Heat and Mass Transfer
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Lecture No. 10
Thermal Radiation-1

You will recall from the introductory lectures that we had 3 modes of heat transfer – conduction, convection and radiation. We have studied 1 mode namely heat conduction in solids. Today, we will now start talking about the second mode that is thermal radiation. If you recall from our introductory lectures, I had said thermal radiation, there are certain laws which we will have to study in order to be able to calculate what is the heat exchange by radiation between surfaces. So let us now state certain basic concepts about thermal radiation. The first thing which we would like to state is that all solid and liquid surfaces at all temperatures emit thermal radiation.

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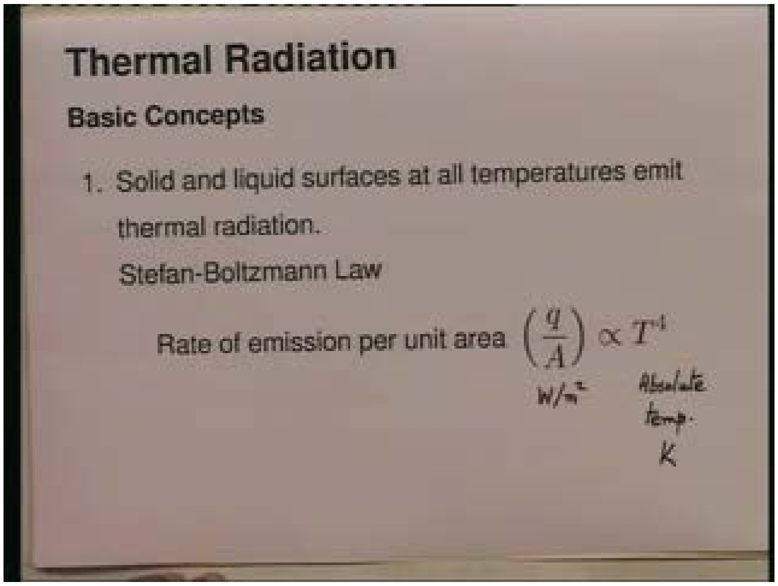

Thermal Radiation

Basic Concepts

1. Solid and liquid surfaces at all temperatures emit thermal radiation.
   Stefan-Boltzmann Law
   Rate of emission per unit area $\left(\dfrac{q}{A}\right) \propto T^4$

W/m²

Absolute temp. K

This is physics, you have any surface whether it be solid or liquid whatever be its temperature level, it will be emitting thermal radiation and if you want to know the overall amount emitted, that is what is given by the Stefan Boltzmann law which I had mention to you earlier. What the law simply says is the rate of emission per unit area in watts per meter squared q by A is proportional to the absolute temperature to the power of 4 T is the absolute temperature in Kelvin and the fourth power of that. So q by A is proportional to the fourth power of the absolute temperature of the surface. Incidentally, gases also - under certain conditions of temperature - will emit radiation but we will not be concerned with that aspect during these lectures. We will be concerned only with emissions from solid and liquid surfaces.

So, we know the rate of emission per unit area and as I said it is given by the Stefan Boltzmann law in an overall sense. Now the thermal radiation which is emitted is in the form of electromagnetic waves; that is the first thing we want to note - the radiation which is emitted.

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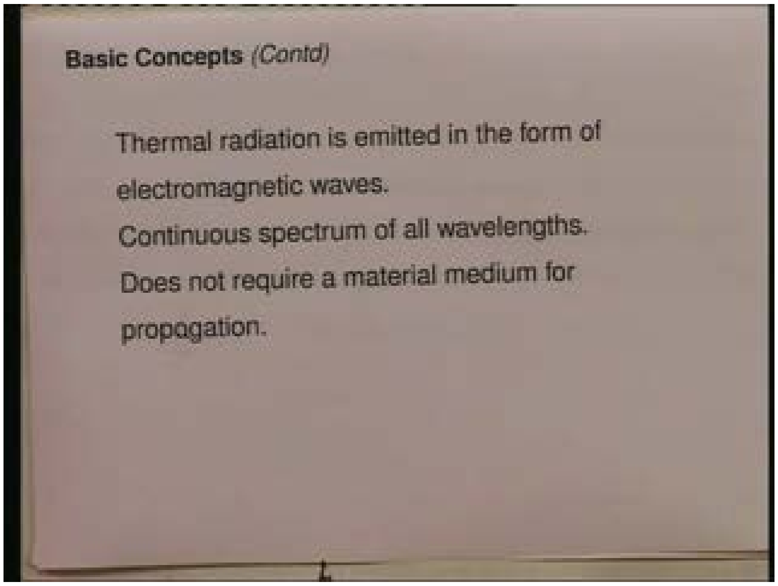

Basic Concepts *(Contd)*

Thermal radiation is emitted in the form of electromagnetic waves.

Continuous spectrum of all wavelengths.

Does not require a material medium for propogation.

Thermal radiation is emitted in the form of electromagnetic waves. What are certain characteristics of electromagnetic waves? That electromagnetic waves travel is a certain speed and if you want to distinguish between different types of electromagnetic waves, we use the attribute of wavelength to talk about various electromagnetic waves. So, let us look at a picture, a sketch of various wavelengths of various electromagnetic waves. Here is a sketch showing the spectrum of electromagnetic waves and their wavelengths.

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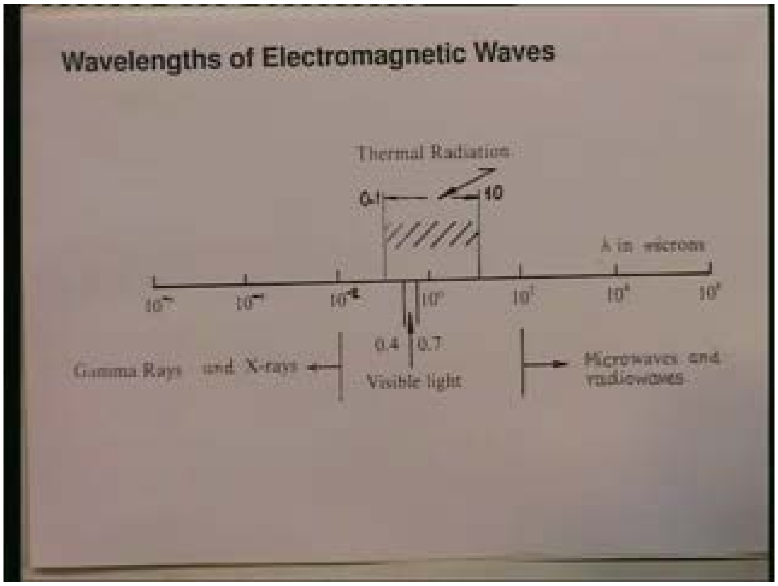

Wavelengths of Electromagnetic Waves

What are different types? For instance, thermal radiation which is what we are interested in in this course are electromagnetic waves which are essentially in the wavelength region from .1 to 10 microns.

That is the range in which thermal radiation is mostly existing; it is not just this, start certain lower wavelengths and goes to higher wavelengths but most thermal radiation is from .1 to 10 microns in that region much of type radiation. Higher wavelengths are generally those which belong to things like microwaves and radiowaves whereas lower wavelengths are those associated with gamma rays and x rays. 10 raise to minus 6, 10 raise to minus 4, 10 raise to minus 2 microns are wavelengths associated with gamma rays and x rays whereas, 10 raise to 2, 10 raise to 4, 10 raise to 6 microns are wavelengths associated with micro waves and radio waves.

Thermal radiation is between, is in between these two extremes; most thermal radiation which is given off by surfaces will have wavelengths in the .1 to 10 micron range. Incidentally, visible light are also electromagnetic waves and the wavelength region is from .4 to .7 micron. So the visible light is within the thermal radiation wavelength and an electric filament lamp for instance is a case where we are giving off thermal radiation from a filament and the part of it that is from .4 to .7 is what we see as light. So an electric filament lamp is a lamp which is really giving off thermal radiation because it is being heated up and we see a certain part is light because it is in the .4 to .7 micron range. So this is the spectrum of electromagnetic waves and thermal radiation is in this spectrum. Any surface mind you again, I repeat when it is giving off thermal radiation, any surface will be giving off all wavelengths.

