

FOOD SCIENCE AND TECHNOLOGY

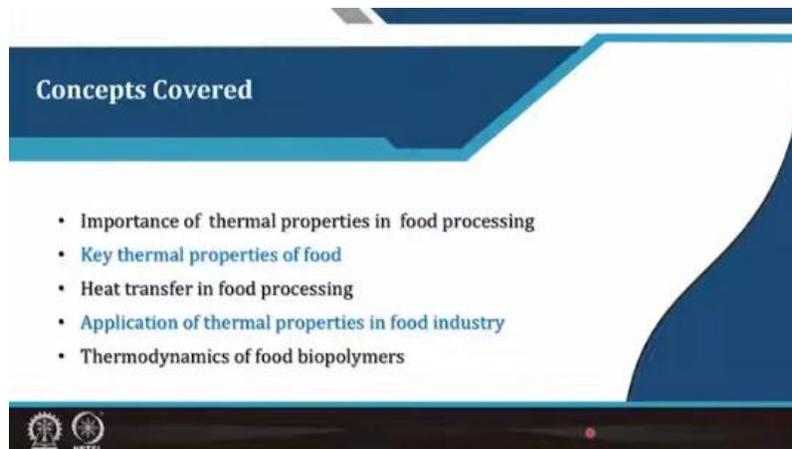
Lecture09

Lecture 09: Thermal Properties Relationships

Hello everyone, Namaste.



Now in this module 2, we are discussing about food structure function relationship. So, in this class today, that is lecture number 9, we will talk about thermal properties relationship. That is how thermal properties of the food material influence its structure and function relationships. We will discuss the concepts like importance of thermal properties in food processing, key thermal properties of food, heat transfer, application of thermal properties in food industry and finally, we will also talk about thermodynamics of food biopolymers. So, let us see how these thermal properties are important to whole food system as well as particularly during the processing of foods. And you know, the food materials often experience the movement of heat around and



Importance of thermal properties

- Food materials often experience the movement of heat around and through them in various forms and degrees during their entire value chain from farm to fork.
- Understanding their thermal properties helps to perform heat transfer calculations for designing storage and refrigeration equipment and estimating refrigerating, freezing, heating, or drying duration of foods and beverages.
- Thermal properties of foods can be predicted by using composition data in conjunction with temperature-dependent mathematical models of thermal properties of the individual food constituents.
- Specific heat capacity, enthalpy, thermal conductivity, and thermal diffusivity are the important thermal properties required for heat transfer calculations.



through them in various forms, even different degrees, etc., during their entire value chain from farm to fork. The food material is harvested in the field, then it is transported, then it comes to the industry where it is processed. In all these steps, these food materials are exposed to varying degrees of temperature and various environmental conditions, heat, etc. The thermal properties of food help to perform heat transfer calculations for designing storage and refrigeration equipment and estimating refrigerating load, freezing load, heating or drying duration of foods and beverages, etc. Because when these thermal properties of food come across heat, this heat goes inside the material, which changes the material characteristics and so what how much heat should go in a food, how it should be done, all these things if we know the heat transfer characteristics if you know the thermal characteristics of the food material, it becomes easy to design thermal process operations in order to maintain a good quality and safety in the food. So thermal properties of the food can be predicted by using composition data in conjunction with temperature-dependent mathematical models of thermal properties of the individual food constituents.

Specific heat capacity, enthalpy, thermal conductivity, and thermal diffusivity are the important thermal properties which are required for heat transfer calculations in different operations. So, let us briefly understand that is the specific heat. Specific heat is a measure of the energy required to change the temperature of a food by 1 degree. And the symbol C_p of the specific heat, the P is included because the specific heat of solids and liquid is determined at a constant pressure.

Key thermal properties of food

Specific heat

- Specific heat (c_p) is a measure of the energy required to change the temperature of a food by one degree.
- The subscript (p) is included because specific heat of solids and liquids is determined at constant pressure.
- The SI unit of specific heat is $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
- This property allows to calculate the heat load imposed on the refrigeration equipment by the cooling or freezing of foods and beverages.
- Specific heat of an unfrozen food (c_u) may be determined as

$$c_u = \sum c_i x_i$$

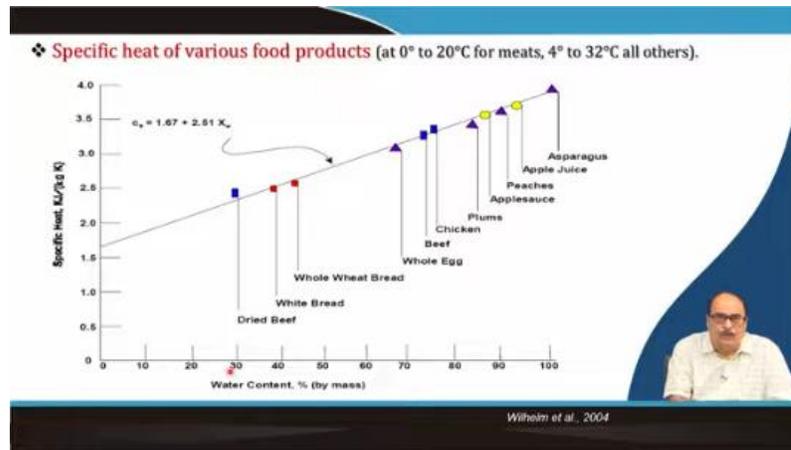
Where, c_i is the specific heat of the individual food components, and x_i is the mass fraction of the food components.



