

A polynomial formula for $(C_p)_{\text{liquid}}$ is given in Table B.2. Since it applies to T expressed in kelvin units, the limits of the integral should be changed to their kelvin equivalents.

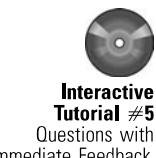
4. Vaporize the liquid at T_{bp} . $\Delta\hat{H}_4 = \Delta\hat{H}_{\text{v}}(80.1^\circ\text{C})$, which from Table B.1 is 30.765 kJ/mol.
5. Heat the vapor from T_{bp} to 300°C .

$$\Delta\hat{H}_5 = \int_{80.1^\circ\text{C}}^{300^\circ\text{C}} (C_p)_{\text{vapor}} dT$$

A formula for $(C_p)_{\text{vapor}}$ is given in Table B.2.

6. Bring the vapor from 1 atm to 15 atm at 300°C . $\Delta\hat{H}_6 \approx 0$ as long as the vapor behaves like an ideal gas, which it would at this high temperature.
7. Add the enthalpy changes for each of the preceding steps to calculate the desired specific enthalpy.

- The *psychrometric chart* (or *humidity chart*) contains values of a number of process variables for air–water vapor systems at 1 atm. The values listed on the chart include *dry-bulb temperature* (the temperature measured by common temperature-measurement instruments), *moisture content* or *absolute humidity* (mass ratio of water vapor to dry air), *relative humidity*, *humid volume* (volume per mass of dry air), *wet-bulb temperature* (the temperature reading on a thermometer with a water-saturated wick around the bulb immersed in a flowing stream of humid air), and *enthalpy per mass of dry air*. If you know the values of any two of these variables for humid air at or near 1 atm, you can use the chart to determine the values of the other four, which can greatly simplify material and energy balance calculations.
- In *adiabatic cooling* operations, a stream of warm gas is brought into contact with a stream of cold liquid, causing the gas to cool and some liquid to evaporate. If (a) the gas is dry or humid air, the liquid is water, and the process takes place at about 1 atm, (b) the process is adiabatic, (c) the heat capacities of liquid water, water vapor, and air can be considered constant over the temperature range of the process, and (d) enthalpy changes associated with temperature changes of the liquid may be neglected, then the final state of the air must lie on the same wet-bulb temperature line as the state of the inlet air on the psychrometric chart.
- An enthalpy change known as the *heat of mixing* or *heat of solution* is associated with the mixing of certain liquids (like acids and water) and the dissolving of some gases or solids in a liquid solvent at a given temperature and pressure. An *ideal solution* is one for which the heat of mixing or solution is negligible, so that the enthalpy of the solution is the sum of the enthalpies of the pure solution components at the same temperature and pressure. All gas mixtures are ideal, as are mixtures of structurally similar liquid compounds (like benzene, toluene, and xylene). Table B.11 gives heats of mixing at 25°C and 1 atm for aqueous sulfuric acid solutions and heats of solution at the same temperature and pressure for aqueous solutions of HCl(g) (hydrochloric acid) and NaOH(s) (caustic soda).
- To perform energy balance calculations on processes involving nonideal solutions, take the pure components at 25°C as references. To determine the specific enthalpy of a feed or product solution, look it up on an *enthalpy–concentration chart* if one is available (e.g., Figure 8.5-1 for sulfuric acid solutions or Figure 8.5-2 for aqueous ammonia solutions). Otherwise, form the solution at 25°C [$\Delta\hat{H} = \Delta\hat{H}_s(25^\circ\text{C})$] and heat or cool it to its state in the process ($\Delta\hat{H} = \int_{25^\circ\text{C}}^T C_p dT$). For the latter step, either find heat capacity data for the solution or (for dilute solutions) assume that the heat capacity is that of the pure solvent.



PROBLEMS

8.1. The specific internal energy of formaldehyde (HCHO) vapor at 1 atm and moderate temperatures is given by the formula

$$\hat{U}(\text{J/mol}) = 25.96T + 0.02134T^2$$

where T is in $^\circ\text{C}$.

- (a)** Calculate the specific internal energies of formaldehyde vapor at 0°C and 100°C . What reference temperature was used to generate the given expression for \hat{U} ?

- (b) The value of \hat{U} calculated for 100°C is not the true value of the specific internal energy of formaldehyde vapor at this condition. Why not? (*Hint:* Refer back to Section 7.5a.) Briefly state the physical significance of the calculated quantity.
- (c) Use the closed system energy balance equation to calculate the heat (J) required to raise the temperature of 3.0 mol HCHO at constant volume from 0°C to 100°C. List all of your assumptions.
- (d) From the definition of heat capacity at constant volume, derive a formula for $C_v(T)$ [J/mol·°C]. Then use this formula and Equation 8.3-6 to calculate the heat (J) required to raise the temperature of 3.0 mol of HCHO(v) at constant volume from 0°C to 100°C. [You should get the same result you got in part (c).]

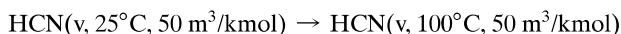
- 8.2.** The heat capacity at constant pressure of hydrogen cyanide is given by the expression

$$C_p[\text{J}/(\text{mol} \cdot \text{°C})] = 35.3 + 0.0291T(\text{°C})$$

- (a) Write an expression for the heat capacity at constant volume for HCN, assuming ideal gas behavior.
- (b) Calculate $\Delta\hat{H}(\text{J/mol})$ for the constant-pressure process



- (c) Calculate $\Delta\hat{U}(\text{J/mol})$ for the constant-volume process

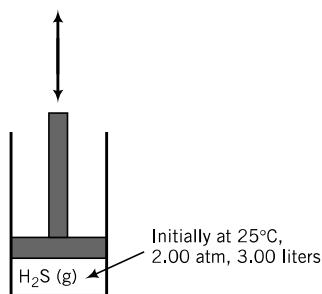


- (d) If the process of part (b) were carried out in such a way that the initial and final pressures were each 0.80 atm but the pressure varied during the heating, the value of $\Delta\hat{H}$ would still be what you calculated assuming a constant pressure. Why is this so?

- 8.3.** The heat capacity at constant volume of hydrogen sulfide at low pressures is

$$C_v[\text{kJ}/(\text{mol} \cdot \text{°C})] = 0.0252 + 1.547 \times 10^{-5}T - 3.012 \times 10^{-9}T^2$$

where T is in °C. A quantity of H₂S is kept in a piston-fitted cylinder with initial temperature, pressure, and volume equal to 25°C, 2.00 atm, and 3.00 liters, respectively.



- (a) Calculate the heat (kJ) required to raise the gas temperature from 25°C to 1000°C if the heating takes place at constant volume (i.e., if the piston does not move), retaining successively one term, two terms, and all three terms of the heat capacity formula. (See Example 8.3-1.) Determine the percentage errors in Q that result from retaining only one and two terms of the heat capacity formula, assuming that the full expression yields the correct result.
- (b) For a closed system at constant pressure with negligible kinetic and potential energy changes, the energy balance equation is $Q = \Delta H$. Use Equation 8.3-12 to determine an expression for the heat capacity at constant pressure (C_p) for H₂S, assuming ideal gas behavior. Then use it to calculate the heat (J) required to raise the gas from 25°C to 1000°C at constant pressure. What would the piston do during this process?
- (c) What is the physical significance of the difference between the values of Q calculated in parts (a) and (b)?
- 8.4.** Use data in Table B.2 to calculate the following:
- (a) The heat capacity (C_p) of liquid benzene at 40°C.
- (b) The heat capacity at constant pressure of benzene vapor at 40°C.

- (c) The heat capacity at constant pressure of solid carbon at 40°C.
 (d) $\Delta\hat{H}$ (kJ/mol) for benzene vapor going from 40°C to 300°C.
 (e) $\Delta\hat{H}$ (kJ/mol) for solid carbon going from 40°C to 300°C.
- 8.5. Estimate the specific enthalpy of steam (kJ/kg) at 350°C and 100 bar relative to steam at 100°C and 1 atm using:
 (a) The steam tables.
 (b) Table B.2 and assuming ideal gas behavior.
 What is the physical significance of the difference between the values of \hat{H} calculated by the two methods?
- 8.6. Calculate $\Delta\hat{H}$ for each of the following processes. In each case, restate your result as a specific enthalpy relative to a reference state. [The solution—which you should verify—and the restatement for part (a) are given as an illustration.] Assume that the process pressures are low enough for \hat{H} to be considered independent of pressure, so that the formulas of Table B.2 (which strictly apply at 1 atm) can be used.
 (a) $\text{CH}_3\text{COCH}_3(\text{l}, 15^\circ\text{C}) \rightarrow \text{CH}_3\text{COCH}_3(\text{l}, 55^\circ\text{C})$.
Solution: $\boxed{\Delta\hat{H} = 5.180 \text{ kJ/mol}}$
The specific enthalpy of liquid acetone at 55°C relative to liquid acetone at 15°C is 5.180 kJ/mol.
- (b) $n\text{-C}_6\text{H}_{14}(\text{l}, 25^\circ\text{C}) \rightarrow n\text{-C}_6\text{H}_{14}(\text{l}, 80^\circ\text{C})$
 (c) $n\text{-C}_6\text{H}_{14}(\text{v}, 500^\circ\text{C}) \rightarrow n\text{-C}_6\text{H}_{14}(\text{v}, 0^\circ\text{C})$. (Make statements about both the specific enthalpy of hexane vapor at 500°C relative to hexane vapor at 0°C and the specific enthalpy of hexane vapor at 0°C relative to hexane vapor at 500°C.)

- 8.7. Two formulas for the heat capacity of CO are given here:

$$C_p[\text{cal}/(\text{mol}\cdot^\circ\text{C})] = 6.890 + 0.001436T(\text{°C})$$

$$C_p[\text{Btu}/(\text{lb-mole}\cdot^\circ\text{F})] = 6.864 + 0.0007978T(\text{°F})$$

Starting with the first formula, derive the second. (Recall Section 2.5, and remember that the temperature unit in the denominator of C_p refers to a temperature interval.)

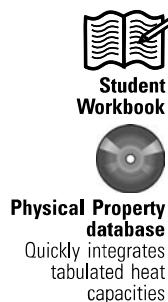
- 8.8. Table B.2 lists values of the heat capacity of liquid ethanol at two temperatures. Use the tabulated values to derive a linear expression for $C_p(T)$; then use the derived expression and data in Table B.1 to calculate the heat transfer rate (kW) required to bring a stream of liquid ethanol flowing at 55.0 L/s from 20°C to the boiling point at 1 atm.
- 8.9. Chlorine gas is to be heated from 100°C and 1 atm to 200°C.
 (a) Calculate the heat input (kW) required to heat a stream of the gas flowing at 5.0 kmol/s at constant pressure.
 (b) Calculate the heat input (kJ) required to raise the temperature of 5.0 kmol of chlorine in a closed rigid vessel from 100°C and 1 atm to 200°C. (Suggestion: Evaluate $\Delta\hat{U}$ directly from the result of the first calculation, so that you do not have to perform another integration.) What is the physical significance of the numerical difference between the values calculated in parts (a) and (b)?
 (c) To accomplish the heating of part (b), you would actually have to supply an amount of heat to the vessel greater than the amount calculated. Why?
- 8.10. The heat required to raise the temperature of m (kg) of a liquid from T_1 to T_2 at constant pressure is

$$Q = \Delta H = m \int_{T_1}^{T_2} C_p(T) dT \quad (1)$$

In high school and in first-year college physics courses, the formula is usually given as

$$Q = mC_p \Delta T = mC_p(T_2 - T_1) \quad (2)$$

- (a) What assumption about C_p is required to go from Equation 1 to Equation 2?
 (b) The heat capacity (C_p) of liquid *n*-hexane is measured in a **bomb calorimeter**. A small reaction flask (the bomb) is placed in a well-insulated vessel containing 2.00 L of liquid *n*-C₆H₁₄ at $T = 300$ K. A combustion reaction known to release 16.73 kJ of heat takes place in the bomb, and the subsequent temperature rise of the system contents is measured and found to be 3.10 K. In a separate experiment, it is found that 6.14 kJ of heat is required to raise the temperature of



Physical Property database
Quickly integrates tabulated heat capacities

everything in the system except the hexane by 3.10 K. Use these data to estimate $C_p[\text{kJ}/(\text{mol}\cdot\text{K})]$ for liquid *n*-hexane at $T \approx 300$ K, assuming that the condition required for the validity of Equation 2 is satisfied. Compare your result with a tabulated value.

- 8.11.** The heat capacities of a substance have been defined as

$$C_v = \left(\frac{\partial \hat{U}}{\partial T} \right)_V, \quad C_p = \left(\frac{\partial \hat{H}}{\partial T} \right)_P$$

Use the defining relationship between \hat{H} and \hat{U} and the fact that \hat{H} and \hat{U} for ideal gases are functions only of temperature to prove that $C_p = C_v + R$ for an ideal gas.

- 8.12.** Ralph Rackstraw, your next-door neighbor, surprised his wife last January by having a hot tub installed in their back yard while she was away on a business trip. It surprised her, all right, but instead of being pleased she was horrified. “Have you lost your mind, Ralph?” she sputtered. “It will cost a fortune to keep this thing hot.” “Don’t be silly, Josephine,” he replied. “It can’t cost more than pennies a day, even in the dead of winter.” “No way—and when did you become such an expert, anyway?” “I guarantee it will cost nothing—and I don’t see your Ph.D. certificate on the kitchen wall either.” They argued for awhile and then, remembering your chemical engineering education, came to ask you to settle it for them. You asked a few questions, made several observations, converted everything to metric units, and arrived at the following data, all corresponding to an average outside air temperature of about 5°C.

- The tub holds 1230 liters of water.
- Rackstraw normally keeps the tub temperature at 29°C, raises it to 40°C when he plans to use it, keeps it at 40°C for about one hour, and drops it back to 29°C when he is finished.
- During heating, it takes about three hours for the water temperature to rise from 29°C to 40°C. When the heat is shut off, it takes eight hours for the water temperature to drop back to 29°C.
- Electricity costs 10 cents per kilowatt-hour.

Taking the heat capacity of the tub contents to be that of pure liquid water and neglecting evaporation, answer the following questions.

- (a) What is the average rate of heat loss (kW) from the tub to the outside air? (*Hint:* Consider the period when the tub temperature is dropping from 40°C to 29°C.)
- (b) At what average rate (kW) does the tub heater deliver energy to the water when raising the water temperature? What is the total quantity of electricity (kW·h) that the heater must deliver during this period? [Consider the result of part (a) when performing the calculation.]
- (c) (These answers should settle the argument.) Consider a day in which the tub is used once. Use the results of parts (a) and (b) to estimate the cost (\$) of heating the tub from 29°C to 40°C and the cost (\$) of keeping the tub at a constant temperature. (There is no cost for the period in which T is dropping.) What is the total daily cost of running the tub? Assume the rate of heat loss is independent of the tub temperature.
- (d) The tub lid, which is an insulator, is removed when the tub is in use. Explain how this fact would probably affect your cost estimates in part (c).
- 8.13.** Use tabulated specific enthalpies from Tables B.8 and B.9 to calculate $\Delta\hat{H}$ for the following processes, all taking place at low pressures:
- (a) $\text{N}_2(25^\circ\text{C}) \rightarrow \text{N}_2(700^\circ\text{C})$ (c) $\text{CO}_2(300^\circ\text{C}) \rightarrow \text{CO}_2(1250^\circ\text{C})$
 (b) $\text{H}_2(800^\circ\text{F}) \rightarrow \text{H}_2(77^\circ\text{F})$ (d) $\text{O}_2(970^\circ\text{F}) \rightarrow \text{O}_2(0^\circ\text{F})$
- 8.14.** Calculate the rate of cooling (kW) required to bring 300 kg/min of carbon monoxide from 450°C to 50°C, performing the calculation (a) using Table B.2 and (b) using Table B.8. Considering how much simpler the second calculation is, why would you ever use the polynomial formulas of Table B.2 as opposed to tabulated enthalpies to calculate enthalpy changes?
- 8.15.** A stream of water vapor flowing at a rate of 250 mol/h is brought from 600°C and 10 bar to 100°C and 1 atm.
- (a) Estimate the required cooling rate (kW) three ways: (i) from the steam tables, (ii) using heat capacity data in Table B.2, and (iii) using specific enthalpy data in Table B.8.
- (b) Which of the answers in part (a) is most accurate, and why?
- (c) What is the physical significance of the difference between the values calculated with methods (i) and (ii)?