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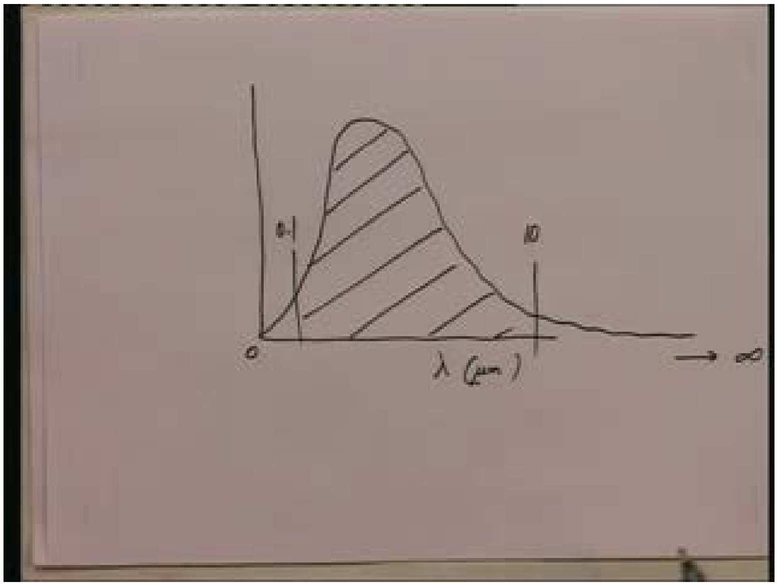

It is a continuous spectrum so if I were to plot for instance a surface giving off thermal radiation, it would be typically something like this. So this is 0, this is tending to infinity here. This is lambda - the wavelength in microns - but most of the thermal radiation area under this graph is the amount of thermal radiation being given off; most of that thermal radiation will be in the .1 to 10 micron range. That is what we mean - it is not as if there is not thermal radiation below .1, greater than 10 but much of this area of this graph which is the total amount of thermal radiation being given off is in the .1 to 10 micron range.

So, it is a continuous spectrum and not a discrete spectrum, much of it lying in the .1 to 10 micron range, that’s the point we want to make. The other thing which is to be noted about electromagnetic waves which needs to be also stated is I have, let me go back to the first tracing again. The other thing which I want to say is that an electromagnetic wave does not require a material medium for propagation. So once a surface is at a certain temperature, it gives off thermal radiation. It does not require a material medium for that energy to move in the form of electromagnetic waves unlike conduction or convection modes of heat transfer which require some material medium a solid or a liquid or a gas in order for the energy to get transferred from one point to another. So this is also a difference between thermal radiation and conduction or convection.

So these are certain characteristics worth noting - the wavelength dependence that it is an electromagnetic wave and that it does not require any material medium for being propagated from one point to another.

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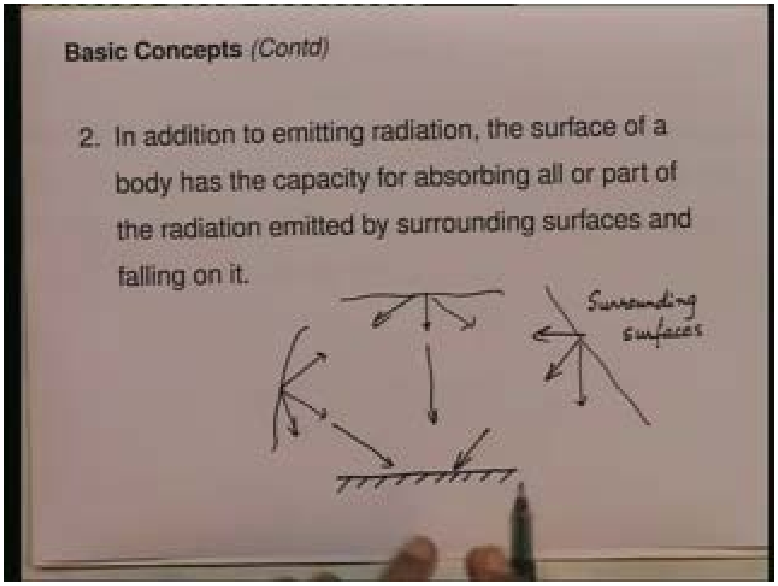

Basic Concepts *(Contd)*

2. In addition to emitting radiation, the surface of a body has the capacity for absorbing all or part of the radiation emitted by surrounding surfaces and falling on it.

Now the second basic concept, the second basic concept we want to put forward is in addition to emitting radiation, the surface of a body has the capacity for absorbing all or part of the radiation emitted by surrounding surfaces and falling on it. So far we have said a surface is at a certain temperature, it will give off radiation by virtue; it will emit radiation by virtue of being at that temperature.

Now I am saying a surface of a body also has the capacity to absorb all are part of the radiation which is emitted by surrounding surfaces and falls on that surface - that is the second aspect which need to note. So say for instance, suppose I have a surface; let us say this is a surface, there is some surface, arbitrary surface and there are some surrounding surfaces at different temperatures giving off radiation - emitting radiation in all directions by virtue of that temperature levels whatever be the amounts. This is the radiation being emitted by their surrounding surfaces; these are surrounding surfaces. Part of this radiation is going to hit this surface which is coming from these surrounding surfaces, isn't it? Part of this radiation emitted by these surrounding surfaces is going to hit this surface which is of interest to us. When this radiation hits the surface, this surface has the capacity to absorb all or part of this radiation. So this is a second characteristic which is to be noted about surfaces. They emit radiation by virtue of that temperature level.

They have a capacity for absorbing radiation partly or wholly radiation which comes to them from surround surfaces - second characteristic to be noted. Therefore, suppose now I consider a solid body just to take an example now about emission and absorption of radiation.

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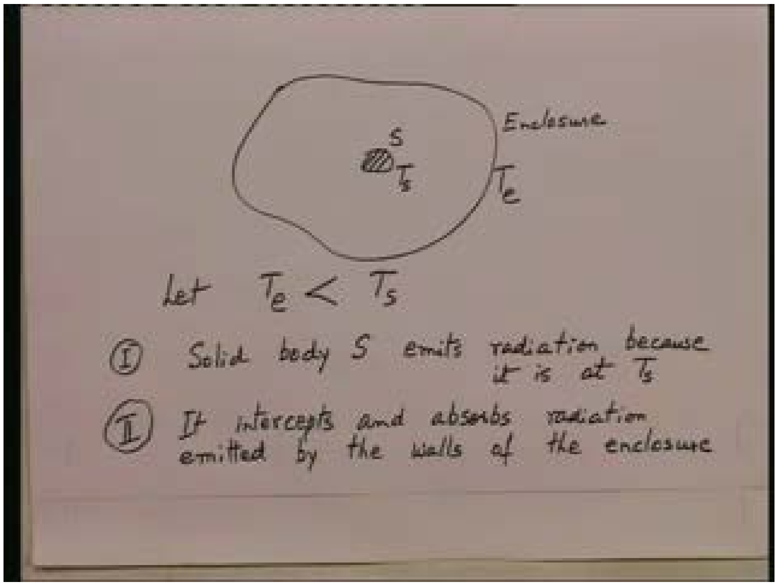

let $T_e < T_s$

Ⓘ Solid body S emits radiation because it is at T_s

Ⓘ It intercepts and absorbs radiation emitted by the walls of the enclosure

Consider that I have some enclosure - some enclosure - hollow enclosure - at a temperature T_e; consider some enclosure like this and let us say inside this enclosure, I have a solid body s, some solid body s at a temperature T_s, some different temperature; Ts is different from Te. Let us say let T_e be less than T_s, could be greater, it doesn't matter; we are just trying to say they are different. So what will happen? The solid body which is here by virtue of being at a temperature T_s will emit radiation because it is at T_s. So number 1 - solid body emits S, emits radiation because it is at a temperature T_s, number 2 - the solid body also intercepts and absorbs radiation emitted by the walls of the enclosure which is at a temperature T_e. The second thing is it intercepts and absorbs radiation emitted, absorbs radiation emitted by the walls of the enclosure.

