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The physics of temperature

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Definitions

Heat: a measure of the total kinetic energy of a body. Measured in joules (J). It depends on the mass of the body and the specific heat capacity of the body.[1]
Temperature: a measure of the average kinetic energy within a body. It describes the potential for heat energy to move from one body to another down a gradient from an area of high temperature to an area of lower temperature. It is measured using a temperature scale which is defined against fixed physical events such as absolute zero or the triple point of water.[1]
Heat capacity: the amount of heat energy necessary to be added to an entire body to increase the temperature by one degree Kelvin (J/K).[2]
Specific heat capacity: the amount of heat energy necessary to be added to one kilogram of a body to increase the temperature by one degree Kelvin (J/K/kg).[2]
Absolute zero: a hypothetical temperature at which all molecular movement stops (zero kinetic energy). This is not possible in reality.[2]
The ice point: this is the temperature at standard pressure (101.3 kPa) at which water exists in both a solid (ice) and a liquid form. Designated as 0 °C or 32 °F.[1]
The steam point (boiling point): the temperature at standard pressure (101.3 kPa) at which water exists in both a liquid and a vapour form. Designated as 100 °C or 212 °F.[1]
Triple point of water: the temperature at a pressure of 611 Pa (0.006 atm) at which water exists in a solid (ice), liquid and a vapour form. Designated as 0.01 °C.[1]

Keywords: physics of temperature, heat, heat capacity

Temperature scales

Fahrenheit

This is the oldest temperature scale which was developed in 1724 by Daniel Fahrenheit. This scale became popular because it was used in accurate, commercially available mercury thermometers. There are 180-Fahrenheit degrees between the ice point and the boiling point of water.[1,3]

Temperature in Fahrenheit	Physical point
0 °F	The temperature of a mixture of solid water (ice), sodium chloride and ammonium chloride
32 °F	Ice point of water
212 °F	Boiling point of water

Celsius

This scale was developed by Anders Celsius in 1736. It uses the ice point of water as 0 °C and the boiling point of water as 100 °C. It is also referred to as the centigrade scale because there are 100 Celsius degrees between the ice point and the boiling point of water.[1,3]

Kelvin

This was developed by Lord Kelvin about 100 years after the Celsius scale and is the SI unit of measurement of temperature.[1,2]

Temperature in Kelvin	Physical point
0 K	Absolute zero
273.16 K	Triple point of water

Kelvin and Celsius use the same grading intervals, i.e. a degree Kelvin and a degree Celsius are identical in size so that 0 °C–100 °C is equal to 273.15 K–373.15 K.

Fixed point	Celsius (°C)	Fahrenheit (°F)	Kelvin (K)
Absolute zero	-273.15	-459.7	0
Freezing point of water	0	32	273.15
Triple point of water	0.01	32.018	273.16
Average room temperature	20	68	293
Average body temperature	37	98.6	310.15
Boiling point of water	100	212	373.15

Temperature scale conversion

Kelvin to Celsius: K = °C + 273

Celsius to Fahrenheit: °C = (°F – 32) X 5/9

Fahrenheit to Celsius: °F = (°C X 9/5) + 32

Measurement of temperature

All thermometers work by exploiting a thermometric property of a substance. This is a physical change in the substance which correlates with a temperature change of that substance. Thermometers are classified into those that exploit non-electrical and those that exploit electrical thermometric property changes.

Types of thermometers

Non-electrical thermometers	Electrical thermometers
Liquid expansion	Resistance
Gas	Thermistor
Bimetallic strip	Thermocouple
Liquid crystal	
Infrared	

Non-electrical thermometers

Liquid expansion thermometers[1,4]

These comprise a glass reservoir connected to a sealed capillary tube. The reservoir contains either mercury or an alcohol solution. As the temperature changes up or down the liquid expands or contracts within the capillary tube. The fluid level is read off an adjoining calibrated scale. The expansion and contraction of the fluid is linearly related to the temperature change within the range of the thermometer. (Body temperature range in the case of clinical alcohol or mercury thermometers). There is usually a narrowed connection between the reservoir and the capillary tube to slow the return of fluid to the reservoir, allowing a reading to be taken before the fluid drops back after removing the thermometer from the patient. Typically, the thermometer must be shaken to return the fluid to the reservoir.

Advantages:

- Cheap
- Simple to use
- Accurate over the body temperature range
- Reusable
- Does not require an external power source

Disadvantages:

- Slow response time (2–3 mins)
- Cannot be used for core temperature measurement
- Fragile and can easily break, which is especially concerning with mercury thermometers
- May cause cross-infection between patients as it is used in direct patient contact

Gas thermometers[1,4]

Gas thermometers use the principle that the temperature of a gas is directly proportional to the pressure and the volume of the gas as stated in the following gas laws:

Universal Gas Law: PV = nRT

P = pressure (kPa), V = volume (m^3), n = number of moles of the gas, T = temperature (K)

Charles Law: 'At a fixed volume, the pressure of a gas is directly proportional to its absolute temperature.'

Gay-Lussac's Law: 'At a fixed pressure, the volume of a gas is directly proportional to its absolute temperature.'

Gas thermometers either keep the pressure or the volume of the gas constant and the corresponding change in volume or pressure relative to the change in temperature is read from a calibrated gauge.

Examples are:

- The Hydrogen thermometer, where a fixed volume of hydrogen is contained in a syringe type of device, which can change volume with temperature change.
- A Bourdon thermometer, where a fixed volume of gas is kept in a bulb attached to a bourdon coil gauge, which measures the pressure change on a temperature-calibrated scale.

