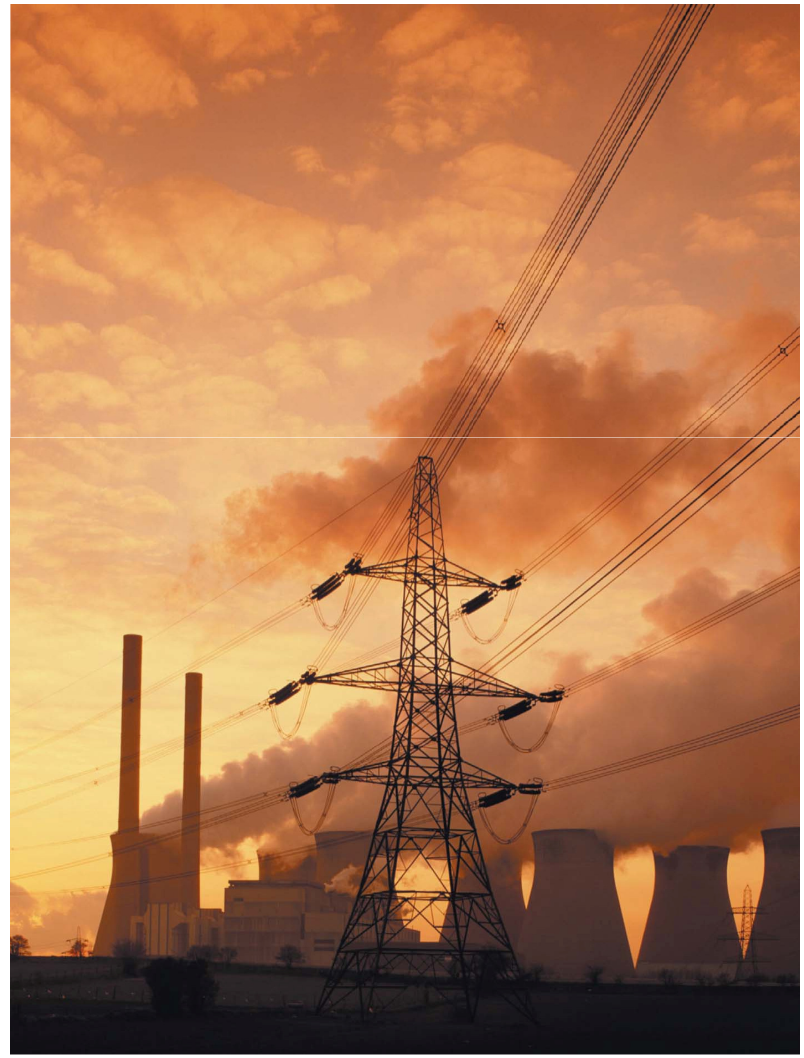
Chapter 19. Heat Engines and Refrigerators

That's not smoke. It's clouds of water vapor rising from the cooling towers around a large power plant. The power plant is generating electricity by turning heat into work.



Chapter Goal: To study the physical principles that govern the operation of heat engines and refrigerators.

Chapter 19. Heat Engines and Refrigerators

Topics:

- Turning Heat into Work
- Heat Engines and Refrigerators
- Ideal-Gas Heat Engines
- Ideal-Gas Refrigerators
- The Limits of Efficiency
- The Carnot Cycle

Chapter 19. Reading Quizzes

What is the generic name for a cyclical device that transforms heat energy into work?

A. Refrigerator
B. Thermal motor
C. Heat engine
D. Carnot cycle
E. Otto processor

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The area enclosed within a *pV* curve is

A. the work done by the system during one complete cycle.
B. the work done on the system during one complete cycle.
C. the thermal energy change of the system during one complete cycle.
D. the heat transferred out of the system during one complete cycle.

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The maximum possible efficiency of a heat engine is determined by

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B. the amount of heat that flows.
C. the maximum and minimum pressure.
D. the compression ratio.
E. the maximum and minimum temperature.

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The engine with the largest possible efficiency uses a

A. Brayton cycle.
B. Joule cycle.
C. Carnot cycle.
D. Otto cycle.
E. Diesel cycle.

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Chapter 19. Basic Content and Examples

Turning Heat into Work

- Thermodynamics is the branch of physics that studies the transformation of energy.
- Many practical devices are designed to transform energy from one form, such as the heat from burning fuel, into another, such as work.
- Chapters 17 and 18 established two laws of thermodynamics that any such device must obey.

First law Energy is conserved; that is, $\Delta E_{th} = W + Q$.

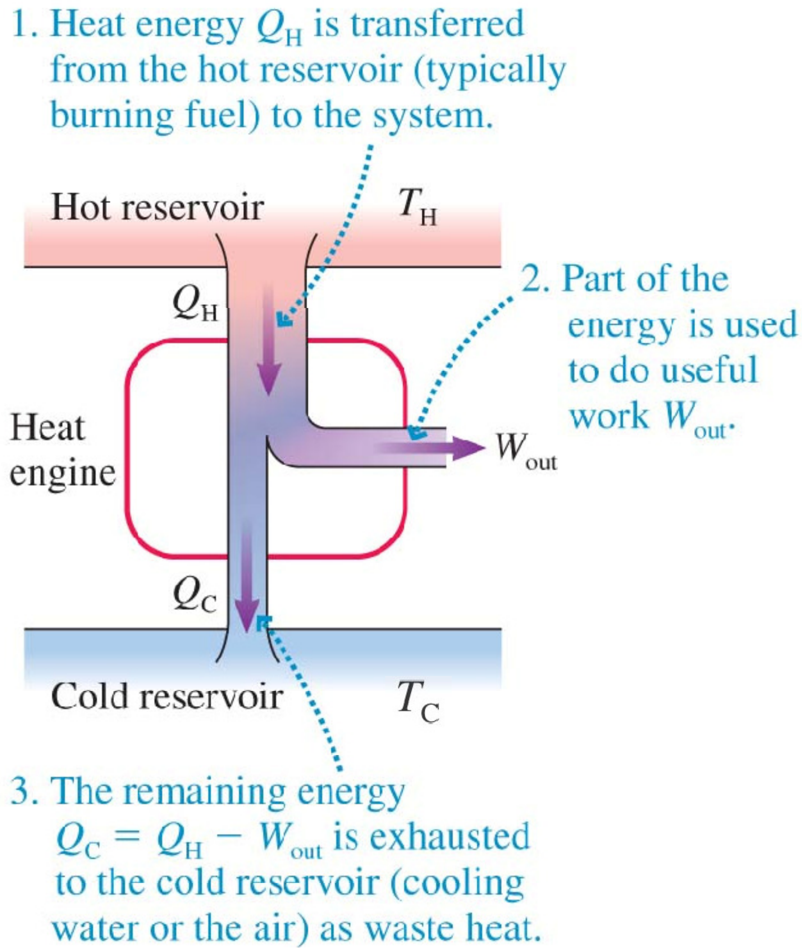
Second law Most macroscopic processes are irreversible. In particular, heat energy is transferred spontaneously from a hotter to a colder system but never from a colder system to a hotter system.

Heat Engines

- A heat engine is any closed-cycle device that extracts heat from a hot reservoir, does useful work, and exhausts heat to a cold reservoir.
- A closed-cycle device is one that periodically returns to its initial conditions, repeating the same process over and over.
- All state variables (pressure, temperature, thermal energy, and so on) return to their initial values once every cycle.
- A heat engine can continue to do useful work for as long as it is attached to the reservoirs.

Heat Engines

FIGURE 19.6 The energy-transfer diagram of a heat engine.