So, 2 things happen; I will repeat - the solid body emits radiation because it is at T_s, the solid body surface also intercepts and absorbs radiation which is emitted by the walls of the enclosure and falls on that solid body. Whatever it intercepts, heat absorbs part of it. Now since the solid body is at a temperature T_s which is greater that T_e, what is going to happen is the following the quantity 1?

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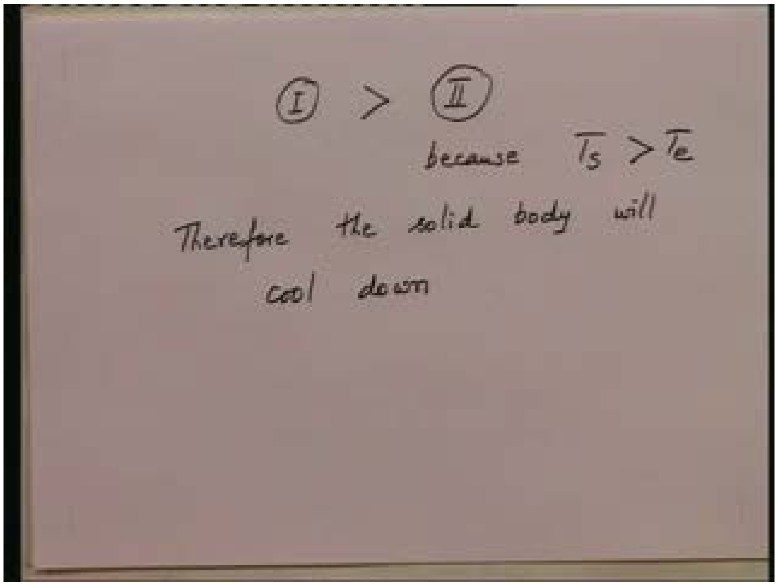

(I) > (II)

because $T_s > T_e$

Therefore the solid body will cool down

So many watts, whatever it is, is going to be greater than the quantity 2. The amount that it emits is going to be greater than the amount that it intercepts and absorbs which is coming from the other walls of the enclosure because 1 is going to be greater than 2 because T_s is greater than T_e. Therefore, what will happen is the body will cool. So this is how the process of heat exchange by radiation takes place if we have 2, I repeat again, if we have 2 bodies - an enclosure and a solid body. They are at different temperatures then each gives off, emits radiation. The body which is hotter will emit more than it receives and absorption the other body; therefore the hotter body will cool because of the exchange of heat by radiation. That is how radiant heat exchange takes place between the surfaces of bodies which are at different temperatures.

Now, the third concept which we want to put across is, I have already shown it when I drew arrows a movement ago but let me repeat it again.

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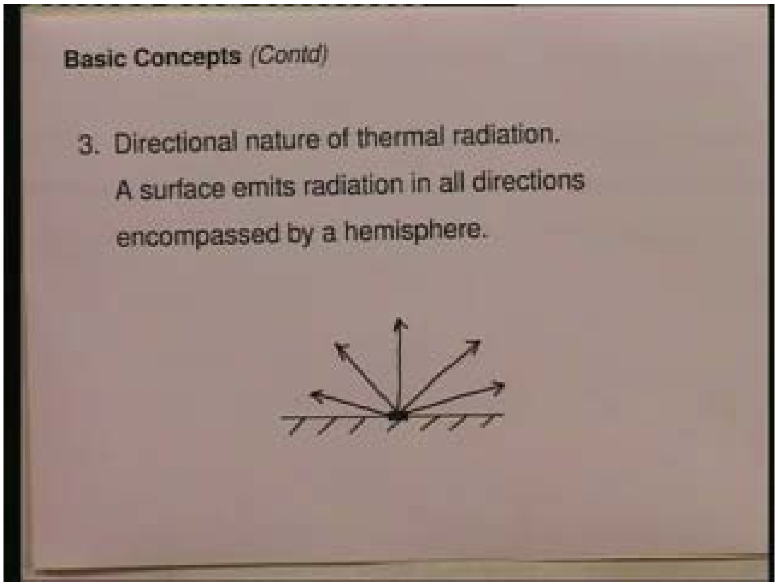

Basic Concepts *(Contd)*

3. Directional nature of thermal radiation.
   A surface emits radiation in all directions encompassed by a hemisphere.

The third concept which I want put across is that there is a directional nature to the radiation given off by the surface of body. Suppose I have a surface, then a surface emits radiation in all directions encompassed by a hemisphere. Suppose I have a surface like this - let me draw some surface, could be flat, need not be flat. Then this surface and if I take on this surface some element area, some elementary area like this; then from this element radiation emitted by virtue of being at some temperature T_s will be radiation, will be emitted in all directions in 3 dimensions. Those directions would encompass a hemisphere; in 3 dimensions all the directions would encompass a hemisphere. So there is a directional nature to radiation and if your consider all the radiation emitted from the element on a surface, its those direction are together encompass a whole hemisphere. So that's the third concept.

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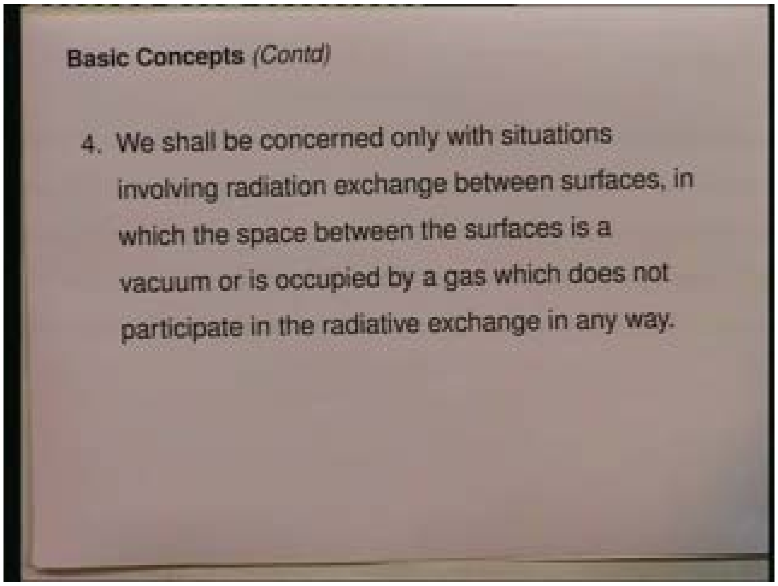

Basic Concepts *(Contd)*

4. We shall be concerned only with situations involving radiation exchange between surfaces, in which the space between the surfaces is a vacuum or is occupied by a gas which does not participate in the radiative exchange in any way.

The final thing I want to say is that we will be dealing in these few lectures on thermal radiation, we shall be concerned with situations, we shall be concerned only with situations involving radiation exchange between surfaces in which the space between the surfaces is a vacuum or is occupied by a gas which does not participate in the radiative exchange in any way - this is what, these are the situations with which we'll be concerned. Just to go back again to the sketch I drew a moment earlier when I showed a solid body cooling inside an enclosure. You recall I took this example; I said I have a solid body which is cooling in an enclosure.

Now, since I talked only of radiant heat exchange the assumption which I made was that there was probably only a, there was probably a vacuum in this enclosure in which case obviously there cannot be any other mode of heat transfer like convection or that if there was a gas that gas was not participating in any way in the radiative heat exchange process. The radiation heat exchange occurs by itself; the presence of a medium does not interfere, presence of gaseous medium does not interfere with that radiative heat exchange – that is the point which I want to make.