- 8.16.** A stream of air at 77°F and 1.2 atm absolute flowing at a rate of 200 ft³/h is blown through ducts that pass through the interior of a large industrial motor. The air emerges at 500°F. Using tabulated specific enthalpy data, calculate the rate at which the air is removing heat generated by the motor. What assumption have you made about the pressure dependence of the specific enthalpy of air?



Student Workbook

- 8.17.** Calculate the heat required to raise 50 kg of solid sodium carbonate (Na₂CO₃) from 10°C to 50°C at 1 atm using

- (a) the true heat capacity of Na₂CO₃, which is 1.14 kJ/(kg·°C).
 (b) a heat capacity estimated by Kopp's rule. Calculate the percentage error in the latter calculation.

- 8.18.** A liquid mixture of 30 wt% acetone and 70 wt% 2-methyl-1-pentanol (C₆H₁₄O) is cooled from 45°C to 20°C. Calculate the associated specific enthalpy change in J/g, using Kopp's rule to estimate any heat capacity for which a tabulated value cannot be found. State all assumptions you make.

- 8.19.** A gas mixture contains one-third methane by volume (recall what that means in terms of mole %) and the balance oxygen at 350°C and 3.0 bar. Calculate the specific enthalpy of this stream in kJ/kg (not per kmol) relative to the pure components at 25°C and 1 atm. *State clearly all assumptions.*

- 8.20.** The radiant energy incident on the earth's surface on a sunny day is roughly 900 W/m². Collecting and focusing sunlight and using the focused beam to heat a fluid is an old idea, and as the environmental costs of fossil fuel combustion mount, solar heating becomes an increasingly attractive alternative.

Suppose a house is to be designed that will have a circulating forced air central heating unit, and solar energy is contemplated as a heat source (backed up with a conventional furnace to be used on cloudy days). If air is to be fed at a rate of 1000 m³/min at 30°C and 1 atm, and the air is to be heated to 55°C before being discharged into the living space, what is the required area of the solar collector plates? Assume 30% of the radiant energy incident on the plates is used to heat the air.

- 8.21.** Propane is to be burned with 15.0% excess air. Before entering the furnace, the air is preheated from 32°F to 575°F. At what rate (Btu/h) must heat be transferred to the air if the feed rate of propane is 1.35×10^5 SCFH [ft³(STP)/h]?



Student Workbook

Equipment Encyclopedia
boiler

- 8.22.** A fuel gas containing 95 mole% methane and the balance ethane is burned completely with 25% excess air. The stack gas leaves the furnace at 900°C and is cooled to 450°C in a **waste heat boiler**, a heat exchanger in which heat lost by cooling gases is used to produce steam from liquid water for heating, power generation, or process applications.

- (a) Taking as a basis of calculation 100 mol of the fuel gas fed to the furnace, calculate the amount of heat (kJ) that must be transferred from the gas in the waste heat boiler to accomplish the indicated cooling.
 (b) How much saturated steam at 50 bar can be produced from boiler feedwater at 40°C for the same basis of calculation? (Assume all the heat transferred from the gas goes into the steam production.)
 (c) At what rate (kmol/s) must fuel gas be burned to produce 1250 kg steam per hour (an amount required elsewhere in the plant) in the waste heat boiler? What is the volumetric flow rate (m³/s) of the gas leaving the boiler?
 (d) Briefly explain how the waste heat boiler contributes to the plant profitability. (Think about what would be required in its absence.)

- 8.23.** Twenty liters of liquid *n*-propyl benzoate (C₆H₅CO₂C₃H₇, SG = 1.021) and 15 liters of liquid benzene are mixed and heated from 25°C to 75°C. Calculate the required heat input (kJ), using Kopp's rule when necessary. State all assumptions you make.

Equipment Encyclopedia
heat exchanger

- 8.24.** Propane gas enters a continuous adiabatic heat exchanger¹⁶ at 40°C and 250 kPa and exits at 240°C. Superheated steam at 300°C and 5.0 bar enters the exchanger flowing countercurrently to the propane and exits as a saturated liquid at the same pressure.

- (a) Taking as a basis 100 mol of propane fed to the exchanger, draw and label a process flowchart. Include in your labeling the volume of propane fed (m³), the mass of steam fed (kg), and the volume of steam fed (m³).
 (b) Calculate values of the labeled specific enthalpies in the following inlet-outlet enthalpy table for this process.

¹⁶An adiabatic heat exchanger is one for which no heat is exchanged with the surroundings. All of the heat lost by the hot stream is transferred to the cold stream.

References: $\text{H}_2\text{O(l, 0.01°C)}$, $\text{C}_3\text{H}_8(\text{g, 40°C})$

Species	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}
C_3H_8	100 mol	$\hat{H}_{\text{a}}(\text{kJ/mol})$	100 mol	$\hat{H}_{\text{c}}(\text{kJ/mol})$
H_2O	$m_{\text{w}}(\text{kg})$	$\hat{H}_{\text{b}}(\text{kJ/kg})$	$m_{\text{w}}(\text{kg})$	$\hat{H}_{\text{d}}(\text{kJ/kg})$

- (c) Use an energy balance to calculate the required mass feed rate of the steam. Then calculate the volumetric feed ratio of the two streams (m^3 steam fed/ m^3 propane fed). Assume ideal gas behavior for the propane but not the steam and recall that the exchanger is adiabatic.
- (d) Calculate the heat transferred from the water to the propane (kJ/m^3 propane fed). (Hint: Do an energy balance on either the water or the propane rather than on the entire heat exchanger.)
- (e) Over a period of time, scale builds up on the heat transfer surface, resulting in a lower rate of heat transfer between the propane and the steam. What changes in the outlet streams would you expect to see as a result of the decreased heat transfer?



- 8.25. Saturated steam at 300°C is used to heat a countercurrently flowing stream of methanol vapor from 65°C to 260°C in an adiabatic heat exchanger. The flow rate of the methanol is 5500 standard liters per minute, and the steam condenses and leaves the heat exchanger as liquid water at 90°C .
- (a) Calculate the required flow rate of the entering steam in m^3/min .
 - (b) Calculate the rate of heat transfer from the water to the methanol (kW).
- 8.26. An adiabatic membrane separation unit is used to dry (remove water vapor from) a gas mixture containing 10.0 mole% $\text{H}_2\text{O(v)}$, 10.0 mole% CO, and the balance CO_2 . The gas enters the unit at 30°C and flows past a semipermeable membrane. Water vapor permeates through the membrane into an air stream. The dried gas leaves the separator at 30°C containing 2.0 mole% $\text{H}_2\text{O(v)}$ and the balance CO and CO_2 . Air enters the separator at 50°C with an absolute humidity of 0.002 kg $\text{H}_2\text{O}/\text{kg}$ dry air and leaves at 48°C . Negligible quantities of CO, CO_2 , O_2 , and N_2 permeate through the membrane. All gas streams are at approximately 1 atm.
- (a) Draw and label a flowchart of the process and carry out a degree-of-freedom analysis to verify that you can determine all unknown quantities on the chart.
 - (b) Calculate (i) the ratio of entering air to entering gas (kg humid air/mol gas) and (ii) the relative humidity of the exiting air.
 - (c) List several desirable properties of the membrane. (Think about more than just what it allows and does not allow to permeate.)
- 8.27. A gas containing water vapor has a dry-basis composition of 8.5 mole% CO, 10.5% CO_2 , 0.5% O_2 , and 80.5% N_2 . The gas leaves a catalyst regeneration unit at 620°C and 1 atm with a dew point of 57°C at a flow rate of 28.5 SCMH [$\text{m}^3(\text{STP})/\text{h}$]. Valuable solid catalyst particles entrained in the gas are to be recovered in an electrostatic precipitator, but the gas must first be cooled to 425°C to prevent damage to the precipitator electrodes. The cooling is accomplished by spraying water at 20°C into the gas.
- (a) Use simultaneous material and energy balances on the spray cooler to calculate the required water feed rate (kg/h). Treat the spray cooler as adiabatic and neglect the heat transferred from the entrained solid particles as they cool.
 - (b) In terms that a high school senior could understand, explain the operation of the spray cooler in this problem. (What happens when the cold water contacts the hot gas?)
- 8.28. On a cold winter day the temperature is 2°C and the relative humidity is 15%. You inhale air at an average rate of 5500 mL/min and exhale a gas saturated with water at body temperature, roughly 37°C . If the mass flow rates of the inhaled and exhaled air (excluding water) are the same, the heat capacities (C_p) of the water-free gases are each $1.05 \text{ J/(g}\cdot{}^\circ\text{C)}$, and water is ingested into the body as a liquid at 22°C , at what rate in J/day do you lose energy by breathing? Treat breathing as a continuous process (inhaled air and liquid water enter, exhaled breath exits) and neglect work done by the lungs.
- 8.29. Seventy-five liters of liquid ethanol at 70.0°C and 55 L of liquid water at 20.0°C are to be mixed in a well-insulated flask. The energy balance for this constant pressure process is $Q = \Delta H$.
- (a) Neglecting evaporation and the heat of mixing, estimate the final mixture temperature. (As part of the calculation, use data in Table B.2 to estimate a linear formula for the heat capacity of liquid ethanol.)



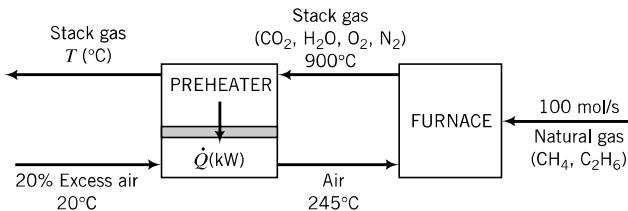
- (b) If the experiment were actually performed and the final mixture temperature were measured, it would almost certainly not equal the value estimated in part (a). List as many reasons as you can think of. (There are at least seven of them, most involving approximations made in the estimation.)

8.30. A stream of air at 500°C and 835 torr with a dew point of 30°C flowing at a rate of 1515 L/s is to be cooled in a spray cooler. A fine mist of liquid water at 25°C is sprayed into the hot air at a rate of 110.0 g/s and evaporates completely. The cooled air emerges at 1 atm.

- (a) Calculate the final temperature of the emerging air stream, assuming that the process is adiabatic. (*Suggestion:* Derive expressions for the enthalpies of dry air and water at the outlet air temperature, substitute them into the energy balance, and use a spreadsheet to solve the resulting fourth-order polynomial equation.)
 (b) At what rate (kW) is heat transferred from the hot air feed stream in the spray cooler? What becomes of this heat?
 (c) In a few sentences, explain how this process works in terms that a high school senior could understand. Incorporate the results of parts (a) and (b) in your explanation.

8.31. In the manufacture of nitric acid, ammonia and preheated air are mixed to form a gas containing 10.0 mole % NH₃ at 600°C. The ammonia is then catalytically oxidized to form NO₂, which is absorbed in water to form HNO₃. If ammonia enters the gas blending unit at 25°C at a rate of 520 kg/h and heat is lost from the mixer to its surroundings at a rate of 7.00 kW, determine the temperature to which the air must be preheated. (See Example 8.3-6.)

8.32. A natural gas containing 95 mole % methane and the balance ethane is burned with 20.0% excess air. The stack gas, which contains no unburned hydrocarbons or carbon monoxide, leaves the furnace at 900°C and 1.2 atm and passes through a heat exchanger. The air on its way to the furnace also passes through the heat exchanger, entering it at 20°C and leaving it at 245°C.



- (a) Taking as a basis 100 mol/s of the natural gas fed to the furnace, calculate the required molar flow rate of air, the molar flow rate and composition of the stack gas, the required rate of heat transfer in the preheater, \dot{Q} (write an energy balance on the air), and the temperature at which the stack gas leaves the preheater (write an energy balance on the stack gas). *Note:* The problem statement does not give you the fuel feed temperature. Make a reasonable assumption, and state why your final results should be nearly independent of what you assume.
 (b) What would \dot{Q} be if the actual feed rate of the natural gas were 350 SCMH [standard cubic meters per hour, m³(STP)/h]? Scale up the flowchart of part (a) rather than repeating the entire calculation.

8.33. The heat capacity at constant pressure of a gas is determined experimentally at several temperatures, with the following results:

T (°C)	0	100	200	300	400	500	600
C_p [J/(mol·°C)]	33.5	35.1	36.7	38.4	40.2	42.0	43.9

- (a) Calculate the heat (kW) required to raise 150 mol/s of the gas from 0°C to 600°C, using Simpson's rule (Appendix A.3) to integrate the tabulated heat capacities.
 (b) Use the method of least squares (Appendix A.1) to derive a linear expression for $C_p(T)$ in the range 0°C to 600°C, and use this expression to estimate once again the heat (kW) required to raise 150 mol/s of the gas from 0°C to 600°C. If the estimates differ, in which one would you have more confidence, and why?

- *8.34.** As part of a design calculation, you must evaluate an enthalpy change for an obscure organic vapor that is to be cooled from 1800°C to 150°C in a heat exchanger. You search through all the standard references for tabulated enthalpy or heat capacity data for the vapor but have no luck at all, until you finally stumble on an article in the May 1922 *Antarctican Journal of Obscure Organic Vapors* that contains a plot of $C_p[\text{cal}/(\text{g}\cdot^\circ\text{C})]$ on a logarithmic scale versus $[T(\text{°C})]^{1/2}$ on a linear scale. The plot is a straight line through the points ($C_p = 0.329$, $T^{1/2} = 7.1$) and ($C_p = 0.533$, $T^{1/2} = 17.3$).

(a) Derive an equation for C_p as a function of T .

(b) Suppose the relationship of part (a) turns out to be

$$C_p = 0.235 \exp[0.0473T^{1/2}]$$

and that you wish to evaluate

$$\Delta\hat{H}(\text{cal/g}) = \int_{1800^\circ\text{C}}^{150^\circ\text{C}} C_p \, dT$$

First perform the integration analytically, using a table of integrals if necessary; then write a spreadsheet or computer program to do it using Simpson's rule (Appendix A.3). Have the program evaluate C_p at 11 equally spaced points from 150°C to 1800°C, estimate and print the value of ΔH , and repeat the calculation using 101 points. What can you conclude about the accuracy of the numerical calculation?

- 8.35.** A stream of ethylene glycol vapor at its normal boiling point and 1 atm flowing at a rate of 175 kg/min is to be condensed at constant pressure. The product stream from the condenser is liquid glycol at the condensation temperature.

