The constant C depends on the mode of heat transfer as

$$\text{Conduction:} \quad C = \frac{kA}{\Delta x} \qquad \text{Convection: } C = hA$$

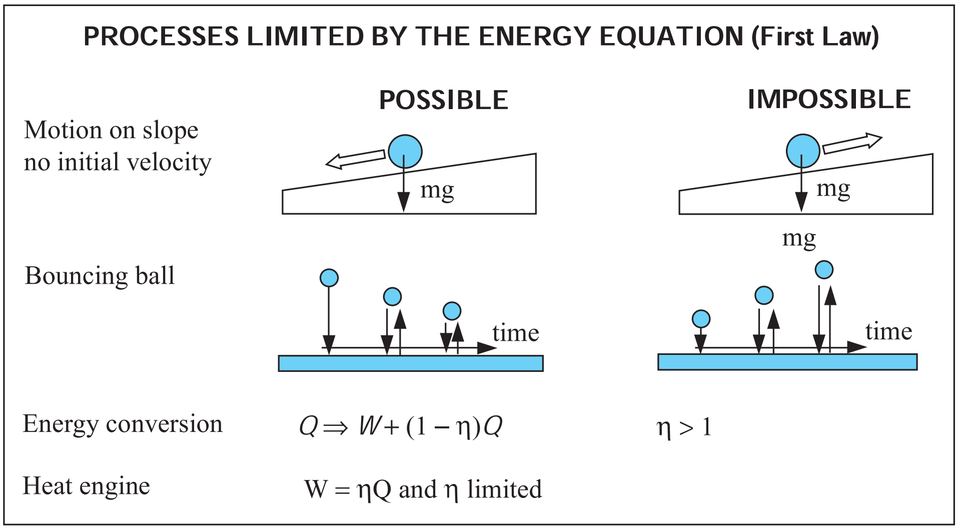
$$\text{Radiation:} \quad C = \varepsilon\sigma A(T_s^2 + T_\infty^2)(T_s + T_\infty)$$

For more complex situations with combined layers and modes, we also recover the form in Eq. 7.14, but with a value of C that depends on the geometry, materials, and modes of heat transfer. To have a heat transfer, we therefore must have a temperature difference so that the working substance inside a cycle cannot attain the reservoir temperature unless the area is infinitely large.

7.10 ENGINEERING APPLICATIONS

The second law of thermodynamics is presented as it was developed, with some additional comments and in a modern context. The main implication is the limits it imposes on processes: Some processes will not occur but others will, with a constraint on the operation of complete cycles such as heat engines and heat pumps.

Nearly all energy conversion processes that generate work (typically converted further from mechanical to electrical work) involve some type of cyclic heat engine. These include the engine in a car, a turbine in a power plant, or a windmill. The source of energy can be a storage reservoir (fossil fuels that can burn, such as gasoline or natural gas) or a more temporary form, for example, the wind kinetic energy that ultimately is driven by heat input from the sun.



Machines that violate the energy equation, say generate energy from nothing, are called perpetual-motion machines of the first kind. Such machines have been "demonstrated" and investors asked to put money into their development, but most of them had some kind of energy input not easily observed (such as a small, compressed air line or a hidden fuel supply). Recent examples are cold fusion and electrical phase imbalance;

these can be measured only by knowledgeable engineers. Today it is recognized that these processes are impossible.

Machines that violate the second law but obey the energy equation are called perpetual-motion machines of the second kind. These are a little more subtle to analyze, and for the unknowledgeable person they often look as if they should work. There are many examples of these and they are even proposed today, often hidden by a variety of complicated processes that obscure the overall process.

PROCESSES LIMITED BY THE SECOND LAW

	POSSIBLE	IMPOSSIBLE
Heat transfer No work term	$\dot{Q}$ (at T_{hot}) $\dot{Q}$ (at T_{cold})	$\dot{Q}$ (at T_{cold}) $\dot{Q}$ (at T_{hot})
Flow, $\dot{m}$ No KE, PE	P_{high} P_{low}	P_{low} P_{high}
Energy conversion	W Q (100%)	Q W (100%)
Energy conversion	Q W $(1 \quad \eta)Q$ W ηQ and η limited	η $\eta_{rev.\ heat\ eng}$
Chemical reaction like combustion	Fuel air products	Products fuel air
Heat exchange, mixing	hot | cold ⇨ warm	warm ⇨ hot | cold
Mixing	O_2 | N_2 ⇨ air	air ⇨ O_2 | N_2

Actual Heat Engines and Heat Pumps

The necessary heat transfer in many of these systems typically takes place in dual-fluid heat exchangers where the working substance receives or rejects heat. These heat engines typcially have an external combustion of fuel, as in coal, oil, or natural gas-fired power plants, or they receive heat from a nuclear reactor or some other source. There are only a few types of movable engines with external combustion, notably a Stirling engine (see Chapter 12) that uses a light gas as a working substance. Heat pump or refrigerators all have heat transfer external to the working substance with work input that is electrical, as in the standard household refrigerator, but it can also be shaft work from a belt, as in a car air-conditioner system. The heat transfer requires a temperature difference (recall Eq. 7.14) such that the rates become

$$\dot{Q}_H = C_H \Delta T_H \qquad \text{and} \qquad \dot{Q}_L = C_L \Delta T_L$$

where the C's depend on the details of the heat transfer and interface area. That is, for a heat engine, the working substance goes through a cycle that has

$$T_{high} = T_H - \Delta T_H \qquad \text{and} \qquad T_{low} = T_L + \Delta T_L$$

so the operating range that determines the cycle efficiency becomes

$$\Delta T_{HE} = T_{high} - T_{low} = T_H - T_L - (\Delta T_H + \Delta T_L) \tag{7.15}$$

For a heat pump the working substance must be warmer than the reservoir to which it moves $\dot{Q}_H$, and it must be colder than the reservoir from which it takes $\dot{Q}_L$, so we get

$$T_{\text{high}} = T_H + \Delta T_H \qquad \text{and} \qquad T_{\text{low}} = T_L - \Delta T_L$$

giving an operating range for the working substance as

$$\Delta T_{\text{HP}} = T_{\text{high}} - T_{\text{low}} = T_H - T_L + (\Delta T_H + \Delta T_L) \tag{7.16}$$

This effect is illustrated in Fig 7.27 for both the heat engine and the heat pump. Notice that in both cases the effect of the finite temperature difference due to the heat transfer is to decrease the performance. The heat engine's maximum possible efficiency is lower due to the lower T_{high} and higher T_{low}, and the heat pump's (also the refrigerator's) COP is lower due to the higher T_{high} and the lower T_{low}.

