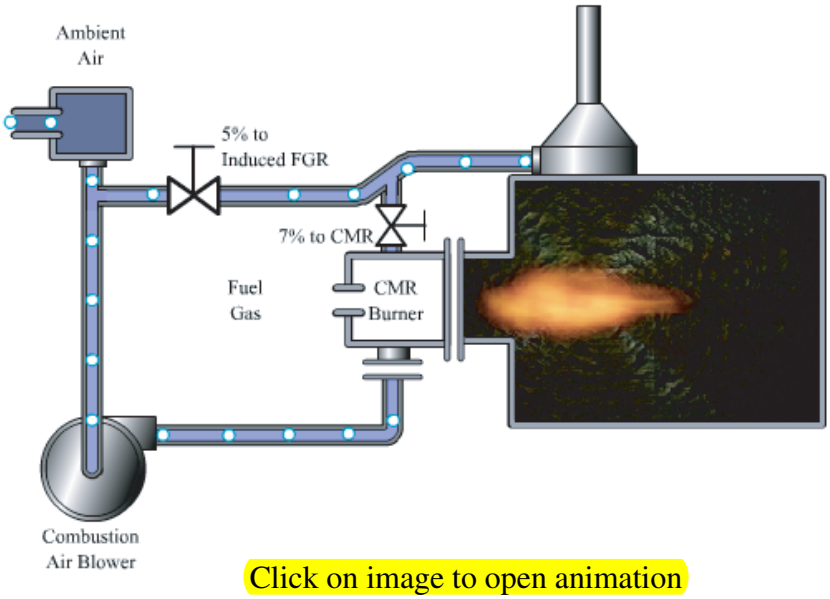
$$(1)\,\Delta\hat{H}_{CO_2}^T + (1)\,\Delta\hat{H}_{H_2}^T + (1)\,\Delta\hat{H}_{H_2O}^T = 39.802 + 24.426 + 31.011 = 95.239$$

and the energy balance sums to –1.53kJ.

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

An alternate way to solve the energy balance would be to substitute the heat capacity equations for the compounds into the energy balance, and solve the resulting polynomial equation using Polymath.

FURNACE



Click on image to open animation

Fig 22 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.

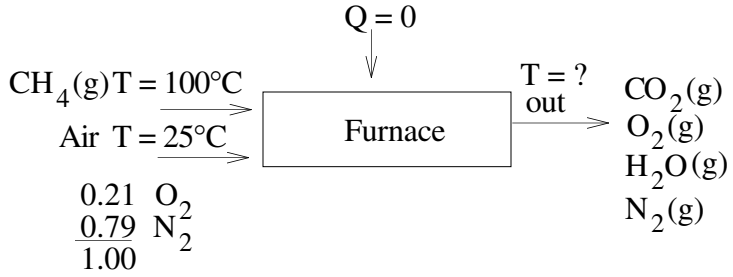
Problem 10.6

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

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

	$CH_4(g)$	$2O_2(g)$	$CO_2(g)$	$2H_2O(g)$
$\Delta\hat{H}_f^\circ$(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

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

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

Chapter 11 Humidity (Psychrometric) Charts and Their Use

Problem 11.1

A gas mixture contains 0.0083 g mol of water vapor per g mol of dry CH_4 at a temperature of 27˚C and a total pressure of 200 kPa. Calculate the:

a. percent relative saturation of the mixture.
b. percent saturation of the mixture
c. temperature to which the mixture must be heated at 200 kPa in order that the relative saturation will be 0.20.

Solution

Basis: 1 lb mol CH_4

$p^*_{H_2O}$ (27˚C) = 3.536 kPa $\quad p_{total}$ = 200 kPa $\quad p_{H_2O} = p_{total}\ y_{H_2O}$

a. Percent relative saturation = $\dfrac{p_{H_2O}}{p^*_{H_2O}}$ (100)

$$y_{H_2O} = \frac{0.0083}{1 + 0.0083} = 0.0082$$

$$p_{H_2O} = (200 \text{ kPa})\,(0.0082) = 1.64 \text{ kPa}$$

$$\frac{1.64}{3.536}(100) = \mathbf{46.4\%}$$

b. Percent saturation = (rel. saturation) $\left(\dfrac{p_T - p^*_i}{p_T - p_i}\right) 100$

$$= (0.464)\left(\frac{200 - 3.54}{200 - 1.64}\right) 100 = \mathbf{46.0\%}$$

Note that the percent saturation is always less than the percent relative saturation.

c. In the heating at constant pressure, the mole fraction of the water vapor does not change so p_{H_2O} = 1.64 kPa.

$$\frac{p_{H_2O}}{p^*_{H_2O}} = 0.20 \quad \text{or} \quad \frac{1.64}{p^*_{H_2O}} = 0.20$$

The vapor pressure has to be calculated to get the temperature.

