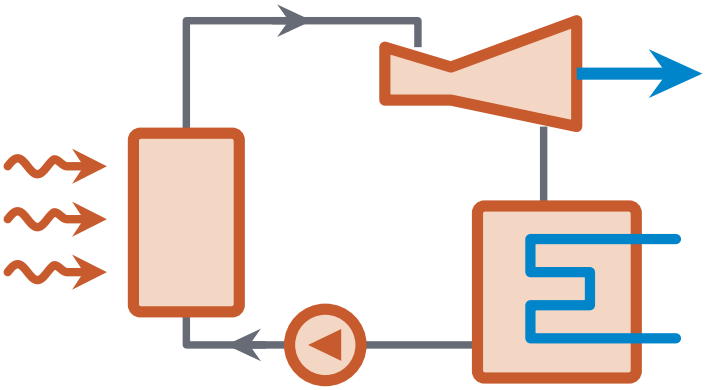
THERMODYNAMICS 2

PROBLEM BOOK

SAMPLE PAGES

10 chapters · 168 problems · step-by-step solutions



Ertan Sinan Şahin

ertansinansahin.com

How to use this book

- Each chapter opens with a reminder box summarizing the definitions and formulas the problems rely on.
- Difficulty: ★☆☆ basic ★★☆ intermediate ★★★ advanced. Each chapter has a few multiple-choice concept questions; its last problem is an exam-style mixed problem combining several topics.
- The dotted area below each problem is for your own work. Solve first; if stuck, go back to the reminder box and the lecture notes, and look at the solution last.
- All solutions are at the end of the book. The Solution → link next to a problem takes you to its solution, and ← Problem takes you back. Short answers are in the **ANSWER** box.
- **Property tables:** The problems are solved with the *Appendix: Property Tables* at the end of the book; values not listed directly in a table are found by linear interpolation.
- **Shared chapters:** Chapters 7–8 (entropy, exergy) are the same as in *Thermodynamics 1*. They are included here for schools whose second course begins with these topics; for others they serve as review. The book starts with Chapter 7: of the earlier chapters, the energy balance, the use of property tables, and the second law are assumed, and they are summarized in the reminder boxes where needed.
- **Midterm and final:** The midterm usually covers entropy, exergy, and power cycles (Chapters 7–10); the final covers refrigeration cycles, thermodynamic property relations, gas and gas–vapor mixtures, combustion, and chemical equilibrium (Chapters 11–16). The selection of topics varies from school to school; choose the chapters to study according to your own course syllabus.

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CHAPTER 9

GAS POWER CYCLES

thermal efficiency $\eta_{th} = \dfrac{w_{net,out}}{q_{in}} = 1 - \dfrac{q_{out}}{q_{in}}$

compression ratio $r = \dfrac{V_{max}}{V_{min}}$

mean effective pressure $\mathrm{MEP} = \dfrac{w_{net,out}}{v_{max} - v_{min}}$

Otto (cold air) $\eta_{th} = 1 - \dfrac{1}{r^{k-1}}$

Diesel ($r_c = v_3/v_2$) $\eta_{th} = 1 - \dfrac{1}{r^{k-1}} \dfrac{r_c^k - 1}{k(r_c - 1)}$

isentropic (constant c_p) $\dfrac{T_2}{T_1} = \left(\dfrac{v_1}{v_2}\right)^{k-1} = \left(\dfrac{P_2}{P_1}\right)^{(k-1)/k}$

isentropic (Table T-11) $\dfrac{P_{r2}}{P_{r1}} = \dfrac{P_2}{P_1}, \quad \dfrac{v_{r2}}{v_{r1}} = \dfrac{v_2}{v_1}$

Brayton (cold air) $\eta_{th} = 1 - \dfrac{1}{r_p^{(k-1)/k}}$

back work ratio $r_{bw} = \dfrac{w_C}{w_T}$

isentropic efficiencies $\eta_C = \dfrac{h_{2s} - h_1}{h_2 - h_1}, \quad \eta_T = \dfrac{h_3 - h_4}{h_3 - h_{4s}}$

regenerator effectiveness $\varepsilon = \dfrac{h_5 - h_2}{h_4 - h_2}$

jet propulsion $F = \dot{m}(V_{out} - V_{in}), \quad \eta_P = \dfrac{F\,V_{aircraft}}{\dot{Q}_{in}}$

exergy destruction $x_{dest} = T_0\left(s_{out} - s_{in} + \dfrac{q_{out}}{T_L} - \dfrac{q_{in}}{T_H}\right)$

Air-standard assumptions: the working fluid is air, an ideal gas circulating in a closed cycle; all processes are internally reversible; combustion is modeled as heat addition from an external source, and the exhaust as heat rejection to the surroundings. In the cold-air standard the specific heats are constant at their 300 K values (Table T-10(a): $c_p = 1.005$, $c_v = 0.7178$ kJ/(kg·K), $k = 1.4$); the gas constant from Table T-1 is $R = 0.2870$ kJ/(kg·K). In problems solved with temperature-dependent specific heats, the properties of air (h, u, s°, P_r, v_r) are read from Table T-11, and intermediate values are found by linear interpolation; the problem states which approach is to be used. Temperatures are in kelvins. Unless stated otherwise, changes in kinetic and potential energy are neglected. The quantities q, w, $\dot{Q}$, and $\dot{W}$ are positive; their directions are indicated by the subscripts (in, out); the compressor work w_C is supplied to the cycle, while the turbine work w_T and the net work $w_{net,out}$ are delivered by the cycle. In exergy (availability) calculations the dead state is given in the problem. In the figures, heat transfer is shown by red arrows, work by blue arrows, and mass flow by black arrows; the cycle is drawn in blue, and ideal (isentropic) comparison processes in gray dashed lines.

