

THERMAL PROPERTIES

Heat transfer occurs by

Conduction: is heat transfer between part of the same material or different material which are adjacent to one another.

Convection is heat transfer from one material to another via a medium, such as air or water.

Radiation is heat transfer without any medium and through electromagnetic waves, such as between the Sun and the Earth. Its efficiency is based on the texture of the receiving surface.

- These mechanisms can occur **individually** or simultaneously.
- In food processing, heat transfer is usually a **combination** of conduction and convection.

Conduction heat transfer occurs when **heat moves through a material** (usually a solid or a viscous liquid) due to molecular action only. Conduction heat transfer may occur simultaneously in one, two, or three directions.

One dimensional conduction heat transfer ($\text{J/s} = \text{W}$) is a function of the temperature difference, the material thickness, the area through which the heat flows, and the resistance of the material to heat flow. This relationship is expressed in equation form as:

$$\dot{Q} = -k A \frac{dt}{dx} = k A \frac{(t_1 - t_2)}{\Delta x} = \frac{A (t_1 - t_2)}{\left(\frac{1}{k}\right) \Delta x} = \frac{A \Delta t}{R}$$

or

$$\dot{q} = \frac{\dot{Q}}{A} = \frac{\Delta t}{R}$$

where: A = area, m^2

k = thermal conductivity, $\text{W}/(\text{m K})$

\dot{Q} = heat transfer, W

\dot{q} = heat transfer per unit area, W/m^2

R = thermal resistance of the material $\Delta x/k$, $(\text{m}^2 \text{ K})/\text{W}$

t = temperature, $^{\circ}\text{C}$ (or K)

Convection is the **transfer between solids (walls of pipes, vats, rooms) and fluids (food materials)**. In other cases, the food may be the solid and the fluid might be air or water. Convection heat transfer is the transfer of energy due to the movement of a heated (or cooled) fluid.

Assuming heat transfer from the fluid to the surface, the equation is:

$$Q = hA(t_b - t_s) \text{ or } Q = \frac{A(t_b - t_s)}{R_s}$$

where: h = convective (surface) heat transfer coefficient, $\text{W}/(\text{m}^2 \text{ K})$

R_s = the surface resistance ($R_s = 1/h$), $(\text{m}^2 \text{ K})/\text{W}$

t_b = bulk temperature of the fluid, $^{\circ}\text{C}$ or K

t_s = the surface temperature of the object exposed to the fluid, $^{\circ}\text{C}$ or K

Radiant heat transfer is the transfer of heat from one object directly to another **without the use of an intervening medium**. Thermal radiation forms a part of the electromagnetic spectrum which ranges from radio waves to gamma rays. Thermal energy can be radiated through space (solar energy) and through gases (e.g., air). The thermal energy radiated by a blackbody radiator per second per unit area is proportional to the fourth power of the absolute temperature and is given by **Stefan-Boltzmann Law** :

$$E = \sigma T^4$$

where: E = the energy radiated per unit time and per unit area, W/m^2
 σ = the Stefan-Boltzmann constant ($5.669 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$)
 T = the absolute temperature, (K), ($\text{K} = 273.15 + ^\circ\text{C}$)

For hot objects other than ideal radiators, the law is expressed in the form:

$$E = \epsilon \sigma T^4$$

where ϵ (epsilon) is called the **emissivity** of the particular body and is a number between 0 and 1. Bodies obeying this equation are called **grey bodies**.

Important Thermal Properties

- Heat capacity
- Specific heat
- Thermal conductivity
- Thermal diffusivity
- Surface heat transfer co-efficient
- Latent heat of fusion and vapourization
- Heat of respiration
- Co-efficient of thermal expansion
- Thermal Emissivity

Heat capacity

Heat capacity may be defined as the **thermal capacity**, is the **amount of heat required to change a substance's temperature by one degree**. In the International system of units (SI), heat capacity (C) is expressed in units of joule (J) per kelvin (K).

It is the Ratio of heat supplied (Q) to the corresponding temp rise (Δt)

$$C = Q / \Delta t$$

Specific heat

Specific heat (c_p) or mass heat capacity is the **heat required to increase the temperature of one unit of mass by one degree**. The subscript (p) is included because specific heat of solids and liquids is determined at constant pressure.

$$Q = Mc_p (T_2 - T_1)$$

The specific heat is expressed in kJ/(kg-K).