Heat Engines

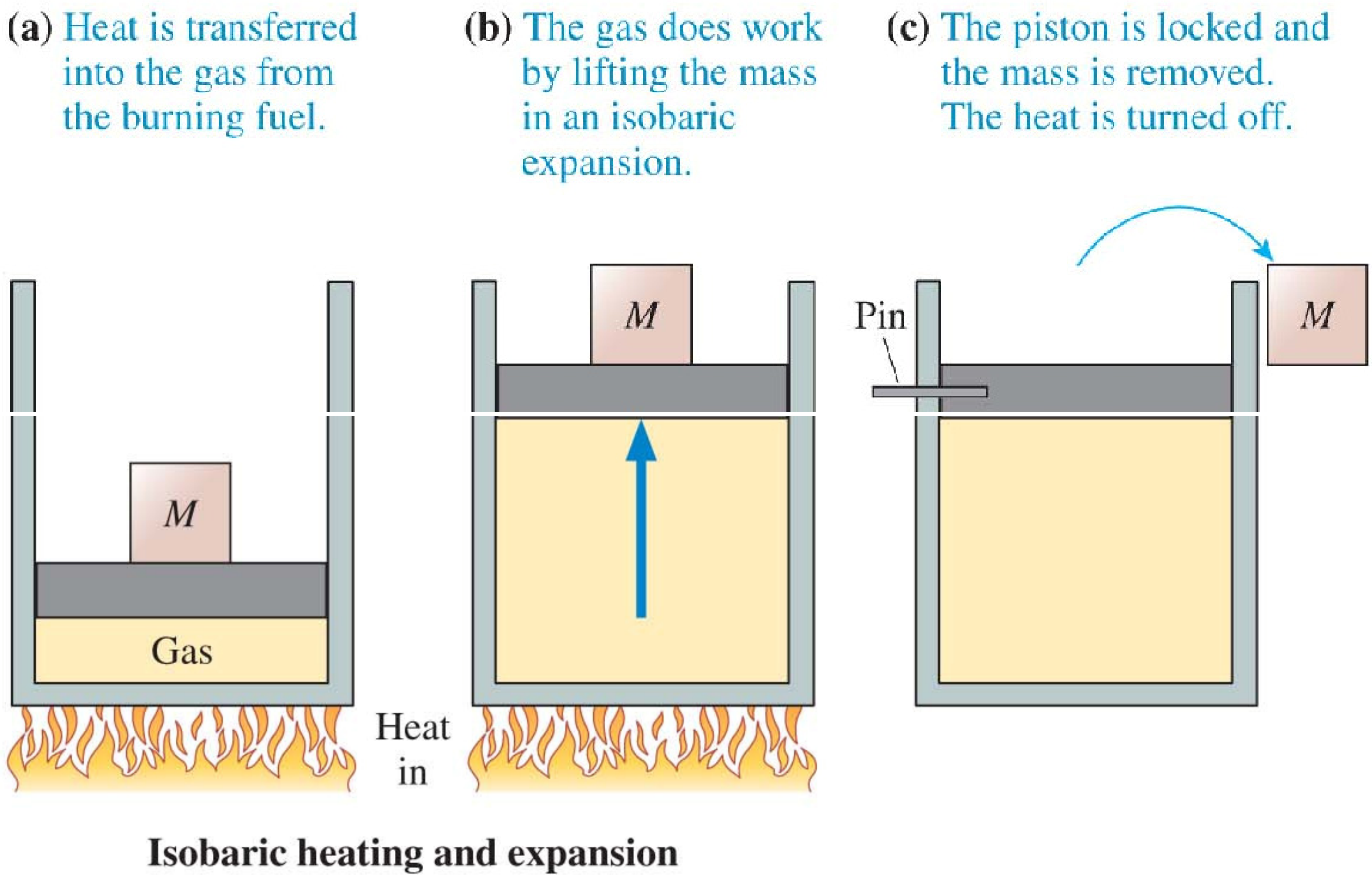
For practical reasons, we would like an engine to do the maximum amount of work with the minimum amount of fuel. We can measure the performance of a heat engine in terms of its thermal efficiency η (lowercase Greek eta), defined as

$$\eta = \frac{W_{\text{out}}}{Q_{\text{H}}} = \frac{\text{what you get}}{\text{what you had to pay}}$$

We can also write the thermal efficiency as

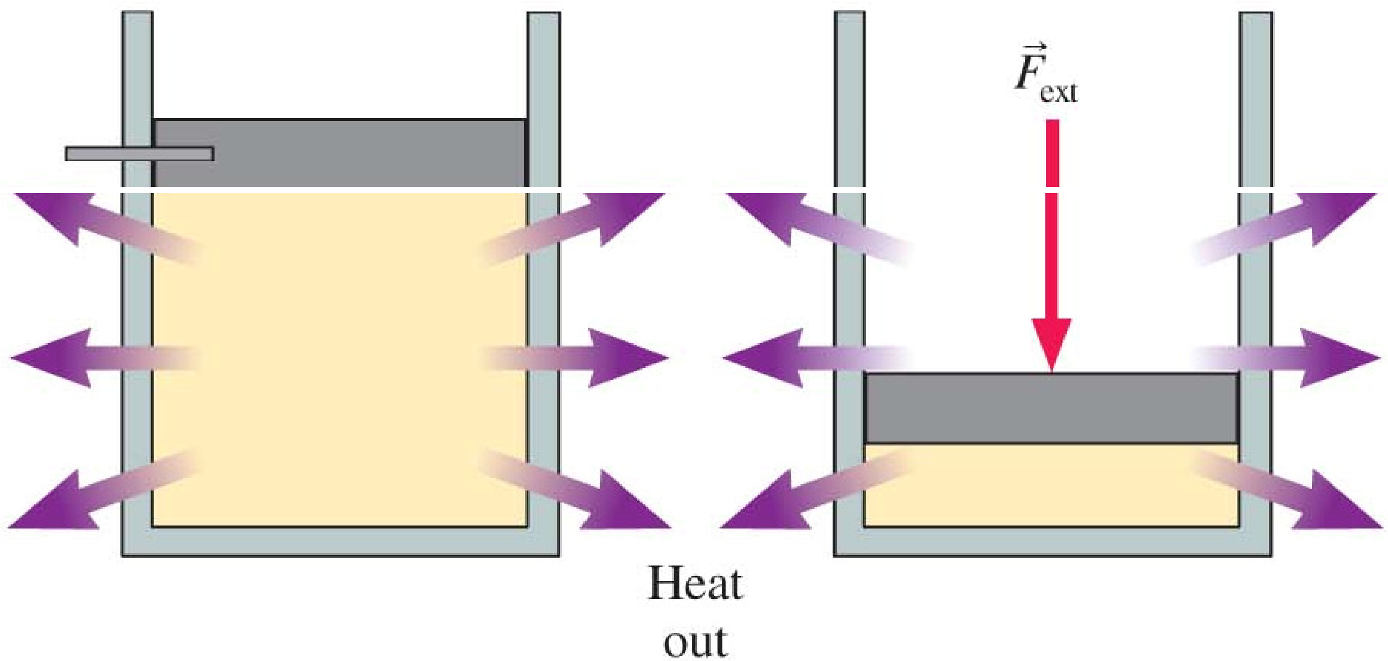
$$\eta = 1 - \frac{Q_{\text{C}}}{Q_{\text{H}}}$$

FIGURE 19.8 A simple heat engine transforms heat into work.



(d) The gas cools back to room temperature at constant volume. Then the piston is unlocked.

(e) A steadily increasing external force steadily raises the pressure in an isothermal compression until the pressure has been restored to its initial value.



Constant-volume cooling **Isothermal compression**

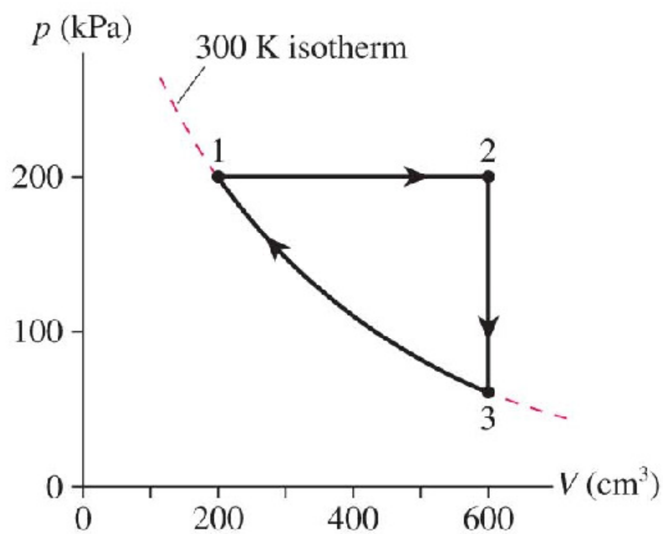
EXAMPLE 19.1 Analyzing a heat engine I

QUESTION:

EXAMPLE 19.1 Analyzing a heat engine I

Analyze the heat engine of FIGURE 19.10 to determine (a) the net work done per cycle, (b) the engine's thermal efficiency, and (c) the engine's power output if it runs at 600 rpm. Assume the gas is monatomic.

