Conduction and Radiation

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Lecture No 1
Importance of Thermal Radiation

So good morning. There are three modes of heat transfer: like conduction, convection radiation, but the basic modes of heat transfer are only two - conduction and radiation. And convection is a special case of conduction where, there is a microscopic movement also. So, we saw the mechanisms of… we explained the mechanism...I explained the mechanism of conduction and heat transfer. Then we also looked at boundary layer theory, and very brief introduction of boundary layer theory, and convicted heat transfer and the concept of nusselt number what is the heat transfer coefficient of nusselt number, Nekton’s law of cooling and all that anyway, we restrict our attention to conduction and radiation in this course, convection is not a part of this course.

Now, in this class we look at the importance of thermal radiation, why thermal radiation is important? Lot of you will have a general… everybody most people have a general feeling that thermal radiation is important only when the temperatures are high. Generally when the temperatures are low we say radiation can be neglected and that is the argument, generally put forward by many people, who are not inclined to include radiation in their analysis for reasons best known to them.

So, we will just see, we will just take a simple example and see whether this assumption is justified that that is neglecting radiation in a heat transfer analysis. Then we look at the electromagnetic spectrum and I will show some pictures of electromagnetic spectrum and look at the various portions of the spectrum, we will solve one or two basic problems connecting wavelength, the wave number, velocity, frequency and all that and then we will start off with the definition of a blackbody and properties of a blackbody. So, that will be the route we will be taking.

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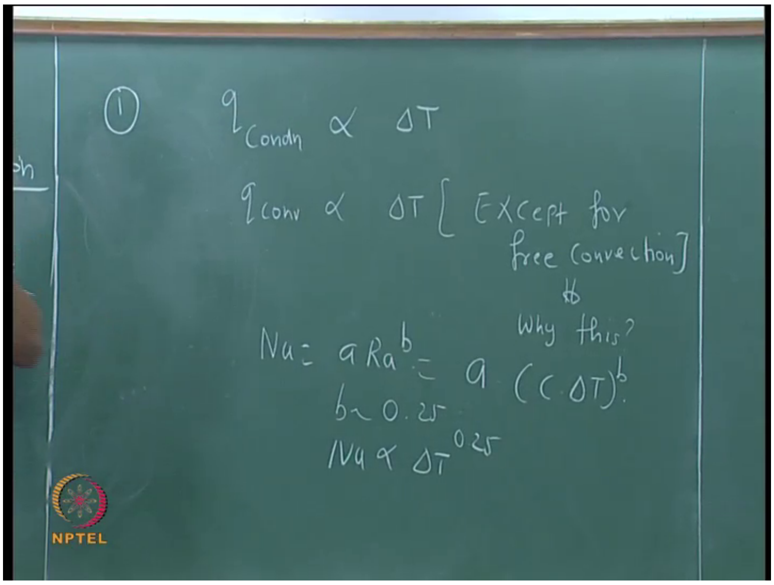

So, the importance of thermal radiation basically the first point is q conduction is proportional to delta T, q convention is also proportional to delta T except for free convection, correct why this? Because, nusselt number is a Rayleigh number to the power of b for free convection. So, this is a into some constant, b is usually about 0.25. So, therefore, the nusselt number goes.

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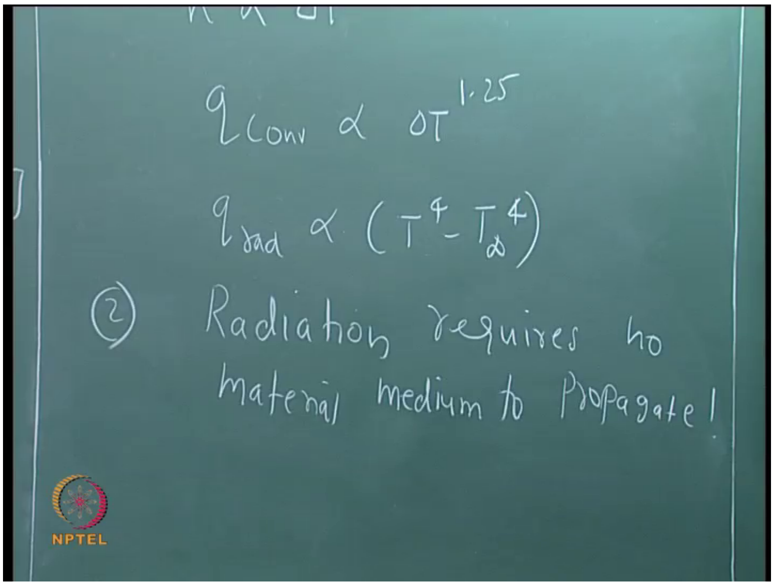

So, q will go as delta T to the power of 1.25 for laminar natural convection flows for turbulence natural convection flows it will go as one delta T to the power of 1.33. Tthis r a is the Rayleigh number, acceleration due to gravity isobaric cubic expansivity, which is for ideal gases we can equate it to one by T where, T is the temperature in Kelvin, delta T is the temperature difference imposed in the problem, L is your characteristic length characteristic dimension it could be length of a plate diameter of a cylinder or diameter of a sphere, nu is the kinematic viscosity, alpha is the thermal diffusability.

