Fundamentals of Conduction and Radiation

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Lecture - 32
Gas Radiation

Hello everyone. So, today we will study the radiation exchange with participating media. So, this is the first lecture of module 12. So, till now we have studied the radiation exchange between the surfaces in an enclosure where there was no participating medium right. So, we have considered some vacuum or air and those mediums did not participate in radiation.

It did not absorb or scattered or emitted. So, this is non-participating medium. But when the gases take part in the radiation, then it will absorb the radiation, it will emit the radiation and sometime it will scatter the radiation. So, obviously those are known as participating medium.

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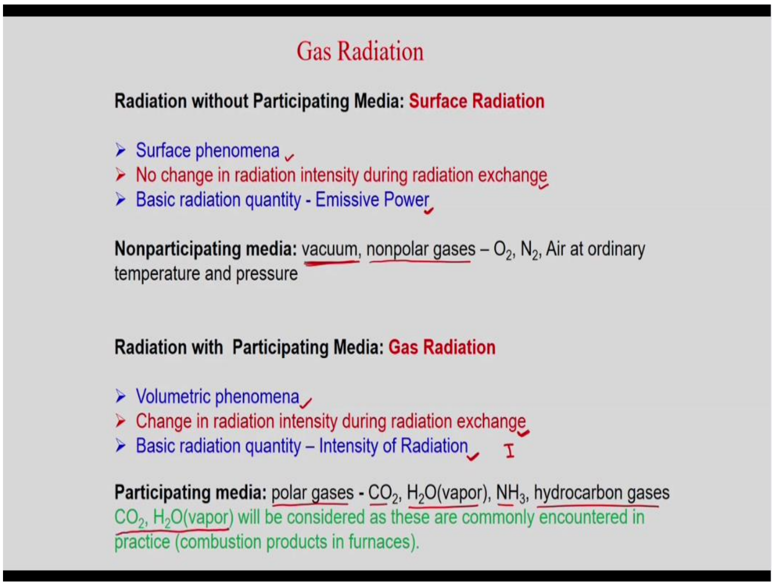

So, you can see from this slide. So, when radiation happens without participating media, these are surface phenomena. Obviously we have seen that when the radiation exchange is happening between two surfaces, these gases do not participate, obviously these are surface phenomena. No change in radiation intensity during radiation exchange. So, when the radiation is going from one surface to another surface, there is no change in the intensity.

Whatever it is leaving from the surface 1 actually using the view factor, we see that all the radiation is reaching to the other surface. There is no attenuation or augmentation is happening of the intensity. And in this case basic radiation quantity is emissive power because we have seen that always we talk about the emissive power which is black body emissive power if you consider then it is, $E_b = \sigma T^4$ okay. So, these are for radiation without participating media. Now, if you consider the participating media. So, you can see generally vacuum is your perfect non-participating media and some nonpolar gases right like oxygen, nitrogen okay or air at ordinary temperature and pressure are considered to be non-participating media even Argon is considered to be non-participating media.

But when we consider participating media, or when we consider the gas radiation, so then it is volumetric phenomena, you can see okay. And obviously change in radiation intensity occurs during radiation exchange. So, when radiation actually leaving from some surface and going to another surface and it passes through the gases actually gases absorbs the radiation either or emits the radiation or it scatters the radiation.

So, there will be change of intensity when it is travelling from one surface to another surface. So, there will be change in the radiation intensity. In this case, your basic radiation quantity is considered to be intensity of radiation. So, we consider I, I is considered to be intensity of radiation in participating medium.

So, you can see that generally polar gases like carbon dioxide and water vapour, ammonia or hydrocarbon gases are considered to be participating media. So, mostly this carbon dioxide and water vapor we will consider in our study because these are commonly encountered in practice like when combustion is happening in a combustion chamber. So, these are the two gases found majorly or commonly, carbon dioxide and the water vapor. So, we will consider these carbon dioxide and water vapour in our study.

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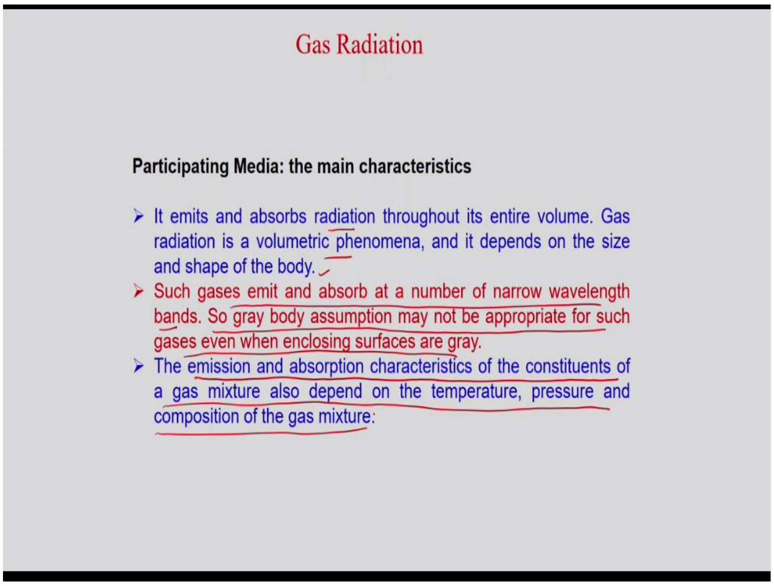

So, what are the main characteristic of this participating medium? So, you can see, it emits and absorbs radiation throughout its entire volume. Gas radiation is a volumetric phenomena and it depends on the size and shape of the body, because obviously the gases actually whatever is there inside, it depends on the shape and size of the body and it is a volumetric phenomena.

Such gases emit and absorb at a number of narrow wavelength bands. So, gray body assumptions may not be appropriate for such gases even when enclosing surfaces are gray. So, although you consider the enclosure as gray surface but when you are considering the gas radiation, this assumption of gray body is not valid. Next, the emission and absorption characteristic of the constituents of a gas mixture also depend on the temperature, pressure and composition of the gas mixture.

As you may have only carbon dioxide or only water vapour or combination of these two or other gases. So, obviously it depends on the constituents of the gas mixture and also its temperature and pressure.

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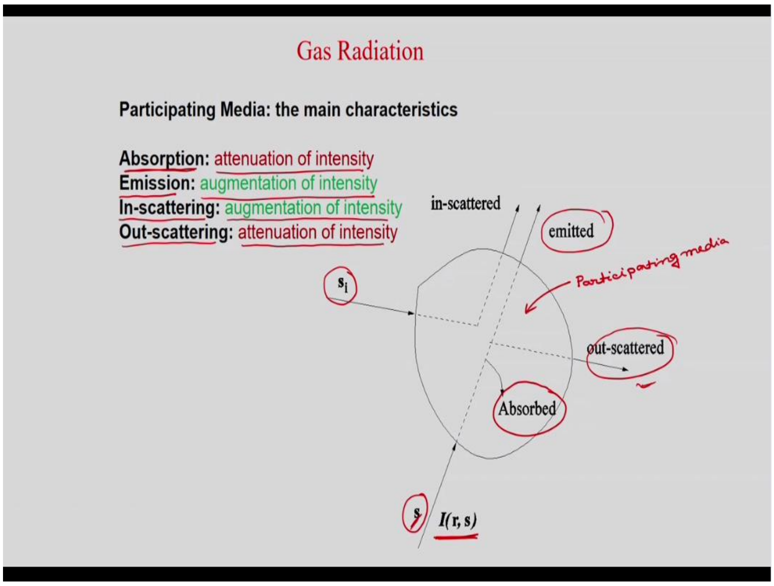

So, you can see whatever we have just considered the characteristic, we are just summarizing. So, you can see in this figure, a pencil ray of radiation in terms of intensity is going in the direction S. So, in this direction it is going and it is passing through this medium.