FIGURE 19.10 The heat engine of Example 19.1.



EXAMPLE 19.1 Analyzing a heat engine I

MODEL The gas follows a closed cycle consisting of three distinct processes, each of which was studied in Chapters 16 and 17. For each of the three we need to determine the work done and the heat transferred.

EXAMPLE 19.1 Analyzing a heat engine I

SOLVE To begin, we can use the initial conditions at state 1 and the ideal-gas law to determine the number of moles of gas:

$$n = \frac{p_1 V_1}{RT_1} = \frac{(200 \times 10^3\ \text{Pa})(2.0 \times 10^{-4}\ \text{m}^3)}{(8.31\ \text{J/mol K})(300\ \text{K})} = 0.0160\ \text{mol}$$

EXAMPLE 19.1 Analyzing a heat engine I

Process $1 \rightarrow 2$: The work done *by* the gas in the isobaric expansion is

$$(W_s)_{12} = p\Delta V = (200 \times 10^3\ \text{Pa})(6.0 - 2.0) \times 10^{-4}\ \text{m}^3$$
$$= 80\ \text{J}$$

We can use the ideal-gas law at constant pressure to find $T_2 = (V_2/V_1)T_1 = 3T_1 = 900$ K. The heat transfer during a constant-pressure process is

$$Q_{12} = nC_P\Delta T$$
$$= (0.0160\ \text{mol})(20.8\ \text{J/mol K})(900\ \text{K} - 300\ \text{K})$$
$$= 200\ \text{J}$$

where we used $C_P = \frac{5}{2}R$ for a monatomic ideal gas.

EXAMPLE 19.1 Analyzing a heat engine I

Process $2 \rightarrow 3$: No work is done in an isochoric process, so $(W_s)_{23} = 0$. The temperature drops back to 300 K, so the heat transfer is

$$\begin{aligned} Q_{23} &= nC_V \Delta T \\ &= (0.0160\ \text{mol})(12.5\ \text{J/mol K})(300\ \text{K} - 900\ \text{K}) \\ &= -120\ \text{J} \end{aligned}$$

where we used $C_V = \frac{3}{2}R$.

EXAMPLE 19.1 Analyzing a heat engine I

Process 3 → 1: The gas returns to its initial state with volume V_1. The work done *by* the gas during an isothermal process is

$$(W_s)_{31} = nRT\ln\left(\frac{V_1}{V_3}\right)$$

$$= (0.0160\text{ mol})(8.31\text{ J/mol K})(300\text{ K})\ln\left(\frac{1}{3}\right)$$

$$= -44\text{ J}$$

W_s is negative because the environment does work on the gas to compress it. An isothermal process has $\Delta E_{th} = 0$ and hence, from the first law,

$$Q_{31} = (W_s)_{31} = -44\text{ J}$$

Q is negative because the gas must be cooled as it is compressed to keep the temperature constant.

EXAMPLE 19.1 Analyzing a heat engine I

a. The *net* work done by the engine during one cycle is

$$W_{out} = (W_s)_{12} + (W_s)_{23} + (W_s)_{31} = 36\ \mathrm{J}$$

As a consistency check, notice that the net heat transfer is

$$Q_{net} = Q_{12} + Q_{23} + Q_{31} = 36\ \mathrm{J}$$

Equation 19.6 told us that a heat engine *must* have $W_{out} = Q_{net}$, and we see that it does.

EXAMPLE 19.1 Analyzing a heat engine I

b. The efficiency depends not on the net heat transfer but on the heat Q_H transferred into the engine from the flame. Heat is transferred in during process $1 \to 2$, where Q is positive, and out during processes $2 \to 3$ and $3 \to 1$, where Q is negative. Thus

$$Q_H = Q_{12} = 200 \text{ J}$$

$$Q_C = |Q_{23}| + |Q_{31}| = 164 \text{ J}$$

Notice that $Q_H - Q_C = 36 \text{ J} = W_{out}$. In this heat engine, 200 J of heat from the hot reservoir does 36 J of useful work. Thus the thermal efficiency is

$$\eta = \frac{W_{out}}{Q_H} = \frac{36 \text{ J}}{200 \text{ J}} = 0.18 \text{ or } 18\%$$

This heat engine is far from being a perfect engine!

EXAMPLE 19.1 Analyzing a heat engine I

c. An engine running at 600 rpm goes through 10 cycles per second. The power output is the work done *per second:*

$$P_{out} = (\text{work per cycle}) \times (\text{cycles per second})$$
$$= 360 \text{ J/s} = 360 \text{ W}$$

EXAMPLE 19.1 Analyzing a heat engine I

ASSESS Although we didn't need Q_{net}, verifying that $Q_{net} = W_{out}$ was a check of self-consistency. Heat-engine analysis requires many calculations and offers many opportunities to get signs wrong. However, there are a sufficient number of self-consistency checks so that you can almost always spot calculational errors *if you check for them.*

Problem-Solving Strategy: Heat-Engine Problems

PROBLEM-SOLVING STRATEGY 19.1 **Heat-engine problems**

MP

MODEL Identify each process in the cycle.

Problem-Solving Strategy: Heat-Engine Problems

VISUALIZE Draw the pV diagram of the cycle.

Problem-Solving Strategy: Heat-Engine Problems

SOLVE There are several steps in the mathematical analysis.

- Use the ideal-gas law to complete your knowledge of n, p, V, and T at one point in the cycle.
- Use the ideal-gas law and equations for specific gas processes to determine p, V, and T at the beginning and end of each process.
- Calculate Q, W_s, and ΔE_{th} for each process.

Problem-Solving Strategy: Heat-Engine Problems

- Find W_{out} by adding W_s for each process in the cycle. If the geometry is simple, you can confirm this value by finding the area enclosed within the pV curve.
- Add just the *positive* values of Q to find Q_H.
- Verify that $(\Delta E_{th})_{net} = 0$. This is a self-consistency check to verify that you haven't made any mistakes.
- Calculate the thermal efficiency η and any other quantities you need to complete the solution.

Problem-Solving Strategy: Heat-Engine Problems

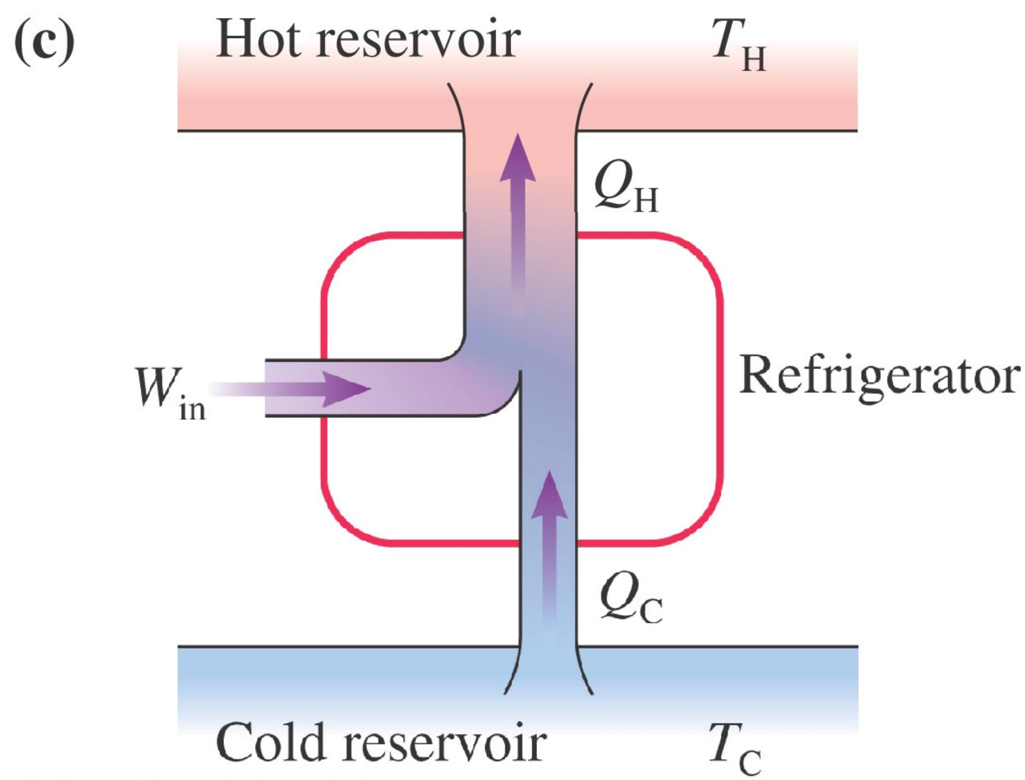
ASSESS Is $(\Delta E_{th})_{net} = 0$? Do all the signs of W_s and Q make sense? Does η have a reasonable value? Have you answered the question?