It may vary with the, if the pressure is varied, then the specific heat also may be different. So, it is determined always at a constant pressure. And in the SI system, unit of specific heat is $\text{J}\cdot\text{Kg}^{-1}\cdot\text{K}^{-1}$. This property allows to calculate the heat load imposed on the refrigeration equipment by the cooling or freezing of food and beverages. Specific heat of an unfrozen food that is C_u may be determined as

$$C_u = \sum C_i X_i$$

where C_i is the specific heat of the individual food component and X_i is the mass fraction of that particular food component or mass fraction of the food components.



And here in this figure, I have tried to show you that how the specific heat varies with the water content of the food material. So, obviously, if a food material is having more moisture content, its specific heat also will be more. So, that is the linearly that is a related specific heat and the moisture content of the food. That is you can see here that

dried beef. It has that is specific heat around 1.6 or 1.7 that kilojoule per kg per K. And similarly, the whole egg it may have around somewhere 2.9 or so kilojoule per kg. And then asparagias which contains more moisture etc. It may have specific heat around 4 kilo joule per kg. So, it is exactly and there is a linear relationship and equation like general equation $y=m_x + c$ is similar equation $C_p = 1.67 + 2.51 X_w$. So, means X_w is the water content and if the C_p is the specific heat. So, if you know the water content of the food material applying this equation you can calculate the specific heat.

Then comes another important thermal property, the enthalpy. Enthalpy is the heat content in a system per unit mass. Its unit is joule per kg in the SI system. It is a thermodynamic property that depends only on the state of the system and it is expressed in terms of internal energy, pressure and volume like $H = U + P V$. The change in a food's enthalpy can be used to estimate the energy that must be added or removed to affect a temperature change. Above the freezing point for example, enthalpy consists of sensible energy and below the freezing point enthalpy consists of both sensible and latent energy.

□ Enthalpy

- Enthalpy is the heat content in a system per unit mass. Its unit is J/kg in SI system.
- It is a thermodynamic property that depends only on the state of the system and it is expressed in terms of internal energy, pressure, and volume as $H = U + PV$
- The change in a food's enthalpy can be used to estimate the energy that must be added or removed to effect a temperature change.
- Above the freezing point, enthalpy consists of sensible energy; below the freezing point, enthalpy consists of both sensible and latent energy.
- Enthalpy may be obtained from the definition of constant-pressure specific heat

$$c_p = \left(\frac{\partial H}{\partial T} \right)_p$$

Where, c_p is constant pressure specific heat, H is enthalpy, and T is temperature.



Enthalpy may be obtained from the definition of constant pressure specific heat like

$$C_p = (dH/dT)_p$$

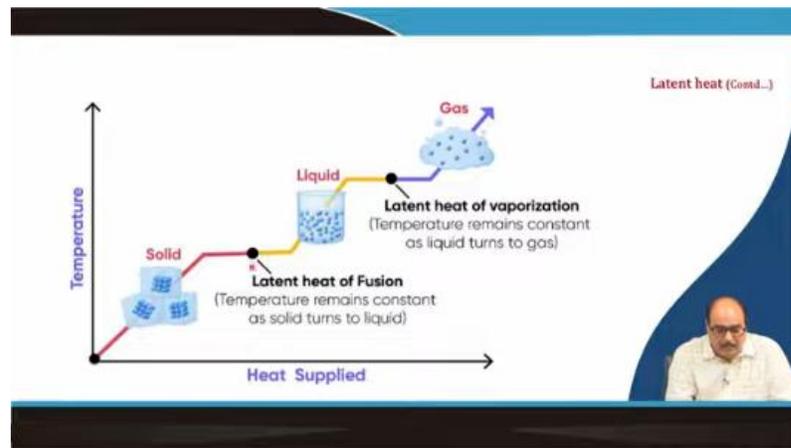
where C_p is the constant pressure specific heat, H is enthalpy and T is the temperature. So, by this you can find out enthalpy of a food system.

Latent heat

- Latent heat is the amount of heat released or absorbed at a specific temperature when unit mass of material is transformed from one state to another.
- The SI unit of latent heat is joules per kilogram (J/kg).
- Latent heat involves heat exchange without a temperature change.
- The heat exchange during the phase change from liquid to solid is the heat of fusion (hsf) or heat of solidification. Freezing water into ice or the opposite (thawing) is a common example of heat of fusion.
- The energy to change a liquid to vapor is the latent heat of vaporization.
- Latent heat of vaporization (hfg) is useful in applications involving drying or evaporation where a liquid is vaporized for ease of separation from the mixture.



Then latent heat, another important component, thermal property and the latent heat is the amount of heat released or absorbed at a specific temperature when unit mass of the material is transformed from one state to another. The SI unit of latent heat is joules per kilogram. Latent heat involves heat exchange without a temperature change. The heat exchange during the phase change from liquid to solid is the heat of fusion or also called as heat of solidification. Freezing water into ice are the opposite that is the ice when it is a it comes change to water which is called thawing and these are the common examples of heat of fusion. The energy to change the liquid to vapor is the latent heat of vaporization. Latent heat of vaporization HFG is useful in applications involving drying or evaporation where a liquid is vaporized for ease of separation from the mixture.



And in this figure that is you can understand very well what is the latent heat of fusion and latent heat of vaporization. You take that any solid material is there, then heat is supplied the temperature increases, then the solid it will come to the that is it will take that is first some for some time heat will the temperature will increase and then the

temperature becomes constant. There is no rise in the temperature of the system and here also but you are supplying the heat.

