Thermodynamics
Heat Transfer

Lana Sheridan

De Anza College

April 30, 2018

Last time

- heat transfer
- conduction
- Newton's law of cooling

Overview

- continue heat transfer mechanisms
- conduction over a distance
- convection
- radiation and Stephan's law

Heat Transfer

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

Thermal Conduction over distance

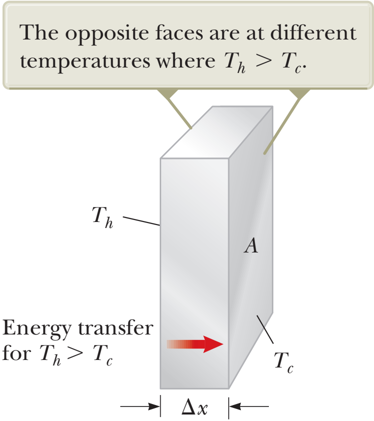
For Newton's law of cooling, we assumed we have a system at one temperature throughout, T, and an environment at another temperature T'.

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.

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:

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

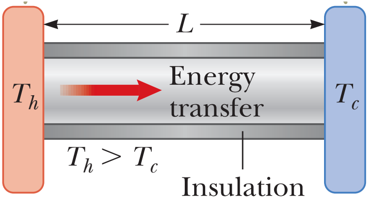
where k is the thermal conductivity and $\left|\frac{\mathrm{dT}}{\mathrm{dx}}\right|$ is called the temperature gradient.

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

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

Thermal Conduction over distance

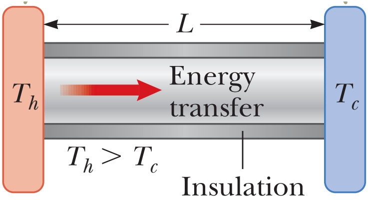
Imagine a uniform rod of length L, that has been placed between two thermal reservoirs for a long time. Assume for this bar k does not depend on temperature or position.



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

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

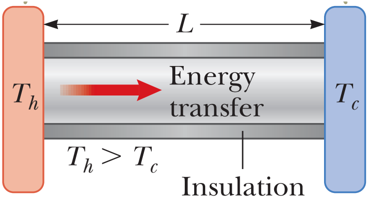
Thermal Conduction over distance



Then,

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

Thermal Conduction over distance

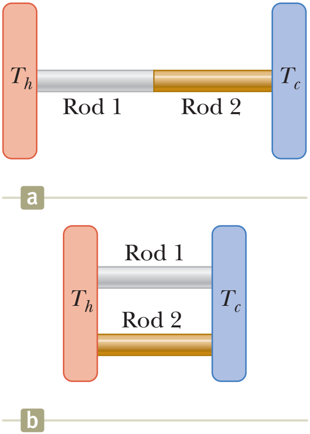


Then,

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

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:

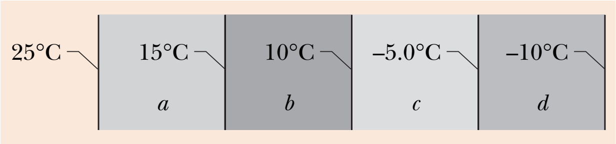
$$P = \left(\sum_i \frac{1}{r_i} \right) \Delta T$$

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

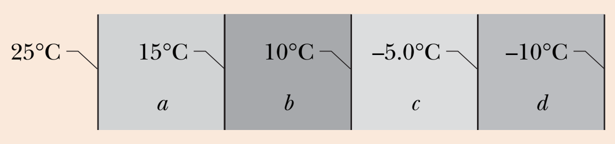
(C) c, a, (b and d)

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

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

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

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

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 $\text{ft}^2\,{}^\circ\text{F h / Btu}$. (h is hours, Btu is British thermal units, 1 Btu = 1.06 kJ)

Convection

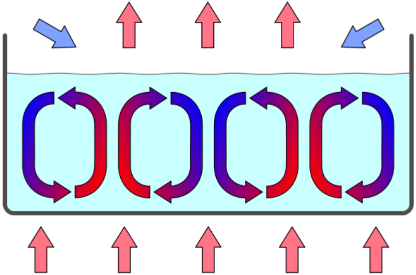
In liquids and gases convection is usually a larger contributor to heat transfer.

In convection, the fluid itself **circulates** distributing hot (fast moving) molecules throughout the fluid.

When there is gravity present, convection current circulations can occur.

Convection

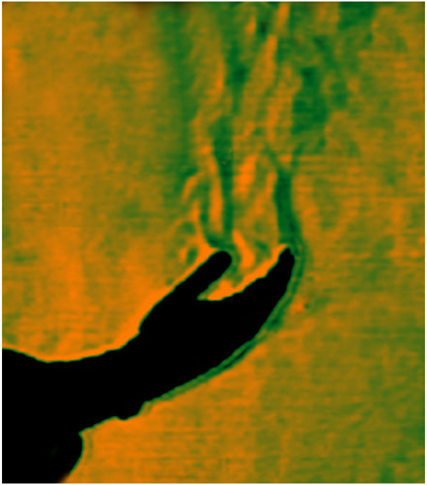
Hot fluid expands, and since it is less dense, it will have a greater buoyant force and rise.



Cooler, denser fluid will tend to sink.

Convection

Heat loss by convection from a person's hand:



This type of convection is called "free convection".

Forced Convection

External energy can also drive convection by means of a pump or fan.

This is used in convection ovens to evenly heat food.

It is also used in cooling systems to keep cool air flowing over hot components.

Summary

- heat transfer mechanisms: conduction, convection, radiation

Collected Homework due Monday, May 7.

Homework Serway & Jewett:

- Ch 20, onward from page 615. OQs: 11; CQs: 1, 9; Probs: 43, (45, 47,) 51, 55