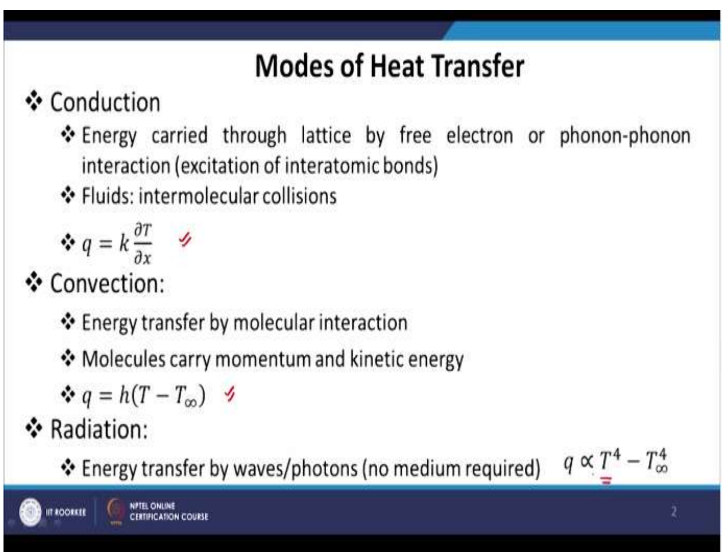
Radiative Heat Transfer
Prof. Ankit Bansal
Department of Mechanical and Industrial Engineering
Indian Institute of Technology – Roorkee

Lecture - 01
Introduction

Hello friends, I welcome you to this course on radiative heat transfer. Heat transfer plays an important role in engineering applications. In engineering, we often require to transfer heat from one fluid to the other, sometimes from one surface to the other and this is very important in the application of combustion, energy production, power generation units and many other applications.

So heat transfer is an important topic in engineering. There are many modes of heat transfer. Heat can transfer from one fluid or one surface to another by means of conduction, by means of convective heat transfer as well as by virtue of photon that is called radiative heat transfer. In this course, we will learn about the radiative heat transfer. Before, we discuss the basics of radiative heat transfer, it is important to distinguish the 3 modes of heat transfer, namely the conduction, convection and radiation.

(Refer Slide Time: 01:38)



If we look into the physical aspects of the heat transfer, the heat transfer by conduction takes place due to phonon-phonon interaction. So at a molecular level if you look at the structure of the solids, we have atomic lattice and due to the vibration in the lattice which we call phonon-phonon interaction, the conductive heat transfer takes place. So the effect is very local.

Similarly, if we are talking about conduction in fluids, we have intermolecular interaction and this is also very local.

So conductive heat transfer is basically a local effect. Similarly, convective heat transfer, in convective heat transfer mostly the mechanism remains the same that is the intermolecular interaction in fluids and phonon-phonon interaction in solids but in convection which is basically the predominant mode of heat transfer in fluids, we also have bulk motion of the fluid which basically increases the heat transfer by significant magnitude.

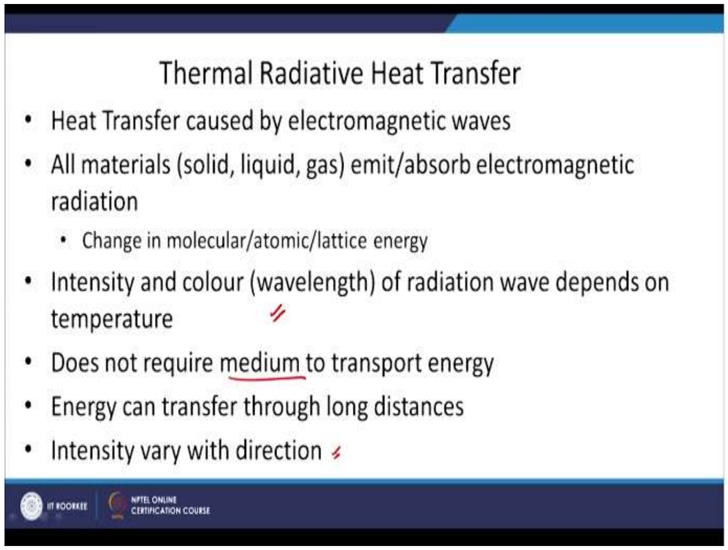
But again the convective heat transfer is also a local effect. Also, in conduction the heat flux is basically proportional to the gradient of temperature which is basically linear dependence on temperature and in convective heat transfer also, the heat flux is basically a linear function of the temperature of the fluid. On the other hand, radiation is not a local phenomena. Radiation can travel from one point to another; it does not require any medium.

It can travel long distances without attenuation. The heat flux in radiation basically depends on the fourth power of temperature. So that makes it very crucial in high temperature applications. So whenever we have high temperature applications, the effect of radiation is going to be important because it depends on power fourth of the temperature.

So there are many aspects that make radiation much more difficult and different from the other two modes of heat transfer that is conduction and convection. So we will learn what are those factors that make radiation different and challenging from heat transfer point of view.

So just looking at the basic fundamental aspect of radiation, radiation is basically electromagnetic waves. Although, there are particle theory and there is a wave theory and electromagnetic radiation can also be represented in the form of photons but primarily it can be represented as electromagnetic wave. All materials whether it is solid, liquid or gas, they have the capacity to absorb radiation as well as emit radiation.

(Refer Slide Time: 04:01)



In fact, all the substances, all materials, they continuously emit radiation or photons if the temperature of the material is >0 K. So even at the lowest most temperature >0, the substances or materials are emitting radiation and the mechanism of emission and absorption of radiative energy is basically the change in internal energy. So for example, in gases we have internal energy in the form of rotational and vibrational degrees of freedom.

In molecules and atoms of gases, we have these degrees of freedom, internal degrees of freedom in which energy is stored and when energy state changes, internal energy state changes there may be an emission of photon. Similarly, when the photon is absorbed, then the energy stored in the internal modes of the gas may change. Same thing happens with fluid and in solids.

