Heat Transfer
Prof. Sunando Dasgupta
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 60
Gaseous Radiation (Participating Medium)

This is going to be the last class of heat transfer. I hope you have learned something some basic fundamentals about heat transfer, it is applications the design of heat exchangers, the different modes of heat transfer both steady state and at unsteady state. And for the last few classes, we were learning radiation in how and where radiation is important in how can you make furnace calculations, which are consisting of more than one surfaces forming an enclosure.

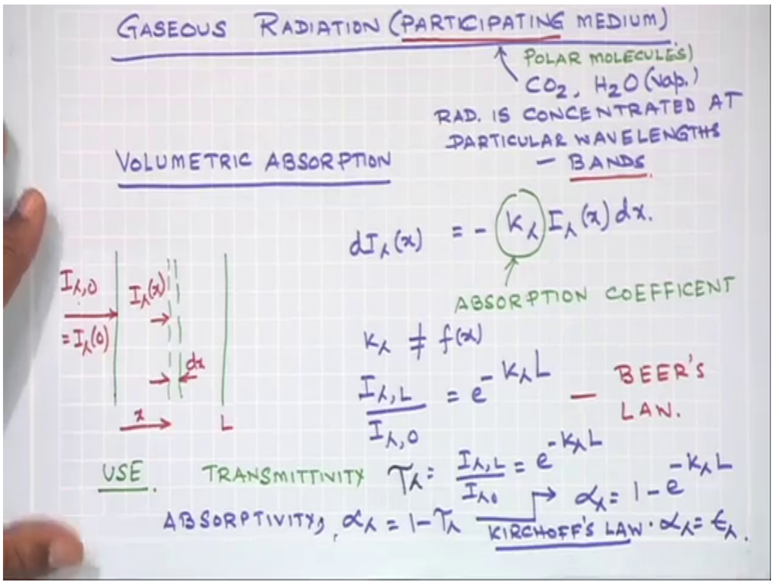
So, we saw the fundamental nature of radiation the emissivity, absorptivity, reflectivity, transmittivity, the relation between emissivity and absorptivity and what is Kirchhoff's law, when and under what conditions, the different forms of Kirchhoff's law are going to be valid that. We also studied the concept of view factors and based on view factors, how much of energy coming out of an object at a specific temperature is going to be intercepted by another object, which is situated nearby and the view factor plays a very important role in it, that is how much of the first surface, how much of the second surface is directly visible from the first surface, which is going to be a function of the solid angle and so on.

In after that we introduced the concept of a radiosity. So, it is the potential the radiative potential of a surface, which is observed by someone standing just outside of the surface. So, it not only takes into account the emission coming out of the object, it is also going to account for the reflected part of any irradiation on the surface. So, if any irradiation is falling on the surface part of it is going to get reflected based on the reflectivity of the surface and therefore, what we see as the radiate, true radiative potential of the surface is not just the emissive power, but also the part of the reflection part of the incident energy which gets reflected. So, it is the sum of the 2.

And the difference between the emissive power of the surface had this been a black body and the radiosity of the surface is expressed in the form of a in the form of a circuit, where e b lambda t that is a radiative potential the emissive power of the surface if it is a blackbody at a specific temperature, the tempering the same temperature as that of the surface and j being the radiosity of the object these 2 potentials are related by us resistance, which is known as the surface resistance to radiation and the difference between the potential of these 2 and based on the resistance for radiation of the surface, we can find out what's the heat flowing from the surface to the outside? Or how much of heat is to be supplied to the surface to maintain it is temperature constant?

Based on this, the enclosure method has been developed and we have seen what it is going to look like for a 2 zone enclosure? What it is going to like for a 3 zone enclosure? How to convert it into star delta? And so on. So, more or less the concepts, which you have already which you already know based on your based on, your concepts of electrical technology would be equally applicable here for example, the sum of all heat coming to a node would be algebraic sum would be equal to 0 and so on. So, you when you when you think of the triangular, the triangular type of resistive resistance circuit curve then, you know that 1 resistance is going to be in parallel with the sum of the 2. So, whether it is a series resistance in series already in parallel based on that, you would be able to connect the potentials of the 2 surfaces and find out, how much of heat gets transported from one surface to the other by radiation and as I said before that the main application of this method is in trying to find out, what is going to be the heat to be supplied to a furnace to maintains it is hot surface at a constant temperature or how much heat is going to be received by the surface, which you would like to treat if it is inserted in if it forms one of the surfaces of the furnace? So, if you put something in the furnace, how much of heat it is going to receive by radiation from the adjoining hot walls.