(a) Using data in Table B.1, calculate the rate (kW) at which heat must be transferred from the condenser.

(b) If heat were transferred at a lower rate than that calculated in part (a), what would the state of the product stream be? (Deduce as much as you can about the phase and the temperature of the stream.)

(c) If heat were transferred at a higher rate than that calculated in part (a), what could you deduce about the state of the product stream? Sketch a phase diagram (see Figure 6.1-1 on p. 241) and use it to explain your answer.



- 8.36.** (a) Determine the specific enthalpy (kJ/mol) of *n*-hexane vapor at 200°C and 2.0 atm relative to *n*-hexane liquid at 20°C and 1.0 atm, assuming ideal gas behavior for the vapor. Show clearly the process path you construct for this calculation and give the enthalpy changes for each step. State where you used the ideal gas assumption.

(b) What is the enthalpy of *n*-hexane liquid at 20°C and 1.0 atm relative to *n*-hexane vapor at 200°C and 2.0 atm? (This part should not take much time to complete.)

(c) Beginning with the value of \hat{H} calculated in part (a) and still assuming ideal gas behavior, determine the specific internal energy of the vapor at 200°C and 2.0 atm. Once again, state where you used the ideal gas assumption.

- 8.37.** Calculate the heat of vaporization of water (kJ/mol) at 50°C and low pressures from the tabulated heat of vaporization in Table B.1 and data in Table B.2 and Table B.8. Show clearly the process path you construct for the calculation. Compare your answer with the value of $\Delta H_v(50^\circ\text{C})$ given in Table B.5 (convert it to kJ/mol for the comparison). What might account for the difference between the two values?

- 8.38.** Benzene vapor at 580°C is cooled and converted to a liquid at 25°C in a continuous condenser. The condensate is drained into 1.75-m³ drums, each of which takes 2.0 minutes to fill. Calculate the rate (kW) at which heat is transferred from the benzene in the condenser.

- 8.39.** In gas adsorption a vapor is transferred from a gas mixture to the surface of a solid. (See Section 6.7.) An approximate but useful way of analyzing adsorption is to treat it simply as condensation of vapor on a solid surface.

Suppose a nitrogen stream at 35°C and 1 atm containing carbon tetrachloride with a 15% relative saturation is fed at a rate of 10.0 mol/min to a 6-kg bed of activated carbon. The temperature and pressure of the gas do not change appreciably from the inlet to the outlet of the bed, and there



Equipment Encyclopedia
condenser



Equipment Encyclopedia
adsorption column

*Computer problem.

is no CCl_4 in the gas leaving the adsorber. The carbon can adsorb 40% of its own mass of carbon tetrachloride before becoming saturated. Neglecting the effect of temperature on the heat of vaporization of CCl_4 , estimate the rate at which heat must be removed from the adsorber (kJ/min) to keep the process isothermal and the time (min) it will take to saturate the bed.

- 8.40.** If carbon dioxide is cooled at 1 atm, it condenses directly to a solid (**dry ice**) at -78.4°C . The heat of sublimation at this temperature is $\Delta\hat{H}_{\text{sub}}(-78.4^\circ\text{C}) = 6030 \text{ cal/mol}$.
- Calculate the heat removal rate (kW) required to produce 300 kg/h of dry ice at 1 atm and -78.4°C if $\text{CO}_2(\text{v})$ at 20°C is the feed.
 - Suppose the process is carried out at 9.9 atm instead of 1 atm with the same initial and final temperatures. Referring to Figure 6.1-1b on p. 241, write an expression for the required heat removal rate in terms of heat capacities and latent heats of CO_2 in different phases.
- 8.41.** Molten sodium chloride is to be used as a constant-temperature bath for a high-temperature chemical reactor. Two hundred kilograms of solid NaCl at 300 K is charged into an insulated vessel, and a 3000 kW electrical heater is turned on, raising the salt to its melting point of 1073 K and melting it at a constant pressure of 1 atm.
- The heat capacity (C_p) of solid NaCl is $50.41 \text{ J}/(\text{mol}\cdot\text{K})$ at $T = 300 \text{ K}$, and $53.94 \text{ J}/(\text{mol}\cdot\text{K})$ at $T = 500 \text{ K}$, and the heat of fusion of NaCl at 1073 K is 30.21 kJ/mol. Use these data to determine a linear expression for $C_p(T)$ and to calculate $\Delta\hat{H}$ (kJ/mol) for the transition of NaCl from a solid at 300 K to a liquid at 1073 K.
 - Write and solve the energy balance equation for this closed system isobaric process to determine the required heat input in kilojoules.
 - If 85% of the full power of 3000 kW goes into heating and melting the salt, how long does the process take?
- 8.42.** Estimate the heat of vaporization of ethyl benzene at its normal boiling point using Trouton's rule and Chen's rule and compare the results with a tabulated value of this quantity. Then estimate $\Delta\hat{H}_v$ at 100°C using Watson's correlation.
- 8.43.** You are writing energy balances for a compound for which you cannot find heat capacity or latent heat data. All you know about the material are its molecular formula ($\text{C}_7\text{H}_{12}\text{N}$) and that it is a liquid at room temperature and has a normal boiling point of 200°C . Use this information to estimate the enthalpy of the vapor of this substance at 200°C relative to the liquid at 25°C . (Recall Section 8.3c.)
- 8.44.** Estimate the heat of vaporization (kJ/mol) of benzene at a pressure of 100 mm Hg, using each of the following correlations and data:
- The heat of vaporization at the normal boiling point given in Table B.1, the boiling point at 100 mm Hg as determined from the Antoine equation, and Watson's correlation.
 - The Clausius–Clapeyron equation and the boiling points at 50 mm Hg and 150 mm Hg as determined from the Antoine equation.
 - The heat of vaporization at the normal boiling point given in Table B.1, the boiling point at 100 mm Hg as determined from the Antoine equation, and heat capacity data given in Table B. 2.
- 8.45.** A stream of pure cyclopentane vapor flowing at a rate of 1550 L/s at 150°C and 1 atm enters a cooler in which 55% of the feed is condensed at constant pressure.
- What is the temperature at the condenser outlet? Explain how you know (a single sentence should suffice).
 - Prepare and fill in an inlet–outlet enthalpy table and calculate the required cooling rate in kW.
- 8.46.** Humid air at 50°C and 1.0 atm with 2°C of superheat is fed to a condenser. Gas and liquid streams leave the condenser in equilibrium at 20°C and 1 atm.
- Assume a basis of calculation of 100 mol inlet air, draw and label a flowchart (including Q in the labeling), and carry out a degree-of-freedom analysis to verify that all labeled variables can be determined.
 - Write in order the equations you would solve to calculate the mass of water condensed (kg) per cubic meter of air fed to the condenser. Circle the unknown variable for which you would solve each equation. Do not do any of the calculations.
 - Prepare an inlet–outlet enthalpy table, inserting labels for unknown specific enthalpies (\hat{H}_1 , \hat{H}_2, \dots). Write expressions for the labeled specific enthalpies, substituting values or formulas for heat capacities and latent heats but not calculating the values of the specific enthalpies. Then



Equipment
Encyclopedia
condenser



Student
Workbook



Equipment
Encyclopedia
condenser

write an expression for the rate at which heat must be transferred from the unit (kJ) per cubic meter of air fed to the condenser.

- (d) Solve your equations by hand to calculate kg H₂O condensed/m³ air fed and kJ transferred/m³ air fed.

*(e) Use an equation-solving program to perform the calculations of part (d).

- (f) What cooling rate (kW) would be required to process 250 m³ air fed/h?

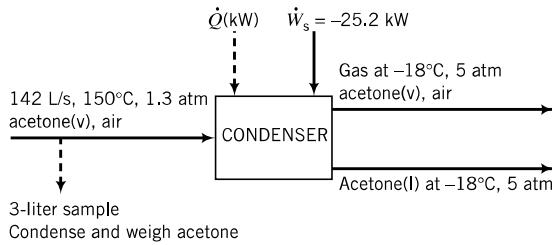
- 8.47.** An air conditioner cools 226 m³/min of humid air at 36°C and 98% relative humidity to 10°C.

(a) Do a degree-of-freedom analysis to prove that enough information is available to determine the required cooling duty (rate of heat transfer).

(b) Calculate the rate of condensation of water in the unit and the cooling duty in tons (1 ton = 12,000 Btu/h).

- 8.48.** A gas stream containing *n*-hexane in nitrogen with a relative saturation of 90% is fed to a condenser at 75°C and 3.0 atm absolute. The product gas emerges at 0°C and 3.0 atm at a rate of 746.7 m³/h. Calculate the percentage condensation of hexane (moles condensed/mole fed) and the rate (kW) at which heat must be transferred from the condenser.

- 8.49.** A gas stream containing acetone in air flows from a solvent recovery unit at a rate of 142 L/s at 150°C and 1.3 atm. The stream flows into a condenser which liquefies most of the acetone, and the liquid and gas outlet streams are in equilibrium at -18°C and 5.0 atm. Shaft work is delivered to the system at a rate of 25.2 kW to achieve the compression from 1.3 atm to 5.0 atm. To determine the condenser feed stream composition, a 3.00-liter sample of the gas is taken and cooled to a temperature at which essentially all the acetone in the sample is recovered as a liquid. The liquid is poured into an empty flask with a mass of 4.017 g. The flask containing the liquid acetone is weighed and found to have a mass of 4.973 g.



(a) Carry out a degree-of-freedom analysis to show that enough information is available to determine the compositions of all streams and the required heat transfer rate.

(b) Write out a complete set of equations for the molar flow rates of all streams, the mole fractions of acetone in the feed and product gas streams, and the rate (kW) at which heat must be removed in the condenser. *Do no calculations.*

(c) Solve the equations of part (b) by hand.

*(d) Solve the equations of part (b) using an equation-solving program.

- 8.50.** A mixture of *n*-hexane vapor and air leaves a solvent recovery unit and flows through a 70-cm diameter duct at a velocity of 3.00 m/s. At a sampling point in the duct the temperature is 40°C, the pressure is 850 mm Hg, and the dew point of the sampled gas is 25°C. The gas is fed to a condenser in which it is cooled at constant pressure, condensing 60% of the hexane in the feed.

(a) Perform a degree-of-freedom analysis to show that enough information is available to calculate the required condenser outlet temperature (°C) and cooling rate (kW).

(b) Perform the calculations.

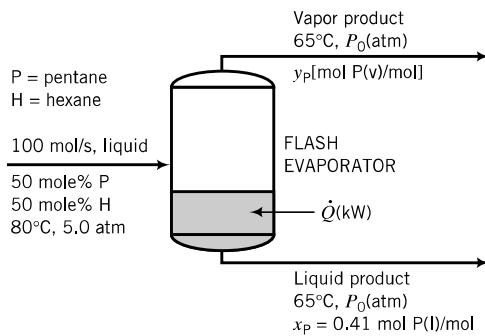
(c) If the feed duct diameter were 35 cm for the same molar flow rate of the feed gas, what would the gas velocity be?

- 8.51.** An equimolar liquid mixture of *n*-pentane and *n*-hexane at 80°C and 5.00 atm is fed into a flash evaporator at a rate of 100.0 mol/s. When the feed is exposed to the reduced pressure in the evaporator, a substantial amount is vaporized. The temperature in the tank is maintained at 65°C by adding heat. The vapor and liquid phases, which are in equilibrium with each other, are separated and discharged



*Computer problems.

as separate streams. The liquid product stream contains 41.0 mole% pentane. A flowchart and an inlet-outlet enthalpy table for the process are given below.



References: P(l, 65°C), H(l, 65°C)

Substance	\dot{n}_{in}	\hat{H}_{in}	\dot{n}_{out}	\hat{H}_{out}
P(l)	\dot{n}_a	\hat{H}_a	\dot{n}_c	\hat{H}_c
P(v)	—	—	\dot{n}_d	\hat{H}_d
H(l)	\dot{n}_b	\hat{H}_b	\dot{n}_e	\hat{H}_e
H(v)	—	—	\dot{n}_f	\hat{H}_f

- (a) Using Raoult's law for vapor-liquid equilibrium calculations, calculate (i) the system pressure, $P_0(\text{atm})$, (ii) the mole fraction of pentane in the vapor product, y_P , (iii) the volumetric flow rate of the vapor product, $\dot{V}(\text{L/s})$, and (iv) the fractional vaporization of pentane, $f(\text{mol vaporized/mol fed})$.
- (b) Determine values for all the \dot{n} 's and \hat{H} 's in the enthalpy table and calculate the required rate of heat addition to the evaporator, $\dot{Q}(\text{kW})$.



Student Workbook



Equipment Encyclopedia



Equipment Encyclopedia
evaporator

- 8.52. A liquid stream containing 50.0 mole% benzene and the balance toluene at 25°C is fed to a continuous single-stage evaporator at a rate of 1320 mol/s. The liquid and vapor streams leaving the evaporator are both at 95.0°C. The liquid contains 42.5 mole% benzene and the vapor contains 73.5 mole% benzene.

- (a) Calculate the heating requirement for this process in kW.
(b) Using Raoult's law (Section 6.4b) to describe the equilibrium between the vapor and liquid outlet streams, determine whether or not the given benzene analyses are consistent with each other. If they are, calculate the pressure (torr) at which the evaporator must be operating; if they are not, give several possible explanations for the inconsistency.

- 8.53. The off-gas from a reactor in a process plant in the heart of an obscure banana republic has been condensing and plugging up the vent line, causing a dangerous pressure buildup in the reactor. Plans have been made to pass the gas directly from the reactor into a cooling condenser in which the gas and liquid condensate will be brought to 25°C.

You have been called in as a consultant to aid in the design of this unit. Unfortunately, the chief (and only) plant engineer has disappeared and nobody else in the plant can tell you what the off-gas is (or what anything else is, for that matter).

However, a job is a job, and you set out to do what you can. You find an elemental analysis in the engineer's notebook indicating that the gas formula is C₅H₁₂O. On another page of the notebook, the off-gas flow rate is given as 235 m³/h at 116°C and 1 atm. You take a sample of the gas and cool it to 25°C, where it proves to be a solid. You then heat the solidified sample at 1 atm and note that it melts at 52°C and boils at 113°C. Finally, you make several assumptions and estimate the heat removal rate in kW required to bring the off-gas from 116°C to 25°C. What is your result?



Equipment Encyclopedia
dryer

- 8.54. A sheet of cellulose acetate film containing 5.00 wt% liquid acetone enters an adiabatic dryer where 90% of the acetone evaporates into a stream of dry air flowing over the film. The film enters the dryer at $T_{f1} = 35^\circ\text{C}$ and leaves at $T_{f2}(\text{°C})$. The air enters the dryer at $T_{a1}(\text{°C})$ and 1.01 atm and exits the dryer at $T_{a2} = 49^\circ\text{C}$ and 1 atm with a relative saturation of 40%. C_p may be taken to be 1.33 kJ/(kg·°C) for dry film and 0.129 kJ/(mol·°C) for liquid acetone. Make a reasonable assumption regarding the heat capacity of dry air. The heat of vaporization of acetone may be considered independent of temperature. Take a basis of 100 kg film fed to the dryer for the requested calculations.

- (a) Estimate the feed ratio [liters dry air (STP)/kg dry film].
(b) Derive an expression for T_{a1} in terms of the film temperature change, $(T_{f2} - 35)$, and use it to answer parts (c) and (d).
(c) Calculate the film temperature change if the inlet air temperature is 120°C.
(d) Calculate the required value of T_{a1} if the film temperature falls to 34°C, and the value if it rises to 36°C.