So, the fourth point which I making under basic concepts is we shall be concerned only with situations involving radiation exchange between surfaces in which the space between the surface is a vacuum or the space is occupied by a gas which does not participate in the radiative exchange in any way. So let me repeat the basic concepts; what were they? Number 1 - I said thermal radiation is an electromagnetic wave, it does not require a material medium for its transmission. Most thermal radiation is in the .1 to 10 micron range. All surfaces at all temperature levels emit thermal radiation and the amount emitted or the rate of emission is proportional to the fourth power of the absolute temperature of the surface. That was point number 1.

The second point I made was - every surface apart from having the capacity to emit radiation by virtue of its temperature level also has a capacity to absorb radiation falling on it, which has been emitted by surrounding surfaces and falls on it. So whenever radiation exchange takes place between a surface and another surface there is emission and there is also absorption of radiation which is emitted by other surfaces and falling on it. That is how radiation heat exchange takes place.

The third point which I made was that when radiation exchange takes place between surfaces we need to consider often that there is a directional nature to that radiation; that means the radiation given off from a surface is in all directions and compassed by a hemisphere. And the forth point which I made was that in this course in the few lectures we are going to do on thermal radiation, whenever we talk of radiation heat exchange, we will assume that there is a vacuum between the surfaces which are exchanging it by radiation by virtue of their different temperatures or we will assume that if there is gas or air in that space between the 2 surfaces that air or gas is not participating in the radiative heat exchange in any way. These are certain basic ideas which I wanted put across first.

Now let us take them up one by one; let us talk first about the emission characteristics of surfaces, that's the first thing we want to do now. How much do surfaces emit and we want to define certain terms associated with the emission characteristics of surfaces. The first notion, the first term which we want to define is what is called as a black surface.

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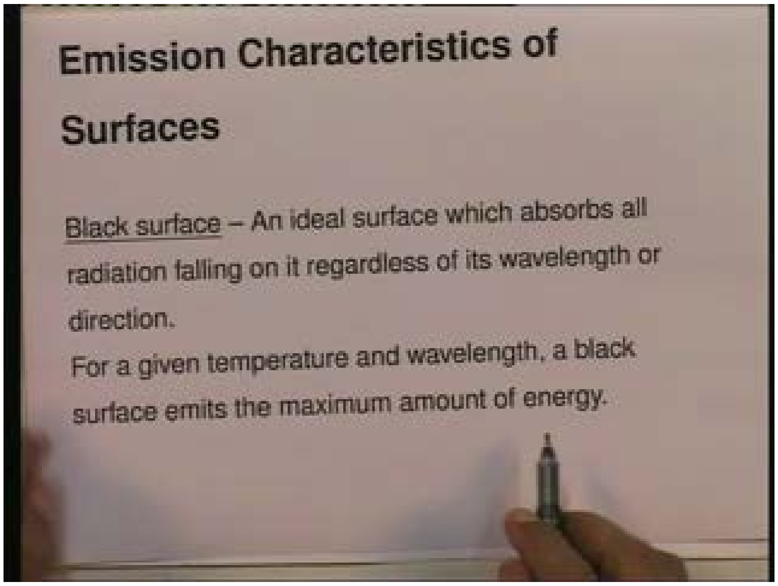

Emission Characteristics of Surfaces

Black surface – An ideal surface which absorbs all radiation falling on it regardless of its wavelength or direction.

For a given temperature and wavelength, a black surface emits the maximum amount of energy.

We say a black surface is an ideal surface which absorbs all radiation falling on it regardless of its wavelength or direction – that is the definition of a black surface. A surface which absorbs all radiation falling on it regardless of the direction of that radiation, where its coming from or regardless of the wavelength of that radiation. It will absorb everything, that is called a black surface is an ideal surface. Real surfaces may approach black surfaces but are not exactly black surfaces. The second point to note which we are not proving but stating is - for a given temperature and a wavelength, a black surface emits in the maximum amount of energy. For a given temperature and

wavelength a black surface emits the maximum amount of energy. Any other surface, any other surface would emit a smaller amount therefore a surface is a kind of bench mark.
So I repeat again, for a given temperature and wavelength a black surface emits the maximum amount of energy and is therefore a kind of a bench mark for us as a maxim providing for a maximum. Now let us define certain terms based on this. The first term which I am going to define is the following - I am going to define a term called the total hemispherical emissive power and I am going to use the symbol e for it - total hemispherical emissive power.

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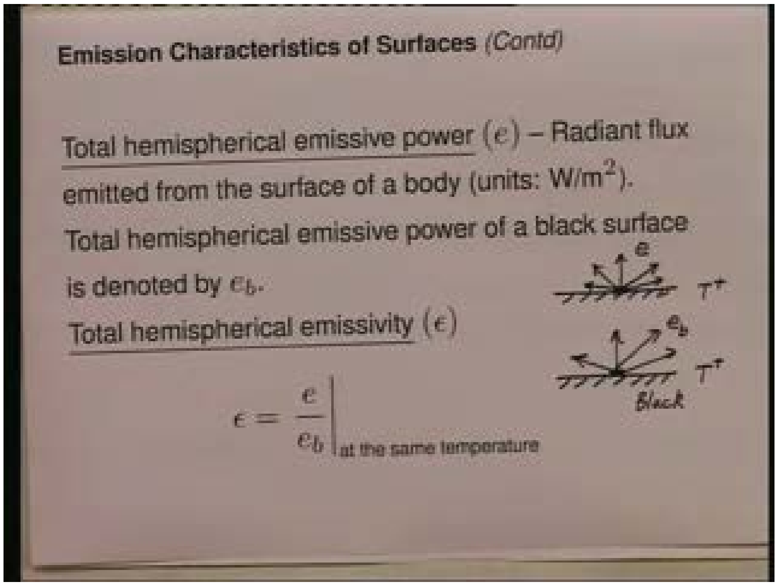

Emission Characteristics of Surfaces *(Contd)*

Total hemispherical emissive power (e) – Radiant flux emitted from the surface of a body (units: W/m^2).

Total hemispherical emissive power of a black surface is denoted by e_b.

Total hemispherical emissivity (ϵ)

$$\epsilon = \frac{e}{e_b}\Bigg|_{\text{at the same temperature}}$$

What is it? The total hemispherical emissive power of a surface is the radiant flux emitted from the surface of a body. Suppose I have a surface, some surface; it is at a temperature T plus some temperature by virtue of being at T plus every element on this body on the surface is going emit radiation and that radiation if you count all the directions will encompass a hemisphere like this - all directions of hemisphere and all wave wavelengths. If I add it all up and ask how many, what is the flux being emitted from this body in watts per meter squared? That is called the total hemispherical emissive power of the surface, the radiant flux emitted from the surface of a body.

What is the word total here mean? The word total means sum - the summation over all wavelength; that is all wavelength that is why the word total. Hemispherical means a summation over all directions that is why the word hemispherical. Total hemispherical means the radiation being emitted summed over all wavelengths and summed over all directions; that is why the words total and hemispherical. And and we will use the symbol e and obviously the units would be watts per meter square. So, that is a term; obviously if you want to talk about the total hemispherical emissive power of a black surface, we will use a subscript and we will say its e_b. So for the same quantity but defined for a black surface we will use the symbol e_b.

So, the total hemispherical emissive power of a black surface is denoted by e_b. Now let us say, let us go back to this sketch here. We had a real surface at a temperature T plus and its emissive power was e. Let us say I have another surface also at a temperature T plus – same temperature T plus and let us say it is a black surface. Its total hemispherical emissive power if I take an element here, its total hemispherical emissive power that is the amount being radiated per unit area per unit time is going to be e_b.

The ratio e by e_b, the ratio e by e_b is called the total hemispherical emissivity of the surface of this real surface. The total hemispherical emissivity of a real surface is the ratio of the total hemispherical emissive power of the surface to the total hemispherical emissive power of a black surface at the same temperature T plus. That is how we define a quantity called as total hemispherical emissivity and we use the symbol epsilon for it. So we have defined 2 quantities - e which is total hemispherical emissive power and epsilon which is total hemispherical emissivity; we have defined 2 terms now for us. The word total I again repeat in those 2 terms stood for summation over all wavelengths.

