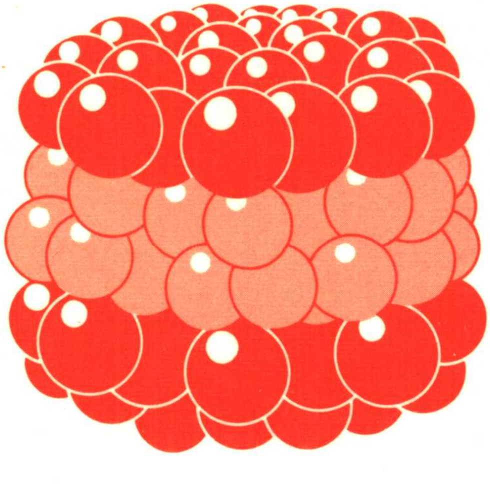
HEAT TRANSFER & Food Products



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Preface

Heat transfer problems in chemical engineering are treated in several books, and these problems are also well covered at different levels of understanding. For homogeneous materials the theories are general for heat transfer within solids and liquids as well as between a solid surface and a liquid. There are few problems in applying theoretical models, especially with modern calculating facilities. However, non-homogeneous materials, to which most food products belong, often present problems and the literature covering this field is much more sparse.

In the heat treatment of foodstuffs the product properties play an important role. The first problem is that these materials are normally non-homogeneous. Second, the physical properties may vary remarkably not only with origin but also due to previous treatment. Moreover, variations often take place also during heating or cooling. Thus the major problem in food process engineering theories and calculations relates to the physical, or engineering, properties. Normally for these complex materials we do not have enough knowledge to be able to describe them qualitatively and quantitatively well enough to predict how they vary with origin, pretreatment and during processing.

It is our hope that this book will fill a gap. Food process engineering is, in our opinion, chemical engineering adapted to the treatment of food materials. In a similar way, this book attempts to apply basic and general knowledge of heat transfer to the treatment of food products.

From the start the aim has been to write an advanced book, i.e. it is intended for use by qualified engineers and technologists as well as for university teaching. Hopefully it is theoretical enough for the latter purpose and at the same time practical enough to provide those working in industry with valuable information.

The first chapter considers the physical properties of food materials. As the purpose here is to use them for engineering calculations, special emphasis has been focused on their mathematical description.

The second chapter outlines the basic concepts of heat transfer. It describes heat transfer both as a molecular motion phenomenon and as a transfer phenomenon. To improve understanding, a descriptive presentation accompanies the mathematical presentation. It treats conductive, convective, radiative and microwave heat transfer and concludes with numerical methods applicable to solving the differential equations describing the transfer process.

The two subsequent chapters are also devoted to heat transfer, but in connection with different applications. Thus, Chapter 3 is on heat transfer and solid foods, where the theoretical basis for unit operations such as baking, frying, canning, freezing, etc. is given. It is divided into sections, one on heat transfer to the product and one within the product. Chapter 4, on heat transfer and liquid foods, is restricted to heat transfer, both conductive and convective, within the product and to a suspended solid phase. As the thermal treatment is very much influenced by the flow conditions in the equipment, a special presentation is made here of relevant flow models to be combined with heat exchanger performance calculations.

In Chapter 5, processing equipment is presented. It covers equipment for the heating of liquid and solid foods, as well as for the freezing and thawing of foods. It incorporates theories applied to industrial processes and equipment as well as practical aspects of the equipment in order to compare and evaluate them.

Optimization itself is of such importance that a separate chapter has been devoted to it. Methodologies as well as examples are given to demonstrate how an optimization is carried out.

We are grateful to Magnus Dagerskog and Thomas Ohlsson for their help in the preparation of the parts treating infrared and dielectric heating. Helen Sheppard made the necessary linguistic check.