So, this is your participating medium. So, when it is passing through this participating media or gas, so obviously this gas you can see some portion may be absorbed. Some portion obviously when it is passing through it will be emitted okay, and when it is passing through it okay due to these gaseous particles, some portion of the radiation will be out scattered.

So it will actually leave from this direction and also from some other direction S_i in scatter may happen and it may go in this direction S. So, it is known as in scattering. So, you can see there are 4 phenomena happening. So, one is absorption. So, the gas itself actually absorbing the radiation; emission, the gas is having some temperature and at that temperature it is emitting the radiation.

From some other direction if radiation is coming and adding to this surface, then obviously it is known as in scattering and some radiation when it is passing through it, it actually go away from this direction. So, that is known as out scattering. So, you can see from here that in the absorption obviously attenuation of intensity is happening. What is attenuation? Actually decrease in the intensity is happening because it is absorbed by the gas okay.

Emission, so it is obviously augmentation of the intensity because the gas at that temperature it is emitting. So, obviously in that direction, there will be increase in the intensity. So, that is augmentation of the intensity is happening. In scattering, so when from other direction the radiation is coming and adding to that direction, obviously increase the intensity will happen, so obviously it is augmentation of the intensity.

And when out scattering is happening; obviously it is going away from this direction. So, there will be again decrease in the intensity or attenuation of intensity. So, these are some main characteristic of the participating media.

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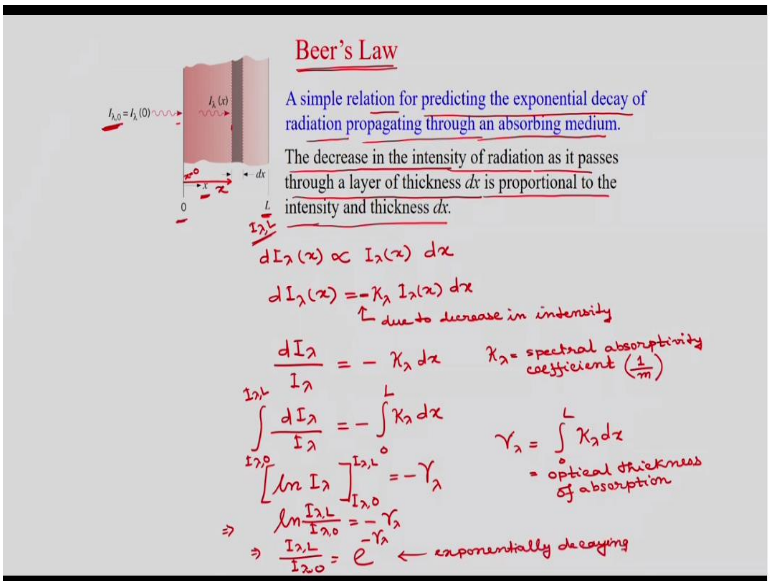

So, first we will discuss Beer's law. Actually, it is a simple relation for predicting the exponential decay of radiation propagating through an absorbing medium. So, we can see this figure. So, some spectral radiation beam of intensity $I_{\lambda,0}$ actually is incident on the surface where x = 0.

Now, when it is actually passing through this participating media where some gases are there, obviously this radiation will be attenuated due to absorption. So the attenuation process due to absorption is stated by this Beer's law.

So, what is this? The decrease in the intensity of radiation as it passes through a layer of thickness dx is proportional to the intensity and thickness dx. So, if $I_{\lambda,0}$ is the incident intensity and it is travelling in this direction x. So, at distance x, in the dx width there will be some absorption and this $I_{\lambda,x}$ or whatever it is actually incident at this x location, there will be some absorption and there will be some decrease in the intensity.

So decrease in the intensity you consider as dI_λ, which is a function of x. This is the decrease in the intensity is proportional to the intensity itself $I_\lambda(x)$ and the thickness.

$$dI_\lambda(x) \propto I_\lambda(x)dx$$

So when we equate it with some proportionality constant, so we can write

$$dI_\lambda(x) = -\kappa_\lambda I_\lambda(x)dx$$

There will be a negative sign, which is coming due to decrease in intensity.

$$\Rightarrow \frac{dI_\lambda}{I_\lambda} = -\kappa_\lambda dx$$

So, this κ_λ is known as spectral absorptivity coefficient and its unit is 1/m or m^{-1}. So, if the radiation is passing from 0 to L, then the attenuation you can integrate from 0 to L and find out, where the intensity will be $I_{\lambda L}$. So if you add the limits

$$\Rightarrow \int_{I_{\lambda,0}}^{I_{\lambda L}} \frac{dI_\lambda}{I_\lambda} = -\int_0^L \kappa_\lambda dx$$

$$\Rightarrow [\ln I_\lambda]_{I_{\lambda,0}}^{I_{\lambda L}} = -\gamma_\lambda$$

Where γ_λ is the optical thickness of absorption which is nothing but $\int_0^L \kappa_\lambda dx$. Putting the limits now

$$\Rightarrow \ln \frac{I_{\lambda L}}{I_{\lambda,0}} = -\gamma_\lambda$$

$$\Rightarrow \frac{I_{\lambda L}}{I_{\lambda,0}} = e^{-\gamma_\lambda}$$

So, you can see that your intensity whatever it is decreasing, it is exponentially decaying okay, from this relation you can see it is exponentially decaying.

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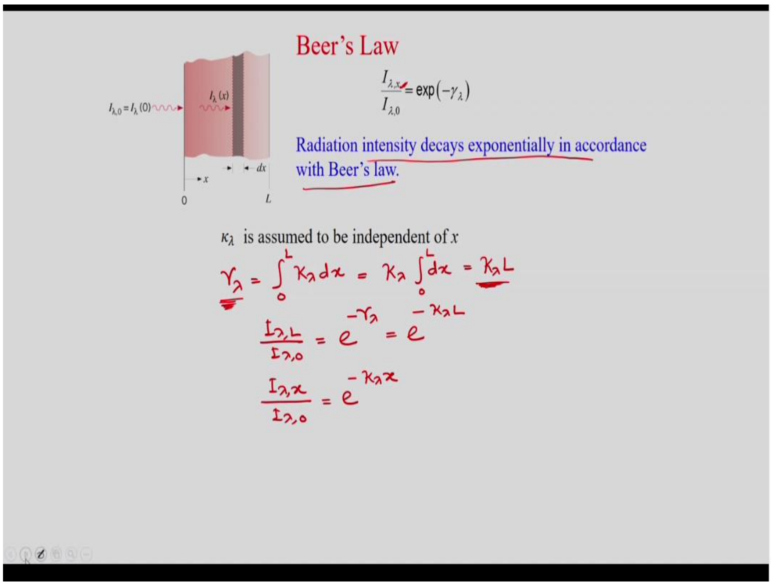

So, now for any x if we integrated

$$\Rightarrow \frac{I_{\lambda,x}}{I_{\lambda,0}} = e^{-\gamma_\lambda}$$

So, obviously we have already told that radiation intensity decays exponentially in accordance with Beer's Law.

Now, let us consider that this κ_λ is independent of x, then

$$\gamma_\lambda = \int_0^L \kappa_\lambda dx = \kappa_\lambda \int_0^L dx = \kappa_\lambda L$$

So, you can write

$$\frac{I_{\lambda L}}{I_{\lambda,0}} = e^{-\gamma_\lambda} = e^{-\kappa_\lambda L}$$

And if you consider at any distance x, then

$$\frac{I_{\lambda,x}}{I_{\lambda,0}} = e^{-\kappa_\lambda x}$$

So, γ_λ is the optical thickness of absorption and your κ_λ is the spectral absorption coefficient.