Refrigerators

- Understanding a refrigerator is a little harder than understanding a heat engine.
- **Heat is always transferred from a hotter object to a colder object.**
  - The gas in a refrigerator can extract heat Q_C *from* the cold reservoir only if the gas temperature is *lower* than the cold-reservoir temperature T_C. Heat energy is then transferred *from* the cold reservoir *into* the colder gas.
  - The gas in a refrigerator can exhaust heat Q_H *to* the hot reservoir only if the gas temperature is *higher* than the hot-reservoir temperature T_H. Heat energy is then transferred *from* the warmer gas *into* the hot reservoir.

Refrigerators

FIGURE 19.17 A refrigerator that extracts heat from the cold reservoir and exhausts heat to the hot reservoir.



Refrigerators

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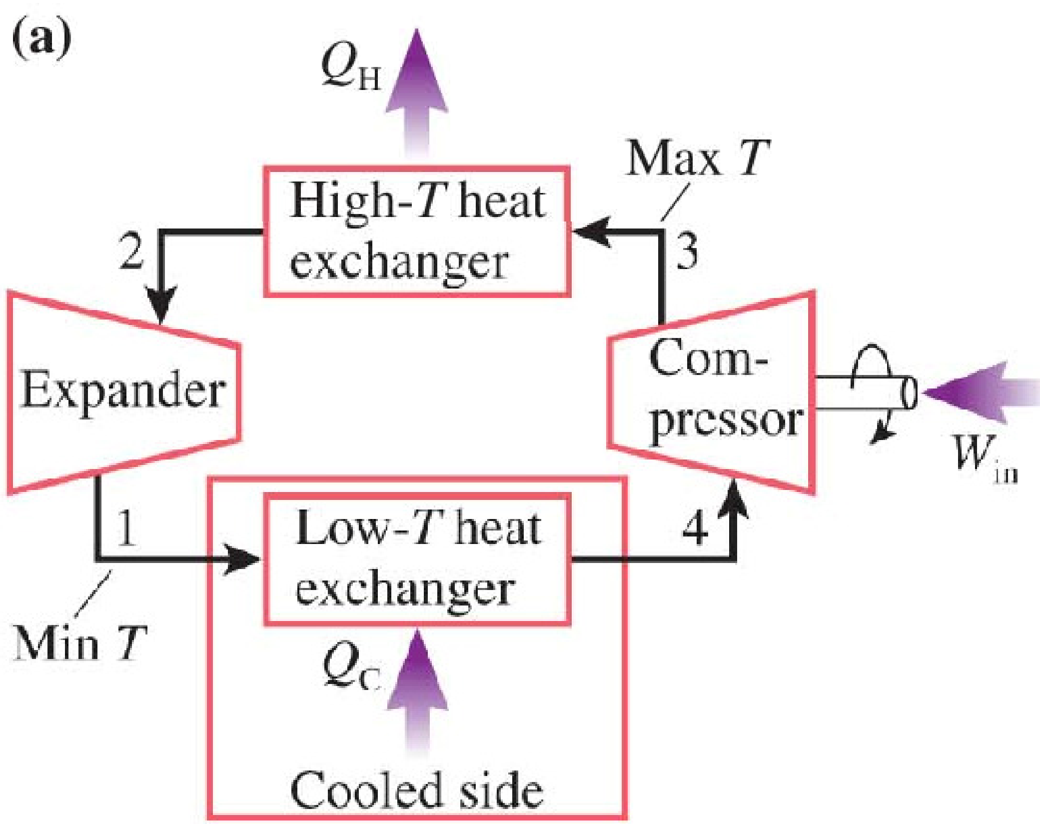


Refrigerators

These cooling coils are the refrigerator's high-temperature heat exchanger. Heat energy is being transferred from hot gas inside the coils to the cooler room air.

EXAMPLE 19.3 Analyzing a refrigerator

QUESTION:

EXAMPLE 19.3 Analyzing a refrigerator

A refrigerator using helium gas operates on a reversed Brayton cycle with a pressure ratio of 5.0. Prior to compression, the gas occupies 100 cm^3 at a pressure of 150 kPa and a temperature of $-23°C$. Its volume at the end of the expansion is 80 cm^3. What are the refrigerator's coefficient of performance and its power input if it operates at 60 cycles per second?

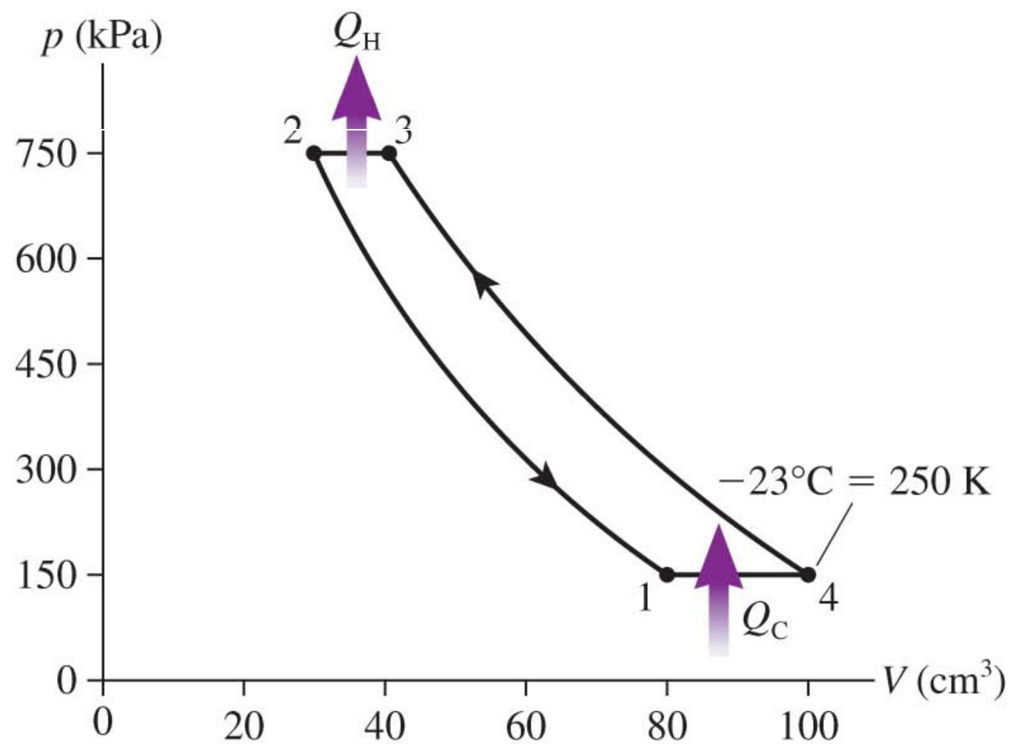
EXAMPLE 19.3 Analyzing a refrigerator

MODEL The Brayton cycle has two adiabatic processes and two isobaric processes. The work per cycle needed to run the refrigerator is $W_{in} = Q_H - Q_C$; hence we can determine both the coefficient of performance and the power requirements from Q_H and Q_C. Heat energy is transferred only during the two isobaric processes.

EXAMPLE 19.3 Analyzing a refrigerator

VISUALIZE **FIGURE 19.20** shows the pV cycle. We know from the pressure ratio of 5.0 that the maximum pressure is 750 kPa. Neither V_2 nor V_3 is known.

FIGURE 19.20 A Brayton-cycle refrigerator.