So, the Rayleigh number you can do a scaling analysis and prove that the Rayleigh number is the fundamental, dimensionless, parameter, governing free convection much in the same way as the fundamental dimensionless parameter, which governs force convection is basically Reynolds number.

So, it will be the actually, many times it will be Reynolds number and prandtl number, but Reynolds into prandtl, if you combine Reynolds into prandtl it becomes it becomes the pickley number it becomes the pickley number, the rayleigh number can also be written as the product of g r into p r where g r is the grashof of number, this can be written as. So, this is g r one scientist gets multiplied by the second scientist, and becomes the third scientist.

Now, you can see that q convection is proportional to delta T in convection, you will take it with a pinch of salt because, it is delta T to the power of 1.25 for natural convection. So, q radiation is proportional to T to the power of 4. So, non-linearity enters the problem right away because, q is proportional to the difference in the 4 powers of 4th powers of temperature, the difficulty with radiations first stems from the fact that the radiated heat transfer is proportional to T to the power of 4 minus T infinity to the power of 4.

So, therefore, it is importance nonlinearly increases with the increase in temperature. So, at high temperatures whether, it is an IC engine or a boiler or a furnace and all that then, it becomes inevitable that you will have to consider radiation in the analysis, if you are talking about a temperature of 1200 degree centigrade or 1500 degree centigrade, there is no escape from considering radiation. Radiation will be the dominant mode of heat transfer, are you getting the point.

In fact, in your boiler there is a radiance super heater section where, the ultimate heat transfer takes place where, the temperature of the steam is lifted. In the steam drum the liquid is separated from the vapour and then you get steam at a temperature which is just above the temperature at which it changes phase, after that the super heating is done by the radiance super heaters, or in a paint baking oven, if you want to if you want to coat some tubes or metal pipes and then these are all invariably baked. Even a microwave oven works on the principle of… microwave oven basically there is radiative heating then microwave will be the region of spectrum.

So, the importance of thermal radiation stems from the fact that the first point is q is nonlinearly varies with temperature, number two it requires radiation requires no material medium to propagate. So, the proof of that is we receiving the solar radiation now as we receive the solar radiation now it is coming from millions (( )) billions of kilometers away. So, it is ample proof that radiation is able to travel without a medium that is radiation is able to travel through vacuum.

The best part is radiation travels best in vacuum because, there is no absorption or scattering and all that. Once it enters the atmosphere all these activities start, there is absorption by certain molecules then they again reflect or we call it as scattering which is this because, of which you get the blue sky, norman scattering for which he got a Nobel prize. So, there is scattering, there is absorption and since all these molecules are also at a temperature greater than 0 kelvin as a consequence of the Prevost law they also emit.

So, the atmosphere is emitting, absorbing, and scattering are you getting the point, but outside the atmosphere the radiation is able to travel without any distortion at all. So, radiation requires no material medium to propagate, radiation can travel in vacuum also. Therefore when you travel in a shatabdi or rajdhani express or when you are travelling by plane, when you are having a double pane window which is used to eliminate heat transfer, you get two glass two glasses two glass plates the gap in between, have you seen in a c chair compartment. There are two glass plates in between there is a gap you though that you are very smart, you killed all heat transfer, you killed only convectively transfer, you put air inside. So, the convection is replaced by conduction, but; however, even if air is there when the temperature is sufficiently large it will setup a natural convention.

Forget for the time being for that the gap is so small that natural convection does not set in, but these two glass plates are at some temperature and in between even if there is vacuum there will be radiative heat transfer. So, thus there will be radiative heat transfer in that situation are you getting that point. So, radiation requires no material medium to propagate therefore, we cannot it is not easy to say that under these media radiation is not important we can neglect.

