Radiative Heat Transfer
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Module - 8
Lecture - 37
Combustion and Flame

Hello friends, so we have almost come to the end of this course on radiative heat transfer. We have discussed various methods for solving radiation problems. Starting from radiation balance method, radiative transfer equation, approximate solution methods. We discussed properties of gases and particles and approximate models to represent the properties of gas averaging over various narrow and wide band models.

Now, we will see certain applications of the things that we have learned in this course. And the major application of radiative transfer basically we find in combustion and chemically reacting systems, where we have high temperature together with gas and particles which radiate energy. And this radiative transfer directly affects the performance of these systems. So, we are basically are going to discuss the applications in combustion and flame.

And the first application that I will take is the coal fired furnaces, which we have in power plants. We may have different type of furnaces. We have furnaces to generate steam, as is shown in this slide.

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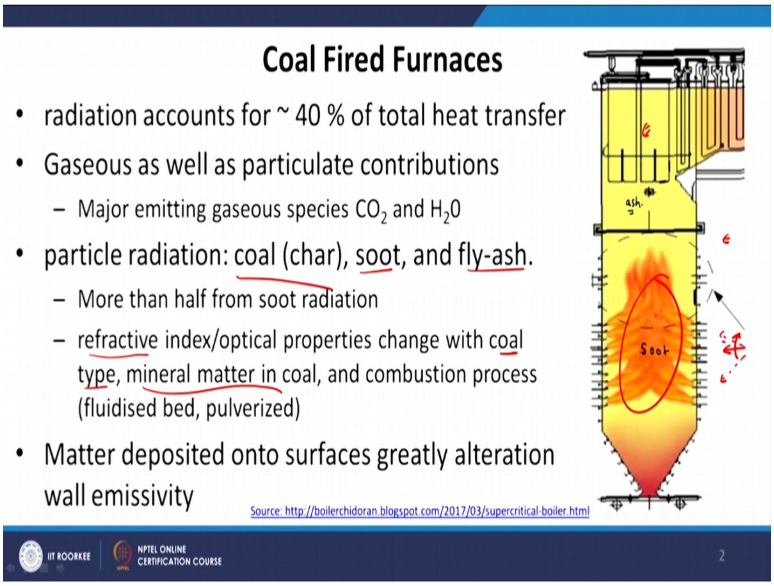

There are number of burners. These burners basically burn sometimes natural gas, sometimes liquid fuel, together with pulverized coal. So, there is a combustion taking place, there is a formation of flame, there are soot particles, there are ash particles. So, it represents a complicated scenario of radiative heat transfer. And the radiation from this environment is transmitted to the surfaces here, where we have superheaters, boilers and many other heat transfer equipments, which generate steam at various operating conditions.

Now, radiation in these type of applications is not the soul heat transfer mode. There is convection and conduction taking place. But, radiation is one of the most important mechanism by which heat transfer is taking place. Almost 40% of total heat transfer is contributed by radiation in these applications. And radiation in this, is not just governed by gases. So, we have major gases, carbon dioxide and water vapor which radiate most of the energy in this system.

But there is significant radiation coming from carbon particles, soot particles as well as ash particles, especially when we have coal, Indian coal especially, which has high amount of ash content. So, all these particles basically tend to contribute to radiation. Coal or partly burnt coal, char, soot and fly-ash. The radiation from soot may in fact be the single most component of radiative heat transfer.

So, it may dominate the gas radiation in this applications. Because there is significant amount of soot present in this coal burning furnaces, we have most radiation coming from soot itself. The properties like refractive index, the change with coal type. So, different coals from different countries, different mines, they have different properties, complex (()) (03:56). So, we need to characterize each and every coal before we apply the radiation program that we have learnt to find out the properties and then solve for radiative heat transfer.

We have to understand what kind of coal we have. The mineral matter in coal; some coals have high volatile content, some coals have low volatile content, some have high ash content, some have low ash content, they may have moisture. So, all these things basically affect the properties of the coal and also the radiative characteristic of these particles. And also, we have the type of burning type of processes governing the burning of the coal.

We may have fluidized bed combustion, we may have pulverized coal. If you are using pulverizer, what is the size of the coal we are using; whether we have uniform distribution in the pulverizer or we have a distribution given by modified gamma function or whatever. So, we have to take into account all these parameters, if you are interested in calculating radiative heat transfer accurately, we must answer these things, before we go for the actual analysis.

Then, this soot and ash particles they fly from this zone. So, mostly in the hot region we have mostly what we called soot. So, this is the region where we from soot, because soot is formed in high temperature region. So, most of the soot is present here. And it may deposit on the walls. Okay. So, some soot will deposit at the walls, making the emittance of the wall change. If we have no soot present on the wall, the emittance may be different.

While, if there soot is present and in fact most of the walls of this furnaces are basically black because the soot is deposited on the walls. So, depending on what kind of soot formation is taking place on the wall, we may have different emittance of the wall. Then, in the upper portion, we have more of ash. Because the coal is totally burned soot, in fact soot is also burned. So, what is left with is ash.

And ash is basically present in the above portion. And because most of the furnace heat transfer equipments like boiler and super heater are also present in this part, the ash may actually act as a barrier. It absorbs radiation or it scatters radiation. And it does not allow radiation from the lower furnace to reach the heat transfer equipment. And heat transfer may actually reduce on the surfaces. Further slag may form on the surface of the equipment.

As time progress, the ash may get deposited on the surface. And this again may alter the properties, the radiative properties of the heat transfer surfaces, as well as it may change conduction and the surface properties of the heat transfer surfaces as well. So, basically, we are interested in finding the heat transfer in this equipment. We are interested in finding the temperature, the heat fluxes.

So, we are, when we are designing a boiler, we are basically interested in: What is the temperature distribution in this furnace? What is the distribution of heat flux? How to keep the heat transfer surfaces so that they are exposed to maximum amount of radiation? So, all these questions are very relevant if you are designing a boiler. Especially, nowadays the emphasis is on high efficiency and low amount of emissions. So, every organization has to project the efficiency of the furnaces and the amount of emission they are generating in a given process.

