Chapter 3

Heat, Fluids, and Radiation

3.1 Processes

1. Why do the phenomena shown in Fig. 3.1 show that temperatures rather than quantities of heat equilibrate when bodies are in thermal contact?

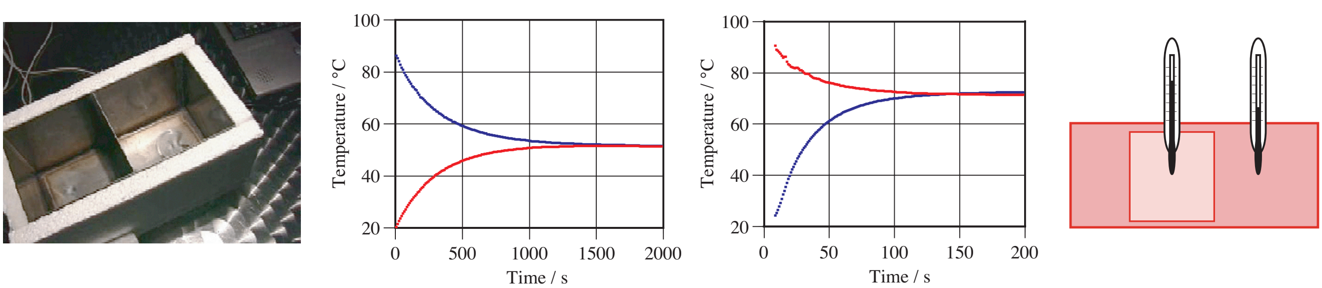


Figure 3.1: A hot and a cold body of water in thermal contact inside a well insulated container (left). The temperatures adjust until they have become equal (graph at center). The same happens if a cold block of copper is put into hot water in a well insulated tank (graph on the right).

2. What does temperature measure?

3. In Fig. 3.1, the temperature reached by copper and water (diagram on the right) is above the average of the initial temperatures of the two bodies. Why is this so? How does this compare to similar phenomena in hydraulics or electricity?

4. Does heat always make a body warmer? Compare the examples shown in Fig. 3.2 and Fig. 3.3.

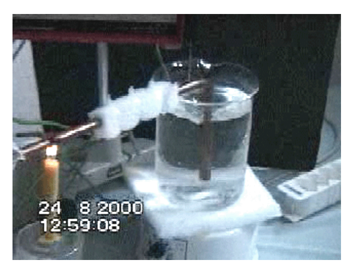


Figure 3.2: A candle indirectly heats water. A copper rod transfers the heat produced by the candle to the water.

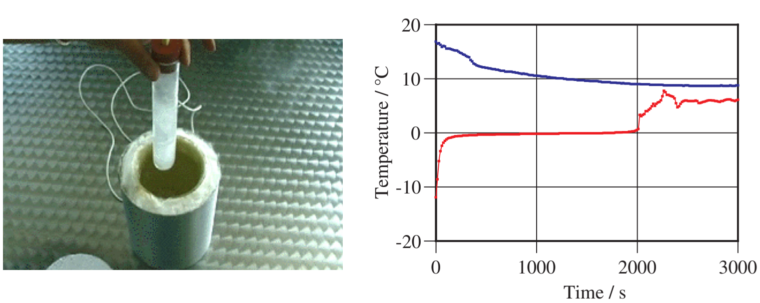


Figure 3.3: A test tube filled with cold ice is placed in water, everything is in a well-sealed container. Temperatures of the water bath (upper curve) and of the ice-water mixture in the test tube (lower curve) are recorded.

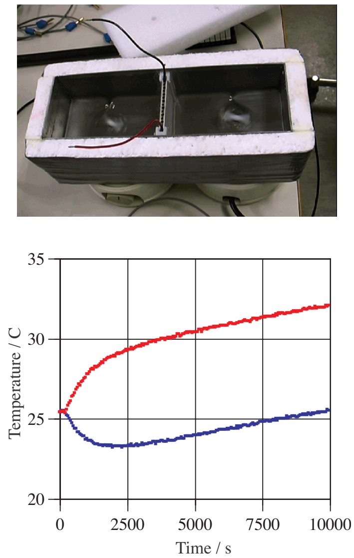


Figure 3.4: Two bodies of water inside an insulated tank are separated by a Peltier device. When operated, the Peltier device cools one body of water and heats the other. (See also Fig. 3.6.)