In solids, there is a phonon-phonon interaction in the case of conduction but when a solid absorb radiation there may be increase in the lattice vibration of the solid. So we basically have a change in internal energy as a result of emission and absorption of photon. Now there are many factors that makes radiation difficult and different from conduction and convection. The first is basically the wavelength.

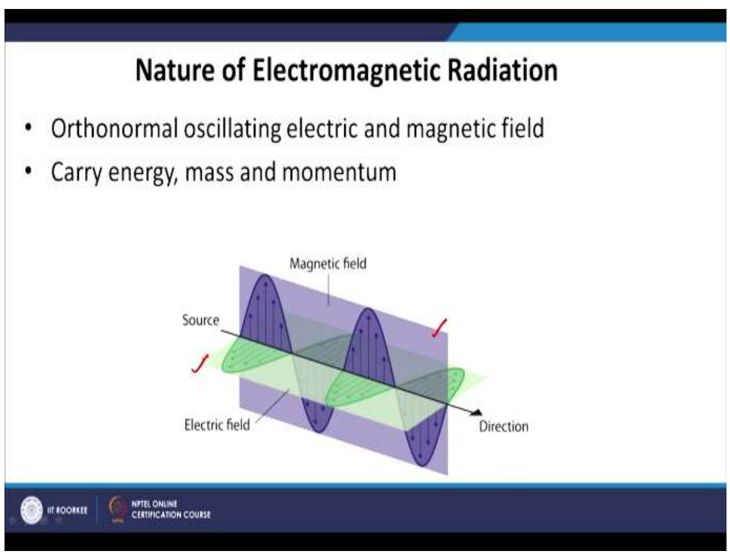
So radiation is a mechanism of heat transfer which depends on wavelength and wavelength is basically identified by the color of radiation. We have red light, we have blue light and we have radiation all the way up to radio waves, microwaves on the higher wavelength side and we have radiation in gamma rays, x-rays on the lower wavelength side. All these are basically form of electromagnetic radiation.

And the color or wavelength of emission and absorption depends on the temperature of the solid or the fluid. So temperature basically decides what will be the wavelength of the emission and absorption. Radiation does not require a medium, so radiation can travel in vacuum. We have solar radiation reaching us. Solar radiation basically travels in vacuum without being affected by any sort of attenuation or absorption in the atmosphere.

Because there is no atmosphere as such from sun to earth outer atmosphere while the same radiation when enters into earth's atmosphere is subjected to absorption by the gases in the atmosphere. The third aspect that makes radiation different is the intensity variation with direction. So intensity or radiation, radiative heat transfer, it depends on direction. If you look at up heated metal plate, normal to the surface of the plate it looks like a different in brightness.

While you same plate when holded at an angle appears at a different intensity, different brightness.

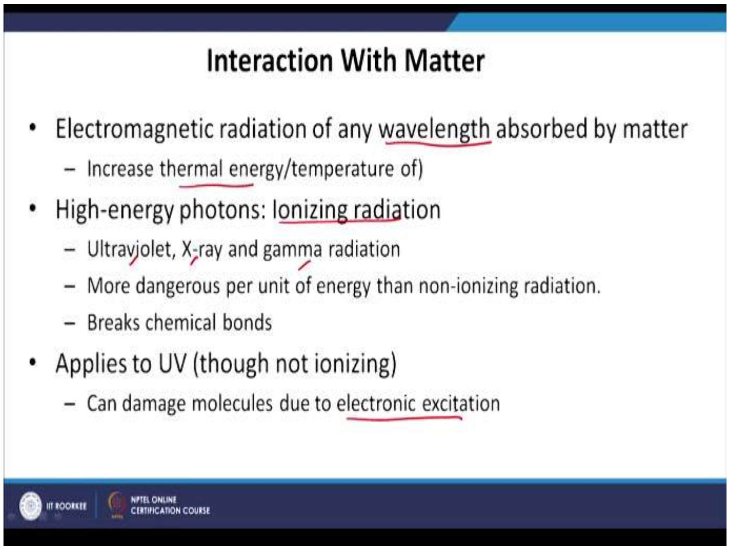
(Refer Slide Time: 07:36)



So what is the basic nature, fundamental nature of electromagnetic radiation? So the name itself basically gives you an idea that it is basically electro and magnetic radiation or waves, it is basically oscillating electric and magnetic waves which are orthonormal to each other. That means they oscillate in the perpendicular planes. So this is the plane of magnetic field which is oscillating and this is the plane of electric field.

And they basically are orthonormal to each other. That means they are in perpendicular planes. These waves carry energy but they also carry mass and momentum.

(Refer Slide Time: 08:12)



Now how this radiation basically interacts with matter? Now electromagnetic radiation can be absorbed by a matter whether it is solid, liquid or gas, all the wavelengths, all wavelengths that means starting from x-rays to radio waves, all sort of wavelengths can be absorbed by a matter and the manifestation of this absorption of radiation will be the increase in internal energy of the matter.

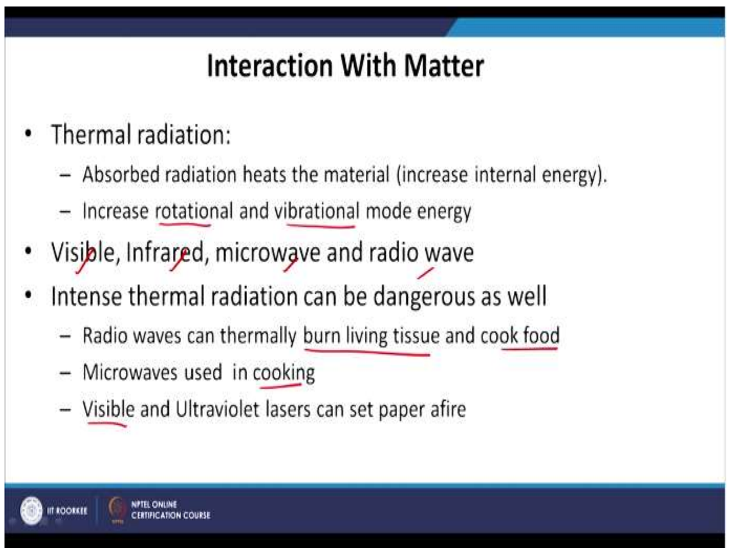
So it increases the thermal energy or temperature of the matter. Now we basically distinguishing two types of electromagnetic radiation, one which we have very high energy, we call it ionizing radiation because the energy of these radiation is so high that they can ionize or eject an electron from the substance such as ultraviolet, x-rays, gamma radiation. They have low wavelength, they are very energetic and they can eject an electron from the substance.