$p^*_{H_2O} = \dfrac{1.64}{0.20}$ = 8.2 kPa and from stream table **T = 315K (42°C)**

Problem 11.2

A gas at 200˚F and 30 in Hg abs. has a molal humidity of 0.10. Calculate:

a. the percentage humidity
b. the relative humidity
c. the dew point of the gas (˚F)

Solution

$p^*_{H_2O}$(at 200˚F) = 11.525 psia

p_T = 30 in Hg = 1.003 atm = 14.74 psia

$$\text{molal humidity} = \frac{n_{vapor}}{n_{vapor\ free\ gas}} = \frac{p_{vapor}}{p_{vapor\ gas}}$$

$$\left.\begin{aligned} &\frac{p_{H_2O}}{p_{gas}} = 0.10 \\ &p_T = p_{H_2O} + p_{gas} \end{aligned}\right\} \quad \begin{aligned} &p_{H_2O} = 1.34 \text{ psia} \\ &p_{gas} = 13.4 \text{ psia} \end{aligned}$$

a. Percentage humidity $= \dfrac{p_{H_2O}}{p^*_{H_2O}} \left(\dfrac{p_T - p^*_{H_2O}}{p_T - p_{H_2O}} \right) 100 =$ **2.79%**

b. Relative humidity $\dfrac{p_{H_2O}}{p^*_{H_2O}} (100) =$ **11.6%**

c. The dew point of the gas can be determined from the steam tables. It is the temperature of which the partial pressure is equal to the vapor pressure of vapor (cooling at constant total pressure)

$$p_{H_2O} = 1.34 \text{ psia} = p^*$$

The corresponding T is **T = 112˚F**

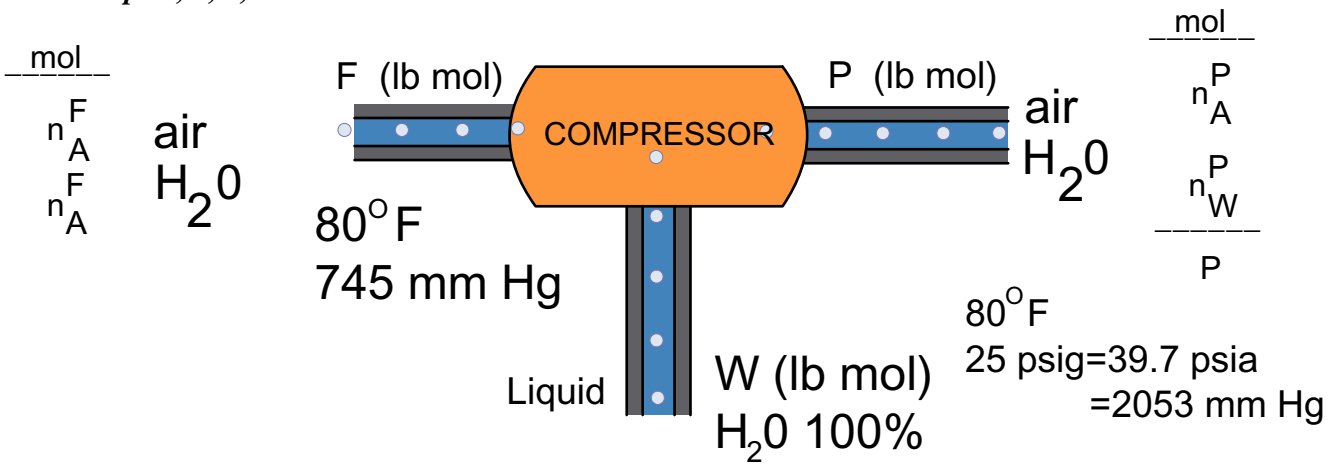
Problem 11.3

Air saturated with water vapor at 80°F and 745.0 mm Hg abs. is passed through an air compressor and then stored in a tank at 25.0 psig and 80ûF. What percentage of the water originally in the air was removed during the processing?

Solution

This problem can be treated as a steady state problem without reaction, or as an unsteady state problem. We will carry out the solution as a steady state problem. Recall that the water vapor condenses on compression so that the compressed gas is still saturated.

Steps 1, 2, 3, and 4



Step 5 Several basis can be considered: F = 100 lb mol, P = 100 lb mol, W = 100 lb mol, F = 745 lb mol, and so on, but we will take a tie component as a convenient basis

Basis: F = 1.00 lb mol

Step 4 Calculate the gas compositions.

F	P
p_W^* at 80ûF is 0.5067 psia (26.2 mm Hg abs.)	p_W^* = 26.2 mm Hg
p_A in F = 745 - 26.2 = 718.8 mm Hg	p_A in P = 2053 Ð 26.2 = 2027 mm Hg
$\frac{n_A^F}{n_T^F} = \frac{p_A^F}{p_T^F} = \frac{718.8}{745}$	$\frac{n_A^P}{n_T^P} = \frac{p_A^P}{p_T^P} = \frac{2027}{2053}$

Steps 6, 7, 8 and 9

We can make two component balances and one total balance (F = P + W) of which two are independent. Two unknowns exist: W and P.