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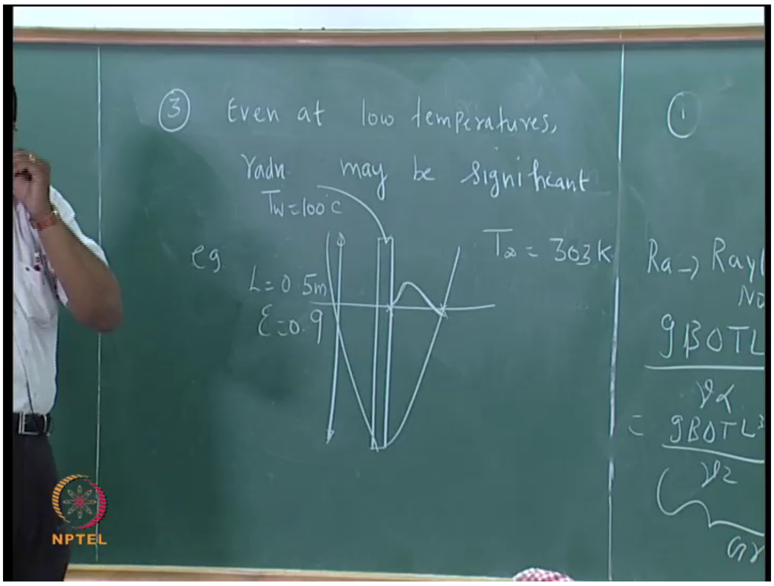

Point number three, even at low temperatures radiation may be significant, let us consider a simple let us consider an example, let us take a vertical flat plate let us say it is about so l equal to 0.5, meter this glass plate is maintained at 100 degrees centigrade, again you do not ask me how is maintained somehow I am maintaining it at 100 degrees centigrade.

Now, outside is let us say 303, there is a heated plate which is standing in still or quiescent air, what will happen now, what will be the story of this plate, what will happen around this plate?

Convection.

Convection what which convection it is still air.

Natural convection.

Natural convection. So, boundary layer will develop. So, boundary layer will develop on both sides, correct right I will draw it here, I will keep this by chance I wrote this I am going to use this one.

Let us say, that the emissivity of the plate is also 0.9 that is it is coated with a black paint what is the definition of emissitivity and how do you characterize emissitivity is emissivity is a function of length is emissivity is a function of angle and all that will be a part of this course, but now for the time being let us say that there is some average there is an overall average emissivity which is characterizing the surface.

Now, the boundary layer will develop like this, the beauty of this boundary layer is now the velocity is 0 here the velocity is zero here because, it is still air, if it is 0 everywhere if it is like this then we have to go home there is no convection problem, we know that there is a velocity very close to the plate that is within the boundary layer. So, it will go up like this is the velocity boundary layer.

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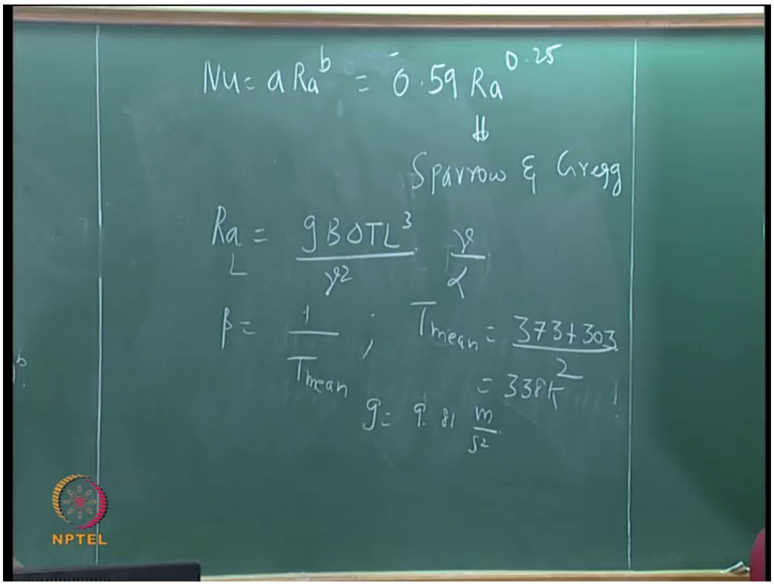

Now, what is the heat transfer coefficient in this? So, we know that the nusselt number is given by a into Rayleigh number to the power of b. So, this is for a and b will change depending upon the configuration whether it is a plate, cylinder, or whether it is laminar or turbulent. I will take a very simple well know correlation 0.59 Rayleigh to the power of 0.2, I think it is a sparrow and Gregg's correlation maybe they did it in 1959 or so.

Now, let us use this let us let us calculate the Rayleigh number for this please switch on your calculators.

So, the Rayleigh number for this based on the length l, g is 9.81, delta T is delta T is 70, beta basically the isobaric cubic expansivity 1 by T mean. So, T mean will I make it 303, what is T mean?

338 Kelvin.

Good. 338 Kelvin.