And that is why they are very dangerous, so you must have read some many times in the x-ray rooms, there is a warning sign because these are ionizing radiation. Overexposure to this type of radiation may be very harmful to the body. It may leads to breaking down of chemical bonds whether it is in the biological material or otherwise. So these materials are dangerous. When exposed to this type of radiation, a material may undergo what we call ionization and chemical bonds may break.

Ultraviolet light which basically is intermediate energy content also is a dangerous. Although, it is classified as non-ionizing but still it is dangerous in the sense that it can leads to electronic excitation within the matter and this electronic excitation itself is very dangerous. So with short wavelengths and high-energy photons are basically classified as ionizing radiation.

On the other hand, there is something called thermal radiation which is basically the most important from heat transfer point of view and we have basically in this category visible radiation, infrared, microwave and radio waves.

(Refer Slide Time: 10:22)



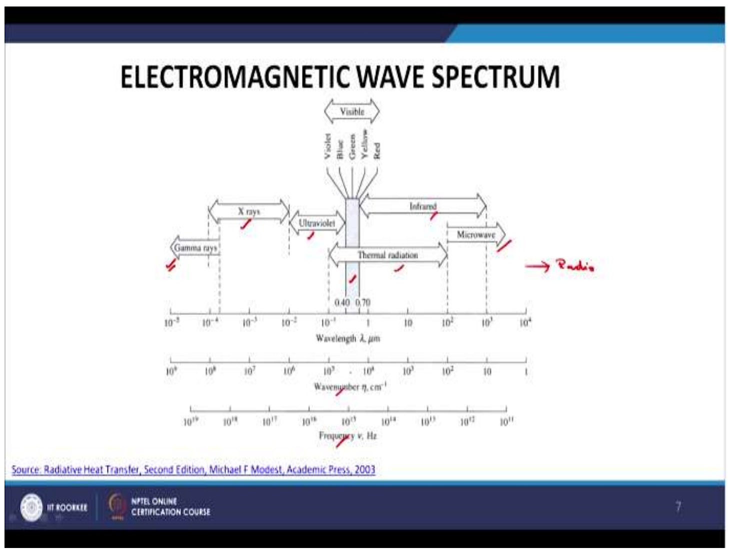
So all these radiations are basically long wavelength >0.1 micron, so the wavelength of these radiation will be >01.1 micron and they are classified as thermal radiation because these radiation are basically responsible for transferring heat when absorbed within the matter, they increases the internal energy of the material and that is why they are called thermal radiation. The increase in internal energy is basically attributed to rotational and vibrational mode of energy which are basically increased or excitation.

The rotational modes may get excited when the radiation is absorbed. Vibrational modes may also get excited and these internal modes when excited basically absorb or emit radiation. It is not to be misunderstood that thermal radiation is not dangerous. When the intensity of thermal radiation is high, it can also be dangerous. For example, radio waves of significantly high intensity can also burn the tissues.

They are in fact used for cooking food. Microwaves we all know is used in cooking. So when the intensity of radiation in thermal radiation is high, that means long wavelength radiation when the intensity is significantly high, they can also be pretty dangerous. Lasers are also in this category which lasers are normally long wave radiation and they can also be potentially very dangerous.

We all have seen focusing visible radiation of sun using some kind of lens on a piece of paper basically leads to fire, the paper may burn. So when focused, when concentrated, the intensity is very high even the long wavelength radiation can be dangerous.

(Refer Slide Time: 12:10)

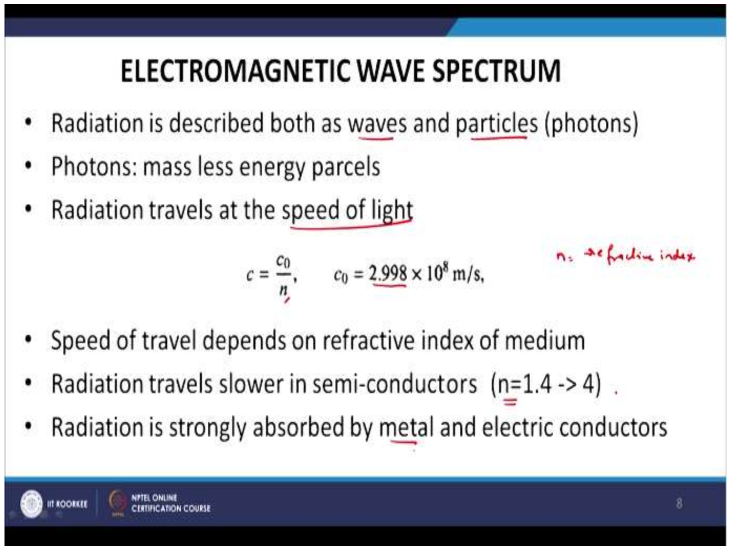


So this is a basically spectral distribution of the electromagnetic spectrum. The shortest wavelength is basically the gamma rays. So on the left, the shortest wavelength, the most energetic photon or gamma rays followed by x-rays, ultraviolet then visible. Visible is very short wavelength interval starting from 0.4 micron to 0.7 micron. The most energy visible photons are basically violet and then they decrease in intensity.