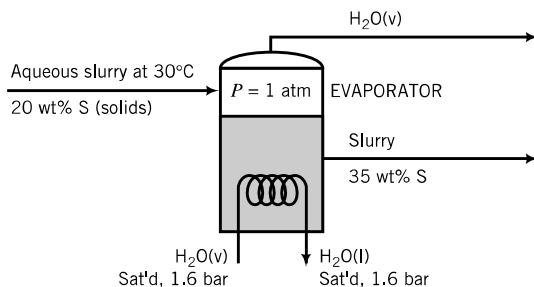
- (e) If you solved parts (c) and (d) correctly, you found that even though the air temperature is consistently higher than the film temperature in the dryer, so that heat is always transferred from the air to the film, the film temperature can drop from the inlet to the outlet. How is this possible?



- 8.55.** Saturated propane vapor at 2.00×10^2 psia is fed to a well-insulated heat exchanger at a rate of 3.00×10^3 SCFH (standard cubic feet per hour). The propane leaves the exchanger as a saturated liquid (i.e., a liquid at its boiling point) at the same pressure. Cooling water enters the exchanger at 70°F, flowing cocurrently (in the same direction) with the propane. The temperature difference between the outlet streams (liquid propane and water) is 15°F.
- (a) What is the outlet temperature of the water stream? (Use the Cox chart on p. 247.) Is the outlet water temperature less than or greater than the outlet propane temperature? Briefly explain.
- (b) Estimate the rate (Btu/h) at which heat must be transferred from the propane to the water in the heat exchanger and the required flow rate (lb_m/h) of the water. (You will need to write two separate energy balances.) Assume the heat capacity of liquid water is constant at 1.00 Btu/(\mathbf{lb}_m \cdot ^\circ\text{F}) and neglect heat losses to the outside and the effects of pressure on the heat of vaporization of propane.



- 8.56.** An aqueous slurry at 30°C containing 20.0 wt% solids is fed to an evaporator in which enough water is vaporized at 1 atm to produce a product slurry containing 35.0 wt% solids. Heat is supplied to the evaporator by feeding saturated steam at 1.6 bar absolute into a coil immersed in the liquid. The steam condenses in the coil, and the slurry boils at the normal boiling point of pure water. The heat capacity of the solids may be taken to be half that of liquid water.



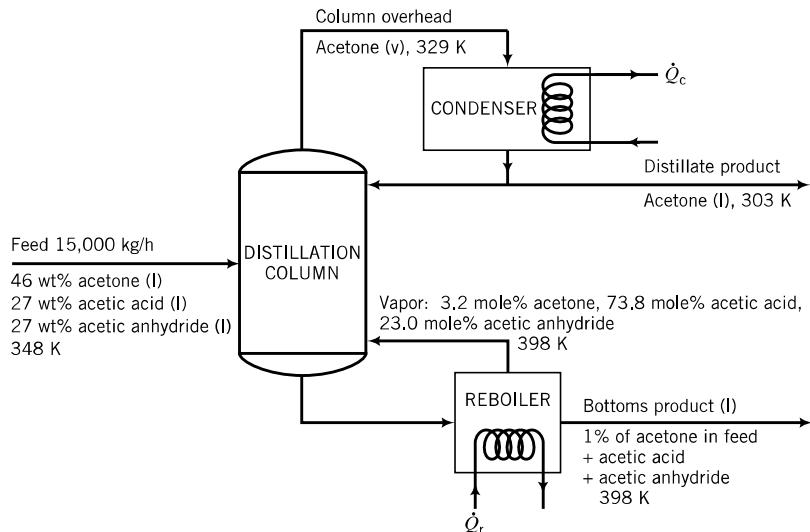
- (a) Calculate the required steam feed rate (kg/h) for a slurry feed rate of 1.00×10^3 kg/h.
- (b) **Vapor recompression** is often used in the operation of an evaporator. Suppose that the vapor (steam) generated in the evaporator described above is compressed to 1.6 bar and simultaneously heated to the saturation temperature at 1.6 bar, so that no condensation occurs. The compressed steam and additional saturated steam at 1.6 bar are then fed to the evaporator coil, in which isobaric condensation occurs. How much additional steam is required?
- (c) What more would you need to know to determine whether or not vapor recompression is economically advantageous in this process?



- 8.57.** A mixture that contains 46 wt% acetone (CH_3COCH_3), 27% acetic acid (CH_3COOH), and 27% acetic anhydride [$(\text{CH}_3\text{CO})_2\text{O}$] is distilled at $P = 1$ atm. The feed enters the distillation column at $T = 348$ K at a rate of 15,000 kg/h. The distillate (overhead product) is essentially pure acetone, and the bottoms product contains 1% of the acetone in the feed.

The vapor effluent from the top of the column enters a condenser at 329 K and emerges as a liquid at 303 K. Half of the condensate is withdrawn as the overhead product, and the remainder is refluxed back to the column. The liquid leaving the bottom of the column goes into a steam-heated reboiler, in which it is partially vaporized. The vapor leaving the reboiler is returned to the column at a temperature of 398 K, and the residual liquid, also at 398 K, constitutes the bottoms product. A flowchart of the process and thermodynamic data for the process materials follow.

- (a) Calculate the molar flow rates and compositions of the product streams.
- (b) Calculate the condenser cooling requirement \dot{Q}_c (kJ/h).
- (c) Use an overall energy balance to determine the reboiler heating requirement \dot{Q}_r (kJ/h).
- (d) If the reboiler heat is provided by the condensation of saturated steam at 10 bar gauge, at what rate must steam be fed?



Thermodynamic Data (All temperatures are in kelvin)

Acetone: $C_{pl} = 2.30 \text{ kJ/(kg}\cdot\text{K)}$

$$C_{pv}[\text{kJ/(kg}\cdot\text{K}]] = 0.459 + 3.15 \times 10^{-3}T - 0.790 \times 10^{-6}T^2$$

$$\Delta\hat{H}_v(329 \text{ K}) = 520.6 \text{ kJ/kg}$$

Acetic acid: $C_{pl} = 2.18 \text{ kJ/(kg}\cdot\text{K)}$

$$C_{pv}[\text{kJ/(kg}\cdot\text{K}]] = 0.688 + 1.87 \times 10^{-3}T - 0.411 \times 10^{-6}T^2$$

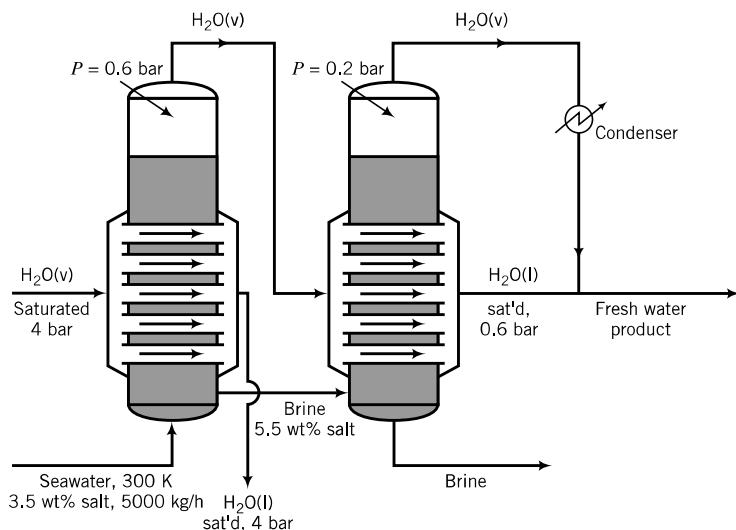
$$\Delta\hat{H}_v(391 \text{ K}) = 406.5 \text{ kJ/kg}$$

Acetic anhydride: $C_{pl}[\text{kJ/(kg}\cdot\text{K}]] = ?$ (Estimate it—see Section 8.3c.)

$$C_{pv}[\text{kJ/(kg}\cdot\text{K}]] = 0.751 + 1.34 \times 10^{-3}T - 0.046 \times 10^{-6}T^2$$

$$\Delta\hat{H}_v(413 \text{ K}) = ?$$
 (Estimate it—see Section 8.4b.)

- 8.58.** A **double-effect evaporator** (two evaporators in series) is used to produce fresh water from seawater containing 3.5 wt% dissolved salts. A flowchart for the process is shown here.



Seawater enters the first effect at 300 K at a rate of 5000 kg/h, and saturated steam at 4.00 bar absolute is fed into a tube bundle in the first effect. The steam condenses at 4.00 bar, and the condensate is withdrawn at the saturation temperature corresponding to this pressure.

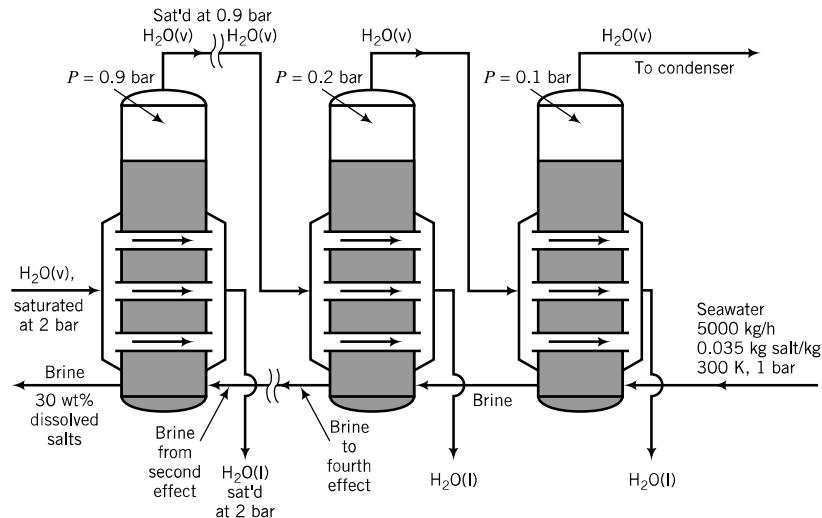
The heat given up by the steam condensing in the tubes causes water to evaporate from the brine solution at the pressure of 0.60 bar maintained in the effect. The exiting brine contains 5.5 wt% salt. The steam generated in the first effect is fed to a tube bundle in the second effect. The condensate from the bundle and the steam generated in the second effect at a pressure of 0.20 bar constitute the fresh water produced in the process.

In solving the problems to be given, assume that the brine solutions in both effects have the physical properties of pure water and that the effects operate adiabatically.

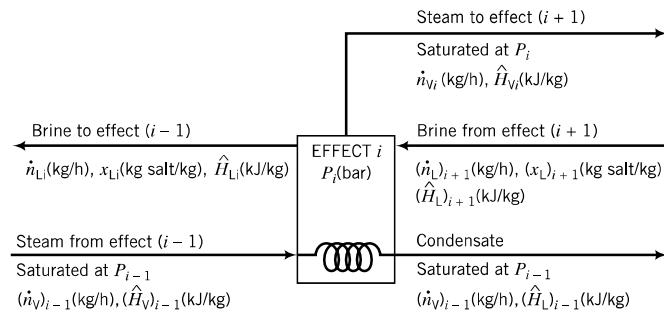
- Draw and label a flowchart of this process, giving the temperature and specific enthalpy of each stream.
- At what rate must steam be fed to the first effect?
- What is the production rate of fresh water? What is the salt concentration (weight percent) of the final brine solution?
- Why is it necessary that the pressure decrease from one effect to the next?
- Suppose a single-effect evaporator were used, operating at $P = 0.20$ bar. Calculate the feed rate of saturated steam at $P = 4.00$ bar that would be required to achieve the same production rate of fresh water. What more would you need to know to determine which process is more economical?



- *8.59.** Seawater containing 3.5 wt% dissolved salts is to be desalinated in an adiabatic six-effect evaporator. (See Problem 8.58.) Backward feed is to be used: the seawater is fed to the last evaporator, and successively concentrated brine solutions flow countercurrent to the direction of flow of steam from one effect to the next. Saturated steam at $P = 2$ bar is fed to the tube bundle in the first effect. The operating pressures in bars of the six effects are, respectively, 0.9, 0.7, 0.5, 0.3, 0.2, and 0.1. The brine leaving the first effect contains 30 wt% salt. The flowchart shows Effects 1, 5, and 6.



Following is a labeled diagram of the i th effect:



*Computer problem.

In terms of the variables defined in this diagram,

$$\begin{aligned}\dot{n}_{L7} &= 5000 \text{ kg/h} \\ x_{L7} &= 0.035 \text{ kg salt/kg} \\ x_{L1} &= 0.30 \text{ kg salt/kg} \\ \dot{n}_{V0} &= \text{feed rate of steam to the first effect}\end{aligned}$$

- (a) Use a salt balance to calculate \dot{n}_{L1} . Then use this result to determine how much fresh water is produced in the process.
 (b) Prepare a table as follows:

	P (bar)	T (K)	\dot{n}_L (kg/h)	x_L	\hat{H}_L (kJ/kg)	\dot{n}_V (kg/h)	\hat{H}_V (kJ/kg)
Fresh steam	2.0	—	—	—	—	—	—
Effect 1	0.9	—	—	0.30	—	—	—
2	0.7	—	—	—	—	—	—
3	0.5	—	—	—	—	—	—
4	0.3	—	—	—	—	—	—
5	0.2	—	—	—	—	—	—
6	0.1	—	—	—	—	—	—
(7)	1.0	300	5000	0.035	—	—	—

Fill in all *known* variable values (do not calculate any yet), including values obtained from the steam tables, *assuming that the physical properties of the brine solution are those of pure water*.

- (c) Show that the following equations can be derived from balances:

$$x_{Li} = (\dot{n}_L)_{i+1}(x_L)_{i+1}/\dot{n}_{Li} \quad (1)$$

$$(\dot{n}_V)_{i-1} = \frac{\dot{n}_{Vi}\hat{H}_{Vi} + \dot{n}_{Li}\hat{H}_{Li} - (\dot{n}_L)_{i+1}(\hat{H}_L)_{i+1}}{(\hat{H}_V)_{i-1} - (\hat{H}_L)_{i-1}} \quad (2)$$

$$(\dot{n}_L)_{i-1} = \dot{n}_{Li} - (\dot{n}_V)_{i-1} \quad (3)$$

- (d) The missing entries in the table of part (b) may be determined by solving Equations 1 through 3 for all effects simultaneously, but this is a cumbersome task. Instead, a relatively simple trial-and-error method may be used, which consists of assuming a value for \dot{n}_{V6} , calculating $\dot{n}_{L6} = \dot{n}_{L7} - \dot{n}_{V6}$, and successively solving Equations 1 through 3 for x_{L6} , \dot{n}_{V5} , \dot{n}_{L5} , then x_{L5} , \dot{n}_{V4} , \dot{n}_{L4} , and so on, until finally x_{L1} is calculated. If the calculated value of x_{L1} is less than the known value of 0.3, a higher value of \dot{n}_{V6} is assumed and the process is repeated; if $x_{L1} > 0.3$, a lower value of \dot{n}_{V6} is assumed. A reasonable first guess for \dot{n}_{V6} is 1/6 of the total rate of evaporation [determined in part (a)].

Construct a spreadsheet program to perform these calculations, using the goalseek tool to carry out the trial-and-error search for the correct value of \dot{n}_{V6} . Fill in the table of part (b).

