Physical principles of heat transfer

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Thermodynamic temperature is one of seven base quantities in physics. A physical property of a system that does not depend on the system size or the amount of material in the system, is called intensive. The base quantity temperature is an intensive quantity of heat energy and represents the mean kinetic energy of atoms or molecules in a substance.

Energy can be defined as the ability to do work and is expressed by the same equation as work. It exists in many forms, such as mechanical, electrical, nuclear, and thermal. Transformation of one form of energy into another is possible, for example a thermally powered generating station can produce electricity. The transformation of all other forms of energy into heat can be total, but the contrary, i.e., the transformation of heat into one of the other forms, is never 100 percent efficient. Heat thus appears to be a special form of energy. The SI unit of energy is the Joule. For thermal energy, 1 Joule is the energy dissipated as heat when an electric current of one ampere passes through a resistance of one ohm for one second. In relation to temperature, 1 Joule is expressed as the 1/4.184 part of heat energy required to raise the temperature of a unit weight (1 g) of water from 0oC to 1oC. 4.184 Joules are equal to the traditional unit of 1 calorie [1].

In any closed system with an outer membrane (diathermal wall) permissive to energetic, but not to material exchange, energy is transferred from the high level to the low level. Thermal energy can be transferred without or with change of state of matter. Heat transfer without change of state can occur by either conduction, convection, or radiation. During heat exchange, the temperature at the high level of thermal energy falls, whilst the temperature at the low-level rises, until equilibration is achieved. [1].

In heat transfer with change of state, the temperature of the phase changing matter is constant. Since change of the state either requires or releases thermal energy, the system in which the phase change occurs gains or loses heat. Changing liquid water into vapour requires thermal energy. In a condition in which a thin film of water is evaporating from a surface, the temperature of the surface is decreasing. [1].

The minimal thermodynamic temperature is absolute zero, where the thermal motion of all fundamental particles in matter reaches a minimum. Temperature can be expressed in several scales. The International System of Units (SI) scale is the Kelvin (K), which has as its null point absolute zero, and is defined as the fraction (1?273.16) of the thermodynamic temperature of the triple point of water. The triple point of a substance is described by the temperature and pressure at which the three phases (gas, liquid, and solid) of that substance coexist in thermodynamic equilibrium. Other commonly used scales are the Celsius scale (°C), informally known as degrees centigrade and originally defined by the freezing (0°C) and boiling (100°C) points of water at a pressure of 1 atmosphere, and the Fahrenheit scale (°F), in which the null point is defined as the temperature of a solution of brine made from equal parts of ice, water and salt, and there are 180°F of separation between the freezing and boiling points of water [2-5].

In conduction, thermal energy is transmitted through a medium from one particle to another, requiring direct contact. With convection, it is transferred by fluid motion (gas or liquid), which may be caused by density differences (natural) or external mechanical forces (forced). Radiation transmits thermal energy through electromagnetic waves, the movement of heat of the charged particles inside the atoms is converted into electromagnetic radiation [3-5].

The electromagnetic spectrum describes the range of frequencies (the spectrum) of the electromagnetic radiation and their respective wavelengths and photon energies, and it can be used to characterise existing bodies and materials. This frequency range is divided into separate bands called by different names. It begins at the low frequency (long wavelength) end of the spectrum: radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and ends with gamma rays at the high-frequency region (short wavelength). The spectral range from gamma rays to high ultraviolet are classified as ionizing radiation, since their photons have enough energy to ionize atoms, causing chemical reactions which are harmful for humans. The infrared spectrum is located at the left of the visible region, ranging from 0.7 μm to 1000 μm in wavelength, and it is divided into three parts: near-infrared, medium-infrared and far-infrared [2-6].

Infrared radiation is invisible to the human eye, lower in energy than visible red light, and is naturally emitted by any object with a temperature above absolute zero. Blackbody radiation is thermal electromagnetic radiation within or surrounding a body in thermodynamic equilibrium with its environment, or emitted by a blackbody (an idealized object which absorbs all radiation falling on it at all wavelengths). It has a specific spectrum and intensity that depends only on the body's temperature, which is assumed to be uniform and constant [2-10]. The physics of radiation follow the laws of optics and thermodynamics including absorption, diffraction, emission, reflection, refraction, scattering and transmission. For measurements of infrared radiation in medicine and related health, it is recommended to acquire only emitted radiation [7, 8].

Emissivity is the ratio between the radiant emittance produced by an object to that of a blackbody at a specific temperature, being dependent of its surface fine structure. This factor affects the accuracy of a remote temperature measurement. Its value can vary between 0 and 1, with 1 being the emissivity value of a blackbody [2]. The value of the emissivity of human skin is 0.98 [11].

The thermal radiation emitted across all wavelengths by a blackbody (ideal emitter) at any temperature can be calculated by Planck's law. Planck's law expresses the spectral radiance as a function of wavelength and temperature of the blackbody. The dominant frequency interval increases proportionally with the temperature. The rate of electromagnetic radiation emitted at a given frequency is proportional to the total value absorbed by the body at the same frequency. Wien's displacement law describes the relationship between the spectrum of blackbody radiation at any two temperatures. The emission of radiation of a blackbody has a spectral distribution that depends only on temperature, and the wavelength at which maximal radiation is emitted is inversely proportional to the temperature of the blackbody. According to the Stefan-Boltzmann law, the total amount of radiation, across all frequencies increases with the fourth power of the temperature, and it is with modified versions of this law that an infrared camera can determine the temperature from a perceived radiation source, comparing with an internal calibration source [1-12].

Consequences for temperature measurements in medicine

To promote thermal equilibrium between the body and the surrounding environment there are environmental factors that must be considered such as the environment temperature and the relative humidity, and the period of acclimatization to this before performing temperature recordings [12]. The dew point is a given temperature at which air containing a specific amount of water becomes saturated (condensation). Given a constant dew point in the air, if the ambient temperature rises, relative humidity falls and vice-versa. Other factors such as air flow, incident lighting and examination room size, have also to be considered.

Equipment available to assess temperature can be chemical, electrical or mechanical in operation. Examples of mechanical devices are: mercury in glass thermometers, bimetallic thermometers and pressure spring thermometers; chemical instruments include: liquid crystal sheets; and electrical examples are: thermocouples, resistance temperature detectors, infrared pyrometers and infrared cameras. Only the last two examples allow remote temperature recording, and both are based on the principle of infrared radiation [13].

The main characteristics of an infrared camera are the type of detector (which can be cooled or uncooled), the wavelength (which normally is medium or long wavelength), the focal plane array sensor size, the noise-equivalent temperature difference and the measurement uncertainty. When performing an examination with an infrared camera it is important to know the time required to stabilize the electronics, the image uniformity and the image focus. Appropriate camera settings such as emissivity, environmental temperature, relative humidity, distance to the target and temperature range are also recommended [12, 14-16].

The infrared sensors of a camera perceive an incident thermal radiation, which is then transformed into a voltage and, depending on the thermal resolution (bits), it is then coded into a radiometric value that is recorded into the camera proprietary file format. This, along with other parameters such as the emissivity and reflected temperature, along with the Planck constants, allows through the altered Stefan-Boltzmann law the calculation of a temperature value in Kelvin, and by the translation formula to degrees Celsius [6].

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