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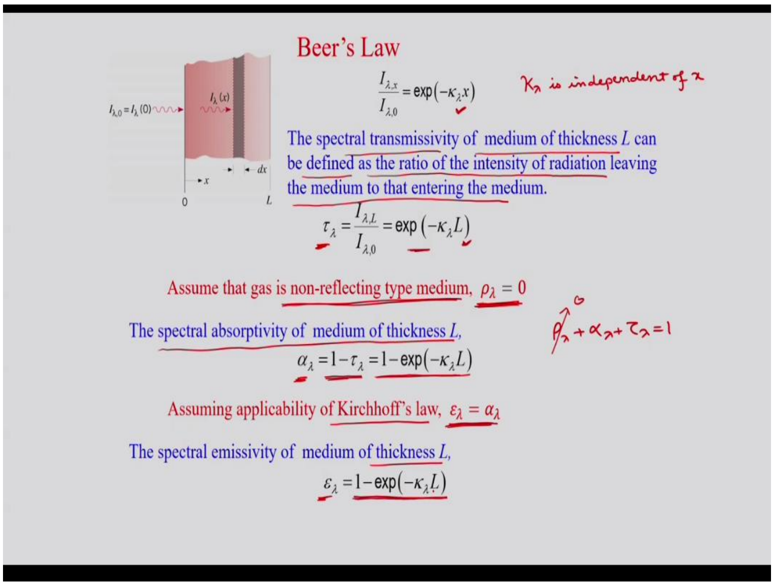

So, with this now you know this relation,

$$\frac{I_{\lambda,x}}{I_{\lambda,0}} = e^{-\kappa_\lambda x}$$

Where, your κ_λ is independent of x. So, if you consider that then the spectral transmissivity of the medium you can consider. So the spectral transmissivity of the medium of thickness L can be defined as the ratio of the intensity of radiation leaving the medium to that entering the medium.

So, at x = 0 what is the incident radiation intensity? That is, $I_{\lambda,0}$ and what is leaving at x = L? That is $I_{\lambda L}$. So, obviously your transmissivity of the medium will be

$$\tau_\lambda = \frac{I_{\lambda L}}{I_{\lambda,0}} = e^{-\kappa_\lambda L}$$

So, now if you consider that gas is non-reflecting type medium, then you can consider $\rho_\lambda = 0$. So the spectral reflectivity of the medium is 0. So, if you write that then obviously you can write the spectral absorptivity of medium of thickness L is

$$\alpha_\lambda = 1 - \tau_\lambda = 1 - e^{-\kappa_\lambda L}$$

Because you know

$$\rho_\lambda + \alpha_\lambda + \tau_\lambda = 1$$

And here ρ_λ is your 0, so $\alpha_\lambda = 1 - \tau_\lambda$. And now you know Kirchhoff's law right. Assuming the applicability of the Kirchhoff's law

$$\epsilon_\lambda = \alpha_\lambda$$

That is spectral emissivity is equal to spectral absorptivity. So, that if you write, then obviously you can write

$$\epsilon_\lambda = 1 - e^{-\kappa_\lambda L}$$

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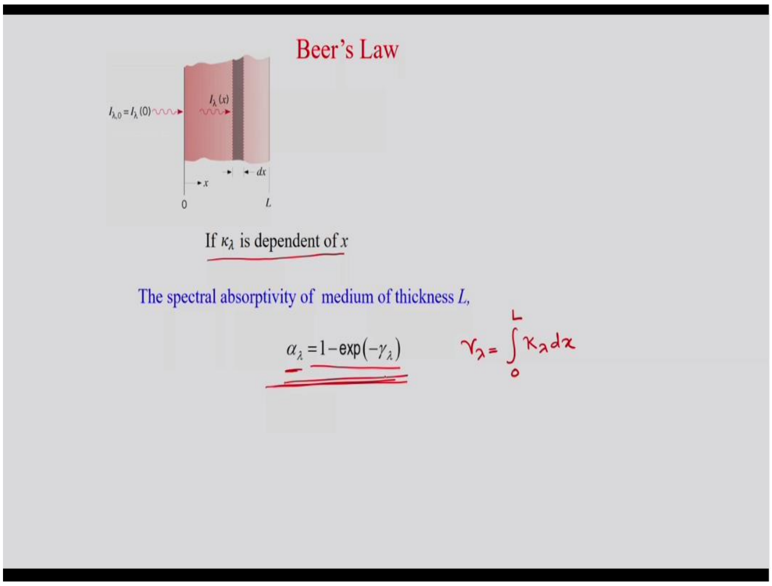

But if you consider that κ_λ is dependent of x then obviously you can write your spectral absorptivity is

$$\alpha_\lambda = 1 - e^{-\gamma_\lambda}$$

In this case $\gamma_\lambda = \int_0^L \kappa_\lambda dx$.

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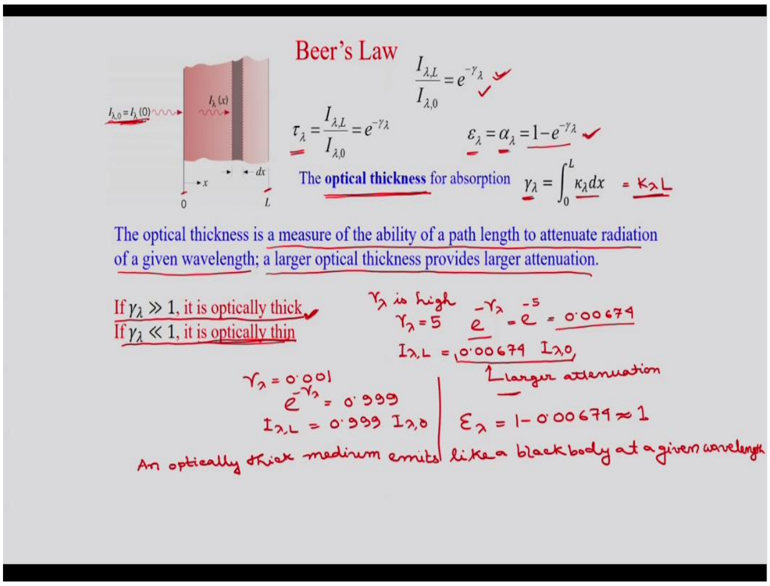

So, now we have seen from the Beer's law that

$$\frac{I_{\lambda L}}{I_{\lambda,0}} = e^{-\gamma_\lambda}$$

And also we have calculated the ϵ_λ and τ_λ and you have seen that this ϵ_λ from Kirchhoff's law is equal to $\alpha_\lambda = 1 - e^{-\gamma_\lambda}$ okay and we have defined that γ_λ as optical thickness.

And obviously it is $\int_0^L \kappa_\lambda dx$ and if κ_λ is independent of x then obviously it will be $\kappa_\lambda L$. So, what is actually this optical thickness? So, you can see here the optical thickness is a measure of the ability of a path length to attenuate radiation for a given wavelength; a larger optical thickness provides larger attenuation.

So, what does it mean? So, optical thickness actually determines the ability of a path length for attenuating the radiation at a given wavelength. So, when γ_λ is let us say high and let us take one example that γ_λ value is around 5, it is high and it is 5. So, what does it mean? So, what will be the $e^{-\gamma_\lambda}$?

$$e^{-\gamma_\lambda} = e^{-5} = 0.00674$$

And hence

$$I_{\lambda L} = 0.00674 I_{\lambda,0}$$

So, $I_{\lambda,0}$ is the incident radiation at x = 0, so that is incident intensity. Now when it is passing through a participating medium where the length is L then you can see that whatever $I_{\lambda L}$ at distance length L, it will be 0.00674 times the incident intensity. So, we can see that actually large amount of intensity is absorbed by the participating media right.