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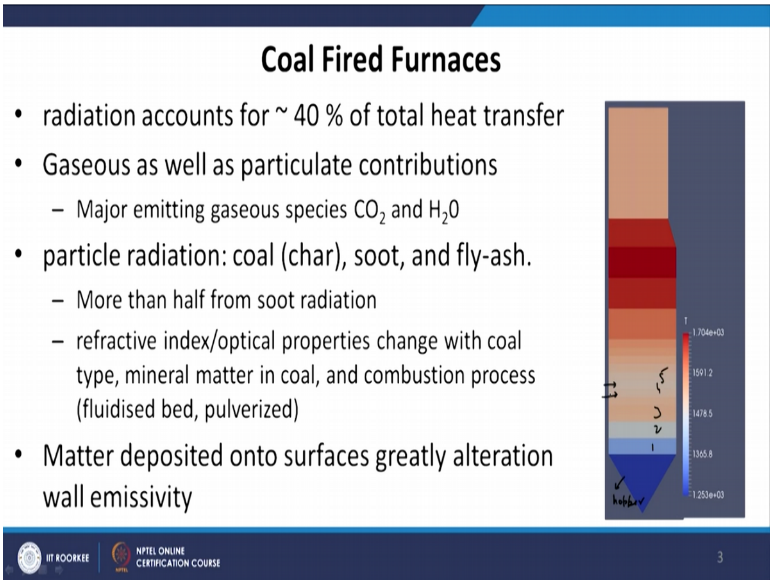

So, what we do in radiative heat transfer analysis, mostly we use the zone model that we have discussed. So, we divide the furnace into a number of zones as has been here. 1, 2, 3, 4, 5 and so on. So, we divide the furnace into a number of zones. At the bottom we have what we call hopper, form which the ash is fall down. So, this is the ash that we, ash falls down. We have lot of burners here in this region.

This is burner section. And the top section basically have the heat transfer equipment. So, we are interested in finding the temperature distribution in this furnace and heat flux in this furnace.

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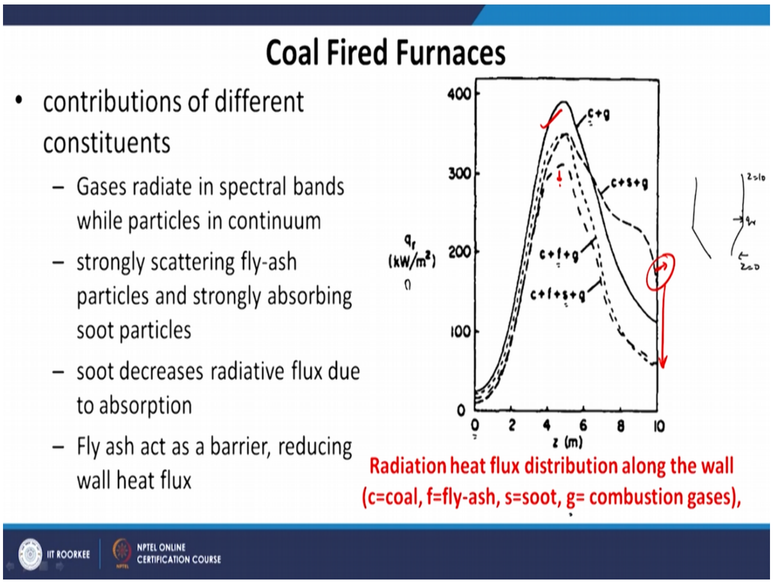

Now, the method used to solve this problem are already discussed. So, mostly we use zone model to solve for heat fluxes and temperature distribution. We use the weighted-sum-of-gray-gas model or k-distribution model to represent the properties of gases. And we also use particle distribution. So, here we are interested in only the qualitative behavior; how the qualitative heat flux basically change.

So, what you see in this is basically the heat flux on the wall. So, z is = 0 is the bottom portion of the; so, we have this furnace. So, z is = 0 means, at the bottom of the furnace. And z is = 10 here is the highest portion of the furnace. So, we are finding the heat flux on the wall. So, radiative heat flux on the wall is basically plotted here. So, the things that you should observe is: So, here c represents char or coal, f represents ash, s represents soot and g represents the gas.

So, just to emphasize on the point, how important the particles are, the soot and ash particles, we see this image. And we see that, if we neglect the soot particle, we neglect the ash particle, the radiative heat flux plotted is very large. So, this is the heat flux. If we neglect the presence of soot, if we neglect the presence of ash; so, we predict very large amount of heat flux. So, of course if we have error in predicting heat flux, our design is going to be not performing as per our expectations.

If we have soot present, then this is the radiative heat flux. Okay. So, this is amount of heat flux if we have soot and ash present. And we see that is a great reduction in the heat flux. So, why? Because soot absorbs significant amount of radiation. Soot is a small particle. Very less amount of energy is scattered by soot. Most of the energy is absorbed by soot. And we see a grade reduction in radiative heat flux.

So, there is a great reduction in heat flux here. While at the top motion, there is no soot. In the topmost portion, there is no soot. But if we neglect fly-ash; because in the top portion of the furnace, as I explained, we have most of the fly-ash present. In the top portion of the flux, topmost furnace portion, where z is = 10; if we neglect fly-ash, again the heat flux is very high. Here the heat flux is very high if we do not include the effect of fly-ash.

Because fly-ash is present in large amount in the topmost portion of the furnace. The including of fly-ash significantly results in reduction in heat flux. So, in the top portion of the heat flux, fly-ash basically scatters significant amount of radiation. And it basically does not allow heat flux or radiation reach the heat transfer equipments. So, presence of ash is a severe drawback in furnaces, because severe reduction in heat flux is observed when we have presence of ash.

So, that is why, now the companies basically are looking for burning coal which has less ash content or mixing different type of coals. Because, India has large coal reserve, but most of the coal in India is having large ash content. So, the effort has now been on either changing the burning technology from pulverize burning to fluidized bed. Or mixing different types of coal with coal having less ash content. Otherwise the radiative transfer is severely affected by this ash present.