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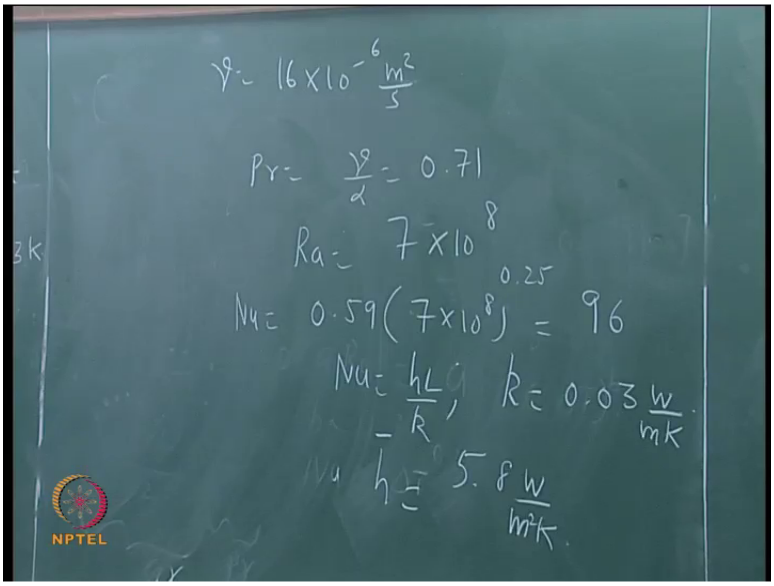

So, we got g beat, we got delta T l is 0.5 I will give the value of nu, nu varies with temperature, but do not worry just go ahead and tell me the Rayleigh number it has to be less than 10 to power of 9 in order that is laminar, if it is more than 10 to power of 9 it will begin transition to a turbulent flow.

Student: (( ))

7 into 10 power of 8 is it. So, Vikram get it (( )) 7 into 10 to power of 8 correct.

Now, what is the nusselt number? 99, 100, 105 and how much is it?

Please bring your calculators otherwise, you will waste time in the class, every class we will solve a problem more or less.

96.

96 good. So, nusselt number is 96. So, the nusselt number is a dimensionless heat transfer coefficient, nusselt number is given by h l by k the k of air is about 0.03 watt per meter per kelvin.

So, now what is heat transfer coefficient? this is what I call as h bar that is h average, that is the average heat transfer coefficient of the plate because, the heat transfer coefficient will vary from the leading edge to the top, it is an averaged out quantity. How is it Deepak? Whatever you do you will get a value which is between 5 and 8

Student: (( ))

because of you, if we get anything outside of this range for air for these temperatures then you have made some mistake. So, generally people will assume a same this thing of 6 or 7 watts per meter square per Kelvin even without doing the calculation 5. 5.8.

So, now I taught you free convection in 20, this how you approach a free convection problem.

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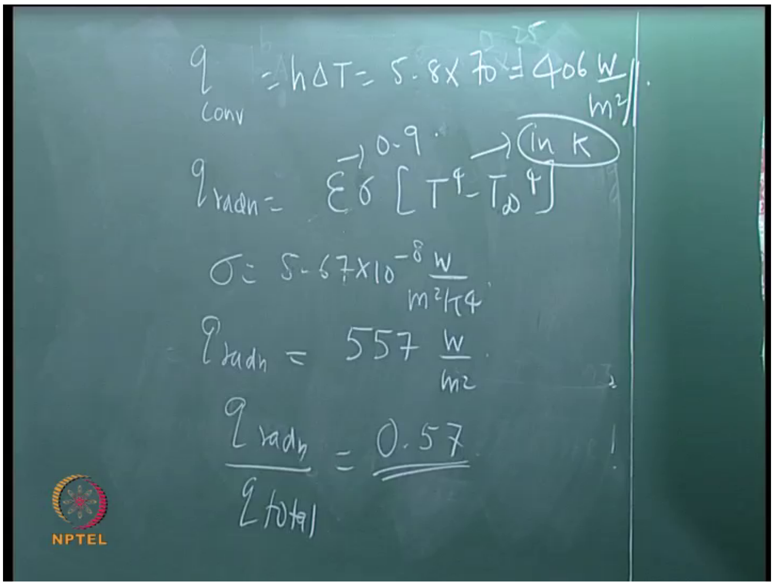

Now, the heat flux convection let us worry let us worry only about one side because both radiation and convection are taking place from both sides, let us consider one side. So, h a 5.8 into 0.5 into 1, but the area is the same let us stick with the q convection, how much is it 400?

406.

So, such type of calculations are also very profound because, the temperatures we are talking about the 100 degrees is what is normally infact, it is more than the reliable operating temperature electronic equipment. Electronic equipment will work about 8 work at above 80 or 85 degrees centigrade. So, if you if you do all this Rayleigh number business you are getting 4 and 6 watts per meter square. So, let us say approximately you have some other situation where h can be 6 or 6.5 or something.

The q convection may can touch about 500 watts per meter square. So, you are talking about flux levels of half a kilo watt per meter square in natural convection that is what is possible. If you talking about the flux level in your equipment which is more than 0.5 kilo watt per meter square fan.