So, this is known as optically thick medium. So, from here you can see that you have larger attenuation. So, if $\gamma_\lambda \gg 1$ then it is known as optically thick medium and if $\gamma_\lambda \ll 1$ then it is known as optically thin medium.

Let us take one example γ_λ value let us say it is 0.001. So, if you take that

$$e^{-\gamma_\lambda} = e^{-.001} = 0.999$$

$$\Rightarrow I_{\lambda L} = 0.999 I_{\lambda,0}$$

So, you can see from here that whatever incident intensity was there, it is almost same at x=L. So, that means your radiation intensity actually not absorbed by the participating medium.

So, those medium is known as optically thin medium. So, when more attenuation happens, that means optically thick medium and the reverse is your optically thin medium. So, from this you can see that for a larger attenuation what will be your ϵ_λ?

$$\epsilon_\lambda = 1 - 0.00674 \approx 1$$

So it will be order of 1. So, what does it mean? If $\epsilon = 1$ that means it is known as a black body radiation. So, we can say that an optically thick medium, emits like a black body at a given wavelength. So, that is the physical significance of optical thickness.

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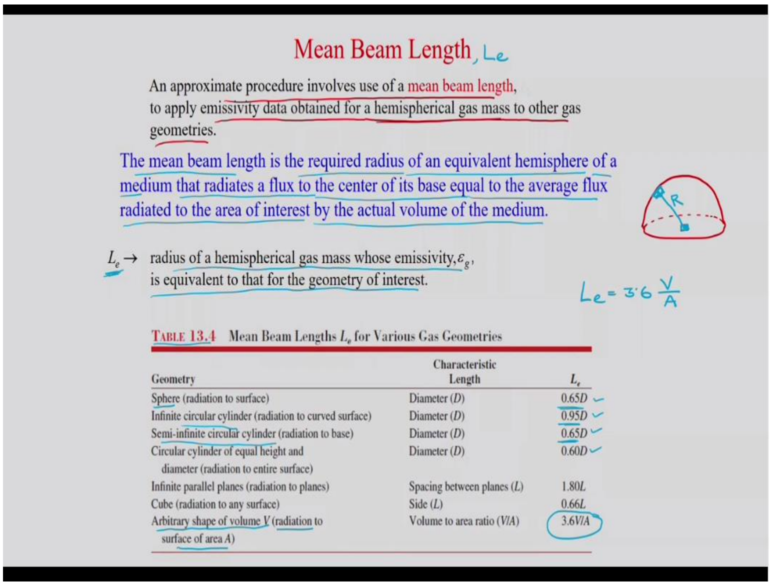

Now, let us talk about mean beam length okay. So an approximate procedure involves use of a mean beam length, to apply emissivity data obtained for a hemispherical gas mass to other gas geometries. So, in general when we study the gas radiation, it is having different geometries. If you consider two plates and in between if you have a participating medium, and you need to find the radiation exchange through this participating medium between these two plates.

Or you have a six surfaces enclosure or any surfaces enclosure, so you will have different geometries and you can have this radiation exchange through this participating medium. Now, here generally for a gas radiation, we talk about the hemispherical gas mass. What does it mean? So, you consider one hemispherical mass.

So, you can see this is one volume of hemisphere and let us consider this is one surface and one another surface is there at the hemisphere. So one small surface is there like this. Now, this if it is residing on this hemisphere, then the distance between these two, the center of the hemisphere and the surface, this radius is R let us say. So, this radius R is known as mean beam length when you are considering the gas radiation in a hemispherical gas mass. So, this is your mean beam length for this radiation exchange between these two surfaces where one is on the center of this hemisphere and one is residing on the hemisphere. So, this length whatever it is in this case, obviously it is radius of the hemisphere.

So, in this case, R is known as mean beam length, but when you are considering for any geometry, then if you consider the equivalent hemisphere and find what is the mean radius, so that is known as mean beam length. So, you see here, the mean beam length is the required radius of an equivalent hemisphere of a medium that radiates a flux to the center of its base equal to the average flux radiated to the area of interest by the actual volume of the medium.

So, in general whatever we consider, that is in any geometry we have to find the equivalent radius and it is given in this table you can see. So, it is denoted by L_e, which is the radius of a hemispherical gas mass whose emissivity is equivalent to that of the geometry of interest.

So, like sphere this is your 0.65D, infinite circular cylinder it is 0.95D, semi-infinite circular cylinder it is 0.65D and if you have any arbitrary geometry, then general formula is given by 3.6V/A. So, the gas volume is V and whatever surface is there that surface area is A.

$$L_e = 3.6\frac{V}{A}$$

But if you know that surface is a sphere or infinite circular cylinder or semi-infinite circular cylinder, then accordingly you can take the value of mean beam length from this table. So, table 13.4 of that Incropera and DeWitt heat transfer book.

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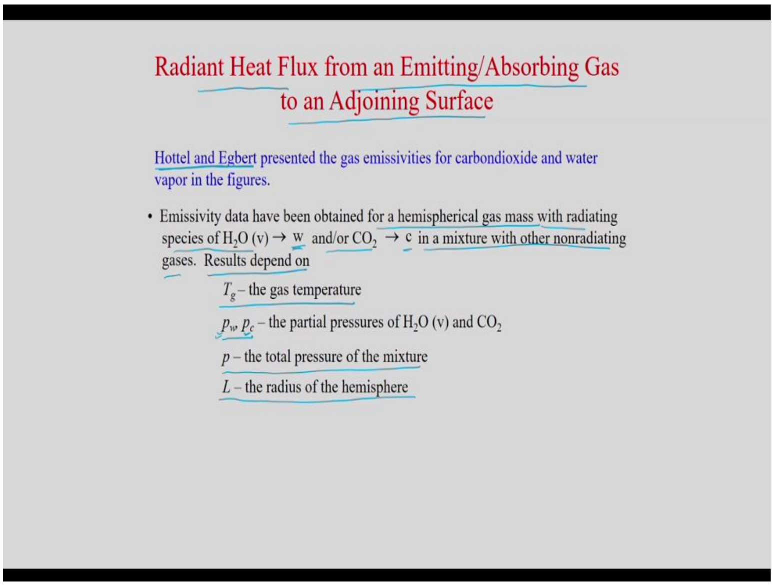

So, now we need to calculate the radiation heat flux from an emitting or absorbing gas to an adjoining surface. So, now let us say one enclosure is there and inside you have participating medium. Now we need to find what is the radiation exchange? So, for this we have to find the emissivity of the gas but it is very difficult to find. So for that we will use some figure which is actually given by Hottel and Egbert.

Actually they have presented the emissivity at one atmospheric pressure for gas emissivities of carbon dioxide and water vapour separately. So, now this emissivity data have been obtained for a hemispherical gas mass with radiating species of water vapour denoted by w and carbon dioxide with c, in a mixture with other non-radiating gases.

So, you have participating medium but other gases like non-participating medium like nitrogen or you can have air. So, those will not participate in the radiation but it may be present in that gas. The results depends on the T_g the gas temperature, p_w, p_c which is the partial pressure of water vapour and partial pressure of carbon dioxide, p is the total pressure of the mixture and L_e or L the radius of the hemisphere.

So, for the calculation we will use the figures given by Hottel and Egbert. Let us first see these figures then will describe how to find the radiation exchange.