(Refer Slide Time: 05:23)



GASEOUS RADIATION (PARTICIPATING MEDIUM)

POLAR MOLECULES)

CO_2, H_2O (Vap.)

RAD. IS CONCENTRATED AT PARTICULAR WAVELENGTHS – BANDS.

VOLUMETRIC ABSORPTION

$$dI_\lambda(x) = -\boxed{k_\lambda} I_\lambda(x)\, dx.$$

ABSORPTION COEFFICENT

$$k_\lambda \neq f(x)$$

$$\frac{I_{\lambda,L}}{I_{\lambda,0}} = e^{-k_\lambda L} \text{ — BEER'S LAW.}$$

USE. TRANSMITTIVITY $\tau_\lambda : \frac{I_{\lambda,L}}{I_{\lambda 0}} = e^{-k_\lambda L}$ $\rightarrow \alpha_\lambda = 1 - e^{-k_\lambda L}$

ABSORPTIVITY, $\alpha_\lambda = 1 - \tau_\lambda$ KIRCHOFF'S LAW $\cdot\ \alpha_\lambda = \epsilon_\lambda$.

So, those are very important calculations and I which with the applications with the examples that I have solved in the class. I think you are probably you do probably know, how it is going to be, how the radiation is going to be treated for an enclosure as well. In all the discussion that we have had so far, we have assumed something very important for example, the case of an enclosure an enclosure is usually never under vacuum ok. So, the enclosure has some gases present in it, it could be air, it could be nitrogen, inert atmosphere or something else in all our assumptions in all our calculations. So far, we assume that the gas or the vapor present inside the enclosure, the gases they do not take part into the radiation process.

So, as far as the radiative heat transfer is concerned, all these gases are truly transparent. So, the either they do not do not absorb anything, they do not emit anything and so on, which this assumption is mostly true for non-polar gases for example, nitrogen, oxygen and so on, but the moment you have polar gases or vapor present in the enclosure, they start to absorb radiation and they will also depending on their temperature can emit radiation as well.

Whenever such gases or vapors these gases and vapors, who do participate in the radiative process, it is called radiation under participating media, radiation in the presence of participating media. Now many of the common, common gases or vapors that we deal with which are expected to be present in an enclosure are polar are a polar in nature, non polar in nature. So, whatever we have done so far will still be valid, but let us take the case, when we have humid air present in the in the in the furnace or the furnace is filled up with carbon dioxide or something else, which starts to participate in the radiation process then, we whatever be the emission coming out of a hot surface and you have you have another hot surface nearby and the intervening space is filled with water vapour then, all these emission are not going to come directly to the surface part of it is going to be absorbed and; obviously, as the thickness of this film, thickness of this vapour film increases more is going to be the absorption.

So, if you have absorption on one side of the film as the gas as the radiation proceeds deeper and deeper into the gas film, it is going to be absorbed and it is intensity is going to reduce. Now this reduction of intensity as a function of the thickness of the film or as a function of the distance traveled by the by the incident radiation into the participating media, that is going to be important in our calculations. Secondly, the gas itself may start emitting radiation as well. So, there are two aspects to the participating media that, we have to be careful about, one is the absorption and second is the emission. So, we are going first were going to start with the absorption of radiation as absorption of radiation as a function of distance; that means, as a function of thickness of the gas.

So, that is the first thing, we are going to start with. So, our first thing is the important point here is the participating medium. So, the gas that present in it is going to be going to participate in it. So, examples for this are carbon dioxide, this also H2O vapor or a combination of these 2. So, these are polar molecules, the polar molecules the polar molecules start to participate in it and they absorb over a wide range. And the complication to this if even more is that radiation is concentrated, radiation for these molecules is concentrated at particular wavelengths at particular wavelengths, these particular wavelengths are called bands.