Now, let us and by the way before I go forward, let me say, obviously by definition it follows that emissivity which is the ratio of e by e_b; eb is the maximum. No surface can emit more that - what a black surface emits - therefore it follows that epsilon by definition must always be a quantity between 0 and 1. It follows straight away epsilon has to be something between 0 and 1; is that clear? So by definition, epsilon is something which is bounded and it is going to be between 0 and 1. Now let us distinguish radiation by its wavelength and we now define a new set of 2 terms again. We are now going to define a term called as the monochromatic hemispherical emissive power of a surface.

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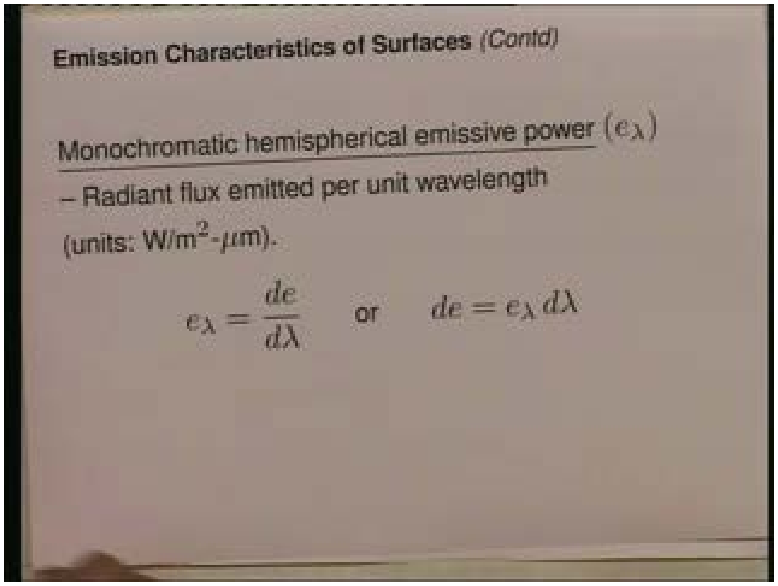

Emission Characteristics of Surfaces *(Contd)*

Monochromatic hemispherical emissive power (e_λ)

– Radiant flux emitted per unit wavelength

(units: W/m^2-μm).

$$e_\lambda = \frac{de}{d\lambda} \quad \text{or} \quad de = e_\lambda \, d\lambda$$

The monochromatic hemispherical emissive power of a surface for which we will use the symbol e lambda is the radiant flux emitted per unit wavelength of the surface. We will have the units watts per meter squared per micron or micrometer for measuring it. So e lambda is de d lambda or de is equal to e lambda d lambda; that is how we define the quantity e lambda - the radiant flux emitted by the surface per unit wavelength watts per meter squared micron. e lambda, another way of describing e lambda is to say e lambda is the quantity.

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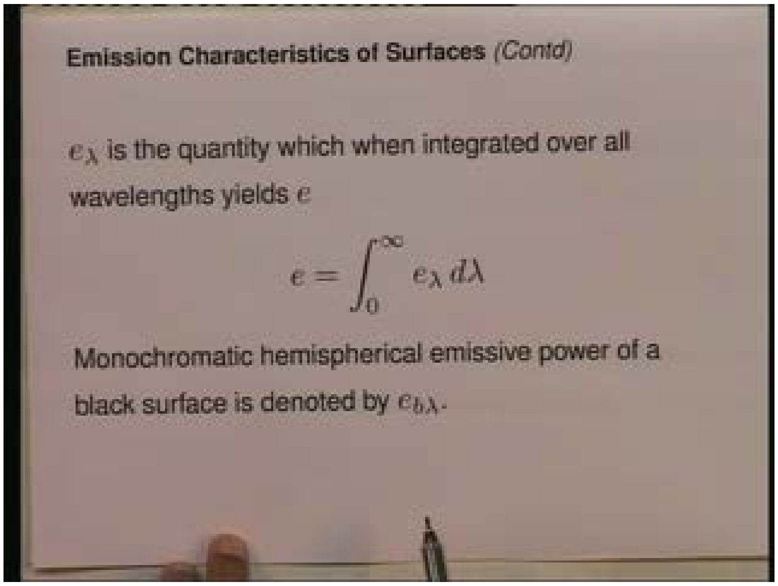

Emission Characteristics of Surfaces *(Contd)*

e_λ is the quantity which when integrated over all wavelengths yields e

$$e = \int_0^\infty e_\lambda \, d\lambda$$

Monochromatic hemispherical emissive power of a black surface is denoted by $e_{b\lambda}$.

which when integrated over all wavelengths yields the quantity e. e is equal to integral 0 to infinity e lambda d lambda. Let me draw a sketch again to indicate what I mean by this what I am trying to say is the following.

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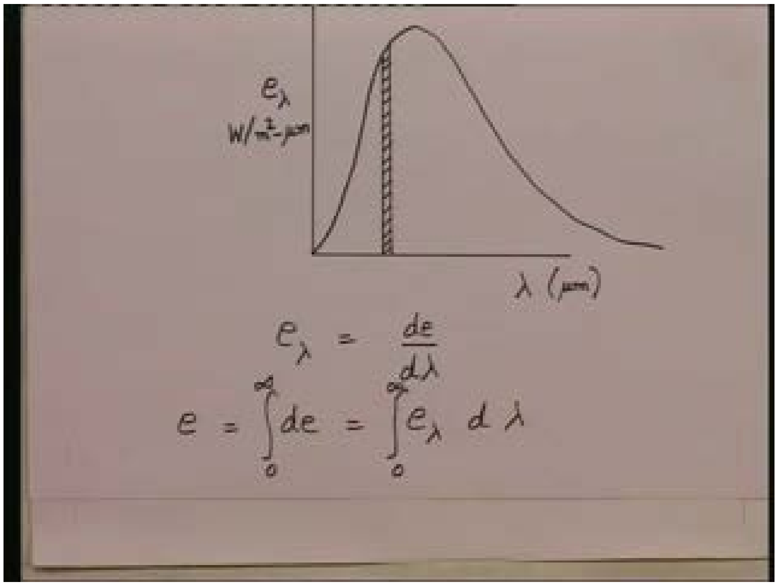

$$e_\lambda = \frac{de}{d\lambda}$$

$$e = \int_0^\infty de = \int_0^\infty e_\lambda \, d\lambda$$

Suppose I have, on a graph like this, a surface. I show on a graph - here is lambda in microns and this is some surface for which I wish to plot the quantity e lambda in watts per meter squared micron. The radiation emitted, radiant flux emitted by this surface is going to be some thing like this: starting at 0 going up and then again tapering off with much of it in the .1 to 10 micron range.

Now, what I am trying to say is the following - I am trying to say that if I take at some wavelength lambda, if I take at some wavelength lambda, if I take a quantity d lambda; this is lambda and this is lambda plus d lambda, then this shaded strip will be de. Therefore e lambda is nothing but de d lambda or de is equal to e lambda d lambda. If I integrate both sides over the whole wavelength region from 0 to infinity, if I integrate over both sides, both sides from the whole wavelength region, then the left hand side will become the emissive power - the total hemispherical emissive power of the surface and that is nothing but the integral 0 to infinity e lambda d lambda.

So, e lambda is that quantity which when integrated overall wavelengths - the entire spectrum of wavelengths - will give the total hemispherical emissive power of the surface. So there are 2 ways of looking at it - a quantity which when integrated over all wavelengths gives me the total hemispherical emissive power or it can also be looked upon, e lambda can also be looked upon as the radiant flux emitted per unit wavelength; either way is equivalent. Now let us having defined what is meant by monochromatic hemispherical emissive power; again let me just say monochromatic means at a particular wavelength hemispherical means again for all directions - now having done that, let us define a term called as monochromatic hemispherical emissivity that would be epsilon lambda.