For heat engines with an energy conversion process in the working substance such as combustion, there is no heat transfer to or from an external energy reservoir. These are typically engines that move and thus cannot have large pieces of equipment, as volume and mass are undesirable, as in car and truck engines, gas turbines, and jet engines. When the working substance becomes hot, it has a heat transfer loss to its surroundings that lowers the pressure (given the volume) and thus decreases the ability to do work on any moving boundary. These processes are more difficult to analyze and require extensive knowledge to predict any net effect like efficiency, so in later chapters we will use some simple models to describe these cycles.

A final comment about heat engines and heat pumps is that there are no practical examples of these that run in a Carnot cycle. All the cyclic devices operate in slightly different cycles determined by the behavior of the physical arrangements, as shown in Chapters 11 and 12.

Some Historical Developments in Thermodynamics

Progress in understanding the physical sciences led to the basic development of the second law of thermodynamics before the first law. A wide variety of people with different backgrounds did work in this area, Carnot and Kelvin among others, that, combined with developments in mathematics and physics, helped foster the Industrial Revolution. Much of this work took place in the second half of the 1800s followed by applications continuing into the early 1900s such as steam turbines, gasoline and diesel engines, and modern refrigerators. All of these inventions and developments had a profound effect on our society.

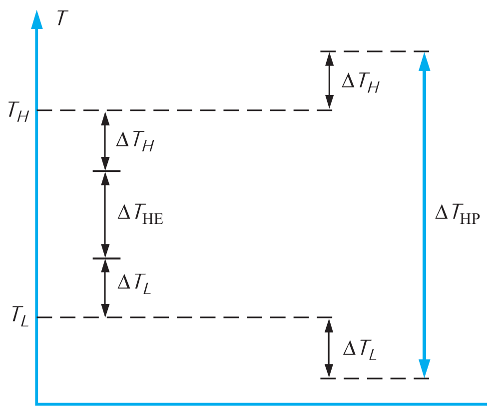


FIGURE 7.27 Temperature span for heat engines and heat pumps.

Year	Person	Event
1660	Robert Boyle	$P = C/V$ at constant T (first gas law attempt)
1687	Isaac Newton	Newton's laws, gravitation, law of motion
1712	Thomas Newcomen & Thomas Savery	First practical steam engine using piston-cylinder
1714	Gabriel Fahrenheit	First mercury thermometer
1738	Daniel Bernoulli	Forces in hydraulics, Bernoulli's equation (Ch. 9)
1742	Anders Celsius	Proposes Celsius scale
1765	James Watt	Steam engine that includes a separate condenser (Ch. 11)
1787	Jaques A. Charles	Ideal gas relation between V and T
1824	Sadi Carnot	Concept of heat engine, hints at second law
1827	George Ohm	Ohm law formulated
1839	William Grove	First fuel cell (Ch. 15)
1842	Julius Robert Mayer	Conservation of energy
1843	James P. Joule	Experimentally measured equivalency of work and heat
1848	William Thomson	Lord Kelvin proposes absolute temperature scale based on the work done by Carnot and Charles
1850	Rudolf Clausius and later, William Rankine	First law of energy conservation, Thermodynamics is a new science.
1865	Rudolf Clausius	Entropy (Ch. 8) increases in a closed system (second law)
1877	Nikolaus Otto	Develops the Otto cycle engine (Ch. 12)
1878	J. Willard Gibbs	Heterogeneous equilibria, phase rule
1882	Joseph Fourier	Mathematical theory of heat transfer
1882		Electrical generating plant in New York (Ch. 11)
1893	Rudolf Diesel	Develops the compression-ignition engine (Ch. 12)
1896	Henry Ford	First Ford (quadricycle) built in Michigan
1927	General Electric Co.	First refrigerator made available to consumers (Ch. 11)

SUMMARY

The classical presentation of the second law of thermodynamics starts with the concept of heat engines and refrigerators. A heat engine produces work from a heat transfer obtained from a thermal reservoir, and its operation is limited by the Kelvin–Planck statement. Refrigerators are functionally the same as heat pumps, and they drive energy by heat transfer from a colder environment to a hotter environment, something that will not happen by itself. The Clausius statement says in effect that the refrigerator or heat pump does need work input to accomplish the task. To approach the limit of these cyclic devices, the idea of reversible processes is discussed and further explained by the opposite, namely, irreversible processes and impossible machines. A perpetual motion machine of the first kind violates the first law (energy equation), and a perpetual-motion machine of the second kind violates the second law of thermodynamics.

The limitations for the performance of heat engines (thermal efficiency) and heat pumps or refrigerators (coefficient of performance or COP) are expressed by the corresponding Carnot-cycle device. Two propositions about the Carnot cycle device are another way of expressing the second law of thermodynamics instead of the statements of Kelvin–Planck or Clausius. These propositions lead to the establishment of the thermodynamic absolute temperature, done by Lord Kelvin, and the Carnot-cycle efficiency. We show this temperature to be the same as the ideal-gas temperature introduced in Chapter 3.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Understand the concepts of heat engines, heat pumps, and refrigerators.
- Have an idea about reversible processes.
- Know a number of irreversible processes and recognize them.
- Know what a Carnot cycle is.
- Understand the definition of thermal efficiency of a heat engine.
- Understand the definition of coefficient of performance (COP) of a heat pump.
- Know the difference between absolute and relative temperature.
- Know the limits of thermal efficiency as dictated by the thermal reservoirs and the Carnot-cycle device.
- Have an idea about the thermal efficiency of real heat engines.
- Know the limits of COP as dictated by the thermal reservoirs and the Carnot-cycle device.
- Have an idea about the COP of real refrigerators.

KEY CONCEPTS AND FORMULAS

(All W, Q can also be rates $\dot{W}$, $\dot{Q}$)

Heat engine	$W_{HE} = Q_H - Q_L;\quad \eta_{HE} = \dfrac{W_{HE}}{Q_H} = 1 - \dfrac{Q_L}{Q_H}$
Heat pump	$W_{HP} = Q_H - Q_L;\quad \beta_{HP} = \dfrac{Q_H}{Q_{HP}} = \dfrac{Q_H}{Q_H - Q_L}$
Refrigerator	$W_{REF} = Q_H - Q_L;\quad \beta_{REF} = \dfrac{Q_L}{W_{REF}} = \dfrac{Q_L}{Q_H - Q_L}$
Factors that make processes irreversible	Friction, unrestrained expansion ($W = 0$), Q over ΔT, mixing, current through a resistor, combustion, or valve flow (throttle)
Carnot cycle	1–2 Isothermal heat addition Q_H in at T_H
	2–3 Adiabatic expansion process T does down
	3–4 Isothermal heat rejection Q_L out at T_L
	4–1 Adiabatic compression process T goes up
Proposition I	$\eta_{any} \leq \eta_{reversible}$ Same T_H, T_L
Proposition II	$\eta_{Carnot\ 1} = \eta_{Carnot\ 2}$ Same T_H, T_L
Absolute temperature	$\dfrac{T_L}{T_H} = \dfrac{Q_L}{Q_H}$
Real heat engine	$\eta_{HE} = \dfrac{W_{HE}}{Q_H} \leq \eta_{Carnot\ HE} = 1 - \dfrac{T_L}{T_H}$
Real heat pump	$\beta_{HP} = \dfrac{Q_H}{W_{HP}} \leq \beta_{Carnot\ HP} = \dfrac{T_H}{T_H - T_L}$
Real refrigerator	$\beta_{REF} = \dfrac{Q_L}{W_{REF}} \leq \beta_{Carnot\ REF} = \dfrac{T_L}{T_H - T_L}$
Heat-transfer rates	$\dot{Q} = C\,\Delta T$

CONCEPT-STUDY GUIDE PROBLEMS

7.1 Two heat engines operate between the same two energy reservoirs, and both receive the same Q_H. One engine is reversible and the other is not. What can you say about the two Q_L's?

