Radiative Heat Transfer
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Module - 8
Lecture - 40
Experimental Methods

Hello friends. Now, towards the end of this course, we will discuss some experimental techniques used in radiative heat transfer. Experimental techniques are important because we want to find out the properties of various materials and gases without which the solution of radiation problem is incomplete. We need to have correct information about the emittance, absorptance and reflectance of surfaces.

We need to have correct data for the properties of gases. And all these properties need to be determined through some experimental mechanism. Also, we need to find out heat fluxes in many applications. In many experiments, we need to find out the heat flux. So, in this lecture, we will see what are the different techniques used in radiation to find out these properties through experiments.

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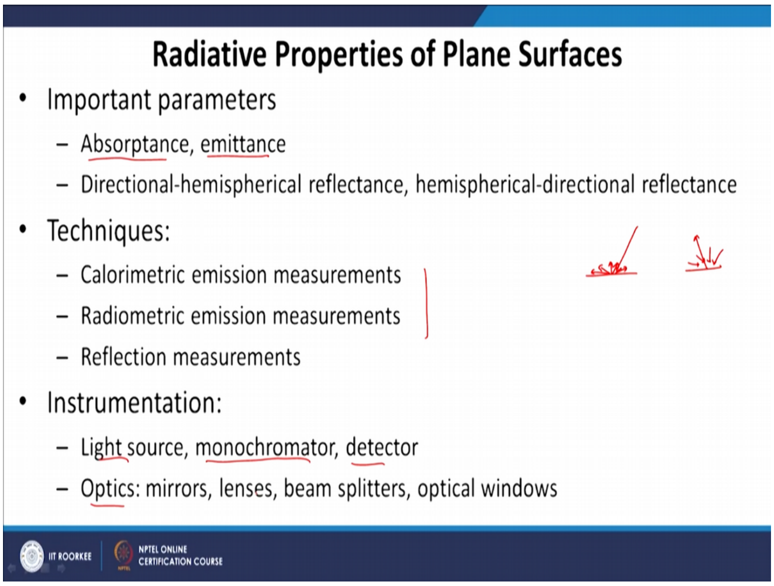

So, the first thing that we will discuss is radiative properties of plane surfaces. The techniques used to determine the properties of plane surfaces are basically used in the determination of properties of gases as well. Because the setup remains more or less the same. We need a number of things that will be common for surfaces as well as for gases. In the case of surfaces, we are basically interested in finding absorptance, emittance, directional-hemispherical reflectance.

That means, directional-hemispherical means, the reflectance for radiation coming from some direction and going into the entire solid angle. This is called directional-hemispherical reflectance. And hemispherical-directional reflectance: radiation coming from all direction and going into a single direction. So, these 2 properties can be measured. Directional-directional reflectance is very difficult to measure.

So, normally this is not measured. But rather calculated from the theory Maxwell's theory. So, I will give you the setup the schematic for this hemispherical-directional reflectance. Broadly the experiments in radiative heat transfer can be classified into 3 categories, calorimetric, radiometric and reflection measurements. So, we will take 1 example of each of these categories. Now, what are the instruments that are required in experiments?

For radiative heat transfer, we need light source. If you want to measure absorptance, then definitely we need a light source. This light source may be black, gray, monochromatic. That means, if you are interested in measuring properties at a given wavelength, then we should have light source of that particular wavelength. Or we may have a monochromator which basically converts a light, a black surface, radiation coming from a black surface.

Then by using filters or monochromator, we can convert it into a single wavelength or single wavelength color light. We need detectors that will basically absorb the radiation and gives us an idea about the intensity. We need to have good optics that will basically take the radiation from source to the detector. In the optics we have mirrors, lenses, beam splitter, optical windows and so on. So, optics is very important to design a good experimental setup in radiative heat transfer.

