FDE449
Physical Properties of Foods
Thermal properties of foods

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***Thermal conductivity**
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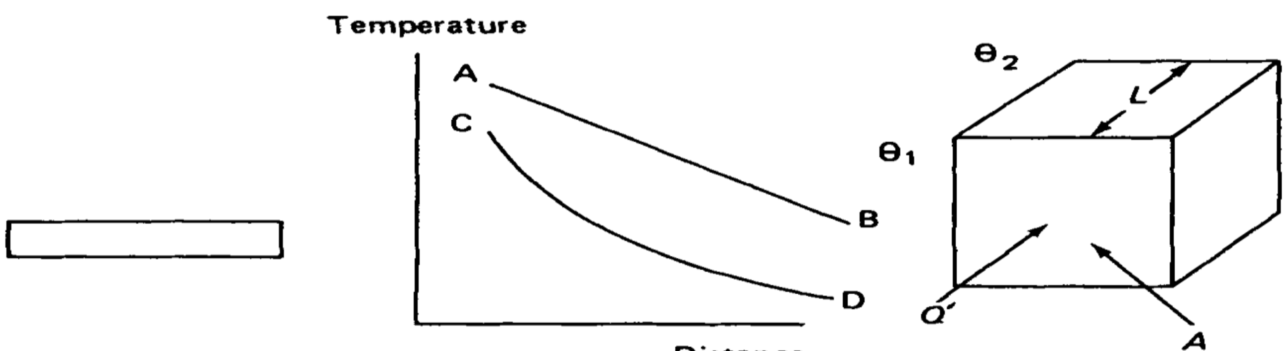
Thermal conductivity

- The thermal conductivity of a material is defined as a measure of its ability to conduct heat.

- Unit of the thermal conductivity: W/m K in the SI system.

  Btu/ h ft ^{o}F in Imperial system



(a) (b)

Thermal conductivity

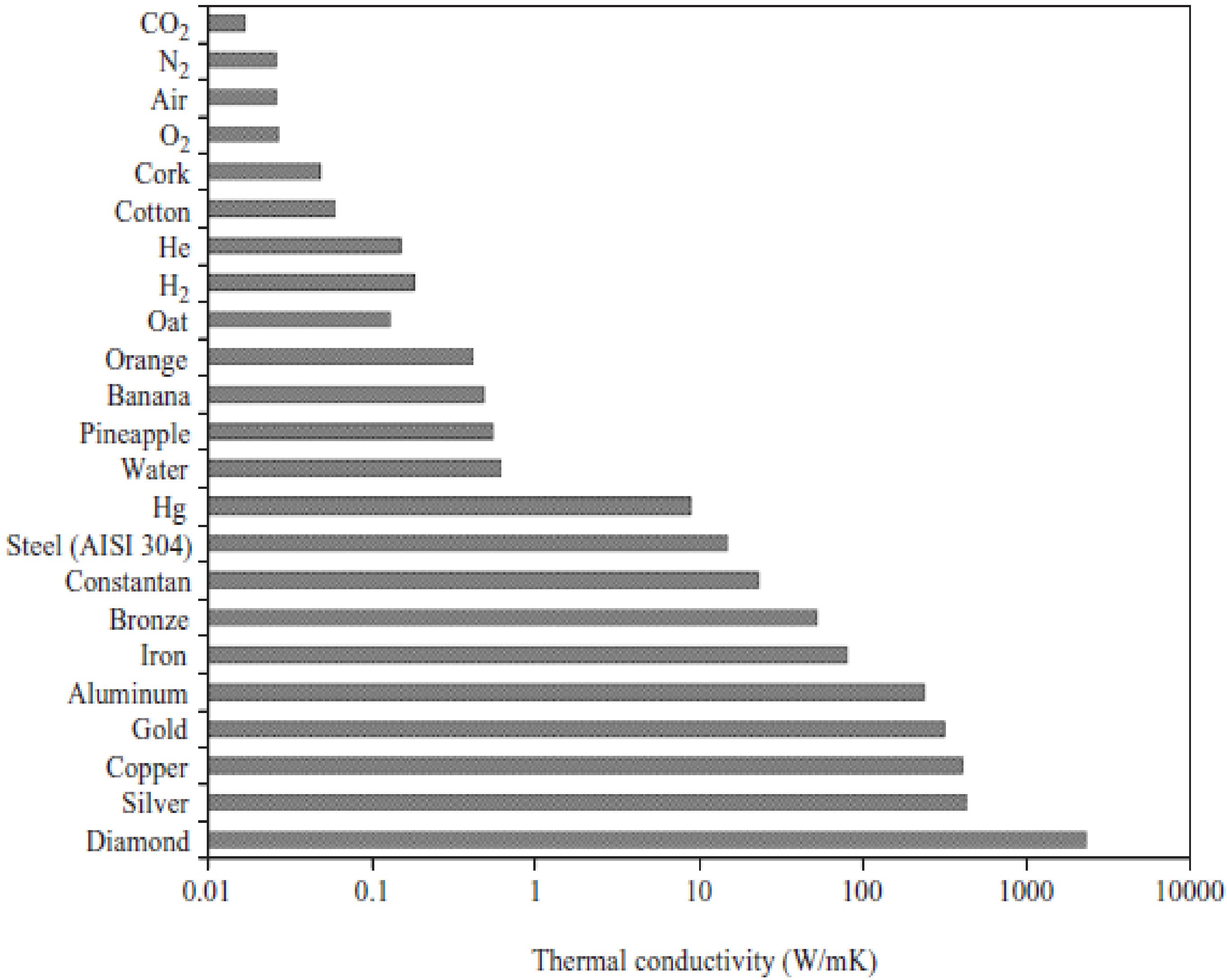
- A solid may be comprised of free electrons and atoms bound in a periodic arrangement called a lattice.
- Thermal energy is transported through the molecules as a result of two effects: lattice waves and free electrons. These two effects are additive:

$$k = k_e + k_l$$

- In pure metals, heat conduction is based mainly on the flow of free electrons and the effect of lattice vibrations is negligible.
- In alloys and nonmetallic solids, which have few free electrons, heat conduction from molecule to molecule is due to lattice vibrations.
- Therefore, metals have higher thermal conductivities than alloys and nonmetallic solids.

Heat conductivity values of some materials

- Metals : 50-400 W/m^{o}C
- Alloys : 10-120 W/m^{o}C
- Water : 0.597 W/m^{o}C (at 20^{o}C)
- Air : 0.0251 W/m^{o}C (20^{o}C)
- Insulation materials : 0.035-0.173 W/m^{o}C



Thermal conductivities of various materials at 27^{o}C

Thermal conductivity

- The regularity of the lattice arrangement has an important effect on the lattice component of thermal conductivity.

- For example, diamond has very high thermal conductivity because of its well ordered structure.

- As temperature increases, lattice vibrations increase.
- Therefore, thermal conductivities of alloys increase with an increase in temperature while the opposite trend is observed in metals because the increase in lattice vibrations impedes the motion of free electrons.

Thermal Conductivity of Foods

- Most foods are poor conductors of heat, and so heat transfer processes in which conduction is the predominant mechanism are slow.
- Heating and cooling times can be shortened by size reduction processes.
- In canning operations the term conduction pack is used for products where conduction is the major mechanism.

The thermal conductivity of a food is influenced by

- the composition of the food,
- the pressure,
- The temperature.

Thermal Conductivity of Foods

- The thermal conductivity of various foods varies between the thermal conductivity values of water and air.

- Water and air are the two components in food with the highest and lowest thermal conductivity.

k_{water}= 0.614 W/m^{o}C at 27^{o}C

k_{air}= 0.026 W/m^{o}C at 27^{o}C

Thermal conductivity of some materials

Material	Temperature (^oC)	Thermal conductivity (W/m^oC)
Silver	0	428
Copper	0	403
Copper	100	395
Aluminum	20	218
Stainless steel	0	8-16
Glass	0	0.1-1
Polystyrene	0	0.035
Beef meat (parallel to fibrils)	0	0.491
Frozen beef	-10	1.37