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Notation

a	thermal diffusivity m^2/s
a_w	water activity
A	area m^2
A	van Driest damping coefficient
b	Wien displacement constant K m
b	width m
B	coefficient
c	concentration
c_w	water concentration
$c_p c_v$	specific heat capacity J/kg K
C	coefficient
C	cook value at 100°C min
d	diameter m
D	mass diffusivity m^2/s
D	differential operator
D	dispersion m^2/s
D	decimal reduction time min
E	spectral density function (frequency function)
E	electric field strength V/m
E_a	activation energy J/mol
E	shift operator
f	momentum source m/s
f	weighting factor for implicit difference schemes
f	friction factor
F	probability function
F	lethal effect at 121·1°C min
g	gravity acceleration m/s^2
h	specific enthalpy J/kg
h	Planck constant J s

h	height m
J	integral operator
k	circular wavenumber 1/m
k	total heat transfer coefficient W/m²K
k	reaction rate coefficient 1/s
k	turbulent kinetic energy J/kg
ℓ	characteristic length m
ℓ	mixing length m
l	length m
l	specific latent heat J/kg
l_s	specific latent heat of melting J/kg
L	integral length scale m
$\dot{m}$	mass flux kg/m²s
M	mass kg
MW	molecular weight
$\dot{M}$	mass flow rate kg/s
n	number of free electrons
n	rheological parameter for power law and Ellis fluids
n	reaction order
N	Avogadro number
N	number of organisms
N	number of screw
$\dot{N}$	revolutions per second, rotation speed 1/s
p	partial pressure Pa
P	total pressure Pa
Po	power W
$\dot{q}$	energy flux J/m²s
$\dot{q}_v$	volumetric mass flux m/s
$\dot{Q}$	energy flow rate J/s
r	mass source or sink (reaction rate) 1/s
r	radial coordinate m
r	specific latent heat of vaporization J/kg
R	correlation coefficient
R	radius m
R	electrical resistance Ω
R	gas constant J/mol K
s	thickness of layer m
S	signal value
S	energy source term K/s
t	time s

T	temperature °C, K
u	velocity (in x direction) m/s
U	time mean value of u m/s
u_w^*	$=\sqrt{\tau_w/\rho}$ friction velocity
v	velocity (in y direction) m/s
V	volume m^3
w	velocity (in z direction) m/s
x	cartesian rectangular coordinate m
y	cartesian rectangular coordinate m
y^+	$=yu_w^*\rho/\eta$ dimensionless distance from a solid wall
Y	relaxation modulus Pa
z	cartesian rectangular coordinate m
Z	required increase in temperature to reduce the D-value one order of magnitude °C
α	surface heat transfer coefficient W/m^2K
α_s	radiant scattering coefficient 1/m
α_a	radiant absorption coefficient 1/m
β	surface mass transfer coefficient m/s^2
γ	shear strain 1/s
γ_c	cubic expansion coefficient 1/K
Γ	diffusivity m^2/s
δ	thickness m
δ	differential operator
δ	loss angle
Δ	difference, differential operator
ε	turbulence energy dissipation rate J/s kg
ε	emissivity
ε'	relative dielectric constant
ε''	loss factor
ζ	vorticity 1/s
η	dynamic viscosity Pa s
η	tortuosity factor
θ	scalar quantity like T, c, u, ζ
θ	angle between z-axes and r_0 rad
Θ	time mean value of θ
κ	Stokes–Einstein coefficient
κ	von Karman constant
λ	wavelength m
λ	microscale m

λ	thermal conductivity W/mK
λ	boundary layer coefficient
Λ	mean free path of gas molecules
ν	frequency Hz(1/s)
ρ	density kg/m^3
σ	Stefan–Boltzmann constant
σ	surface tension N/m
σ	electric conductivity S/m
τ	shear stress Pa
τ_w	$= -(\partial P/\partial x)d = f\rho u^2/8$ wall shear stress Pa
ϕ	angle between x-axis and projection of r on the x–y plane rad
ϕ	normalized probability function
ψ	porosity
Ψ	stream function m^2/s
ω	angular frequency rad/s

Dimensionless ratios

$$\mathrm{Bi} = \frac{\alpha d}{\lambda}$$

$$\mathrm{Bi}_{\mathrm{mass}} = \frac{\beta d}{D}$$

$$\mathrm{Fo} = \frac{\alpha t}{d^2}$$

$$\mathrm{Gr} = \frac{g l^3 \gamma_c \Delta T \rho^2}{\eta}$$

$$\mathrm{Gz} = \frac{\eta A}{a l}$$

$$\mathrm{Le} = \frac{a}{D}$$

$$\mathrm{Ne} = \frac{P_0}{\rho \dot{N}^3 d_w^4 l}$$

$$\mathrm{Nu} = \frac{\alpha d}{\lambda}$$

$$\mathrm{Pe} = \frac{ud}{a}$$

$$\mathrm{Pr} = \frac{c_p\eta}{\lambda}$$

$$\mathrm{Re} = \frac{\rho ud}{\eta}$$

$$\mathrm{Re}_{\mathrm{axial}} = \frac{\rho u(d_{\mathrm{w}} - d_{\mathrm{rot}})}{\eta}$$