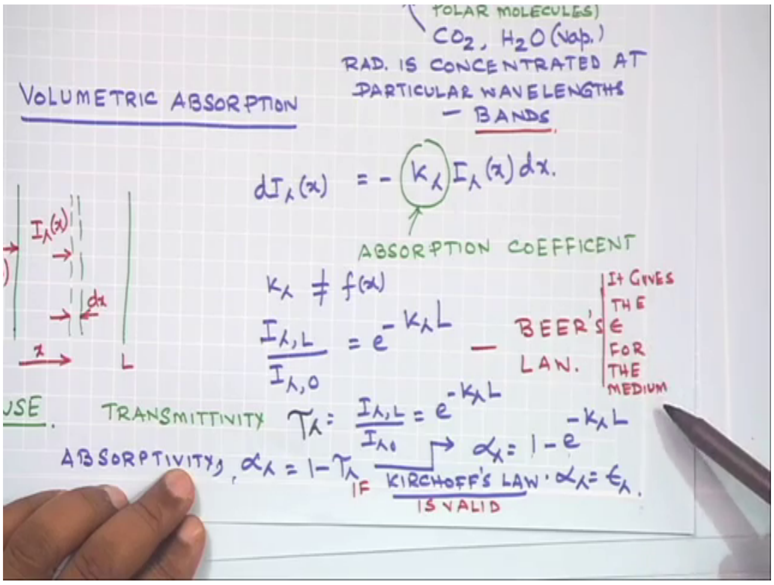
So, that is a further complication, which we will also have to keep in mind, but this coming back to the volumetric absorption of radiation in participating gases. This is a figure which so this is the starting of the gas film, which is participating is of thickness L and you have some spectral radiation, which is falling on the surface and it starts to propagate as it propagates some amount of radiation is going to get is going to get absorbed by it. So, if you have a monochromatic beam of I lambda 0, which is incident on the medium the intensity gets on reducing. And let us take an infinitesimal thickness of the participant medium denoted by d x then the amount of absorption or change in the radiative intensity due to the passage of radiation through a thickness d x is given as minus K lambda I lambda x d x. This K lambda, this K lambda is a property, which is known as the absorption coefficient, which is going to be different for different gases.

So, for a non participating medium the value of K lambda would be 0, but for participating medium; For example, CO2 H20 depending on what whatever be, the participating medium, the value of the absorption coefficient would be different and they are known as well. So, if we assume that K lambda is not a function of x that it is independent of x then this equation can simply be integrated with the boundary condition that at x equal to 0. The value of the monochromatic irradiation is equal to I lambda 0, then integrating this equation the intensity the spectral intensity after a distance L as compared to the spectral intensity at the beginning at x equal to 0 would simply be equal to e to the power minus K lambda times L, where L is the thickness of the film and this equation is known as Beer's law.

So, Beer's law it states that the intensity of radiation after the incident radiation passes through a distance L is going to decay exponentially and the constant is known is a property of the gas, which is the absorption, which is the absorption coefficient. So, what are going to be the use of this equation, the obvious use of this equation is it gives you as some idea of the transmittivity. The transmittivity the spectral transmittivity tau lambda, which would be equal to I lambda L by I lambda 0, whatever I have written over here is nothing, but the definition of transmittivity. So, it would be equal to K lambda L and the absorptivity, which is denoted by alpha lambda spectral 1 is simply 1 minus tau lambda by definition.

So, if we assume that the reflectivity to be equal to 0 and this would give you alpha lambda is equal to 1 minus e to the power minus K lambda L. And if Kirchhoff's law is valid, if we assume that Kirchhoff's law is valid in that case, alpha lambda would be equal to epsilon lambda.

(Refer Slide Time: 14:46)



POLAR MOLECULES)

CO_2, H_2O (vap.)

RAD. IS CONCENTRATED AT PARTICULAR WAVELENGTHS — BANDS

VOLUMETRIC ABSORPTION

$$dI_\lambda(x) = -\boxed{k_\lambda} I_\lambda(x)\,dx.$$

ABSORPTION COEFFICENT

$$k_\lambda \neq f(x)$$

$$\frac{I_{\lambda,L}}{I_{\lambda,0}} = e^{-k_\lambda L} \quad \text{— BEER'S LAW.}$$

IT GIVES THE ϵ FOR THE MEDIUM

USE.