Air standard and reciprocating engines

9.1 ★☆☆ Solution →

Which of the following statements about reciprocating engines and the air-standard assumptions is true?

A) The mean effective pressure is obtained by dividing the net work of the cycle by the displacement volume; it is used to compare engines of different sizes.

B) The compression ratio is the ratio of the highest pressure in the cylinder to the lowest pressure.

C) In the air-standard assumptions, combustion is modeled as heat rejection from the working fluid to the outside.

D) In the cold-air standard, the specific heats of air increase with temperature.

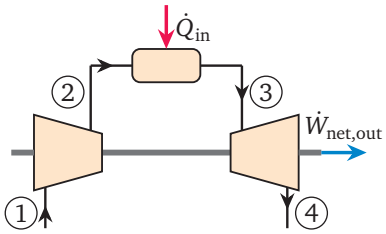
E) In a four-stroke engine, each cylinder executes one power stroke per revolution.

Brayton cycle

9.11

★☆☆ Solution →

The gas turbine driving the emergency generator of an airport is modeled as an ideal Brayton cycle with a pressure ratio of 9. Air enters the compressor at 290 K; the turbine inlet temperature is 1250 K; the air mass flow rate is 15 kg/s. Use the cold-air standard.



a. Find the compressor and turbine exit temperatures.

b. Find the back work ratio and the thermal efficiency.

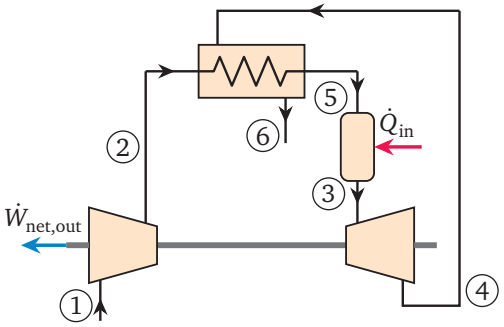
c. Find the net power, the rate of heat addition in the combustion chamber, and, if the lower heating value of the fuel is 43 000 kJ/kg, the amount of fuel burned per hour (kg/h).

Regeneration, intercooling, and reheating

9.15

★★☆ Solution →

In a microturbine that generates part of the electricity of a shopping mall, the pressure ratio is 7, the compressor inlet temperature is 300 K, and the turbine inlet temperature is 1200 K. The isentropic efficiency of the compressor is 0.85, and that of the turbine is 0.88. Use the cold-air standard.



a. Find the net work and the thermal efficiency without a regenerator.

b. What is the minimum regenerator effectiveness required for a thermal efficiency of 0.36?

c. In this case, what is the temperature of the exhaust gas leaving the regenerator (in kelvins)?

CHAPTER 13
GAS MIXTURES

mass and mole fractions

$$\mathrm{mf}_i = \frac{m_i}{m}, \quad y_i = \frac{N_i}{N}, \quad \mathrm{mf}_i = y_i \frac{M_i}{M_m}$$

apparent (average) molar mass, gas constant

$$M_m = \sum y_i M_i = \frac{1}{\sum \mathrm{mf}_i / M_i}, \quad R_m = \frac{R_u}{M_m}$$

Dalton (at the mixture T and V)

$$P_i = y_i P, \quad P = \sum P_i$$

Amagat (at the mixture T and P)

$$V_i = y_i V, \quad V = \sum V_i$$

Kay's rule (real-gas mixture)

$$T'_{\mathrm{cr}} = \sum y_i T_{\mathrm{cr},i}, \quad P'_{\mathrm{cr}} = \sum y_i P_{\mathrm{cr},i}$$

mixture properties

$$U = \sum m_i u_i, \quad H = \sum m_i h_i, \quad S = \sum m_i s_i$$

specific heats (per unit mass)

$$c_{p,m} = \sum \mathrm{mf}_i\, c_{p,i}, \quad c_{v,m} = \sum \mathrm{mf}_i\, c_{v,i}$$

entropy change of a component

$$\Delta s_i = c_{p,i} \ln \frac{T_2}{T_1} - R_i \ln \frac{P_{i,2}}{P_{i,1}}$$

mixing at the same T and P

$$S_{\mathrm{gen}} = -R_u \sum N_i \ln y_i$$

minimum separation work (at T_0)

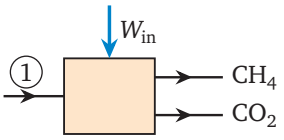
$$W_{\mathrm{min,in}} = -R_u T_0 \sum N_i \ln y_i$$

exergy destruction $X_{\mathrm{dest}} = T_0 S_{\mathrm{gen}}$

In this chapter every component of a mixture is treated as an ideal gas (a real-gas mixture appears only in the problem on Kay's rule); each component behaves as if it existed alone at the temperature and volume of the mixture. Molar mass, gas constant and critical-point properties are read from Table T-1, constant specific heats (300 K) from Table T-10(a), temperature-dependent molar enthalpies from Table T-15(a), and the compressibility factor from the chart in Table T-12; $R_u = 8.314$ kJ/(kmol·K). For an ideal-gas mixture a volumetric analysis is identical to a molar analysis. Kinetic and potential energy changes are neglected. Heat and work are positive quantities; their directions are shown by the subscripts in/out (Q_{in}, $\dot{Q}_{\mathrm{out}}$, $W_{b,\mathrm{out}}$); if the direction is not known in advance, the net quantity ($Q_{\mathrm{net,in}}$) is used. In exergy (availability) calculations the dead state is given in the problem.

Mixed problems

13.13 ★★★ Solution →



At a biomethane plant, biogas (60% CH_4, 40% CO_2 by mole) at 25 °C and 101.325 kPa is separated into pure methane and pure CO_2; the products are also at 25 °C and 101.325 kPa. The plant consumes 0.25 kWh of electricity per normal cubic meter (0 °C, 101.325 kPa) of raw biogas. The lower heating value of methane is about 50 000 kJ/kg.

a. Determine the minimum work required to separate one kilomole of biogas.

b. Determine the minimum work per kilogram of methane and compare it with the lower heating value of methane.

c. Determine the second-law efficiency of the plant.