The fan will be you can also do calculations like this and find out what is the maximum capacity, what is the maximum flux which one fan can withstand then, you will make two fans, just like in your desktop you have 2 fans. After that liquid cooling, (( )) cooling datacenter I mean in datacenters you cannot cool everything with fan, but there the air itself will be conditioned, there it will be heavily conditioned the datacenter will be maintained at 16 degree centigrade.

So, that q is equal to h a delta T where, delta T also you will get an advantage then inside the computer you will have all cooling strategy. So, you must as engineers you must have a feel for what is a flux level associated with natural… how much of flux can be dissipated using natural convection. So, the ball park or the approximate figure is more than half kilo watt per meter square you cannot do, you can convert it into equivalent centimeter, square millimeter, square and work out the numbers.

Now, the beauty here is what will be the q radiation from the problem for this problem I assume, that I assume that the sink for the radiation is the same as the sink for the convection which is allright. So, I assume, that the walls of the room are at the same temperature as the ambient which is a reasonable assumption, sometimes these two may not be the same, are you getting the point to cut a long story short T infinity for convection need not be same as the T infinity for radiation often, times we assume them to be the same.

So, sigma is a stefan-boltzmann constant. So, epsilon I gave 0.9, sor T in kelvin watch out, do not put it into centigrade then whole thing will coup, It is easy to remember this 5,6,7,8. 5.67 but you should know where the decimal place and put the minus . So, that is a Stefan-boltzmann's constant, stefan-boltzmann, stefan's guide and boltzmann was a student, I think what is the other way, I think stefan was a guide and boltzmann was a student. So, stefan-boltzmann's constant is 5.6710 to the power of minus 8 watts per meter square Kelvin to the power of 4.

So, q radiation is. So, q radiation by q total is how much ?

0.58.

0.58.

Who says radiation is negligible at lower temperature, the people who say this are the people who do not know heat transfer, but again this analysis has to be taken with a pinch of salt, suppose I blow air I have a fan then the natural convection become the force will become forced convection, instead of 5 I might get heat transfer to 15 or 20.

Then what will happen is I may get a q convection of 1 kilo watt per meter square or1.2 kilo watt per meter square or 1.5 kilo watt. Even, if the convection quarter proves that is it becomes 4 times, if the flux level is 1.8 this fellow is 0.578 it is not negligibly small. So, it depends on what radiation can be neglected only in relation to the other mode of heat transfer, what is the strength of the other mode of heat transfer? If it is convection in air regardless of whether it is free or forced convection radiation cannot be neglected; however, if it is water then the story is turns completely upside down.

Water is also an absorber of radiation you cannot do this simple analysis, if it is water it has got such a terrific thermal conductivity of 0.6 watt per meter per Kelvin as opposed to air, but as opposed to liquid metal it is having a poor thermal conductivity. Air thermal conductivity 0.03 watt per meter per Kelvin, water is 0.6 immediately all these numbers will change because, the nusselt number is h l by k. So, the k h will increase. So, if it is water the radiation contribution will become very negligible.

So, if you are having air cooling, if you are doing a CFD analysis of desktop or all these you cannot neglect radiation analysis.

Now, thankfully fluent, more fluent as radiation modules many people use a combined analysis nowadays their prediction of a maximum temperatures or prediction of operating temperatures of electronic equipment. So, this places things in perspective.

So, if it is natural convection or even in mixed convection where both natural and free convection are important, radiation may play a part and radiation cannot often be neglected by simply putting the argument, the temperature is the temperature is very low, again I will ask the question how low is low? this is a reasonable temperature 80 to 100 degree centigrade also radiation is important.

Now, let us go to the electromagnetic spectrum.

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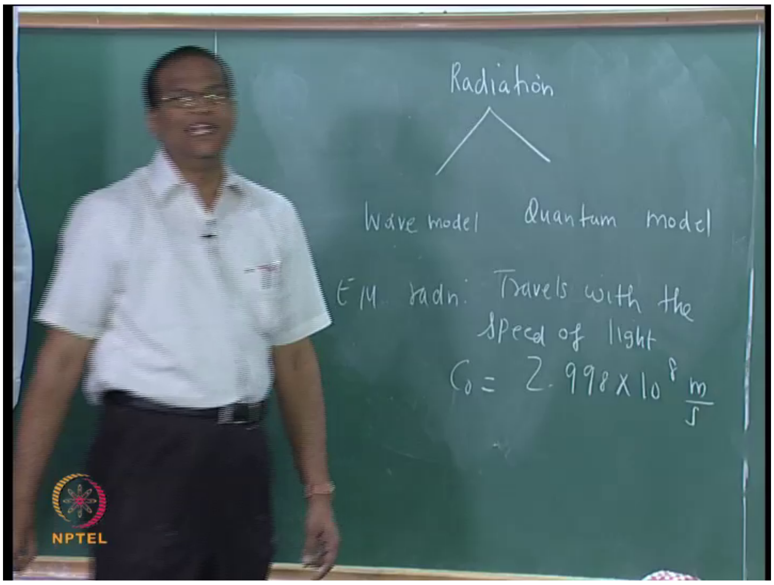