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

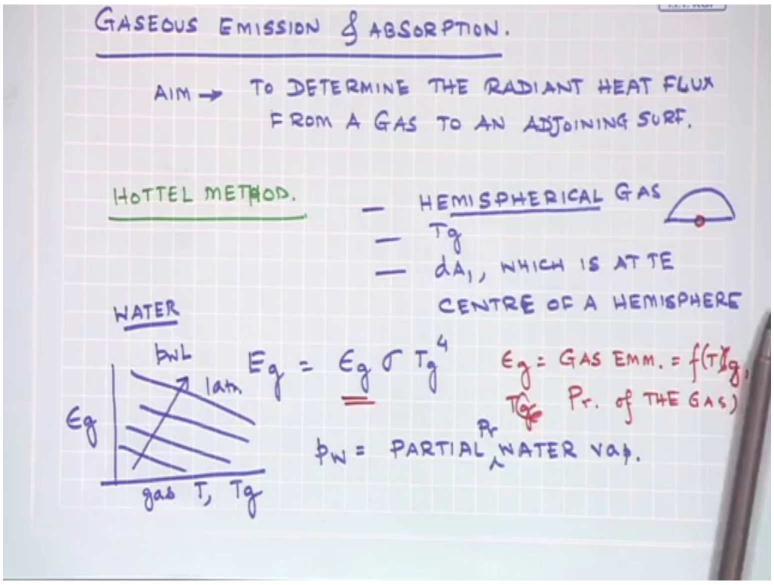
ABSORPTIVITY, $\alpha_\lambda = 1 - \tau_\lambda \rightarrow \alpha_\lambda = 1 - e^{-k_\lambda L}$

IF KIRCHOFF'S LAW IS VALID $\cdot\ \alpha_\lambda = \epsilon_\lambda$.

So, Beer's law provides the spectral emissivity of the medium. So, the important thing that I would like to here is that it gives the epsilon for the medium. So, what you see over here is that rather to several applications of Beer's law, first of all it gives you an idea of how much of radiation you are going to get at a distance L, if the incident radiation has a value I lambda 0. So, that is what is Beer's law, and this is a traditional definition of transmittivity. So, transmittivity is nothing, transmittivity is going is simply going to be e to the power minus K lambda L.

And since for non reflecting surface, which is a valid approximation for a gas, absorptivity and transmittivity are related by this expression. So, what you get is the absorptivity as 1 minus this and if Kirchhoff's law is valid. So, this is if Kirchhoff's law is valid, then we can write epsilon alpha lambda is equal to epsilon lambda. So, Beer's law gives you and I; and at the estimate of the value of the emissivity for the medium. So, that is what the now there is few more things we also know. So, we have now an idea of what is going to be the absorptivity in gas mass. But we would also like to have some idea of what is the emissive potential of a participating gas participating gas or a vapor, because not only it is going to absorb since it absorbs, it is going to emit as well.

(Refer Slide Time: 16:44)



GASEOUS EMISSION & ABSORPTION.

AIM → TO DETERMINE THE RADIANT HEAT FLUX FROM A GAS TO AN ADJOINING SURF.

HOTTEL METHOD.
- HEMISPHERICAL GAS
- T_g
- dA_1, WHICH IS AT TE CENTRE OF A HEMISPHERE

WATER

$$E_g = \underline{\underline{\epsilon_g}} \sigma T_g^4$$

ϵ_g = GAS EMM. = $f(T_g$, Pr. of THE GAS)

p_W = PARTIAL Pr WATER VAP.

So, how do I express the emissive power of a participating medium which is a gas or a vapor. So, our next analysis starts with the gaseous emission and you understand that for in many cases a hot gas is going to emit radiation, which is substantial gaseous emission and absorption. So, the aim is to the aim is to evolve to determine, the radiant heat flux from a gas to an adjoining surface. So, this is what the aim of the present analysis is and the method, which is used here is known as the Hottel method. This is method is a graphical method, which involves determining the radiation emission from a hemispherical gas. So, the first thing that is assumed here that it is a hemispherical gas mass, gas mass with a temperature T g and it is emitting a to a surface element d A 1, which is at the center of the hemisphere.

So, the Hottel method a Hottel method gives us first it assumes that there is a hemispherical mass of hot gas and whatever be the emission, it is going to be it is going to be concentrated at it is center. So, if I have a hemispherical mass of hot gas, the Hottel method gives you the emission from the hemispherical mass of gas concentrated on the unit area, which is placed at it is center.

