CONVECTION AND CONDUCTION

Lexile Measure: 1230L

FIELDS OF STUDY

Thermodynamics

ABSTRACT

Convection and conduction are thermal processes. Conduction is the movement of heat through a material via very small atomic or molecular collisions in the material. Convection is the movement of head specifically through a fluid, via larger-scale movement of the material. First observed in steam engines in the nineteenth century, these processes are used in such applications as cooling computers and nuclear reactors, and in heating homes.

PRINCIPAL TERMS

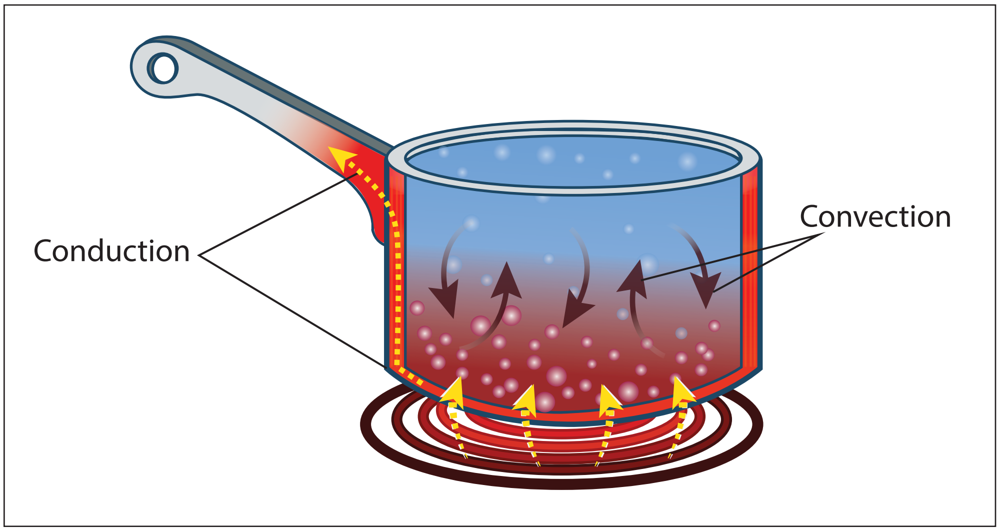
- **heat transfer:** transfer of thermal energy from one region or system to another.
- **ideal gas law:** the scientific law relating pressure, volume, and temperature in a gas where the particles do not interact except to collide in perfectly elastic collisions.
- **radiation:** heat transfer via subatomic particle emission.
- **temperature:** a value proportional to the average speed of the particles inside a material.
- **thermal conductivity:** the ease with which heat propagates through a material; measured in watts per meter kelvin.
- **thermodynamics:** the study of heat flow and related forms of energy.

Convection, Conduction, and Heat

Heat is the collective random motion (kinetic energy) of atoms in a substance. In any material, atoms move randomly, vibrating, spinning, and even changing location. **Temperature** indicates the average speed of the particles, while heat is about the total energy. The amount of this kinetic energy is the heat of an object.

According to the principles of **thermodynamics**, heat can be transferred from one material to another by three methods. The first is **radiation**, which requires no physical contact. The second and third methods, convection and conduction, do require contact. In essence, the difference between convection and conduction is that in convection, the matter moves, but in conduction, only the heat does.

The ideal gas law provides a good idea of what goes on when one heats something, based on the idea of heat as exciting atoms. It states that the product of absolute pressure (p) and volume (V) equals the product of the number of molecules present (n), the universal gas constant R, and the absolute temperature (T), written as $pV = nRT$. Basically, the more molecules are wedged into an area and the faster they are moving, the more they



Water boiling in a pot of water on a stovetop demonstrates heat transfer via conduction and via convection. Convective heat transfer occurs with hot water transferring to the top of the pot, pushing cooler water down to be heated. Conductive heat transfer occurs from the stovetop to the pot it touches and from the pot through the connected handle to the hand.

will try to spread out and the more pressure they will put on their enclosure (since they are moving faster, they collide with more force). The next area to consider is how that energy gets around, known as the process of **heat transfer**.

Convection and Conduction

Convection only occurs in materials where the molecules are free to move. A hot fluid or gas is less dense than a cold one because the molecules in the hot one are more energetic and spread out. In a teacup, the cool tea sinks to the bottom and the warm tea rises, but if one thinks of a pot of water on a stove, then as the warm water rises and the cool water sinks, one finds that the warm water is cooled by the contact with the air and the cold water is warmed by the stove. Soon a cycle forms as the now-cooled water at the surface begins to sink and the now-hot water near the flame begins to rise. In this cycle, the water is circulated through the pot, rising from the bottom as hot water, coming to the surface, cooling, and sinking back down to be warmed again. This is a convection cycle.

Conduction is easier to visualize. Imagine a cup of tea that is very hot. The molecules of tannin and water and even the cellulose in the leaves at the bottom are vibrating and shaking and bouncing. They strike the walls of the teacup with a lot of energy, causing them to vibrate too. Soon the atoms and molecules in the walls of the teacup are nearly as energetic as the tea inside. When one goes to drink the tea, one's skin comes in contact with the energetic molecules in the cup. These collide with the skin, causing the molecules there to gain energy and move faster. Soon the warmth spreads through one's fingers.