Total balance (lb mol)

$$1.00 = P + W$$

Air balance (lb mol)

$$1.00\left(\frac{718.8}{745}\right) = P\left(\frac{2027}{2053}\right) \text{ so that } P = 0.977 \text{ lb mol}$$

$$W = 1.00 - 0.977 = 0.023 \text{ lb mol}$$

100 (0.023/0.0364) = 63%

GAS COMPRESSORS (TURBO COMPRESSORS)

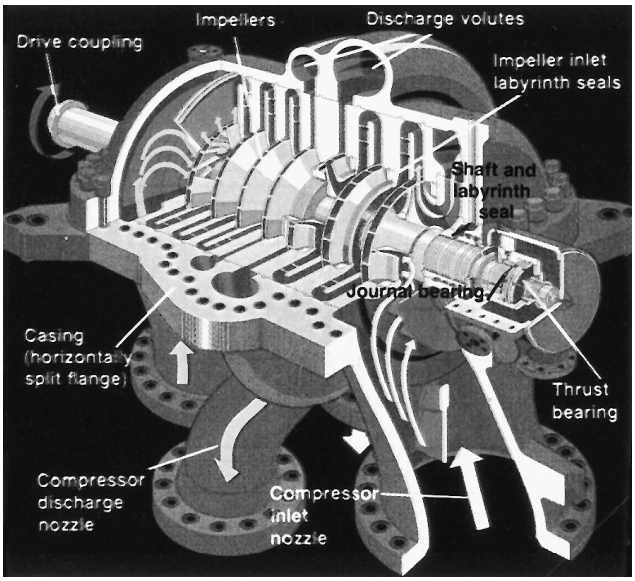


Fig. 23a Centrifugal compressor, quarter section open

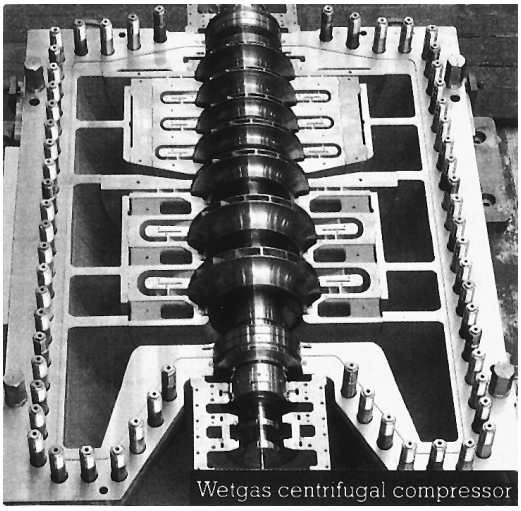


Fig. 23b One half section of a wet gas centrifugal compressor (courtesy of Sultzer Turbosystems)

Compressors take in gas at one pressure and release it at a higher pressure. Some axial flow compressors have adjustable guide vanes such as occur in units for natural gas liquification. A minimum flow exists below which the compressor operation becomes unstable (surges) and back flow can occur as well as mechanical damage. A different type of compressor found in common use is the reciprocating compressor which uses pistons to compress gases to higher pressures than can be achieved with axial flow units, but can only handle smaller volumes of gas. Both types of compressors can be used in stages to achieve higher pressures than provided by a single unit. The approximate range of functioning of compressors is in Fig. 18c.