CHAPTER 14

GAS–VAPOR MIXTURES AND AIR CONDITIONING

total pressure $P = P_a + P_v$

specific humidity (per unit mass of dry air)
$\omega = \dfrac{m_v}{m_a} = \dfrac{0.622\,P_v}{P - P_v}$

relative humidity (P_g: saturation pressure at T)
$\phi = \dfrac{P_v}{P_g(T)}$

enthalpy (kJ/kg dry air, T in °C)
$h = c_p T + \omega h_g(T)$

specific volume of dry air $v = \dfrac{R_a T}{P_a}$

dew point $P_g(T_{\text{dp}}) = P_v$

adiabatic saturation (2: saturated exit, $T_2 \approx T_{\text{wb}}$) $\omega_1 = \dfrac{c_p(T_2 - T_1) + \omega_2 h_{fg2}}{h_{g1} - h_{f2}}$

mass balance (dry air and water separately)
$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}}$

energy balance (steady flow)
$\dot{Q}_{\text{in}} + \sum(\dot{m}h)_{\text{in}} = \dot{Q}_{\text{out}} + \sum(\dot{m}h)_{\text{out}}$

adiabatic mixing $\dfrac{\dot{m}_{a1}}{\dot{m}_{a2}} = \dfrac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \dfrac{h_2 - h_3}{h_3 - h_1}$

Dry air and water vapor are ideal gases; for dry air $c_p = 1.005$ kJ/(kg·K) (Table T-10(a)), $R_a = 0.2870$ kJ/(kg·K), and $0.622 = 18.015/28.97$ (Table T-1). P_g (saturated vapor pressure), h_g, and h_f are read from Table T-2 (T-3 if needed) with linear interpolation. ω (kg water vapor/kg dry air) and h are per unit mass of dry air; the enthalpy reference is dry air and liquid water at 0 °C. The psychrometric chart (Table T-14) is for 101.325 kPa; values read from it are given with "≈" to two significant figures. Flow is steady; kinetic and potential energy changes are neglected. In the schematics air is shown by black and heat by red arrows; on the chart the process is a blue line.

Adiabatic saturation, wet-bulb temperature, and the psychrometric chart

14.7 ★☆☆ Solution →

Which of the following statements about the dry-bulb temperature T, the wet-bulb temperature T_{wb} and the dew-point temperature T_{dp} of air is true?

A) In unsaturated air the wet-bulb temperature is lower than the dew-point temperature.

B) The wet-bulb temperature depends only on the dry-bulb temperature of the air; it is not affected by the humidity of the air.

C) In an adiabatic saturation process the specific humidity of the air decreases and its temperature increases.

D) The larger the difference between the dry-bulb and wet-bulb temperatures, the higher the relative humidity of the air.

E) In saturated air the dry-bulb, wet-bulb and dew-point temperatures are equal to one another.

Air-conditioning processes

14.11 ★★☆ Solution →

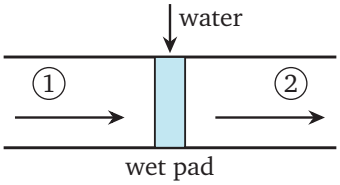
A poultry house in Şanlıurfa is cooled by a pad-and-fan system: outdoor air at 40 °C with a relative humidity of 15% passes through wet pads at 4 m^3/s. The saturation efficiency of the pads is $\eta = (T_1 - T_2)/(T_1 - T_{wb}) = 0.85$ (T_{wb}: wet-bulb temperature of the outdoor air). The pressure is 101.325 kPa.

a. According to Table T-14, what is the wet-bulb temperature of the outdoor air (in °C)?

b. Determine the temperature (in °C) and the relative humidity of the air leaving the pads.

c. How many kilograms of water evaporate in the pads per hour?

d. What is the lowest temperature (in °C) to which the air can theoretically be cooled by this method? Why is the method not effective in humid climates?



Mixed problems

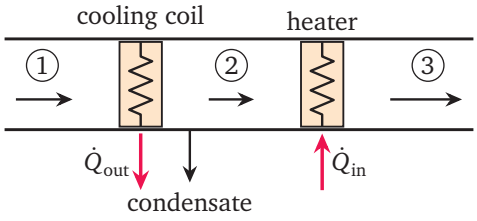
14.17 ★★★ Solution →

Air at 20 °C with a relative humidity of 45% must be supplied to the packaging hall of a chocolate factory (to prevent moisture and sugar bloom on the chocolate surface). In summer the outdoor air is at 33 °C with a relative humidity of 55%. The outdoor air is first dehumidified in a cooling coil by cooling it until it becomes saturated (state 2), and then heated to 20 °C in a heater (state 3). The condensate leaves the coil at the temperature of state 2. The mass flow rate of dry air is 1.5 kg/s, and the pressure is 101.325 kPa.

a. What must the air temperature at the coil exit be (in °C)?

b. Determine the condensate flow rate (in kg/h), the cooling load of the coil (in kW) and the power of the heater (in kW).

c. Read the enthalpies of states 1 and 3 from Table T-14 and compare them with the calculation.



SOLUTIONS

9 GAS POWER CYCLES

9.1

← Problem

The mean effective pressure (MEP) is the constant pressure that, if it acted on the piston during the power stroke, would produce the net work of the cycle: $\text{MEP} = W_{\text{net,out}}/(V_{\max} - V_{\min})$. Because the net work is divided by the displacement volume, it is independent of engine size. **A** is correct.