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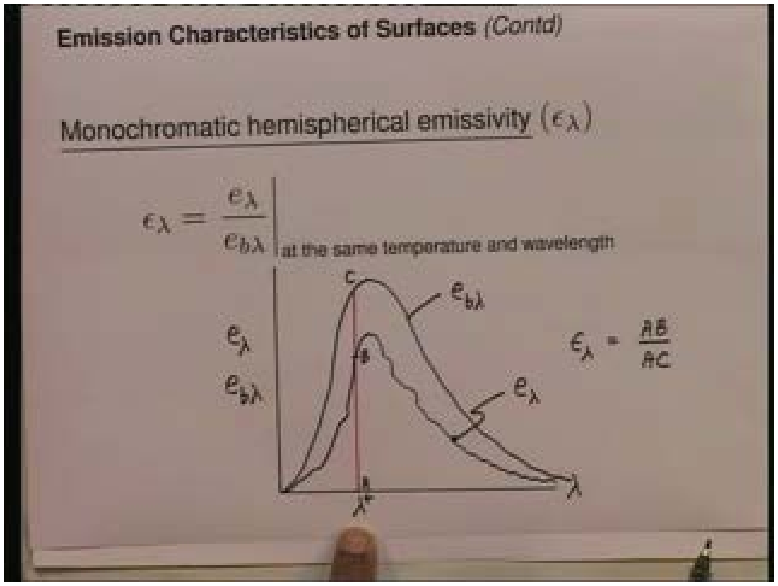

Emission Characteristics of Surfaces *(Contd)*

Monochromatic hemispherical emissivity (ϵ_λ)

$$\epsilon_\lambda = \frac{e_\lambda}{e_{b\lambda}}\Bigg|_{\text{at the same temperature and wavelength}}$$

$$\epsilon_\lambda = \frac{AB}{AC}$$

How will we define it? We would say epsilon lambda - the monochromatic hemispherical emissivity of a surface - is the ratio of the monochromatic hemispherical emissive power of a surface divided by the monochromatic hemispherical emissive power of a black surface at the same temperature and the same wavelength; that is how we define the quantity monochromatic hemispherical emissivity. To draw a sketch again just to illustrate ideas, what we are trying to say is the following. Suppose this is a graph on this axis, on the x axis, I have lambda on the y axis I plot that surface I plot e lambda and I plot e_b lambda - the monochromatic hemispherical emissive power and the monochromatic hemispherical emissive power of a black surface at the same temperature for the black surface - I will get a graph like this.

For the actual surface I will get something lower; it may not be that smooth, may be up and down but I will get something like this. So the outer one is e_b lambda the inner one is e lambda; at a particular wavelength - say lambda plus - if I want to know the value of epsilon lambda, then what I will do is the following at a particular wavelength. Let us say that particular wavelength is lambda plus, then at that wavelength on the lower graph that is the e lambda graph, I will get let us say an intercept A B and on the other graph for e_b

lambda, let us I get an intercept AC. Then it follows that epsilon lambda is equal to AB upon AC.

The ratio of the monochromatic hemispherical emissive power of the real surface with which we are concerned to the monochromatic hemispherical emissive power of a black surface at the same wavelength mean lambda plus and both these e lambda and e_b lambda graphs are drawn at the same temperature T plus. So both these are corresponding to the same temperature; that's how we defined monochromatic hemispherical emissivity of a surface. Now we have defined 4 terms, let me put them down again. 4 quantities have been defined; what were these?

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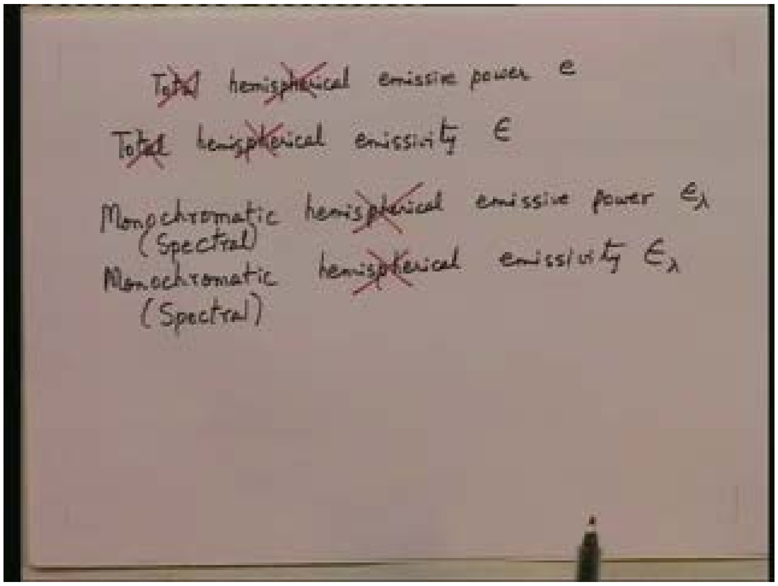

~~Total~~ ~~hemispherical~~ emissive power e

~~Total~~ ~~hemispherical~~ emissivity ϵ

Monochromatic (Spectral) ~~hemispherical~~ emissive power e_λ

Monochromatic (Spectral) ~~hemispherical~~ emissivity ϵ_λ

We defined total hemispherical emissive power - that was the first term we defined e. Then we defined total hemispherical emissivity epsilon; we defined these 2. After that we defined monochromatic hemispherical emissive power e lambda and then finally we defined monochromatic hemispherical emissivity epsilon lambda - these are the 4 quantities which we have defined. Now the words, we get tired of using the words over and over again. So generally one seizes to use the words total and hemispherical for the first 2 quantities and we say instead of keeping on saying total hemispherical emissive power, we only use the phrase emissive power. When we say emissive power we mean total hemispherical emissive power. When we use the word emissivity we mean total hemispherical emissivity. This is the accepted practice.

Similarly for the next 2 terms again; we usually delete the words hemispherical. So when we use the term monochromatic emissive power, we mean monochromatic hemispherical emissive power; when we use the term monochromatic emissivity, we mean monochromatic hemispherical emissivity. So the words that I have crossed out are not used and they are sort of assumed to be in the meaning. Just keep that in mind. Also the second thing which I have want to state is: instead of the word monochromatic, the word spectral is also used. So we refer to monochromatic emissive power also as spectral emissive power; it means the same thing or we refer to monochromatic emissivity as spectral emissivity. So you should get used to the shorted, abbreviated forms which are used instead of going on using the longer versions all the time.

In the last 2 terms, a word hemispherical is dropped in the first 2 terms - the words total as well as hemispherical are dropped. Now we have defined these terms, finally for emission characteristics I want to define a term called as a gray surface.

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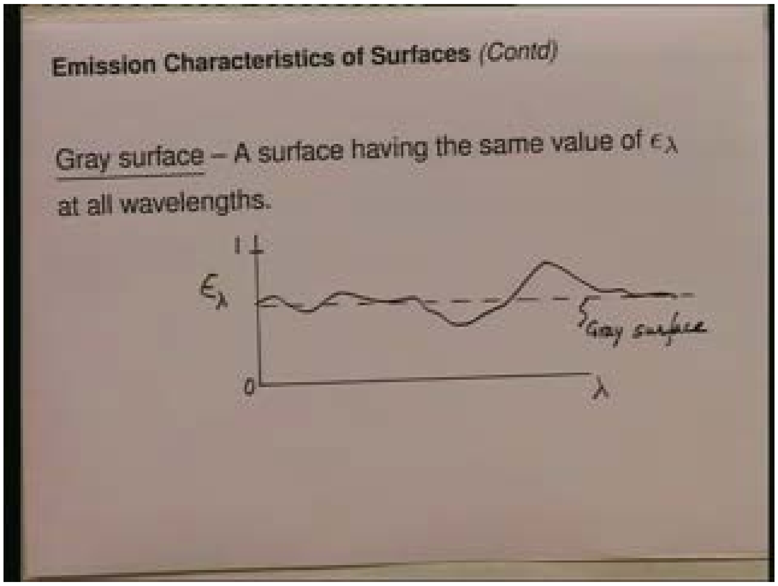

Emission Characteristics of Surfaces *(Contd)*

Gray surface – A surface having the same value of ϵ_λ at all wavelengths.

