Thermodynamics
Heat Transfer

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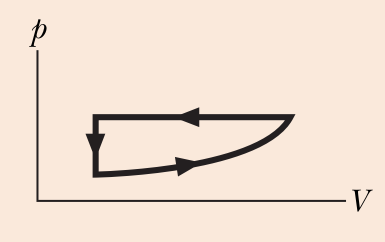
Last time

- work, heat, and the first law of thermodynamics
- P-V diagrams
- applying the first law in various cases

Warm Up Question



For one complete cycle as shown in the P-V diagram here, ΔE_{int} for the gas is

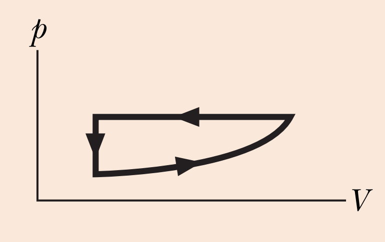
(A) positive

(B) negative

(C) zero

[1] Halliday, Resnick, Walker, page 495.

Warm Up Question



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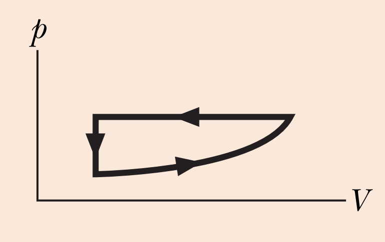

For one complete cycle as shown in the P-V diagram here, the net energy transferred as heat Q is

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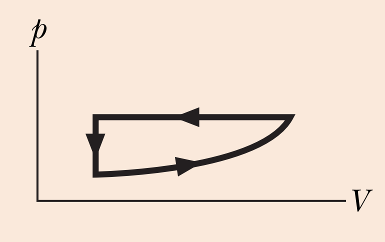

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Overview

- first law and ideal gas example
- heat transfer
- (Newton's law of cooling - Skipping)
- thermal conduction

Example 20.6: Boiling water

This example illustrates how we can apply these ideas to liquids and solids also, and even around phase changes, as long as we are careful.

Suppose 1.00 g of water vaporizes isobarically at atmospheric pressure (1.013×10^5 Pa).

Its volume in the liquid state is $V_i = V_{\text{liq}} = 1.00 \text{ cm}^3$, and its volume in the vapor state is $V_f = V_{\text{vap}} = 1671 \text{ cm}^3$.

Find the work done in the expansion and the change in internal energy of the system. Ignore any mixing of the steam and the surrounding air; imagine that the steam simply pushes the surrounding air out of the way.

Example 20.6: Boiling water

$V_i = V_{\text{liq}} = 1.00\ \text{cm}^3$
$V_f = V_{\text{vap}} = 1671\ \text{cm}^3$
$L_v = 2.26 \times 10^6\ \text{J/kg}$

Work done,

Example 20.6: Boiling water

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Work done,

$$\begin{aligned} W &= -P(V_f - V_i) \\ &= -(1.013 \times 10^5 \text{ Pa})(1671 - 1.00) \times 10^{-6} \text{ m}^3 \\ &= -169 \text{ J} \end{aligned}$$

Internal energy, ΔE_{int}?

Example 20.6: Boiling water

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Internal energy, ΔE_{int}? Know W, must find Q:

$$\begin{aligned} Q &= L_v m \\ &= (2.26 \times 10^6 \text{ J/kg})(1^{-3} \text{ kg}) \\ &= 2260 \text{ J} \end{aligned}$$

So,

$$\Delta E_{\text{int}} = W + Q = 2.09 \text{ kJ}$$

Heat Transfer

We are now changing gears.

We are still thinking about heat in more detail, but we are not necessarily talking about ideal gases.

(Section 20.7 of the textbook.)

Heat Transfer Mechanisms

When objects are in thermal contact, heat is transferred from the hotter object to the cooler object

There are various mechanisms by which this happens:

- conduction
- convection
- radiation

Conduction

Heat can "flow" along a substance.

When it does, heat is said to be transferred by **conduction** from one part of the substance to another.

Some materials allow more heat to flow through them in a shorter time than others.

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Some materials allow more heat to flow through them in a shorter time than others.

These materials are called “good conductors” of heat:

- metals (copper, aluminum, etc)

Conduction

In solids, conduction happens via

- vibrations
- collisions of molecules
- collective wavelike oscillations (phonons)
- diffusion and collisions of free electrons

In liquids and gases, conduction happens through diffusion and collisions of molecules.

Conduction

Some materials are not good conductors and are referred to as **thermal insulators**.

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Examples:

- air (and hence down feathers, wool)
- styrofoam
- wood
- snow

Newton's Law of Cooling (Applies for thermal conduction) - Skipping

Newton found a relation between the rate that an object cools and its temperature difference from its surroundings.