- (B): The compression ratio is a *volume* ratio: $r = V_{\max}/V_{\min}$.
- (C): Combustion is modeled as heat *addition* to the working fluid from an external source; the exhaust is modeled as heat rejection.
- (D): In the cold-air standard the specific heats are constant and are taken at their room-temperature (300 K) values.
- (E): In a four-stroke engine one cycle is completed in two revolutions; each cylinder executes one power stroke every two revolutions.

ANSWER A

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9.11

← Problem

Assumptions: cold-air standard; steady flow; isentropic compression and expansion; kinetic and potential energy neglected.

Here $r_p^{(k-1)/k} = 9^{0.2857} = 1.8734$.

a. Isentropic compression and expansion:

$$T_2 = 290(1.8734) = 543.3\ \text{K},$$

$$T_4 = \frac{1250}{1.8734} = 667.2\ \text{K}.$$

b. Compressor and turbine work:

$$w_{\text{C}} = 1.005(543.3 - 290) = 254.57\ \text{kJ/kg},$$

$$w_{\text{T}} = 1.005(1250 - 667.2) = 585.71\ \text{kJ/kg},$$

$$r_{\text{bw}} = \frac{254.57}{585.71} = 0.4346 \approx 0.435,$$

$$\eta_{\text{th}} = 1 - \frac{1}{1.8734} = 0.4662 \approx 0.466.$$

About 43% of the turbine work goes to driving the compressor; the back work ratio of gas turbines is much larger than that of vapor cycles.

c. $w_{\text{net,out}} = 585.71 - 254.57 = 331.14\ \text{kJ/kg}$, $q_{\text{in}} = 1.005(1250 - 543.3) = 710.23\ \text{kJ/kg}$:

$$\dot{W}_{\text{net,out}} = 15(331.14) = 4967\ \text{kW},$$

$$\dot{Q}_{\text{in}} = 15(710.23) = 10\,653 \approx 10\,650\ \text{kW},$$

$$\dot{m}_{\text{fuel}} = \frac{10\,653}{43\,000} = 0.2477\ \text{kg/s} = 892\ \text{kg/h}.$$

ANSWER a. 543.3 K; 667.2 K b. 0.435; 0.466 c. 4967 kW; 10 650 kW; 892 kg/h

9.15

← Problem

Assumptions: cold-air standard; adiabatic compressor and turbine; no pressure losses; kinetic and potential energy neglected.

Here $7^{0.2857} = 1.7436$. States: 1 compressor inlet, 2 compressor exit, 5 regenerator exit (combustion chamber inlet), 3 turbine inlet, 4 turbine exit, 6 exhaust.

a. Isentropic and actual temperatures:

$$T_{2s} = 300(1.7436) = 523.09 \text{ K},$$

$$T_2 = 300 + \frac{223.09}{0.85} = 562.46 \text{ K},$$

$$T_{4s} = \frac{1200}{1.7436} = 688.22 \text{ K},$$

$$T_4 = 1200 - 0.88(511.78) = 749.63 \text{ K}.$$

$$w_{\text{net,out}} = 1.005\big[(1200 - 749.63) - (562.46 - 300)\big]$$
$$= 188.85 \approx 188.9 \text{ kJ/kg},$$

$$q_{\text{in}} = 1.005(1200 - 562.46) = 640.73 \text{ kJ/kg},$$

$$\eta_{\text{th}} = \frac{188.85}{640.73} = 0.2947 \approx 0.295.$$

b. The net work does not change with the regenerator. The heat required for $\eta_{\text{th}} = 0.36$ and the combustion chamber inlet temperature:

$$q_{\text{in}} = \frac{188.85}{0.36} = 524.58 \text{ kJ/kg},$$

$$T_5 = 1200 - \frac{524.58}{1.005} = 678.03 \text{ K},$$

$$\varepsilon = \frac{T_5 - T_2}{T_4 - T_2} = \frac{115.57}{187.17} = 0.61746 \approx 0.617.$$

c. In the regenerator the heat given up by the hot gas equals the heat received by the air:

$$T_6 = T_4 - (T_5 - T_2) = 749.63 - 115.57$$
$$= 634.06 \approx 634.1 \text{ K}.$$

Check: $T_6 = 634.1 \text{ K} > T_2 = 562.46 \text{ K}$; heat flows from hot to cold.

ANSWER a. 188.9 kJ/kg; 0.295 b. $\varepsilon = 0.617$ c. 634.1 K

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13 GAS MIXTURES

13.13

← Problem

Assumptions: steady flow; ideal-gas mixture; reversible separation for the minimum work; inlet and outlets at T_0 and P_0.

a. Separation is the reverse of mixing at the same T and P. The minimum work is the work of reversible separation ($T_0 = 298.15$ K, $R_u T_0 = 2478.8$ kJ/kmol):

$$\bar{w}_{\text{min,in}} = -R_u T_0 (y_{CH_4} \ln y_{CH_4} + y_{CO_2} \ln y_{CO_2})$$
$$= 2478.8[0.60(0.5108) + 0.40(0.9163)]$$
$$= 2478.8(0.67301) = 1668 \text{ kJ/kmol}.$$

b. One kilomole of biogas contains $0.60(16.043) = 9.626$ kg of methane (Table T-1). Minimum work per kilogram of methane:

$$w_{\text{min,in}} = \frac{1668.3}{9.626} = 173.3 \text{ kJ/kg}.$$

Ratio to the lower heating value:

$$\frac{173.3}{50\,000} = 0.00347 \approx 0.35\%.$$

In theory, the separation requires only 3.5 thousandths of the energy carried by the methane.

c. The molar volume of an ideal gas at normal conditions is $R_u T/P = 8.314(273.15)/101.325 = 22.413 \text{ m}^3/\text{kmol}$. Actual work:

$$\bar{w}_{\text{in}} = 0.25(3600)(22.413) = 20\,172 \text{ kJ/kmol},$$

$$\eta_{\text{II}} = \frac{\bar{w}_{\text{min,in}}}{\bar{w}_{\text{in}}} = \frac{1668.3}{20\,172} = 0.0827.$$

The plant uses about 12 times the minimum work; the actual work amounts to 4.2% of the methane energy ($20\,172/9.626 = 2096$ kJ/kg of methane).