5. Do we always need heat to make a substance warmer?

6. Why do the processes of melting (or of vaporization) and of compression of air demonstrate clearly that heat and temperature cannot be the same quantity?

7. To make water warmer, we need heat. Where can the heat come from? Does it matter where the heat comes from?

8. What happens with entropy and temperature in the following processes?
   a. Melting of ice.
   b. Water vapor condensation.
   c. Heating a stone.
   d. Isothermal compression of air.
   e. Adiabatically reversible air compression.
   f. Cooling of air at constant volume.

9. Prepare a temperature-heat diagram (temperature on the vertical axis, heat content on the horizontal axis). Sketch with the help of a line what happens in (a) heating of water, (b) condensation of steam, (b) compression of air.

10. What is the role of energy in the phenomenon of Fig. 3.4 (thermoelectric heat pump)?

11. The Stirling engine in Fig. 3.5 is cooled by letting water from a faucet flow through the cooler of the engine. What happens to the operation of the engine if the flow of water is increased?

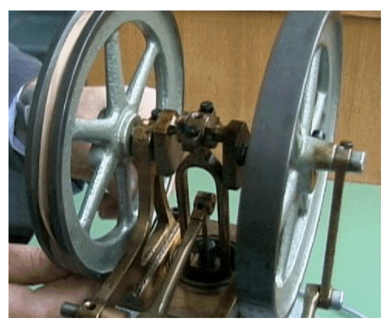
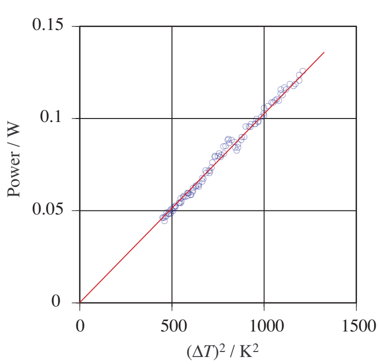


Figure 3.5: The mechanical part of a Stirling engine. When the engine is heated and cooled, the wheels drive a mechanical process.

12. Why does the result of measurements for the power of a thermoelectric device (Fig. 3.6) suggest that thermal processes (in particular, the relation between thermal processes and energy) can be described in analogy to electric processes?



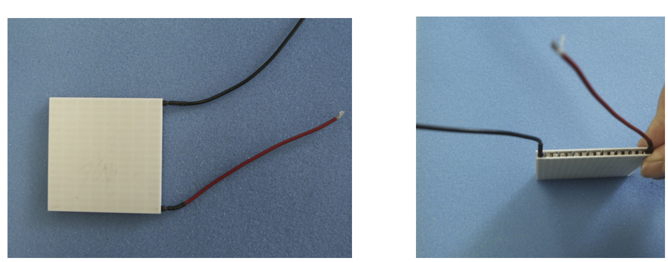


Figure 3.6: Photographs of Peltier device (left). The electric power of a thermoelectric generator (a Peltier device between two heat reservoirs at different temperatures) depends upon the square of the temperature difference.

13. How can a thermoelectric device be used to measure temperatures?

14. Air used in an air thermometer becomes liquid long before it can be cooled to – 273°C. Does this mean that the temperature calculated from extrapolating the measurements in Fig. 3.7 is irrelevant?

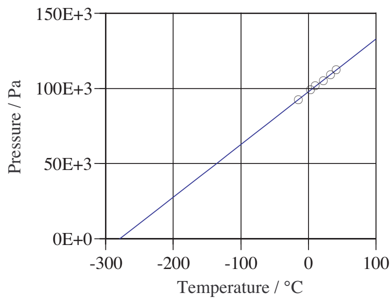


Figure 3.7: Resistance of a resistor as a function of temperature (left), and pressure of air at constant volume as a function of temperature (right; the relation is extrapolated backwards to zero pressure).