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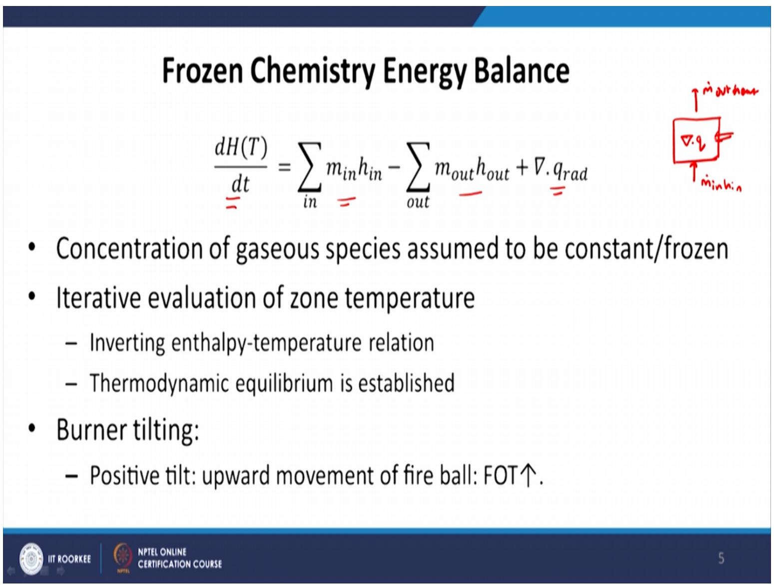

Now, just to show you how the analysis is done. There is a special case; how the radiative heat transfer basically governs inside the furnace. We do, and what we called frozen chemistry energy balance. So, we have a, let us say we have divided the furnace into number of volume zones. So, what we are doing is, we are doing an energy balance. So, amount of energy deposited or extracted from a zone is = amount of energy coming in the zone by convection.

So, the first room represents convection in and convection out convective fluxes. And the third term is basically radiative energy absorbed or emitted within the volume. So, we have a volume in which radiative energy is either absorbed or emitted. And we have flux coming in, m dot in h in; and energy going out m dot out h out; by convection. So, convection + radiation. And then, what is the amount of energy that is changing inside this control volume.

Frozen chemistry, because we assume that the gas concentration is not changing, it is frozen. So, we iterate; we do an energy balance; we find out the steady state of the problem; we find out the enthalpy; and then the find out the temperature. So, based on this energy balance, we are interested in finding the temperature of the furnace. Okay. We will also show result. I will show you the results on burner tilting.

What is burner tilting? Many times, what we are interested in this boilers in furnaces is, to increase the heat flux on the heat transfer surfaces, because we want to increase the load. So, what we do is, we basically tilt the burner in upward and downward direction. This is the burner. So, we either tilt it up or we tilt it down. Okay. By tilting the burner up and down, the fireball is basically lifted up or down.

And by virtue of this fireball moving up and down, the flux, radiative heat flux on the surfaces here in the top portion are changed. And we see different amount of steam generation rate.

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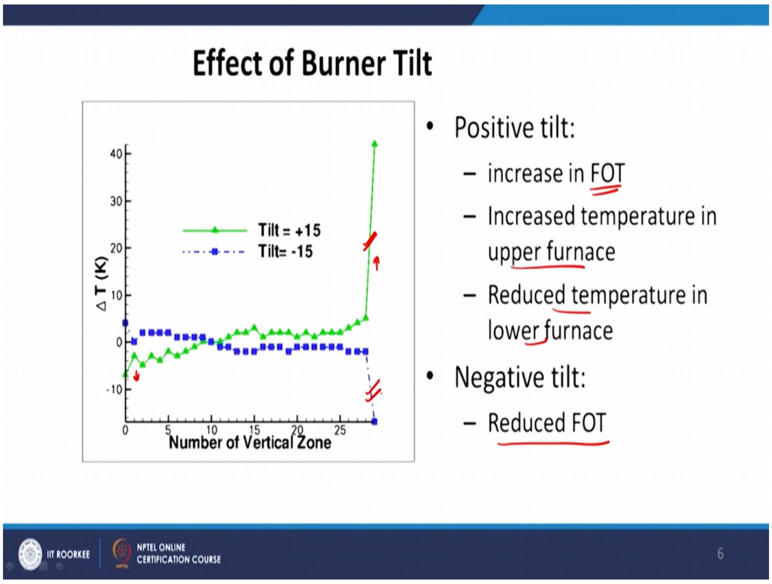

So, this we are going to study. The first is effect of burner tilt. So, if we tilt the burner, the fireball is going to shift up. Okay. So, tilt by 15 degree angle basically shifts the entire fireball in the upward direction. So, view factor will change. So, the view factor from the fireball to the surfaces in the top portion of the furnace change. And we see increase in furnace outlet temperature.

So, FOT is furnace outlet temperature. So, when we have positive burner tilt, the furnace outlet temperature increases by virtue of increasing the view factor there. So, increased temperature in upper furnace while reduced temperature in lower furnace. So, the temperature here has increased, temperature here has decreased in the lower furnace. Because the entire fireball has been lifted up.

The negative tilt means, when we have tilted the burner down, similarly, it reduce the furnace outlet temperature by the same thing. The furnace outlet temperature decreases when we tilt the burner down.