- (e) Solve the equations of part (c) for all six effects using an equation-solving program. Fill in the table of part (b).

- 8.60. A liquid is placed in a well-insulated container, which is then sealed. Initially, the container and its contents (the liquid and pure nitrogen) are at 93°C and 1 atm; the liquid volume is 70 cm³, and the gas volume is 3.00 L. The liquid partially evaporates, and the system cools down and eventually comes to thermal equilibrium at 85°C with liquid still present. Physical property data for the liquid and its vapor are:

$$\Delta\hat{U}_v = 20 \text{ kcal/mol at } 90^\circ\text{C}$$

$$(C_p)_{liq} = 20 \text{ cal/(mol}\cdot^\circ\text{C)}$$

$$(C_p)_{vap} = 10 \text{ cal/(mol}\cdot^\circ\text{C)}$$

$$(SG)_{liq} = 0.90$$

$$MW = 42$$

- (a) Determine $(C_v)_{\text{liq}}$ and $(C_v)_{\text{vap}}$. (See Equations 8.3-11 and 8.3-12.)
- (b) Draw and label a flowchart for this closed system process, and write and simplify the energy balance equation, assuming adiabatic operation.
- (c) Use the energy balance to calculate the mass of liquid that evaporates, taking 4.97 cal/(mol·°C) as the heat capacity of nitrogen.
- (d) Calculate the vapor pressure of the liquid at 85°C, assuming that the gas volume remains constant at 3.00 L.



- 8.61.** A small pharmaceutical firm plans to manufacture a new drug and has hired you as a consultant to design a condenser to remove the drug from a gas–vapor mixture. The mixture, which contains 20 mole% of the drug and the balance nitrogen, will be fed to the condenser at 510 K and 1 atm at a rate of 3.5 L/s. Of the drug fed to the unit, 90% must be condensed. No physical property data are available for the drug, and part of your job is to acquire the data needed to design the condenser. The company has sent you a large sample of the liquid drug for this purpose.

You acquire an insulated 2.000-liter container with a known heat capacity and a built-in electrical heating coil that can deliver a known heat input to the contents of the container. A calibrated thermocouple is used to measure the temperature in the vessel, and the pressure is measured with a mercury manometer.

You carry out a series of experiments on a day when atmospheric pressure is 763 mm Hg.

Experiment 1. Fill the container with the liquid, then seal and weigh.

$$\text{mass of container + liquid} = 4.4553 \text{ kg}$$

$$\text{mass of evacuated container} = 3.2551 \text{ kg}$$

Next, starting at each of two temperatures (T_0), add a fixed quantity of heat to the liquid, observe the final temperature (T_f), and subtract the heat absorbed by the container from the total heat input to determine the amount of the heat added to the liquid, Q_a .

$$T_0 = 283.0 \text{ K}, Q_a = 800.0 \text{ J} \implies T_f = 285.4 \text{ K}$$

$$T_0 = 330.0 \text{ K}, Q_a = 800.0 \text{ J} \implies T_f = 332.4 \text{ K}$$

Assume that the liquid heat capacity may be expressed as a linear function of temperature ($C_v = aT + b$) when analyzing these results.

Experiment 2. Pour a small quantity of the drug into the container, place the container in a liquid nitrogen bath to freeze the drug, evacuate all of the air, and seal the container. Weigh the container after it comes back to room temperature.

$$\text{mass of container + drug} = 3.2571 \text{ kg}$$

Next heat the sealed container until all of the liquid evaporates, and repeat Experiment 1.

$$T_0 = 363.0 \text{ K}, h_{\text{manometer}} = -500 \text{ mm}, Q_a = 1.30 \text{ J} \implies T_f = 366.9 \text{ K}$$

$$T_0 = 490.0 \text{ K}, h_{\text{manometer}} = -408 \text{ mm}, Q_a = 1.30 \text{ J} \implies T_f = 492.7 \text{ K}$$

Assume that the vapor heat capacity may be expressed as a linear function of temperature when analyzing these results.

Experiment 3. Fill approximately half the container with the drug, freeze, evacuate the air, and seal. Measure the pressure at several temperatures, verifying that liquid is present in the container at each temperature.

$$T = 315.0 \text{ K}, h_{\text{manometer}} = -564 \text{ mm}$$

$$T = 334.0 \text{ K}, h_{\text{manometer}} = -362 \text{ mm}$$

$$T = 354.0 \text{ K}, h_{\text{manometer}} = -2 \text{ mm}$$

$$T = 379.0 \text{ K}, h_{\text{manometer}} = +758 \text{ mm}$$

- (a) Using the given data, determine the following physical properties of the drug: (i) liquid specific gravity, (ii) molecular weight, (iii) linear expressions for the heat capacities at constant volume [in J/(mol·K)] for both the liquid and vapor [$C_v = a + bT(K)$], (iv) linear expressions for C_p for both liquid and vapor, (v) a Clausius–Clapeyron expression for $p^*(T)$, (vi) the normal boiling point, and (vii) the heat of vaporization (in J/mol) at the normal boiling point.
- (b) Calculate the required condenser temperature, assuming operation at 1 atm.



- (c) Calculate the rate at which heat must be removed in the condenser, taking the heat capacity of nitrogen to be constant at $29.0 \text{ J}/(\text{mol}\cdot\text{K})$.

8.62. Freeze drying is a technique for dehydrating substances at low temperatures, thereby avoiding the degradation that may accompany heating. The material to be dried is cooled to a temperature at which all of the water present turns to ice. The frozen substance is then placed in a vacuum chamber and may also be subjected to radiant or microwave heating; the ice in the food sublimates, and the vapor is carried off by the vacuum pump.

Steaks are to be freeze-dried in a heated chamber at 1 torr (1 mm Hg). The steaks, which contain 72% water by mass, enter the chamber at -26°C at a rate of 50 kg/min. Of the water entering with the steaks, 96% leaves as a vapor at 60°C ; the remainder leaves as a liquid with the steaks at 50°C .

- (a) Use the heat capacity data given below and additional tabulated data for water to calculate the required heat input in kilowatts.

$$(C_p)_{\text{ice}} = 2.17 \text{ J}/(\text{g}\cdot\text{C}^\circ)$$

$$(C_p)_{\text{dry meat}} = 1.38 \text{ J}/(\text{g}\cdot\text{C}^\circ)$$

- (b) When large temperature changes are not involved in a phase-change operation, a reasonable estimate of the required heat transfer rate may be obtained by neglecting contributions of temperature changes to the overall process enthalpy change (i.e., by taking only phase changes into account). Moreover, it is often reasonable to use any available values of latent heats, neglecting their dependence on temperature and pressure. In the case of the freeze-drying process, the approximation might be to calculate only the heat needed to melt all the water and vaporize 96% of it, using latent heats at the normal melting and boiling points (Table B.1) and neglecting the heat required to raise the temperature of the meat and water. What percentage error in the calculated value of \dot{Q} would result from this approximation? Take the value determined in part (a) to be exact.



8.63. Freeze concentration is used to produce a fruit-juice concentrate. A stream of fresh juice containing 12 wt% soluble solids in water at 20°C is combined with a recycle stream to form a preconcentrate, which is fed to a crystallizer. The mixture is cooled in the crystallizer to -7°C , thereby crystallizing 20,000 kg/h of ice. A slurry leaves the crystallizer containing 10 wt% ice and is fed to a filter. The filtrate, which contains 45 wt% dissolved solids, is removed as the process product. The remaining slurry, which contains all the ice and some concentrate (also containing 45% dissolved solids), is sent to a separator that cleanly removes all of the ice. The residual liquid is the recycle stream that combines with the fresh feed to form the preconcentrate.

- (a) Determine the rates (kg/h) at which fresh fruit juice is fed and concentrate is produced, and the mass flow rate (kg/h) and solids concentration of the preconcentrate.
 (b) Calculate the cooling requirement (kW) for the freezer, assuming that the temperature of the recycle stream is 0°C and the heat capacity of all solutions is $4.0 \text{ kJ}/(\text{kg}\cdot\text{C}^\circ)$.



8.64. A mixture containing 35.0 mole% *n*-butane and the balance isobutane at 10°C enters a heat exchanger at a rate of 24.5 kmol/h and a pressure high enough for the mixture to be a liquid. The exchanger has been designed to heat and vaporize the liquid and heat the vapor mixture to 180°C . The heating fluid is a high molecular weight liquid with a constant heat capacity $C_p = 2.62 \text{ kJ}/(\text{kg}\cdot\text{C}^\circ)$. It enters the exchanger at 215°C and flows countercurrently to the hydrocarbon mixture.

- (a) Estimate the minimum pressure (bar) required for the hydrocarbon feed to be a liquid. Use Raoult's law and the Cox chart (Figure 6.1-4) in your calculation.
 (b) Assuming that the heat capacities and heats of vaporization of *n*-butane and isobutane are independent of pressure (so that the values in Tables B.1 and B.2 may be used), calculate the enthalpy change $\Delta\dot{H}$ (kJ/h) undergone by the hydrocarbon mixture in the heat exchanger. Show the process paths you use for *n*-butane and *i*-butane in your calculation. (*Hint:* Since you don't have heat capacities for liquid *n*-butane and *i*-butane in this text, use process paths that don't require them.)
 (c) According to the heat exchanger design calculations, the heating fluid exit temperature should be 45°C . Assuming that all the heat lost by the heating fluid is transferred to the hydrocarbon mixture, what is the required mass flow rate of the heating fluid, \dot{m}_{hf} (kg/h)?
 (d) When the heat exchanger is run with \dot{m}_{hf} equal to the value calculated in part (b), the exit temperature of the hydrocarbon mixture is measured and found to be only 155°C instead of the design value of 180°C . The process operator observes that the outside of the exchanger is hot to the touch, indicating that some of the heat lost by the heating fluid is escaping into the plant

instead of being transferred to the hydrocarbon mixture. After discussing the situation with a production engineer, the operator gradually increases the flow rate of the heating fluid while continuing to monitor the outlet temperature of the hydrocarbon. When the flow rate reaches 2540 kg/h, the outlet fluid temperatures level out at their design values (180°C for the hydrocarbon and 45°C for the heating fluid). At what rate (kJ/h) is heat being transferred from the exchanger to the plant air?

- (e) When the heating fluid leaves the exchanger, it passes through a heater, which raises its temperature back to 215°C, and is recycled back to the exchanger. How is the profitability of the process being decreased by the heat loss from the exchanger to the surroundings? (Try to think of two costs that result from the heat loss.)
 - (f) The engineer proposes adding more insulation to the heat exchanger, which would cut down on the heat loss and reduce the required heating fluid flow rate. What are advantages and disadvantages of the two responses to the heat loss problem (adding insulation versus increasing the heating fluid flow rate)? Which would you guess would be the preferable response in the long run, and why?
- 8.65.** A liquid mixture of benzene and toluene containing 50.0 wt% benzene at 90°C and pressure P_0 is fed at a rate of 32.5 m³/h into a **flash evaporator**, a heated tank maintained at a pressure $P_{\text{tank}} \ll P_0$. When the feed is exposed to the reduced pressure in this unit, a portion of it evaporates. The liquid and vapor product streams are in equilibrium at 75°C and P_{tank} . The liquid product contains 43.9 mole% benzene. When carrying out the requested calculations, assume volume additivity of liquid benzene and toluene, use Raoult's law and the Antoine equation where necessary, and neglect the effect of pressure on enthalpy.
- (a) Calculate the molar flow rate (mol/s) and molar composition (component mole fractions) of the feed stream. Then calculate the minimum value of P_0 (atm) needed to keep the feed stream in the liquid state until it enters the flash tank.
 - (b) Calculate P_{tank} (atm), the mole fraction of benzene in the vapor, and the molar flow rates of the liquid and vapor products.
 - (c) Calculate the required heat input rate in kilowatts.
 - (d) An hour after the system is started up, a chromatographic analysis of the vapor product is run and the benzene mole fraction is found to be 3% higher than the value calculated in part (b). The system temperature and pressure are rechecked and found to have the correct values. Give several possible explanations of the discrepancy between the calculated and measured values.
 - (e) Briefly explain why the product temperature is lower than the feed temperature. What would be required to run the unit isothermally?
- *8.66.** A continuous adiabatic flash tank is to be used to separate a liquid mixture of two substances (A and B). The feed enters at temperature T_F and a high pressure and flashes to a low pressure, P , whereupon its temperature drops to T . For an assumed basis of 1 mol/s of feed, let

\dot{n}_L, \dot{n}_V = molar flow rates of liquid product and vapor product

x_F, x, y = mole fractions of A in the feed, liquid product, and vapor product

$p_A^*(T), p_B^*(T)$ = vapor pressures of A and B

T_{RA}, T_{RB} = reference temperatures for enthalpy calculations

$$\left. \begin{array}{l} \hat{H}_{AF}(T_F), \hat{H}_{AL}(T), \hat{H}_{AV}(T) \\ \hat{H}_{BF}(T_F), \hat{H}_{BL}(T), \hat{H}_{BV}(T) \end{array} \right\} \begin{array}{l} \text{specific enthalpies of A and B in} \\ \text{the feed, liquid product, and vapor} \\ \text{product, relative to } T_{RA} \text{ and } T_{RB} \end{array}$$

- (a) Derive the following relations from Raoult's law and material and energy balances on the flash tank:

$$x = \frac{P - p_B^*(T)}{p_A^*(T) - p_B^*(T)} \quad (1)$$

$$y = xp_A^*(T)/P \quad (2)$$

$$\dot{n}_L = \frac{y - x_F}{y - x} \quad (3)$$

*Computer problem.

$$\dot{n}_V = 1 - \dot{n}_L \quad (4)$$

$$\begin{aligned} \Delta \dot{H} &= \dot{n}_L[x\hat{H}_{AL}(T) + (1-x)\hat{H}_{BL}(T)] + \dot{n}_V[y\hat{H}_{AV}(T) + (1-y)\hat{H}_{BV}(T)] \\ &\quad - [x_F\hat{H}_{AF}(T_F) + (1-x_F)\hat{H}_{BF}(T_F)] = 0 \end{aligned} \quad (5)$$

- (b) Write a spreadsheet program to perform flash calculations for a feed mixture of *n*-pentane and *n*-hexane. When calculating enthalpies of these species, the following heat capacity formulas should be used for liquid and vapor, respectively:

$$C_{pl} = a_l$$

$$C_{pv} = a_v + b_v T(^{\circ}\text{C})$$

The spreadsheet should have the following form. Some values are given, others should be looked up in data tables, and the remainder should be calculated from Equations 1 to 5 and appropriate formulas for specific enthalpies.

Chapter 8—Problem 8.66								
Tref = 25 deg. C								
Compound	A	B	C	al	av	bv	Tbp	DHv
n-pentane	6.84471	1060.793	231.541	0.195	0.115	3.41E-4	36.07	25.77
n-hexane				0.216	0.137	4.09E-4		
xF	0.5	0.5	0.5	0.5				
Tf(deg.C)	110	110	150					
P(mm Hg)	760	1000	1000					
HAF (kJ/mol)								
HBF (kJ/mol)								
T(deg.C)	80.0							
pA* (mm Hg)								
pB* (mm Hg)								
x								
y								
nL (mol/s)								
nV (mol/s)								
HAL (kJ/mol)								
HBL (kJ/mol)								
HAV (kJ/mol)								
HBV (kJ/mol)								
DH (kJ/s)	-51.333							

In this table, A, B, and C are Antoine equation constants, al, av, and bv are the coefficients of the given heat capacity formulas; Tbp(°C) and DHv(kJ/mol) ($\Delta\hat{H}_v$) are the normal boiling point and heat of vaporization, xF(mol pentane/mol) is the mole fraction of pentane in the feed, Tf(°C) is the feed temperature, P(mm Hg) is the system pressure, HAF (\hat{H}_{AF}) and HBF (\hat{H}_{BF}) are the specific enthalpies of pentane and hexane in the feed stream, pA* is the vapor pressure of *n*-pentane (to be determined using the Antoine equation), x and nL (x and n_L) are the mole fraction of pentane in the liquid product stream and the molar flow rate of that stream, respectively, y and nV are the corresponding properties of the vapor product stream, HAL is the specific enthalpy of pentane in the liquid product stream, and DH ($\Delta\dot{H}$) is the expression given in Equation 5 for the change in total enthalpy from inlet to outlet.