So, this heat being used for conversion of state that is matter is changing from solid to liquid all right. So, that is called latent heat of fusion that is temperature remain constant as the solid turns to liquid and when whole solid is turned to liquid again the temperature increases and then again, a phase will come when the you are supplying the heat, but temperature will not change. Temperature remains constant, but and the liquid evaporates. It converts into the form of gas. So, here this is the latent heat of vaporization. So, this is a clear that is a presentation that is how latent heat of fusion and latent heat of vaporization are taking place or playing the role in the state matter transfer from of the state from a matter of from one state to other state.

□ **Thermal conductivity**

- The thermal conductivity of a material is defined as a measure of its ability to conduct heat. It has a unit of W/m K in the SI system.
- Thermal conductivity relates the conduction heat transfer rate to the temperature gradient.
- Thermal conductivity of foods depends on temperature, composition, and porosity of material. In porous solids void fraction, shape, size and arrangement of void spaces, the fluid contained in the pores, and homogeneity plays important role.

For fruits and vegetables with water content greater than 60%, thermal conductivity can be computed by the equation, $k = 0.148 + 0.493 X_w$ where, k is thermal conductivity in W/(m K); and X_w is mass fraction of water.

- For meat products of 60% to 80% water content, Sweat (1974) suggested $k = 0.08 + 0.52X_w$
- An alternate approach is to use an equation based upon the overall food composition to estimate thermal conductivity.

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


Then thermal conductivity very important characteristics of food material or any biological material. The thermal conductivity is defined as a measure of its ability to conduct the heat. It has a unit of watt per meter degree Kelvin in the SI system. Thermal conductivity relates the conduction heat transfer rate to the temperature gradient. Thermal conductivity of foods depends on temperature, composition and porosity of material. In porous solids, void fraction, shape, size and arrangement of void spaces the fluid content in the pore and homogeneity plays important role in determining the thermal conductivity. For fruits and vegetables with water content greater than 60%, thermal conductivity can be computed by the equation

$$K = 0.148 + 0.493 X_w$$

where K is the thermal conductivity in watt per meter K and X_w is the mass fraction of water in the material in the fruits or vegetable. For materials which has moisture content more than 60% for like that of meat or meat products where moisture may be as high as 60 to 80%. Then equation a part calculation of thermal conductivity may be used

$$k = 0.08 + 0.52 X_w.$$

So, here you can see that calculation that is the constant report depending upon the water content, moisture content of the food material. So, an alternate approach is to use an equation based upon the overall food composition to estimate thermal conductivity and where this relation is given

$$K = 0.25 X_c + 1.155 X_p + 0.16 X_f + 0.135 X_a + 0.58 X_w$$

and where X_c , X_p , X_f , X_a and X_w these are the various components of the food material.

❖ Thermal conductivity values of components at 25 °C

Component	Thermal conductivity equation	k_i (W/m K)
Water	$k_{\text{water}} = 0.57109 + 1.7625 \times 10^{-3} T - 6.7036 \times 10^{-6} T^2$	0.610
Carbohydrate	$k_{\text{CHO}} = 0.20141 + 1.3874 \times 10^{-3} T - 4.3312 \times 10^{-6} T^2$	0.233
Protein	$k_{\text{protein}} = 0.17881 + 1.1958 \times 10^{-3} T - 2.7178 \times 10^{-6} T^2$	0.207
Fat	$k_{\text{fat}} = 0.18071 - 2.7604 \times 10^{-3} T - 1.7749 \times 10^{-7} T^2$	0.112
Ash	$k_{\text{ash}} = 0.32961 + 1.4011 \times 10^{-3} T - 2.9069 \times 10^{-6} T^2$	0.363

So, here these are the various thermal conductivity values of different components at 25 °C and you can find that the thermal conductivity value of water at 25 °C is 0.610 that is watt/ m k, that is the high value and the equations here can be given that is

$$k_{\text{water}} = 0.57109 + 1.7625 \times 10^{-3} T - 6.7436 \times 10^{-6} T^2$$

So, this is the equation. Similarly, the equations for the computing the thermal conductivity of carbohydrate, proteins, fat and ice etcetera are provided here. So, that is you know the food material they contain all these waters, carbohydrate, protein, fat, ice etcetera. So, when for complete that is how this material will conduct the heat and their conductivity will influence with these equations one can find out easily. Because the different components that is in the next class, we will study that food that is component

how the macromolecules how they influence the structure of the food. So, they may be placed in different that is these various components might be organized arranged in different ways. systems, etc., pores, crystals and all those things, then it will all influence the thermal conductivity of the food material. So, you can see here water obviously has maximum thermal conductivity as below these are minerals and then the least thermal conductivity of the food is the fat.

Thermal diffusivity

- Thermal diffusivity (α) is a physical property associated with transient heat flow. It is a derived property. The unit of thermal diffusivity is m^2/s in the SI system.
- It measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy.
- Materials with large thermal diffusivity will respond quickly to changes in their thermal environment while materials of small thermal diffusivity will respond more slowly, taking longer to reach a new equilibrium condition.
- The ratio of heating times of two materials of the same thickness will be inversely proportional to their respective diffusivities.
- Thermal diffusivity can be defined as

$$\alpha = \frac{k}{\rho c}$$

Where, α is thermal diffusivity,
 k is thermal conductivity,
 ρ is density, and c is specific heat.