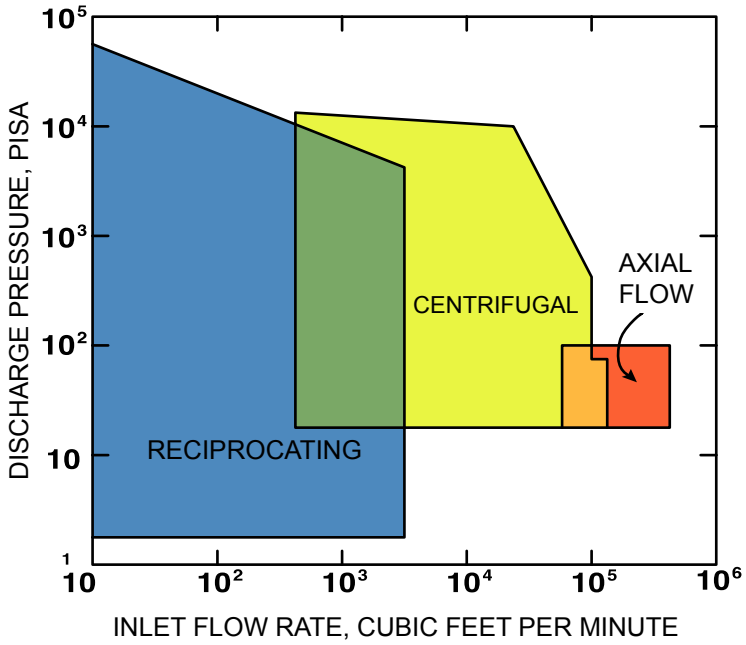


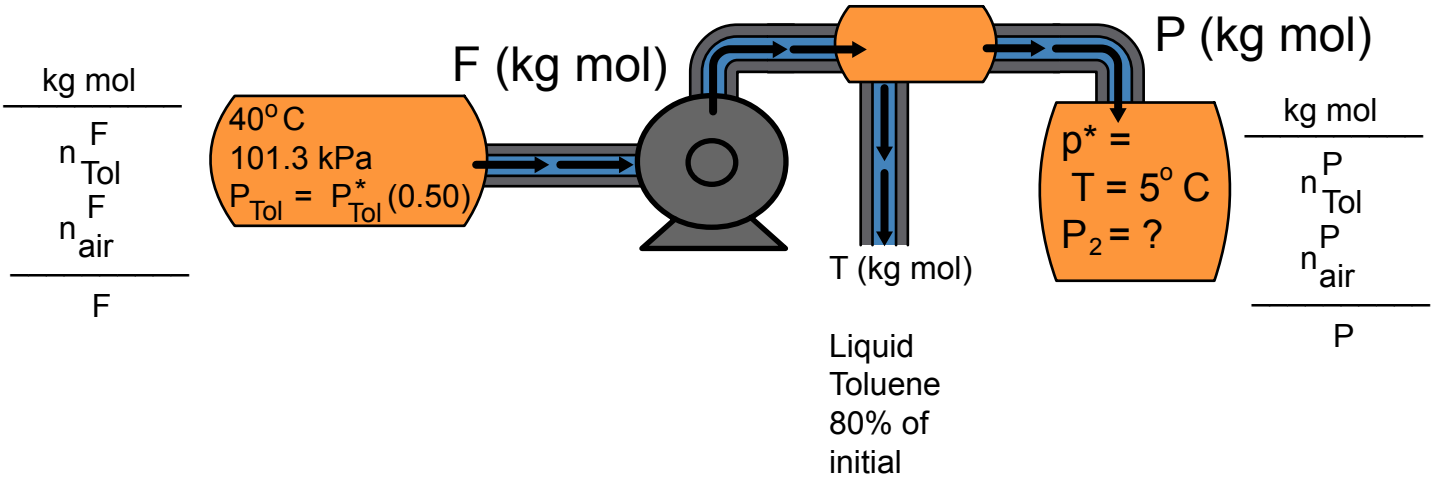
Fig. 23c Range of operation of compressors

Problem 11.4

Toluene is evaporated into dry air. The resulting mixture at 40ºC and a pressure of 101.3 kPa has a percentage saturation of 50%. It is desired to condense 80% of the toluene in the mixture by a process of cooling and compressing. If the temperature is reduced to 5ûC, determine the pressure to which gas must be compressed.

Solution

Steps 1, 2, and 3, This is a steady state process without reaction.



Step 4 Use the Antoine Equation for toluene to get p^* for toluene

A = 16.0137 B = 3096.52 C = -53.67

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

at T = 40ûC p^*_T = 58.71 mm Hg abs.

at T = 5ûC p^*_T = 9.118 mm Hg abs.

p_{Total} = 101.3 kPa = 760 mm Hg. At 40°C

$$P_{Tol} = 0.50 \quad p^*_{Tol} = 0.50\ (58.71) = 29.36 \text{ mm Hg}$$

Step 5 Basis: F = 100 kg mol

Step 4ÊÊ The toluene condensed is

$$T = 0.80(100)\ (0.0386) = 3.088 \text{ kg mol}$$

Calculate the composition of the inlet gas.

$$\frac{n^F_{Tol}}{n^F_{Tot}} = \frac{p^F_{Tol}}{p^F_{Tot}} = \frac{29.36}{760} = 0.0386$$

Step 6 Unknown are: n^P_{Air}, n^P_{Tol}, P

Steps 7, 8, and 9

An overall balance, an air balance, and a toluene balance can be written; only two are independent. But $n_A^P + n_{Tol}^P = P$ is the third equation needed.

Air balance (kg mol): $100\ (1 - 0.0386) = n_{Air}^P$

Toluene balance (kg mol): $100\ (0.0386) = 3.088 + n_{Tol}^P$

Note that because of condensation, the toluene in P is saturated, and amounts to 20% of the original toluene, or 0.77 kg mol. The partial pressure of the saturated toluene in P is 9.118 mm Hg abs.

$$\frac{p_{Tol}}{p_{Tot}} = \frac{p_{Tol}^*}{p_{Tot}} = \frac{n_{Tol}}{n_{Tot}} = \frac{0.77}{0.77 + 96.14} = \frac{0.77}{96.91}$$

$$p_{Tot} = 9.118\left(\frac{96.91}{0.77}\right) = \mathbf{1150\ mm\ Hg\ abs.\ (153\ kPa)}$$

