HEAT AND ENERGY

Preamble

You may have wondered how a refrigerator cools, what transformations occur in a car engine, or what happens to the kinetic energy of a falling object once it hits the ground? The laws of thermodynamics and the concepts of heat and temperature enable us to answer such practical questions.

We start with temperature, which is a central concept in thermodynamics and forms one of the seven basic SI units.

1. Temperature & Thermal Properties of Matter

Preview:

In this first part of the course we will

- define the concepts of heat and temperature
- explore the nature of heat and the ways in which we measure temperature
- examine the nature of thermal expansion of solids and liquids, and look at the special properties of water
- discuss the gas laws, which relate macroscopic properties such as pressure and temperature
- discuss the kinetic theory of gases, which shows how microscopic behaviour (such as the random motion of molecules in a gas) can be related to macroscopic properties such as temperature

1..1Temperature and Heat

Objectives:

To be able to

- define and distinguish between temperature and heat
- define internal energy
- discuss everyday examples to illustrate these concepts

- Picture a child with a sparkler. Although the temperature of the sparks flying off the stick exceeds 2000^0C, the heat they impart when striking the skin is very small. This illustrates that *temperature* and *heat* are different concepts. We need to learn to distinguish between such closely related concepts.
- *What is temperature*?
- **The quantity that tells how warm or cold an object is relative to some standard scale is called *temperature***. We express the temperature of matter by a number that corresponds to the degree of hotness on some chosen scale.
- *Temperature* is a relative measure, or indication, of hotness or coldness. It's some sort of indication, or measure, of heat.
- We can perceive temperature *by touch*. However, this temperature sense is somewhat unreliable: if we remove a metal tray and a frozen package of vegetables from the freezer, we 'feel' the former as colder, even though they have the same temperature (this is because the metal removes energy more quickly from our hands).
- Also, the range of our temperature sense is too limited to be useful for scientific purposes.
- *What is heat?*
- If you touch a hot stove, energy enters your hand because the stove is warmer than your hand. When you touch a piece of ice, energy passes out of your hand and into the colder ice. The direction of spontaneous energy transfer is always from a warmer object to a neighbouring colder object.

- **The energy transferred from one object to another because of a temperature difference between the objects is called *heat*.**
- Matter does **not** contain *heat*. Matter contains molecular kinetic energy and possibly potential energy, *not heat*.
- Heat is energy in transit from a body of higher temperature to one of lower temperature; it is energy that is transferred from one body to another because of a temperature difference. It is related to temperature and describes the process of energy transfer from one object to another.
- Once transferred, the energy ceases to be heat; the energy becomes part of the total energy of the molecules of the object or system, its *internal energy*.
- As an analogy, *work* is also energy in transit. A body does **not** contain work. It *does* work, or has work done on it.
- The energy resulting from *heat flow* is often called *thermal energy*, to make clear its link to heat and temperature. Scientists, however, often prefer to use the term *internal energy*.
- *What is internal energy*?
- **Internal energy is the grand total of all the energies inside a substance:**
  - translational kinetic energy of jostling atoms
  - rotational and vibrational kinetic energy of molecules
  - kinetic energy due to internal movements of atoms within molecules
  - potential energy due to (attractive) forces between molecules
- So a substance does not contain heat, but it does contain internal energy.
- For objects in thermal contact, heat flow is from the substance at higher to the one at lower temperature, but not necessarily from a substance with more internal energy to a substance with less internal energy. Example: immerse a glass of hot water into the sea, and the glass of water cools down, even though the sea (as an object) contains far more internal energy.
- How much heat flows depends not only on the temperature difference between substances, but on the amount of material as well (there is generally more internal energy in a larger amount of water than a smaller one, as illustrated by the example of the sea and the glass of water).
- A higher temperature does not necessarily mean that one system has a greater internal energy than another. Example: Consider the air temperature in a classroom on a cold day, relative to the cold air outside. The latter has more internal energy, even though it is colder.
- Internal energy of a system also depends on its mass, or the number of molecules in the system.

1..2 Thermometers and Temperature Scales

Objectives:

To be able to

- define what a thermometer is
- describe the physical principles on which the use of a thermometer is based
- state the Zeroth Law of Thermodynamics, and discuss its physical implications with respect to thermometers
- explain how a temperature scale is constructed
- convert temperatures from one scale to another
- obtain a feel for the range of temperature values in everyday life and throughout the Universe

- *What is a thermometer*?
- **A measure of temperature is obtained using a *thermometer*, a device constructed to make evident some property of a substance that changes with temperature.**
- Many physical properties of materials change sufficiently with temperature to be used as the bases for thermometers:
  - the change in volume of a liquid
  - the change in length of a solid
  - the change in pressure of a gas held at constant volume
  - the change in electrical resistance of a conductor

- the change in colour of a very hot object.
- **By far the most obvious and commonly used property is ***thermal expansion*****, a change in the dimensions or volume of a substance that occurs when the temperature changes.**
- A common thermometer is the *liquid-in-glass type*, which is based on the thermal expansion and contraction of a liquid, usually mercury or coloured alcohol. These substances were chosen because of their relatively large thermal expansion and because they remain liquids over normal temperature ranges.

