Text Sections 19.11

Sample Problems 19.11

Suggested Questions None

Suggested Problems 11P

Summary
Heat transfer by convection
Newton’s Law of Cooling
Heat transfer by radiation
Black body radiation
Greenhouse effect

Specific objectives

- Describe the mechanisms of heat transfer (conduction, convection, radiation)
- Solve heat transfer problems
Convection

Convection is the mechanism whereby heat is transferred by movement of fluid material. It is usually a more effective method of heat transfer for fluids (liquids and gases) than conduction.

Remember that most materials expand when their temperature is increased. The temperature of a layer of fluid next to a hot object is increased by conduction. The layer expands and its density therefore decreases. It is then lighter than any cooler fluid above and will rise (float). Similarly the temperature of a layer of fluid next to a cool object is decreased by conduction. The layer contracts and its density therefore increases. It is then heavier than any warmer fluid below and will fall (sink). This creates circulation currents in the fluid and transfer of heat.

Convection is the reason why the top part of an oven is hotter than the bottom part even though the heating elements or burners are at the bottom of the oven.

The air in a fire is heated and rises. It is replaced by colder air flowing in from the sides. The hot air carries small particles (smoke) with it as it rises up a chimney.

Convection plays a very important role in climate and weather. For example, the Gulf Stream transfers heat by convection from warm equatorial regions to higher latitudes (North America and Europe) raising their temperature by several degrees. Cyclones are driven by convection and the Earth’s rotation.

Convection can be either natural or forced. The latter describes situations where convection currents are driven by an external agency, e.g. a fan, rather than by buoyancy as discussed above.

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Newton’s Law of Cooling

For small differences between the temperature \( T_O \) of an object and that \( T_S \) of its surroundings the rate of change of temperature of the object is approximately proportional to the temperature difference, i.e.

\[
\frac{dT_o}{dt} = -B ( T_o - T_s )
\]

where \( B \) is a positive constant. The minus sign indicates that \( T_O \) decreases with time if the object is hotter than its surroundings (i.e. \( T_O > T_S \)).
Radiation

Heat transfer from an object by conduction and convection is possible only if the object is in direct contact with some form of matter.

More than 99.9% of the energy transferred to the Earth’s surface and its atmosphere is from the Sun – about \(1.73 \times 10^{17}\) W. (A small amount – about \(4 \times 10^{13}\) W – generated by radioactive decays inside the Earth flows upwards from the interior.) The number of particles per cubic metre in the interplanetary medium between the Sun and the Earth is about the same as that in the best vacuum which can be created in a laboratory – about \(10^{-18}\) of the number in the air around us. How does energy get from the Sun to the Earth?

All objects continuously emit and absorb electromagnetic radiation. This radiation carries energy and results in heat transfer. The rate at which energy is emitted by an object is given by

\[
P_r = \varepsilon \sigma A T^4.
\]

where \(A\) is the surface area of the object, \(\varepsilon\) is a number between 0 and 1 called the emissivity of the surface and \(\sigma = 5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}\) is the Stefan – Boltzmann constant. Note the very strong dependence of \(P_r\) on temperature!

An ideal black body radiator has \(\varepsilon = 1\) but all real surfaces have \(\varepsilon < 1\). A surface with emissivity \(\varepsilon\) absorbs a fraction \(\varepsilon\) of any electromagnetic radiation incident on it and reflects the remaining fraction \(1 - \varepsilon\). Good emitters are also good absorbers.

In daylight most of the radiation coming from an object is reflected sunlight. Good emitters (also good absorbers) look black because very little of the visible light which shines on them is reflected (see Fig 19-20). At night the radiation coming from objects is thermal infrared emission. This can be “seen” with night-vision glasses which “convert” infrared to visible (see Fig 19-19).

An object surrounded by an environment at a uniform temperature \(T_{env}\) absorbs radiation at a rate

\[
P_a = \varepsilon \sigma A T_{env}^4.
\]

The net heat transferred to an object by radiation is the difference between the radiation from its surroundings absorbed by the object (including radiation from hot objects like the Sun and from cooler objects nearby) and the radiation emitted by the object itself.
The frequency spectrum of radiation emitted depends on the temperature of the object and the nature of its surface. A plot of the energy radiated at each wavelength by an ideal black body radiator peaks at a temperature $\lambda_{\text{MAX}}$. The Sun is approximately an ideal black body radiator with a temperature of about 6000 K. Its radiation peaks at $\lambda_{\text{MAX}}$ equal to about 500 nm, green in the visible part of the electromagnetic spectrum (see Fig 34-1). The radiation from an ideal black body radiator at 300 K peaks at $\lambda_{\text{MAX}}$ equal to about 10 $\mu$m, in the infrared. The famous 3K cosmic microwave background radiation in astronomy peaks at $\lambda_{\text{MAX}}$ equal to about 1 mm, in the microwave region.

In general $\varepsilon$ also depends on wavelength. An ideal black body radiator has $\varepsilon = 1$ at all wavelengths. A selective surface coated onto the absorbing section of a solar hot water system has $\varepsilon$ close to 1 for wavelengths less than about 5 $\mu$m and $\varepsilon$ close to 0 above 5 $\mu$m. These surfaces therefore absorb most of the solar radiation incident on them but emit very little radiation in the infrared. There is therefore a net heat transfer to the surface and hence to the water.

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**The Greenhouse Effect**

(See [http://www.earth.nasa.gov/science/climate2.html](http://www.earth.nasa.gov/science/climate2.html))

Just outside the Earth’s atmosphere, solar energy is received at a rate 1.36 kW $\cdot$ m$^{-2}$ on a flat surface perpendicular to the line joining the Sun and the Earth. The Earth intercepts about $1.73 \times 10^{17}$ W of this electromagnetic radiation. If the Earth absorbed all the energy and then re-emitted it in all directions as an ideal black body radiator, the temperature of the Earth’s surface would be $T = 278$ K or 5 °C. Cold!! In fact the temperature would actually be about 23 °C less than this because some of the incident energy would be reflected by the Earth’s surface rather than absorbed.

In reality the surface of the Earth radiates at an average temperature about 33 °C higher, i.e. about 288 K. This is because the Earth is surrounded by its atmosphere which contains greenhouse gases such as carbon dioxide, water, methane, oxides of nitrogen, etc. These gases absorb the infrared radiation emitted by the Earth’s surface and reradiate some of the absorbed energy downwards keeping the surface temperature at the higher value. This is called the natural greenhouse effect and is very necessary for life as we know it. Man-made increases in the amount of these greenhouse gases cause global warming.