A gray surface is the surface having the same value of epsilon lambda at all wavelengths. How have you defined epsilon lambda? epsilon lambda was defined as e lambda upon e_b lambda where e lambda and e_b lambda are taken, are values at the same wavelength and at the same temperature of the surface. Now for a real surface typically and of course epsilon lambda has to be something between 0 and 1 that follows from the definition; so for a typically real surface if I want to plot epsilon lambda, it is going to typically fluctuate between 0 and 1 if I were to plot for any real surface. The variation of an epsilon lambda then if this is 0, here this is 1 and this were against lambda, then typically epsilon lambda if plotted for any real surface may be something like this. This is how the variation would look for a real surface - some values between 0 and 1 for different wavelengths.

Now, a gray surface is an idealization for engineering purposes in order to do calculations. We make this idealization and we say a gray surface is a surface having the same value of epsilon lambda at all wavelengths; that means if there is some variation, we idealize it and say why not take some constant value? Say like this, that would be a gray surface idealization, that means instead of taking actual variation which is going up and down we idealize it, take some average value which is the constant value and then we get the gray surface idealization. So a gray surface is a surface having the same value of epsilon lambda at all wavelengths. It is an idealization and it turns out to be useful idealization for doing calculation. So we make that idealization quite often; so this is one more term that we have defined.

So, let me repeat now: what are the terms we defined? The black surface as a surface which has the maximum amount of radiation that we get; we defined terms like the emissive power of a surface, the emissivity of a surface, the monochromatic emissive power of a surface, the monochromatic emissivity of a surface and finally what is meant by a gray surface. Now with these definitions, we are ready to take up the laws of black body radiation.

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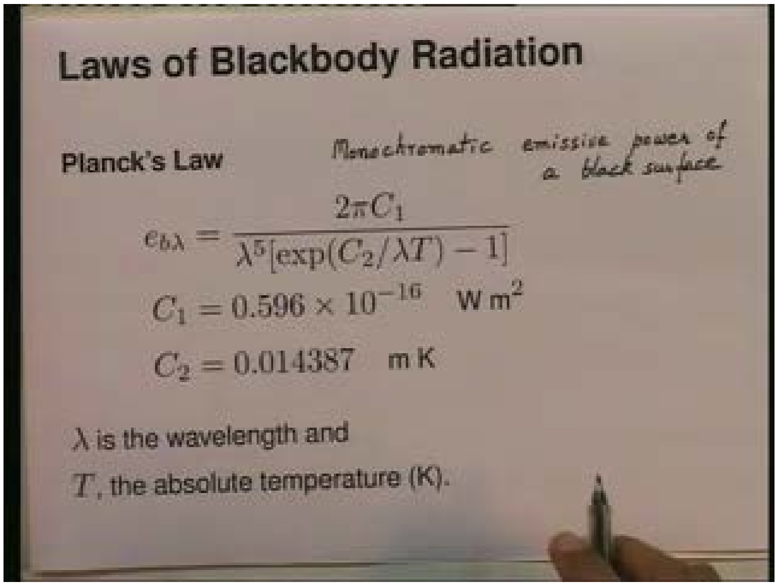

Laws of Blackbody Radiation

Planck's Law Monochromatic emissive power of a black surface

$$e_{b\lambda} = \frac{2\pi C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]}$$

$C_1 = 0.596 \times 10^{-16}$ W m^2

$C_2 = 0.014387$ m K

λ is the wavelength and

T, the absolute temperature (K).

We are going to take up one by one the laws of blacks body radiation. I have mentioned the Stefan Boltzmann law to you earlier and I said at that time there are other laws like Planck's law, Wien's law which we will take up later. So now let us look at the laws in some detail - the first law which we want to look at is Planck's law. Planck's law is a statement which allows us to calculate the value of the monochromatic emissive power of a black surface e_b lambda. Planck's law gives us the monochromatic emissive power of a black surface, the monochromatic emissive power of a black surface; that's what Planck's law gives us.

It states e_b lambda is equal to 2 pi C_1 upon lambda to the power of 5 multiplied by e to the power of C_2 divided by lambda T minus 1 where lambda is the wavelength and T is the absolute temperature in Kelvin and the constant C_1 and C_2 in this Planck's law, in Planck's law have come from experimental data. So from certain electromagnetic considerations, Planck derived or gave the nature of his law and then with the help of experimental data, the values of C_1 and C_2 were obtained which are given here. C_1 is equal to .596 into 10 to the minus 16 watts meter square and C 2 is equal to .014387 meter Kelvin; these are the values of the constants from experimental data.

The nature of the law comes from certain electromagnetic considerations; lambda is the wavelength, T is the absolute temperature. So Planck’s law gives us the monochromatic emissive power of a black surface; so what would be the monochromatic emissive power of a non black surface? Well straight away you will say if the surface is non black, for a non-black surface e lambda.

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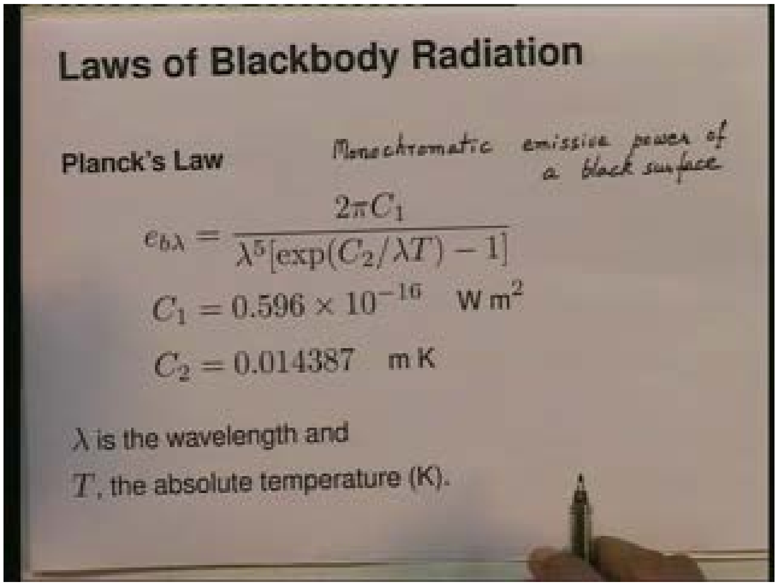

Laws of Blackbody Radiation

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$$C_2 = 0.014387 \quad \text{m K}$$

λ is the wavelength and

T, the absolute temperature (K).

which is the monochromatic emissive power of a non-black real surface will be nothing but epsilon lambda into e_b lambda. So e_b lambda will come from Planck’s law and epsilon lambda will be a property of the surface which I should know in order to calculate e lambda. So any time I do calculation in radiation, I need to know the emissivity of the surface either the epsilon or epsilon lambda in order to calculate 2 radiation calculations for a surface. So Planck’s law gives me the value for a black surface and for a non black surface, I need to multiply Planck’s law by the value of the monochromatic emissivity of the surface.

Now, let us plot Planck’s, the equation of Planck’s law; what will we get? If I want to plot Planck’s law, I will get graph something like this and those are seen here.