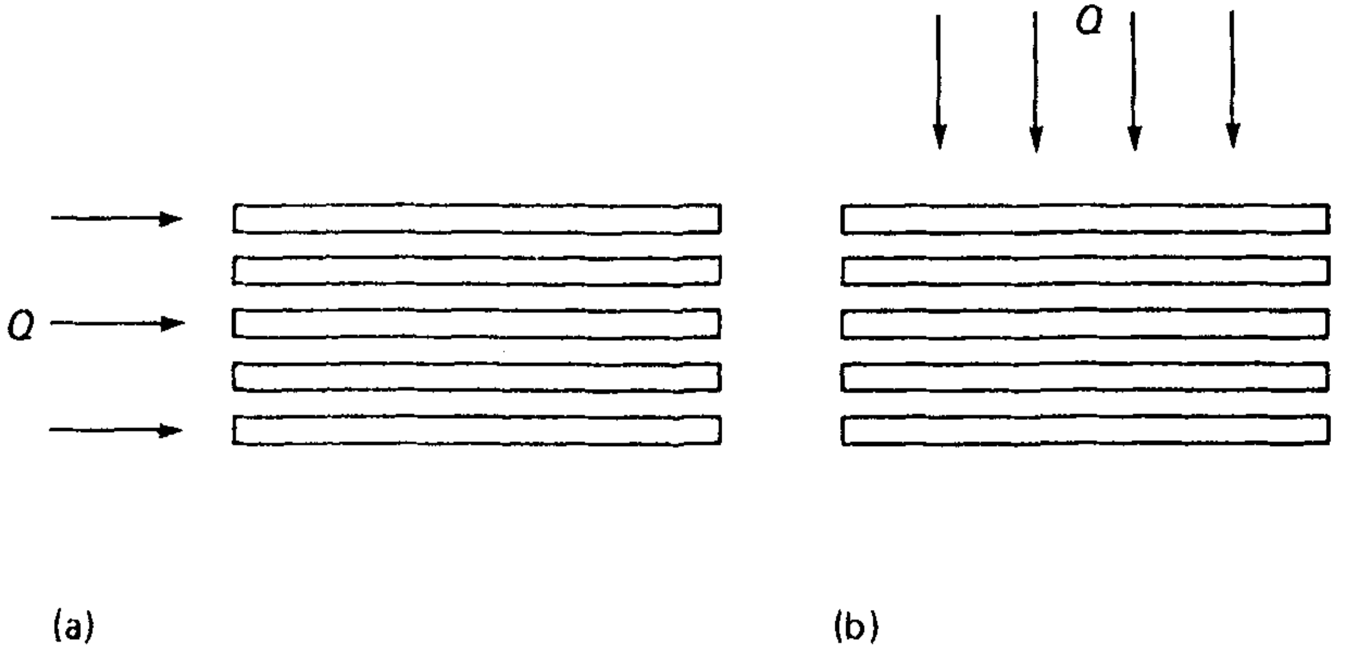
Thermal Conductivity of Foods

- Some biological materials and fabricated foods have different conductivities in different directions; their properties are direction orientated or anisotropic.
- One example is meat and fish, where heat may be transferred better along the fibres than across the fibres.
- Thermal conductivities for a range of food materials are given in
- There are many published equations relating thermal conductivity to the moisture content of the food, e.g. for fish

$$k = 0.0324 + 0.3294 m_w$$

Where m_w, is the mass fraction of water.

Thermal Conductivity of Foods

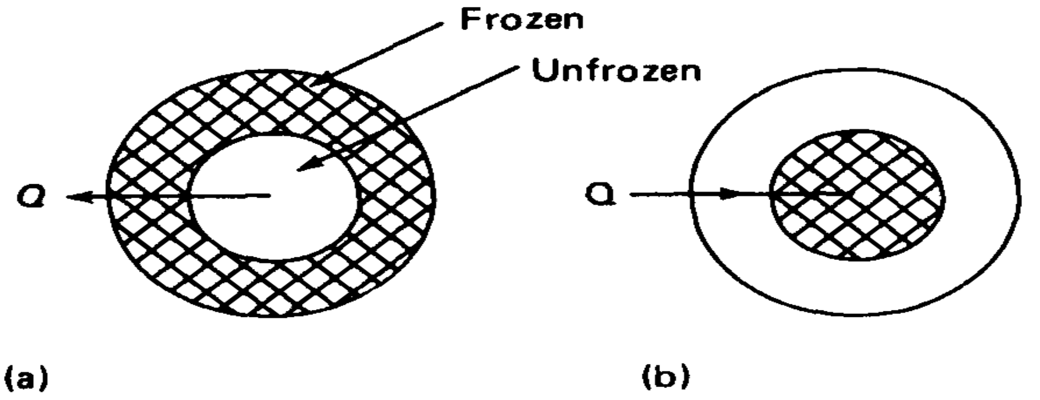


Heat transmission parallel to the fibres; (b) Heat transmission across the fibres.