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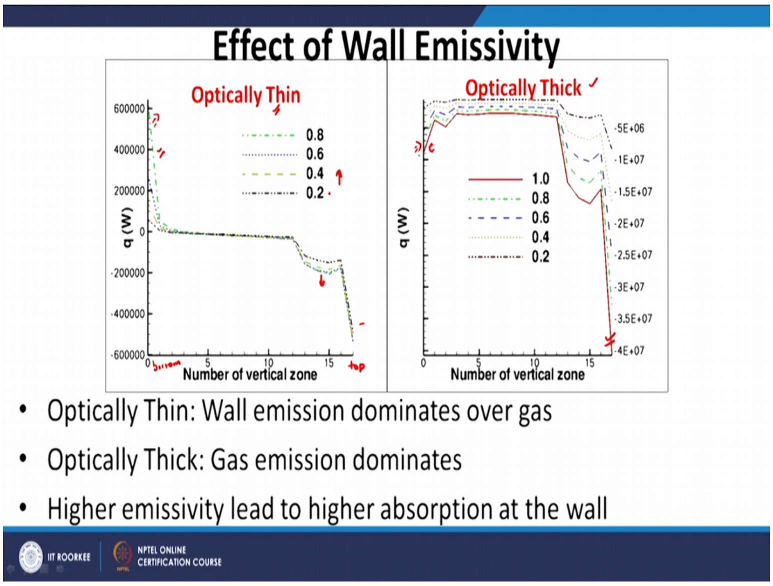

Now, how the wall emissivity affects? As I said, by the deposition of ash by deposition of coal, the emissivity of the furnace wall changes. So, we take 2 special cases. 1 is the optically thin. That means, the absorption coefficient of the gas inside the furnace is small. And the second case is optically thick, where absorption coefficient is large. When we have optically thin, that means, the gas radiation is very small.

And most of the radiation is coming from the surfaces. When we consider optically thick, most of the radiation is coming from the gas and very less amount of radiation is basically emitted from the surface. So, for optically thin, we see that, if we increase the amount of emissivity from 0.2 to 0.8; most of the radiation is coming from the wall and we have higher absorption. Higher absorption means higher fluxes.

So, we have higher fluxes when we increase the emissivity. Negative heat flux means, the heat is absorbed by the surface. While positive means, heat is rejected by the surface. So, we see larger negative values means, when we increase the emissivity, the heat flux increases. So, by the deposition of coal or char or soot particles, the heat flux is going to increase, okay; in the top portion.

So, number of vertical zones means, in the vertical direction, this is the top portion of the furnace and this is bottom portion of the furnace. So, number of vertical zone means, 0 start from the bottom furnace and top 15 is the top furnace. So, number of vertical zones represents as we move in the upward direction of the furnace. So, same thing is observed in the lower furnace also.

By increasing the emissivity, the heat flux increases. While it is increasing in the positive direction, that means more amount of energy is emitted in the bottom portion and more amount of energy is absorbed in the up top portion. The scenario is similar in optically thick case. In optically thick case, there is significant amount of absorption when the wall is completely black, emissivity = 1.

So, amount of radiation absorbed in the top furnace increases by large magnitude. Okay. However, in the lower portion; now, because the gas radiation is basically dominating and most of the radiation in the bottom portion is not due to gas; because the gas is present in the middle portion of the furnace. We see a reduction in heat flux. So, this is the difference between optically thin and optically thick case.

In optically thin case, the lower portion was emitting radiation. And it emitted more because emissivity was increasing. While in this case, the lower portion was not able to emit much radiation, because it is optically thick case and we see a reduction in heat flux in the bottom portion also.

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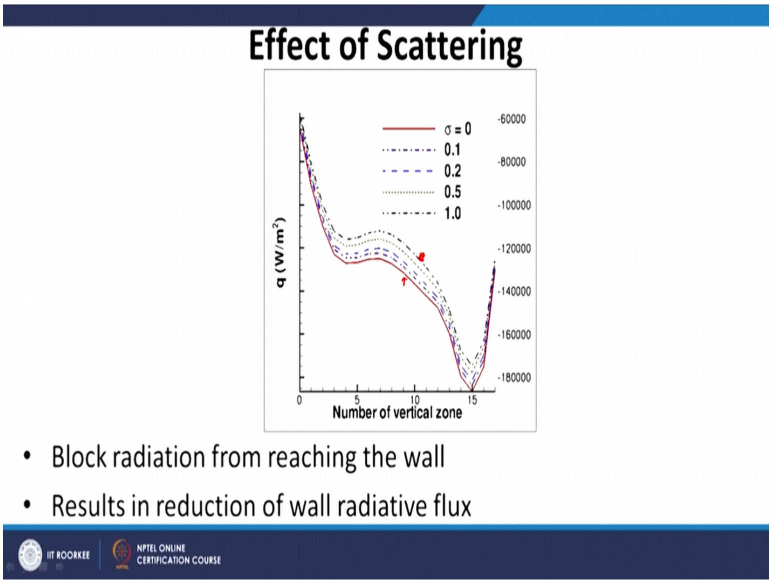

Now, effect of scattering. This thing I mentioned in detail. The effect of scattering. Scattering is mainly present in the top portion. Some scattering particles may also be present in the bottom portion. But the overall effect of scattering is that, it blocks radiation. It does not allow radiation to reach the wall and we see a reduction in heat flux. So, we see that this heat flux is less than this value. And the reason is because it blocks radiation, rescatters the radiation away from the wall. And we see a overall reduction in heat flux because of scattering.

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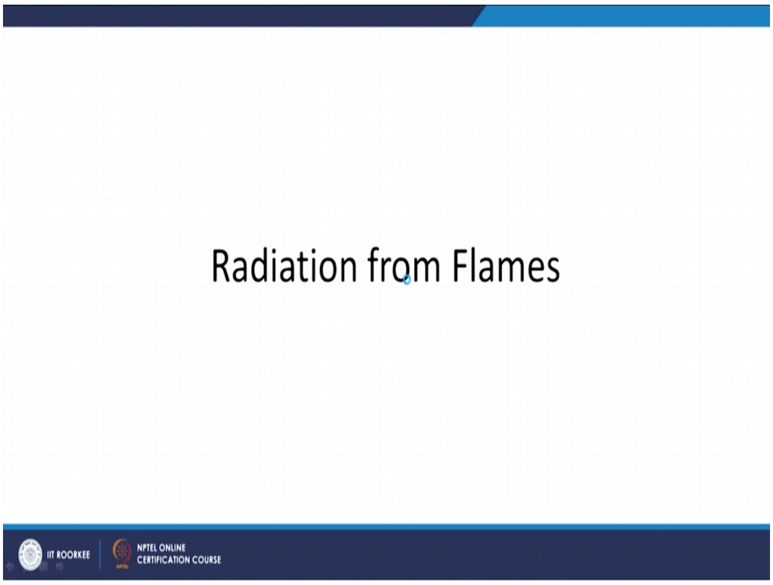

So, that was the furnace. Now, let us look at a, have a look at flame. Now, in many application, we have flames like say diesel engine, petrol engine. We have what we called laminar diffusion flames. Now, laminar diffusion flames typically we find in let us say diesel engines. In these type of flames, what we observe; and also in fires, what we observe here is that, the effect of radiative heat transfer is to decrease the temperature of the flame.