So, radiation travels… radiation actually there are two. So, wave model and the quantum model. I told you that using the wave model, you can characterize it with a wavelength, you can characterize with a frequency speed and all that, q is equal to h mu and all those things which are applicable for optics is applicable, but the radiative properties of blackbody, blackbody behaviour could not be explained using electromagnetic theory therefore, the quantum theory had to be invented.

Electromagnetic radiation travels with the speed of light. So, the c naught that is the velocity of light in vacuum you can consider the velocity of light in vacuum to be the velocity of electromagnetic radiation when it is passing through vacuum. So, 2.998 or approximately 3 into 10, 10 to the power of 8 meters per second. c naught is the velocity in vacuum.

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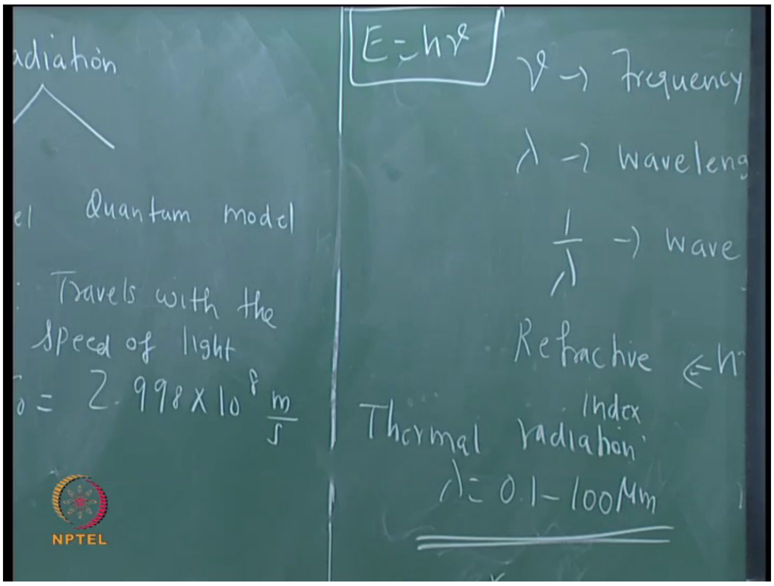

Now, you can characterize mu frequency correct 1 by lambda wave number, if the velocity if the velocity if the velocity of light in a medium is c, we know that c has to be less than or equal to c naught. So, c naught by c is equal to this is the refractive index of the medium.

Glass, what is refractive index? 1.5 good, for gases for air generally it will be very close to 1. You can say n is approximately is 1 for gases for vacuum it is 1.000 whatever, for other gases it will be slightly more, but will be equal to 1.

Now, look at the electromagnetic spectrum I will host it on moodle, but do not worry, but important things you can copy down even that too take down every detail, if I am using a power point presentation I will put that… I will host that PDF or PPT on moodle www.iitm then you can go to courses m e 6200 and click you can use students, student user id and password, students student and open it and then you will be able to see it.

Now, let us look at the electromagnetic spectrum, there are various ways of characterizing it, one way of looking at it is through the wave length lambda you can also look at it from frequency or these two can be related to get an electromagnetic radiation of such a wavelength or such a frequency what should be the temperature of a body which can emit radiation of this wavelength of frequency and this gives you the approximate size. The wavelength corresponds to what is the order of magnitude of the various things we encounter?

For example radio waves 10 to the power of 3 meters wavelength, gamma rays are 10 to the power of minus 12, gamma rays have got a terrific frequency. What is that 10 to the power of 12 hertz? The energy of electromagnetic radiation e is given my h mu, but I have to derive that. e is given by h mu where, h is the Planck's constant 6.6276, 6.6276 10 ten to the minus 34 joules second.

Now, look at atomic nuclei, now look at this gamma rays, gamma rays have got a terrific gamma rays have terrific terrific frequency therefore, e is equal to h mu is very high. So, there are all high energy radiation. So, people who are dablling in this are the high energy physicists BABA atomic research center. People are working on the collider this thing, and people are doing research, high energy physicists are interested in this.

Look at the other angle of the spectrum where, the frequency is very low, e is very small. This is used by electronics and communication engineers where, e is equal to very small where e is very small therefore, they have to do modulation, there is a carrier wave and then you modulate than it is sent across, then it is demodulated. And mechanical engineers somewhere in between, the e c guys are here, the physicists are here, we are here, sometimes they are visible; sometimes they are invisible. So, visible is 0.4 to 0.7 you are either in ultra violet or infra red. Why you we engineers are operating on this? Engineers are operating on this because, this correspond to the reasonable level of temperatures encountered in engineering applications.