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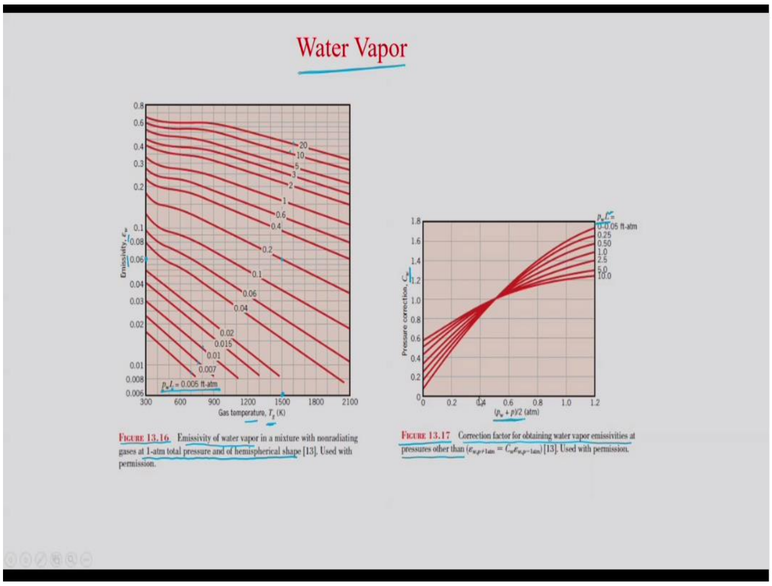

So, this is actually for water vapor. So we can see this figure, figure 13.16. This is actually gas temperature versus emissivity. T_g is the gas temperature in K versus emissivity. So, if you know the gas temperature then you can find the emissivity and different line you can see, it is for different p_wL okay. And remember here this unit is given as ft.atm.

So, p_w is in atm and L_e is the length in feet. So you have to convert that if it is given in other units. So, this L is the mean beam length, p_w is the partial pressure of the water vapor and you can see this line is 0.005 and 0.007, 0.01 to 10, 20 so these are the different lines for different p_wL. So, for a particular temperature if you know the p_wL you can find.

So if 1500 K is the temperature and let us say 0.2 is the p_wL, then you can find 0.06 as the emissivity. So using this figure you will be able to find the emissivity of water vapour in a mixture with non-radiating gases at 1 atm total pressure of a hemispherical shape. So, hemispherical shape we are considering so obviously you have to calculate the mean beam length and it is for 1 atm total pressure.

So, that you have to understand. So, if it is other than 1 atm pressure, then we have to use this second figure, figure 13.17 which is correction factor for obtaining water vapour emissivity at a pressure other than your 1 atm. So, obviously you can see here this is plotted in the x-axis

p_w the partial pressure of water vapour plus the total pressure p divided by 2 and this is the pressure correction C_w.

So, whatever you will find at 1 atm if you multiply with this correction factor, then you will get at that total pressure what is the emissivity other than the 1 atm. So, you can see, so it is plotted for different p_wL.

So, you can calculate the correction factor or pressure correction factor for the emissivity. Similar graphs are there for carbon dioxide.

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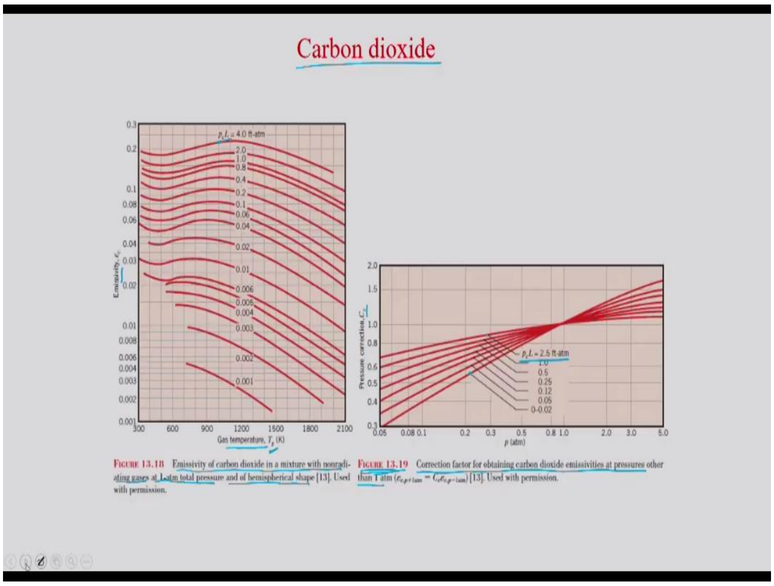

So, this is for carbon dioxide. So, you can see here. So here again it is gas temperature versus emissivity and it is given for 1 atm. You can see emissivity of carbon dioxide in a mixture with non-radiating gases at 1 atm total pressure and of hemispherical volume and also this is given with p_cL, p_c is the partial pressure of the carbon dioxide and L is the mean beam length.

So, similarly for a particular gas temperature if you know the p_cL; then you can find the emissivity of this carbon dioxide participating medium. Now, if it is other than 1 atm then again you need to use this correction factor. So this is correction factor for obtaining carbon dioxide emissivity at pressure other than 1 atm okay. So, you can see it in figure 13.19 and it is plotted for different p_cL value, p_cL value it is 2.5 this is 1 and this is your 0.02 okay.

So, different p_cL values, you need to find this correction factor C_c and other than 1 atm if you find the C_c then $C_c\epsilon_c$ will be your correct ϵ at that pressure other than the 1 atm. But now these are for only single participating medium either carbon dioxide or water vapour. So, only water vapour is present then you can use only ϵ_w and if it is other than 1 atm then you multiply C_w, then $C_w \epsilon_w$ will give you the emissivity of the gas.

Now, if it is only carbon dioxide, then similarly ϵ_c you find and if it is other than 1 atm then you calculate your correction factor C_c. Then, $C_c \epsilon_c$ will give you the emissivity of the gas. But if mixture of this two are there, then you need to add another figure.

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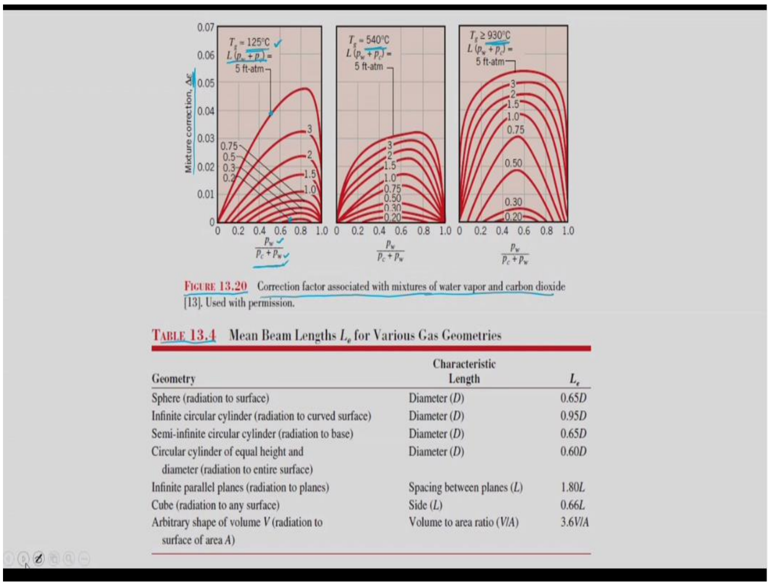

TABLE 13.4 Mean Beam Lengths L_e for Various Gas Geometries

Geometry	Characteristic Length	L_e
Sphere (radiation to surface)	Diameter (D)	$0.65D$
Infinite circular cylinder (radiation to curved surface)	Diameter (D)	$0.95D$
Semi-infinite circular cylinder (radiation to base)	Diameter (D)	$0.65D$
Circular cylinder of equal height and diameter (radiation to entire surface)	Diameter (D)	$0.60D$
Infinite parallel planes (radiation to planes)	Spacing between planes (L)	$1.80L$
Cube (radiation to any surface)	Side (L)	$0.66L$
Arbitrary shape of volume V (radiation to surface of area A)	Volume to area ratio (V/A)	$3.6V/A$

So, that is your figure 13.20 where you will find the mixture correction, $\Delta\epsilon$. So, if there is mixture of water vapour and carbon dioxide, then how we will calculate that I will tell in the next slide but before that you need to find the mixture correction factor that is $\Delta\epsilon$ from this figure and you can see this is correction factor associated with mixtures of water vapour and carbon dioxide.