Because flame has very high temperature, the temperatures of flame is of the order of 2,000 kelvin. Significant amount of radiative energy is basically emitted from the flame. And the effect is the temperature of the flame is reduced. If we do not take into account any radiative heat transfer or any mode of heat transfer what we called, what we get is adiabatic flame temperature. But if we take into account radiative heat losses, then the temperature will be less than the adiabatic flame temperature.

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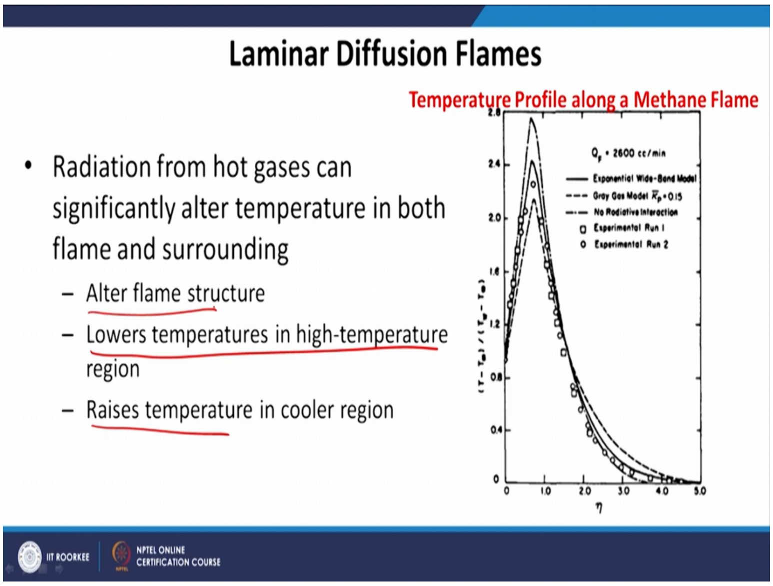

And the effect is basically, it lowers the temperature in high-temperature region. So, wherever the temperature was high without radiation, the temperature will reduce. And wherever the temperature was low, the temperature is increased. So, we get more uniform temperature distribution in flame when radiation is taken into account. And that is what we are doing basically in the simulation parts.

So, if you simulate a flame, in a computer simulation, if we do and we neglect radiation in the simulation, we get high temperature gradients. But if we include radiation, the temperature gradients will be small. It also alters the flame structure. The flame structure is also altered if radiative heat transfer is taken into account. And this is related to the temperature gradient and heat transfer taking place within the flame. So, now, in this; what you see is basically a jet flame.

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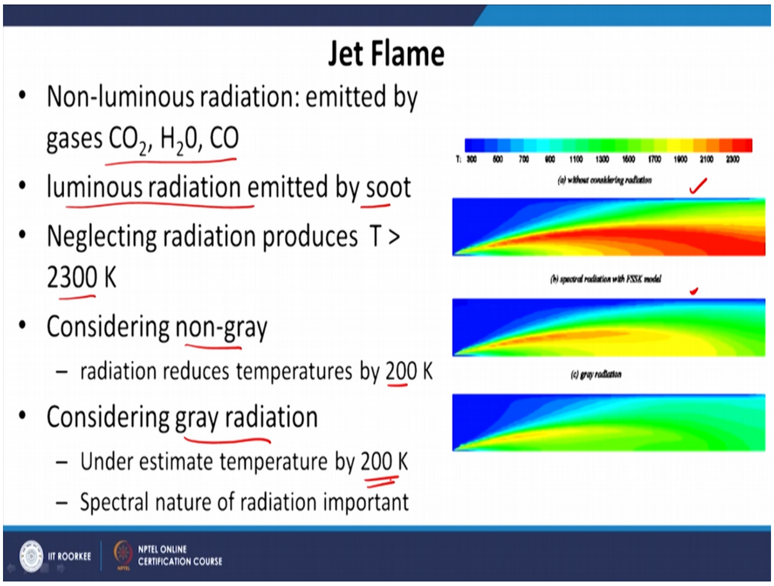

So, most of the gases I have shown 3 different images of a jet flame. So, we have 3 main radiating gases in this application, carbon dioxide, water vapor and carbon monoxide. We also have luminous radiation from soot. Okay. Now, if we neglect any sort of radiation. So, this is a computer simulation. If we neglect any sort of radiation, then we get temperature of the order of 2300 kelvin. And this is given by the first image.

So, we see that there is significant temperature. The flame has very high temperature of the order of 2300 kelvin. Now, when this was compared with practical values experimental results, it was found that the temperature is relatively high. When we include radiation, non-gray radiation using the k-distribution model, full-spectrum-k-distribution model, we get a reduction in temperature of the order of 200 kelvin.

So, this figure gives you temperature which is 200 kelvin less than the figure without radiation. And this matches with experiments much more than the figure without radiation. However, if we considered gray radiation, that means, we take Planck mean absorption coefficient, a single average absorption coefficient or we go for wide band model or some approximate model, we see that there is a further reduction in temperature of 200 kelvin. And this is in an underestimate.

So, this result is wrong. Because it underestimates the result by 200 kelvin. So, what we conclude here is that radiation is very important in finding the temperature within the flame. And radiation has to be represented accurately using a accurate spectral model. We cannot use approximate models to model radiation in flames. Otherwise, the results will be as much inaccurate as without radiation.