Thermal conductivity of foods

- The thermal conductivity decreases **as** the food becomes drier.
- Freeze-dried materials, which are usually very porous, have extremely low thermal conductivities.
- During freeze drying, heat is normally transferred to the frozen material through the dried layer. Therefore, this is a slow process and the overall drying rate is limited by the rate of heat transfer.
- The conversion of water to ice increases the thermal conductivity approximately four-fold.
- Rates of heat transfer can be increased by heating through the frozen layer. It is also important to ensure a good contact between the heating surface and the food.
- The application of pressure to push the food against the surface and the use of a porous metal mesh to allow the vapour to escape have been adopted to accelerate the process (accelerated freeze drying).

Comparison of (a) the freezing and (b) the thawing mechanisms



Since frozen foods are better conductors than fresh foods, the rate of heat transfer during freezing (where heat is removed through the frozen layer) is greater than during thawing (where heat is added through the defrosted material); this is particularly ***so*** if conduction offers the major resistance to heat transfer.

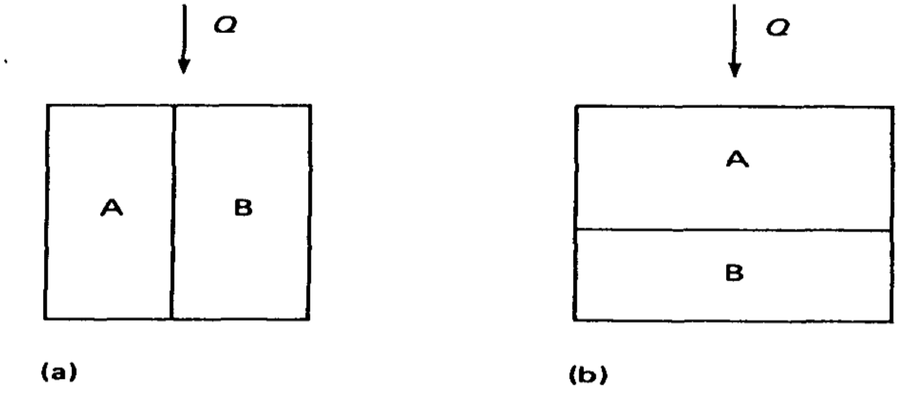
Compositional factors

- Compositional data can also be used to obtain a more accurate thermal conductivity value.

Two models have been proposed:

- the parallel model
- the perpendicular model.

These are shown for a two-component system in Fig.



The thermal conductivity of two-component systems: (a) the parallel model; (b) the perpendicular model.

- For such a system containing solids and water, the equations for the thermal conductivity are given, for the parallel model:

$$k = V_s k_s + V_w k_w$$

for the perpendicular model:

$$\frac{1}{k} = \frac{V_s}{k_s} + \frac{V_w}{k_w}$$

Where,

V_s and V_w: volume fractions of solids and water, respectively

k_s and k_w: the thermal conductivities of the solids and water, respectively

*It is important to note that volumetric fractions are used rather than mass fractions.

The thermal conductivities of various components have been given by Miles et al. (1983) as follows:

- k_a (air) = 0.025;
- k_p (protein) = 0.20;
- k_c (carbohydrate) = 0.245;
- k_s (solids) = 0.26;
- k_f (fat) = 0.18;
- k_w (water) =0.6;
- k_i (ice) = 2.24.

Thus, for an n-component system, using the parallel model (the same principle would apply to the perpendicular model)