So, you can see the x-axis is $\frac{p_w}{p_c+p_w}$ so p_w is the partial pressure of water vapour; p_c is the partial pressure of carbon dioxide. And y-axis is just mixture correction factor which we have to calculate. And these are given at different gas temperatures. So, you can see this gas temperature is 125 ºC, this is your 540 ºC and it is ≥ 930 ºC okay.

So, now if it is in between you have to take some approximation and close to that temperature you have to find this correction factor. And if you consider only let us say T_g =125 ºC then you can see these are plotted at different $L(p_w + p_c)$. So you can see that this is for maximum of 5 ft.atm and minimum is your 0.2.

So if you can find $L(p_w + p_c)$ and $\frac{p_w}{p_c+p_w}$ then for a particular point you can find the $\Delta\epsilon$ and that $\Delta\epsilon$ is your correction factor for the mixture of carbon dioxide and water vapor. And mean beam length obviously you can find from this table 3.4. So let us see how we will calculate this emissivity.

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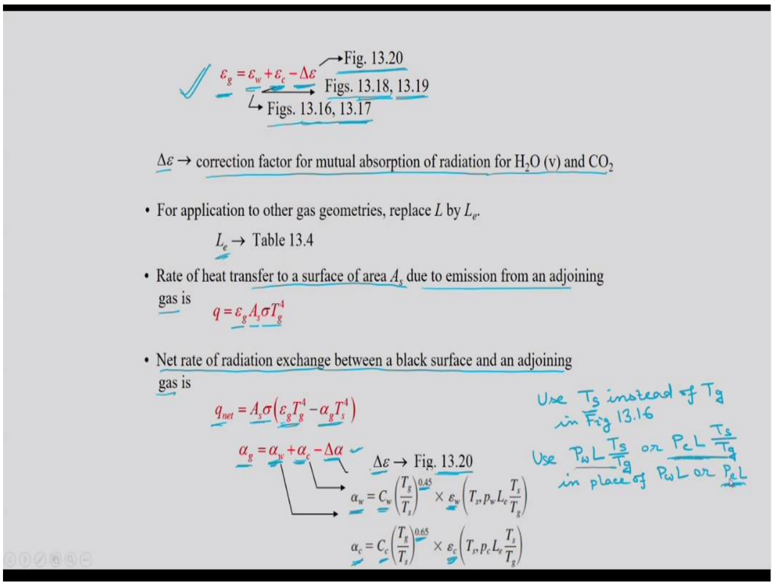

So, emissivity of the gas mixture can be written as

$$\epsilon_g = \epsilon_w + \epsilon_c - \Delta\epsilon$$

So, it is in general. So, if you have mixture of water vapor and carbon dioxide then this will be the gas emissivity. So, this ϵ_w you can find from the figure 13.16 and 13.17.

This 13.16 is given for 1 atm and if other than 1 atm you want to calculate then you have to use 13.17 figure and you have to multiply that correction factor. Similarly, ϵ_c for carbon dioxide emissivity you will find for 1 atm from the figure 13.18 and if it is other than 1 atm then use 13.19 then correction factor C_c you calculate and $C_c\epsilon_c$ will give you this ϵ_c.

And if it is a mixture, then you have to subtract this $\Delta\epsilon$ which you will get from the figure 13.20 already we have discussed. So, this $\Delta\epsilon$ obviously correction factor for mutual absorption of radiation for water vapour and carbon dioxide and obviously L_e you can find from the table 13.4. So, now once you calculate the ϵ_g, that is the emissivity of the gas whether it is mixture of water vapour or carbon dioxide or only water vapour or carbon dioxide then, you can find q, the rate of heat transfer to a surface of area A_s due to emission from an adjoining gas as

$$q = \epsilon_g A_s \sigma T_g^4$$

Then the net rate of radiation exchange between a black surface and an adjoining gas is

$$q_{net} = A_s \sigma \left(\epsilon_g T_g^4 - \alpha_g T_g^4 \right)$$

Now here ϵ_g you can calculate from this expression, but α_g how we will calculate? So we have to now discuss that from the figure. So, α_g expression is similar to ϵ_g you can see, α_g is the absorptivity of the gas.

$$\alpha_g = \alpha_w + \alpha_c - \Delta\alpha$$

So, this is α_w that means absorptivity of the water vapour, this is the absorptivity of the carbon dioxide and this is the correction factor.

So in similar way you will calculate for 1 atm what is the α_w then you will correct it if it is not 1 atm from the other figure and that correction factor we will multiply. Similarly, if it is a mixture of carbon dioxide and water vapour, then you have to use this relation and where $\Delta\alpha$ will calculate from the figure 13.20 which is equal to $\Delta\epsilon$.

But here one correction is there. When you will calculate from the figures, say figure 13.16, x-axis is your gas temperature. So, instead of gas temperature you will use the surface temperature. So, one correction is that you use surface temperature T_s instead of T_g in figure 13.16.

And now you have seen that with partial pressure $p_w L$ we have calculated. But now you have to use $p_w L \frac{T_s}{T_g}$ and $p_c L \frac{T_s}{T_g}$ instead of $p_w L$ and $p_c L$. So, this correction you have to make when you will read from the figure. Now, α_w what you will do? It will be now

$$\alpha_w = C_w \left(\frac{T_g}{T_s} \right)^{0.45} \times \epsilon_w \left(T_s, p_w L_e \frac{T_s}{T_g} \right)$$

$$\alpha_c = C_c \left(\frac{T_g}{T_s} \right)^{0.65} \times \epsilon_c \left(T_s, p_c L_e \frac{T_s}{T_g} \right)$$

In these equations ϵ_w we have to find out using T_s in the x-axis and $p_w L \frac{T_s}{T_g}$. Similarly for ϵ_c we have to find out using T_s in the x-axis and $p_c L_e \frac{T_s}{T_g}$. C_w and C_c we have to use if pressure is other than 1 atm. So, let us see from the figure how we will do it.

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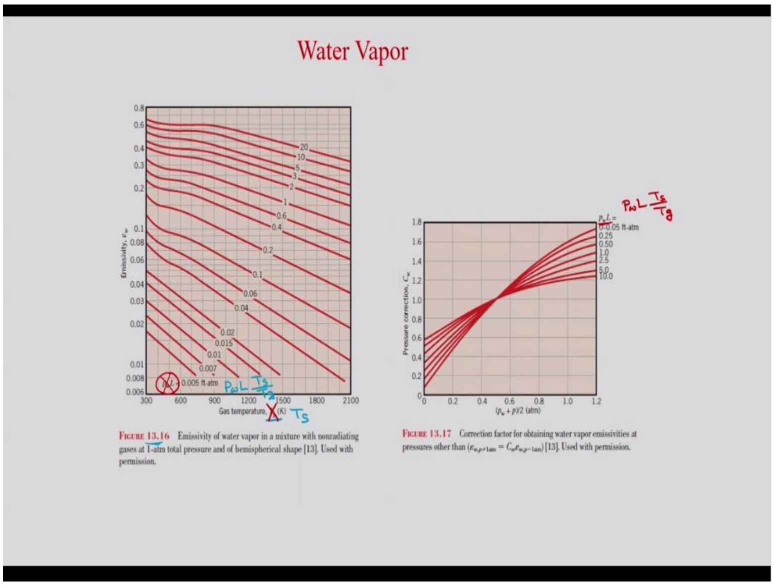

So, if it is 13.16 you can see this is the gas temperature. Instead of gas temperature you use T_s. So, here you find the surface temperature and that surface temperature you use here along with $p_w L \frac{T_s}{T_g}$. So you use $p_w L \frac{T_s}{T_g}$ instead of $p_w L$ both in 13.16 and 13.17. So, this is the correction you have to make when you are finding the absorptivity of the medium.