$$\mathrm{Re}_{\mathrm{radial}} = \frac{\rho \dot{N} d_{\mathrm{w}}^2}{\eta}$$

$$\mathrm{Sc} = \frac{\eta}{\rho D}$$

$$\mathrm{Sh} = \frac{\beta l}{D}$$

$$\mathrm{Ta} = 2\pi \sqrt{\frac{d_{\mathrm{w}} - d_{\mathrm{rot}}}{d_{\mathrm{rot}}}}\, \dot{N}\rho d_{\mathrm{rot}} \left(\frac{d_{\mathrm{w}} - d_{\mathrm{rot}}}{4\eta}\right)$$

$$\mathrm{Vi} = \frac{\eta}{\eta_0}$$

Superscripts

(k)	iteration number
$'$	root mean square of a fluctuating quantity except in eqn (2.5) where it means fluctuating quantities
$+$	dimensionless variable
k	finite time step

Subscripts

a	air
b	bulk
BL	boundary layer
e	entrance
eff	effective
g	gas
i	inlet

i, j, k	spatial node number in finite difference formulas
l	summation over all dimensions
l	liquid
m	mean
o	outlet
0	initial or reference value
r, θ, ϕ	tensor value in r, θ, ϕ direction
s	surface
s	solid
t	turbulence
v	vapour
x	local value at spatial coordinate x
x, y, z	tensor value in x, y, z-direction
w	wall
w	water
Overbar	time mean value
Overdot	time derivative

Contents

CHAPTER 1

Classification and Characterization of Foodstuffs

CLASSIFICATION

Foodstuffs are, in general, divided into groups according to their source and state.

Raw materials
These are foodstuffs originating from animal and vegetable sources.

Semi-raw materials
This category includes raw materials which have been pretreated to reach a certain state with regard to an earlier treatment or with regard to their biochemical status etc. To this group belong 'synthetic' raw materials such as SCP (single cell protein), i.e. raw food materials manufactured from unconventional sources.

Processed food
This includes products produced by the food industry. Convenience food is also included in this group.

Solids
Homogeneous, such as gels, protein solutions. Heterogeneous, which in turn may be divided into:

—capillary-porous rigid materials, e.g. beds of wheat kernels;
—capillary-porous colloidal materials (materials with a certain pore

structure which often develops during the process, and with a matrix of colloidal nature), e.g. meat and vegetables.

Powders

Liquids
Low-viscosity liquid foods.
High-viscosity liquid foods.

Even if almost all liquid foods are non-Newtonian, low-viscosity liquids are in technical calculations normally supposed to be Newtonian. The more viscous the product is, the more essential it is to use non-Newtonian analysis in dealing with different technical problems.

Slurries or dispersions
These can be colloidal (e.g. milk) or coarse (e.g. peas in water).

Emulsions (e.g. milk)

Foams (e.g. whipped cream)

Most liquid foods cannot be classified in only one of these groups but may be emulsions, dispersions and solutions, such as milk.

Liquid foods are characterized by means of density and viscosity or rheological properties.

Solid foodstuffs are characterized by means of geometry and density. For semi-solid materials rheology may also be of interest. For homogeneous foodstuffs classification according to density is normally sufficient; for heterogeneous foodstuffs porosity and even also bulk density are of interest. Both of these properties—bulk density and porosity—are also needed to characterize powders. For certain groups of solids some properties are different in different directions and this may also have to be considered.

Slurries and dispersions are more difficult to define. The liquid phase and the solid phase have to be characterized separately and their proportions determined.

Some of the properties already mentioned—as well as those listed below—may change during heat processing, and the way in which the procedure develops with increasing time and temperature will be exemplified. Especially heterogeneous foodstuffs exhibit a considerable change in structure during heat treatment. One drastic example is bread where the almost homogeneous visco-elastic dough develops into a firm sponge-like structure during baking.

FOOD CONSTITUENTS

The main constituents of foods are the following:

Water

All food contains water and in the original state (the raw material) the content is usually very high, being 60–70% or more. Water in food is defined not only by the amount present but also by its activity (see below).