So, that is what Hottel method. Hottel method tells you and the expression that, he has used in order to express this irradiation on the surface is given as this E sub g that is the irradiation is equal to epsilons of g sigma t to the peak of the gas to the power 4 this epsilon g, we have we already know what this epsilon g is the gas emissivity and it is correlated it is. Obviously, it is going to be a function of temperature and Tg is and it is going to be a function of temperature, it is going to be a function of the function sorry, the it is going to be a function of the temperature of the gas, it is going to be a function of pressure of the gas and so on.

So, what he has shown is that, the in a graphical way, he has calculated what is this value of epsilon g going to be and the this is a function of gas temperature, which is Tg and he has got a family of curves and this is in increasing order of Pw times L. So, P w this is for water. So, for water the value of the value of the emissivity is obtained by a curve like this, where this Pw is equal to the partial pressure of the water vapor, how much of water vapor is present in air partial pressure of water vapor.

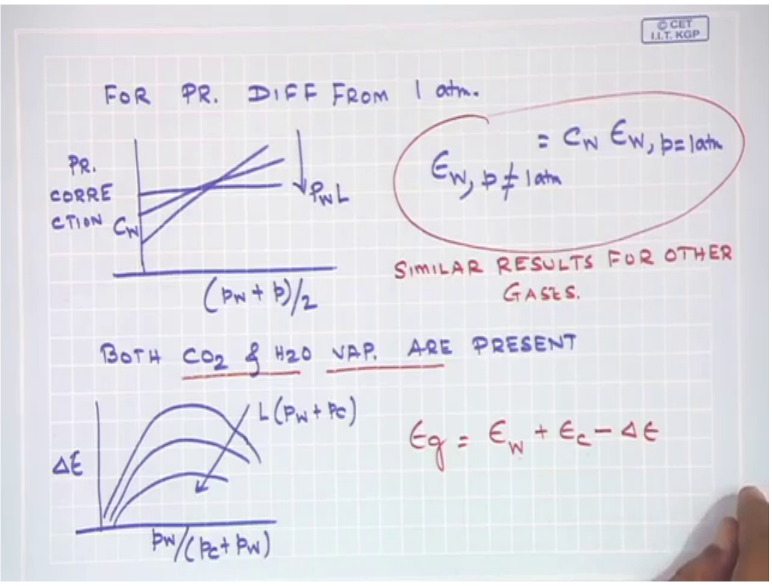
So, which is logical right because, the more the water more vapor is present in air the more it is going to absorb. So, whatever expression that he has provided whatever values that he has calculated for epsilon g, it is definitely a function of f will be the function of T g, which is the temperature of the gas, but it is also a function of the amount of water present into it at a given point of time. So, the figure that you see over here is for 1 atmosphere. So similarly, pressures the value of epsilon at other pressures can also be calculated.

So, there are 2 major issues in here, the first one is this is for 1 atmosphere. So, similar curves must be obtained for higher or lower pressures and secondly, it is assumed that the gas forms a hemispherical enclosure around an object, which is placed at the center of the hemisphere. So, these 2 are limitations of Hottels approach or Hottels method. So, for each of the each of the pressure different from 1 atmosphere, you have to have a similar such curve for the water vapor, I will come to that hemispherical part later on, not only that if you have instead of water, you have carbon dioxide present in air then, you are going to going to have a different curve for the value of epsilon g.

So in other words, a pressure correction must be made, if the pressure is different from that of the atmospheric pressure. Secondly, if it is something not a not water vapor, but some other participating medium is present another family of curves would have to be would have to be available in order for us to make the calculation. There is a third part as well, what if 2 participating medium are simultaneously present in the mixture of gas at temperature Tg. For example, you may have air in, in air both water vapor and carbon dioxide present simultaneously which can happen. So, if that happens and if that air mass is at a certain temperature then, how do you calculate the value of epsilon g? The emissivity of the gas mass containing different quantities, different partial pressures of water and carbon dioxide present simultaneously.

So, you need furthermore charts and so on, in order to get an idea of what is the value of epsilon g going to be. So, quickly give you an example in more examples of these are available in your text, which if you can refer to whenever you need to calculate the value of epsilon g for a participating medium, which is present at a given partial pressure and when the system pressure is 1 atmosphere or maybe different from 1 atmosphere. So, the first thing is the effect of pressure then, we are going to look at the effect of the presence of more than one participating medium. And finally, at the last part that we are going to clarify is how to take care of this hemispherical assumption and how to take, how to express, how to obtain the proper length scale to be used to evaluate, what is going to be the value of epsilon g? But first let us look at the effect of pressure.