EXAMPLE 19.3 Analyzing a refrigerator

SOLVE To calculate heat we're going to need the temperatures at the four corners of the cycle. First, we can use the conditions of state 4 to find the number of moles of helium:

$$n = \frac{p_4 V_4}{RT_4} = 0.00722 \text{ mol}$$

EXAMPLE 19.3 Analyzing a refrigerator

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Process $1 \rightarrow 4$ is isobaric; hence temperature T_1 is

$$T_1 = \frac{V_1}{V_4} T_4 = (0.80)(250 \text{ K}) = 200 \text{ K} = -73°\text{C}$$

With Equation 19.16 we found that the quantity $p^{(1-\gamma)/\gamma}T$ remains constant during an adiabatic process. Helium is a monatomic gas with $\gamma = \frac{5}{3}$, so $(1-\gamma)/\gamma = -\frac{2}{5} = -0.40$. For the adiabatic compression $4 \rightarrow 3$,

$$p_3^{-0.40} T_3 = p_4^{-0.40} T_4$$

Solving for T_3 gives

$$T_3 = \left(\frac{p_4}{p_3}\right)^{-0.40} T_4 = \left(\frac{1}{5}\right)^{-0.40} (250 \text{ K}) = 476 \text{ K} = 203°\text{C}$$

EXAMPLE 19.3 Analyzing a refrigerator

The same analysis applied to the $2 \rightarrow 1$ adiabatic expansion gives

$$T_2 = \left(\frac{p_1}{p_2}\right)^{-0.40} T_1 = \left(\frac{1}{5}\right)^{-0.40} (200\text{ K}) = 381\text{ K} = 108°\text{C}$$

Now we can use $C_P = \frac{5}{2}R = 20.8$ J/mol K for a monatomic gas to compute the heat transfers:

$$Q_H = |Q_{32}| = nC_P(T_3 - T_2)$$

$$= (0.00722\text{ mol})(20.8\text{ J/mol K})(95\text{ K}) = 14.3\text{ J}$$

$$Q_C = |Q_{14}| = nC_P(T_4 - T_1)$$

$$= (0.00722\text{ mol})(20.8\text{ J/mol K})(50\text{ K}) = 7.5\text{ J}$$

EXAMPLE 19.3 Analyzing a refrigerator

Thus the work *input* to the refrigerator is $W_{\text{in}} = Q_{\text{H}} - Q_{\text{C}} = 6.8\ \text{J}$. During each cycle, 6.8 J of work are done *on* the gas to extract 7.5 J of heat from the cold reservoir. Then 14.3 J of heat are exhausted into the hot reservoir.

The refrigerator's coefficient of performance is

$$K = \frac{Q_{\text{C}}}{W_{\text{in}}} = \frac{7.5\ \text{J}}{6.8\ \text{J}} = 1.1$$

The power input needed to run the refrigerator is

$$P_{\text{in}} = 6.8\ \frac{\text{J}}{\text{cycle}} \times 60\ \frac{\text{cycles}}{\text{s}} = 410\ \frac{\text{J}}{\text{s}} = 410\ \text{W}$$

EXAMPLE 19.3 Analyzing a refrigerator

ASSESS These are fairly realistic values for a kitchen refrigerator. You pay your electric company for providing the work W_{in} that operates the refrigerator. The cold reservoir is the freezer compartment. The cold temperature T_C must be higher than T_4 ($T_C > -23°C$) in order for heat to be transferred *from* the cold reservoir *to* the gas. A typical freezer temperature is $-15°C$, so this condition is satisfied. The hot reservoir is the air in the room. The back and underside of a refrigerator have heat-exchanger coils where the hot gas, after compression, transfers heat to the air. The hot temperature T_H must be less than T_2 ($T_H < 108°C$) in order for heat to be transferred *from* the gas *to* the air. An air temperature $\approx 25°C$ under a refrigerator satisfies this condition.

The Limits of Efficiency

Everyone knows that heat can produce motion. That it possesses vast motive power no one can doubt, in these days when the steam engine is everywhere so well known. . . . Notwithstanding the satisfactory condition to which they have been brought today, their theory is very little understood. The question has often been raised whether the motive power of heat is unbounded, or whether the possible improvements in steam engines have an assignable limit.

Sadi Carnot

The Limits of Efficiency

A perfectly reversible engine must use only two types of processes:

1. Frictionless mechanical interactions with no heat transfer ($Q = 0$)
2. Thermal interactions in which heat is transferred in an isothermal process ($\Delta E_{th} = 0$).

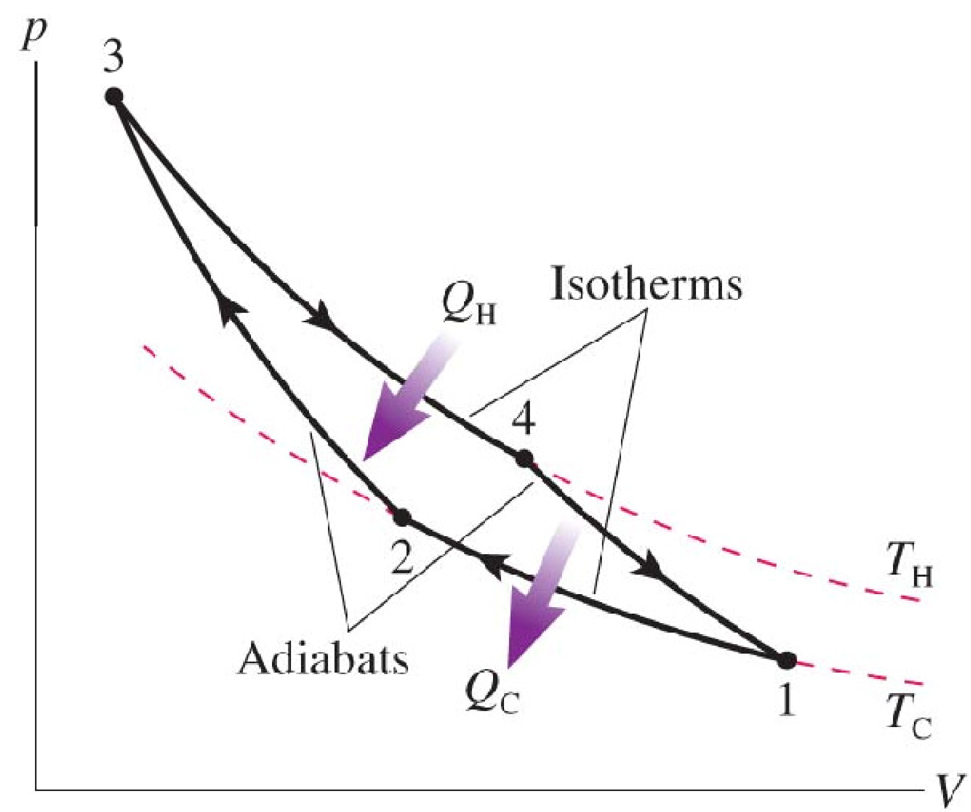
Any engine that uses only these two types of processes is called a **Carnot engine**.

A Carnot engine is a perfectly reversible engine; it has the maximum possible thermal efficiency η_{max} and, if operated as a refrigerator, the maximum possible coefficient of performance K_{max}.

The Carnot Cycle

The Carnot cycle is an ideal-gas cycle that consists of the two adiabatic processes ($Q = 0$) and the two isothermal processes ($\Delta E_{th} = 0$) shown. These are the two types of processes allowed in a perfectly reversible gas engine.

FIGURE 19.23 The Carnot cycle is perfectly reversible.



The Carnot Cycle

As a Carnot cycle operates,

1. The gas is isothermally compressed at T_C. Heat energy $Q_C = |Q_{12}|$ is removed.
2. The gas is adiabatically compressed, with $Q = 0$, until the gas temperature reaches T_H.
3. After reaching maximum compression, the gas expands isothermally at temperature T_H. Heat $Q_H = Q_{34}$ is transferred into the gas.
4. The gas expands adiabatically, with $Q = 0$, until the temperature decreases back to T_C.

Work is done in all four processes of the Carnot cycle, but heat is transferred only during the two isothermal processes.