Problem 11.5

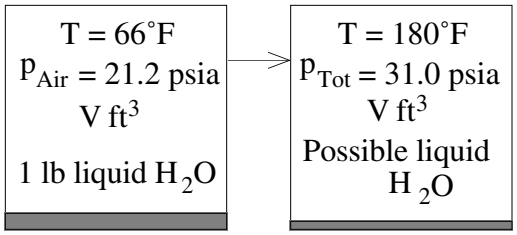
A constant-volume vessel contains dry air at 66˚F and 21.2 psia. One pound of liquid water is introduced into the vessel. The vessel is then heated to a constant temperature of 180˚F. After equilibrium is reached, the pressure in the vessel is 31.0 psia. The vapor pressure of water at 180˚F is 7.51 psia.

a. Did all of the water evaporate?
b. Compute the volume of the vessel in cubic feet.
c. Compute the humidity of the air in the vessel at the final conditions in pounds of water per pound of air.

Solution

Steps 1, 2, and 3 Assume the liquid water occupies a negligible volume in the vessel. The system is the vessel.

Gas	F (lb mol)
H_2O	$n^F_{H_2O}$
Air	n^F_{Air}
Total	n^F_{Tot}



Gas	G (lb mol)
H_2O	$n^G_{H_2O}$
Air	n^G_{Air}
Total	n^G_{Tot}

$p^*_{H_2O}$ (66˚F) = 0.3162 psia

$p^*_{H_2O}$ (180˚F) = 7.51 psia

Step 5 Basis: Initial gas at conditions shown in the Figure.

Steps 6, 7, 8, and 9

First we have to determine if all the water is vaporized or not in the vessel. We can calculate the partial pressure of the air in the vessel at 180°F by applying the ideal gas law to both the initial and final conditions, and using as the material balance the equality of the initial and final moles of air, $n^F_{Air} = n^G_{Air}$.

$$\frac{p^F_{Air}V}{p^G_{Air}V} = \frac{n^F_{Air}RT^F}{n^G_{Air}RT^G}$$

$$\text{or} \qquad p^G_{Air} = p^F_{Air}\left(\frac{T^G}{T^F}\right) = 21.2\left(\frac{180+460}{66+460}\right) = 26.9 \text{ psia}$$

Thus, the pressure of the water vapor in the air at the final conditions is

$$p^G_{H_2O} = 31.1 - 26.9 = 4.2 \text{ psia}$$

Because 4.2 < 7.51 psia, the air at the final state is not saturated.

a. All the water vaporizes

b. We can calculate the volume of the vessel from the final given conditions plus the value of the partial pressure of the water vapor in the final state

$$V_{H_2O} = \frac{n^G_{H_2O} R T^G}{p^G_{H_2O}} = \frac{(1/18)(0.73)(640)}{4.2} = \mathbf{90.8\ ft^3}$$

The volume of the water vapor at its partial pressure is the same as the volume of the vessel.

c. The humidity is

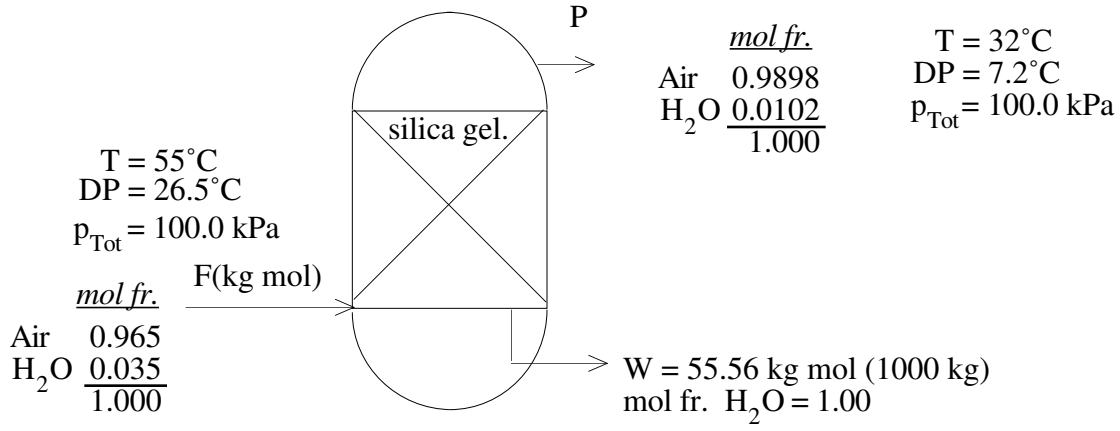
$$\frac{4.2 \text{ lb mol } H_2O}{26.9 \text{ lb mol air}} \left| \frac{18 \text{ lb } H_2O}{1 \text{ lb mol } H_2O} \right| \frac{1 \text{ lb mol air}}{29 \text{ lb air}} = 0.097 \frac{\text{lb } H_2O}{\text{lb air}}$$

Problem 11.6

A silica gel drier removes 1000 kg of water per hour. Air is supplied at a temperature of 55˚C and a dew point of 26.5˚C. The air leaves the drier at a temperature of 32˚C and a dew point of 7.2˚C. The pressure in the system is constant at 100.0 kPa. Calculate the volume of the wet air (at the initial conditions) which is supplied per hour.