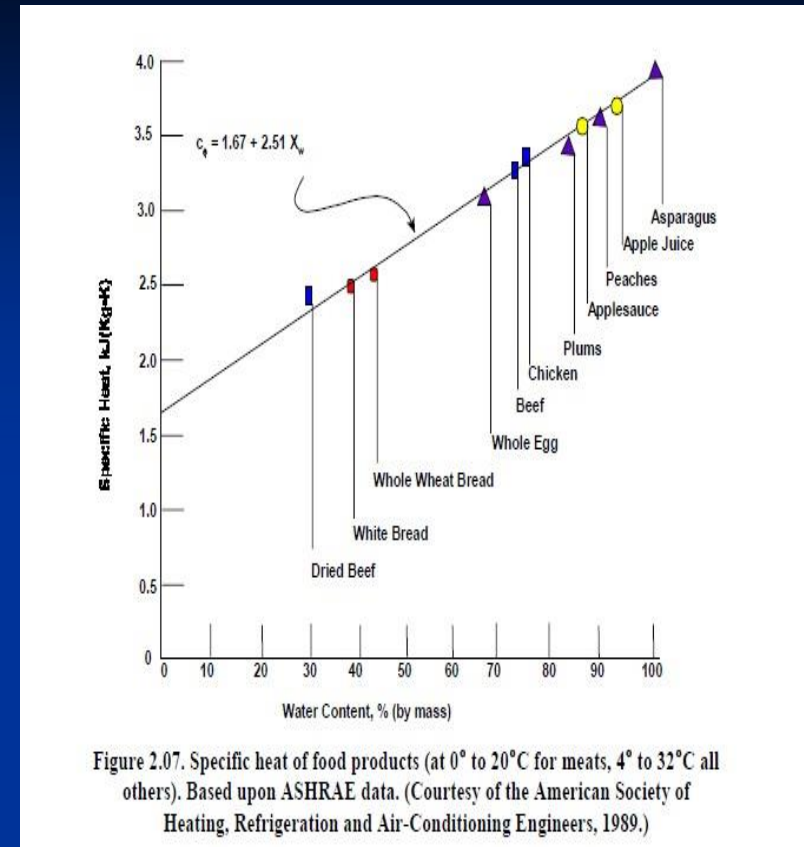


Figure 2.07. Specific heat of food products (at 0° to 20°C for meats, 4° to 32°C all others). Based upon ASHRAE data. (Courtesy of the American Society of Heating, Refrigeration and Air-Conditioning Engineers, 1989.)

Methods of measurement

1. Method of mixing: Simple & suitable for food & agril material
2. Method of guarded plate: solid slab
3. Method of comparision (calorimetric): specially for liquids
4. Differential scanning calorimeter: Possible with very small sample

The thermal properties of materials varies with the **composition**

The empirical equation used for the specific heat of foods

$$C_p = 4.180 X_w + 1.711 X_p + 1.928 X_f + 1.547 X_c + 0.908 X_a$$

where "w" is water, "p" is protein, "f" is fat, "c" is carbohydrate, and "a" is ash and (X) the mass fraction of all the solids that make up the food.

Equations used to predict **specific heats for food products** based on the **Wet basis moisture content, (M, decimal)** of the product.

Above freezing: $C_p = 0.837 + 3.348M$

Below freezing: $C_p = 0.837 + 1.256M$

These equations predict specific heat in kJ/(kg-K).

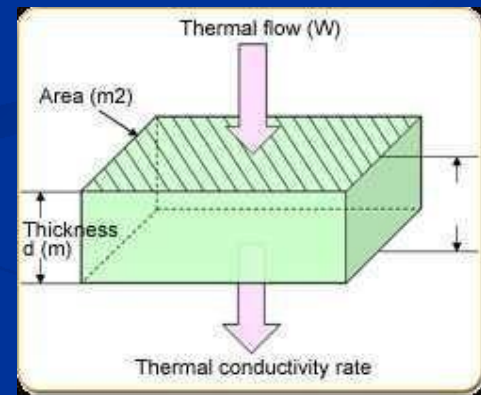
water has the greatest effect

Thermal Conductivity

In steady state conduction through a solid-like material the important thermal property is **thermal conductivity** (k). **Thermal conductivity is a measure of the ease with which heat flows through a material.**

It is defined as the “heat flow through the material per unit of time (dQ/dt), the cross sectional area of the material through which the heat flows (A), and the temperature difference per unit thickness of the conducting material (dT/dx)”.

$$(dQ/dt) = k A (dT/dx)$$



Thermal conductivity can be greatly influenced by a number of factors such as the water content, porosity, and even fiber orientation of the material.

Estimation of thermal conductivity:

The equation based upon the overall **food composition**:

$$k = 0.58X_w + 0.155X_p + 0.16X_f + 0.25X_c + 0.135X_a$$

where the parameters of the equations are as defined for Sp heat. The thermal conductivity of most food materials is in a relatively narrow range between 0.2 and 0.5 W/m K.

The equation based on **moisture contents**:

$$k = k_w X_w + k_s (1 - X_w)$$

weight fraction of water X_w , thermal conductivity of water k_w , and the thermal conductivity of the solids portion of the material k_s , which is assumed to be 0.259 W/(m·K). (thermal conductivity of ice 2.18 W/(m·K) at 0 °C) melts to form liquid water (thermal conductivity of 0.56 W/(m·K) at 0 °C).