The Celsius Scale

- *How do we calibrate thermometers*?
- Thermometers are calibrated so that a numerical value may be assigned to a given temperature. For the definition of any standard scale or unit, two fixed reference points are needed. The ice point and the steam point of water are two convenient fixed points (temperatures at which water freezes and boils under a pressure of one atmosphere).
- On the scale commonly used in laboratories, the number 0 is assigned to the temperature at which water freezes and the number 100 to the temperature at which water boils (at standard atmospheric pressure).
- The space between is divided into 100 equal parts called *degrees*.
- A thermometer so calibrated is often called a *centigrade thermometer* (from *centum*: hundred; *gradus*: degree). It is now called a *Celsius thermometer*, in honour of the Swedish astronomer Anders Celsius (1701-1744), who first suggested the scale (or at least, an inverted version of it).
- Temperature readings are written as ^{0}C; temperature differences are commonly written as C^0.

The Fahrenheit Scale

- In the USA, the number 32 is assigned to the temperature at which water freezes, and the number 212 to the temperature at which water boils.
- On the Fahrenheit scale, there are 180 equal intervals, or degrees, between the two reference points.
- Such a scale makes up a *Fahrenheit thermometer*, named after its originator, the German physicist Gabriel Daniel Fahrenheit (1686-1736).
- Not wanting to deal with negative values, he set the 0 mark at the coldest temperature he could produce (a mixture of water, ice, and sea salt), and the upper reference he took as normal human body temperature, which he took as 96 (probably because it is divisible by 12 and easily halved and quartered) -- now known to be 98.6^{0}F.
- The Fahrenheit scale does have some advantages in everyday use:
  - Its degrees are smaller (1F^0 = 5/9C^0), which gives greater accuracy when reporting the weather in whole-number temperature readings.
  - When the temperature of a hot day is reported to reach 100^{0}F, the idea of heat is conveyed more dramatically than by saying it is 38^{0}C.
  - The Fahrenheit scale is geared to human beings (like much of the British system of measure).
- Temperature readings are written as ^{0}F; temperature differences are commonly written as F^0.

The Kelvin Scale: Thermodynamic Temperature and Absolute Zero

- The Fahrenheit and Celsius scales have little or nothing to do with the fundamental nature of the concept of temperature -- on another planet there may be no water to refer to.
- The *Kelvin scale*, named after the British physicist Lord Kelvin (born William Thomson) (1824-1907), is a more fundamental temperature scale favored by scientists.

- The Kelvin scale is calibrated not in terms of the freezing and boiling points of water, but in terms of energy itself.
- **The number 0 is assigned to the universal zero of temperature, i.e., the lowest possible temperature: *absolute zero*.**
- The second reference (fixed) point is the *triple point of water*, which represents a unique set of conditions where water co-exists simultaneously in equilibrium as a solid, liquid and a gas. The conditions for the triple point are a pressure of 610 Pa, and a temperature taken to be 273.16 K (0.01^0C). Note that this provides some connection with the other temperature scales, which are based on the properties of water.
- The kelvin is defined as 1/273.16 of the temperature at the triple point of water.
- Absolute zero corresponds to -273^0C on the Celsius scale (-273.15^0C to be precise).
- Units on the Kelvin scale are the same size as degrees on the Celsius scale (so the temperature of melting ice is +273 kelvins).
- There are no negative numbers on the Kelvin scale.
- Temperature and temperature differences are stated in *kelvins* (not degrees Kelvin), abbreviated as K (not ^{0}K).

Conversions

- Arithmetic formulas are used to convert between the Fahrenheit, Celsius, and Kelvin temperature scales.
- To convert between the Celsius and Fahrenheit temperature scales:

$$T_F = \frac{9}{5}T_C + 32 \quad \text{Celsius to Fahrenheit conversion}$$

$$T_C = \frac{5}{9}(T_F - 32) \quad \text{Fahrenheit to Celsius conversion}$$

  Note: this is of the form of an equation for a straight line: $y = mx + c$, with m the slope and c the intercept on the vertical axis.
- To convert between the Celsius and Kelvin temperature scales:

$$T_K = T_C + 273.15 \quad \text{Celsius to Kelvin conversion}$$

$$T_C = T_K - 273.15 \quad \text{Kelvin to Celsius conversion}$$

Temperature Ranges

- The Universe sustains an incredible temperature range. The highest temperatures likely to exist at this moment are found deep within stars: ~ 4 x 10^9K seems to be a theoretical extreme. At a temperature only ten times higher matter fragments into subatomic particles. At the start of the Universe (10-20 billion years ago), the temperature is believed to have been 10^{39}K (now it has cooled down to 3K - we are lucky to have a star called the Sun to keep us warm!).
- We live our delicate lives within a tiny band of hot and cold. The hottest thing you are likely to find around the house is a tungsten light bulb filament: ~ 2800 K. Body temperature is about 310K (37^0C; 98.6^0F)
- Although temperature has a lower limit, there does not appear to be an upper limit.
- In the quest for absolute zero, experimenters have got bulk matter close to temperatures ~ 0.00000002K.

1..3 Thermal Expansion of Liquids and Solids

Objectives:

To be able to

- discuss everyday examples and consequences of the thermal expansion of solids and liquids
- quantify the linear (1-dimensional) thermal expansion of solids, and define the linear coefficient of thermal expansion
- quantify the area (2-dimensional) thermal expansion of solids, and define the area coefficient of thermal expansion
- quantify the volume (3-dimensional) thermal expansion of solids, and define the volume coefficient of thermal expansion
- derive relations between the different coefficients of thermal expansion for solids
- quantify the volume (3-dimensional) thermal expansion of liquids, and define the volume coefficient of thermal expansion
- describe the (anomalous) thermal expansion of water, and its practical consequences for life on Earth

- *What is thermal expansion, and what are its (practical) consequences*?
- When the temperature of a substance is increased, the molecules or atoms jiggle faster and tend to move further apart, on average. The result is an expansion of the substance.
- With few exceptions, all forms of matter -- solids, liquids, gases and plasmas -- generally expand when they are heated and contract when they are cooled (note: contraction can be considered as 'negative' expansion).
- In many cases, the change in size is not very noticeable, but careful observation will detect them:
  - Telephone wires are longer and sag more on a hot summer day than a cold winter day.
  - Metal lids on glass fruit jars can often be loosened by heating them under hot water.
  - If one part of a piece of glass is heated or cooled more rapidly than adjacent parts, the expansion or contraction that results may break the glass. This is especially true with thick glass; pyrex glass is especially formulated to expand very little (three times less than ordinary glass) with increasing temperature (ovenware).
- The expansion of substances must be allowed for in structures and devices of all kinds.
  - A dentist uses filling material that has the same rate of expansion as teeth.
  - Blacksmiths used to put red-hot iron rims on wooden wagon wheels, so they would cool and shrink tight.
  - The aluminium pistons of some car engines are made a little bit smaller in diameter than the steel cylinders to allow for the greater expansion rate of aluminium.
  - A civil engineer uses reinforcing steel of the same expansion rate as concrete.
  - Long steel bridges have one end of the bridge fixed, while the other end rides on rockers.
  - The roadway is segmented with tongue-and-groove type gaps called *expansion joints*.
  - Similarly, concrete roadways and sidewalks are intersected by gaps, sometimes filled with tar, so that the concrete can expand freely in summer and contract in winter.
- Different substances expand at different rates.
- This has the consequence that when two strips of different metals, such as brass and iron, are welded or riveted together, the greater expansion of one metal results in a bending. Such a compound thin bar is called a *bimetallic strip*. When the strip is heated, one side of the double strip becomes longer than the other, causing the strip to bend into a curve. When the strip is cooled, it tends to bend in the opposite direction, because the metal that expands more (brass) also shrinks more. The movement of the strip may be used to turn a pointer, regulate a valve, or close a switch:
  - A practical application is the *thermostat*. The back-and-forth bending of the bimetallic coil opens and closes an electric circuit. Refrigerators are equipped with thermostats to prevent them from becoming either too hot or too cold.
  - Coils formed from such strips are used in dial thermometers.
  - Bimetallic strips are used in oven thermometers, electric toasters, automatic chokes on carburettors, and various other devices.

- Liquids expand appreciably with increase in temperature. In most cases the expansion of liquids is greater than the expansion of the (corresponding) solids (a typical metal expands about 7% when its temperature rises from near 0K to its melting point). This has practical consequences:
  - The petrol overflowing a car's tank on a hot day is evidence that the tank and its contents expand at different rates.
  - The expansion of liquid mercury is greater than the expansion of glass. If the expansion of the glass of a thermometer were as great as the expansion of mercury, the mercury would not rise with increasing temperature.
- Below we discuss the thermal expansion of solids and liquids quantitatively. It should be noted in advance that the equations for thermal expansion used here are only approximations.