Enter the appropriate constants and formulas for A, B, C, al, av, bv, Tbp, and DHv for *n*-pentane and *n*-hexane, an initial guess for T in Column 2 (= 80.0), and the appropriate formulas for the rest of the variables in Column 2. Then vary the value of T until the value of $\Delta\dot{H}$ is suitably close to zero, using the goalseek tool if your spreadsheet program provides it. The value of $\Delta\dot{H}$ (-51.33 kJ/s) corresponding to the initial guess of 80°C is shown in the second column of the table. Your spreadsheet should generate the same value.

After completing the calculations in the second column, copy the formulas into the third and fourth columns and perform the calculations for these two sets of input parameter values. State how increasing the system pressure and feed temperature affect the fraction of the feed vaporized (nV) and the final system temperature (T), and briefly explain why your results make sense.

- *c)** Write a computer program to read in and print out values of x_F , T_F (°C), and P (mm Hg), and for each of the feed mixture components the Antoine equation coefficients, a reference temperature (e.g., 25°C), the liquid heat capacity (assume constant), normal boiling point, heat of vaporization, and coefficients of a two-term vapor heat capacity formula $C_p = a + bT$. Then have the program carry out a trial-and-error procedure to calculate and print out the flash tank temperature and the flow rates and compositions of the vapor and liquid product streams.

An inefficient but simple procedure is to assume a value of T (T_F is a reasonable first guess), solve Equations 1 through 4 successively, and then evaluate the left side of Equation 5 (which equals $\Delta\dot{H}$ for the assumed temperature and must be positive when $T = T_F$). The value of T is then decreased by a small fixed amount, such as 0.5°C, and the procedure is repeated until the sign of $\Delta\dot{H}$ changes from positive to negative from one T to the next. The true T (for which $\Delta\dot{H} = 0$) must lie between the two last assumed values and may be estimated by linear interpolation. When calculating specific enthalpies, use the heat capacity formulas for pentane and hexane given in part (b).

A flowchart for a program to implement this procedure is shown in Figure P8.1. Write the program and test it by estimating the flash tank temperature and product stream flow rates (mol/s) and compositions (mole fractions) for the flash vaporization of one mol/s of an equimolar mixture of *n*-pentane (A) and *n*-hexane (B), if the feed temperature is 110°C and the tank pressure is 1.0 atm.

- 8.67.** A saturated vapor stream containing 10.9 mole% propane, 75.2% isobutane, and 13.9% *n*-butane passes from the top of a distillation column to a total condenser. Seventy-five percent of the condensate is returned to the column as reflux, and the remainder is removed as the overhead column product at a rate of 2500 kmol/h.

A decision must be made on whether to use a refrigerant or cooling water in the condenser. If the refrigerant is used, it will be fed to the condenser as a liquid and vaporized by the heat released by the condensing column vapor. The refrigerant pressure will be such that the vaporization takes place at -6°C, at which temperature $\Delta\hat{H}_v = 151$ kJ/kg. The other option calls for cooling water to be taken from a nearby river at its average summer temperature of 25°C. To avoid environmental problems, the temperature of the water returned to the river can be no greater than 34°C. With either system, the temperature of the condensate should be 6°C greater than the outlet temperature of the coolant, so that if the refrigerant is used the saturated condensate should have a temperature of 0°C, and if cooling water is used the saturated condensate should be at 40°C. The condenser pressure will be set to the minimum value needed to condense all of the vapor, which is to say the condensate



*Computer problem.

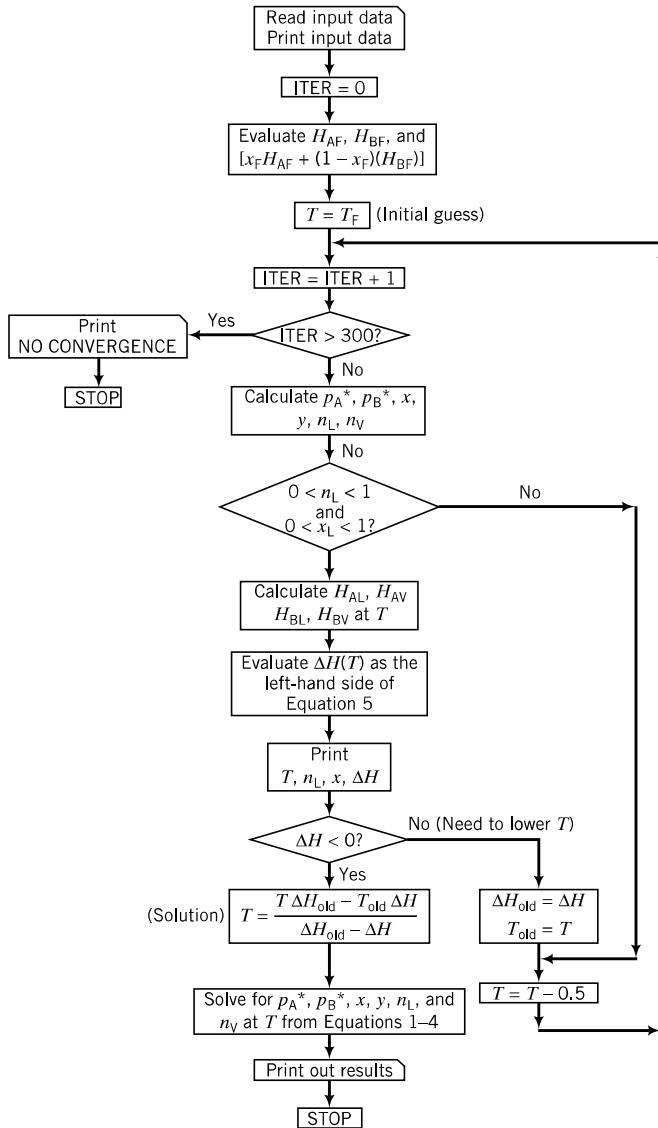


Figure P8.1 Flowchart for program of Problem 8.66.

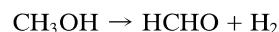
will be at its bubble-point temperature at the condenser pressure. Raoult's law may be used for all bubble-point and dew-point calculations (see Section 6.4c).

(a) Suppose the refrigerant is used for cooling. Estimate the condenser pressure P (mm Hg); the temperature T_f (°C) of the vapor fed to the condenser, assuming that the vapor is at its dew point at pressure P ; and the required coolant flow rate (kg/h).

(b) Repeat part (a) assuming that cooling water is fed to the condenser.

(c) What more would you need to know to be able to choose between the two options?

- 8.68. Formaldehyde is produced from methanol in a catalytic oxidation reactor. The following reactions take place:



A stream of methanol is joined by a recycle stream, also methanol, and the combined stream is fed to the conversion reactor. Also entering the reactor are air (to oxidize some of the hydrogen produced in the methanol conversion reaction) and steam (to control the reactor temperature). The product

gas from the reactor contains 19.9 mole% formaldehyde, 8.34% methanol, 30.3% nitrogen, 0.830% oxygen, 5.0% hydrogen, and 35.6% water vapor and is at 600°C and 1 atm.

The following process is used to separate the formaldehyde from the unreacted methanol and noncondensable gases. The gases leaving the reactor are fed to a waste-heat boiler, in which they are cooled to 145°C, in the process generating steam at 3.1 bar from saturated liquid water (i.e., liquid water at its boiling point) at the same pressure. The gases are cooled further to 100°C in a heat exchanger, where they come into thermal contact with cooling water fed at 30°C. To reduce scaling on the heat exchanger tubes, the temperature increase of the cooling water is limited to 15°C. The cooled gases are fed to an absorption column, where methanol and formaldehyde are absorbed in water. Pure water at 20°C is fed to the top of the column. The gas leaving the absorber is saturated with water vapor at 27°C and 1 atm and contains 200 parts of formaldehyde per million parts (by volume) of total gas. The aqueous solution leaving the bottom of the absorber at 88°C is fed to a distillation column that operates at 1 atm. The final product solution, which contains 37 wt% formaldehyde, 1% methanol, and the balance water, is removed from the reboiler at the bottom of the column, while pure methanol vapor emerges as the overhead product and is condensed at 1 atm. A portion of the condensate is refluxed to the top of the column, and the rest is recycled to the methanol conversion reactor. The reflux ratio, or ratio of methanol refluxed to methanol recycled to the reactor, is 2.5:1.

- (a) Taking as a basis of calculation 100 mol of gas leaving the conversion reactor, draw and completely label a flowchart of this process. Then calculate the moles of fresh methanol feed, formaldehyde product solution, recycled methanol, and absorber off-gas, the kg of steam generated in the waste-heat boiler, and the kg of cooling water fed to the heat exchanger between the waste-heat boiler and the absorber. Finally, calculate the heat (kJ) that must be removed in the distillation column overhead condenser, assuming that methanol enters as a saturated vapor at 1 atm and leaves as a saturated liquid at the same pressure.
- (b) By what factor must all of the calculated quantities be multiplied to scale the flowchart to a production rate of 3.6×10^4 metric tons per year of formaldehyde solution, assuming that the process is on-stream 350 days per calendar year?

- 8.69.** The latest weather report states that the temperature is 24°C and the relative humidity is 50%.
- (a) Use the psychrometric chart to estimate the absolute humidity, humid volume, specific enthalpy, wet-bulb temperature, and dew-point temperature of the air.
 - (b) A thermometer is mounted on the back porch of your house. What temperature would it read?
 - (c) A sample of outside air is cooled at constant pressure. At what temperature would condensation begin?
 - (d) You step out of your neighborhood pool and feel quite cold until you dry off. Explain why. Estimate your skin temperature while you were still wet. Explain your answer. What would be different if the relative humidity were 98%?
- 8.70.** An open vessel containing 0.205 lb_m of liquid water is placed in an empty room 5 ft wide, 4 ft deep, and 7 ft high, which initially contains dry air at 90°F. All the water evaporates without changing the room temperature. Use the psychrometric chart to estimate the final relative humidity, wet-bulb temperature, humid volume, dew-point temperature, and specific enthalpy of the room air. Take the molecular weight of dry air to be 29.0, and for simplicity, assume the mass of dry air in the room stays constant at its initial value.

- 8.71.** A **sling psychrometer** is a device to measure the humidity of air. A porous cloth (the **wick**) is wrapped around the bulb of a mercury thermometer, which is then whirled around in the air. As the water in the wick evaporates, the temperature of the thermometer bulb drops, and finally stabilizes at the wet-bulb temperature of the air. The dry-bulb temperature is read from a second thermometer mounted on the sling.

One summer day, the weather bureau reports a temperature of 33°C and a relative humidity of 40%. You wipe the sweat from your forehead and remark to a friend that you'd bet \$5 that the report is wrong, and the relative humidity is higher than 80%. He immediately puts a \$5 bill on the table, accepting your challenge. You bring out your sling psychrometer, whirl it around, and read a dry-bulb temperature of 35°C and a wet-bulb temperature of 27°C. Who wins the bet?

- 8.72.** Humid air is enclosed in a 2.00-liter flask at 40°C. The flask is slowly cooled. When the temperature reaches 20°C, drops of moisture become visible on the flask wall. Although the pressure in the flask changes when the temperature drops, it remains close enough to 1 atm for the psychrometric chart



Equipment
Encyclopedia
thermometer



Equipment
Encyclopedia
sling psychrometer



Student
Workbook

to provide a close representation of the behavior of the system throughout the process. Use the chart to solve the following problems.

- What were the relative humidity, absolute humidity, and wet-bulb temperature of the air at 40°C?
- Calculate the mass of the water in the flask. (See Example 8.4-5.)
- Calculate the enthalpy change in joules undergone by the air in going from 40°C to 20°C.
- Write an energy balance for this closed-system process, taking the wet air in the flask as the system, and use it to calculate the heat in joules that must be transferred from the air to accomplish the cooling. (Assume ideal gas behavior, so that $\dot{H} = \dot{U} + RT$.)



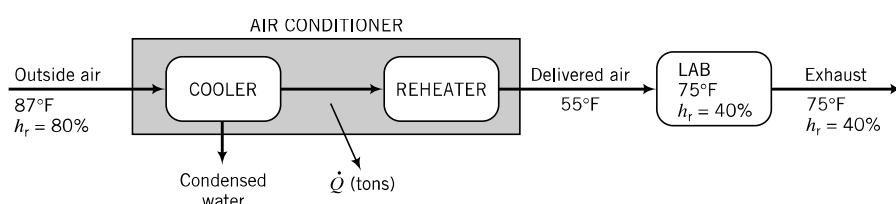
- 8.73.** Wet solids pass through a continuous dryer. Hot dry air enters the dryer at a rate of 400 kg/min and picks up the water that evaporates from the solids. Humid air leaves the dryer at 50°C containing 2.44 wt% water vapor and passes through a condenser in which it is cooled to 10°C. The pressure is constant at 1 atm throughout the system.

- At what rate (kg/min) is water evaporating in the dryer?
- Use the psychrometric chart to estimate the wet-bulb temperature, relative humidity, dew point, and specific enthalpy of the air leaving the dryer.
- Use the psychrometric chart to estimate the absolute humidity and specific enthalpy of the air leaving the condenser.
- Use the results of parts (b) and (c) to calculate the rate of condensation of water (kg/min) and the rate at which heat must be transferred from the condenser (kW).
- If the dryer operates adiabatically, what can you conclude about the temperature of the entering air? Briefly explain your reasoning. What additional information would you need to calculate this temperature?



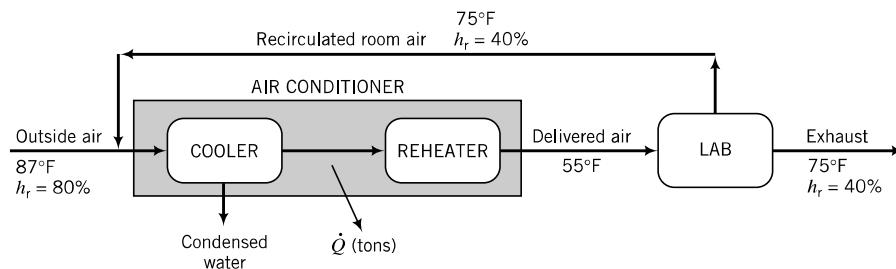
- 8.74.** On an uncomfortable summer day, the air is at 87°F and 80% relative humidity. A laboratory air conditioner is to deliver $1.00 \times 10^3 \text{ ft}^3/\text{min}$ of air at 55°F in order to maintain the interior air at an average temperature of 75°F and a relative humidity of 40%.

- If the vent switch on the air conditioner is turned to the "open" position, outside air enters the unit as shown below.