Red is the weakest visible radiation and after red is all infrared we have thermal radiation, infrared radiation, microwave and further microwave we have radio waves. So we have classified the spectrum into different regions. The most energetic is gamma rays and the weakest are radio waves. Now this wavelength is just one way of representing the spectrum or the color of the wave light or the electromagnetic spectrum.

The other modes may be frequency and wave number; we will discuss this in the next slides. So there are number of waves of representing the spectrum. Wavelength is just one way of representing it.

(Refer Slide Time: 13:30)



So we represent radiation as waves as well as particles. Photons are basically massless particle but that does not mean that all electromagnetic radiation basically have are massless. Some particles may carry momentum and mass such as alpha particles and so on, so all the particles may not be massless. Photons may be massless but some particles may carry momentum as well.

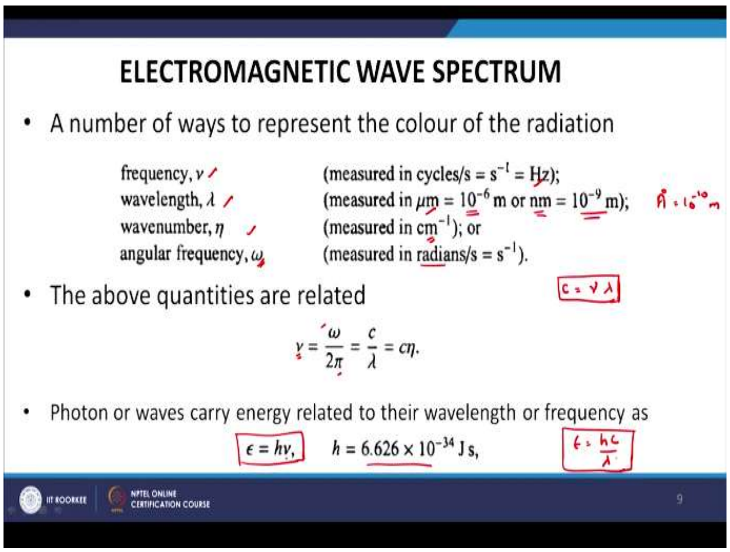
Normally, the radiation, electromagnetic radiation travels with the speed of sound sorry the speed of light. The speed of light is given by 2.998×10^8 m/s in vacuum while the same when taken in a medium with refractive index n is given by c_0/n where n is the refractive index of the medium. Now how fast the electromagnetic radiation travels, it depends on the refractive index.

In vacuum, the speed is almost 3×10^8 m/s but when the same light or electromagnetic spectrum travels through a semiconductor where the refractive index may be 1.4 to 4, the speed will be significantly low, so the speed of light will be less than the speed in the vacuum and semiconductors also strongly absorb radiation. So some amount of radiation will be absorbed in the semiconductor.

Because they are also metals which have electric conductors, so metals have electrons, free electrons. So wherever the material contains free electrons, the radiation will be strongly absorbed. Semiconductors also absorb radiation but the mechanism of absorption in semiconductor is little different. So both semiconductors and metals, they absorb radiation and the mechanism of absorption of radiation in metals is basically the free electrons which absorb significant radiation.

We will discuss this aspect as we go into this course more thoroughly.

(Refer Slide Time: 15:37)



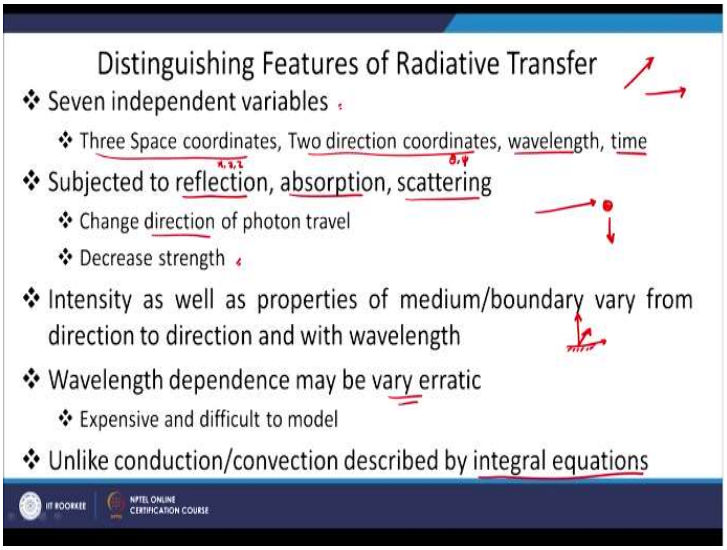
So there are a number of ways of representing the color or the spectrum, we have frequency which is represented in cycles per second or Hertz. Then, we have wavelength which is normally represented in micron or sometimes angstrom also. So micron is 10^{-6} meter, nanometer is 10^{-9} meters, angstrom is 10^{-10} meter. Now wave number is also very important especially in combustion wave number is used.

So wave number is basically the units are in centimeter^{-1} and sometimes but very rarely angular frequency is also used to represent the electromagnetic spectrum. The units are radians per sec or sec^{-1}. Now how to convert one units into another, this is some rules, so frequency is basically angular frequency/(2 π) and this is c/λ. So c is the speed of light and it is equal to n times λ where n is the v λ, v is the frequency of the light or radiation and λ is the wavelength.

So $c = v\,\lambda$ basically gives you the conversion from one unit to the another, so $c = v\,\lambda$. Now the energy of the photon can also be written as the amount of energy a photon single photon carries is given by the frequency v and h where h is the Planck constant. So energy of a single photon is basically equal to $h \times v$ where h is the Planck constant equal to 6.626×10^{-34} J-s and v is the frequency.

We can also write the energy of this photon as equal to $h \times c/\lambda$ where we have substituted v as c/λ. So this is again the energy of a single photon in terms of wavelength and speed of light.

(Refer Slide Time: 17:40)



So what are the distinguishing features of radiative heat transfer compared to conduction and convection, the problem of radiative heat transfer is going to be very challenging. As we go along this course, we will understand there are many challenges. The first challenge is that the number of independent variable is very large. So we have 3 space coordinates, normally this we will have in conduction and convection also *xyz*.