Proteins

Proteins, being polymers, occur either as separate molecules, usually with very large molecular weight from 10 000 to millions, or as constituents of cells. Proteins are nitrogenous substances containing approximately 16% nitrogen in addition to carbon, hydrogen, oxygen etc. When proteins are heated in acid or basic solutions they undergo hydrolysis producing substances called amino-acids. Twenty-four amino-acids have been recognized as important constituents of proteins, and 9 of these are essential in human food.

Lipids

Natural fats and oils are esters. Animal fats consist mainly of the glycerol esters, palmitic acid and stearic acid.

Carbohydrates

Carbohydrates are substances with the general formula $C_x(H_2O)_y$. The simpler carbohydrates are called sugars and the more complex ones with very large molecules are called polysaccharides. Examples of sugars are dextrose, sucrose, fructose, maltose and lactose. Important polysaccharides are starch, glycogen and cellulose.

Vitamins and minerals

Organic compounds, which in most cases act biocatalytically in human metabolism, are called vitamins. At least 13 vitamins are essential in human nutrition. Vitamins are more or less denatured during heat treatment. Minerals or ash contain inorganic substances which remain after burning.

Sometimes in the literature thermal properties are related to the different components of foodstuffs; some formulae for estimating the properties of certain foodstuffs will be given below.

FOOD PROPERTIES

It is important to study the change in properties of foodstuffs during heat treatment for two main reasons:

1. Some properties (often called engineering properties) influence heat transport; such properties are, for instance, density, specific heat and thermal conductivity. Knowledge of these properties is needed in calculations and in the design of processes and equipment.
2. Some properties are of importance in judging the safety and the quality of the product. Examples are bacteriological status, nutritional and organoleptic properties.

All these properties are influenced to a greater or lesser extent by the temperature during heat treatment. The changes brought about by heat treatment may be intentional or unintentional. These changes may be of importance for the quality of the product (protein denaturation, vitamin degradation, changes in colour, taste etc.) but may also affect the basic properties important for heat transport.

For these reasons not only thermal properties are discussed in this chapter but also properties affecting the quality which may be changed during heat treatment.

PHYSICAL PROPERTIES

Density

Bulk density, bulk (kg/m^3), is the mass per unit bulk volume. Porosity is defined as

$$\psi = \frac{\rho_{\text{bulk}}}{\rho_{\text{dry matter}}}$$

Most solid foodstuffs contain gas which is in general a mixture of air and water vapour. The gas is contained in capillaries which can be open or completely closed. If the diameter of some of the pores is less than 10^{-7} m the material is said to be capillary-porous.

Energy

According to the SI system the unit of energy is the same for thermal energy (heat) as well as work, the joule (J) kg m^2/s^2. The heat flow rate is accordingly expressed in joules per second (J/s) or watts (W) = kg m^2/s^3.

Specific enthalpy

This term is thermodynamically defined as the sum of the internal energy and the kinetic energy. Specific enthalpy is identical to the older expression 'heat content'. Enthalpy is expressed per unit mass, which gives the units J/kg, N m/kg or W s/kg.

Specific heat or specific heat capacity

When there is no change in mass the specific heat is defined as the amount of heat necessary to raise the temperature of 1 kg of the material by 1°C or 1 K. The unit is therefore J/kg K. If 0°C is defined as the reference temperature,

$$h = \int_0^T c_p \, \mathrm{d}T$$

Normally c_p is almost constant within the temperature region of interest and therefore the equation may be approximated to

$$h = c_p T \qquad \text{with } T \text{ in } ^\circ\text{C}$$

The specific heat capacities for foodstuffs depend very much on the composition. The specific heat capacity of water is 4·18 kJ/kg K while that of the solid constituents is much lower, 1–2 kJ/kg K (see Table 1.1). Heldman[1] suggests the following formula and figures to estimate the specific heat capacities of foodstuffs based on composition:

$$c_p = \sum c_i c_{pi} \tag{1.1}$$

where c_i is the mass concentration, i.e. the proportion of each constituent (i) by mass.

Table 1.1
Thermal properties of food constituents[2]

Component	*Mass conc. (kg/kg)*	*Density (kg/m³)*	*Spec. heat (kJ/kg)*	*Thermal conductivity (W/m K)*
Water	c_w	1 000	4·182	0·60
Carbohydrate	c_c	1 550	1·42	0·58
Protein	c_p	1 380	1·55	0·20
Fat	c_f	930	1·67	0·18
Air	c_a	1·24	1·00	0·025
Ice	c_i	917	2·11	
Inorganic minerals	c_m	2 400	0·84	