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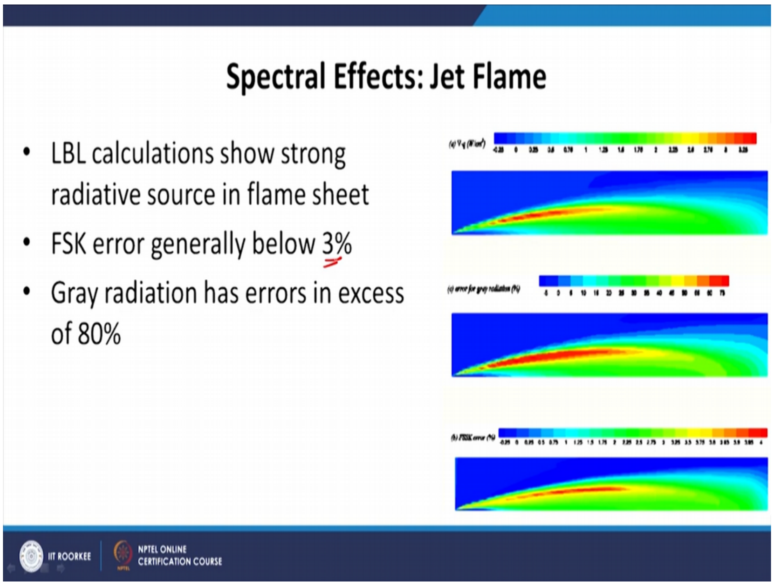

So, spectral effects have been highlighted again in this image. We see that the k-distribution gives you only 3% error as compared to line-by-line calculation. Line-by-line calculation involves integration over the entire spectrum using very fine spectral resolution. And k-distribution uses only 8 points for integration. So, we see that the method is very accurate. Only 3% error is there.

However, if we assume radiation to be gray, then we have significant error of the order of 80%. So, spectral effects are important as far as radiation in the flame is concerned. Just a contrast on a radiation phenomena in diesel engine and petrol engines. Diesel engines, they burn diesel which is heavy fuel. And it leads to lot of soot formation. So, diesel engines, you must have seen lot of smoke coming out of many trucks.

That is basically soot. Soot is a strong radiator. We have seen this in furnace also. Soot leads to lot of radiation. In diesel engine, radiation is going to be very very important, because of this formation of soot. Not because of gases, but rather soot that makes diesel engine, radiative heat transfer in diesel engine very important. In petrol engine, there is no formation of soot. Okay. So, we, they are necessarily soot free.

And radiative heat transfer is not important in petrol engines. However, there are some engines where they are ceramicly ceramic line engines, where convection has been reduced significantly. In such engines where convection has been reduced, the radiation may become important. And we have to include the effect of radiation in such engines, such as engines with ceramic liners.

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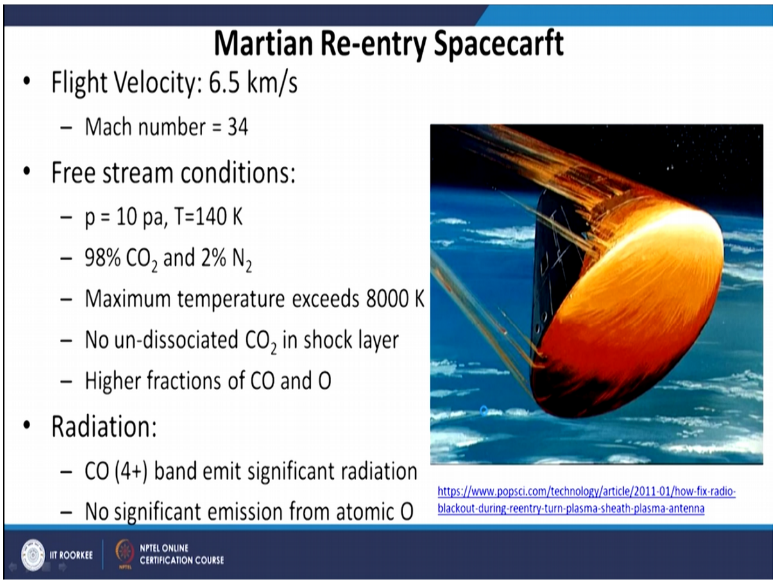

Then finally, the entry of reentry vehicles, especially the spacecrafts that are flying at very high velocity, such as space shuttle which flies to the outer atmosphere and then comes back to earth. It has to travel at very high speed of the order of mark 30 and so. And it has to penetrate the earth atmosphere. At such a high speed, it is subjected to what we called shock layer. And this shock layer exposes this spacecraft to very high temperatures.

Now, what you see on this slide is basically a spacecraft. This is just an image of the space craft, not the actual spacecraft. We have done this simulation for the Martian reentry spacecraft, a spacecraft entering into the atmosphere of Mars which has a atmosphere of carbon dioxide mostly, some amount of nitrogen. Temperatures in the atmosphere are 140 kelvin. But because the speed of the spacecraft is very large, 6.5 kilometer per second, which is based basically close to the escape velocity from the planet.

The mark number turns out to be very large. And the temperature in the shock layer are very large. The temperature typically in this applications comes out to be 8,000 kelvin or so. And under these extreme conditions, most of the diatomic gases like C O 2 will be dissociated. And the shock layer basically is formed of carbon monoxide and oxygen atoms. Now, we did a radiative calculations for this spacecraft.

And we found that, mostly the radiation is coming from carbon monoxide band. Okay. There is a electronic brand of carbon monoxide. Its nomenclature of this band is basically fourth positive band. This is an electronic band, because the temperature is very high. We get electronic transitions together with Ro-vibrational transitions. So, this is the most important band that radiates in the atmosphere. We solve for this problem. So, this is the spacecraft. This is the geometry of the spacecraft.