Then thermal diffusivity, that is alpha, it is a physical property associated with transient heat flow. It is a derived property. The unit of thermal diffusivity is meter square per second in the SI system. It measures ability of a material to conduct thermal energy related to its ability to store thermal energy. Materials with large thermal diffusivity will respond quickly to changes in their thermal environment while materials of small thermal diffusivity will respond more slowly taking larger to reach a new equilibrium condition. So, the ratio of heating times of two materials of the same thickness will be inversely proportional to their respective diffusivity. So, thermal diffusivity can be calculated as

$$\alpha = \frac{k}{\rho c}$$

where k is the thermal conductivity, ρ is the density and c is the specific heat and α is the thermal diffusivity.

□ Boiling point

- The boiling point of a substance is the temperature at which its vapor pressure equals the atmospheric pressure, leading to a phase change from liquid to gas.
- The vapor pressure of most aqueous solutions is lower than that of water at the same temperature. Therefore, for a given pressure, the boiling temperature (boiling point) of the solution is higher than that of pure water.
- The boiling point is useful in evaporation and drying operations. The increase in boiling point of liquid foods, is a property of interest in the design and operation of evaporators.
- The boiling point is elevated by the presence of solute in the liquid phase as found in most foods.
- The equation used to calculate the increase in the boiling point is $\Delta T_b = k_b \cdot m \cdot i$ where, ΔT_b is increase in boiling point, k_b is boiling point elevation constant, m is molality of solution, and i is the number of particles formed when the compound dissolves.



Boiling point, boiling point of a substance is the temperature at which its vapor pressure equals the atmospheric pressure leading to a phase change from liquid to gas. The vapor pressure of most aqueous solutions is lower than that of the water at the same temperature. Therefore, for a given pressure both boiling temperature like boiling point of the solutions is higher than that of the pure water. The boiling point is useful in evaporation and drying operations. The increase in boiling point of liquid foods is a property of interest in the design and operation of evaporators. The boil point is evaluated by the presence of solutes in the liquid phase as found in the most of the foods. And the equation used to calculate the increase in the boiling point, that is if there are some solutes is present, then solutes, presence of solutes causes the elevation of boiling point. So, that can be calculated by

$$\Delta T_b = k_b m i$$

where ΔT_b is the increase in the boiling point, k_b is the boiling point elevation constant, m is the molality of the solution and i is the number of particles formed when the compound dissolves. So, by this if you know that what are the type of solutes, how much is quantity and how the solutes will result in cause the elevation of boiling point that can be find out using this equation.

Freezing point

- The freezing point of a substance is the temperature at which it transitions from a liquid to a solid.
- For water, the freezing point is 0°C (32°F) at standard atmospheric pressure (1 atm).
- The freezing point is lowered due to the presence of solutes, solids, in the water, known as freezing point depression.
- The change in the freezing point temperature is primarily dependent on the concentration or amount of solids.
- Knowing the exact freezing point temperature is useful in operations involving freezing and thawing.
- The equation $\Delta T_f = k_f \cdot m \cdot i$ is used to calculate the decrease in the freezing point, where, ΔT_f is the amount the freezing temperature decreases, and K_f is the freezing point depression constant which depends on the solvent.




<https://chem.libretexts.org>

Similarly, freezing point the freezing point of a substance is the temperature at which it transitions from a liquid to a solid. For freezing That water, for water, the freezing point is 0 °C or 32 °F at standard atmospheric pressure. That is important. that is one atmosphere, freezing point is 0 °C. The freezing point is lowered due to the presence of solute. Like boiling point was getting elevated, so here the solute presence of solutes causes depression, lowering of the freezing point. and this is known as that is the lowering of the freezing point is known as the freezing point depression. The change in the freezing point temperature is primarily dependent on the concentration or amount of the solid ah that is and knowing the exact freezing point temperature is useful in operations involving freezing and thawing that is thawing is the just reverse of freezing like freezing is the change from liquid to solid then thawing is the conversion of solid to liquid like ice to water. So, the equation

$$\Delta T_f = k_f m i$$

is used to calculate the decrease in freezing point where ΔT_f is the amount of freezing point freezing temperature decreases and k_f is the freezing point depression constant which depends on the solvent.

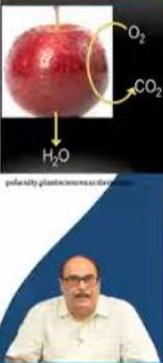
Heat of respiration & transpiration

- Fruit and vegetable products are living organisms. To maintain their life processes, they combust sugar to produce CO₂ and heat.
- The heat produced by this process is commonly called the heat of respiration (QR).
- Commodity's respiratory heat generation rate W in W/kg as a function of temperature t in °C

$$W = \frac{10.7f}{3600} \left(\frac{9t}{5} + 32 \right)^g$$

Where, f and g are respiration coefficients

- Fresh fruits and vegetables lose moisture through transpiration, which are driven by difference in water vapor pressure between the surface of a commodity and the surrounding air.
- The basic form of the transpiration model is $m = k_t (p_s - p_a)$



Then let us also touch upon the heat of respiration and heat of transpiration. You know this is an important phenomenon in the fruits, vegetables or such other perishable materials that is even after they are harvested. They these products they maintain their life processes and they combust sugar to produce carbon dioxide and heat that is the normal respiration process that is they consume oxygen, release carbon dioxide in which process sugars are converted into carbon dioxide and water and finally energy is released. So, the heat produced by this process is commonly called the heat of respiration. So, commodities respiratory heat generation rate that is W in watt/kg is as a function of the temperature that is T in degree Celsius. can be found out using the equation like

$$W = \frac{10.7fk}{3600} \left(\frac{9t}{5} + 32 \right)^g$$

where F and G are the respiration coefficients. Fresh fruits and vegetables lose moisture through transpiration, through pores, etc., which are there in the skin or peel, etc., and which are driven by difference in the water vapor pressure between the surface of a commodity and the surrounding air. So, the basic form of transpiration model is

$$m = k_t (p_s - p_a)$$

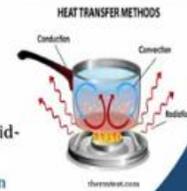
So, because of the differences in the pressure and the surface or atmospheric pressure and the pores they transfer water that is water in the form of vapors etcetera that is sweating etcetera like that.