We do not have billions of Kelvin and all that, we do not do such type of experiments. The only time where, you encounter that may be in nuclear fusion or these things and that is also taking place only in the lab. Generally will talk about the temperature of 500 kelvin, 800 kelvin, 1000 Kelvin, gas (( )) 1500 Kelvin and So on.

So, thermal radiation lambda is 0.100 micrometer these of the interest to the thermal engineer, these are of interest to us because, you look at the temperatures, that the yellow color is there, if you look at the temperature of bodies emitting the wavelength this yellow color is of interest to us. So, there are other ways of looking at the spectrum. This corresponds to basically the wavelength corresponds to building, this atomic, nuclei and all that. So, I will put this upon this is another way of looking at it.

So, radio waves, micro waves these are used by electronic and communication people. Gamma rays and x rays are used by physicists they can also be used for x rays are used they can penetrate the flesh and they can give you information on the bones, radiology and inter analysis radiology is. So, so these are basically of interest to the high energy physicists these are of interest to electronics and communication engineers.

Now, look at this visible; this visible is 400 nanometer to 700 nanometer. So, that is the 0. 4 to 0.7 micrometer. So, violet to red. So, this is the spectrum.

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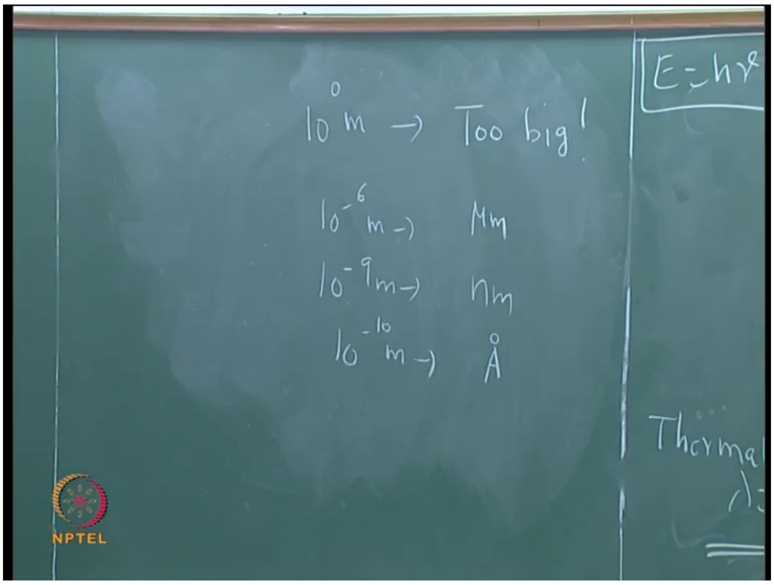

Now, for us the 10 to the power of 0 meter is too big. So, we do not talk about meter wave length and all that mechanical engineers. So, will say 10 to the power of minus 6. So, that is a micrometer. what is this?

Nanometer.

10 to the power of minus 10.

Angstrom.

Angstrom. So, we either work with micrometer or nanometer or Angstrom. Angstrom we do not engineers they normally use, physicists use I think nobody uses Angstrom now.

We always talk about micrometer. So, this is of interest to us. So, that is why I am saying 0.1 to 100 is of interest to us.

So, these people will this one 400 to 700 they will divide it into 255 colors depending upon the resolution and the camera they will put into 255 colors. So, as far as a thermal engineer is are concerned suppose I take a picture, I can resolve the 255 colors then, if I have if I have a backup of thermocouple measurements I will correspond each these colors to some temperature, and I can use a color map and I can use a color map as a code for getting the temperature.

One of my student is doing PhD on this. Here are sheets which are available when you paste on a surface, if the temperature of the plate increases, its color will change: this called liquid crystal thermography. You can come to the heat transfer lab one day, anytime you can walk, you can talk to Pradeep Kamath, my student, there is a student called Konda reddy he was working on liquid crystals. So, we imported the sheets. So, it is very nice. So, you can get a full color map. So, you have to take a on a CCTV camera you take this picture use, an image processing software.

So, so basically it will be a color picture simultaneously, you have a thermocouple and then independently measure the temperature then you link up this color with the temperature, and in future this is the color pattern, this is the temperature. Color can also be used so. In fact, in measurements there is something called the color temperature there is something also called the color temperature.

Now, this as far as the electromagnetic spectrum is concerned, let us solve two small problems and close for the day.

So, problem number one problem number one; the radiation at a wavelength of lambda equal to 3 micrometer radiation at the wavelength of lambda equal to 3 micrometer travels through vacuum radiation at a wavelength of lambda equal to three micrometer travels through a vacuum into a medium radiation at a wavelength of lambda equal to 3 micrometer travels through vacuum into a medium with n equal to 1.4, that is refractive index equal to 1.4.