$$k = V_1 k_1 + V_2 k_2 + \ldots + V_n k_n$$

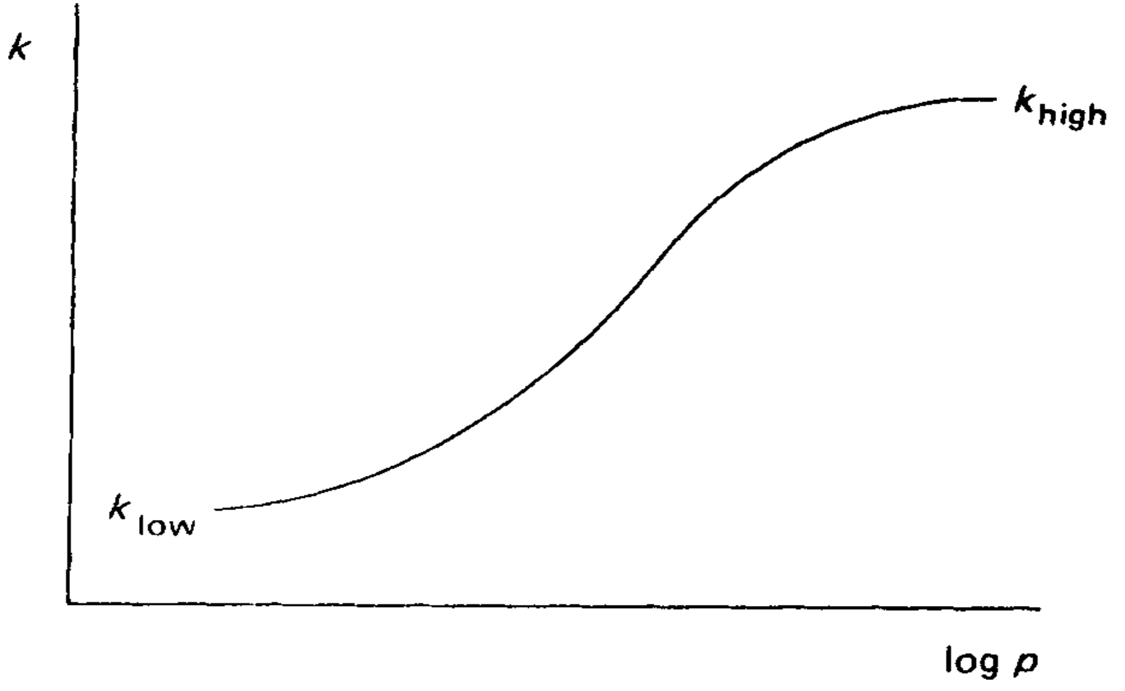
Example-1: The composition of an apple is 0.844 water and 0.156 solid (mass fractions) and the densities of water and solids are 1000 kg/m^3 and 1590 kg/m^3 respectively.

Temperature effecs

- For many structrual materials (particularly metals), the thermal conductivity of the material changes considerably with temperature.
- However, in most food materials the temperature effect is not so pronounced; the conductivity is more affected by cellular structure and moisture content.
- Note that the obvious exception to this is during the transition from water to ice or vice versa. Furthermore, the range of temperatures to which foods are subjected is not as large as some other materials.
- Mohsenin (1980) suggests that, if k varies linearly with temperature, the temperature effect can be taken into consideration by taking the value at the average temperature.
- There is very little published information about the thermal conductivity of foods at higher temperatures.

Pressure effects

- the thermal conductivity of a material increases as the pressure increases, over the pressure range 10-104Pa, as shown in Fig.



The relationship between thermal conductivity and pressure of materials.

Thermal conductivity in fluids

- Heat conduction in liquids and gases occurs through the collision of molecules.
- Compared to solid materials in fluids, heat energy is more difficult to transport because of the greater intermolecular spaces and the randomness of intermolecular motion.
- Therefore, the thermal conductivity of fluids is lower than the thermal conductivity of solid materials.

Thermal conductivity of foods

- The thermal conductivity of porous foods largely depends on their composition.
- On the other hand, many factors that prevent heat flow also affect thermal conductivity. For example:

- cavities in food,
- the shape and size of the food,
- placement of cavities in food,
- liquids in the pores,
- homogeneity of food.

Thermal conductivity in fluids

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Thermal conductivity in fluids

- The mechanism of heat conduction in liquids is the same as in gases.
- However, liquids have less intermolecular spaces than gases, and there are strong interactions between molecules.
- In contrast to gases, the thermal conductivity of non-metallic liquids generally decreases with increasing temperature.
- Generally, as the molecular weight increases, the thermal conductivity decreases.

Prediction of thermal conductivity

- Predictive models have been used to estimate the effective thermal conductivity of foods.
- Modeling of thermal conductivity based on composition has been a subject of considerable interest.
- It is important to include the effect of air in the porous foods and ice in the case of frozen foods.
- Temperature dependence of thermal conductivities of major food components has been studied.
- Thermal conductivities of pure water, carbohydrate (CHO), protein, fat, ash, and ice at different temperatures can be empirically expressed according to Choi and Okos (1986) as follows:

*The thermal conductivity coefficients of fruits and vegetables with a water content of more than 60% are calculated with the following equation:

$$k = 0.148 + 0.493\ m_w$$

k : Thermal conductivity, W/ m ^oC

m_s : mass fraction of water in fruit and vegetables

*The thermal conductivity coefficients of meat and fish with a water content between 60-80% and the temperature ar 0-60^oC are calculated with the following equation:

$$k = 0.08 + 0.52\ m_w$$

k : thermal conductivit, W/ m ^oC

m_w : mass fraction of water in meat and fish

In the equation developed by Sweat (1986), the thermal conductivity coefficients of solid and liquid foods can be calculated with the following formula.