Heat transfer in food processing

☐ Modes of heat transfer

Heat transfer occurs by **conduction, convection, and radiation**. These mechanisms can occur individually or simultaneously.

- **Conduction** is principally involved during heat transfer within solid-like materials.
 - ✓ It is the movement of heat by direct transfer of molecular energy within solids.
- **Convection** is the transfer of heat between solids and fluids.
 - ✓ It is transferred by groups of molecules that move because of a gradient of density or agitation.
- **Thermal radiation** is generated through the emission of electromagnetic waves that carry energy away from any thermal body.



Then, now after having this brief knowledge, we study of the various key thermal properties. Now, let us talk another because these thermal properties influence that is the process phenomena that is the heat transfer in the food processing. Then, when you are heating, how the heat conducts from one place to other place and then this you know I am sure that you all know very well that heat transfer occurs by three modes that is conduction, convection and radiation and this mechanism can occur individually or even in simultaneously even there are processes like baking or many other processes where different modes of heat transfer occur simultaneously even. So, the conduction is principally involved during heat transfer within solid like materials and it is the movement of heat by direct transfer of the molecular energy with the solids that is the different solid molecules they transfer the energy from one molecule to another molecule. Whereas, the convection is the transfer between solids and fluids, it is transferred by groups of molecules and that the molecules get heated and they move and the new molecule comes then the new molecule gets heated. That molecule, it moves because of a gradient of density or agitation. Then thermal radiation is generated through the emission of electromagnetic waves that carry energy away from any thermal body.

Governing equation of different heat transfer operations

Type of heat transfer	Condition	Governing equation
Radiation	Infrared heating	$Q = \sigma A T^4$
	Microwave heating	$X = \frac{\lambda_0}{\sqrt{2\pi(\epsilon' \tan \delta)^{1/2}}}$
Conduction (Unidirectional)	Steady state	$Q = k A \frac{(\theta_1 - \theta_2)}{x}$
	Unsteady state	$\frac{d\theta}{dt} = \alpha \frac{d^2\theta}{dx^2}$
Convection	Natural	$Q = h_c A (\theta_1 - \theta_2); Gr = \frac{\rho^2 g \beta^2 l^3 \Delta T}{\mu^2}; Nu = K (Gr \cdot Pr)^n$
	Forced	$Nu_c = f(Re, Pr) = \frac{h}{k}; Pr = \frac{c\mu}{k}; Re = \frac{\rho v l}{\mu}$

ρ = Density,
 β = Coefficient of thermal expansion,
 l = Characteristic length,
 μ = Dynamic viscosity,
 Gr = Grashof number,
 Nu = Nusselt number,
 Pr = Prandtl number,
 v = Velocity,
 Re = Reynolds number

Q = Heat transfer, σ = Stefan-Boltzmann constant, A = Surface area, X = Characteristic term,
 λ_0 = Free-space wavelength, ϵ' = dielectric constant, $\tan \delta$ = Loss tangent, k = Thermal conductivity,
 θ = Temperatures, x = Distance, α = Thermal diffusivity, h_c = Convective heat transfer coefficient.

These are the, I have given the different governing equations for different heat transfer operations. Like we take the radiation, that heat example of radiation where heat is transferred through radiation in the food processing is maybe you can say infrared heating or even microwave heating, etc., So, similarly for the conduction heat transfer that is unidirectional whether it is steady state or unsteady state. In the steady state

$$Q = k A \frac{(\theta_1 - \theta_2)}{x}$$

or in unsteady state it may be

$$\frac{d\theta}{dt} = \alpha \frac{d^2\theta}{dx^2}$$

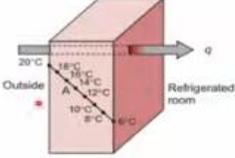
Similarly, in the equations the governing equations for convection that is natural convection or force convection are given here that you can use. So, these equations can be used to study that is to find out how the heat is transferring in different food materials and accordingly to make calculations and optimize the process parameters and processing conditions and so on.

Steady and unsteady state heat transfer you can see, Steady state conditions imply that time has no influence on temperature distribution within an object although temperature may be different and different equations within the object that you can see here. It is outside it is the cube the heat is getting transfer. It is a refrigerated room when you keep the material etcetera ok and the in different here there is it is the area. So, at different places the temperature might be different. So, through steady state conditions

are though steady state conditions are uncommon their mathematical analysis is much simpler.

Steady and unsteady state heat transfer

- Steady-state conditions imply that time has no influence on the temperature distribution within an object, although temperature may be different at different locations within the object.
- Though steady state conditions are uncommon, their mathematical analysis is much simpler. Thus, steady-state conditions are assumed for the analysis of a given problem.
- Unsteady-state (or transient) heat transfer is that phase of the heating and cooling process when the temperature changes as a function of both location and time.