15. Why does the temperature of a liquid in a (sealed) container gently stirred stay above ambient temperature even after a long time? (See Fig. 3.8.) What does the fact that the temperature reaches a constant value (in a constant temperature environment) tell us about the processes?

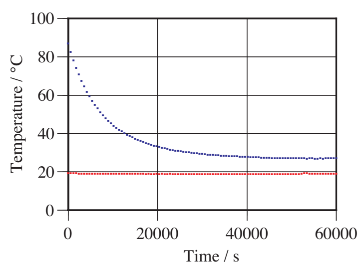


Figure 3.8: Left: Temperature of hot water left standing in a thin-walled aluminum can. The final temperature is above the temperature of the environment (here about 20°C).

16. Consider a book sliding across a table and coming to a stop. What part(s) of this process can be reversed? Which part(s) cannot? What does this have to do with the production of heat?

17. List different ways of producing entropy.

18. A body is thermally insulated.
    a. What is the entropy current?
    b. What could happen with its entropy?

19. A gas goes through several heating and cooling processes which form a cycle. At the end, it is in the same state as at the beginning.
    a. What is the absorbed entropy compared to the entropy emitted when all the individual steps are reversible?
    b. How do the amounts of absorbed and emitted entropy compare to each other when some of the steps are irreversible?

3.2 ENTROPY AND TEMPERATURE

20. Which properties make entropy a fluidlike quantity?

21. What is the law of balance of entropy for a process in a thermally insulated system?

22. What is the role of a temperature difference in thermal processes?

23. If you take hydraulic or electric processes for comparison, what do the phenomena of pumping heat and heat engines tell us about the relation between entropy and energy.

24. The factor relating thermocouple voltages to temperature differences is called the (differential) Seebeck coefficient. Estimate this coefficient for the copper-constantan couple in Fig. 3.9.

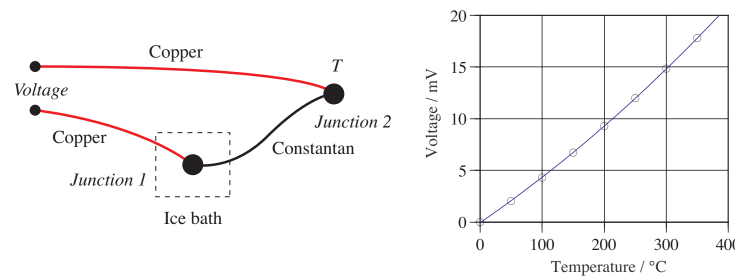


Figure 3.9: A thermocouple is made of wires of two different materials (here, copper and constantan which is called a T-type thermocouple). Voltage versus temperature difference for a T-type thermocouple (note that the relation is not perfectly linear).

25. Which observations concerning simple gases are used to construct the model of the ideal gas? Do these observations follow from the ideal gas relation

$$pV = nRT$$

26. How can we tell that the voltage-temperature-difference relation of a thermocouple is not linear? If we took thermoelectricity as the basis for temperature measurements, would other scales be nonlinear? How do we choose a basic scale to compare other scales to?

27. The entropy currrent in a house decreases linearly within one hour from 12 W/K to 7 W/K. How much entropy has flowed out?

28. The entropy in a certain amount of water rises linearly from 20 J/K to 60 J/K in 100 s. During the same period, the entropy current due to heat loss increases at a constant rate from 0.10 W/K to 0.25 W/K.
    a. What is the rate of change of the entropy in the body?
    b. Determine the entropy current of heating as a function of time.

3.3 ENERGY IN THERMAL PROCESSES

29. How big does an entropy current flowing from a point at 500 K to one at 350 K have to be for the thermal power to measure 1.0 MW?

30. A mechanical stirrer driven by 50 W is put into a viscous liquid.
    a. What is the rate of dissipation?
    b. What is the rate of entropy production when the liquid's temperature is 60°?