Objects that are much hotter than their surroundings lose heat much faster than objects that are only a bit hotter than their surroundings.

Using Q for heat:

$$\frac{\mathrm{dQ}}{\mathrm{dt}} = hA\Delta T$$

where A is the heat transfer surface area and h is the heat transfer coefficient

Newton's Law of Cooling (Applies for thermal conduction) - Skipping

$$\frac{\mathrm{dQ}}{\mathrm{dt}} = hA\,\Delta T$$

If there is no phase change in the substance and the cooling object remains in thermal equilibrium, then we can use the relation for heat capacity:

$$Q = -C\,\Delta T$$

where in this case the heat is transferred out of the hot object to the environment.
to get:

$$\frac{\mathrm{d}(\Delta \mathrm{T})}{\mathrm{dt}} = -r\,\Delta T$$

where the constant $r = hA/C$.

Newton's Law of Cooling Example - Skipping

Hot leftover soup must be cooled before it can be put in the refrigerator. To speed this process, you put the pot in a sink with cool, running water, that is maintained at 5°C. The hot soup cools from 75°C to 40°C in 8 minutes. Why might you predict that its temperature after another 8 minutes will be 22.5°C?

Newton's Law of Cooling Example - Skipping

Let $y = \Delta T$, then the solution to the differential equation is:

$$y = Ae^{-rt}$$

where $r = \ln 2/(8\text{min})$ and $A = y_i = 75 - 5 = 70^\circ$C.
We call the time $t = 8$ min the "half life" of the process, because after 8 min y has fallen by $\frac{1}{2}$:
At $t = 8$ min, $y = 40 - 5 = 35^\circ$C.
After another 8 min (t=16 min):

$$\begin{aligned} y &= (70)e^{-\ln 2t/(8\text{ min})} \\ &= (70)e^{-16\ln 2/8} \\ &= (70)e^{-2\ln 2} \\ &= (70)e^{\ln(1/4)} \\ &= 70/4 \\ &= 17.5^\circ\text{C} \end{aligned}$$

And so the soup is at a temperature $17.5 + 5 = 22.5^\circ$C.

Thermal Conduction over distance

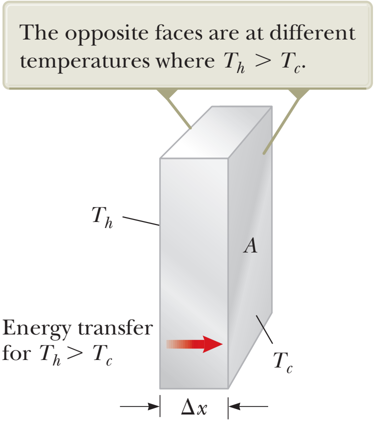
For Newton's law of cooling, we assumed we have a system at one temperature throughout, T, and an environment at another temperature T'.

What if we have a system that is in contact with two different environments (thermal reservoirs) at *different* temperatures?

The system will conduct heat from one reservoir to the other.

The system will not be the same temperature throughout. (The system is **not** in thermal equilibrium!)

Thermal Conduction over distance



Rate of heat transfer between surfaces:

$$\text{power, } P = \frac{Q}{\Delta t} = kA\,\frac{\Delta T}{\Delta x}$$

Thermal Conduction over distance

Fourier's Law

Imagining a subsection of the slab with an area A and an infinitesimal thickness dx:

$$P = kA\left|\frac{\mathrm{dT}}{\mathrm{dx}}\right|$$

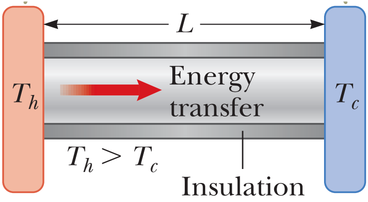
where k is the thermal conductivity and $\left|\frac{\mathrm{dT}}{\mathrm{dx}}\right|$ is called the temperature gradient.

If k is large for a substance, the substance is a good conductor of heat.

The units of k are W m^{-1} K^{-1}.

Thermal Conduction over distance

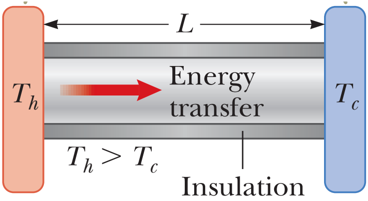
Imagine a uniform rod of length L, that has been placed between two thermal reservoirs for a long time. Assume for this bar k does not depend on temperature or position.