Advantages:

- Robust
- Sensitive
- Accurate over a wide temperature range (can measure up to 600 °C)

Disadvantages:

- Bulky
- Slow response time

Bimetallic strip thermometers[1,4]

Different metals expand and contract to different extents at the same temperature. By binding two dissimilar metal strips together, differential expansion or contraction of the two metals will cause the combined strip to twist relative to the temperature change. Brass and Invar (a combination of nickel and iron) are often used for the two strips. Bimetallic strips are used as thermostatic switches in the temperature compensation mechanism of vaporisers or in thermometers. When used in a thermometer, the strip is usually coiled. One end of the coil is fixed and the other end is attached to a pointer. As the temperature change causes movement of the coil, the pointer moves across a calibrated temperature scale.

Advantages:

- Robust
- Cheap
- Can operate up to 600 °C

Disadvantages:

- Slow response time
- Not very accurate and requires frequent calibration

Liquid crystal thermometers[1,4]

Liquid crystals are substances which have a regular layered crystalline molecular structure, similar to solids, but which still flow like liquids. The wavelength of light reflected from a liquid crystal changes as the temperature of the crystal changes. This wavelength change presents as a change in crystal colour. Liquid crystals can be built into a plastic strip, which forms a surface contact thermometer when placed on an object such as a patient's forehead. The temperature reading corresponds to the colour of the thermometer strip. The usual temperature range measured in this application is 35 °C to 40 °C.

Advantages:

- Cheap
- Easy to use
- Disposable therefore less risk of cross-infection between patients

Disadvantages:

- Slow response time (15–20 seconds)
- Not very accurate (variance may be up to 1 °C)

Infrared thermometers[1,4]

All objects emit infrared radiation. The amplitude and the frequency of the emitted infrared waves change relative to the temperature of the emitting object. Infrared thermometers register the emitted radiation via a pyroelectric ceramic crystal or via a thermopile, which converts the infrared signal to an electrical impulse. The generated impulse size is related to the temperature of the radiation emitting body. Infrared thermometers are typically used in tympanic membrane thermometers. Measuring the tympanic membrane temperature gives a very close approximation of body core temperature.

Advantages:

- Rapid response time
- Accurate when used correctly

Disadvantages:

- Not accurate if the path between the measured object and the thermometer is blocked, as happens, for example, with an earwax build-up.

Electrical thermometers

Resistance thermometers[1,5]

When a metal is heated or cooled, the kinetic energy and the resultant molecular movement within the metal changes. This change in molecular movement influences the electrical resistance to a current passed through the metal in a predictable fashion. Using Ohm's law (V = IR), if a fixed voltage is maintained across a metal, then the measured current will be inversely proportional to the resistance. This calculated resistance can then be converted to a temperature reading. A Wheatstone bridge and a galvanometer are used to measure the resistance change. Platinum is often used as the measuring metal because it has a characteristically linear relationship between temperature and resistance over a wide temperature range (15 K–900 K).

Advantages:

- Accurate over a wide temperature range
- Able to measure small temperature changes (as small as 10^{-3} K or 0.0001 °C)

Disadvantages:

- Slow response time
- Bulky
- Metal may corrode over time
- Less sensitive than thermistor thermometers

Thermistors[1,5]

Thermistors are temperature sensitive resistance devices, which use a semiconductor metal oxide rather than an inert metal such as platinum. The material used is typically an oxide of a metal such as manganese, copper, nickel, iron or titanium. Unlike a metal thermal resistor such as platinum, which has a linear temperature to resistance relationship, a metal oxide thermistor has an exponential temperature to resistance relationship (usually a negative temperature relationship where the resistance increases as the metal oxide temperature decreases). Thermistors also use a Wheatstone bridge and a galvanometer to measure the resistance change. Thermistors are usually very small and can be used on catheter tips and at the end of nasogastric probes.

Advantages:

- Usually very robust so can be steam sterilised for reuse
- Rapid response time
- Very sensitive and accurate
- Often very small in size

Disadvantages:

- A calibration equation is required within the processor due to the non-linear temperature-resistance relationship of semiconductors. This is often overcome by choosing a semiconductor with an almost linear resistance to temperature relationship within the measured temperature range.
- Accuracy may drift as the resistance of the semiconductor changes over time.

Thermocouples[1,5]

The kinetic energy of different metals varies at the same temperature. When two dissimilar metals are placed in contact with each other, the difference in kinetic energy between them causes an electrical current to be established. This phenomenon is known as the Seebeck effect. The electrical potential difference created between the two metals can be measured. This value can then be converted to a corresponding temperature reading. Depending on which metals are chosen for the thermocouple thermometer, temperatures ranging from minus 200 °C up to plus 2 000 °C can be measured. These thermometers are typically used in the food industry and for hospital autoclaves.

Advantages:

- Rapid response time
- Cheap
- Small in size

Disadvantages:

- Not accurate enough for the clinical setting
- Contains complicated electronic components

Heat transfer and loss

Patient heat loss is a serious problem in theatre. Heat transfer occurs by four mechanisms: radiation, convection, conduction and evaporation.

Radiation: electromagnetic heat transfer from a body to the surrounding environment.[1]

Convection: as the air around a body is heated, it rises and moves away, being replaced by cooler air and ongoing heat loss.[2]

Conduction: direct transfer of heat from one body to the other,[2] e.g. from patient to theatre table.

Evaporation: liquid on the surface of a body is heated and is then converted to water vapour. Heat is lost as the liquid evaporates.[2]

Heat transfer mechanism	% patient heat loss caused in theatre
Radiation	40%
Convection	30%
Conduction	5%
Evaporation	15%

Respiratory heat loss: this accounts for about 10% of patient heat loss and is a combination of the above four heat transfer methods.[2]

Conflict of interest

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