A; determine the speed frequency and wave number A; determine the speed frequency and wave number a determine the speed frequency and wave number for radiation in vacuum, I mean the speed frequency and wave number for radiation in vacuum a determine the speed frequency and wave wave number for radiation in vacuum.

B; determine the above quantities B; determine the above quantities and also the wavelength determine the above quantities and also the wavelength for radiation in the medium. determine the above quantities and also the wavelength for radiation in the medium just try this.

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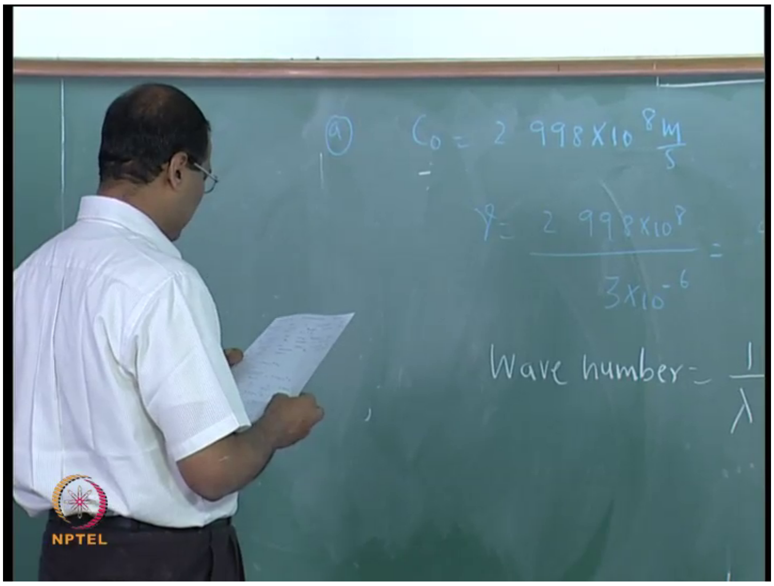

So, C naught a. So, 9.993 into 10 to the power of 13 second inverse, that is second to the power of minus 1 or you can also write it as hertz. Is it clear? blue is it, is not? Why? Now. So, determine the speed frequency, speed is this, determines the speed frequency wavelength, we have done this.

So, the beauty is even when it changes from vacuum to medium; the frequency does not change only the wavelength will change.

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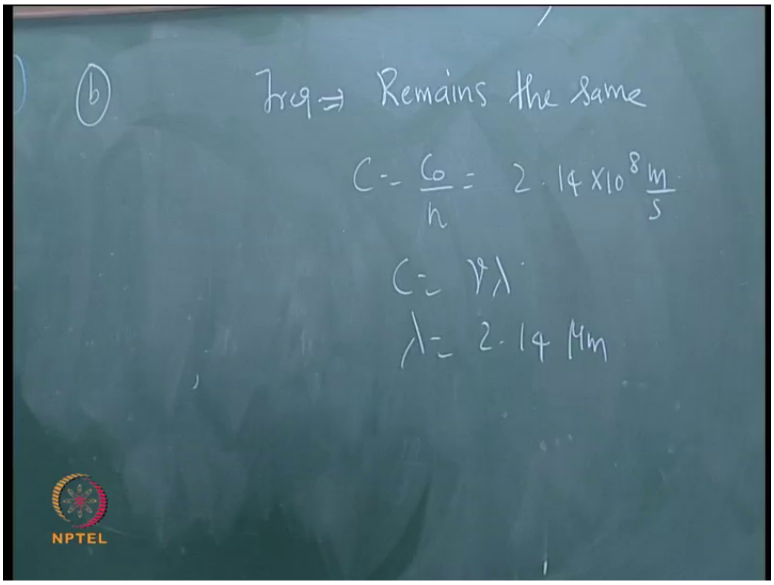

So, for part b; very simple just reinforces the concept that is all. Everybody through with this, problem number two. The wavelength and speed of radiation problem number two the wavelength and speed of radiation. The wavelength and speed of radiation travelling within a medium the wavelength and speed of radiation travelling within a medium are 3.2 micrometer the wavelength and speed of radiation travelling within a medium are 3.2 micrometer and 2.3 into 10 by 8 meters per second are 3.2 micrometer and 2.3 into 10 to the power of 8 meters per second respectively. Determine the wavelength of the determine the wavelength of the radiation in vacuum determine determine the wavelength of the radiation in vacuum, same problem I am restating in how many different ways the same problem can be post that is the whole idea of this exercise. Determine the wavelength of radiation in vacuum just take 2 minutes finish it off and then we will close for the day.

So, we will stop here.