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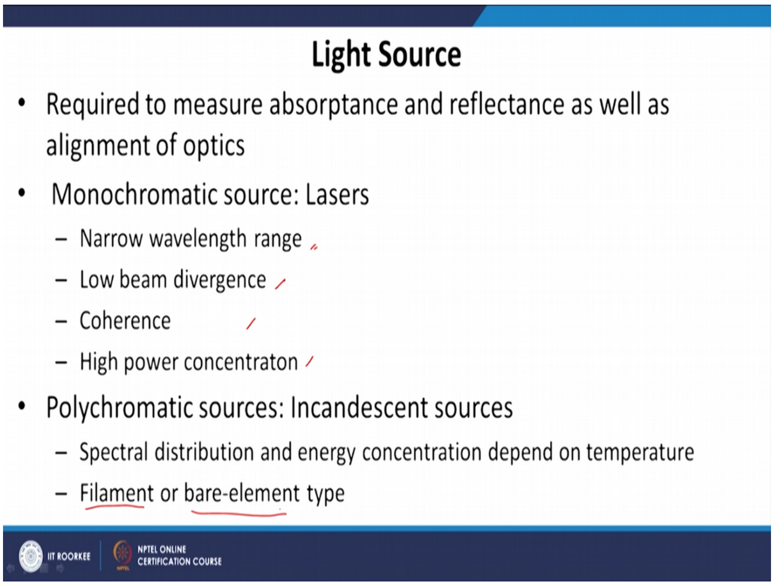

Now, what are the light source we can use. There are basically 2 types of light sources, monochromatic and polychromatic. Monochromatic as the name basically implies, it is a monochrome; that means, same color, 1 color. So, it has narrow wavelength range. It cannot be single wavelength. There will be some spread over small wavelength range. But still it is called monochromatic.

It is basically single wavelength spread over small narrow wavelength range. So, we have many lasers that basically are coming to this category. The advantages, they have very low beam divergence, they are coherent and they have high power concentration. So, lasers are very popular when we use monochromatic source of light. They are polychromatic source, they do not have a special color, they are basically mixture of wavelengths.

We may have in this filament type or bare element type. So, simple tungsten bulb is basically a filament type of light source. So, similar type of light source are used in experiments where polychromatic light source is required.

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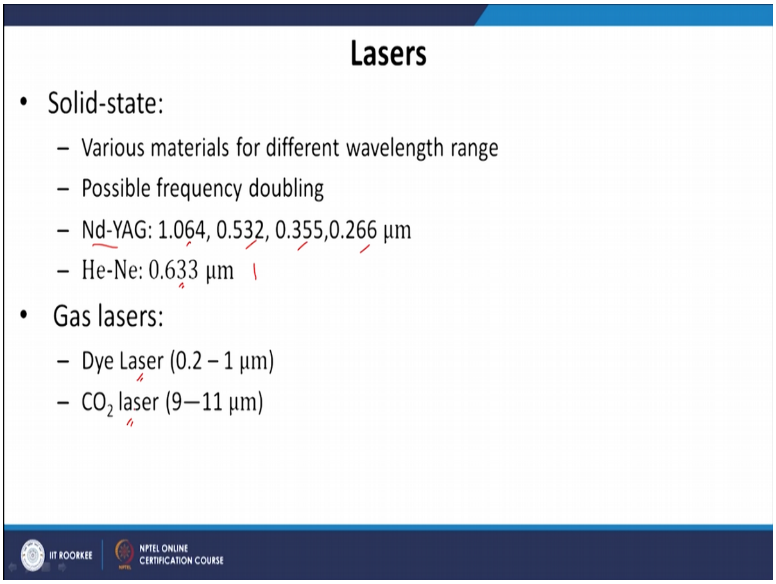

So, many many lasers are popular in experiments. Specially the helium-neon laser is very popular in the experiments. Various materials are used for solid state laser. So, lasers are again of 2 types, solid state lasers and gas lasers. Solid state lasers, again various materials can be used to generate monochromatic light source. These may be like helium-neon laser which has a wavelength of 0.633 micron.

But we can also have a idim YAG laser which basically is available in number of frequencies, number of wavelengths like starting from 1.064 micron, 0.532, 0.355, 0.266 micron. And the, in optics, by applying proper optics, we can do what we call frequency doubling. So, same material can be used to give different lasers by the concept of frequency doubling.