(Singh & Hollman, 2014)

Steady state conditions are assumed for the analysis of a given problem. Unsteady state or transient heat transfer is the phase that phase of heating and cooling process when the temperature changes as a function of both location and time and the You can see here the since the temperature is a function of two dependent variables that is the time allocation the partial differential equation which is given

$$\frac{dT}{dt} = \frac{k}{\rho C_p r^n} \frac{d}{dr} \left(r^n \frac{dT}{dr} \right)$$

This can be used to the is the governing equation for one dimensional case that is where T is the temperature in degree Celsius, t is the time in seconds and r is the distance from the center of the center location that is m in meter. So, another special case of heat transfer involves changes in the temperature inside an object with time, but not with location and this is called lumped system.

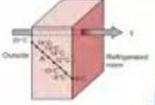
Steady and unsteady state heat transfer (Contd..)

- Since temperature is a function of two independent variables, time and location, the following partial differential equation is the governing equation for a one-dimensional case.

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p r^n} \frac{\partial}{\partial r} \left(r^n \frac{\partial T}{\partial r} \right)$$

Where, T is temperature (°C),
t is time (s), and
r is distance from center location (m).

- Another special case of heat transfer involves change in temperature inside an object with time but not with location. This is called a lumped system.



(Singh & Hollman, 2014)

Then different heat transfer equations may be that is heat content like the equation for calculating the heat content is simple that

$$Q = m C_p \Delta T$$

where m is the mass in kg, C_p is the specific heat at a constant pressure that is kilo joule per kg per Kelvin and ΔT is the temperature difference between the object and a reference temperature.

Heat transfer equations

- ❖ **Heat content**
The equation for calculating heat content is $Q = m C_p \Delta T$
Where, m is mass (kg), C_p is specific heat at constant pressure (kJ/[kg K]), and ΔT is the temperature difference between the object and a reference temperature.
- ❖ **Fourier's law of heat conduction/ Conductive heat transfer**
This law describes the rate at which heat is conducted through a material.

$q_x \propto \frac{(\text{Wall surface area})(\text{Temperature difference})}{(\text{Wall thickness})} \rightarrow q_x = -k A \frac{dT}{dx}$

Where, q_x is the rate of heat flow in the direction of heat transfer by conduction (W); k is thermal conductivity (W/[m °C]); A is area through which heat flows (m²); T is temperature (°C); and x is length (m), a variable.

(Singh & Heldman, 2014)

Fourier's law of heat conduction or conductive heat transfer. This law describes the rate at which the heat is conducted through a material. That is q_x is equal to wall surface area multiplied by temperature difference divided by wall thickness.

$$q_x = -k A \frac{dT}{dx}$$

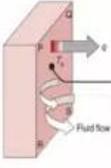
That is, you see here this is the system. That is wall thickness cross section, the heat is getting from outside and this all the dimension, length, width, all thickness are there. That is q_x is the rate which direct direction of the heat transfer by conduction, k is the thermal conductivity, A is the area, T is the temperature and dx is the length which is the variable.

Then Newton's law of cooling or convective heat transfer that is depending on whether the flow of the fluid is artificially induced or natural, that is the or whether it is artificially induced or natural, there are two types of convective heat transfer like forced convection and three which is also called a natural convection.

Heat transfer equations (Contd...)

❖ **Newton's law of cooling/ Convective heat transfer**

Depending on whether the flow of the fluid is artificially induced or natural, there are two types of convective heat transfer: **forced convection** and **free** (also called natural) **convection**.



- Consider heat transfer from a heated plate, PQRS, exposed to a flowing fluid.
- The surface temperature of the plate is T_s , and the temperature of the fluid far away from the plate surface is T_∞ .
- Rate of heat transfer from the solid surface to the flowing fluid is proportional to the surface area (A) of solid in contact with the fluid, and the difference between the temperatures T_s and T_∞ .

$q = h A (T_s - T_\infty)$ Where, A is area (m^2), and h is the convective heat-transfer coefficient expressed as $W/(m^2 \cdot ^\circ C)$.

(Singh & Firdman, 2014)

So, considering the heat transfer from a heated place that is P, Q, R and S exposed to a flowing fluid, the surface temperature of the plate is T_s and the temperature of the fluid away from the plate surface is T_∞ . So, the rate of heat transfer from the solid surface to the flowing fluid is proportional to the surface area A of solid in contact with the fluid and the difference between the temperature T_s and T_∞ .

$$q = h A (T_s - T_\infty)$$

where A is the area, h is the convective heat transfer coefficient. So, you can calculate the q convective heat transfer.

Then Stephen Boltzmann law of radiation or radiation heat transfer and this radiation heat transfer occurs between two surfaces by emission and later absorption of electromagnetic waves. All objects at a temperature above 0-degree absolute like at 0-degree Kelvin or at above $-273.5 \text{ }^\circ C$ they emit thermal radiation. Thermal radiation emitted from an object surface is proportional to the absolute temperature raised to the fourth power and the surface characteristics.

Heat transfer equations (Contd...)

❖ **Stefan-Boltzmann law of radiation / Radiation heat transfer**

- Radiation heat transfer occurs between two surfaces by the emission and later absorption of electromagnetic waves.
- All objects at a temperature above 0 absolute (0 K or $-273.5 \text{ }^\circ C$) emit thermal radiation.
- Thermal radiation emitted from an object's surface is proportional to the absolute temperature raised to the fourth power and the surface characteristics.
- More specifically, the rate of heat emission (or radiation) from an object of a surface area (A) is expressed by the equation $q = \sigma \epsilon A T_A^4$

Where, σ is the Stefan-Boltzmann constant equal to $5.669 \times 10^{-8} W/(m^2 K^4)$; T_A is absolute temperature; A is the area (m^2); and ϵ is emissivity, which describes the extent to which a surface is similar to a blackbody. For a blackbody, the value of emissivity is 1.