31. Water is heated electrically by an immersion heater whose temperature is 127°C. The electric current is 0.80 A and the voltage is 220 V.
    a. What is the dissipation rate?
    b. What is the rate of production of entropy?
    c. How much entropy is produced in one minute?

32. Water at 27°C is heated with an immersion heater. The current is 0.80 A and the voltage is 220 V.
    a. Find the energy current from the immersion heater into the water.
    b. What is the entropy current into the water?
    c. Compare the results to those in Exercise 31.

33. To keep the interior of a home at 27°C in winter, the heating power of the oven is 6 kW. What is the entropy current leaving the home?

34. The absorber of a solar hot water collector receives energy at a rate of 1800 W by absorbing solar radiation.
    a. If we assume that the sunlight brings relatively little entropy with it, what is the rate of entropy production in the absorber when its temperature is 100°C?
    b. Due to heat loss, 40% of the entropy created in the absorber is radiated into the surroundings. What is the entropy current emitted into the water being heated by the collector?
    c. What is the energy current emitted from the absorber into the environment?
    d. What is the entropy currrent into the environment at 20°C?
    e. What is the rate of entropy production between the absorber and the environment?
    f. What are the energy current and the entropy current into the water which has a mean temperature of 50°C?

35. Sunlight brings energy with it but relatively little entropy. Between 8 a.m. and 6 p.m., the energy current of solar radiation upon a surface goes sinusoidally from 0 W to 900 W and back to 0 W. 70% of the incident radiation is absorbed. The temperature of the absorber changes sinusoidally from 20°C to 50°C and back to 20°C.
    a. Determine the rate of entropy production as a function of time.
    b. How much entropy is produced in one day?

3.4 TEMPERATURE COEFFICIENTS AND ENTROPY-TEMPERATURE CHARACTERISTIC OF SIMPLE FLUIDS

36. A copper rod that is 2.0000 m long at 20°C, is 2.0170 m long at 500°C. Determine the temperature coefficient for the length of this material.

37. The temperature coefficient of expansion of copper is $17 \cdot 10^{-6}$ K^{-1}. What is the size of the surface of a thin copper plate at 700°C if it is 0.50 m^2 at 0°C? What is the temperature coefficient of the copper surface?

38. Imagine the world's oceans as 3000 m deep straight sided tanks. If all the water becomes 5°C warmer due to climate change, how much would the level of the oceans rise? The volume temperature coefficient of water is $207 \cdot 10^{-6}$ K^{-1}.

39. What is the temperature of water when a Pt-100 element (resistive thermometer) has an electric resistance of 118.2 Ω? At 20°C the resistance of this resistive thermometer is 100 Ω. The linear and quadratic temperature coefficients of resistances are $3.0 \cdot 10^{-3}$ K^{-1} and $0.6 \cdot 10^{-6}$ K^{-2}.

40. The pressure of a gas in a gas thermometer rises from 0.90 bar to 1.30 bar. The gas starts at a temperature of 10°C. What is the end temperature?

41. Which quantities are calculated with the help of entropy capacitance and energy capacitance (heat capacity)?

42. How are the entropy capacitance and the energy capacitance of a body related?

43. What is the meaning of entropy capacitance, and specific and molar entropy capacitance?

44. Between 200°C and 500°C, the entropy capacitance of a body is constant.
    a. Sketch its energy capacitance as a function of temperature.
    b. How much does the entropy change?
    c. How much does the energy change?

45. Why doesn't the concept of entropy capacitance have anything to do with phase changes?

46. Why does the change of energy in heating at constant volume equal the amount of energy introduced into the heating system? Can the same statement be made for entropy?

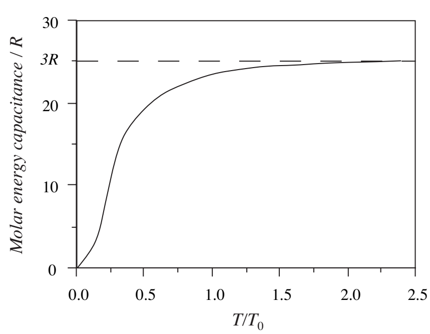


Figure 3.10: Molar energy capacitance (molar heat) of solids as a function of (relative) temperature.

