mainly a matter of transmission of light. Other foods are opaque and derive their colour mostly from reflection. Optical properties can be used to perform quality control and continuous inspection during processing operations. Major requirements for a quality control system are ease of calibration and use, stability, precision, speed, cheapness, and industry-wide applicability. A complete colour description requires the use of three dimensions, and a control automatic system may be based on this complete specification. Specifications may be set to provide an idea of fruit ripeness, milk or cream discolouration during sterilisation, degree of roasting of coffee grains, or browning of apples slices during storage. Continuous colour measurements are used in tasks involving colour sorting (or electronic sorting) by using in-line systems.

Colour sorting is used for a very wide range of food materials in screening defects. Visible, infrared, and ultraviolet laser beams can provide continuous inspection through scanning of product size, symmetry, damage, irregular shape, fill level, and label placement by adding automatic software in connection with mechanical devices. For example, during conveying of pre-fried potato chips, optical devices detect any with defects (for example, black spots), and automatically deploy an air nozzle to deflect their path from the conveyor belt.

ELECTRICAL PROPERTIES

There are two main electrical properties in food engineering: electrical conductivity and electrical permittivity. Electrical properties are important when processing foods involving electric fields, electric current conduction, or heating through electromagnetic waves. These properties are also useful in the detection of processing conditions or the quality of foods.

Electrical Conductivity and Permittivity

Electrical conductivity is a measure of how well electric current flows through a food of unit cross-sectional area A, unit length L, and resistance R. It is the inverse value of electrical resistivity (measure of resistance to electric flow) and is expressed in SI units S/m in the following relation:

$$\sigma = L/(AR)$$

Electrical permittivity is a dielectric property used to explain interactions of foods with electric fields. It determines the interaction of electromagnetic waves with matter and defines the charge density under an electric field. In solids, liquid, and gases the permittivity depends on two values:

- The dielectric constant ε', related to the capacitance of a substance and its ability to store electrical energy.
- The dielectric loss factor ε'', related to energy losses when the food is subjected to an alternating electrical field (i.e. dielectric relaxation and ionic conduction).

The electrical conductivity of foods has been found to increase with temperature (linearly), and with water and ionic content. Mathematical relationships have been developed to predict the electrical conductivity of food materials: for example, for modelling heating rates through electrical conductivity measurements, or for probability distribution of conductivity through liquid-particle mixtures. Electrical conductivity shows different behaviours during ohmic and conventional heating. At freezing temperatures, electrical conductivity increases with temperature, as ice conducts less well than water. Starch transitions and cell structural changes affect electrical conductivity, and fat content decreases conductivity. As in thermal properties, the porosity of the food plays an important role in the conduction of electrons through the food.

materials, compression functions depend on the type of cell wall collapse occurring, which can be brittle or plastic (as in gels). Techniques that quantify the ruggedness of products such as fractal analysis are used to estimate the surface areas of these shapes. Fractals, in combination with micro-structural studies, can predict the efficiency of the transformation process and food particle properties (such as solubility, puffing ability, emulsifying ability) used to optimise food ingredient selection for product development.

Mechanical properties in food microstructure are explained by understanding the main mechanisms leading to structure formation, which can be studied using the most appropriate microscopy techniques and supported by other experimental data. Surface structure microscopy can enhance the characterisation of the strength properties through traditional qualitative methods such as transmission light microscopy, scanning electron microscopy, and transmission electron microscopy. Furthermore, the kinetics of structural changes can be inferred from rheological or mechanical responses. Mathematical models should be derived based on available structural data and previous findings, which allow predictions of properties for any changes in structure (for example, that induced by change in formulation).

