Fundamentals of Physics in Engineering I

Unit 4.- HEAT AND TEMPERATURE

• Introduction

Temperature is often said to be a measure of the degree of hotness or coldness of a body, but this definition is not valid from the point of view of physics. When a body heats up or cools down, some of its physical properties change. For example, most solids and liquids dilate when heated, when an electrical conductor is heated its resistance varies, etc. A physical property that varies with temperature is called a *thermometric property* and a change in this property indicates that the *temperature* of the object has changed.

• Thermal equilibrium and zeroth law of thermodynamics

Two systems in contact are in *thermal equilibrium* when their properties no longer change with time. For two systems to be in contact they must be separated by a *diathermal wall* that facilitates their thermal interaction. An *adiabatic wall* does not allow such interaction: each system is isolated from the other and each may remain in its equilibrium state. The *zeroth law of thermodynamics* states that if two systems are in thermal equilibrium with a third system, they are also in thermal equilibrium with each other. The concept of temperature is related to the state of thermal equilibrium of two systems since they will be in thermal equilibrium if they have the same temperature.

• Thermometers and ideal gas temperature scale

In order to establish a temperature scale a thermometric property is used. Gas thermometers are characterized by the fact that they all register the same temperature provided that the density of the gas used in the thermometer is very low. The temperature of an ideal gas is defined using a limit with real gases diluted in a *constant volume gas thermometer*. The temperature scale is adjusted taking a temperature of 273.16 K as the triple point of water. In this state, the melting point, boiling point and sublimation point coincide and it occurs at a vapour pressure of 610 Pa and temperature of 0.01°C. The ideal gas temperature is defined as:

$$T = 273.16\,K\,\frac{p}{p_3}$$

where p is the pressure of the gas in the thermometer when it is in thermal equilibrium with the system whose temperature is to be measured, and p_3 is the pressure when the thermometer is in a ice-water-steam bath at its triple point.

• Ideal gas law

The ideal gas equation is:

$$pV = nRT$$

where p is the pressure, V the volume, n the number of moles, T the absolute temperature and R the ideal gas constant, whose numerical value depends on the units of the other physical magnitudes in the equation. In SI units, p is in Pa, V in m^3, n in moles and T in K:

$$R = 8.31 \text{ J mol}^{-1}\text{ K}^{-1}$$

If p is expressed in atmospheres (atm) and V in litres (l)

$$R = 0.082 \text{ l atm mol}^{-1}\text{ K}^{-1}$$

• Thermal dilation

Most substances expand or dilate when their temperature rises and contract when it falls.
(i) *Linear dilatation lineal:* The change ΔL in length L_0 of an object due to a change in temperature ΔT is:

$$\Delta L = \alpha L_0 \Delta T$$

where α is the coefficient of linear dilatation of the substance.

(ii) *Surface dilatation:* The change ΔS in the surface S_0 of an object due to a change in temperature ΔT is given by:

$$\Delta S = \gamma S_0 \Delta T$$

where $\gamma$is the coefficient of surface dilatation of the substance. For an isotropic substance $\gamma = 2\alpha$.

(iii) *Cubic dilatation:* The change ΔV in volume V_0 of an object due to a change in temperature ΔT is given by:

$$\Delta V = \beta V_0 \Delta T$$

where β is the coefficient of cubic dilatation or volume expansion. In the case of an isotropic substance, $\beta = 3\alpha$. Water exhibits an anomalous thermal expansion between 0° and 4°C, since it contracts when the temperature rises.

• Quantity of heat: heat capacity and specific heat

When a cold spoon is put into a cup of hot coffee, the spoon heats up and the coffee cools down in order to approach thermal equilibrium. These changes in temperature are basically caused by a transfer of energy from one substance to the other. The transfer of energy that occurs solely due to a difference in temperature is called *heat flow or heat transfer*, and the energy transferred is called *heat.* The symbol Q is used to denote the quantity of heat.
A **calorie** is the quantity of heat necessary to raise the temperature of 1 g of water from 14.5ºC to 15.5ºC. The relation between a joule and a calorie is: 1 cal = 4.186 J.
The quantity of heat dQ supplied to a system of mass m and the change in temperature produced dT are related by the *specific heat c* which depends on the material:

$$dQ = mc\,dT \qquad c = \frac{1}{m}\frac{dQ}{dT}$$

The quantity of heat Q needed to raise the temperature of a mass m of a material from T_1 to T_2 éis approximately proportional to the change in temperature $\Delta T = T_2 - T_1$ and mass m of the material

$$Q = mc\Delta T$$

If the number of moles n is known we can refer to the *molar heat capacity C*:

$$dQ = nC\,dT \qquad C = \frac{1}{n}\frac{dQ}{dT}$$

where $n = m/M$, and M is the molecular mass. We can write:

$$Q = nC\Delta T$$

In the case of solids, we normally work with specific heat and molar heat capacity at constant pressure (c_p and C_p), whereas with gases, constant volume (c_V and C_V).

• Calorimetry, phase changes and latent heat

The heat necessary to melt a solid substance is given by:

$$Q_f = mL_f$$

where L_f is the *latent heat of fusion*. For water at atmospheric pressure L_f = 333.5 kJ/kg = 80 cal/g. The heat necessary to vaporize a liquid is given by:

$$Q_v = mL_v$$

where L_v is the *latent heat of vaporization*. For water at atmospheric pressure L_f = 2257 kJ/kg = 540 cal/g. Under the same conditions, each phase change occurs at a certain temperature, and while a phase change is taking place the temperature of the system remains constant.

• Propagation of heat by conduction

The heat Q is the energy transferred between a system and its surroundings due solely to a difference in temperature between the system and a part of its surroundings. The heat flow continues until the temperatures are the same. When heat is propagated due to conduction, it is transmitted between two systems by direct contact. If the means separating the systems, whose temperatures are T_1 and T_2, has a length L and section S, in the stationary state (T no longer changes with time) the heat that passes through a transversal section per unit of time (thermal current, $H = Q/t$) is given by:

$$H = kS\frac{T_2 - T_1}{L}$$

where k is the *thermal conductivity* of the medium. The *thermal resistance of the medium*, R, is given by:

$$R = \frac{L}{kS}$$

and $H = \Delta T/R$. For a compound wall in the stationary state, its equivalent thermal resistance is the sum of the thermal resistances of the wall components if they have the same surface area.

The thermal current H in the case of non-stationary conditions and diverse geometries is given by.

$$H = -kS\frac{dT}{dx}$$

which is known as Fourier's law. dT/dx is the temperature gradient and H is the instantaneous heat current through an element of area S. The negative sign indicates that the heat flows from high to low temperatures.

• Propagation of heat by convection and radiation

When heat is propagated by *convection,* heat is transferred from one place to another by movement of heated material giving rise to macroscopic convection currents, which may appear in liquids in a gravitational field whose density varies with temperature (natural convection). Convection may also be forced using ventilators.

When heat is transferred by *radiation*, the power P radiated by a surface is given by Stefan-Boltzmann's law:

$$P = e\sigma ST^4$$

where e is the emissivity and $\sigma = 5.67 \times 10^{-8}$ $Wm^{-2}K^{-4}$ is the Stefan-Boltzmann constant. All objects emit energy from their surfaces when they are hot and thermal radiation is a type of electromagnetic radiation.

In all types of heat propagation, if the temperature difference between the body and its surroundings is small, the body's rate of cooling is approximately proportional to the temperature difference (*Newton's law of cooling*).