47. How are the changes in entropy and energy calculated in a body being cooled at a constant volume? Its entropy capacitance and energy capacitance are both variable.

48. At what rate do the entropy and energy of a piece of granite with 100 kg mass increase when the temperature increases at a rate of 1.0°C/h?

49. Solid bodies have a molar energy capacitance as shown in the Figure. $T_0 = 343$ K for copper. Assuming that copper has no entropy at 0°C, determine the entropy content of 1 kg copper at 686 K. R is the gas constant.

50. Glycol is heated with an immersion heater in a perfectly insulated container. Electric current, voltage and temperature are measured as functions of time. How can this data be used to determine the entropy capacitance as a function of temperature?

51. What is the molar entropy capacitance of water at 20°C? The specific energy capacitance is 4200 J/(K·kg).

52. An aluminum pan has a a mass of 2.0 kg. At 100°C its rate of change of temperature is 0.20 K/s.
    a. What is the rate of change of the energy?
    b. What is the rate of change of the entropy?
    c. What is the entropy current into the pan at that moment?

53. At 100°C, the specific entropy capacitance of copper is 1.0 J/(K^2kg).
    a. How much does the entropy of 5.0 kg of copper increase if its temperature is raised to 102°C?
    b. How much entropy needs to be added to it?
    c. How much energy must be added?
    d. How much does the body's energy increase?

54. The specific energy capacitance (specific heat) of water is an almost constant 4200 J/(K·kg).
    a. Determine the energy capacitance of 20 kg of water as a function of temperatures between 0°C and 100°C. Show graphically.
    b. What is the change of energy of this amount of water for a temperature change from 0°C to 100 °C?
    c. What is the change of entropy?
    d. Construct the *TS* diagram for 20 kg of water.

55. When 2.0 kg of water at 20°C and 1.0 kg of water at 80°C are mixed in a perfectly insulated container, the temperature adjusts to 40°C.
    a. By how much does the energy of the first and second amounts of water change? How much do they change together?
    b. How much entropy is produced?

56. At 0°C, ethylene glycol has a specific energy capacitance of 2100 J/(K·kg). At 150°C, it is 3000 J/(K·kg). In between, it is rather linear. What temperature results from mixing 1.0 kg of glycol at zero degrees and the same amount of glycol at 150°C?

3.5 ENTROPY AND ENERGY TRANSFER IN HEATING AND COOLING

57. To keep a home at a constant 20°C in winter (outside temperature 0°C), the oven has to work at a power of 6.0 kW. How large is the entropy conductance of the home? If its surface is 250 m^2, what is the entropy transfer coefficient of the shell of the home?

58. The energy conductance (thermal conductance) of a building is 300 W/K. The temperature inside it is kept a constant 20°C. Outside, the temperature is a constant – 10°C.
    a. What is the entropy conductance for the temperature of the building?
    b. What are the entropy and energy currents from the building?
    c. What is the rate of entropy production between the building and its surroundings as a result of heat loss?

d. What must the power of the heating system in the building be?

59. An installatiion of thermal solar collectors with a surface of 10.0 m^2 absorbs energy from radiation at a rate of 6.0 kW. When it is in use, the temperature of the absorber is 90°C. The temperature in the surroundings is 30°C.
    a. The waste energy current into the environment is 2.4 kW. What is the energy conductance of the installation?
    b. What is the overall heat transfer coefficient of the collectors?
    c. What is the energy current from the absorber into the environment?
    d. What is the energy current into the water flowing through the collector?
    e. The average temperature of the water is 50°C. What is the entropy current into the water?

60. The radiators in a room should emit an entropy current of 3.12 W/K from the water that has an average temperature of 45°C. The room's air temperature is 20°C. The transfer coefficient of the entropy from the water into the room is about 0.030 $W/(K^2 \cdot m^2)$.
    a. How big does the surface of the radiators need to be?
    b. What is the energy current out of the water?
    c. What is the energy conductance of the radiators?
    d. What is the rate of entropy production during the transport of heat from the water into the room?
    e. What is the entropy currrent into the air?