ANSWER a. 1668 kJ/kmol b. 173.3 kJ/kg per kg of methane; 0.35% of the lower heating value c. $\eta_{\text{II}} = 0.0827$

14 GAS–VAPOR MIXTURES AND AIR CONDITIONING

14.7

← Problem

In saturated air there is no evaporation from the wick, and the wet-bulb thermometer does not cool: $T_{\text{wb}} = T$. Since $P_v = P_g(T)$ in saturated air, the dew point is also T. **E** is correct.

- (A): In unsaturated air the order is $T_{dp} < T_{wb} < T$ (in Table T-14, from a point, the temperature at which the saturation curve is reached along the wet-bulb line is higher than the one reached by moving horizontally).
- (B): The rate of evaporation from the wick depends on the humidity of the air; at the same T, T_{wb} is lower in drier air.
- (C): In adiabatic saturation the air evaporates water: its specific humidity increases, and since it supplies the heat of vaporization from its own sensible heat, its temperature decreases.
- (D): As the difference increases, evaporation from the wick increases, that is, the air is drier; the relative humidity decreases.

ANSWER E

14.11 ← Problem

Assumptions: steady flow; adiabatic pad; enthalpy of the added water neglected ($h_2 \approx h_1$).

a. In Table T-14, the wet-bulb line through the intersection of $T = 40\ ^\circ\text{C}$ and $\phi = 15\%$ (midway between the 10% and 20% curves) is very close to the 20 line: $T_{wb} \approx 20\ ^\circ\text{C}$.

b. From the saturation efficiency:

$$T_2 = 40 - 0.85(40 - 20) = 23.0 \approx 23\ ^\circ\text{C}.$$

From Table T-2, $P_g(40\ ^\circ\text{C}) = 7.3849$ kPa, $h_g(40\ ^\circ\text{C}) = 2573.5$ kJ/kg:

$$P_{v1} = 0.15(7.3849) = 1.1077 \text{ kPa},$$

$$\omega_1 = \frac{0.622(1.1077)}{101.325 - 1.1077} = 0.006875,$$

$$h_1 = 1.005(40) + 0.006875(2573.5) = 57.89 \text{ kJ/kg}.$$

The temperature 23 °C lies between the 20 and 25 °C rows of Table T-2 (ratio 0.6): $h_g = 2537.4 + 0.6(9.1) = 2542.9$ kJ/kg, $P_g = 2.3393 + 0.6(0.8306) = 2.8377$ kPa. With $h_2 = h_1$:

$$\omega_2 = \frac{57.89 - 1.005(23.0)}{2542.9} = 0.013676,$$

$$P_{v2} = \frac{0.013676(101.325)}{0.622 + 0.013676} = 2.1800 \text{ kPa},$$

$$\phi_2 = \frac{2.1800}{2.8377} = 0.768 \approx 77\%.$$

c. Mass flow rate of dry air and evaporated water:

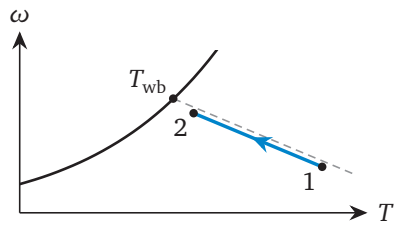
$$v_1 = \frac{0.2870(313.15)}{100.217} = 0.8968 \text{ m}^3/\text{kg},$$

$$\dot{m}_a = \frac{4}{0.8968} = 4.460 \text{ kg/s}.$$

$$\dot{m}_w = \dot{m}_a(\omega_2 - \omega_1) = 4.460(0.006801)$$

$$= 0.03033 \text{ kg/s} = 109 \approx 110 \text{ kg/h}.$$

(The result depends on the T_{wb} reading; an error of 0.3 K in reading T_{wb} changes T_2 by about 0.3 K.)



d. If the saturation efficiency were 1, the air would cool until it became saturated, that is, to the wet-bulb

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temperature (≈ 20 °C). In humid air T_{wb} is close to the dry-bulb temperature; little water can evaporate and the cooling remains small. In a dry, hot climate, however, the same method brings the air down from 40 °C to 23 °C.

ANSWER a. $T_{wb} \approx 20$ °C b. $T_2 \approx 23$ °C, $\phi_2 \approx 77\%$ c. ≈ 110 kg/h d. ≈ 20 °C (the wet-bulb temperature)

14.17

← Problem

Assumptions: steady flow; no moisture change in the heater ($\omega_2 = \omega_3$); kinetic and potential energies neglected.

a. State 2 is saturated and its specific humidity equals that of state 3; the coil exit temperature is the dew point of state 3. From Table T-2, $P_g(20\,°C) = 2.3393$ kPa:

$$P_{v3} = 0.45(2.3393) = 1.0527 \text{ kPa},$$

$$\omega_3 = \frac{0.622(1.0527)}{101.325 - 1.0527} = 0.0065299.$$

In Table T-2, at 5 °C 0.8726 kPa, at 10 °C 1.2282 kPa:

$$T_2 = 5 + 5\,\frac{1.0527 - 0.8726}{1.2282 - 0.8726} = 7.53 \approx 7.5\ °C.$$

b. State 1: for 33 °C, between the 30 and 35 °C rows (ratio 0.6), $P_g = 4.2470 + 0.6(1.382) = 5.0762$ kPa, $h_g = 2555.5 + 0.6(9.0) = 2560.9$ kJ/kg:

$$\omega_1 = \frac{0.622(0.55)(5.0762)}{101.325 - 2.7919} = 0.017624,$$

$$h_1 = 1.005(33) + 0.017624(2560.9) = 78.30 \text{ kJ/kg}.$$

State 2 (7.53 °C; between the 5 and 10 °C rows, ratio 0.5064): $h_g = 2514.7$ kJ/kg, $h_f = 31.66$ kJ/kg.