Solution

Steps 1, 2, 3 and 4 Some of the data in the figure have been calculated in Step 4 below. The process is a steady state one without reaction. Because gas are involved, the calculations will be in moles. The systems is the drier.



Step 5 Basis: 1 hour

Step 4 $p^*_{H_2O}$ (26.5˚C) = 3.50 kPa

$p^*_{H_2O}$ (7.2˚C) = 1.02 kPa

Calculate the stream compositions first.

Inlet air

$p_{H_2O} = p^*_{H_2O}$ (26.5˚C) = 3.50 kPa

p_T = 100.0 kPa

Outlet air

$p_{H_2O} = p^*_{H_2O}$ (7.2˚C) = 1.02 kPa

p_T = 100.0 kPa

Step 6 Unknowns are F and P

Step 7 Balances are H_2O and air (or total)

Steps 8 and 9

Air: F(0.965) = P (0.9898)

H_2O: F(0.035) = P(0.0102) + 55.56

} F = 2214 kg mol

$$V = \frac{nRT}{p} = \frac{(2214)(8.314)(328)}{100.0} = \mathbf{6.04 \times 10^4 m^3/hr}$$

at 55°C and 100 kPa

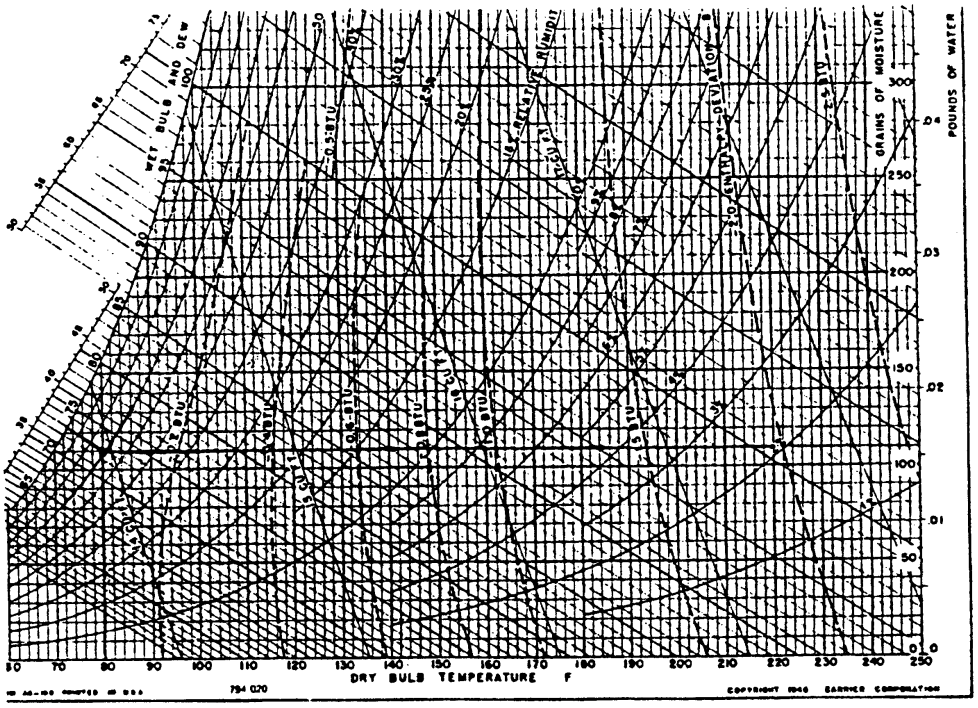
Problem 11.7

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.



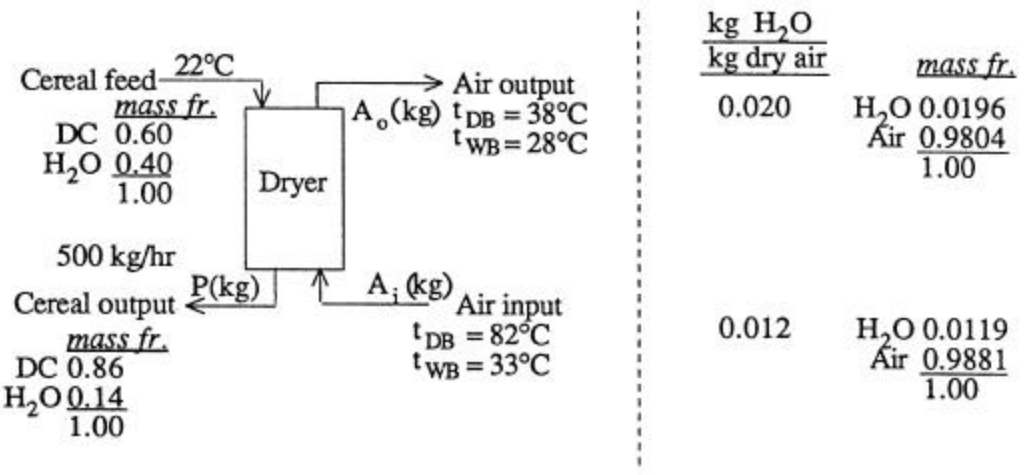
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They are