3.6 HEAT ENGINES AND HEAT TRANSFER

61. A typical nuclear power plant is a thermal engine running between an upper and a lower temperature of about 600 K and 300 K, respectively. What is the ideal thermal efficiency? Why is the real thermal efficiency more like 30%? What is the real second law efficiency in this case?

62. If a heat pump for heating a house gets entropy from the environment at 0°C, what is the ideal coefficient of performance? (Heating at 30°C.)

63. An energy current of 1.0 GW is delivered to the customers of a large thermal power plant. The energy current of the plant's boiler is 3.0 GW. What is the energy current with the waste heat?

64. The energy current associated with the waste heat in a power plant is 1.5 GW at a temperature of 30°C.
    a. What is the entropy current emitted by the power plant into the environment?
    b. If the plant runs completely reversibly, what is the entropy current from the furnace to the heat engine? What might it otherwise be?
    c. If the thermal power should reach 1.25 GW, what must the heating temperature be (for ideal conditions)?

3.7 MELTING AND VAPORIZATION

65. It takes 1520 s to melt 1 kg of ice with an immersion heater running at 220 V and a current of charge of 1.0 A.
    a. How much energy is introduced to the ice/water?
    b. How much entropy is added?
    c. What is the specific entropy of fusion of ice?
    d. What is the molar entropy of fusion?

66. Why does one speak of enthalpy of fusion when discussing melting instead of energy of fusion?

67. Using the data for enthalpy of fusion, determine the molar entropies of fusion of copper, gold and wolfram.

68. 10 kg of water is made into ice in a perfectly insulated freezer at – 20°C. The entropy current from the freezing water averages 0.25 W/K.
    a. How much entropy is coming out of the water?
    b. How long does the process take?
    c. How much entropy flows into the cooling chamber?
    d. What is the energy current from the water into the cooling chamber?
    e. At what rate must the entropy be pumped out of the cooling chamber for the temperature to remain constant?

69. 100 kg of water vapor is cooled at 100°C and condenses.
    a. What is the change of entropy of the mixture of water vapor and water from the beginning to the end?
    b. How much entropy is emitted by the water vapor?
    c. How much energy is emitted from the water vapor along with the entropy?
    d. By how much does the energy in the system change?
    e. By how much does the enthalpy in the system change?

70. How much water at 20°C must be added to a mixture of 1.0 kg ice and 2.0 kg water so that everything melts and water at 0°C remains?

71. 1.0 kg of water vapor (100°C) and 1.0 kg of ice are put into an insulated container. Will there be ice left, or water vapor? Or will there be only water?

SOME ANSWERS

1. If bodies are different, their temperatures equilibrate, even though amounts of heat (entropy in the bodies) will not be the same. Compare to communicating wataer containers.
2. It measures how warm something is (hotness).
3. The capacitance for storing heat (entropy) of the body of water is larger than that of the piece of copper.
4. Heat can melt a body (its temperature does not change).
5. No (compression of air without heating).
6. Heat (entropy) changes, temperature stays the same (or vice-versa).
7. Heat can come from hotter bodies; it can be pumped from the environment; it can be produced (fires, friction, electricity).
8. (a) Entropy increases, temperature does not change. (b) Entropy is emitted, temperature stays the same. (c) Entropy increases, temperature rises. (d) Entropy is emitted (entropy of air decreases), temperature stays constant. (e) Entropy stays constant, temperature rises. (f) Entropy of air decreases, temperature is lowered.
9. Hint: Be sure to clearly specify the system!
10. Energy is used to pump heat (entropy).
11. Efficiency is increased.
12. Electricity: Power is proportional to UI_Q, and I_Q is proportional to U (in a device with linear characteristic). We compare ΔT to U, I_S to I_Q.
13. ΔT across the device sets up a voltage (open circuit voltage).
14.
15. Entropy is produced in the water (by stirring). In steady-state, the entropy produced must constantly flow out into the environment.
16. Mechanical part(s) can be reversed, production of heat (entropy) cannot be reversed.
17.
18. (a) Zero. (b) Entropy can stay the same or increase.
19.
20. Entropy can be stored, entropy can flow.
21.
22. Temperature differences drive entropy transfers. If entropy is transferred, energy is released.