In the air conditioner, the air is cooled to a temperature low enough to condense the necessary amount of water and reheated to 55°F, at which point it has the same absolute humidity as the room air. Use the psychrometric chart to estimate the rate (lb_m/min) at which water is condensed, the temperature to which the air must be cooled to condense water at this rate, and the net tons of cooling required (\dot{Q}), where 1 ton of cooling = -12,000 Btu/h. [Note: The humid volume of the delivered air (at 55°F), which is difficult to read from the psychrometric chart, is $13.07 \text{ ft}^3/\text{lb}_m$ dry air, and the heat capacity of liquid water is $1.0 \text{ Btu}/(\text{lb}_m \cdot ^\circ\text{F})$.]

- If the vent switch is set to the "closed" position (as it normally would be), inside air would be recirculated through the air conditioner as shown in the following diagram.

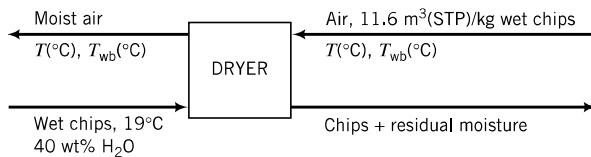


The recycle ratio ($\text{ft}^3 \text{ recirculated}/\text{ft}^3 \text{ exhausted}$) is 6:1. Calculate the condensation rate and the overall cooling requirement in tons if conditioned air is delivered at the same rate, temperature, and relative humidity as in part (a). What percentage of the cooling load on the air conditioner is saved by recirculating the air? Explain in your own words why the cooling rate is lower when room air is recirculated instead of bringing all the air in from the outside.

- (c) An even lower cooling load would be required if *all* of the air passing through the conditioner were recirculated rather than just 6/7 of it, thereby eliminating the need for outside air and exhaust. Why would this be a bad idea? (*Hint:* Think about the people working in the laboratory.)

- 8.75.** Wet wood chips are dried in a continuous rotary dryer that operates at atmospheric pressure. The chips enter at 19°C with a water content of 40 wt% and must leave with a moisture content of less than 15%. Hot air is fed to the dryer at a rate of $11.6 \text{ m}^3(\text{STP})/\text{kg}$ wet chips.

To monitor the performance of the dryer by sampling the exiting chips and determining their moisture content directly would be a cumbersome procedure and almost impossible to automate. Instead, wet- and dry-bulb thermometers are mounted in both the inlet and outlet air lines, and the moisture content of the exiting chips is determined by a material balance.



After the unit goes on-stream, the inlet dry-bulb temperature is found to be 100°C , and the wet-bulb temperature is low enough so that the moisture content of the air may be neglected. The dry-bulb temperature of the exiting air is found to be 38°C , and the wet-bulb temperature is 29°C .

- (a) Use the psychrometric chart to calculate the absolute humidity ($\text{kg H}_2\text{O}/\text{kg dry air}$) and specific enthalpy (kJ/kg dry air) of the outlet air stream. Then calculate the mass of water in the exiting air per kilogram of wet chips fed, assuming dry air has a molecular weight of 29.0.
 (b) Calculate the moisture content of the emerging chips and determine whether the design specification of less than 15% H_2O has been achieved.
 (c) If the unit is operating adiabatically and the heat capacity of the dry chips is $2.10 \text{ kJ}/(\text{kg} \cdot ^\circ\text{C})$, what is the exit temperature of the chips? (In estimating the specific enthalpy of the entering air, recall that the reference temperature for dry air used in constructing the psychrometric chart of Figure 8.4-1 is 0°C .)

- 8.76.** Air at 45°C (dry bulb) and 10% relative humidity is to be humidified adiabatically to 60% relative humidity.

- (a) Use the psychrometric chart to estimate the adiabatic saturation temperature of the air.
 (b) Estimate the final temperature of the air and the rate at which water must be added to humidify 15 kg/min of the entering air. (See Example 8.4-7.)

- 8.77.** Air at 50°C with a dew point of 4°C enters a textile dryer at a rate of $11.3 \text{ m}^3/\text{min}$ and leaves saturated. The dryer operates adiabatically. Use the psychrometric chart to determine the absolute humidity and humid volume of the entering air, and then use the results to determine the flow rate of *dry* air (kg/min) through the dryer, the final temperature of the air, and the rate (kg/min) at which water is evaporated in the dryer. (*Hint:* Refer to Section 8.4e.)

- 8.78.** A solution of sugar in water is to be concentrated from 5 wt% sugar to 20% sugar. The solution is at about 45°C when it is fed continuously to a bubble column. Air at 45°C with a dew point of 4°C is bubbled through the column and emerges saturated. The humidification of the air may be considered adiabatic. (See figure on next page.) Use the psychrometric chart to solve the following problems:

- (a) What are the absolute humidities of the entering and exiting air?
 (b) How many kilograms of dry air must be fed per kilogram of the entering sugar solution? What is the corresponding volume of the entering wet air? (Use the chart for the latter problem as well.)



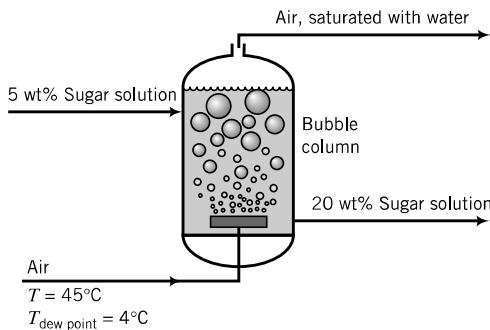
Equipment
Encyclopedia
dryer



Equipment
Encyclopedia
humidifier



Equipment
Encyclopedia
dryer

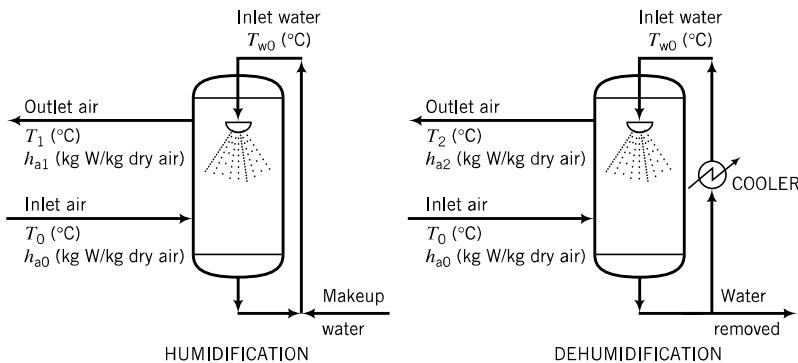


- 8.79.** Cold air at 20°F , 760 mm Hg pressure, and 70% relative humidity is conditioned by being passed through a bank of heating coils, then through a water spray, and finally through a second set of heating coils. In passing through the first coil bank, the air is heated to 75°F . The temperature of the water supplied to the spray chamber is adjusted to the wet-bulb temperature of the air admitted to the chamber, so that the humidifying unit may be assumed to operate adiabatically. It is required that the air emerging from the conditioning unit be at 70°F and 35% relative humidity. Use Figure 8.4-2 to solve the following problems.

- Calculate the temperature of the water supplied to the spray chamber and the relative humidity and dry-bulb temperature of the air leaving the spray chamber.
- Calculate the mass of water evaporated (lb_m) per cubic foot of air fed to the conditioning unit.
- Calculate the required heat transfer rates (Btu/ft³ entering air) in each of the heating coil banks.
- Sketch a psychrometric chart and show the path followed by the air in each of the three steps of this process.

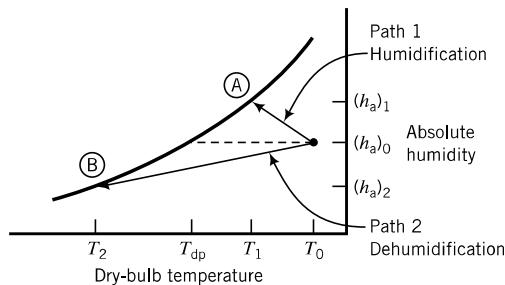


- 8.80.** **Spray cooling** is a technique for cooling and either humidifying or dehumidifying air by contacting it with a liquid water spray.



The liquid water leaving the tower is recirculated and, in the case of dehumidification, cooled before reentering the tower.

Two possible paths on the psychrometric chart corresponding to two different entering liquid temperatures are shown below. On the chart, T_0 and T_{dp} are the entering air dry-bulb temperature and dew point, respectively.



Path (A): The entering liquid temperature (T_{w0}) is above the dew point of the entering air. Liquid water evaporates into the superheated air, causing the absolute humidity of the air to increase (the path rises) and both the evaporation and the contact with the cold liquid cause the air temperature to decrease (the path moves to the left).

Path (B): The entering liquid temperature is below the dew point of the entering air. The temperature of the air contacted by the cold spray drops below the dew point (the path again moves to the left), and water vapor condenses out of the air (the path moves down).

We thus arrive at the interesting conclusion that *you can remove water from air by spraying water into the air*, provided that the entering liquid temperature is below the dew point of the entering air.

Use the psychrometric chart to solve the following spray cooling problems.

- A spray tower is used to cool and humidify air with dry-bulb and wet-bulb temperatures of 40°C and 18°C, respectively. The air emerges from the tower at 20°C. The tower operation is such that the air follows an adiabatic humidification curve (a constant wet-bulb temperature line on the psychrometric chart). How much water must be added as makeup per kg of dry air treated?
- A stream of air at 37°C and 50% relative humidity flowing at a rate of 1250 kg/h is to be cooled to 15°C and dehumidified in a spray tower. The air is saturated as it emerges from the tower. Liquid water leaves the tower at 12°C; some is withdrawn, and the rest is cooled and recirculated. No heat is transferred between the tower and its surroundings. Calculate the rate (kg/h) at which water must be withdrawn from the recirculation loop and the heat duty on the cooler (kW). (*Suggestion:* Use an overall energy balance for the latter calculation.)

- 8.81.** The heat of solution of ammonia in water at 1 atm is

$$\Delta\hat{H}_s(25^\circ\text{C}, r = 2 \text{ mol H}_2\text{O/mol NH}_3) = -78.2 \text{ kJ/mol}$$

Calculate the enthalpy change that accompanies the dissolution of 400 mol of NH₃ in 800 mol of water at 25°C and 1 atm.

- 8.82.** Use Table B.11 to determine the specific enthalpy (kJ/mol HCl) of hydrochloric acid containing 1 mol HCl/5 mol H₂O at 25°C relative to:
- HCl(g) and H₂O(l) at 25°C.
 - H₂O (l) and an infinitely dilute HCl solution at 25°C. (Note Equation 8.5-2.)
- 8.83.** Sodium hydroxide is dissolved in enough water to make up a 20.0 mole % solution. If the NaOH and water are initially at 77°F (25°C), how much heat (Btu/lb product solution) must be removed for the solution also to be at 77°F. Assume the process is carried out at constant pressure, so that $Q = \Delta H$, and use Table B.11 to evaluate $\Delta\hat{H}_s$.
- 8.84.** A sulfuric acid solution is labeled 8N (where 1N = 1 g-equivalent /L, and 1 mol of H₂SO₄ contains two g-equivalents). The specific gravity of the solution is 1.230, and its heat capacity is 3.00 J/(g·°C). Calculate the specific enthalpy of this solution (in kJ/mol H₂SO₄) at 60°C relative to pure H₂O and an infinitely dilute solution at 25°C.
- 8.85.** You are about to dilute 2.00 mol of 100% sulfuric acid with enough water to produce a 30 mole % aqueous solution. The acid and water are initially at 25°C.
 - How much heat would have to be removed to keep the final solution at 25°C?
 - Suppose the flask has a mass of 150 g, and that the heat capacity of the flask and its contents is 3.30 J/(g·°C). If the flask is sufficiently insulated to be considered adiabatic, what will be the final solution temperature?
- 8.86.** An 8-molar hydrochloric acid solution [SG = 1.12, $C_p = 2.76 \text{ J}/(\text{g}\cdot^\circ\text{C})$] is produced by absorbing hydrogen chloride [HCl(g)] in water. Liquid water enters the absorber at 25°C and gaseous HCl is fed at 20°C and 790 torr (absolute). Essentially all of the HCl fed to the column is absorbed. Take one liter of product solution as a basis of calculation.
 - Estimate the volume (liters) of HCl that must be fed to the absorber.
 - Estimate the heat (kJ) that must be transferred from the absorber if the product solution is to emerge at 40°C.
 - Estimate the final solution temperature if the absorber operates adiabatically.
- 8.87.** A 0.1 mole % caustic soda (NaOH) solution is to be concentrated in a continuous evaporator. The solution enters the unit at 25°C at a rate of 150 mol/min and is concentrated to 5 mole % at 50°C. Hot dry air at 200°C and 1.1 bar absolute is bubbled through the evaporator and leaves saturated with water at 50°C and 1 atm. Calculate the required volumetric flow rate of the entering air and the



Student Workbook

Equipment Encyclopedia
absorption columnEquipment Encyclopedia
evaporator

rate at which heat must be transferred to or from the unit. Assume that the heat capacity per unit mass of all liquid solutions is that of pure water.

- 8.88.** Water is added to pure sulfuric acid in a well-insulated flask initially at 25°C and 1 atm to produce a 4.00-molar sulfuric acid solution ($\text{SG} = 1.231$). The final temperature of the product solution is to be 25°C, so that the water added must be chilled liquid ($T < 25^\circ\text{C}$), or a mixture of liquid water and ice. Take as a basis of calculation one liter of the product solution and assume $Q = \Delta H$ for the process. If you need to know the heat capacity of ice, take it to be half that of liquid water.

- (a) If only liquid water is added, what masses (g) of H_2SO_4 and H_2O should be mixed and what should be the initial temperature of the water?
- (b) If a mixture of liquid water and ice is added, how many grams of each should be fed?



- 8.89.** Ortho-phosphoric acid (H_3PO_4) is produced as a dilute aqueous solution that must be concentrated before further use. In one facility, 100 tons/day of a 28 wt% P_2O_5 solution [see part (a) of this problem] at 125°F is to be concentrated in a single evaporator to 42 wt% P_2O_5 . Heat is supplied to the evaporator by condensing saturated steam at 27.5 psia. The evaporator is to operate at 3.7 psia, and there is a boiling point elevation of 37°F for the 42 wt% P_2O_5 solution in the evaporator (see Section 6.5c). The heat of solution of H_3PO_4 at 77°F may be taken to be $-5040 \text{ Btu/lb-mole}$ H_3PO_4 relative to H_3PO_4 (l) and H_2O (l). The heat capacity of the 28% solution is $0.705 \text{ Btu}/(\text{lb}_m \cdot ^\circ\text{F})$ and that of the 42% solution is $0.583 \text{ Btu}/(\text{lb}_m \cdot ^\circ\text{F})$.

- (a) It is conventional for the compositions of phosphoric acid solutions to be expressed in terms of wt% P_2O_5 . Write the stoichiometric equation for the formation of ortho-phosphoric acid ($\text{MW} = 98.00$) from phosphorus pentoxide ($\text{MW} = 141.96$), and use it to derive the expression

$$\text{wt\% H}_3\text{PO}_4 = 1.381(\text{wt\% P}_2\text{O}_5)$$

- (b) Calculate the ratio (lb_m water evaporated/ lb_m feed solution).
- (c) Suppose the water evaporated is subsequently condensed at a constant pressure of 3.7 psia. Determine the condensate flow rate in gal/min. How much heat (Btu/min) can be recovered through condensation of this water? At what temperature is this heat available? (To put it another way, if this heat were to be transferred to another stream, what is an upper bound on the temperature of that stream?)
- (d) How much steam (lb_m/h) must be supplied to the system to evaporate the required amount of water? Recast your answer in terms of lb_m steam per lb_m water evaporated.