Then we have gas lasers based on dye and C O 2 lasers. So, various lasers can be used as monochromatic light source. Of course, compared to polychromatic light source, these are going to be expensive.

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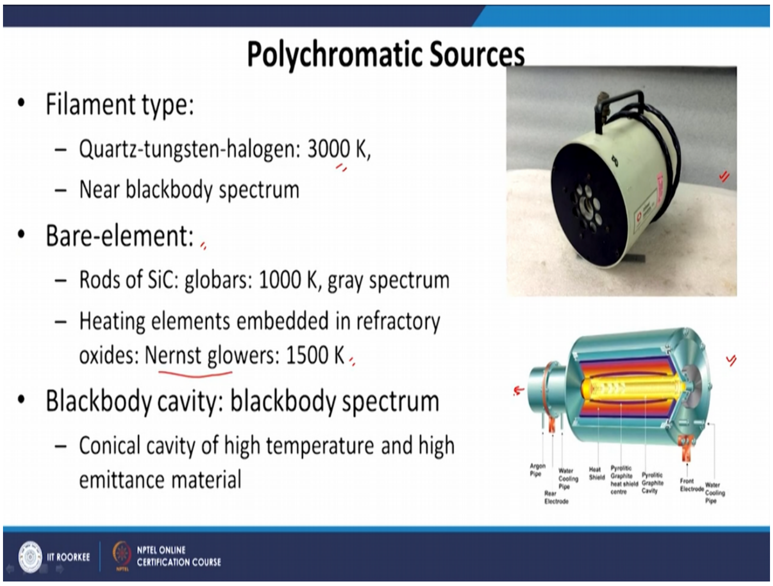

Now, polychromatic light source, again they are 2 types, filament type. In filament type we have quartz, tungsten, halogen light source. The temperature is typically 300 kelvin and it gives you nearly black body spectrum. So, whenever you need a black body spectrum, this type of light source can be used. Then we have bare-element type in which we have rods of silicon carbide which basically glow when heated.

So, inside these globars, maybe some electric heating mechanism, the temperature of these globars may go up to 1000 kelvin and they give gray spectrum. We may also have Nernst glowers where we have heating elements inside the refectory oxides. And the temperature here goes up to 1500 kelvin. So, all these are basically polychromatic light source. Some behave like a black body, others behave like gray body.

And it is important that the spectrum coming out of this light source should be calibrated before we actually do an experiment. So, the spectrum coming out of this light source should be known. Then, there are some simple setups that give black body spectrum. So, we have a conical cavity of a high temperature and high emittance material that behaves like a black body. So, this is a schematic on the right-hand side.

And this is a commercially available black body spectrum generator. And it is basically works on electric principal. What happens is, there is a cavity and this cavity is at high temperature. The emittance is very high. And the radiation coming out of this is basically nearly black body radiation. And it can be available in various temperature ranges. So, whenever we need a black body source in our experiment, these type of sources are available in the market. Then we need to basically use a monochromator.

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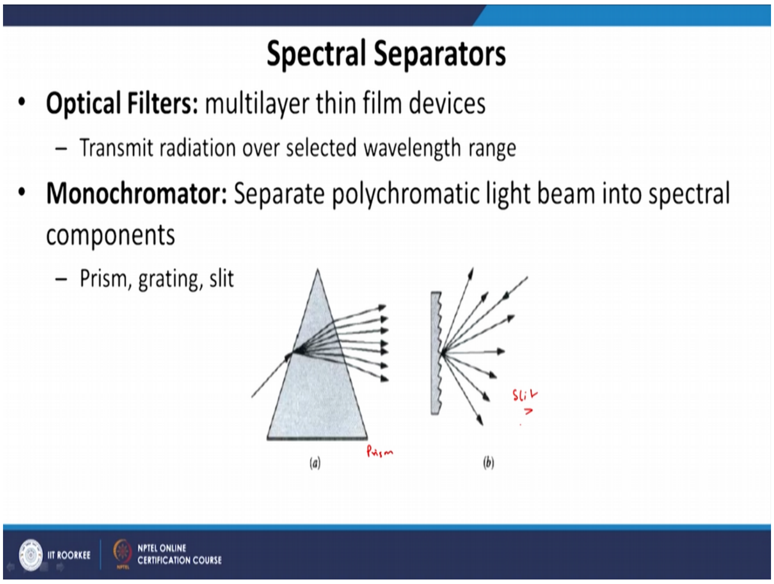