$$h_2 = 1.005(7.53) + 0.0065299(2514.7) = 23.99 \text{ kJ/kg},$$

$$h_3 = 1.005(20) + 0.0065299(2537.4) = 36.67 \text{ kJ/kg}.$$

Condensate:

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_3) = 1.5(0.011094)$$
$$= 0.016641 \text{ kg/s} = 59.9 \text{ kg/h}.$$

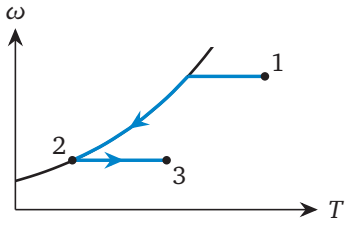
Energy balance of the coil:

$$\dot{Q}_{out} = \dot{m}_a\left[(h_1 - h_2) - (\omega_1 - \omega_3)h_f\right]$$
$$= 1.5\,[54.31 - 0.011094(31.66)] = 80.9 \text{ kW}.$$

$$\dot{Q}_{in} = \dot{m}_a(h_3 - h_2) = 1.5(12.68) = 19.0 \text{ kW}.$$

To dehumidify, the air is cooled well below 20 °C and then reheated; in halls requiring low humidity, reheating is unavoidable.

c. In Table T-14, state 1 (33 °C, 55%) lies between the 70 and 80 enthalpy lines, close to 80: $h_1 \approx 78$ kJ/kg; state 3 (20 °C, 45%) lies between the 30 and 40 lines: $h_3 \approx 37$ kJ/kg. The readings agree with the calculation (78.30 and 36.67 kJ/kg). The figure below is schematic; scaled readings are made from Table T-14.



ANSWER a. 7.5 °C b. 59.9 kg/h; 80.9 kW; 19.0 kW c. $h_1 \approx 78$, $h_3 \approx 37$ kJ/kg (calculated: 78.30, 36.67)

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APPENDIX: PROPERTY TABLES

The values in this appendix are computed from reference equations of state (IAPWS-95 for water, the international standard equation for R-134a) and from ideal-gas specific heats; units are SI. States not in a table are found by **linear interpolation**: if $x_1 < x < x_2$, then $y = y_1 + (y_2 - y_1)(x - x_1)/(x_2 - x_1)$. In the superheated vapor and compressed liquid tables, when both temperature and pressure fall between entries, interpolate first in temperature at the two pressures and then in pressure (double interpolation). The numerical answers of the problems are computed with the values in these tables and with this rule.

This sample includes only the Appendix tables used by the selected problems (T-1, T-2, T-14). The Appendix of the full book has 18 tables on 23 pages: water, ice, R-134a, ideal gases, air, the compressibility and departure charts, the psychrometric chart, and combustion and chemical-equilibrium tables.

Table T-1 Molar mass, gas constant, and critical-point properties

Substance	Formula	M kg/kmol	R kJ/(kg·K)	T_{cr} K	P_{cr} MPa	v_{cr} m³/kmol	Z_{cr}
Hydrogen	H_2	2.016	4.124	33.1	1.296	0.0645	0.303
Helium	He	4.003	2.077	5.2	0.2283	0.0575	0.304
Methane	CH_4	16.043	0.5183	190.6	4.599	0.0986	0.286
Ammonia	NH_3	17.031	0.4882	405.6	11.36	0.0730	0.246
Water	H_2O	18.015	0.4615	647.1	22.06	0.0559	0.229
Neon	Ne	20.180	0.4120	44.4	2.662	0.0415	0.299
Ethylene	C_2H_4	28.054	0.2964	282.4	5.042	0.1309	0.281
Nitrogen	N_2	28.014	0.2968	126.2	3.396	0.0894	0.289
Carbon monoxide	CO	28.010	0.2968	132.9	3.498	0.0922	0.292
Air	—	28.97	0.2870	132.5	3.786	0.0845	0.290
Ethane	C_2H_6	30.070	0.2765	305.3	4.872	0.1458	0.280
Oxygen	O_2	31.998	0.2598	154.6	5.046	0.0750	0.294
Methanol	CH_3OH	32.042	0.2595	513.4	8.216	0.1138	0.219
Argon	Ar	39.950	0.2081	150.7	4.863	0.0746	0.290
Propylene	C_3H_6	42.081	0.1976	364.2	4.555	0.1833	0.276
Carbon dioxide	CO_2	44.009	0.1889	304.1	7.377	0.0941	0.275
Nitrous oxide	N_2O	44.013	0.1889	309.5	7.245	0.0972	0.274
Propane	C_3H_8	44.097	0.1885	369.9	4.251	0.2000	0.276
Ethanol	C_2H_5OH	46.069	0.1805	514.7	6.268	0.1686	0.247
Butane (*n*-)	C_4H_{10}	58.124	0.1430	425.1	3.796	0.2549	0.274
Sulfur dioxide	SO_2	64.058	0.1298	430.6	7.887	0.1238	0.273
Chlorine	Cl_2	70.900	0.1173	416.9	7.642	0.1258	0.277
Benzene	C_6H_6	78.114	0.1064	562.0	4.906	0.2563	0.269
Krypton	Kr	83.798	0.09922	209.5	5.525	0.0922	0.292
R-134a	CH_2FCF_3	102.030	0.08149	374.2	4.059	0.1993	0.260
Xenon	Xe	131.290	0.06333	289.7	5.842	0.1190	0.289

$R = R_u/M$, $R_u = 8.31446$ kJ/(kmol·K). Molar masses from the IUPAC standard atomic weights; the molar mass of air is the conventional value.
$Z_{cr} = P_{cr} v_{cr}/(R_u T_{cr})$; the critical point of air is that of the pseudo-pure fluid model. Substances are listed by molar mass.