But what we do not have in conduction and convection is directional coordinates. As I explained, the intensity of radiation traveling in this direction is going to be different and intensity traveling in this direction is going to be different. So intensity or radiative heat transfer depends on direction of motion of photons. So there are 2 directional coordinates, normally the direction is represented by 2 angles, polar angle theta (θ) and azimuthal angle psi (ψ).

So two angles are required to represent the direction and then we have wavelength and time. So these 7 independent variables make the problems very challenging. Then, the radiation is subjected to reflection, absorption and scattering. Heat transfer by conduction and convection is by diffusion. While heat transfer by radiation involves not only diffusion which is basically the absorption and scattering but also it involves reflection.

Due to scattering, the photon may change direction. Suppose there is a radiation traveling in one direction and then there is a particle, after hitting this particle the photon may travel in a different direction. So this is called scattering. So this change in direction again is going to create lot of problems for us when we solve the radiative transfer equation and the intensity of radiation is subjected to attenuation or it will decrease in strength when it undergoes reflection, absorption and scattering.

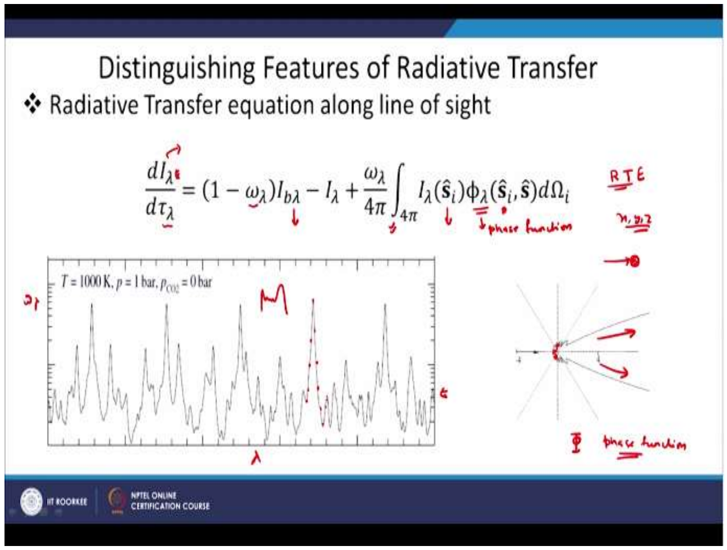
The other challenging part is that the properties of the medium and the boundary they vary with direction as well as wavelength. So let us say we have a surface and we want to find out what is the amount of radiation emitted from this surface. Now this emitted energy depends on wavelength. So this surface will have a different radiation. In red region of the spectrum, it will emit different intensity in infrared.

So this amount of energy emitted by this surface will be different for different wavelengths and it will be different for different angles also. So amount of radiation emitted at this angle may be different. It may be different at this angle, different at this angle. So this directional and wavelength dependence makes the problem very difficult and the story does not end here. The wavelength dependence is normally very erratic.

So it may be very large at one wavelength and then again very small at another wavelength. Again, it may large at other wavelength, so this spectral variation or the dependence of properties on wavelength is going to be very erratic. We will see how this varies in the next slide, so all these effects make the problems very difficult. Conduction and convection problems can be solved using differential equations, partial differential equations.

On the other hand, the radiation problem is not represented by a normal differential equation, ordinary or partial. It is represented by integral equation, the boundary conditions as well as the equation of transfer is represented by an integral equation. We will derive this equation in this course and we will learn that how difficult to solve this integral equation is. So all these factors make the radiation problem very difficult.

(Refer Slide Time: 21:28)



So this is the equation of radiative transfer which we will derive in one of the lectures. This is the radiative transfer equation and if you look at the number of variables here, so we have dependent variable as intensity and then we have wavelength. Now this radiative transfer is written in a given direction, so we have direction as a variable and then this tau lambda (τ_λ) is unknown dimensional coordinate.

So we will have *x, y* and *z* spatial coordinates if you are solving this equation in 3D. In non-dimensional form, it has been written as tau where tau (τ) is the optical distance. So this equation is going to be very challenging but what makes this problem different from conduction and convection is the integral that appears on the right hand side and this integral makes this equation integral equation which is very difficult to solve.

The second difficulty is the spectral part. So here we have coefficient, let us say this is the omega (Ω). So Ω only we are plotting, so Ω is basically a measure of absorption and scattering within the medium how the medium through which the photon is traveling absorbs and scatters the radiation. So that basically is given by this Ω which is also called single-scattering albedo.

So this may very erratically, you see that along the different wavelengths, the value of Ω go up and down very erratically okay. So there is a sharp gradient, sharp fluctuations in the spectrum and when we have to solve this equation for each and every wavelength. So this equation needs to be solved for each and every wavelength and because the spectral is so erratic, we have to solve at very fine resolution.

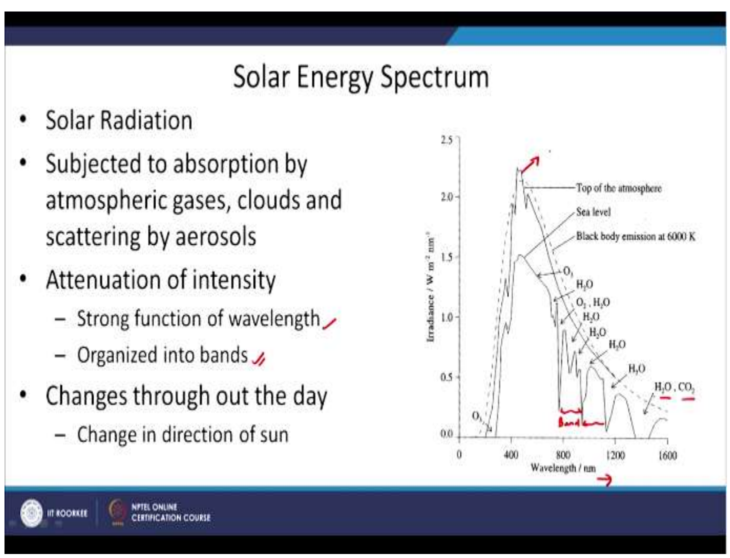
We have to solve for this equation at this wavelength, this wavelength, this wavelength and so on. So we have to solve this equation many times on large number of wavelength and that makes it very challenging and the last part that makes this most challenging is the scattering phase function. This is the phase function *($\phi_\lambda(\hat{\mathbf{s}}_i, \hat{\mathbf{s}})$)*.