The Maximum Efficiency

Second law, informal statement #7 No heat engine operating between energy reservoirs at temperatures T_H and T_C can exceed the Carnot efficiency

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H}$$

Second law, informal statement #8 No refrigerator operating between energy reservoirs at temperatures T_H and T_C can exceed the Carnot coefficient of performance

$$K_{Carnot} = \frac{T_C}{T_H - T_C}$$

EXAMPLE 19.6 Brayton versus Carnot

EXAMPLE 19.6 Brayton versus Carnot

The Brayton-cycle refrigerator of Example 19.3 had coefficient of performance $K = 1.1$. Compare this to the limit set by the second law of thermodynamics.

EXAMPLE 19.6 Brayton versus Carnot

SOLVE Example 19.3 found that the reservoir temperatures had to be $T_C \geq 250$ K and $T_H \leq 381$ K. A Carnot refrigerator operating between 250 K and 381 K has

$$K_{\text{Carnot}} = \frac{T_C}{T_H - T_C} = \frac{250 \text{ K}}{381 \text{ K} - 250 \text{ K}} = 1.9$$

EXAMPLE 19.6 Brayton versus Carnot

ASSESS This is the minimum value of K_{Carnot}. It will be even higher if $T_C > 250$ K or $T_H < 381$ K. The coefficient of performance of the reasonably realistic refrigerator of Example 19.3 is less than 60% of the limiting value.

EXAMPLE 19.7 Generating electricity

QUESTION:

EXAMPLE 19.7 Generating electricity

An electric power plant boils water to produce high-pressure steam at 400°C. The high-pressure steam spins a turbine as it expands, then the turbine spins the generator. The steam is then condensed back to water in an ocean-cooled heat exchanger at 25°C. What is the *maximum* possible efficiency with which heat energy can be converted to electric energy?

EXAMPLE 19.7 Generating electricity

MODEL The maximum possible efficiency is that of a Carnot engine operating between these temperatures.

EXAMPLE 19.7 Generating electricity

SOLVE The Carnot efficiency depends on absolute temperatures, so we must use $T_H = 400°C = 673$ K and $T_C = 25°C = 298$ K. Then

$$\eta_{max} = 1 - \frac{298}{673} = 0.56 = 56\%$$

EXAMPLE 19.7 Generating electricity

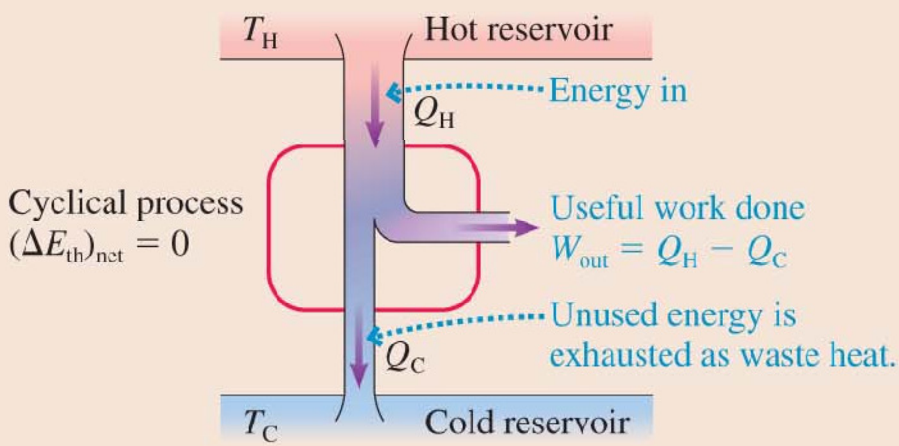
ASSESS This is an upper limit. Real coal-, oil-, gas-, and nuclear-heated steam generators actually operate at $\approx 35\%$ thermal efficiency. (The heat *source* has nothing to do with the efficiency. All it does is boil water.) Thus, as in the photo at the beginning of this chapter, electric power plants convert only about one-third of the fuel energy to electric energy while exhausting about two-thirds of the energy to the environment as waste heat. Not much can be done to alter the low-temperature limit. The high-temperature limit is determined by the maximum temperature and pressure the boiler and turbine can withstand. The efficiency of electricity generation is far less than most people imagine, but it is an unavoidable consequence of the second law of thermodynamics.

Chapter 19. Summary Slides

General Principles

Heat Engines

Devices that transform heat into work. They require two energy reservoirs at different temperatures.



Thermal efficiency

$$\eta = \frac{W_{out}}{Q_H} = \frac{\text{what you get}}{\text{what you pay}}$$

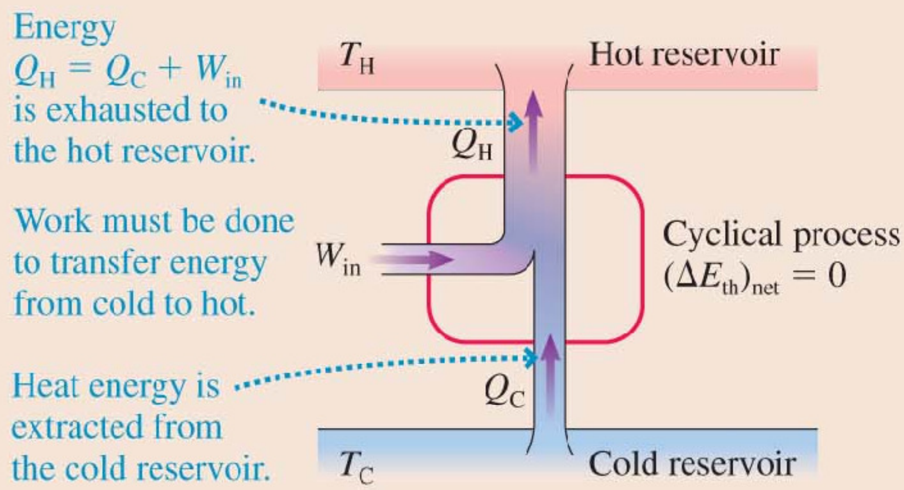
Second-law limit:

$$\eta \le 1 - \frac{T_C}{T_H}$$

General Principles

Refrigerators

Devices that use work to transfer heat from a colder object to a hotter object.



Coefficient of performance

$$K = \frac{Q_C}{W_{in}} = \frac{\text{what you get}}{\text{what you pay}}$$

Second-law limit:

$$K \le \frac{T_C}{T_H - T_C}$$

Important Concepts

A perfectly reversible engine (a **Carnot engine**) can be operated as either a heat engine or a refrigerator between the same two energy reservoirs by reversing the cycle and with no other changes.

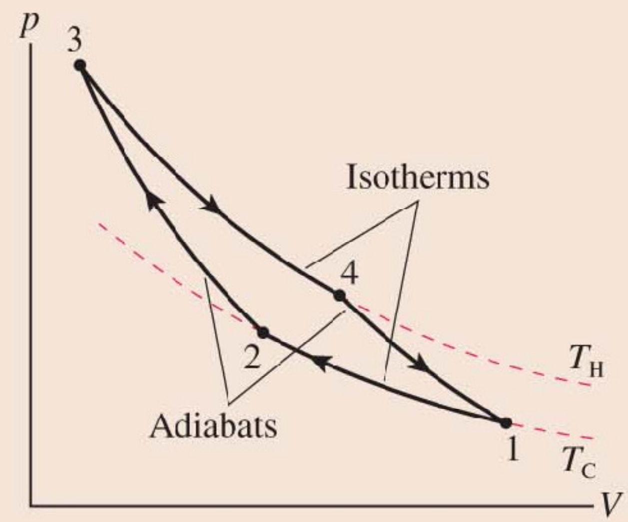
- A **Carnot heat engine** has the maximum possible thermal efficiency of any heat engine operating between T_H and T_C:

$$\eta_{\text{Carnot}} = 1 - \frac{T_C}{T_H}$$

- A **Carnot refrigerator** has the maximum possible coefficient of performance of any refrigerator operating between T_H and T_C:

$$K_{\text{Carnot}} = \frac{T_C}{T_H - T_C}$$

The Carnot cycle for a gas engine consists of two isothermal processes and two adiabatic processes.