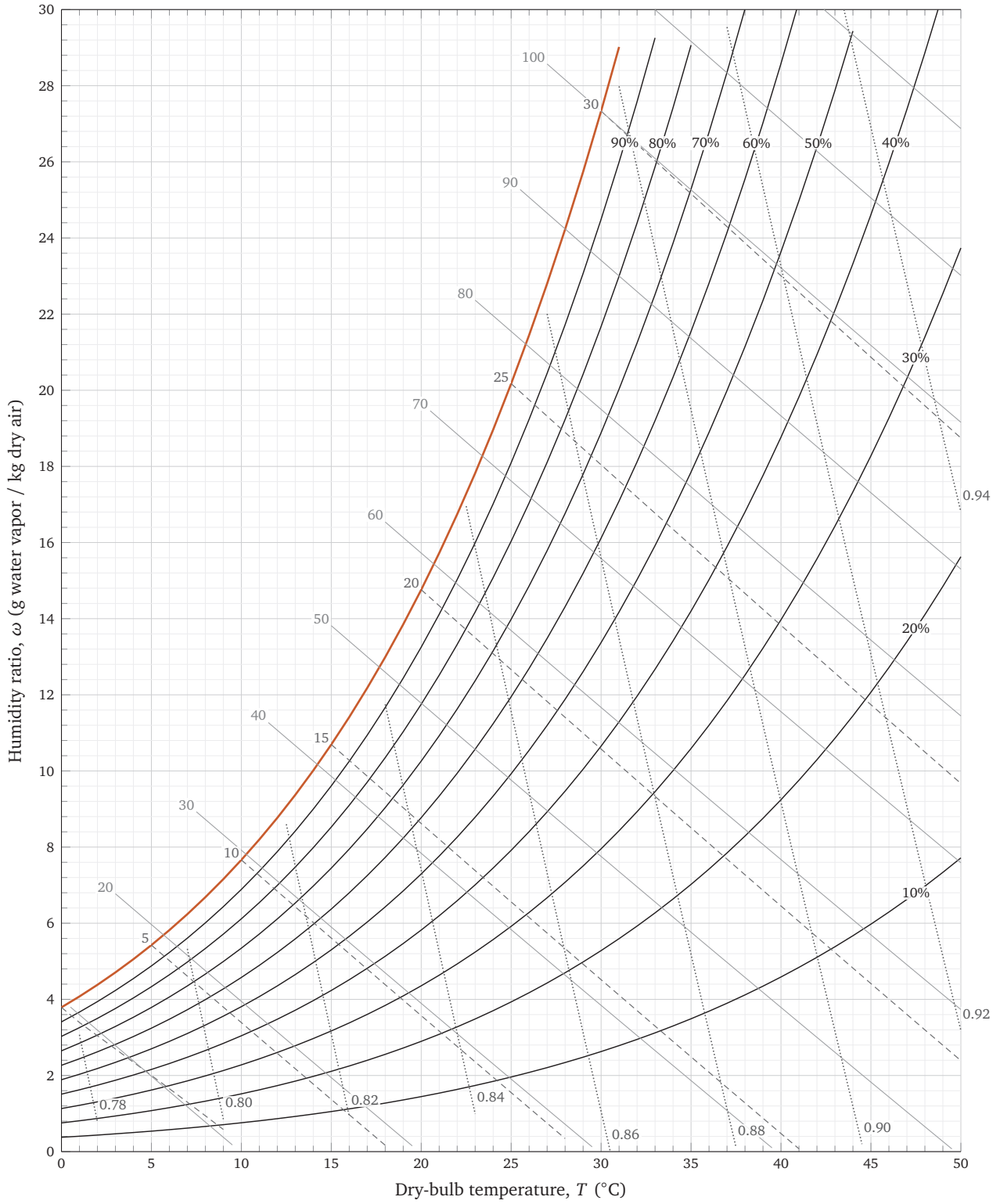
Table T-2 Saturated water: temperature table