(Refer Slide Time: 25:11)



FOR PR. DIFF FROM 1 atm.

$\epsilon_{W, p \neq 1 atm} = C_W \epsilon_{W, p = 1 atm}$

SIMILAR RESULTS FOR OTHER GASES.

BOTH CO_2 & H_2O VAP. ARE PRESENT

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

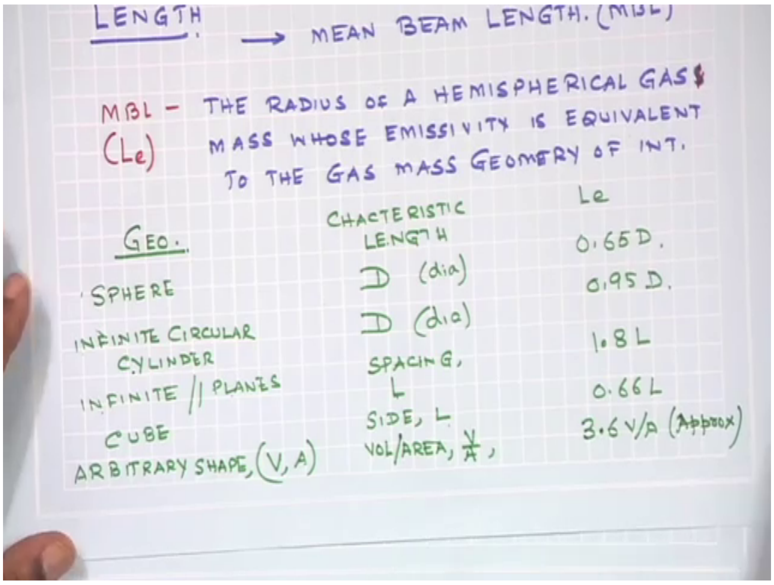
So, the for pressures different from 1 atmosphere, the this is the figure of a pressure correction, which is C w and you get curves like this and these are in increasing order of the partial pressure of water times L where L is the characteristic length and this is Pw the partial pressure plus P, the total pressure divided by 2. So, this is the partial pressure of water vapor, this is the total pressure divided by 2 and epsilon of water for a pressure, which is not equal to 1 atmosphere is equal to C w times epsilon of water, when the pressure is equal to 1 atmosphere.

So, this is a correction factor which must be must be taken into account, when your pressure is different from that of that of 1 atmosphere. And you get similar results that are available in literature for other gases and when you have, when the both let us say both CO2 and H20 vapors are present. If that is the case then you have in this method, you have the collection factor, this is partial pressure of water divided by partial pressure of carbon dioxide plus partial pressure of water. Partial pressure of carbon dioxide and partial pressure of water and you have another family of curves, which these are in increasing order of L, which is the length scale that we are going to talk about next.

So, this in the value of epsilon g when both C02 and water vapor are present is going to be equal to epsilon of water that, you have calculated plus epsilon of carbon dioxide that, you have calculated from your previous 1 minus delta epsilon.

So, this delta epsilon value can be read for can be read from these curves from these graphs and together they would give you some idea of what is the emission from a gas mixture, consisting of water vapour as well as carbon dioxide or any other participating medium. So, the last thing what is remaining in our discussion is how do we get, how do we get an idea of what is going to be the L the length scale. So, what is the length scale to be used, because you are not going to get you know assuming a hemispherical mass of participating gas radiating and your surface of interest is at the center that is something, which is very inconvenient to use and may not be the may not be the right one, right calculation method.

(Refer Slide Time: 29:09)



LENGTH → MEAN BEAM LENGTH. (MBL)

MBL (Le) – THE RADIUS OF A HEMISPHERICAL GAS MASS WHOSE EMISSIVITY IS EQUIVALENT TO THE GAS MASS GEOMETRY OF INT.

GEO.	CHACTERISTIC LENGTH	Le
SPHERE	D (dia)	0.65 D.
INFINITE CIRCULAR CYLINDER	D (dia)	0.95 D.
INFINITE // PLANES	SPACING, L	1.8 L
CUBE	SIDE, L	0.66 L
ARBITRARY SHAPE, (V, A)	VOL/AREA, $\frac{V}{A}$,	3.6 V/A (Approx)

So, we need to get an idea of an equivalent length that can safely be used with whatever we have discussed so far. So, this characteristic length L, this is what I am going to describe to you next.