Through structural microscopy studies, texture properties can predict deformation mechanisms after stress application, effects of heating in baked products, thawing or freezing mechanisms in meats, or changes in the hardness of fleshy fruit tissues during ripening. Controlled destruction of biological materials, such as by pressing or reducing particle size, is needed to release valuable components, microstructural characteristics often dictate the type of breakdown of the material. During roller pressing or milling of fruit pulps or powder cakes, microstructural studies define the rotating directions or speeds of metal rollers in order to obtain the desired product in optimal conditions (for example, faster extraction rates from broken and damaged surface cells). Many foods like meats or vegetables have cellular or fibrous structures that determine mechanical properties. Biochemical microstructural changes in meats (for example, during rigor mortis and cooling) can be monitored by following the stress of a slightly stretched sample. Strain hardening of flesh can also be traced to combined microstructural and molecular changes.

During extrusion, macro- and microstructures are formed by diverse frictional and other mechanisms involving heat release or application. Microscopy, gel permeation, chromatography, and viscosity measurements have demonstrated fragmentation of the starch granule during extrusion as a result of shear at the subcellular level. Distinctive desirable textures controlled by die design and extruder operating conditions can be assured from studies that combine mechanical strength properties and microstructural characterisation. Understanding the nonlinear interactions between the levels becomes essential to controlling the texture of food.

In rheology, deviations from ideal Newtonian behaviour in complex fluids can be traced back by defining the role of macromolecules or particles and their interactions through structural modelling of flow conditions over time. Viscosity will depend on solid-like networks, shear-induced deformation, and transient superstructures at different shear rates. Microscopic image analysis tools can be adapted to represent different shear and normal stresses to express flow at different points of a fluid. Nondestructive methods such as dynamic oscillatory rheometry or mechanical spectroscopy are particularly suitable for this purpose.

Powder flowability is determined by particle deformability and surface roughness (or friction). Flow properties in powders can also be monitored with microstructural surface characterisation techniques. Surface topography is also important in determining friction in sliding conveyors and between particles, or attrition in the breakdown of powders. Attrition mechanisms of food powders have been assessed through the detection of crack propagation paths detected by scanning electron microscopy.

This brings the heater temperature to the set point level. The temperature range, over which the voltage is adjusted from 0 per cent to 100 per cent, is called the proportional band. This is normally expressed as a percentage of the operating range of the system and the set point is centered at 50 per cent. In a proportional controller with a working span of 100°C, a 10 per cent proportional band would be 10°C and the highest and lowest ranges of the band are 5°C away from the set point level. The transfer characteristic of a proportional controller is shown in Fig. 3.8. The figure illustrates that below 100°C, which is the lowest range of the proportional band, the heater power should be 100 per cent.

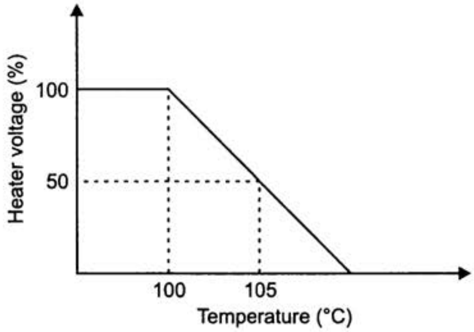

Fig. 3.8: Transfer characteristic of a proportional controller.

On the other hand, above the highest range of the proportional band (i.e. 110°C), the heater voltage should be zero. The voltage to be applied to the heater therefore can be determined from the characteristic graphically. The heater voltage is fixed at 50 per cent at the set point level. There is every possibility that the proportional band might need to be adjusted as per the requirement of the process response and characteristics. Hence the proportional controller can have a wide band or narrow band of control. The transfer characteristics of wide band and narrow band proportional controllers are shown in Fig. 3.9.