Anomalous Expansion of Water

- Increase the temperature of any common liquid and it will expand. But not water at temperatures near the freezing point: ice-cold water does just the opposite!
- Water at the temperature of melting ice *contracts* when the temperature is increased, and continues to do so until it reaches a temperature of 4^0C (3.98^0C, to be precise).
- With further increase in temperature, the water then begins to expand, and this continues until the boiling point. This odd behaviour is shown on the accompanying graph.
- A given amount of water has its smallest volume -- and thus its greatest density -- at 4^0C. Just below 0^0C, when water has become solid ice, its volume is considerably larger (and density smaller). Recall that ice floats in water (icebergs), and frozen water pipes burst: both phenomena provide evidence that ice is less dense than ice-cold water.
- After water has turned to ice, further cooling causes it to contract.
- *Why is ice less dense than water*?
  - The crystals of most solids are arranged in a way that the solid state occupies a smaller volume than the liquid state.
  - Ice, however, has an open-structured crystalline structure; the molecules form a hexagonal (six-sided) lattice pattern, which is why snowflakes have hexagonal shapes.
  - This structure results from the angular shape of the water molecules and the fact that the forces binding water molecules together are strongest at certain angles.
  - Water molecules in this open structure occupy a greater volume than they do in the liquid state. Consequently, ice is less dense than water.
- *Why is there this dip in the volume-temperature graph*?
  - The reason is that two types of volume changes take place in ice-cold water.
  - The open-structured crystals that make up the solid ice are present, to a small extent, in ice-cold water -- a 'microscopic slush'. These crystals are buffeted by neighbouring molecules and have short life spans -- some are broken apart while others form. At any moment there are enough of them to alter the density of water. At about 10^0C, all the ice crystals have collapsed.
  - At the same time that crystals are collapsing due to rising temperature, increased molecular motion results in expansion. Whether ice crystals are in the water or not, increased kinetic energy of the molecules increases the volume of the water.
- The collapsing of ice crystals plus the increased molecular motion with increasing temperature, i.e., the combined effects of contraction and expansion, produces the overall effect of water being most dense at 4^0C.
- This behaviour of water is of great importance in nature:
  - Suppose the greatest density of water was at its freezing point and that it shrank upon freezing (as is true of most liquids). Then the coldest water would settle to the bottom, and ponds would freeze from the bottom up. Pond organisms would then be destroyed in winter months, and ice-skating would be less popular. There would also be no oceanic ice caps at the polar regions; rather, there would be a thick layer of ice at the bottom of the ocean, covered by a layer of water.

- Instead, the densest water that settles at the bottom is 4^0C above the freezing point. Water at the freezing point is less dense and 'floats', so ice forms at the surface while the pond remains liquid below the ice. Since ice is a much poorer conductor of heat than water, its very presence slows further ice formation. The sheet of surface ice essentially seals off the lake from the winter cold, allowing life to continue beneath it.

- In more detail:
  - Most of the cooling in a pond takes place at its surface when the surface air is colder than the water. As the surface water is cooled, it becomes denser and sinks to the bottom. Water will 'float' at the surface for further cooling only if it is equally dense as or less dense than the water below.
  - Consider a pond being cooled from an initial temperature of 10^0C. First it has to be cooled through 4^0C. Before any ice can form, all the water must be cooled to 4^0C. Only when this condition is met can the surface water be cooled to 3^0, ..., 0^0C without sinking. Then ice can form.
  - So water at the surface is the first to freeze. Continued cooling results in the pond freezing from the surface downward. In a cold winter the ice will be thicker than in a warm one.
  - Consider the picture of a lake accompanying these notes: As water is cooled, it sinks until the entire pond is 4^0C. Then, as water at the surface is cooled further, it floats on top and can freeze. Once ice is formed, temperatures lower than 4^0C can extend down into the lake.
  - Very deep bodies of water are not ice-covered even in the coldest of winters, because all the water in the lake must be cooled to 4^0C before lower temperatures can be reached, and the winter is not long enough for this. If only some of the water is at 4^0C, it lies on the bottom. Because of water's high specific heat and poor ability to conduct heat, the bottom of deep lakes in cold regions is a constant 4^0C all the year round. Happily for fish!

Molecular Interpretation of Temperature

- Temperature is related to the random motion of the molecules in a substance. More specifically, it is proportional to the average kinetic energy of molecular translational motion (i.e., molecular motion along a straight or curved path).
- It is important to understand that temperature is not a measure of the *total* kinetic energy of molecules in a substance. For example, there is twice as much molecular kinetic energy in 2l of boiling waters as in 1l of boiling water, even though both amounts of water have the same temperature because the *average* kinetic energy per molecule in each is the same.

References

I have made extensive use of the following references for the course material for the lectures, exercise classes and problem sheets.

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