23.

24. Average: 20 mV / 380 K = $53 \cdot 10^{-6}$ V/K.

25.

26. We would need a thermometer that reads "real" thermodynamic temperatures (i.e., the thermal potential). As long as we do not have this, we do not know if the thermoelectric scale is linear or nonlinear. If we start with the thermoelectric scale, it is to be expected that other measurements (such as with a mercury thermometer) turn out to be "nonlinear." The scale to be used as a basis in thermodynamics is the one provided by the gas thermometer.

27. Average entropy current · time span = 9.5·3600 J/K = $3.4 \cdot 10^4$ J/K

28. (a) dS/dt = (60–40)/100 W/K = 0.40 W/K. (b) $I_{S,loss}(t)$ = 0.10 W/K + 0.0015 W/(K·s) · t, $I_{S,heating}(t) = dS/dt + I_{S,loss}$ = 0.50 W/K + 0.0015 W/(K·s) · t.

29. 6.67 kW/K.

30. (a) 50 W. (b) 0.15 W/K.

31.

32. (a) 176 W. (b) 0.587 W/K. (c) Entropy production rate in the heater is smaller than the entropy current into the water.

33.

34. (a) 4.83 W/K. (b) 2.90 W/K (if the collector operates at steady-state). (c) 720 W. (d) 2.46 W/K. (e) 0.53 W/K. (f) 1080 W, 3.34 W/K.

35.

36. $1.7 \cdot 10^{-5}$ 1/K.

37.

38. 3.1 m.

39.

40. 409 K = 136°C.

41.

42. Energy capacitance = (Kelvin) Temperature · Entropy capacitance.

43.

44. (a) Rising linear function that is zero for 0 K. (b) $K \cdot (500 - 200)$ J/K. (c) Area under $C(T)$ curve from 473 K to 773 K.

45.

46. Energy is exchanged only due to heating. Yes (this is always so, it has nothing to do with the assumption of constant volume heating).

47.

48. dS/dt = 0.078 W/K, dW/dt = 23.3 W (at a temperature of 300 K).

49.

50. Electric quantities give rate of input of energy; divide by the temperature of glycol gives entropy current into glycol. Determine rate of change of temperature of glycol. Divide entropy current by rate of change of temperature.

51.

52. (a) 360 W. (b) 0.96 W/K. (c) 0.96 W/K.

53.

54. (a) 84 kJ/K, constant. (b) 8.4 MJ. (c) 26.2 kJ/K. (d) Exponential function.

55. (a) + 168 kJ, – 168 kJ; zero. (b)

56.

57. 1.02 W/K^2. $4.1 \cdot 10^{-3}$ $W/(K^2 m^2)$.

58. (a) 1.02 W/K^2. (b) 31 W/K, 9.0 kW. (c) 3.2 W/K. (d) 9.0 kW.

59.

60. (a) 4.16 m^2. (b) 992 W. (c) 9.54 W/K. (d) 0.27 W/K. (e) 3.39 W/K.

61. 0.50 (50%). Irreversibilities due to heat transfer. 0.60 (60%).

62. 10.

63. 2.0 GW.

64. (a) 4.95 MW/K. (b) 4.95 MW/K, otherwise it is smaller. (c) 283°C.

65. (a) 334 kJ. (b) 1225 J/K. (c) 1225 J/(K·kg). (d) 22.0 J/(K·mole).

66. The energy added to the system is equal to the change of enthalpy of the system rather than to the change of the energy of the system (some energy is exchanged due to volume change).

67.

68. (a) 12.2 kJ/K. (b) 48800 s. (c) 13.2 kJ/K. (d) 68.4 W. (e) 0.27 W/K.

69. (a) 606 kJ/K. (b) 606 kJ/K. (c) 226 MJ. (d) By more than 226 MJ. (e) 226 MJ.

70.

71.