So, the next one is about the next point is about length. So, what is going to be the length scale for to be used in this case? Ok ah. So, the concept that I am going to introduce is called the mean beam length, what is mean beam length? It mean beam length is let us call it MBL. So, MBL mean beam length is the mean beam length is the emissivity the radius of a hemispherical gas mass, whose emissivity is equivalent to the gas geometry gas mass geometry of interest.

So, this MBL is denoted by Le. So, L e is the radius of a hemispherical gas, hemispherical gas mass whose emissivity is equivalent to the gas mass geometry of interest. So, there is a table, which tells you about the geometry, what is the characteristic length and how the beam length mean beam length is related to the characteristic length? So, these are straightforward, the first one let us say it is a sphere ok. So, the characteristic length is; obviously, D which is the diameter and the mean beam length can be calculated as 0.65 D ok. If it is infinite circular cylinder and you have radiation to curved surfaces again, this is going to be D and this is going to be 0.95 D infinite parallel planes.

So, it is going to be the characteristic length is going to be spacing between the 2 plates, let us call it as l and the main beam length is going to be 1 1.8 L. If it is a cube and you are considering radiation to any of the surfaces then; obviously, the characteristic length is going to be L and this is going to be 0.66 L.

The important one, these are standard standards standard geometries a sphere and infinite circular cylinder, when you are calculating when you are trying to find out, what is the radiation to the curved faces and infinite parallel planes separated by a distance L or if it is a cube of cube of side L then, there analytically you can find out, what is going to be the value of the L e, but if you have an arbitrary shape of volume V in surface area A. So, it is a volume V surface area A then, the characteristic length as we have done before is volume by area, that is your characteristic length or V by A and the beam length is going to be 3.6 V by A and this is just an approx value.

So, the mean beam length as is shown here gives you. If you look at the table once again, that the concept of mean beam length is the radius of a hemispherical gas mass, whose emissivity is equivalent to the gas mass of geometry that, we have with methods. So, the gas mass of gas mass of any geometry that is available to us. If we can find out what is the corresponding beam length mean beam length L e, then that L e would be used in all the relations and correlations that we have developed so far for the case of gaseous emission.

So, the point therefore, is how to find out L e for any arbitrary geometry? The what we have seen is that for specific geometries like a cube, a cylinder, parallel plates and spheres, what is going to be the relation between characteristic length and mean beam length and ultimately, what we have seen is that for the case of any arbitrary shape, the characteristic length is simply going to be V by A and what is the relation between the beam length and V by A for any arbitrary shape.

The aim is to obtain L e because, if we can get L e for the enclosure surface in the volume of the volume of the participating medium inside an enclosure then, the corresponding Le can be obtained the moment, I have L e then using the methods that I have described at the beginning. You can find out what is the value of epsilon? What is the value of emissivity of the participating medium as a function of temperature and as a function of partial pressure and so on; and what is the value of the absorptivity? What is the value of transmittivity? And everything else then can be calculated and you will be in a position to find out, what is the net amount of radiative heat transfer in between a hot gas and an adjoining surface which is something very important that, we would like to know for many of the practical gases that we come across.

So, that is the end of the chapter radiation, which I wanted to wanted to tell you, I wanted to introduce you to in this course and the radiation is therefore, one of the very interesting, very practical branch of heat transfer that; we must be aware of that we know how to calculate the radiative heat exchange, especially for equipments involving elevated temperatures, what is the radiative heat loss or a gain.

And many of the natural phenomena that, we see around us is also due to a due to radiation, how much of heat we receive from the sun and so on. So, radiation plays a critical role in engineering in everyday life and through the discussion of the past few classes, I think you would be in a position now to make a calculation of the heat exchange between objects between solid objects forming an enclosure, and between an solid object and an adjoining gas, if the adjoining gas is a participating medium.

So, let us brings us to the end of this course. I hope you have enjoyed it, if there are any questions, I would encourage you to post them at the forum and they would I and that is would try to answer them. And hopefully this course has given you a foundation for calculating heat transfer in a variety of ways both conduction, convection, radiation steady state, unsteady state, internal flow, external flow, fully developed flow the heat exchanger calculations radiation and so on; so best of luck.

Thank you.