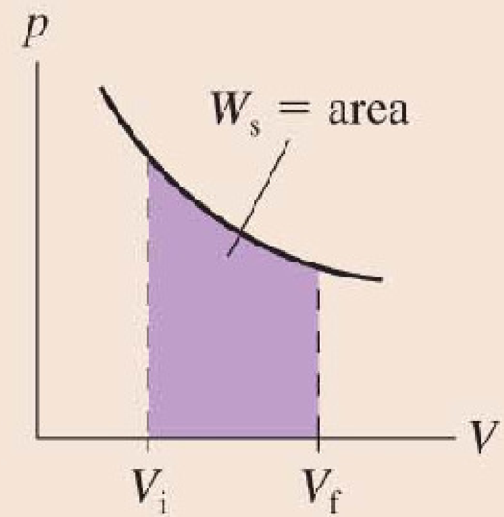
Important Concepts

An energy reservoir is a part of the environment so large in comparison to the system that its temperature doesn't change as the system extracts heat energy from or exhausts heat energy to the reservoir. All heat engines and refrigerators operate between two energy reservoirs at different temperatures T_H and T_C.

Important Concepts

The **work** W_s done *by* the system has the opposite sign to the work done *on* the system.

W_s = area under pV curve



Applications

To analyze a heat engine or refrigerator:

MODEL Identify each process in the cycle.

VISUALIZE Draw the pV diagram of the cycle.

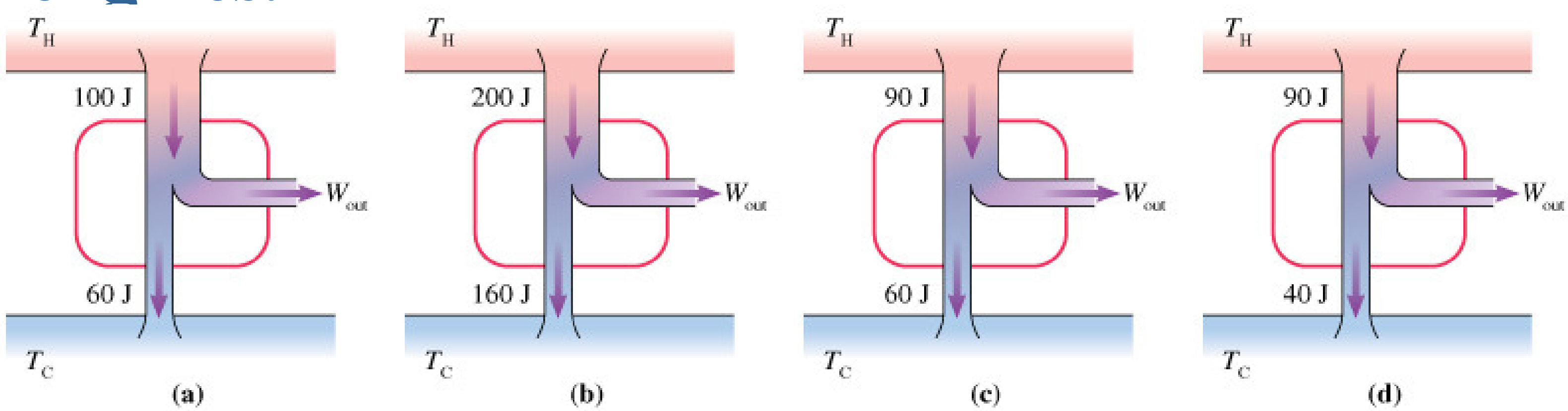
SOLVE There are several steps:

- Determine p, V, and T at the beginning and end of each process.
- Calculate ΔE_{th}, W_s, and Q for each process.
- Determine W_{in} or W_{out}, Q_H, and Q_C.
- Calculate $\eta = W_{out}/Q_H$ or $K = Q_C/W_{in}$.

ASSESS Verify $(\Delta E_{th})_{net} = 0$. Check signs.

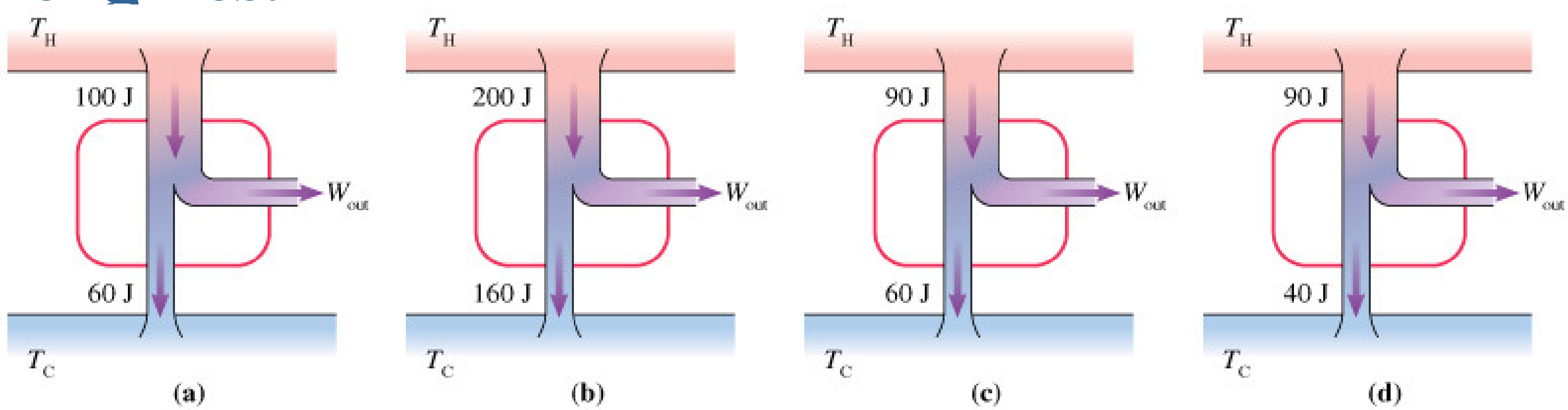
Chapter 19. Questions

Rank in order, from largest to smallest, the work W_{out} performed by these four heat engines.



A. $W_b > W_a > W_c > W_d$
B. $W_d > W_a = W_b > W_c$
C. $W_b > W_a > W_b = W_c$
D. $W_d > W_a > W_b > W_c$
E. $W_b > W_a > W_b > W_c$

Rank in order, from largest to smallest, the work W_{out} performed by these four heat engines.



A. $W_b > W_a > W_c > W_d$

✔ **B. $W_d > W_a = W_b > W_c$**

C. $W_b > W_a > W_b = W_c$

D. $W_d > W_a > W_b > W_c$

E. $W_b > W_a > W_b > W_c$

It's a really hot day and your air conditioner is broken. Your roommate says, "Let's open the refrigerator door and cool this place off." Will this work?

A. Yes.
B. No.
C. It might, but it will depend on how hot the room is.

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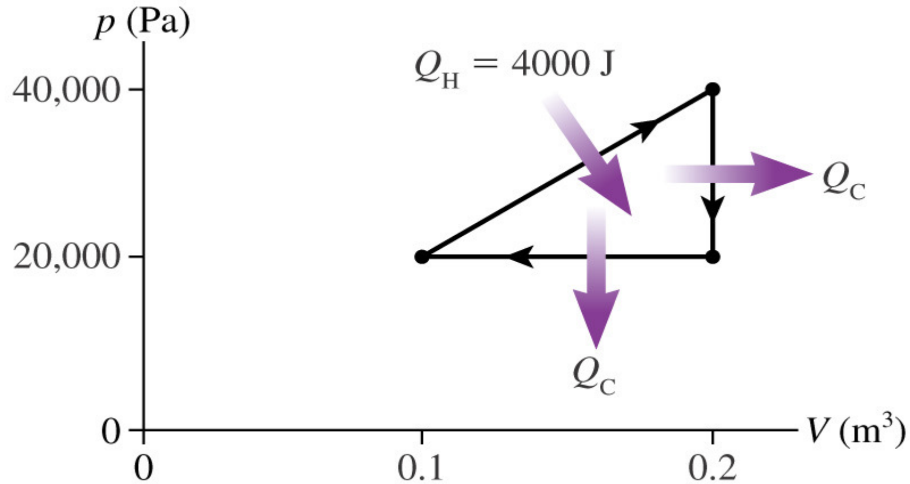
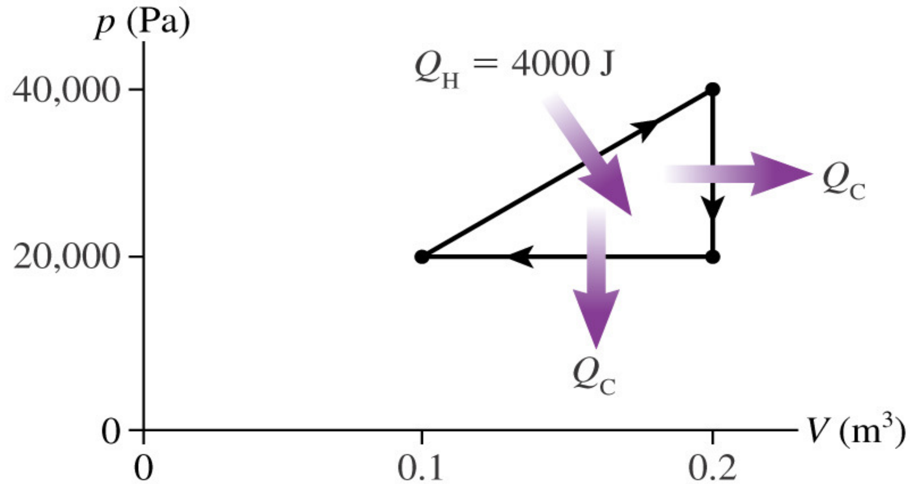
What is the thermal efficiency of this heat engine?