7.2 Compare two domestic heat pumps (A and B) running with the same work input. If A is better than B, which one provides more heat?

7.3 Suppose we forget the model for heat transfer, $\dot{Q} = CA\,\Delta T$; can we draw some information about the direction of Q from the second law?

7.4 A combination of two heat engines is shown in Fig. P7.4. Find the overall thermal efficiency as a function of the two individual efficencies.

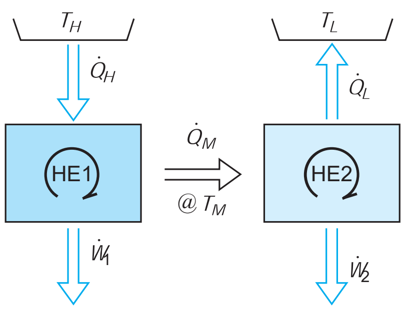


FIGURE P7.4

7.5 Compare two heat engines receiving the same Q, one at 1200 K and the other at 1800 K, both of which reject heat at 500 K. Which one is better?

7.6 A car engine takes atmospheric air in at 20°C, no fuel, and exhausts the air at −20°C, producing work in the process. What do the first and second laws say about that?

7.7 A combination of two refrigerator cycles is shown in Fig. P7.7. Find the overall COP as a function of COP_1 and COP_2.

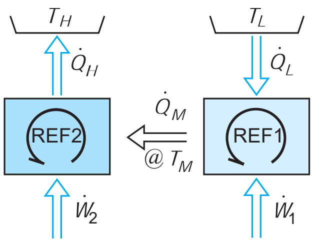


FIGURE P7.7

7.8 After you have driven a car on a trip and it is back home, the car's engine has cooled down and thus is back to the state in which it started. What happened to all the energy released in the burning of gasoline? What happened to all the work the engine gave out?

7.9 Does a reversible heat engine burning coal (which in practice cannot be done reversibly) have impacts on our world other than depletion of the coal reserve?

7.10 If the efficiency of a power plant goes up as the low temperature drops, why do all power plants not reject energy at, say, −40°C?

7.11 If the efficiency of a power plant goes up as the low temperature drops, why not let the heat rejection go to a refrigerator at, say, −10°C instead of ambient 20°C?

7.12 A coal-fired power plant operates with a high temperature of 600°C, whereas a jet engine has about 1400 K. Does this mean that we should replace all power plants with jet engines?

7.13 Heat transfer requires a temperature difference (see Chapter 4) to push the $\dot{Q}$. What does that imply for a real heat engine? A refrigerator?

7.14 Hot combustion gases (air) at 1500 K are used as the heat source in a heat engine where the gas is cooled to 750 K and the ambient is at 300 K. This is not a constant-temperature source. How does that affect the efficiency?

HOMEWORK PROBLEMS

Heat Engines and Refrigerators

7.15 A gasoline engine produces 20 hp using 35 kW of heat transfer from burning fuel. What is its thermal efficiency, and how much power is rejected to the ambient surroundings?

7.16 Calculate the thermal efficiency of the steam power plant given in Example 6.9.

7.17 A refrigerator removes 1.5 kJ from the cold space using 1 kJ of work input. How much energy goes into the kitchen, and what is its COP?

7.18 Calculate the COP of the R-134a refrigerator given in Example 6.10.

7.19 A coal-fired power plant has an efficiency of 35% and produces net 500 MW of electricity. Coal releases 25 000 kJ/kg as it burns, so how much coal is used per hour?

7.20 Assume we have a refrigerator operating at a steady state using 500 W of electric power with a COP of 2.5. What is the net effect on the kitchen air?

7.21 A room is heated with a 1500 W electric heater. How much power can be saved if a heat pump with a COP of 2.0 is used instead?

7.22 An air conditioner discards 5.1 kW to the ambient surroundings with a power input of 1.5 kW. Find the rate of cooling and the COP.

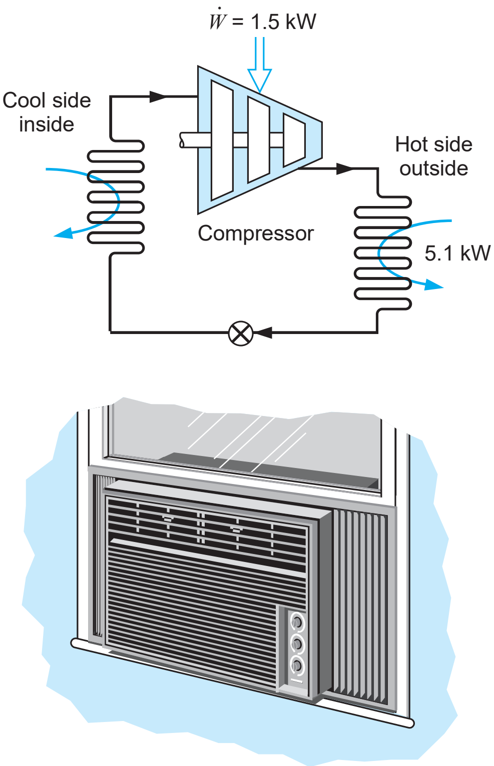


FIGURE P7.22

7.23 Calculate the thermal efficiency of the steam power plant cycle described in Problem 6.103.

7.24 A window air-conditioner unit is placed on a laboratory bench and tested in cooling mode using 750 W of electric power with a COP of 1.75. What is the cooling power capacity, and what is the net effect on the laboratory?

7.25 A water cooler for drinking water should cool 25 L/h water from 18°C to 10°C using a small refrigeration unit with a COP of 2.5. Find the rate of cooling required and the power input to the unit.

7.26 A farmer runs a heat pump with a 2 kW motor. It should keep a chicken hatchery at 30°C, which loses energy at a rate of 10 kW to the colder ambient T_{amb}. What is the minimum COP that will be acceptable for the heat pump?