Now what this phase function implies is that radiation coming from this direction once it strikes a single particle or a particle cloud, some part of this energy may go in the forward direction in this direction and some part small part may go into different directions. So this is the scattering phase function *($\phi_\lambda(\hat{\mathbf{s}}_i, \hat{\mathbf{s}})$)*.that basically tells you a radiation coming from some direction, how this radiation will be redistributed in different directions after scattering. This is called scattering phase function *($\phi_\lambda(\hat{\mathbf{s}}_i, \hat{\mathbf{s}})$)*..

And if you look at this thing, this is very erratic, this phase function is basically not symmetric and it is very non-homogeneous, some part is scattered in the forward direction, some part is scattered in the backward direction and the distribution is not isotropic at all. So this also makes the problem very challenging to solve.

Now as an understanding of all this phenomena that we discussed in the introduction part of this course, solar radiation we all have some idea about solar radiation. We receive radiation from sun, sun behaves like a blackbody, we all know that the temperature of the sun is around 5800 K.

(Refer Slide Time: 24:59)



And at that temperature, the sun spectrum is looked like this. This is the solar spectrum at the outside atmosphere, so when the sun radiation hits the top of the atmosphere of our planet, the spectrum looks like this; however, when the sun spectrum or sun radiation reaches the surface of the earth, it looks very different. So if you look at the two spectrums, one top of the atmosphere and one at the surface of the earth, the two spectrums look very different.

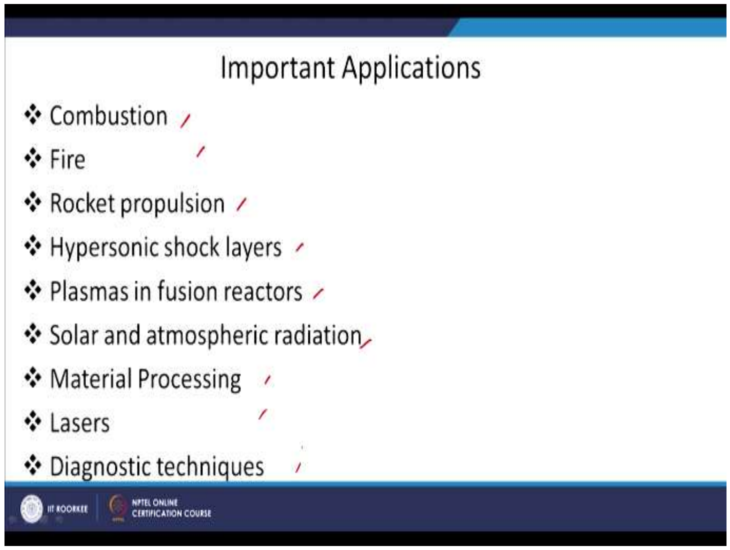
The spectrum at the earth's surface is basically much less, the intensity is much less but the intensity has decreased unevenly, somewhere this intensity has increased more, somewhere the intensity has decreased less and we have what we call the band formation. These are band formation. So energy of sun is absorbed in different band formations and we have to take into account these bands if you want to know how much total energy from the Sun we are receiving at the earth.

So there are strong function of wavelength, as we seen this is the wavelength and it is organized into bands. So these are just few gases that have been taken into account. CO and water vapour are the major species, major gases that absorb radiation in the atmosphere but there may be more like there will be sulfur dioxide, there may be methane, there may be NOx, there may be chlorofluorocarbons, there may be particles, clouds.

So this all phenomena makes the radiative transfer in atmosphere much more complicated and this changes throughout the day because the sun angle changes from noon to evening. From morning to noon and noon to evening, the direction of the sun changes, so the radiation has to travel different distance and different angle and we have already seen that radiation is a phenomena that depends on direction.

So this spectrum will change from time to time, it will look different in the morning, it will look different in the noon and it will look different in the evening because different absorption and scattering will take place at different times of the day.

(Refer Slide Time: 27:06)



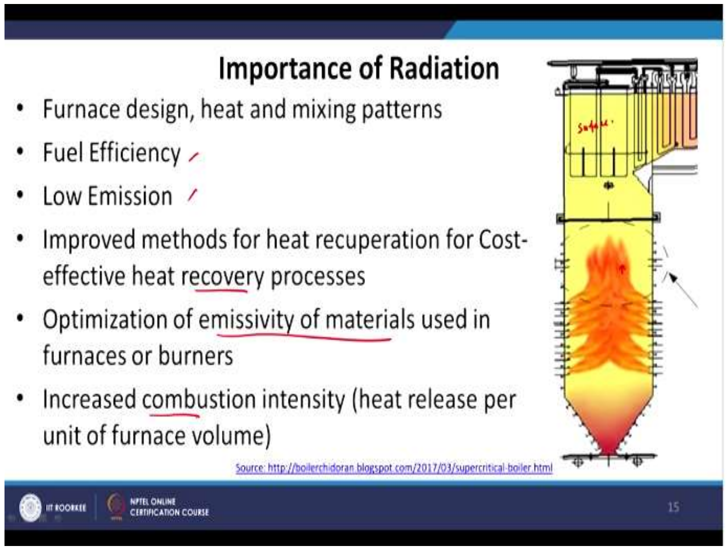
So some important applications of radiation that we will focus and some of these applications are basically combustion, fire, all these are high-temperature applications, rocket propulsion, hypersonic flow around the spacecrafts. Then, fusion reactors, we have plasmas, then solar and atmospheric radiation, furnaces, material processing, lasers and many optical diagnostic techniques.