The heat has spread through the direct collisions of the energetic cup molecules with the more lethargic molecules of the skin. The amount of heat transferred in a given period of time is determined by the materials' **thermal conductivity**, which is measured in watts per meter kelvin (W/m·K).

Thermal conduction is computed as the amount of heat transferred (Q) over time (t). This is equal to the product of the thermal conductivity (k), the area (A), and the difference between the higher and lower temperatures (ΔT), over a given distance (d). Its formula is written as:

$$\frac{Q}{t} = \frac{kA\,(\Delta T)}{d}$$

SAMPLE PROBLEM

Consider the case of a window into a zoo's penguin enclosure. The pane is 2 meters by 5 meters, and 0.01 meters thick. It has a thermal conductivity of 1 watt per meter-kelvin (W/m·K). If the interior of the enclosure is −3 degrees Celsius and the exterior a warm 24 degrees Celsius, how much heat is transferred through the pane in a minute?

Answer:

To solve this problem, first find the area of the window using the length and the width:

$$2\text{ m x }5\text{ m} = 10\text{ m}^2$$

Next, find the difference in temperature by converting from degrees Celsius to kelvins, then subtracting the lower temperature from the higher one:

$$\text{K} = {}^\circ\text{C} + 273.15$$

$$24\ {}^\circ\text{C} + 273.15 = 297.15\text{ K}$$

$$-3\ {}^\circ\text{C} + 273.15 = 270.15\text{ K}$$

$$297.15\text{ K} - 270.15\text{ K} = 27\text{ K}$$

(Note that it does not matter much whether one converts from Celsius to kelvin, because degrees Celsius and kelvins have the same increment, the only difference being the zero point.)

Plug these values, along with the given time, thickness (distance between the inside and outside), and thermal conductivity, into the thermal conduction equation

$$\frac{Q}{t} = \frac{kA\,(\Delta T)}{d}$$

$$Q = \frac{kA\,(\Delta T)\,t}{d}$$

$$Q = \frac{(1\,\frac{\text{W}}{\text{m}\cdot\text{K}})(10\text{ m}^2)(27\text{ K})(60\text{ s})}{0.01\text{ m}}$$

$$Q = \frac{16{,}200\text{ W}\cdot\text{m}\cdot\text{s}}{0.01\text{ m}}$$

$$Q = 1{,}620{,}000\text{ W}\cdot\text{s} = 1{,}620{,}000\text{ J}$$

Thus, we find a transfer of 1,620,000 watt seconds, or 1,620,000 joules.

Applications

Convection is present in many important processes in earth science. It is the driving force behind plate tectonics, where hot magma rises from the molten and radioactive core of the planet and cools as it rises, eventually hardening into a thin crust at the surface. As more magma rises, the hardened crust rides the currents across the surface, before sinking back down to the core. A current rises from Earth's core, reaching the surface in an arc of volcanoes running from Iceland, down the middle of the Atlantic Ocean, and up into East Africa and into the Red Sea. That is why Iceland is so volcanically active. It is growing a little bigger every year. Conversely, hot magma spreading the East African Rift Valley will result in East Africa breaking away and the possible creation of a new ocean. Meanwhile, off the coasts of British Columbia, Alaska, Russia's Kamchatka Peninsula, and Japan, the cooled magma beneath the surface sinks back down into the core. That is why there are deep trenches off the coast.

Equally, convection circulates the water in the oceans. Warm water from the equator cools as it reaches the poles until it sinks. This circulation is very complex, as currents of cold water run beneath the surface until they are warmed at the equator. In essence, this is the reason the Gulf Stream runs north from the Caribbean to the Arctic Ocean. (In practice, it is a little more complicated, as salinity also greatly affects the water's density.) This whole process is called the "thermohaline circulation."

It is hard to find an engineering field where heat transfer is not an important principle. Most machines must be cooled one way or another. Cooling fans make use of convection, while a computer's heat sink uses a block of easily heated material to draw heat from the circuits. In fact, it was the convection in steam engines that gave rise to the early examination of thermodynamics, by scientists like Sadi Carnot (1796–1832). Carnot wrote during the early part of the nineteenth century and outlined much of what would later become thermodynamics by careful analysis of the steam engine and trying to explain questions like why a steam engine using superheated steam was better than one using hot water or whether a better fluid than steam could be used. In so doing, Carnot created a theoretical model of an engine that is still used today. Later scientists would expand these ideas with a greater understanding of atoms and chemistry, although quantum thermodynamics remains an area of active research.

Convection and conduction are vital in any engineering project, from building a more energy-efficient house to keeping a nuclear power plant from overheating. In the case of buildings, the search for better insulation materials, as well as better layouts for passive cooling via convection, is ongoing. In a nuclear reactor, engineers try to design a fault-tolerant means of dispersing a great deal of heat. The cooling towers used in many nuclear plants are designed to work with convection, being open at the bottom. This allows air to flow into them, where it is heated by a hot water pipe. This effectively sucks water into the tower, improving efficiency.

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