7.27 Calculate the COP of the R-410a heat pump cycle described in Problem 6.108.

7.28 A power plant generates 150 MW of electrical power. It uses a supply of 1000 MW from a geothermal source and rejects energy to the atmosphere. Find the power to the air and how much air should be flowed to the cooling tower (kg/s) if its temperature cannot be increased more than 10°C.

7.29 A water cooler for drinking water should cool 25 L/h water from 18°C to 10°C while the water reservoir gains 60 W from heat transfer. Assume that a small refrigeration unit with a COP of 2.5 does the cooling. Find the total rate of cooling required and the power input to the unit.

7.30 A car engine delivers 25 hp to the driveshaft with a thermal efficiency of 30%. The fuel has a heating value of 40 000 kJ/kg. Find the rate of fuel consumption and the combined power rejected through the radiator and exhaust.

7.31 R-410a enters the evaporator (the cold heat exchanger) in an air-conditioning unit at −20°C, $x = 28\%$ and leaves at −20°C, $x = 1$. The COP of the refrigerator is 1.5 and the mass flow rate is 0.003 kg/s. Find the net work input to the cycle.

7.32 For each of the cases below, determine if the heat engine satisfies the first law (energy equation) and if it violates the second law.

a. $\dot{Q}_H = 6$ kW	$\dot{Q}_L = 4$ kW	$\dot{W} = 2$ kW
b. $\dot{Q}_H = 6$ kW	$\dot{Q}_L = 0$ kW	$\dot{W} = 6$ kW
c. $\dot{Q}_H = 6$ kW	$\dot{Q}_L = 2$ kW	$\dot{W} = 5$ kW
d. $\dot{Q}_H = 6$ kW	$\dot{Q}_L = 6$ kW	$\dot{W} = 0$ kW

7.33 For each of the cases in Problem 7.32 determine if a heat pump satisfies the first law (energy equation) and if it violates the second law.

7.34 A large stationary diesel engine produces 15 MW with a thermal efficiency of 40%. The exhaust gas, which we assume is air, flows out at 800 K, and the intake is 290 K. How large is the mass flow rate? Can the exhaust flow energy be used?

7.35 In a steam power plant 1 MW is added in the boiler, 0.58 MW is taken out in the condenser, and the pump work is 0.02 MW. Find the plant's thermal efficiency. If everything could be reversed, find the COP as a refrigerator.

7.36 Calculate the amount of work input a refrigerator needs to make ice cubes out of a tray of 0.25 kg liquid water at 10°C. Assume that the refrigerator has $\beta = 3.5$ and a motor-compressor of 750 W. How much time does it take if this is the only cooling load?

Second Law and Processes

7.37 Prove that a cyclic device that violates the Kelvin–Planck statement of the second law also violates the Clausius statement of the second law.

7.38 Assume a cyclic machine that exchanges 6 kW with a 250°C reservoir and has

a. $\dot{Q}_L = 0$ kW $\qquad \dot{W} = 6$ kW

b. $\dot{Q}_L = 6$ kW $\qquad \dot{W} = 0$ kW

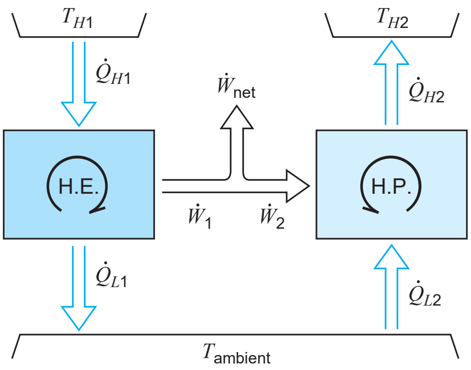
and $\dot{Q}_L$ is exchanged with ambient surroundings at 30°C. What can you say about the processes in the two cases a and b if the machine is a heat engine? Repeat the question for the case of a heat pump.

7.39 Discuss the factors that would make the power plant cycle described in Problem 6.103 an irreversible cycle.

7.40 Discuss the factors that would make the heat pump cycle described in Problem 6.108 an irreversible cycle.

7.41 Consider the four cases of a heat engine in Problem 7.32 and determine if any of those are perpetual-motion machines of the first or second kind.

7.42 Consider a heat engine and heat pump connected as shown in Fig. P7.42. Assume $T_{H1} = T_{H2} > T_{\text{amb}}$ and determine for each of the three cases if the setup satisfies the first law and/or violates the second law.



	$\dot{Q}_{H1}$	$\dot{Q}_{L1}$	$\dot{W}_1$	$\dot{Q}_{H2}$	$\dot{Q}_{L2}$	$\dot{W}_2$
a	6	4	2	3	2	1
b	6	4	2	5	4	1
c	3	2	1	4	3	1

FIGURE P7.42

7.43 The water in a shallow pond heats up during the day and cools down during the night. Heat transfer by radiation, conduction, and convection with the ambient surroundings thus cycles the water temperature. Is such a cyclic process reversible or irreversible?

Carnot Cycles and Absolute Temperature

7.44 Calculate the thermal efficiency of a Carnot-cycle heat engine operating between reservoirs at 300°C and 45°C. Compare the result to that of Problem 7.16.

7.45 A Carnot-cycle heat engine has an efficiency of 40%. If the high temperature is raised 10%, what is the new efficiency, keeping the same low temperature?

7.46 Find the power output and the low T heat rejection rate for a Carnot-cycle heat engine that receives 6 kW at 250°C and rejects heat at 30°C, as in Problem 7.38.

7.47 Consider the setup with two stacked (temperature-wise) heat engines, as in Fig. P7.4. Let $T_H = 900$ K, $T_M = 600$ K, and $T_L = 300$ K. Find the two heat engine efficiencies and the combined overall efficiency assuming Carnot cycles.

7.48 At a few places where the air is very cold in the winter, for example, −30°C, it is possible to find a temperature of 13°C below ground. What efficiency will a heat engine have operating between these two thermal reservoirs?

7.49 Find the maximum COP for the refrigerator in your kitchen, assuming it runs in a Carnot cycle.

7.50 A refrigerator should remove 500 kJ from some food. Assume the refrigerator works in a Carnot cycle between −10°C and 45°C with a motor-compressor of 500 W. How much time does it take if this is the only cooling load?

7.51 A car engine burns 5 kg of fuel (equivalent to adding Q_H) at 1500 K and rejects energy to the radiator and exhaust at an average temperature of 750 K. Assume the fuel has a heating value of 40 000 kJ/kg and find the maximum amount of work the engine can provide.

7.52 A large heat pump should upgrade 5 MW of heat at 85°C to be delivered as heat at 150°C. What is the minimum amount of work (power) input that will drive this pump?

7.53 An air conditioner provides 1 kg/s of air at 15°C cooled from outside atmospheric air at 35°C. Estimate the amount of power needed to operate the air conditioner. Clearly state all assumptions made.