All they rely much on radiative transfer and radiation. So this course takes significance because there are so large number of applications and not just the high temperature combustion problems but also low temperature solar applications also radiation plays an important role.

(Refer Slide Time: 27:49)

So these are some of the images to understand the importance of the radiation. We have fire, then furnaces, then flame and you see there flames of different color, they appear as a result of different gases that radiate within these flames, solar energy, solar radiation and then this is space shuttle. In space shuttle, there is very high temperature in the space shuttle that makes it radiate a significant amount of energy.

(Refer Slide Time: 28:22)



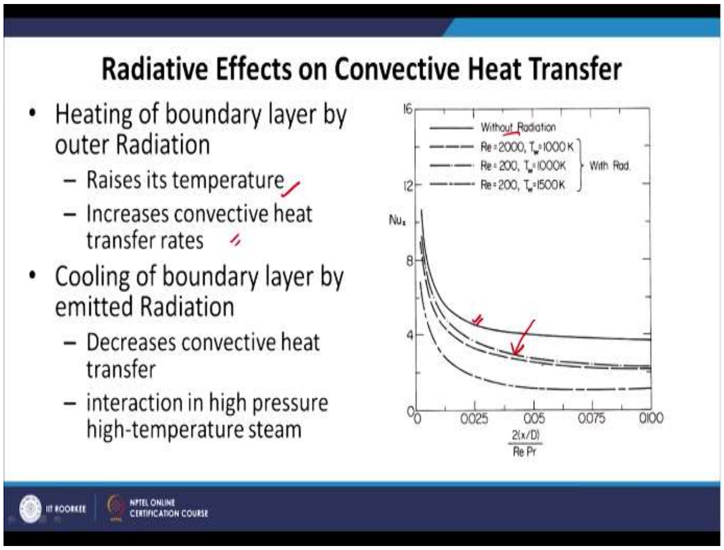
Now why we are studying radiation because there are many things that we want to optimize. For example, in this furnace in the furnace we burn coal and due to burning of coal we have flue gases forming, these are the flame and this flame basically carry heat or through convection but also significant amount of radiation is there and this radiation reaches the surfaces in the top part. These are the heat transfer surfaces of the boiler.

So what we want, why we study radiation, why we should focus on correct calculation of radiative heat transfer here because we want to efficiently burn coal. So fuel efficiency, low emission, then wherever we have gasses of low temperature gases, we want to recover heat. So for heat recovery also we want to develop improved methods, so radiative heat transfer becomes important.

We want to study the emissivity, how the surfaces in the furnace basically radiate, so emissivity of materials in the furnace is important and then can we increase the flame temperature because increasing the frame temperature will lead to higher efficiency but also higher pollutants and also when we increase the temperature of the flame, radiative heat transfer will increase and convection will decrease.

So all these aspects when we want to optimize, radiative heat transfer becomes very important in these applications.

(Refer Slide Time: 29:47)



One more thing that I would emphasize here on the importance of radiation is that radiation and other modes of heat transfer like conduction and convection many times they cannot be treated in isolation. That means they are coupled, so radiation affects conduction and convection and convection may also affect radiation in some way. So in this slide, I will highlight how radiation can affect convection.

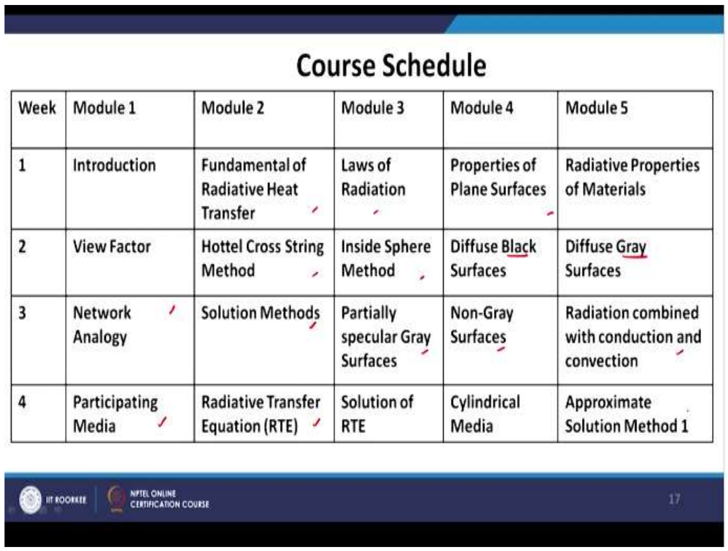
So suppose there is a boundary layer, in the boundary layer we have some hot fluid which is transferring heat to a surface. Now what will happen is that outside the boundary layer, we have a hot gas. Now this gas radiates energy. When this gas radiates energy, some of this energy will be received in the boundary layer and the boundary layer may get heated. So what you see there is that if the boundary layer is cool, the boundary layer will get heated due to radiation.

So the temperature increases as a result of increased heat transfer by radiation to the boundary layer and the convective heat transfer rate will increase. On the other hand, if the boundary layer is hot and the surrounding gas is cold, then the radiative energy from the boundary layer will be radiated out and the boundary layer will become cool and we see that there is a decrease in heat transfer coefficient here.

Without radiation, the heat transfer coefficient, convective heat transfer coefficient is very high but if radiation is taken into account, then the boundary layer will become cool because some amount of energy from the boundary layer is basically rejected outside by radiation and boundary layer becomes cool, so heat transfer coefficient, convective heat transfer coefficient decreases.

So this chart, this image basically tells you how the two may be related and coupled. So the schedule of this course will be this.