(Singh & Firdman, 2014)

Specifically, the rate of the heat submission that is the rate of the heat emission or radiation from an object of a surface area A is expressed by the equation

$$q = \sigma \varepsilon A T_A^4$$

where, σ is the Stephen Boltzmann constant equal to $5.669 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4)$. T_A is the absolute temperature; A is the surface area and ε is the emissivity, which describes the extent to which a surface is similar to a black body. For a black body, the value of emissivity is 1.

Heat transfer equations (Contd...)

❖ **Overall heat transfer coefficient**

- This concept is used when multiple modes of heat transfer occur simultaneously (e.g., conduction through a wall and convection on either side).
- It represents an effective heat transfer coefficient that accounts for conduction, convection, and radiation.

$q = U A \Delta T$

Where, q = Total heat transfer rate (W),
 U = Overall heat transfer coefficient ($\text{W}/\text{m}^2\cdot\text{K}$)
 A = Surface area (m^2)
 ΔT : Temperature difference across the system (K or $^{\circ}\text{C}$)

So, the overall heat transfer coefficient that this concept is used when multiple modes of heat transfer occur simultaneously either through conduction of a wall or convection on either side. It represents that the effective heat transfer coefficient that accounts for conduction, convection or radiation and it is

$$Q = U A \Delta T$$

Where Q is the total heat transfer rate, U is the overall heat transfer coefficient, A is the surface area in square meter and ΔT is the temperature difference across the system that is $^{\circ}\text{K}$ or $^{\circ}\text{C}$.

Application of thermal properties

- Knowledge of the thermal properties of foods is essential in the analysis and design of various food processes and food processing equipment involved in heat transport, with respect to heat transfer or energy use, such as in extrusion cooking, drying, sterilization, cooking, etc.
- Information of heat transfer is needed to design and optimization of handling and processing units such as tanks, pumps, pipes, chillers, freezers, evaporators, and heat exchangers, etc.
- Specific heat is used to determine the amount of heat transfer in a process.
- Thermal conductivity is used in designing of the heat transfer equipment such as heat exchangers.
- Thermal diffusivity is useful in analyzing heat transfer phenomena and design of refrigeration, and other process equipment.



So, application of thermal properties in food processing, obviously, as I told earlier also, the knowledge of thermal properties of food is essential in analysis and design of various food processes and food processing equipment involved in the heat transport with respect to heat transfer or energy use, such as during the extrusion cooking, in the drying, sterilization or general cooking processes. Information of heat transfer is needed to design and optimize thermal optimization of handling and processing units such as the tanks, pumps, pipes, chillers, freezers, evaporators, heat exchangers, etc. Specific heat is used to determine the amount of heat transfer in a process.

Thermal conductivity is used in designing of the heat transfer equipment such as heat exchangers, thermal diffusivity is used in analyzing heat transfer phenomena and designing of refrigeration or other process equipments. Understanding the thermal properties of food helps optimize drying processes by effectively removing moisture while maintaining the product quality.

Thermal properties are critical in determining the temperature and time required to inactivate pathogens and spoil microorganisms in food products. That is during canning process, during pasteurization, sterilization and so on. So, knowledge of these properties helps in designing various equipment like ovens, fryers, extruders and optimizing the processes like baking, frying, extrusion times and temperature that is what are the time, how many times this process should be done or temperatures etcetera that can be found out using their thermal characteristics.

Application of thermal properties (Contd..)

- Understanding the thermal properties of foods helps optimize drying processes by efficiently removing moisture while maintaining product quality.
- Thermal properties are critical in determining the temperature and time required to inactivate pathogens and spoilage microorganisms in food products (e.g. canning, pasteurization, sterilization, etc).
- Knowledge of these properties helps in designing ovens, fryers, extruders, and optimizing baking, frying, extrusion times and temperatures.
- Understanding the thermal resistance of microorganisms helps in designing thermal treatments that ensure food safety without compromising quality.
- Understanding and leveraging these thermal properties in cooking, preservation, and equipment usage are fundamental in ensuring food safety, quality, and efficiency in the food industry.



So, understanding the thermal resistance of microorganisms help in designing the thermal treatments that ensure food safety without compromising the quality. Understanding and leveraging these thermal properties in cooking, preservation and equipment usage are fundamental in ensuring food safety, quality and efficiency in food industry.

Thermodynamics of food biopolymers

- Thermodynamics deals with the study of the exchange of energy between the system and its surroundings, and among the components of the food system.
- When the food is processed, there are series of energy exchanges causing the thermal effects, for example, heating, cooling, initiation, and activation of any reaction.
- Thermodynamics provides insight and related useful information regarding in which direction a system would initiate and what would be the influence of the processing variables (such as temperature, pH, solute : solvent concentration) on the system.

❖ **Key thermodynamic concepts in food**

Gibbs free energy (G) is an important parameter in thermodynamics, required for understanding the phases occurring at the equilibrium.

$$\Delta G_{mix} = \Delta H_{mix} - T\Delta S_{mix}$$

Where, ΔG , ΔH , ΔS , T and mix stand, respectively, for Gibbs free energy, enthalpy, entropy, temperature, and mixing.