7.54 A cyclic machine, shown in Fig. P7.54, receives 325 kJ from a 1000 K energy reservoir. It rejects 125 kJ to a 400 K energy reservoir, and the cycle produces 200 kJ of work as output. Is this cycle reversible, irreversible, or impossible?

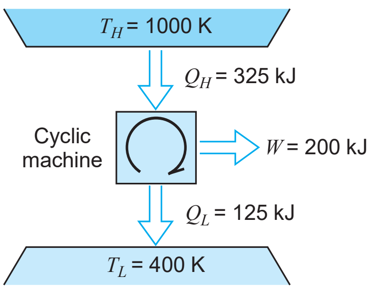


FIGURE P7.54

7.55 A salesperson selling refrigerators and deep freezers will guarantee a minimum COP of 4.5 year round. How would the performance of these machines compare? Would it be steady throughout the year?

7.56 A temperature of about 0.01 K can be achieved by magnetic cooling. In this process, a strong magnetic field is imposed on a paramagnetic salt, maintained at 1 K by transfer of energy to liquid helium boiling at low pressure. The salt is then thermally isolated from the helium, the magnetic field is removed, and the salt temperature drops. Assume that 1 mJ is removed at an average temperature of 0.1 K to the helium by a Carnot-cycle heat pump. Find the work input to the heat pump and the COP with an ambient temperature of 300 K.

7.57 The lowest temperature that has been achieved is about 1×10^{-6} K. To achieve this, an additional stage of cooling is required beyond that described in the previous problem, namely, nuclear cooling. This process is similar to magnetic cooling, but it involves the magnetic moment associated with the nucleus rather than that associated with certain ions in the paramagnetic salt. Suppose that 10 μJ is to be removed from a specimen at an average temperature of 10^{-5} K (10 μJ is approximately the potential energy loss of a pin dropping 3 mm). Find the work input to a Carnot heat pump and its COP required to do this, assuming the ambient temperature is 300 K.

7.58 An inventor has developed a refrigeration unit that maintains the cold space at −10°C while operating in a 25°C room. A COP of 8.5 is claimed. How do you evaluate this?

7.59 Calculate the amount of work input a refrigerator needs to make ice cubes out of a tray of 0.25 kg liquid water at 10°C. Assume the refrigerator works in a Carnot cycle between −8°C and 35°C with a motor-compressor of 750 W. How much time does it take if this is the only cooling load?

7.60 A heat pump receives energy from a source at 80°C and delivers energy to a boiler that operates at 350 kPa. The boiler input is saturated liquid water and the exit is saturated vapor, both at 350 kPa. The heat pump is driven by a 2.5 MW motor and has a COP that is 60% of a Carnot heat pump COP. What is the maximum mass flow rate of water the system can deliver?

7.61 A household freezer operates in a room at 20°C. Heat must be transferred from the cold space at a rate of 2 kW to maintain its temperature at −30°C. What is the theoretically smallest (power) motor required to operate this freezer?

7.62 We propose to heat a house in the winter with a heat pump. The house is to be maintained at 20°C at all times. When the ambient temperature outside drops to −10°C, the rate at which heat is lost from the house is estimated to be 25 kW. What is the minimum electrical power required to drive the heat pump?

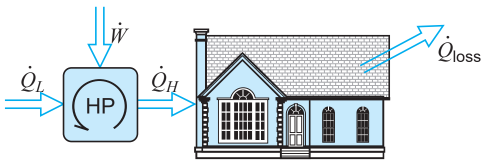


FIGURE P7.62

7.63 A certain solar-energy collector produces a maximum temperature of 100°C. The energy is used in a cyclic heat engine that operates in a 10°C environment. What is the maximum thermal efficiency? What is it if the collector is redesigned to focus the incoming light to produce a maximum temperature of 300°C?

7.64 Helium has the lowest normal boiling point of any element at 4.2 K. At this temperature the enthalpy of evaporation is 83.3 kJ/kmol. A Carnot refrigeration cycle is analyzed for the production of 1 kmol of liquid helium at 4.2 K from saturated vapor at the same temperature. What is the work input to the refrigerator and the COP for the cycle with an ambient temperature at 300 K?

7.65 A thermal storage device is made with a rock (granite) bed of 2 m^3 that is heated to 400 K using solar energy. A heat engine receives Q_H from the bed and rejects heat to the ambient surroundings at 290 K. The rock bed therefore cools down, and as it reaches 290 K the process stops. Find the energy the rock bed can give out. What is the heat engine's efficiency at the beginning of the process, and what is it at the end of the process?

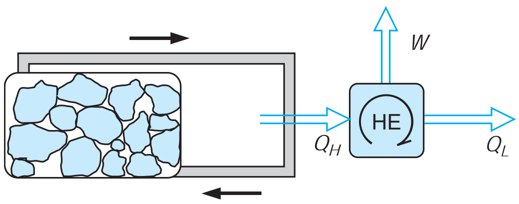


FIGURE P7.65

7.66 In a cryogenic experiment you need to keep a container at −125°C, although it gains 100 W due to heat transfer. What is the smallest motor you would need for a heat pump absorbing heat from the container and rejecting heat to the room at 20°C?

7.67 It is proposed to build a 1000 MW electric power plant with steam as the working fluid. The condensers are to be cooled with river water (see Fig. P7.67). The maximum steam temperature is 550°C, and the pressure in the condensers will be 10 kPa. Estimate the temperature rise of the river downstream from the power plant.

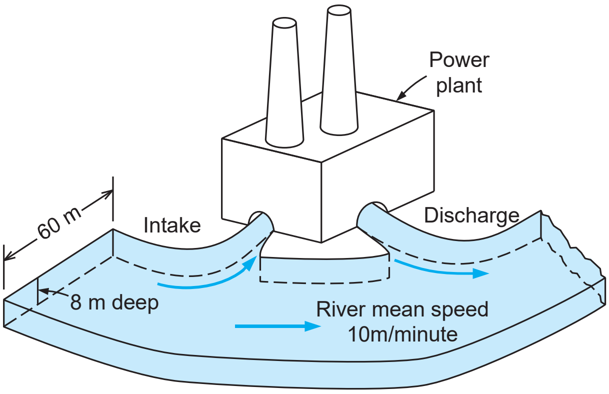


FIGURE P7.67

7.68 Repeat the previous problem using a more realistic thermal efficiency of 35%.

7.69 A steel bottle of $V = 0.1$ m^3 contains R-134a at 20°C and 200 kPa. It is placed in a deep freezer, where it is cooled to −20°C. The deep freezer sits in a room with an ambient temperature of 20°C and has an inside temperature of −20°C. Find the amount of energy the freezer must remove from the R-134a and the extra amount of work input to the freezer to do the process.