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/1b. Subtract about 0.1 Btu/1b for less than saturated (interpolating between the dashed curves) to get **36.7 Btu/1b.**
d. Interpolating between the solid lines, $\hat{V} \cong$ **13.95 ft^3/1b.**
e. Read the value of the humidity from the far right hand axis as about **0.0158 1b H_2O/1b air.**

Problem 11.8

Breakfast cereal is being dried in a fluidized bed dryer in which the cereal moves roughly countercurrent to he 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

$$\frac{1.025\ m^3}{\text{kg dry air}} \left| \frac{1.93x10^4\ \text{kg wet air}}{\text{hr}} \right| \frac{0.9881\ \text{kg dry air}}{1\ \text{kg wet air}} = \mathbf{1.96x10^4\ m^3/hr\ at\ 82^oC\ and\ 1\ atm}$$

DRYERS

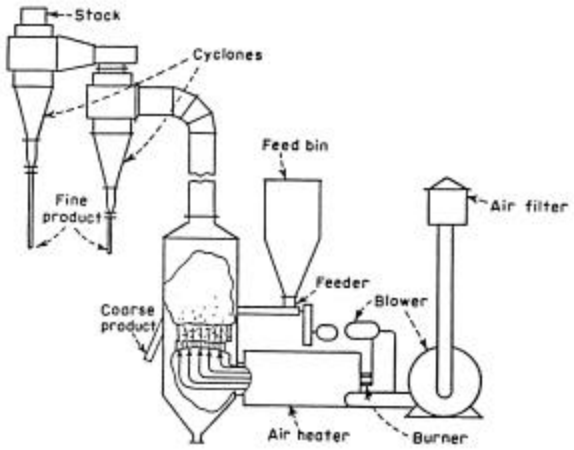


Fig. 24a. Fluidized bed dryer used for materials and high moisture content

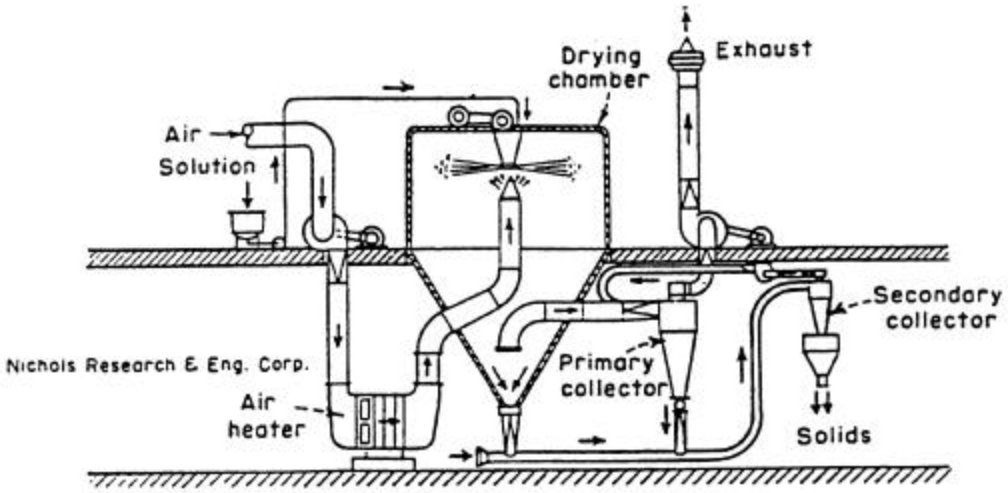


Fig. 24b. Spray dryer used for solutions

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 11.9

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

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 1b 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 1b H_2O/1b 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 lne to **110°F and then to the right axis to get 0.044 1b H_2O/1b 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/1b BDA

$\Delta\hat{H}$ after = 95 – 1.35 = 93.65 Btu/1b BDA

Heat added = $\Delta\hat{H}$ = 93.65 – 74.85 = **18.8 Btu/1b BDA**.

PART 4 – ADDITIONAL PROBLEMS
(Answers will be found in Appendix A)

Chapter 11

11.1 Toluene is mixed with air at 21°C in such proportions that the partial pressure of the vapor is 1.33 kPa. The total pressure is 99.3 kPa. Calculate the following:
(a) The relative saturation.
(b) The moles of toluene per mole of vapor-free gas.
(c) The weight of toluene per unit weight of vapor-free gas.
(d) The percent saturation.
(e) The percentage of toluene by volume.