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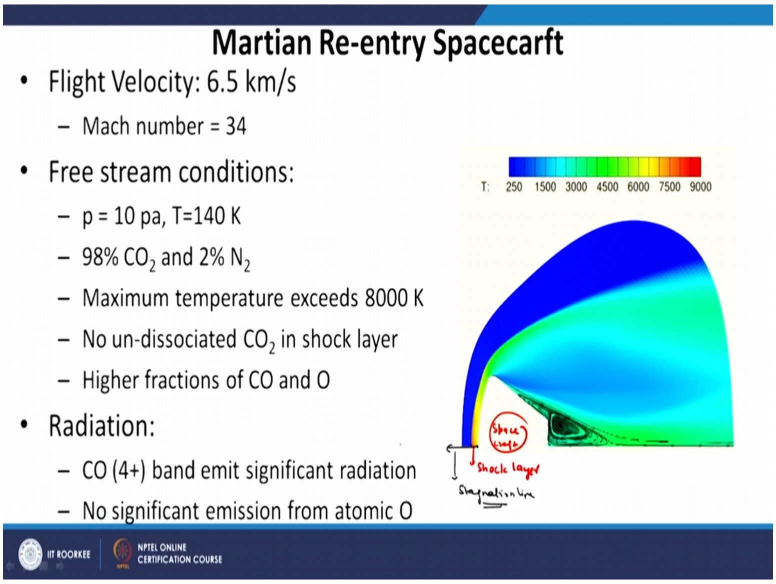

What you see on this is contour code. This is the spacecraft body. And you see only a 2-dimensional picture. So, this hollow space is basically the spacecraft. And this is the shock layer where the temperatures are very high and almost reaching 9,000 kelvin. Okay. And what you see in the next is basically the temperature plots along this line. So, this is called stagnation line. This line is called stagnation line.

So, you will see the simulation for this spacecraft. And the results, you will see along the stagnation line. That means, starting from x is = 0 on the surface of the spacecraft stagnation point, along into the free stream, the along the stagnation line.

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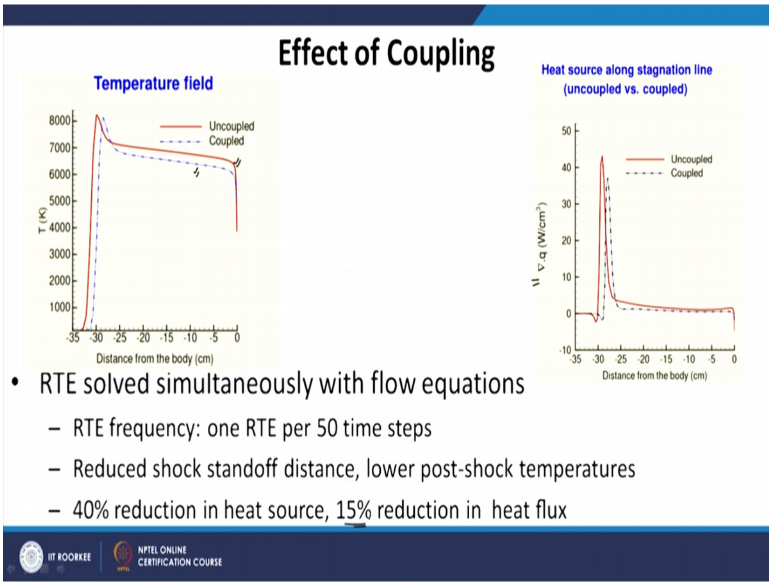

And you see that the effect of radiation on this flow field. If you do not include radiation, the red curve basically gives you the temperature. And if you include the radiation in the simulation, the dotted blue curve gives you the radiation. So, the 2 effects should be observed here. 1 is reduction in temperature, slight reduction in temperature. And the other thing is that shock has moved little bit towards the spacecraft.

So, the 2 phenomena that has been observed is, there is a reduction in temperature, peak temperature, because radiation energy is lost to the space. And there is a small shift in the shock towards the spacecraft. When we see the heat flux and radiative heat source term, we find there is 15% reduction in heat flux because of radiation losses. So, radiation make the problem non-adiabatic.

If we do not include radiation, the problem is adiabatic. If we include radiation, the problems because becomes non-adiabatic. Because radiation leads to loss of energy from the space craft shock layer into the outer atmosphere. There is a 40% reduction in heat source term also observed when radiation is taken into account. So, for these application, radiation becomes very important.

And it leads to significant implications when we have to design the spacecraft for large missions. The final thing that interests us in a CFD simulation is turbulence radiation interaction. Many combustion applications have lot of turbulence. And turbulence is governed by fluctuating temperature. So, we have a what we called temperature fluctuations in turbulent flow.

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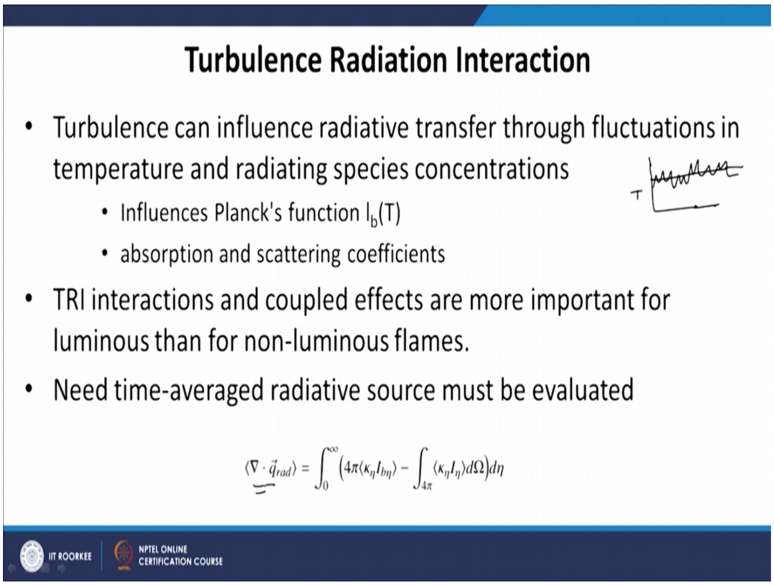

So, there may be a mean temperature of the flame and there may be fluctuations in the temperature. Now, because of these fluctuations in temperature, radiative energy is also going to be fluctuating. So, the emission is going to be fluctuating. There may be fluctuation in concentration of gases also, in turbulent flow. When concentration of gases also fluctuate, we have fluctuations in absorption coefficient. Okay.