7.70 Sixty kilograms per hour of water runs through a heat exchanger, entering as saturated liquid at 200 kPa and leaving as saturated vapor. The heat is supplied by a Carnot heat pump operating from a low-temperature reservoir at 16°C. Find the rate of work into the heat pump.

7.71 A heat engine has a solar collector receiving 0.2 kW/m^2, inside of which a transfer medium is heated to 450 K. The collected energy powers a heat engine that rejects heat at 40°C. If the heat engine should deliver 2.5 kW, what is the minimum size (area) of the solar collector?

7.72 Liquid sodium leaves a nuclear reactor at 800°C and is used as the energy source in a steam power plant. The condenser cooling water comes from a cooling tower at 15°C. Determine the maximum thermal efficiency of the power plant. Is it misleading to use the temperatures given to calculate this value?

7.73 A power plant with a thermal efficiency of 40% is located on a river similar to the arrangement in Fig. P7.67. With a total river mass flow rate of 1×10^5 kg/s at 15°C, find the maximum power production allowed if the river water should not be heated more than 1 degree.

7.74 A heat pump is driven by the work output of a heat engine, as shown in Figure P7.74. If we assume ideal devices, find the ratio of the total power $\dot{Q}_{L1} + \dot{Q}_{H2}$ that heats the house to the power from the hot energy source $\dot{Q}_{H1}$ in terms of the temperatures.

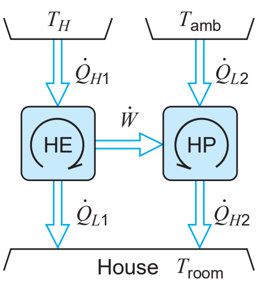


FIGURE P7.74

7.75 A car engine with a thermal efficiency of 33% drives the air-conditioner unit (a refrigerator) besides powering the car and other auxiliary equipment. On a hot (35°C) summer day, the air conditioner takes outside air in and cools it to 5°C, sending it into a duct using 2 kW of power input. It is assumed to be half as good as a Carnot refrigeration unit. Find the rate of fuel (kW) being burned just to drive the air conditioner and its COP. Find the flow rate of cold air the air conditioner can provide.

7.76 Two different fuels can be used in a heat engine operating between the fuel-burning temperature and a low temperature of 350 K. Fuel *A* burns at 2200 K, delivering 30 000 kJ/kg, and costs $1.50/kg. Fuel *B* burns at 1200 K, delivering 40 000 kJ/kg, and costs $1.30/kg. Which fuel would you buy and why?

7.77 A large heat pump should upgrade 5 MW of heat at 85°C to be delivered as heat at 150°C. Suppose the actual heat pump has a COP of 2.5. How much power is required to drive the unit? For the same COP, how high a high temperature would a Carnot heat pump have, assuming the same low temperature?

Finite ΔT Heat Transfer

7.78 The ocean near Hawaii has a temperature of 20°C near the surface and 5°C at some depth. A power plant based on this temperature difference is being planned. How large an efficiency could it have? If the two heat transfer terms (Q_H and Q_L) both require a 2-degree difference to operate, what is the maximum efficiency?

7.79 A refrigerator maintaining an inside temperature of 5°C is located in a 30°C room. It must have a high-temperature ΔT above room temperature and a low-temperature ΔT below that of the refrigerated space in the cycle to transfer the heat. For a ΔT of 0, 5, and 10°C, respectively, calculate the COP, assuming a Carnot cycle.

7.80 A house is heated by a heat pump driven by an electric motor using the outside as the low-temperature reservoir. The house loses energy in direct proportion to the temperature difference as $\dot{Q}_{loss} = K(T_H - T_L)$. Determine the minimum electric power required to drive the heat pump as a function of the two temperatures.

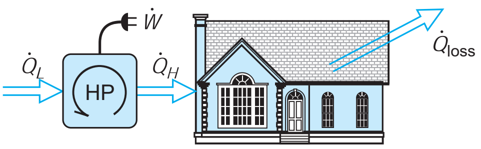


FIGURE P7.80

7.81 A house is heated by an electric heat pump using the outside as the low-temperature reservoir. For several different winter outdoor temperatures, estimate the percent savings in electricity if the house is kept at 20°C instead of 24°C. Assume that the house is losing energy to the outside, as in Eq. 7.14.

7.82 A car engine operates with a thermal efficiency of 35%. Assume the air conditioner has a COP of

$\beta = 3$ working as a refrigerator cooling the inside, using engine shaft work to drive it. How much extra fuel energy should be spent to remove 1 kJ from the inside?

7.83 A refrigerator uses a power input of 2.5 kW to cool a 5°C space with the high temperature in the cycle at 50°C. The Q_H is pushed to the ambient air at 35°C in a heat exchanger where the transfer coefficient is 50 W/m^2 K. Find the required minimum heat transfer area.

7.84 A heat pump has a COP of $\beta' = 0.5\ \beta'_{\text{CARNOT}}$ and maintains a house at $T_H = 20°\text{C}$, while it leaks energy out as $\dot{Q} = 0.6(T_H - T_L)$ [kW]. For a maximum of 1.0 kW power input, find the minimum outside temperature, T_L, for which the heat pump is a sufficient heat source.

7.85 Consider a room at 20°C cooled by an air conditioner with a COP of 3.2 using a power input of 2 kW, with an outside temperature of 35°C. What is the constant in the heat transfer equation (Eq. 7.14) for the heat transfer from the outside into the room?

7.86 A farmer runs a heat pump with a motor of 2 kW. It should keep a chicken hatchery at 30°C, which loses energy at a rate of 0.5 kW per degree difference to the colder ambient T_{amb}. The heat pump has a COP that is 50% of that of a Carnot heat pump. What is the minimum ambient temperature for which the heat pump is sufficient?

7.87 An air conditioner cools a house at $T_L = 20°\text{C}$ with a maximum of 1.2 kW power input. The house gains energy as $\dot{Q} = 0.6(T_H - T_L)$ [kW] and the refrigeration COP is $\beta = 0.6\ \beta_{\text{CARNOT}}$. Find the maximum outside temperature, T_H, for which the air conditioner unit provides sufficient cooling.

7.88 A house is cooled by an electric heat pump using the outside as the high-temperature reservoir. For several different summer outdoor temperatures, estimate the percent savings in electricity if the house is kept at 25°C instead of 20°C. Assume that the house is gaining energy from the outside in direct proportion to the temperature difference, as in Eq. 7.14.

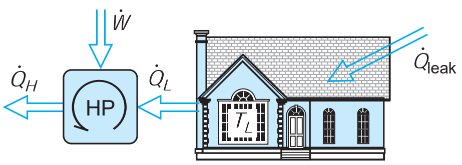


FIGURE P7.88

7.89 A Carnot heat engine, shown in Fig. P7.89, receives energy from a reservoir at T_{res} through a heat exchanger where the heat transferred is proportional to the temperature difference as $\dot{Q}_H = K(T_{\text{res}} - T_H)$. It rejects heat at a given low temperature T_L. To design the heat engine for maximum work output, show that the high temperature, T_H, in the cycle should be selected as $T_H = (T_L T_{\text{res}})^{1/2}$.