So, the thermodynamics of food biopolymers, let us throw some light on this. The thermodynamics deals with the study of the exchange of energy between the system and its surroundings. and among the components in the food system. So, when a food is exposed, there are series of heat exchanges causing the thermal effects. For example, heating, cooling, initiation and activation of any reaction takes place when there is a thermal process or heat transfer. So, thermodynamics provides inside and related useful information regarding in which direction a system would initiate and what will be the would be the influence of the processing variables such as temperature, pH or solute

solvent concentration, etc. on the system. So, the key thermodynamic concepts in food includes temperature gives free energy. It is an important parameter in thermodynamics and it is required for understanding the phase phases occurring at the equilibrium.

$$\Delta G_{\text{mix}} = \Delta H_{\text{mix}} - T \Delta S_{\text{mix}}$$

Where, ΔG , ΔH , ΔS , T and mix is standard respectively for gives free energy enthalpy entropy temperature and mixing.

So, for food thermodynamics can be understood by the Flory-Huggins theory FST. FST is a lattice model based on the dissimilarity among the molecules based on their size. Each lattice site is either occupied by the solvent molecule or by the polymer. And it will deal with the free energy on the polymer solution like

$$\Delta G_{\text{mix}} = RT (x_{12} \theta_1 \theta_2 + \theta_1 \ln \theta_1 + \frac{\theta_1}{x} \ln \theta_2)$$

Where θ represents the volume fraction of the solvent 1 and the solute 2 and

$$X_{12} = -k A \frac{\Delta H_{\text{mix}}}{RTN\theta_2}$$

Key thermodynamic concepts in food (Contd..)

- Food thermodynamics can be understood by Flory Huggins's theory (FHT).
- FHT is a lattice model based on the dissimilarities among the molecules based on their size. Each lattice site is either occupied by the solvent molecule or by the polymer.
- It deals with the free energy of the polymer solution as

$$\Delta G_{\text{mix}} = RT \left(x_{12} \theta_1 \theta_2 + \theta_1 \ln \theta_1 + \frac{\theta_2}{x} \ln \theta_2 \right)$$

Where, Φ represents the volume fraction of the solvent (1) and solute (2).

$$x_{12} = \frac{\Delta H_{\text{mix}}}{RTN\theta_2}$$

The interaction term x_{12} is termed as Flory Huggins Interaction parameter (FHIP).

- The x_{12} represents the ratio of the energy involved in interaction and that of thermal energy.
- The positive and negative values of x_{12} represent repulsion and attraction among the molecules, respectively. *

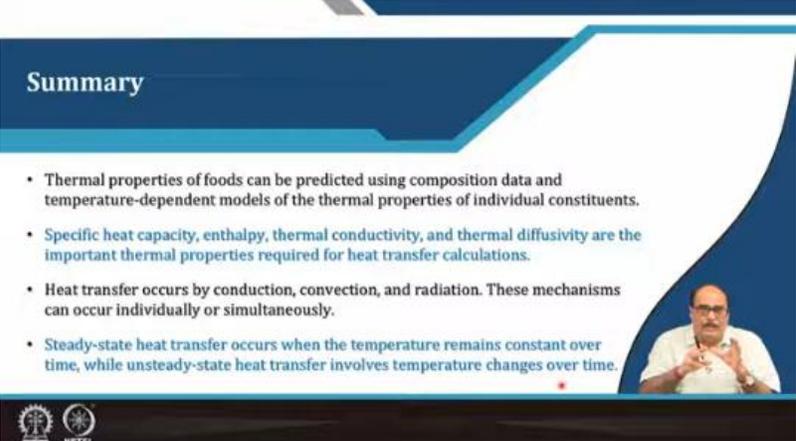


The interaction term X_{12} is termed as Flory-Huygens interaction that is FHI parameter. The X_{12} represents the ratio of the energy involved in interaction and that of the thermal energy. The positive and negative values of X_{12} represent repulsion and attraction among the molecules respectively.

So, regarding the application of thermodynamics in food, thermodynamics can be used for the development of food products and to better understand the factors to determine the

polymer's ability to stabilize the functional ingredients. The crystallization of drugs in the polymer system reduces solubility, bioavailability and dissolution rate. Application of the FHI parameters predicted miscibility and identify the composition of the best thermodynamic stability of drugs in polymer system.

Flory-Rainier theory was applied to understand the soft matter fundamentals during the cooking of more meat to understand the heat and mass transfer phenomena. The theory was also used to understand the mass transfer phenomena in the swelling and shrinkage behaviors or structural integrity of the gels and the water holding capacity of various food products such as meats, jam, jellies, vegetables, etc.



Summary

- Thermal properties of foods can be predicted using composition data and temperature-dependent models of the thermal properties of individual constituents.
- Specific heat capacity, enthalpy, thermal conductivity, and thermal diffusivity are the important thermal properties required for heat transfer calculations.
- Heat transfer occurs by conduction, convection, and radiation. These mechanisms can occur individually or simultaneously.
- Steady-state heat transfer occurs when the temperature remains constant over time, while unsteady-state heat transfer involves temperature changes over time.



So, now finally, I would like to summarize the whole lecture discussed today that is the thermal properties are very important parameters in understanding that is when the food is heated or when we cool down, how the system behaves, how it will influence the various structural and compositional matters, its functionality, its quality and all those things. It becomes very important to really analyze and understand fully the various thermal characteristics of the food. And obviously, as I told you earlier also, the thermal property depends upon its composition. If the moisture is more, specific heat will vary and all those things. And also accordingly, that is depending upon what is the composition of various ingredients. But like fat, water, carbohydrate, vitamin, mineral, all this, their content, how they are present, it may influence the thermal characteristics, etc. So, one has to properly understand this so that wherever required, these processes can be thermal processes, that is either heating or cooling and all those things can be properly regulated and equipment can be properly designed, it can be properly optimized to get the good quality food and safe food.

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Just thank you very much for your patience hearing.



THANK YOU!