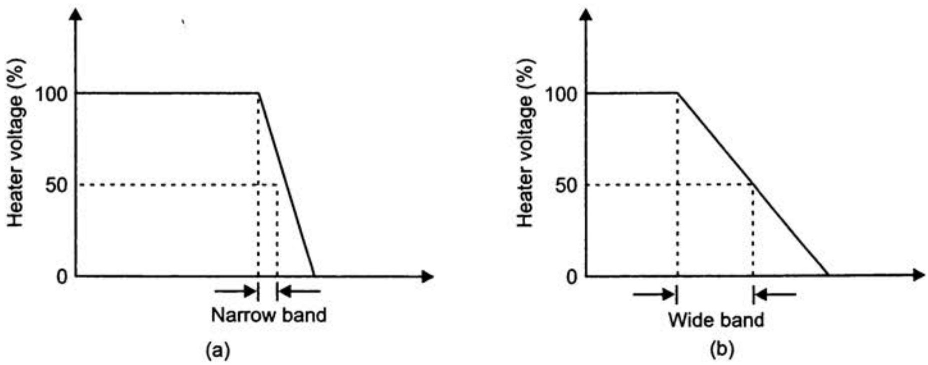

Fig. 3.9: Transfer characteristic of (a) a narrow band and (b) a wide band proportional controller.

In a narrow band proportional controller, a small change in temperature causes a large manipulated output. The performance of a proportional controller can be expressed in terms of the controller gain as

$$\text{Gain} = 100\%/\text{proportional band (per cent)}$$

Finally, considering Fourier's law (4.3) and constant material properties (density ρ, thermal capacity c, conductivity k, and their combination, the thermal diffusivity:

$$a \equiv \frac{k}{\rho c} \qquad \text{...(4.6}$$

one gets the so-called heat equation:

$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \phi, \text{ or } \frac{\partial T}{\partial t} = a\nabla^2 T + \frac{\phi}{\rho c} \qquad \text{...(4.7)}$$

The heat equation (4.7) is the most well-known parabolic partial-differential equation (PDE) in theoretical physics, ϕ being a non-homogeneous term. The heat equation is also known as diffusion equation, and it has solutions that evolve exponentially with time to the steady state. At steady state, the heat equation becomes an elliptic PDE named Poison's equation, which, without the non-homogeneous term, becomes Laplace equation, $\nabla^2 T = 0$. Besides parabolic and elliptic PDE, the third type is the hyperbolic PDE $\partial^2\Psi/\partial t^2 - c^2\partial^2\Psi/\partial x^2 = 0$, typical of wave-like phenomena.

A more general heat equation takes account also of the effect of relative motion between the material system and the coordinate system with a velocity $\vec{v}$, which, in a fix reference frame (Eulerian reference frame) takes the form:

$$\frac{\partial T}{\partial t} = a\nabla^2 T + \frac{\phi}{\rho c} - \nabla \cdot (\overline{T\vec{v}}) \qquad \text{...(4.8)}$$

although we will only consider such motions when analysing moving heat sources in a stationary solid (to change to a reference frame moving with the source), of application to machining, grinding, cutting, sliding, welding, heat treatment, and so many materials processing. The most general heat equation (e.g. to be used in computational fluid dynamics (CFD), must include in the energy release term ϕ, viscous dissipation and the dilatation work due to the time-variation of pressure along a fluid line, if any, although both are usually negligible energy contributions. To solve the heat equation, besides the parameters explicitly appearing in it (a, ϕ, ρ, c...), appropriate bounding conditions for the variables are required, i.e. initial conditions for time and boundary conditions for the space variables.

Modelling Space, Time and Equations

Space-time modelling may refer to the consideration of continuous or discrete processes in space and time, but space-time modelling in heat transfer usually refers to the consideration of processes as steady or nonsteady, zero-dimensional, one-dimensional, two-dimensional or three-dimensional geometry, planar, cylindrical or spherical, etc. So important this modellisation is, that heat transfer books, and in particular the heat conduction part, is usually divided in different chapters for the different space-time models: steady onedimensional conduction, unsteady one-dimensional conduction, steady two-dimensional conduction, etc.

As in many other engineering problems, the steady state solution is usually analysed first, in heat-transfer problems, leaving transient effects for a more advanced phase, but many undesirable events may occur during transients. Here in this context, thermal shock (e.g. breaking a glass by pouring hot water) and local overheating (e.g. charring shoes and cloth before getting warm), can be mentioned.

Every step in problem-solving may have an associated mathematical modelling, from geometrical definition and materials properties, to results and conclusions. We want now to consider the main