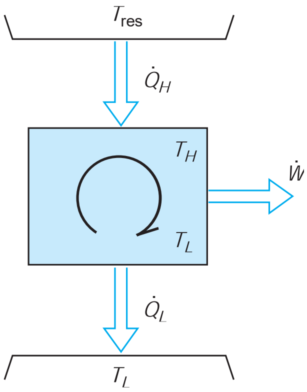


FIGURE P7.89

7.90 Consider a Carnot-cycle heat engine operating in outer space. Heat can be rejected from this engine only by thermal radiation, which is proportional to the radiator area and the fourth power of absolute temperature, $\dot{Q}_{\text{rad}} = KAT^4$. Show that for a given engine work output and given T_H, the radiator area will be minimum when the ratio $T_L / T_H = 3/4$.

7.91 On a cold (−10°C) winter day, a heat pump provides 20 kW to heat a house maintained at 20°C and it has a COP_{HP} of 4. How much power does the heat pump require? The next day, a storm brings the outside temperature to −15°C, with the same COP and the same house heat transfer coefficient for the heat loss to the outside air. How much power does the heat pump require then?

Ideal-Gas Carnot Cycles

7.92 Hydrogen gas is used in a Carnot cycle having an efficiency of 60% with a low temperature of 300 K. During the heat rejection the pressure changes from 90 kPa to 120 kPa. Find the high- and low-temperature heat transfer and the net cycle work per unit mass of hydrogen.

7.93 Carbon dioxide is used in an ideal-gas refrigeration cycle, the reverse of Fig. 7.24. Heat absorption is at 250 K and heat rejection is at 325 K, where the pressure changes from 1200 to 2400 kPa. Find the refrigeration COP and the specific heat transfer at the low temperature.

7.94 An ideal-gas Carnot cycle with air in a piston cylinder has a high temperature of 1200 K and a heat rejection at 400 K. During the heat addition, the volume triples. Find the two specific heat transfers (q) in the cycle and the overall cycle efficiency.

7.95 Air in a piston/cylinder setup goes through a Carnot cycle with the P–v diagram shown in Fig. 7.24. The high and low temperatures are 600 K and 300 K, respectively. The heat added at the high temperature is 250 kJ/kg, and the lowest pressure in the cycle is 75 kPa. Find the specific volume and pressure after heat rejection and the net work per unit mass.

Review Problems

7.96 At a certain location, geothermal energy in underground water is available and used as an energy source for a power plant. Consider a supply of saturated liquid water at 150°C. What is the maximum possible thermal efficiency of a cyclic heat engine using this source as energy with the ambient surroundings at 20°C? Would it be better to locate a source of saturated vapor at 150°C than to use the saturated liquid?

7.97 A rigid insulated container has two rooms separated by a membrane. Room A contains 1 kg of air at 200°C, and room B has 1.5 kg of air at 20°C; both rooms are at 100 kPa. Consider two different cases:

1. Heat transfer between A and B creates a final uniform T.

2. The membrane breaks, and the air comes to a uniform state.

For both cases, find the final temperature. Are the two processes reversible and different? Explain.

7.98 Consider the combination of the two heat engines in Fig. P7.4. How should the intermediate temperature be selected so that the two heat engines have the same efficiency, assuming Carnot-cycle heat engines.

7.99 A house needs to be heated by a heat pump, with $\beta' = 2.2$, and maintained at 20°C at all times. It is estimated that it loses 0.8 kW per degree the ambient temperature is lower than 20°C. Assume an outside temperature of −10°C and find the needed power to drive the heat pump.

7.100 Consider a combination of a gas turbine power plant and a steam power plant, as shown in Fig. P7.4. The gas turbine operates at higher temperatures (thus called a *topping cycle*) than the steam power plant (then called a *bottom cycle*). Assume both cycles have a thermal efficiency of 32%. What is the efficiency of the overall combination, assuming Q_L in the gas turbine equals Q_H to the steam power plant?

7.101 We wish to produce refrigeration at −30°C. A reservoir, shown in Fig. P7.101, is available at 200°C, and the ambient temperature is 30°C. Thus, work can be done by a cyclic heat engine operating between the 200°C reservoir and the ambient surroundings. This work is used to drive the refrigerator. Determine the ratio of the heat transferred from the 200°C reservoir to the heat transferred from the −30°C reservoir, assuming all processes are reversible.

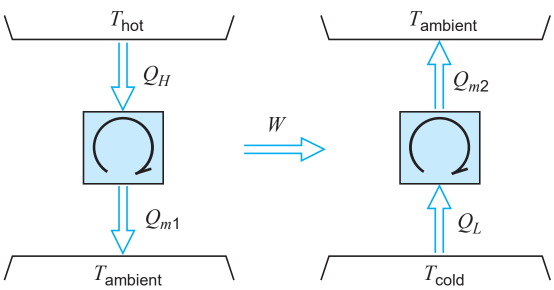


FIGURE P7.101

7.102 A 4 L jug of milk at 25°C is placed in your refrigerator, where it is cooled down to 5°C. The high temperature in the Carnot refrigeration cycle is 45°C, and the properties of milk are the same as those of liquid water. Find the amount of energy that must be removed from the milk and the additional work needed to drive the refrigerator.

7.103 An air conditioner with a power input of 1.2 kW is working as a refrigerator ($\beta = 3$) or as a heat pump ($\beta' = 4$). It maintains an office at 20°C year round, which exchanges 0.5 kW per degree temperature difference with the atmosphere. Find the maximum and minimum outside temperatures for which this unit is sufficient.

7.104 Make some assumption about the heat transfer rates to solve Problem 7.62 when the outdoor temperature is $-20°$C. *Hint*: look at the heat transfer given by Eq. 7.14.

7.105 Air in a rigid 1 m^3 box is at 300 K and 200 kPa. It is heated to 600 K by heat transfer from a reversible heat pump that receives energy from the ambient surroundings at 300 K besides the work input. Use constant specific heat at 300 K. Since the COP changes, write $\delta Q = m_{\text{air}} C_v \, dT$ and find δW. Integrate δW with temperature to find the required heat pump work.

7.106 A combination of a heat engine driving a heat pump (see Fig. P7.106) takes waste energy at 50°C as a source Q_{w1} to the heat engine rejecting heat at 30°C. The remainder, Q_{w2}, goes into the heat pump that delivers a Q_H at 150°C. If the total waste energy is 5 MW, find the rate of energy delivered at the high temperature.