$$k = 0.25\, m_{CHO} + 0.155\, m_p + 0.16\, m_f + 0.135\, m_{ash} + 0.58\, m_w$$

m: mass fraction of carboyhdrate, protein, fat, ash and water, respectively

* Constant numbers are coefficients of thermal conductivity of pure components.

realistic calculations were made by considering both the temperature and the composition of the food in calculating the thermal conductivity coefficients of foods.

In the parallel model, components are assumed to be placed parallel to the direction of heat flow.
The effective thermal conductivity of a food material made of n components can be calculated using volume fractions (X_i^v) and thermal conductivities (k_i) of each component (i) from

$$k=\sum_{i=1}^{n} k_i X_i^v$$

k_i : The thermal conductivities of each component (i)
X_i^v : Volume fraction of each component

Prediction of thermal conductivity of foods for parallel model

- Where

$$X_i^v = \frac{X_i^w/\rho_i}{\sum_{i=1}^{n}(X_i^w/\rho_i)}$$

where

X_i^v= volume fraction of the i th constituent,

X_i^w= mass fraction of the i th constituent,

ρ_i= density of the i th constituent (kg/m^3).

1st step: To calculate the thermal conductivity coefficients of food components in pure form;

$k_{water} = 0.57109 + 0.0017625\ T – 6.7036\ x10–6\ T^2$

$k_{CHO} = 0.20141 + 1.3874x10^{-3}\ T – 4.3312x10^{–6}\ T^2$

$k_{protein} = 0.17881 + 0.0011958\ T – 2.7178x10^{–6}\ T^2$

$k_{fat} = 0.18071 – 0.0027604\ T – 1.7749x10^{–7}\ T^2$

$k_{cellulose} = 0.18331 + 0.0012497\ T – 3.1683x10^{–6}\ T^2$

$k_{ash} = 0.32962 + 0.0014011\ T – 2.9069x10^{–6}\ T^2$

$k_{ice} = 2.2196 – 0.0062489\ T + 1.0154x10^{–4}\ T^2$

where thermal conductivities (k) are in W/m◦C; temperature (T) is in ◦C and varies between 0 and 90◦C in these equations.

Equations used to calculate individual densities (ρ_i):

- $\rho_{protein}$ = 1329.9 – 0.51840 T
- ρ_{fat} = 925.59 – 0.41757 T
- ρ_{CHO} = 1599.1 – 0.31046 T
- $\rho_{cellulose}$ = 1311.5 – 0.36589 T
- ρ_{ash} = 2423.8 – 0.28063 T
- ρ_{water} = 997.18 + 0.0031439 T – 0.0037574 T^2
- ρ_{ice} = 916.89 – 0.13071 T

Example: Calculate the thermal conductivity coefficient of the hamburger patty with a water content of 68.3%, whose composition is given below, at 20°C a) without taking into account the temperature factor and composition elements, b) taking into account the temperature factor.

Composition of the meatball and densities of food components at 20°C

Component	Weight (%)	Density (kg/m^3)
Water	68.3	
Protein	20.7	
Fat	10.0	
Ash	1.0	

Solution:

- 1 st step:To calculate the thermal conductivity of the meatball using predictive models, thermal conductivity values of food components at 20◦C are required. They can be calculated using the following equations:

k_{water} = 0.57109 + 0.0017625 T – 6.7036 x10–6 T^2

$k_{protein} = 0.17881 + 0.0011958\ T - 2.7178\times10^{-6}\ T^2$

$k_{fat} = 0.18071 - 0.0027604\ T - 1.7749\times10^{-7}\ T^2$

$k_{ash} = 0.32962 + 0.0014011\ T - 2.9069\times10^{-6}\ T^2$

Solution:

- 2 nd step: Using the composition and density of components data given in the question, the specific volume of each component is calculated:

$$\text{Specific volume of component } i = \frac{\text{Mass fraction of component } i}{\text{Density of component } i}$$

- 3 rd step:total specific volume is determined by adding the volume of each component. Volume fractions of components are calculated by dividing the component volume to total volume.

- 4 rd step:Thermal conductivity of the food is calculated by using volume fractions and thermal conductivity values of components using the parallel model.