(Refer Slide Time: 31:37)



Course Schedule

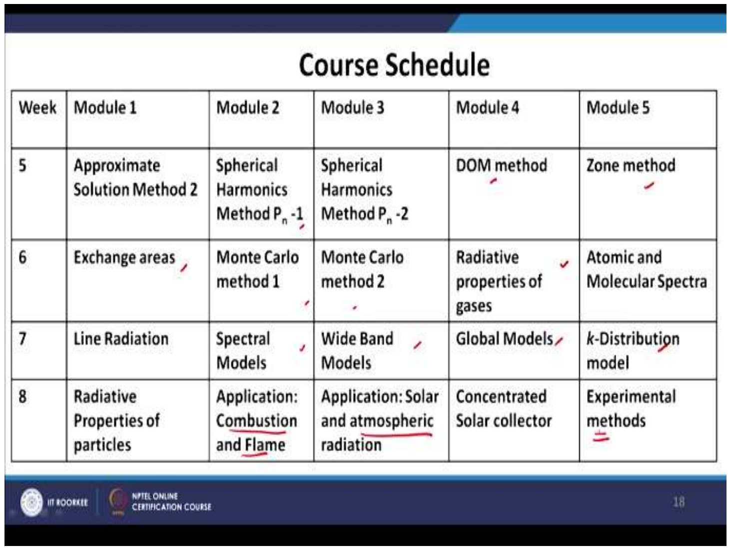
Week	Module 1	Module 2	Module 3	Module 4	Module 5
1	Introduction	Fundamental of Radiative Heat Transfer	Laws of Radiation	Properties of Plane Surfaces	Radiative Properties of Materials
2	View Factor	Hottel Cross String Method	Inside Sphere Method	Diffuse Black Surfaces	Diffuse Gray Surfaces
3	Network Analogy	Solution Methods	Partially specular Gray Surfaces	Non-Gray Surfaces	Radiation combined with conduction and convection
4	Participating Media	Radiative Transfer Equation (RTE)	Solution of RTE	Cylindrical Media	Approximate Solution Method 1

We will discuss first the surfaces properties, heat transfer from plane surfaces, flat surfaces. So after discussing the fundamental laws of radiation, we go to the plane surfaces. We will discuss the traditional view factor approach. We will discuss different methods to find out view factors, the Hottel cross string method, inside sphere method and then we will go for heat transfer between surfaces.

First, we will deal with black surfaces and then we will deal with gray surfaces. We will learn number of methods to solve the governing equation especially the network analogy and various solution methods. Then, we will go for real surfaces. That means specular gray and non-gray surfaces. We will then go for radiation combined with conduction and convection. So this will first focus on the radiative heat transfer between surfaces.

And then we will go for radiative heat transfer between gas and surface, so we will discuss the participating media, we will derive the equation of radiative transfer equation. Then, we will discuss the solution methods.

(Refer Slide Time: 32:40)



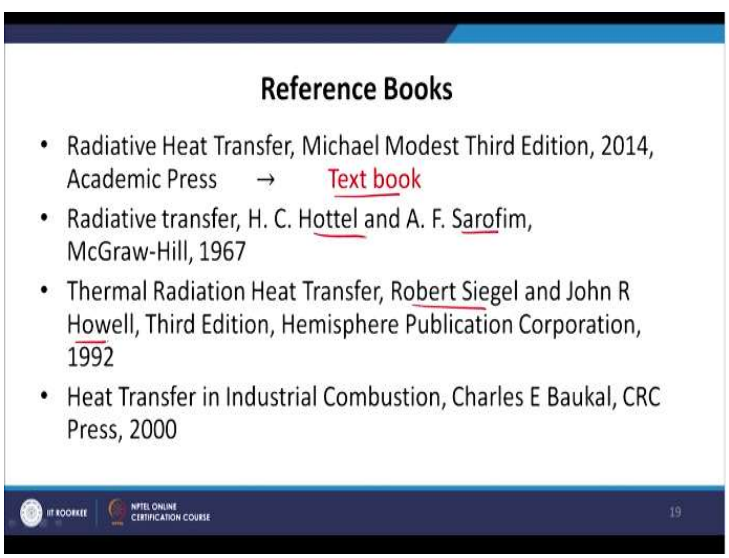
Course Schedule

Week	Module 1	Module 2	Module 3	Module 4	Module 5
5	Approximate Solution Method 2	Spherical Harmonics Method P_n -1	Spherical Harmonics Method P_n -2	DOM method	Zone method
6	Exchange areas	Monte Carlo method 1	Monte Carlo method 2	Radiative properties of gases	Atomic and Molecular Spectra
7	Line Radiation	Spectral Models	Wide Band Models	Global Models	*k*-Distribution model
8	Radiative Properties of particles	Application: Combustion and Flame	Application: Solar and atmospheric radiation	Concentrated Solar collector	Experimental methods

So first we will solve approximate solution methods, P_N spherical harmonics and discrete ordinates method, zone method. We will find exchange areas and then we will go for statistical methods like Monte Carlo methods. Finally, towards the end of this course, we will discuss the properties of the gases and particles. So radiative properties of gases, molecular and atomic spectra.

We will discuss how to approximate the spectral part of the gas properties through wide band model, global model, k-distribution model and finally towards the end of this course, we will focus on some selective applications of this radiation especially to combustion and flame, atmospheric radiation and some experimental methods in the last lecture.

(Refer Slide Time: 33:31)



The books for this course, we will use radiative heat transfer by Michael Modest Third Edition from Academic Press as the textbook. Some other good books on this course are Hottel and Sarofim radiative transfer. This is a pretty old book but very thorough. Then, Thermal Radiative Heat Transfer by Robert Siegel and John Howell. This is a good book and then some applications if you are interested in applications of heat transfer in general not just radiative heat transfer but also heat transfer in general to combustion problems.

Then, this is a good book by Charles E Baukal but the text book for this course will be Radiative Heat Transfer by Michael Modest. So thank you, in the next lecture, we will discuss some fundamental aspects of radiative heat transfer and I am sure this course will be very helpful for those who are working in the area of this radiative heat transfer especially in furnaces and material processing. This course will be very useful to those people. Thank you.