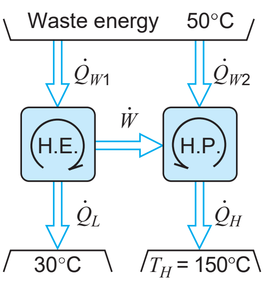


FIGURE P7.106

7.107 A heat pump heats a house in the winter and then reverses to cool it in summer. The interior temperature should be 20°C in the winter and 25°C in the summer. Heat transfer through the walls and ceilings is estimated to be 2400 kJ per hour per degree temperature difference between the inside and outside.

a. If the outside winter temperature is 0°C, what is the minimum power required to drive the heat pump?
b. For the same power as in part (a), what is the maximum outside summer temperature for which the house can be maintained at 25°C?

7.108 A remote location without electricity operates a refrigerator with a bottle of propane feeding a burner to create hot gases. Sketch the setup in terms of cyclic devices and give a relation for the ratio of $\dot{Q}_L$ in the refigerator to $\dot{Q}_{\text{fuel}}$ in the burner in terms of the various reservoir temperatures.

7.109 A furnace, shown in Fig. P7.109, can deliver heat, Q_{H1}, at T_{H1}, and it is proposed to use this to drive a heat engine with a rejection at T_{atm} instead of direct room heating. The heat engine drives a heat pump that delivers Q_{H2} at T_{room} using the atmosphere as the cold reservoir. Find the ratio Q_{H2}/Q_{H1} as a function of the temperatures. Is this a better setup than direct room heating from the furnace?

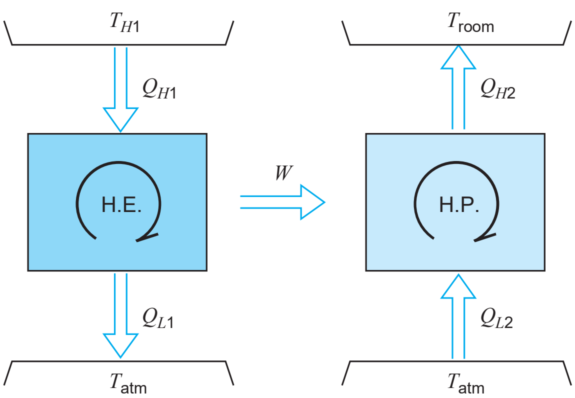


FIGURE P7.109

7.110 Consider the rock bed thermal storage in Problem 7.65. Use the specific heat so that you can write δQ_H in terms of dT_{rock} and find the expression for δW out of the heat engine. Integrate this expression over temperature and find the total heat engine work output.

7.111 On a cold ($-10°$C) winter day, a heat pump provides 20 kW to heat a house maintained at 20°C, and it has a COP_{HP} of 4 using the maximum power available. The next day, a storm brings the outside temperature to $-15°$C, assume the same COP and that the house heat loss is to the oustide air. How cold is the house then?

7.112 A Carnot heat engine operating between high T_H and low T_L energy reservoirs has an efficiency given by the temperatures. Compare this to two combined heat engines, one operating between T_H and an intermediate temperature T_M giving out work W_A and the other operating between T_M and T_L giving out W_B. The combination must have the same efficiency as the single heat engine, so the heat transfer ratio $Q_H/Q_L = \phi(T_H, T_L) = [Q_H/Q_M][Q_M/Q_L]$. The last two heat transfer ratios can be expressed by the same function $\phi()$ also involving the temperature T_M. Use this to show a condition the function $\phi()$ must satisfy.

7.113 A 10 m^3 tank of air at 500 kPa and 600 K acts as the high-temperature reservoir for a Carnot heat engine that rejects heat at 300 K. A temperature difference of 25°C between the air tank and the Carnot-cycle high temperature is needed to transfer the heat. The heat engine runs until the air temperature has dropped to 400 K and then stops. Assume constant specific heat capacities for air and determine how much work is given out by the heat engine.

ENGLISH UNIT PROBLEMS

Concept Problems

7.114E Compare two heat engines receiving the same Q, one at 1400 R and the other at 2100 R, both of which reject heat at 900 R. Which one is better?

7.115E A car engine takes atmospheric air in at 70 F, no fuel, and exhausts the air at 0 F, producing work in the process. What do the first and second laws say about that?

7.116E If the efficiency of a power plant goes up as the low temperature drops, why do they not just reject energy at, say, −40 F?

7.117E If the efficiency of a power plant goes up as the low temperature drops, why not let the heat rejection go to a refrigerator at, say, 10 F instead of ambient 68 F?

English Unit Problems

7.118E A gasoline engine produces 20 hp using 35 Btu/s of heat transfer from burning fuel. What is its thermal efficiency, and how much power is rejected to the ambient surroundings?

7.119E Calculate the thermal efficiency of the steam power plant described in Problem 6.180.

7.120E A refrigerator removes 1.5 Btu from the cold space using 1 Btu of work input. How much energy goes into the kitchen, and what is its COP?

7.121E A coal-fired power plant has an efficiency of 35% and produces net 500 MW of electricity. Coal releases 12 500 Btu/lbm as it burns, so how much coal is used per hour?

7.122E A window air-conditioning unit is placed on a laboratory bench and tested in cooling mode using 0.75 Btu/s of electric power with a COP of 1.75. What is the cooling power capacity, and what is the net effect on the laboratory?

7.123E A water cooler for drinking water should cool 1 ft^3/h water from 65 F to 50 F using a small refrigeration unit with a COP of 2.5. Find the rate of cooling required and the power input to the unit.

7.124E R-410a enters the evaporator (the cold heat exchanger) in an air-conditioning unit at 0 F, $x = 28\%$ and leaves at 0 F, $x = 1$. The COP of the refrigerator is 1.5 and the mass flow rate is 0.006 lbm/s. Find the net work input to the cycle.

7.125E A farmer runs a heat pump with a 2 kW motor. It should keep a chicken hatchery at 90 F, which loses energy at a rate of 10 Btu/s to the colder ambient T_{amb}. What is the minimum acceptable COP for the heat pump?

7.126E A large stationary diesel engine produces 20 000 hp with a thermal efficiency of 40%. The exhaust gas, which we assume is air, flows out at 1400 R and the intake is 520 R. How large a mass flow rate is that? Can the exhaust flow energy be used?

7.127E In a steam power plant 1000 Btu/s is added at 1200 F in the boiler, 580 Btu/s is taken out at 100 F in the condenser, and the pump work is 20 Btu/s. Find the plant's thermal efficiency. Assuming the same pump work and heat transfer to the boiler as given, how much turbine power could be produced if the plant were running in a Carnot cycle?

7.128E Calculate the amount of work input a refrigerator needs to make ice cubes out of a tray of 0.5 lbm liquid water at 50 F. Assume the refrigerator has $\beta = 3.5$ and a motor-compressor of 750 W. How much time does it take if this is the only cooling load?

7.129E Calculate the thermal efficiency of a Carnot-cycle heat engine operating between reservoirs at 920 F