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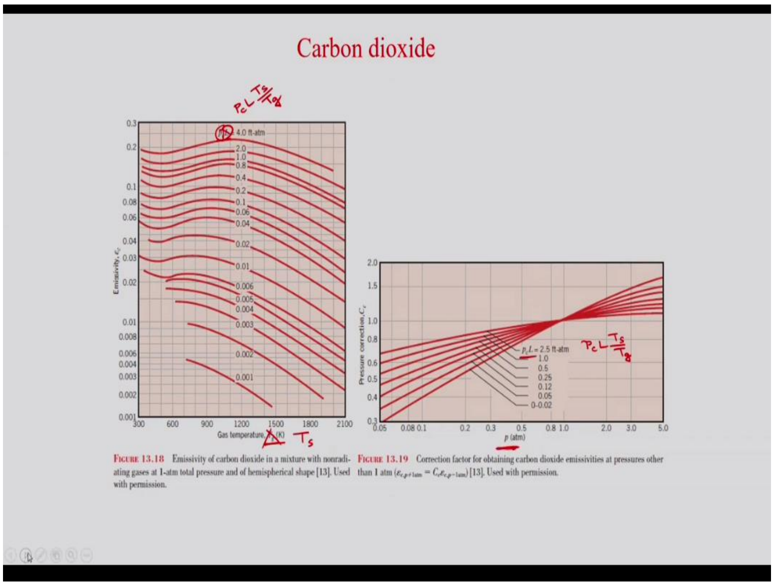

Similarly, in the next figure for carbon dioxide also in place of T_g you will use T_s, surface temperature and $p_c L_e \frac{T_s}{T_g}$ instead of $p_c L_e$ for both figures 13.18 and 13.19. So, just see x axis is only in atm okay, and the correction factor whatever we have calculated it will remain as it is.

So, this emissivity of the gas and absorptivity of the gas you have to find from this figures corresponding to that partial pressure. And then if it is a mixture of carbon dioxide and water vapor, accordingly you make the correction factor. So, first now let us solve one problem so that you will understand how to calculate this ϵ_g and the α_g from the figures.

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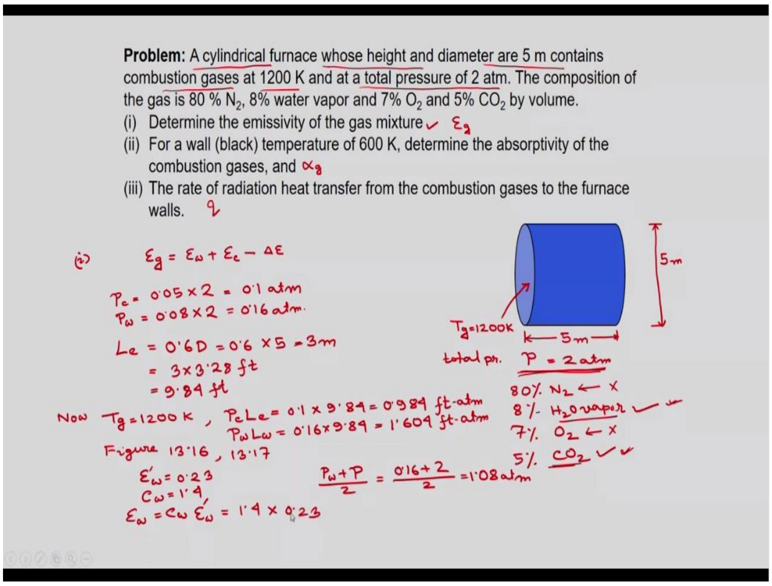

A cylindrical furnace whose height and diameter are 5 m contains combustion gases at 1200K and at a total pressure of 2 atm. So, you we can see this is one cylindrical furnace, height is 5 m, and your diameter is also 5 m, and it contains combustion gases at 1200 K. So, temperature of the gas T_g is your 1200 K and total pressure p is 2 atm.

The composition of gas is 80% nitrogen, 8% water vapour, 7% oxygen and 5% carbon dioxide by volume. So, now you can see that here nitrogen is there, oxygen is there which are not participating in the radiation. Only water vapour and carbon dioxide will participate in the gas radiation. Now, you have to determine the emissivity of the gas mixture that means ϵ_g for a wall (black) temperature of 600 K; determine the absorptivity of the combustion gases.

So, your ϵ_g you have to calculate, your α_g you have to calculate and the rate of radiation heat transfer from the combustion gases to the furnace wall, so q you have to calculate. So, now you know that by volume what are the compositions are there, so you will consider only water vapour and carbon dioxide and total pressure you know.

So you can calculate what will be the partial pressure of water vapour and partial pressure of carbon dioxide. And from there now you can calculate the mean beam length for this case, from that table. Then accordingly you use those figures to calculate ϵ_g and α_g. So, let us see. So, first one is you calculate the emissivity. So it is a mixture. So mixture of water vapour and carbon dioxide is there, so you have to use all those 3 figures okay. So,

$$\epsilon_g = \epsilon_w + \epsilon_c - \Delta\epsilon$$

And it is other than 1 atm as it is 2 atm. So, you have to again use the correction factor. So, from here if you see the partial pressure, for 5% carbon dioxide and 8% water vapor

$$p_c = 0.05 \times 2 = 0.1\ atm$$

$$p_w = 0.08 \times 2 = 0.16\ atm$$

And from the table you can find the L_e. So, we can consider this as circular cylinder of equal height and diameter, so L_e =0.6D.

$$L_e = 0.6D = 0.6 \times 5 = 3\ m = 3 \times 3.28\ ft = 9.84\ ft$$

So, you know the partial pressure of carbon dioxide, partial pressure of water vapour and the characteristic length, so obviously you can calculate $p_w L_e$ and $p_c L_e$ and corresponding correction factor and the emissivity you can calculate.

$$p_c L_e = 0.1 \times 9.84 = 0.984\ ft.atm$$

$$p_w L_e = 0.16 \times 9.84 = 1.604\ ft.atm$$

Now T_g = 1200 K. So from figure 13.16 for $p_w L_e = 1.6$, you do not have a line, so you can take close to 2. So, you can see that it will be somewhere here okay. So, this value you can see that it is between 0.2 and 0.3 and let us say it is 0.23. Now

$$\epsilon'_w = 0.23$$

$$\frac{p_w + p}{2} = \frac{0.16 + 2}{2} = 1.08\ atm$$

So with that 1.08 or the order of 1 let us say and p_wL=1.6 or between this 1 and 2, you will get the point somewhere here. So, this you can see it is close to 1.4 okay, so let us say 1.4. So, your correction factor, C_w is 1.4. So, ϵ_w will be

$$\epsilon_w = C_w \epsilon'_w = 1.4 \times 0.23$$

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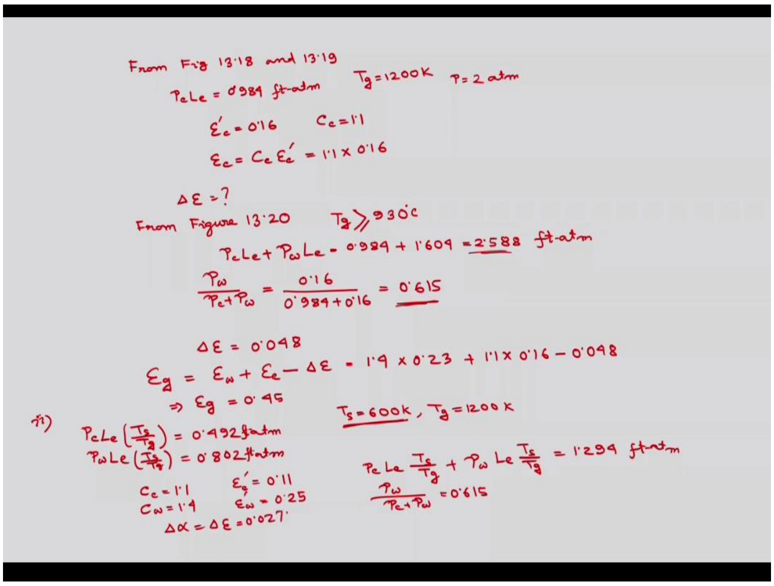