11.2 A rigid vessel which is 1 ft^3 in volume contains 1 lb of N_2 and 1 lb of H_2O at 100F.
(a) What is the pressure (psia) in the vessel?
(b) What is the molal humidity in the vapor phase?
(c) What mass fraction of the water is liquid?

11.3 Around airports jet aircrafts can become major contributors to pollution, and as aircraft activity increases and public concern brings other sources under control, the relative contribution of aircraft to pollution could go up. Recently, federal-, state-, and local-government pressure has speeded the introduction of new combustors in aircraft. In a test for an aircraft fuel with the average composition $C_{1.20}H_{4.40}$, the fuel is completely burned with the exact stochiometric amount of air required. The air is supplied at 24°C and 100 kPa, with a humidity of 80 percent.

For the entering air, compute the following:
(1) The dew point.
(2) The molal humidity.
(3) The relative humidity.

11.4 Leather containing 100 percent of its own weight of water (i.e., if the dry leather is 1 lb, the water is 1 lb) is dried by means of air. The dew point of the entering air is 40°F, and in the exit air it is 55°F. If 2000 lb of leather are forced through the dryer per hour, how many pounds of water are removed per hour? The barometer reads 750 mm Hg.

The following is the solution to the problem. Explain whether the solution is correct or not. If not, what is the solution?

Basis: 750 lb mol wet air in

$p^*_{H_2O}$ at 40°F = 6.29 mm Hg

$p^*_{H_2O}$ at 55°F = 11.05 mm Hg

lb mol dry air in = 750 – 6.29 – 743.7 lb mol

lb mol dry air out = 750 – 11.05 – 739 lb mol

$$\frac{6.29 \text{ lb mol}}{} \left| \frac{18 \text{ lb}}{1 \text{ lb mol}} \right. = 114 \text{ lb } H_2O$$

Dry air balance

$$H_2O_{out} = \frac{11.05 \text{ lb mol}}{} \left| \frac{743.7}{739} \right| \frac{18 \text{ lb}}{1 \text{ lb mol}} = 200 \text{ lb } H_2O$$

$H_2O_{\text{ absorbed}} = 200 - 114 = 86 \text{ lb } H_2O$

Comp.	*mol*	*mol fract*	*mol fract*	*M.W.*	*lb*
Dry Air	743.7	0.991	0.991	29	28.7
H_2O	6.29	0.009	0.009	18	0.2
Total	750	1.0	1.0		28.9

Basis: 2000 lb leather (1 hr)

$$\frac{2000 \text{ lb leather}}{1 \text{ hr}} \left| \frac{0.50 \text{ lb } H_2O}{1 \text{ lb leather}} \right| \frac{86 \text{ lb } H_2O \text{ removed}}{114 \text{ lb } H_2O \text{ in}} = 75.4 \text{ lb / hr}$$

11.5 Air at 300K and 100 kPa has a dew point of 289K.
- (a) What is the percent relative humidity?
- (b) To what pressure must this air be compressed to cause condensation to start (the temperature remains at 300K)?
- (c) To what temperature must this air be cooled to remove 25 percent of the moisture (the pressure stays constant at 100 kPa)?
- (d) What would be the percent relative humidity of this air after heating to 340K (at constant pressure)?
- (e) Did the molal saturation change during the heating indicated in part (d)?

11.6 Air saturated with water vapor is at 140°F and a pressure of 29.68 in. Hg.
- (a) To what temperature must the air be cooled to separate 68 percent of the water in it as liquid water (pressure is constant)?
- (b) To what pressure must the air be compressed to separate 68 percent of the water in it as liquid water (temperature is constant)?
- (c) If the temperature is reduced to 100°F and the gas is compressed to 25 psia, what percentage of the water separates out as liquid?

11.7 Soybean flakes from an extraction process are reduced from 0.96 lb of C_2HCl_3 per pound of dry flakes to 0.05 lb of C_2HCl_3 per pound of dry flakes in a desolventizer by a stream of N_2 which vaporizes the C_2HCl_3. The entering N_2 contains C_2HCl_3 such that its dew point is 30°C. The N_2 leaves at 90°C with a relative saturation of 60%. The pressure in the desolventizer is 760 mmHg, and 1000 lb/hr of dry flakes pass through the drier.
- (a) Compute the volume of N_2 plus C_2HCl_3 leaving the desolventizer at 90°C and 760 mm Hg in cubic feet per minute.
- (b) The N_2 leaving the desolventizer is compressed and cooled to 40°C, thus condensing out the C_2HCl_3 picked up in the desolventizer. What must the pressure in the condenser be if the gas is to have a dew point of 30°C at the pressure of the desolventizer?

11.8 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?

11.9 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 1b 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 1b of dry air entering from the outside?

11.10 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