- 8.90.** Two hundred kilograms per hour of an aqueous solution containing 20.0 mole% sodium acetate ($\text{NaC}_2\text{H}_3\text{O}_2$) enters an evaporative crystallizer at 60°C. When the solution is exposed to the low pressure in the evaporator, 16.9% of the water evaporates, concentrating the remaining solution and causing crystals of sodium acetate trihydrate ($\text{NaC}_2\text{H}_3\text{O}_2 \cdot 3 \text{ H}_2\text{O}$) to form. The product is an equilibrium mixture of crystals and a saturated aqueous solution containing 15.4 mole% $\text{NaC}_2\text{H}_3\text{O}_2$. The effluents (crystals, solution, and water vapor) are all at 50°C.

- (a) Calculate the feed rate to the crystallizer in kmol/h.
- (b) Calculate the production rate (kg/h) of trihydrate crystals and the mass flow rate (kg/h) of the liquid solution in which the crystals are suspended.
- (c) Estimate the rate (kJ/h) at which heat must be transferred to or from the crystallizer (state which), using the following physical property data:

$$(C_p)_{\text{all solutions}} = 3.5 \text{ kJ}/(\text{kg} \cdot ^\circ\text{C})$$

$$(C_p)_{\text{crystals}} = 1.2 \text{ kJ}/(\text{kg} \cdot ^\circ\text{C})$$

$$(C_p)_{\text{H}_2\text{O(v)}} = 32.4 \text{ kJ}/(\text{kmol} \cdot ^\circ\text{C})$$

$$(\Delta\hat{H}_v)_{\text{H}_2\text{O}} = 4.39 \times 10^4 \text{ kJ/kmol}$$

Heat of solution of anhydrous sodium acetate:

$$\Delta\hat{H}_s(25^\circ\text{C}) = -1.71 \times 10^4 \text{ kJ/kmol NaC}_2\text{H}_3\text{O}_2$$

Heat of hydration: $\text{NaC}_2\text{H}_3\text{O}_2(s) + 3 \text{ H}_2\text{O(l)} \rightarrow \text{NaC}_2\text{H}_3\text{O}_2 \cdot 3 \text{ H}_2\text{O(s)}$

$$\Delta\hat{H}(25^\circ\text{C}) = -3.66 \times 10^4 \text{ kJ/kmol NaC}_2\text{H}_3\text{O}_2$$

- 8.91.** Fifty milliliters of 100% H_2SO_4 at 25°C and 84.2 mL of liquid water at 15°C are mixed. The heat capacity of the product solution is 2.43 J/(g·°C). Estimate the maximum temperature attainable by

the product solution and state the conditions under which this temperature would be attained, using heat of mixing data from Table B.11.

- 8.92.** Suppose $m_A(g)$ of species A {molecular weight M_A , heat capacity C_{pA} [J/(g·°C)]} at temperature T_{A0} (°C) and $m_B(g)$ of species B (M_B , C_{pB}) at temperature T_{B0} are mixed adiabatically. The heat of mixing of A and B at 25°C is $\Delta\hat{H}_m(r)$ (J/mol A in solution), where $r = (m_B/M_B)/(m_A/M_A)$. The heat capacity of the product solution is C_{ps} [J/(g·°C)]. All heat capacities may be considered independent of temperature.
- Derive an expression for T_{max} , the highest temperature attainable by the product solution, in terms of the other quantities defined. State the conditions that would have to be met for this temperature to be approached.
 - Use your expression to estimate T_{max} for a process in which 100.0 g of sodium hydroxide at 25°C and 225.0 g of water at 40°C are combined to form a product solution with a heat capacity of 3.35 J/(g·°C).
- 8.93.** One g-mole of pure liquid sulfuric acid at temperature T_0 (°C) is mixed with r g-moles of liquid water, also at temperature T_0 (°C), in an adiabatic container. The final solution temperature is T_s (°C). The mass heat capacities of the pure acid, pure water, and the product solution [J/(g·°C)] are C_{pa} , C_{pw} , and C_{ps} , respectively, all of which may be taken to be constant (independent of temperature).
- Without doing any calculations, sketch the plot of T_s versus r you would expect to obtain for r varying between 0 and ∞ . (*Hint:* Think first about what you would expect T_s to be at the extreme values of r .)
 - Use an energy balance to derive an expression for T_s in terms of the initial acid and water temperatures, the heat capacities, the water/acid mole ratio (r), and the heat of mixing, $\Delta\hat{H}_m(r, 25\text{ }^\circ\text{C})$ (kJ/mol H₂SO₄).
 - A series of 1.00 mol samples of pure liquid sulfuric acid are added to 11 insulated flasks containing varying amounts of water. The quantities of water in the flasks and the mass heat capacities of the product solutions are tabulated below:

r (mol H ₂ O)	0.5	1.0	1.5	2.0	3.0	4.0	5.0	10.0	25.0	50.0	100.0
C_p [J/(g·°C)]	1.58	1.85	1.89	1.94	2.10	2.27	2.43	3.03	3.56	3.84	4.00

The heat capacities of pure sulfuric acid and pure water may be determined from the molar heat capacities in Table B.2 evaluated at 25°C. All heat capacities should be taken to be independent of temperature.

Unfortunately, the laboratory air conditioner has been out of order for three weeks (Physical Plant promises they will get to it any day now) and the temperature on the July afternoon of the experiment (which also equals the initial acid and water temperatures) is an uncomfortable 40°C. Write a spreadsheet to generate a table and then a plot of T_s , the final temperature in each flask, versus r , the water/acid mole ratio of the solution in the flask. (*Suggestion:* Make the r axis logarithmic.) Assume that mixing is adiabatic.

- The actual experimental plot of T_s versus r would lie below the one determined in part (c). Why?

- *8.94.** A stirred tank with volume $V_t(L)$ is charged with $V_l(L)$ of a liquid, B. The space above the liquid (volume $V_g = V_t - V_l$) is filled with a pure gas, A, at an initial pressure $P_0(\text{atm})$. The initial system temperature is $T_0(\text{K})$. The stirrer in the tank is turned on, and A begins to dissolve in B. The dissolution continues until the liquid is saturated with A at the final system temperature (T) and pressure (P).

The equilibrium solubility of A in B is governed by the following expression, which relates the molar A/B ratio in the liquid to the partial pressure of A in the gas phase (which in turn equals the pressure in the tank, since the gas is pure A):

$$r(\text{mol A/mol B}) = k_s p_A(\text{atm})$$

where

$$k_s[\text{mol A}/(\text{mol B}\cdot\text{atm})] = c_0 + c_1 T(\text{K})$$

*Computer problems.

When solving the problems to be given, use the following variable definitions:

- M_A, M_B = molecular weights of A and B
- $C_{vA}, C_{vB}, C_{vs}[\text{J}/(\text{g}\cdot\text{K})]$ = constant-volume heat capacities of A(g), B(l), and solutions of A in B, respectively
- SG_B = specific gravity of B(l)
- $\Delta\hat{U}_s$ (J/mol A dissolved) = internal energy of solution at 298 K (independent of composition over the range of concentrations to be considered)
- n_{A0}, n_{B0} = g-moles of A(g) and B(l) initially charged into the tank
- $n_{A(l)}, n_{A(v)}$ = g-moles of A dissolved and remaining in the gas phase at equilibrium, respectively

Make the following assumptions:

- A negligible amount of B evaporates.
- The tank is adiabatic and the work input to the tank from the stirrer is negligible.
- The gas phase behaves ideally.
- The volumes of the liquid and gas phases may be considered constant.
- The heat capacities C_{vA}, C_{vB} , and C_{vs} are constant, independent of temperature and (in the case of C_{vs}) solution composition.

- (a) Use material balances, the given equilibrium solubility relation, and the ideal gas equation of state to derive expressions for $n_{A0}, n_{B0}, n_{A(v)}, n_{A(l)}$, and P in terms of the final temperature, T , and variables $M_A, M_B, \text{SG}_B, V_t, V_l, T_0, P_0, c_0$, and c_1 . Then use an energy balance to derive the following equation:

$$T = 298 + \frac{n_{A(l)}(-\Delta\hat{U}_s) + (n_{A0}M_A C_{vA} + n_{B0}M_B C_{vB})(T_0 - 298)}{n_{A(v)}M_A C_{vA} + (n_{A(l)}M_{A(l)} + n_B M_B)C_{vs}}$$

- (b) Write a spreadsheet to calculate T from specified values of $M_A (= 47), M_B (= 26), \text{SG}_B (= 1.76), V_t (= 20.0), V_l (= 3.0), c_0 (= 1.54 \times 10^{-3}), c_1 (= -1.60 \times 10^{-6}), C_{vA} (= 0.831), C_{vB} (= 3.85), C_{vs} (= 3.80)$, and $\Delta\hat{U}_s (= -1.74 \times 10^5)$, and a number of different values of T_0 and P_0 . The spreadsheet should have the structure given below. (Calculated values are shown for one initial temperature and pressure.)

Problem 8.94										
Vt	MA	CvA	MB	CvB	SGB	c0	c1	DUs	Cvs	
20.0	47.0	0.831	26.0	3.85	1.76	0.00154	-1.60E-06	-174000	3.80	
VI	T0	P0	Vg	nB0	nA0	T	nA(v)	nA(l)	P	Tcalc
3.0	300	1.0								
3.0	300	5.0								
3.0	300	10.0	17.0	203.1	6.906	320.0	5.222	1.684	8.1	314.2
3.0	300	20.0								
3.0	330	1.0								
3.0	330	5.0								
3.0	330	10.0								
3.0	330	20.0								

The values of V_g , n_{B0} , and n_{A0} should first be calculated from the given values of the other variables. Next, a value of T should be guessed (in the example in the table, the guessed value

is 320 K), the values of $n_{A(v)}$, $n_{A(l)}$, and P should be calculated from the equations derived in part (a), and the temperature should be recalculated from the energy balance in the column labeled T_{calc} (it equals 314.2 in the example). The value of T should then be varied until it equals the recalculated value of T_{calc} . (*Suggestion:* Create a new cell as $T - T_{\text{calc}}$ and use goalseek to find the value of T that drives $T - T_{\text{calc}}$ to zero.)

Enter the formulas in the cells for $V_1 = 3.0 \text{ L}$, $T_0 = 300 \text{ K}$, and $P_0 = 10.0 \text{ atm}$, and verify that your cell values match those shown above. Then find the correct value of T using the procedure just described, copy the formulas into the other rows of the table, and determine T for each set of initial conditions. Summarize the effects of the initial temperature and pressure on the adiabatic temperature rise and briefly explain why your results make sense.

- (c) Write a computer program to perform the same calculations done with the spreadsheet in part (b).

- Define values of V_1 , M_A , C_{vA} , M_B , C_{vB} , SG_B , c_0 , c_1 , $\Delta\dot{U}_s$, and C_{vs} . Use the values shown in the fourth row of the spreadsheet.
- Read in a set of values of V_B , T_0 , and P_0 . Have the program terminate if $V_B \leq 0.0$.
- If a positive value is read in for V_B , calculate V_G , n_B , and n_{A0} .
- Assume a value of T . (Try $1.1T_0$ as a first guess.)
- Calculate $n_{A(v)}$, $n_{A(l)}$, and P from the equations derived in part (a), then recalculate T from the energy balance. Print out the values of T (assumed), P , $n_{A(v)}$, $n_{A(l)}$, and T (recalculated).
- If the assumed and recalculated values of T are within 0.01 K of each other, end the loop and go back to read the next set of input variables. If they are not and more than 15 iterations have been performed, terminate with an error message. Otherwise, repeat the previous step, using the recalculated value of T as the assumed value for this iteration.

Run the program for the eight sets of conditions shown in the spreadsheet table.

- 8.95.** An aqueous solution containing 85.0 wt% H_2SO_4 at 60°F (specific gravity = 1.78) is diluted with pure liquid water at the same temperature. The feed solution volume is 350 mL. The mixing may be considered adiabatic, and the pressure is constant at 1 atm.
- The product solution is to contain 30.0 wt% H_2SO_4 . Calculate the volume (mL) of water needed for the dilution, ideally using a single-dimensional equation.
 - Use the enthalpy-concentration chart of Figure 8.5-1 to estimate the specific enthalpies (Btu/lb_m) of the feed solution and the water. Then write an energy balance on this closed system constant-pressure process and solve it for the specific enthalpy of the product solution. Finally, use Figure 8.5-1 to verify your calculated value of \hat{H}_{product} and to estimate the product solution temperature. (See Example 8.5-3.)
 - Use Figure 8.5-1 to estimate the maximum temperature that could be attained by mixing the feed solution with pure water and the concentration (wt% H_2SO_4) of the product solution.
 - Good laboratory practice calls for adding acid to water when carrying out dilutions rather than vice versa. Use Figure 8.5-1 to justify this rule for the dilution of the feed solution in this problem.
- 8.96.** Aqueous sulfuric acid solutions containing 15.0 wt% H_2SO_4 and 80.0 wt% H_2SO_4 are mixed to form a 60.0 wt% product solution. The 15% solution was in a laboratory in which the temperature was 77°F. The 80% solution had just been taken from a storage cabinet in an air-conditioned stockroom and was at a temperature of 60°F when the mixing occurred.
- The mass of the 15% solution is 2.30 lb_m. What mass of 60% solution should be weighed out?
 - Use Figure 8.5-1 to estimate the product solution temperature if the mixing is adiabatic. (See Example 8.5-3.)
 - The product solution temperature eventually drops to (77°F). How much heat (Btu) is transferred from the solution to the laboratory air in this constant-pressure cooling process?
 - Which would be safer—adding the 15% solution slowly to the 80% solution or vice versa? Use Figure 8.5-1 to justify your answer.
- 8.97.** You have analyzed an aqueous ammonia solution and find that it contains 30 wt% NH_3 .
- Use Figure 8.5-2 to determine the mass fraction of NH_3 in the vapor that would be in equilibrium with this solution in a closed flask at 1 atm and the corresponding system temperature.
 - If the liquid phase in part (a) accounts for 90% of the total system mass, calculate the overall system composition and specific enthalpy using balances. (See Example 8.5-3.)

- 8.98.** An $\text{NH}_3\text{-H}_2\text{O}$ mixture containing 60 wt% NH_3 is brought to equilibrium in a closed container at 140°F. The total mass of the mixture is 250 g. Use Figure 8.5-2 to determine the masses of ammonia and of water in each phase of the system.
- 8.99.** An ammonia solution at a high pressure is flash-vaporized at a rate of 200 lb_m/h . The solution contains 0.70 $\text{lb}_m \text{NH}_3/\text{lb}_m$, and its enthalpy relative to $\text{H}_2\text{O}(\text{l}, 32^\circ\text{F})$ and $\text{NH}_3(\text{l}, -40^\circ\text{F})$ is -50 Btu/lb_m . Liquid and gas streams emerge from the unit at 1 atm and 80°F. Use Figure 8.5-2 to determine the mass flow rates and ammonia mass fractions of the vapor and the liquid product streams and the rate (Btu/h) at which heat must be transferred to the vaporizer. (See Example 8.5-4.)