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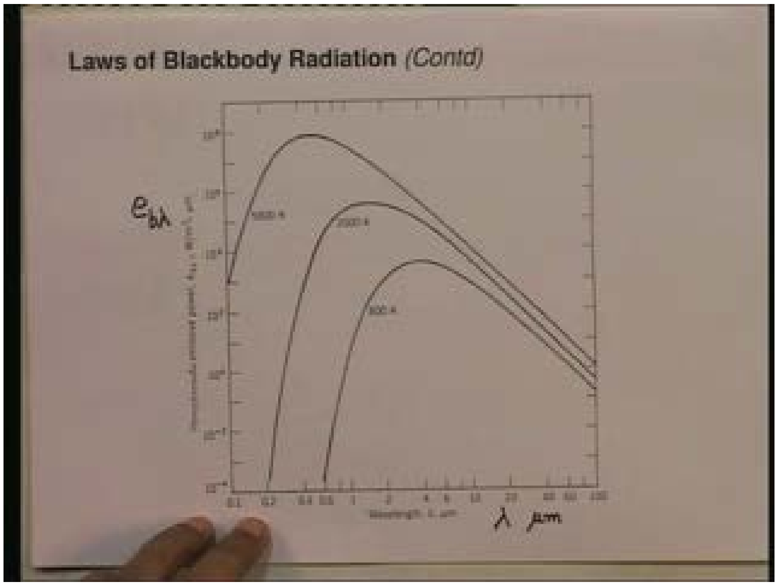

Laws of Blackbody Radiation *(Contd)*

I am plotting on this graph here against lambda; I will just lambda in big letters now against lambda in microns, against lambda in microns. I am not on the, which is on the x axis; I am plotting the quantity e_b lambda on the y axis. I am writing it in big letter because it is not so big in the print here and you can see 3 graphs are for 3 different temperatures. The lower most graph is from 800 Kelvin, the upper one the middle one for 2000 Kelvin and the one above it for 5800 Kelvin.

If I want to extend these graphs, you can see they are stating from .1 to 100 microns; they are not going the whole range from 0 to infinity. The graphs are staring on the x axis here at .1 and going up to 100 microns here on here - so .1 to 100. If these graphs were going the whole range, they would all look like the ones I drew earlier. They would all, if they were going from 0 to infinity, then all these graphs would look, would start from 0, would go up through a maximum which you are seeing and asymptotically go into 0. That would be the nature of the graph that I would get if I want to plot them all the way from 0 to infinity.

We are plotting them in a slightly narrow range; so you are not seeing then starting from 0. You are not seeing them asymptotically going to 0 at infinity. Now what do you notice about these graphs? Let us comment on that; what do we see? The first comment which I want to make about these graphs is - let me write down. The first comment which I want to make is on the law, at graphs which I have draws for 3 different temperatures.

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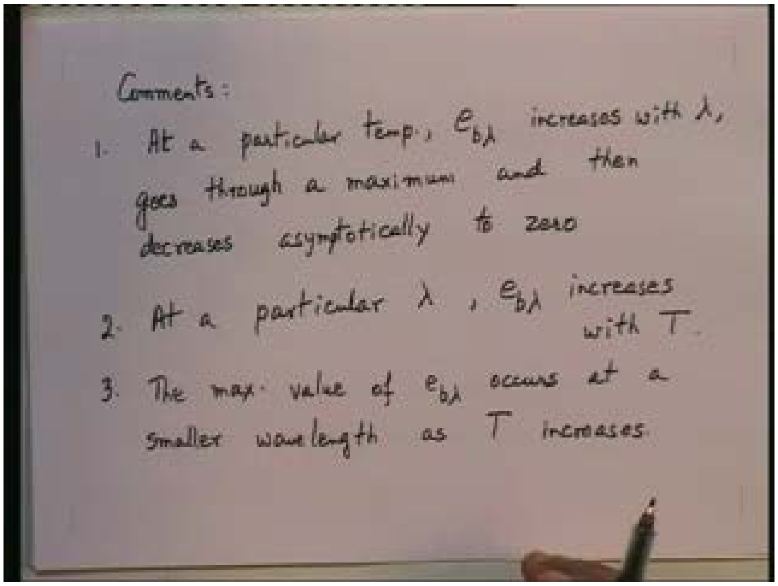

Comments:

1. At a particular temp., $e_{b\lambda}$ increases with λ, goes through a maximum and then decreases asymptotically to zero
2. At a particular λ, $e_{b\lambda}$ increases with T.
3. The max. value of $e_{b\lambda}$ occurs at a smaller wavelength as T increases.

Comment number 1 is: at a particular temperature, e_b lambda, the value of eb lambda increases first, increases with lambda, goes to a maximum and then after going to maximum decreases asymptotically and then decreases asymptotically to 0. That is the first characteristic of the graph which you need to notice. Let me show the graph again, all these graphs if I draw them, all the way from 0 to infinity. First I have increased, gone through a maximum and then asymptotically going into 0; that is the first comment.

Second comment - at a particular lambda, at a particular value of lambda, e_b lambda increases with temperature; that is the second comment. So if I go back again to the set of graphs at a particular lambda; let us take say 4 microns here at, I am drawing. at 800 I get this value, at 200 I get this value, at 5800 I get this value. So at a particular lambda with increasing temperatures, I get higher values of e_b lambda. So, keep that in mind.

The third comment - the maximum value, the maximum value of e_b lambda occurs at a smaller wavelength as T the temperature increases. That is the third comment and let us look at the graphs again in order to understand that. What we are saying is the following - we are saying this location of the maximum, look at 800; the maximum is occurring at about 4 microns. For 2000, maximum is occurring at about 1 and half microns; at 5800, the maximum is occurring at about half a micron. So the maximum value of e_b lambda occurs at a lower wavelength lambda max at which the maximum value of e_b lambda occurs, decreases as the temperature goes on increasing - this value of the maximum. The location of the maximum shifts to the left as the temperature of the surface increases. So this is the third characteristic of these surfaces which is worth noting.

Now, if I want to find out the location of this maximum, what should I do?

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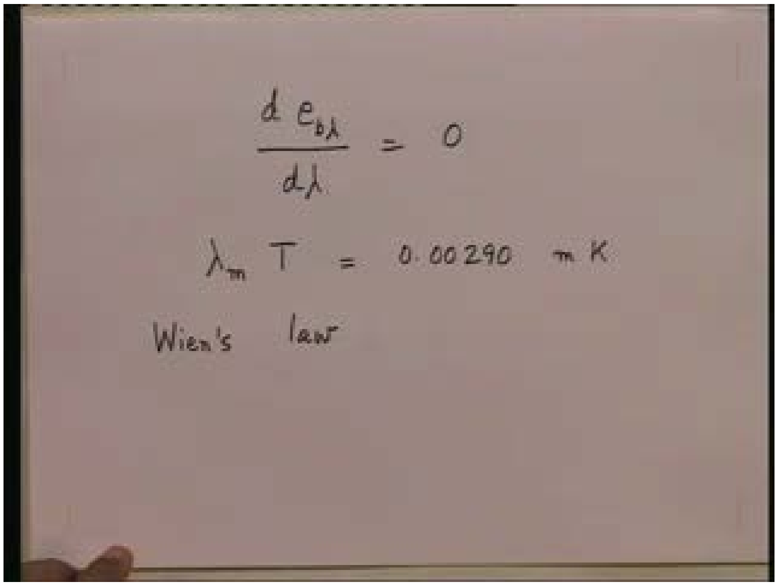

$$\frac{d e_{b\lambda}}{d\lambda} = 0$$

$$\lambda_m T = 0.00290 \text{ m K}$$

Wien's law

I have an expression for a black surface; I have an expression for e_b lambda and if you ask me where does it occur, while all I have to do is to say take d e_b lambda by d lambda and equate it to 0. So, substitute Planck's law in here; do d of d lambda on Planck's law which equal to 0 and I will get the location of the maximum, location of the wavelength at which the maximum e_b lambda occurs. If you do that you will get, lambda max occurs at, lambda occurs, is given by the expression lambda m T is equal to .00290 meter Kelvin; that is what you will get.So in order to find the location of the maximum, differentiate Planck’s law. And I am not doing that here; I am just telling you what will happen if you differentiate Planck’s law and solve.

You can try doing it on your own; it is a trial and error which will have to be done - numerical work. If you do that, you will get lambda m T - lambda m being the wavelength at which the maximum value occurs - you will get lambda m into T is equal to .00290 meter Kelvin and this law is called Wien’s law. This law is called Wien’s law; so Wien’s law gives us the value of the wavelength at which the maximum value of e_b lambda occurs. So let us go back to these graphs again; Wien’s law gives us this lambda, lambda max at which the maximum occurs. That is what Wien’s law will give us; let me again repeat lambda T is equal to .00290 meter Kelvin.