Similarly, now from the other figure, for carbon dioxide you can find. So from fig 13.18 and 13.19, with $p_c L_e = 0.984\ \text{ft.atm}$ and T_g =1200 K corresponding ϵ_c you calculate. And in that case p is your total pressure that is 2 atm.

So, at 2 with corresponding $p_c L_e$ you calculate what is the C_c? So, if you calculate, you will get

$$\epsilon'_c = 0.16$$

$$C_c \sim 1.1$$

Then,

$$\epsilon_c = C_c \epsilon'_c = 1.1 \times 0.16$$

Now, as it is 2 atm other than 1 atm, now we have to make the other correction. So, $\Delta\epsilon$ we have to find for the mixture. Now

$$p_c L_e + p_w L_e = 0.984 + 1.604 = 2.588\ ft.atm$$

And

$$\frac{p_w}{p_c + p_w} = \frac{0.16}{0.984 + 0.16} = 0.615$$

So, now you see in figure 13.20 the x-axis will be 0.615 with this value of 2.588 means close to 2.6. So, that you can see from this figure, so you use this $T_g \geq 930$ °C okay and with 0.615 so let us say this point, at this point it will be closer to 2.6. So, it will be greater than 0.04, so let us say this correction factor $\Delta\epsilon$ from this figure it is 0.048.

So, now ϵ_g we can calculate.

$$\epsilon_g = \epsilon_w + \epsilon_c - \Delta\epsilon = 1.4 \times 0.23 + 1.1 \times 0.16 - 0.048 = 0.45$$

So, now we have calculated the emissivity of the gas, so first part we have done. Now, we have to calculate the absorptivity, α_g. Now to calculate α_g we have to use $p_c L_e \frac{T_s}{T_g}$. Surface temperature is given as 600 K and T_g is 1200 K, so it is half okay. So, it will get as 0.492 ft.atm.

Similarly, $p_w L_e \frac{T_s}{T_g}$ if you calculate you will get 0.802 ft.atm okay. So, in this case now instead of using gas temperature we will use surface temperature. So this is the T_s =600 K will take in the x-axis.

So, with this now you can find from this figure, so you can see here T_s is 600 K, so with this 600 K because T_s you will use for calculating the absorptivity with your $p_w L_e \frac{T_s}{T_g}$ that is 0.802~0.8~1. So, close to 1 let us say. So, it will come almost here right more than 0.2 okay. So, that if we use so we can write this as

$$C_c = 1.1; C_w = 1.4\ ; \epsilon'_c = 0.11; \epsilon'_w = 0.25$$

Now,

$$p_c L_e \frac{T_s}{T_g} + p_w L_e \frac{T_s}{T_g} = 1.294\ ft.atm$$

And

$$\frac{p_w}{p_c + p_w} = 0.615$$

So, with this now you calculate the correction factors from this figure. So, in the figure this is your 0.615, so it is here and 1.294 okay, so it is close to 1.5, so if you calculate it you will get more than 0.025, so your

$$\Delta\alpha = \Delta\epsilon = 0.027$$

So, now you calculate the α_g absorptivity.

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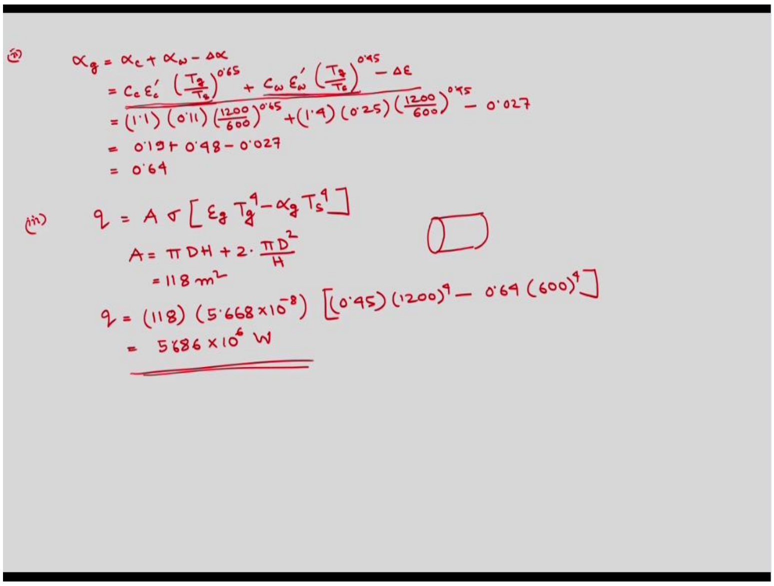

So, α_g will be your

$$\alpha_g = \alpha_c + \alpha_w - \Delta\alpha$$

$$= C_c\epsilon'_c\left(\frac{T_g}{T_s}\right)^{0.65} + C_w\epsilon'_w\left(\frac{T_g}{T_s}\right)^{0.45} - \Delta\alpha$$

$$= (1.1)(0.11)\left(\frac{1200}{600}\right)^{0.65} + (1.4)(0.25\,)\left(\frac{1200}{600}\right)^{0.45} - 0.027 = 0.64$$

So, now this you have calculated, now we need to calculate the q. So,

$$q = A\sigma\left[\epsilon_g T_g^4 - \alpha_g T_s^4\right]$$

So, we know T_g, we know T_s okay, we know already we have calculated ϵ_g and α_g, we have to calculate what is the area. So, total area will be your, so it is like this right. So, you have this circumferential surface as well as 2 ends. So it will be

$$A = \pi DH + 2 \times \frac{\pi D^2}{H} = 118\ m^2$$

So,

$$q = (118)(5.678 \times 10^{-8})[(0.45 \times 1200^4) - (0.64 \times 600^4)] = 5.686 \times 10^6\ W$$

So, now we have learnt how to use those figures to calculate the emissivity of the gas and absorptivity but in this case we have considered mixture of water vapour and carbon dioxide. So accordingly we have calculated. And also it is the pressure, total pressure is 2 atm which is other than 1 atm, so correction factors are involved as well as your correction factor for the mixture also is involved in this case.

But in cases where only single gas is there like water vapour or carbon dioxide then you do not need to use this mixture correction factor. Only you will use this ϵ_g and correction factor if it is other than 1 atm then you can calculate and find the emissivity of the gas and absorptivity of the gas but please remember that for absorptivity of the gas, the expression is something different. So this you have to just remember.

Because if it is a single gas also, then also you have to use $C_c \epsilon'_c \left(\frac{T_g}{T_s}\right)^{0.65}$ and obviously if it is p =1 atm, C_c will be 1, the correction factor will be 1. Or if it is 1 atm if you put C_c is equal to 1 then you can use this expression for either single carbon dioxide or it is for only water vapour is present in the gas medium. So, with this today we will stop here. In the next class will derive the radiative transfer equation. Thank you.