		Specific volume m^3/kg		Internal energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/(kg·K)		
T, °C	P_{sat}, kPa	v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
0.01	0.6117	0.001000	205.99	0.000	2374.9	0.001	2500.9	2500.9	0.0000	9.1555	9.1555
5	0.8726	0.001000	147.01	21.019	2381.8	21.020	2489.0	2510.1	0.0763	8.9486	9.0248
10	1.2282	0.001000	106.30	42.020	2388.6	42.021	2477.2	2519.2	0.1511	8.7487	8.8998
15	1.7058	0.001001	77.875	62.980	2395.5	62.981	2465.4	2528.3	0.2245	8.5558	8.7803
20	2.3393	0.001002	57.757	83.912	2402.3	83.914	2453.5	2537.4	0.2965	8.3695	8.6660
25	3.1699	0.001003	43.337	104.83	2409.1	104.83	2441.7	2546.5	0.3672	8.1894	8.5566
30	4.2470	0.001004	32.878	125.73	2415.9	125.73	2429.8	2555.5	0.4368	8.0152	8.4520
35	5.6290	0.001006	25.205	146.63	2422.7	146.63	2417.9	2564.5	0.5051	7.8466	8.3517
40	7.3849	0.001008	19.515	167.53	2429.4	167.53	2406.0	2573.5	0.5724	7.6831	8.2555
45	9.5950	0.001010	15.252	188.43	2436.1	188.43	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.027	209.33	2442.7	209.34	2381.9	2591.3	0.7038	7.3710	8.0748
55	15.762	0.001015	9.5643	230.24	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.946	0.001017	7.6672	251.16	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9081
65	25.042	0.001020	6.1935	272.09	2462.4	272.12	2345.4	2617.5	0.8937	6.9359	7.8296
70	31.201	0.001023	5.0395	293.03	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.595	0.001026	4.1289	313.99	2475.2	314.03	2320.6	2634.6	1.0158	6.6654	7.6812
80	47.414	0.001029	3.4052	334.96	2481.6	335.01	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.867	0.001032	2.8258	355.95	2487.8	356.01	2295.3	2651.3	1.1346	6.4088	7.5434
90	70.182	0.001036	2.3591	376.97	2494.0	377.04	2282.5	2659.5	1.1929	6.2853	7.4781
95	84.608	0.001040	1.9806	398.00	2500.0	398.09	2269.5	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6718	419.06	2506.0	419.17	2256.4	2675.6	1.3072	6.0469	7.3541
110	143.38	0.001052	1.2093	461.26	2517.7	461.42	2229.6	2691.1	1.4188	5.8193	7.2381
120	198.67	0.001060	0.89121	503.60	2528.9	503.81	2202.1	2705.9	1.5279	5.6012	7.1291
130	270.28	0.001070	0.66800	546.09	2539.5	546.38	2173.7	2720.1	1.6346	5.3918	7.0264
140	361.54	0.001080	0.50845	588.77	2549.6	589.16	2144.3	2733.4	1.7392	5.1901	6.9293
150	476.16	0.001091	0.39245	631.66	2559.1	632.18	2113.7	2745.9	1.8418	4.9953	6.8371
160	618.23	0.001102	0.30678	674.79	2567.8	675.47	2082.0	2757.4	1.9426	4.8066	6.7491
170	792.19	0.001114	0.24259	718.20	2575.7	719.08	2048.8	2767.9	2.0417	4.6233	6.6650
180	1002.8	0.001127	0.19384	761.92	2582.8	763.05	2014.2	2777.2	2.1392	4.4448	6.5840
190	1255.2	0.001141	0.15636	806.00	2589.0	807.43	1977.9	2785.3	2.2355	4.2704	6.5059
200	1554.9	0.001157	0.12721	850.47	2594.2	852.27	1939.7	2792.0	2.3305	4.0996	6.4302
210	1907.7	0.001173	0.10429	895.39	2598.3	897.63	1899.6	2797.3	2.4245	3.9318	6.3563
220	2319.6	0.001190	0.086092	940.82	2601.2	943.58	1857.4	2800.9	2.5177	3.7663	6.2840
230	2797.1	0.001209	0.071503	986.81	2602.9	990.19	1812.7	2802.9	2.6101	3.6027	6.2128
240	3346.9	0.001229	0.059705	1033.4	2603.1	1037.6	1765.4	2803.0	2.7020	3.4403	6.1423
250	3976.2	0.001252	0.050083	1080.8	2601.8	1085.8	1715.2	2800.9	2.7935	3.2785	6.0721
260	4692.3	0.001276	0.042173	1129.0	2598.7	1135.0	1661.6	2796.6	2.8849	3.1167	6.0016
270	5503.0	0.001303	0.035621	1178.1	2593.7	1185.3	1604.4	2789.7	2.9765	2.9539	5.9304
280	6416.6	0.001333	0.030153	1228.3	2586.4	1236.9	1543.0	2779.9	3.0685	2.7894	5.8579
290	7441.8	0.001366	0.025555	1279.9	2576.5	1290.0	1476.7	2766.7	3.1612	2.6222	5.7834
300	8587.9	0.001404	0.021660	1332.9	2563.6	1345.0	1404.6	2749.6	3.2552	2.4507	5.7059
310	9865.1	0.001448	0.018335	1387.9	2547.1	1402.2	1325.7	2727.9	3.3510	2.2734	5.6244
320	11284	0.001499	0.015471	1445.3	2526.0	1462.2	1238.4	2700.6	3.4494	2.0878	5.5372
330	12858	0.001561	0.012979	1505.8	2499.2	1525.9	1140.2	2666.0	3.5518	1.8903	5.4422
340	14601	0.001638	0.010781	1570.6	2464.4	1594.5	1027.3	2621.8	3.6601	1.6755	5.3356
350	16529	0.001740	0.008802	1642.1	2418.1	1670.9	892.75	2563.6	3.7784	1.4326	5.2110
360	18666	0.001895	0.006949	1726.3	2351.8	1761.7	719.83	2481.5	3.9167	1.1369	5.0536
370	21044	0.002215	0.004954	1844.1	2230.3	1890.7	443.83	2334.5	4.1112	0.6901	4.8012
373.95	22064	0.003106	0.003106	2015.7	2015.7	2084.3	0.000	2084.3	4.4070	0.0000	4.4070

Reference: the internal energy and entropy of saturated liquid water at the triple point (0.01 °C) are zero. Values are computed from the IAPWS-95 equation of state. f: saturated liquid, g: saturated vapor, $h_{fg} = h_g - h_f$, $s_{fg} = s_g - s_f$, $u_{fg} = u_g - u_f$.

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Table T-14 Psychrometric chart (101.325 kPa)



Solid black curves are relative humidity ϕ (colored: saturation, $\phi = 100\%$); dashed lines are the wet-bulb temperature T_{wb} (°C, labeled on the saturation curve); thin gray lines are enthalpy h (kJ/kg dry air, referenced to dry air and liquid water at 0 °C; labeled on the extension left of the saturation curve); dotted lines are specific volume v (m^3/kg dry air, labeled at the bottom). Computed from real moist-air properties (ASHRAE RP-1485).

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