The temperature at each point is constant in time and the gradient everywhere is

$$\left|\frac{\mathrm{dT}}{\mathrm{dx}}\right| = \frac{T_h - T_c}{L}$$

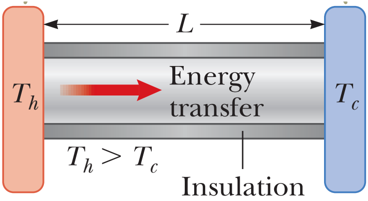
Thermal Conduction over distance



Then,

$$P = kA\left(\frac{T_h - T_c}{L}\right)$$

Thermal Conduction over distance

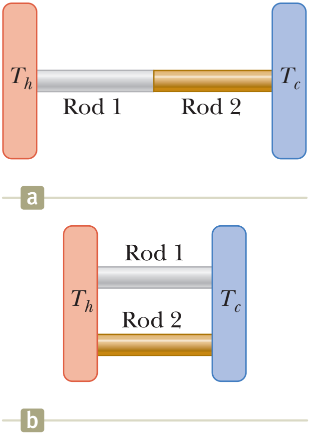


Then,

$$P = kA\left(\frac{T_h - T_c}{L}\right)$$

What if there are many different bars for heat to be transferred through?

Thermal Conduction through multiple materials



For situation (a):

$$P = \frac{A(T_h - T_c)}{(L_1/k_1) + (L_2/k_2)}$$

(See ex. 20.8)

For situation (b):

$$\begin{aligned} P &= P_1 + P_2 \\ &= \left(\frac{k_1 A_1}{L_1} + \frac{k_2 A_2}{L_2}\right)(T_h - T_c) \end{aligned}$$

Thermal Conduction through multiple materials

Compare:

$$
\begin{aligned}
P &= \left(\frac{kA}{L}\right)\Delta T \\
I &= \left(\frac{1}{R}\right)\Delta V
\end{aligned}
$$

On the LHS we have transfer rates, on the RHS differences that propel a transfer.

You can think of $\frac{L}{kA}$ as a kind of resistance. k is a conductivity, like σ (electrical conductivity). Recall, $R = \frac{\rho L}{A} = \frac{L}{\sigma A}$.

Thermal Conduction through multiple materials

For multiple thermal transfer slabs in series:

$$P = \frac{1}{\sum_i (L_i/(k_i A))} \Delta T$$

For multiple thermal transfer slabs in parallel:

$$P = \left(\sum_i \frac{k_i A_i}{L_i} \right) \Delta T$$

Now for convenient comparison, let $r_i = \frac{L_i}{k_i A_i}$. Then r_i is a thermal resistance, for the ith slab.

Thermal Conduction through multiple materials

For multiple resistors in series:

$$I = \left(\frac{1}{\sum_i R_i} \right) \Delta V$$

For multiple thermal transfer slabs in series:

$$P = \left(\frac{1}{\sum_i r_i} \right) \Delta T$$

For multiple resistors in parallel:

$$I = \left(\sum_i \frac{1}{R_i} \right) \Delta V$$

For multiple thermal transfer slabs in parallel:

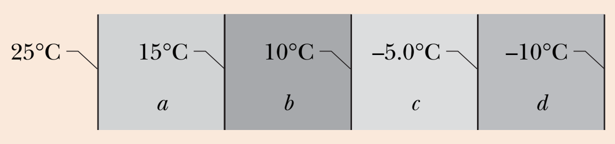
$$P = \left(\sum_i \frac{1}{r_i} \right) \Delta T$$

Thermal Conduction and Ohm's Law

Fourier's work on thermal conductivity inspired Ohm's model of electrical conductivity and resistance!

Thermal Conductivity Question

The figure shows the face and interface temperatures of a composite slab consisting of four materials, of identical thicknesses, through which the heat transfer is steady. Rank the materials according to their thermal conductivities, greatest first.



(A) a, b, c, d

(B) (b and d), a, c

(C) c, a, (b and d)

(D) (b, c, and d), a

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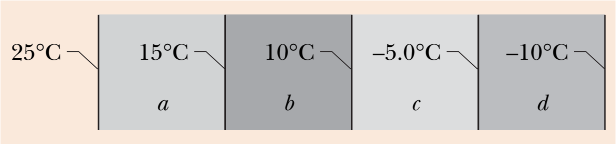

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Thermal Conduction and Insulation

Engineers generally prefer to quote "R-values" for insulation, rather than using thermal conductivity, k.

For a particular material:

$$R = \frac{L}{k}$$

This is its "length-resistivity" to heat transfer.

A high value of R indicates a good insulator.

The units used are ft^2 $^\circ$F h / Btu. (h is hours, Btu is British thermal units, 1 Btu = 1.06 kJ)

Summary

- heat transfer
- Newton's law of cooling