Instrumental methods of measurement

- 1. Guarded hot plate method:** Homogenous material of slab form
- 2. Concentric cylinder method:** Powdered granular, material
- 3. Concentric sphere method:** Powdered granular, material
- 4. Probe method:** Simple, fast, popular for small sample size food
- 5. Differential scanning calorimeter:** Low to high moisture food
- 6. Transient hot wire method:** For fluid and gases

Enthalpy: Total heat content of a material per unit mass

The total enthalpy of a system cannot be measured directly, the *enthalpy change* of a system is measured instead. Enthalpy change is defined by the following equation:

$$H_2 - H_1 = m c_p (T_2 - T_1) + m X_w L$$

Where:

$H_2 - H_1$ = Enthalpy difference

m = Mass of product

X_w = Water fraction

$T_2 - T_1$ = Temperature difference

L = Latent heat

Thermal diffusivity

In transient heat transfer, where temperature varies with time and location, the relevant thermal property is thermal diffusivity. **Thermal diffusivity** (α , m^2/s) is a combination of three basic thermal properties, defined as “The rate at which heat is diffused out of the material. This is a quantity derived from conductivity, which is a measure of its ability to exchange thermal energy with its surroundings”.

Mathematically , **Thermal diffusivity** $\alpha =$

Thermal conductivity/(density \times specific heat) or $\alpha = k/\rho C_p$.

When these three basic properties are known, the diffusivity can be readily computed. Values of thermal diffusivity for food products range from 1×10^{-7} to $2 \times 10^{-7} \text{ m}^2/\text{s}$.

Convective heat transfer coefficient

The thermal property associated with convection heat transfer is the **convective heat transfer coefficient** (h); it also goes by the names *surface heat transfer coefficient*, unit surface conductance or *film coefficient*. It is defined as the “Rate of heat transfer per degree of temp diff across the solid fluid interface per unit of the solid’s surface area”.

$$Q = h A \Delta T$$

The convective heat transfer coefficient varies widely from about 10 to 100 W/m²-°C for still air next to a flat surface to 100,000 W/m²-°C for steam condensing on a metal pipe.

The convective heat transfer coefficient depends upon fluid velocity, fluid properties, surface characteristics of the solid, and the geometry of each situation.

Heat transfer may involve either sensible energy or latent energy.

If the temperature of an object is changed due to the heat transfer, then the heat transfer involves a transfer of **sensible heat**.

- **Latent heat (L)** is the heat that is exchanged with a material during a phase change, when the heat exchanged does not result in a change in the temperature of the material. The units for latent heat are kJ/kg. Latent heat is usually subdivided into latent heat of freezing and latent heat of vaporization.
- **Latent heat of freezing** is the **335 kJ** that 1 kg of water releases while maintaining its temperature at 0 °C when changing from the liquid to the solid state. **Latent heat of vaporization** is represented by the **2257 kJ** that 1 kg of water must absorb while temperature remains constant at 100 °C to evaporate from liquid into vapor.
- Latent heat is best determined through experimentation, but it also can be estimated based on the mass fraction of water in the product.

$$L_f = 335X_w$$

$$L_v = 2257X_w$$

- Differential scanning calorimeter is most suitable for latent heat measurement of food material.

Freezing point depression: It is the lowering of freezing temperature of food. Pure water freezes at 0°C, while food products freeze at lower temperatures. The **freezing point** is lowered due to the presence of solutes, solids, in the water. The change in the freezing point temperature is primarily dependent on the concentration or amount of solids.

Boiling point elevation: Boiling point is elevated by the presence of solute in the liquid phase as found in most foods. This is useful in evaporation and drying operations.

Examples:

The depression of the freezing point for high salt products is i.e., processed meats, etc.
The boiling point rises with sugar content in candy making.

Heat of Respiration

Fruit and vegetable products are living organisms. To maintain their life processes, they must consume energy. They do this by a “combustion” process that “burns” sugar to produce CO₂ and heat. The heat produced by this process is commonly called the **heat of respiration**.



NOTE: Heats of respiration

- ✓ Vary greatly among products (Sugar content))
- ✓ Increase exponentially with temperature.
- ✓ Affected by maturity and storage time.
- ✓ High respiration rates also cause rapid deterioration in food quality.

Measurement

A commodity's rate of carbon dioxide production is related to its temperature. The carbon dioxide production rate can then be related to the commodity's heat generation rate from respiration

Coefficient of thermal expansion

When a material is heated, it leads to density difference. Solids mostly expand in response to heating and contract on cooling. This response to temperature change is expressed as its coefficient of thermal expansion. The physical property relating to this is called **Coefficient of thermal expansion (α , K^{-1})**.

$$\alpha = \Delta V / (V * \Delta T)$$

ΔV : Change in volume, ΔT : Change in Temp

Thermal emissivity:

The emissivity coefficient - ϵ - is the ratio of total emissive power of any body to the total emissive power of a black body at the same temperature. it indicates the radiation of heat from a '**grey body**' according the **Stefan-Boltzmann Law**, compared with the radiation of heat from a ideal '**black body**' with the emissivity coefficient $\epsilon=1$.

If an hot object is radiating energy to its cooler surroundings the net radiation heat loss rate can be expressed as **$Q = A\epsilon\sigma(T_h^4 - T_c^4)$**

Q = rate heat transfer

A = surface area

ϵ = 1 black body and <1 real object

(This thermal constant is associated with the rate of heat transfer by radiation from a hot body to a cold body & is dependent on angle factor of the body & emissivity factor)

σ = Stefan Boltzmann constant

T_h & T_c = Absolute temperature of hot and cold body respectively

THANK YOU