So, now in turbulence, we are interested in finding the fluctuating component of radiative heat source term. How the radiative source term, the amount of energy that is absorbed or emitted fluctuates with this turbulent flow. So, this is the quantity we are basically interested in.

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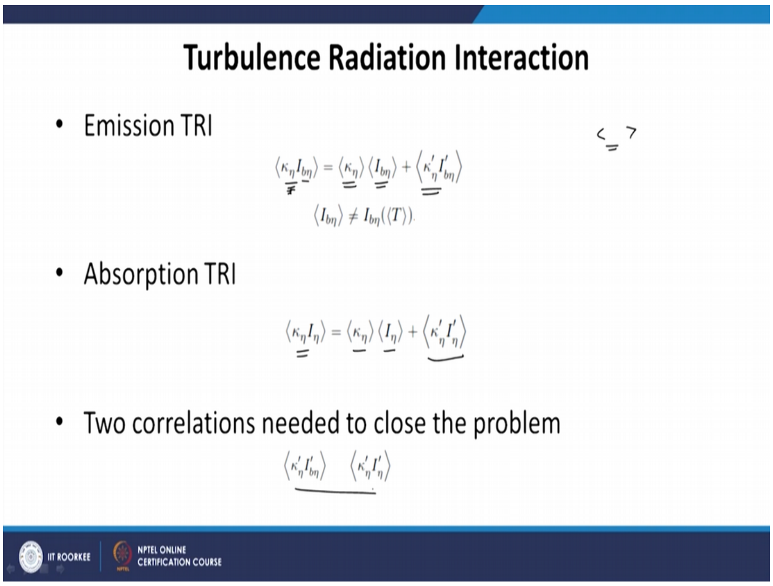

So, we define 2 types of turbulence radiation interaction, the emission TRI and absorption TRI. Emission TRI means fluctuations in the emissions. So, we know emission basically is given by absorption coefficient times black body intensity function. So, the brackets basically represents the components, the average component, the averaged over the tabulating fluctuating quantity. So, both kappa is fluctuating and both black body intensity are fluctuating.

So, what is the average value? Now, we write this average value of emission as = average value of absorption coefficient times average value of black body function. But this is not = average quantity of emission. There will be a unclosed term. Okay. And this term is basically what we called the emission TRI. So, the average of emission is not = average of absorption coefficient times average of black body intensity.

There is a radiational term = the fluctuation in absorption coefficient times fluctuation in black body intensity. And this term is called emission TRI. Similarly, the absorption TRI is defined as: We have to find out the absorption kappa times I, where I is the intensity, we have to take an average over this value. But this average is not = kappa average and I eta average. There will be a fluctuating component.

And this fluctuating component is absorption TRI. So, there are 2 types of turbulence radiation interaction. Turbulent turbulence affects emission by emission TRI and turbulence affect absorption by absorption TRI. So, these are the 2 unclosed terms that need to be solved in turbulence radiation interaction, which are solved in a similar manner that we deal turbulence using some kind of modelling approach.

We have to find out this turbulence radiation interaction. So, how the turbulence radiation affects basically. Turbulence radiation affects the heat loss from the flame. So, the heat loss is always large when turbulence radiation interaction is taken into account. As you see in this, in these images, there is a, this is the flame temperature.

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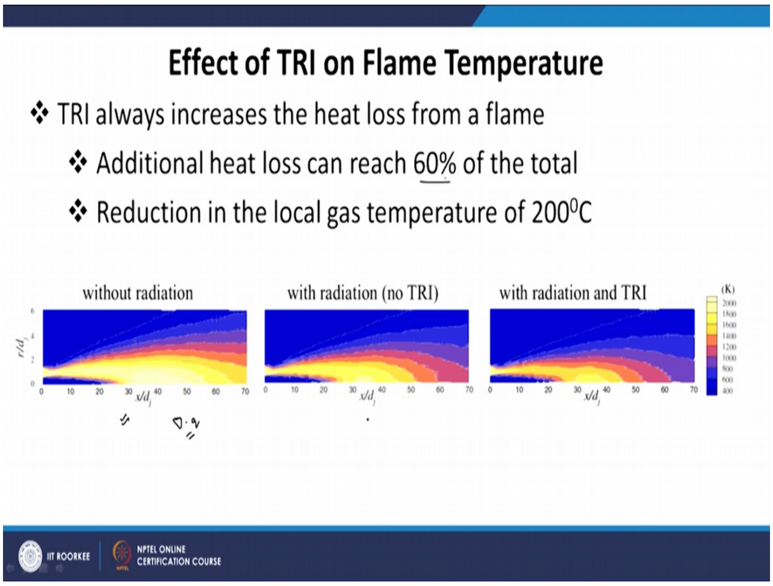

Sorry, this is the del dot q value, the radiative heat source term. Without radiation, with radiation but no TRI and with radiation and TRI. So, the first thing is, if you do not take radiation into account, some amount of energy will be radiated out and the flame temperature will be less than the adiabatic flame temperature. So, if radiation is taken into account, but no TRI, no turbulence is taken into account, then the temperature of the flame is going to be less. Because larger amount of energy will be radiated out.

But if turbulence radiation interaction is taken into account, that energy that is radiated out will be significantly larger, in fact 60% larger. And there will be overall reduction in gas temperature when turbulence radiation interaction is taken into account. So, you have to take into account the radiation, but also sometimes you may have to take into account turbulence radiation interaction to correctly predict the temperature of the flame.

So, in this lecture, we discussed 1 application, 1 important application of the concepts on radiative heat transfer as applied to combustion problems in furnaces and flame. We will discuss 1 more application in the next lecture applied to industrial system; how the industrial systems are designed keeping the radiation into account. And then, 1 more application that we will deal with is atmospheric radiation. So, thank you for your time. We will meet in the next lecture.