A. 4
B. 0.50
C. 0.10
D. 0.25
E. Can’t tell without knowing Q_C.

What is the thermal efficiency of this heat engine?



A. 4
B. 0.50
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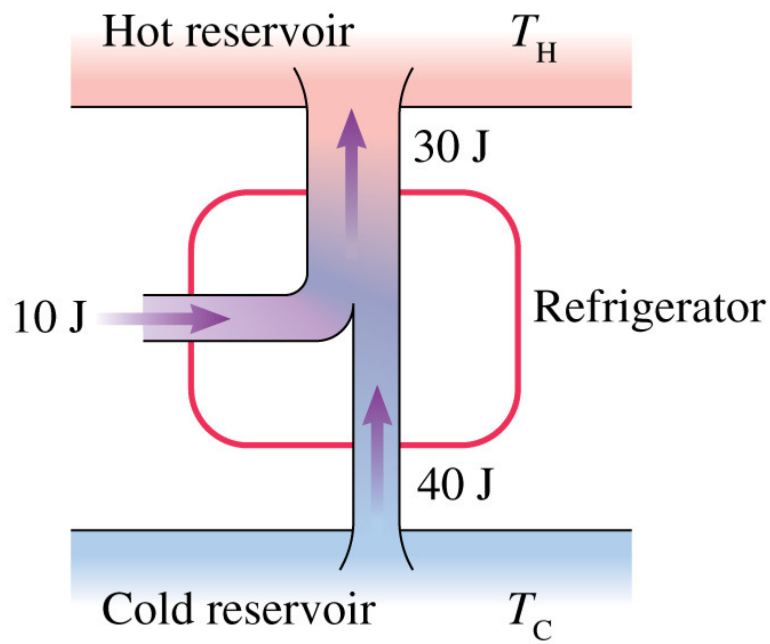
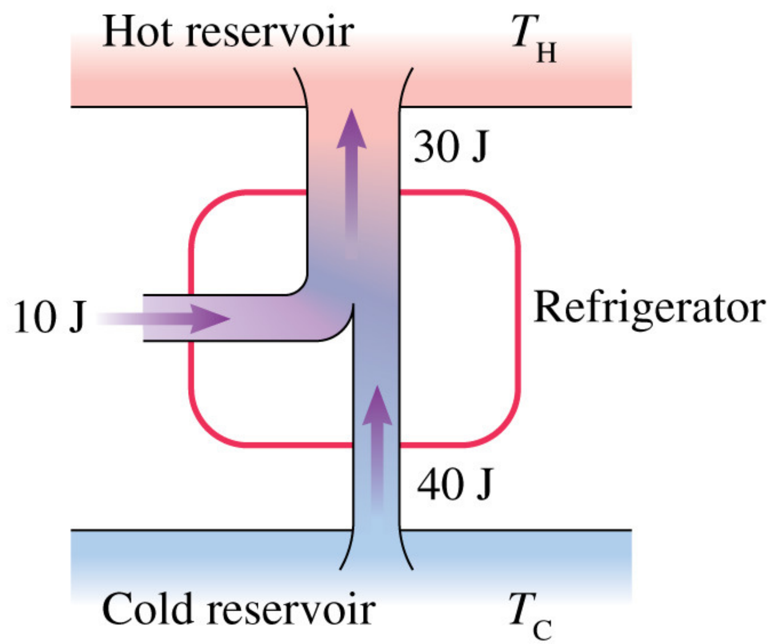
✔ **D. 0.25**
E. Can’t tell without knowing Q_C.

What, if anything, is wrong with this refrigerator?



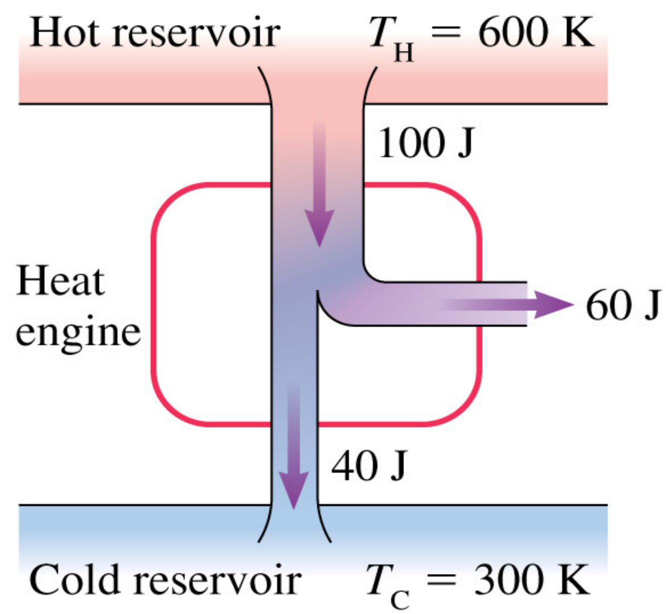
A. It violates the second law of thermodynamics.
B. It violates the third law of thermodynamics.
C. It violates the first law of thermodynamics.
D. Nothing is wrong.

What, if anything, is wrong with this refrigerator?



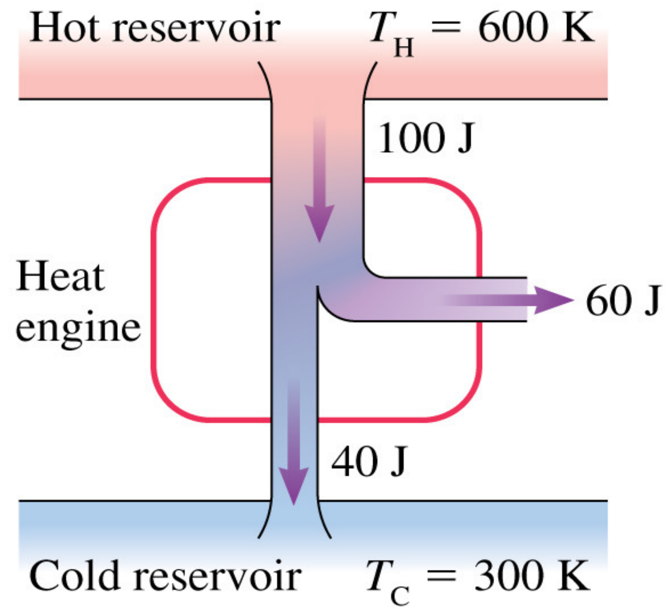
A. It violates the second law of thermodynamics.
B. It violates the third law of thermodynamics.
✔ **C. It violates the first law of thermodynamics.**
D. Nothing is wrong.

Could this heat engine be built?



A. No.
B. Yes.
C. It's impossible to tell without knowing what kind of cycle it uses.

Could this heat engine be built?



✔ **A. No.**
B. Yes.
C. It's impossible to tell without knowing what kind of cycle it uses.