That means, if you are using a black body source, if you are using a polychromatic source, many times we need to split the radiation, polychromatic radiation into its constituents. That means, in different wavelengths. And 1 application, 1 setup you already know. Prism for example. You know prism basically splits the radiation into different colors. So, prism can be used to split the spectrum into multi into colors.

Then there is a slit also. This is a prism on the right-hand side is slit. So, this also is basically used to split the spectrum into its constituents. They are called monochromator. So, prisms, grating, slits, all these are basically called monochromator. What way the what they do is, they basically distributes the polychromatic light into its constituents. And by blocking some components of this splitted spectrum, we can get a monochromatic light.

There are also optical filters, bandpass filters, narrow bandpass filters, which basically blocks most of the radiation except in this, in the narrow band range. And these filters can also be used to generate monochromatic light from polychromatic light.

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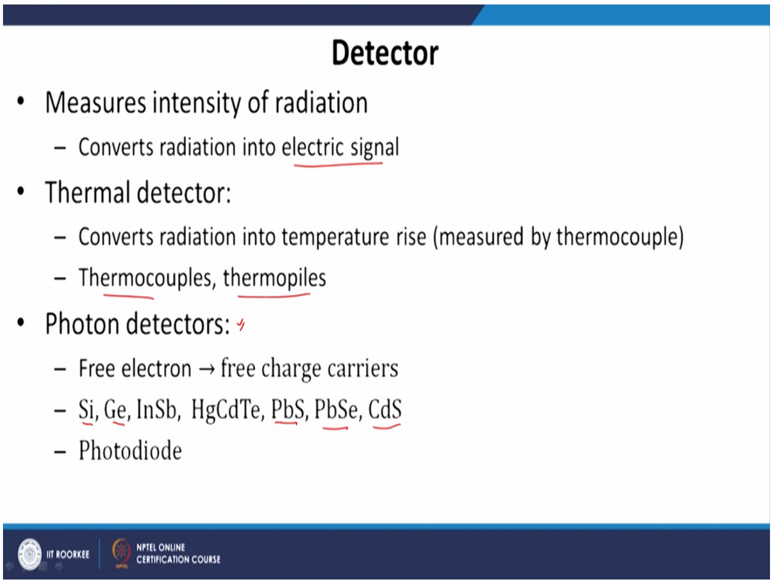

Then, we need to have a detector. After reflecting refraction and after emission, we need to have a retractor on which the light will fall. And we should be able to measure its intensity. So, the principal is, they convert radiation into electrical signals. And this electric signal is measured. And this detectors are calibrated for different amount of known radiation. In this category, we have 2 type of detectors.

Thermal detector, it converts radiation into temperature. And then, temperature is basically measured through some kind of thermocouple which again is basically converts temperature into electric signal. So, thermocouples are used to measure the temperature. But that detector, the radiation detector is basically thermal based. Because it converts radiation into thermal temperature.

So, thermocouples, thermopiles are basically this type of detectors that can measure radiation. Now, more advance detectors basically are based on photon detectors. In this, we have free electrons. And based on the amount of radiation absorbed, different amount of free careers or free charge carriers will be present in these materials. So, we will have a silicon, geranium and other lead sulfide, lead selenide, cadmium sulfide.

So, these type of materials can also be used for detectors. They absorb radiation. And then, convert this relation into a pool of free charge careers which basically leads to formation of current. And that can be measured electrically. And photodiode is the simplest example of photon detector.

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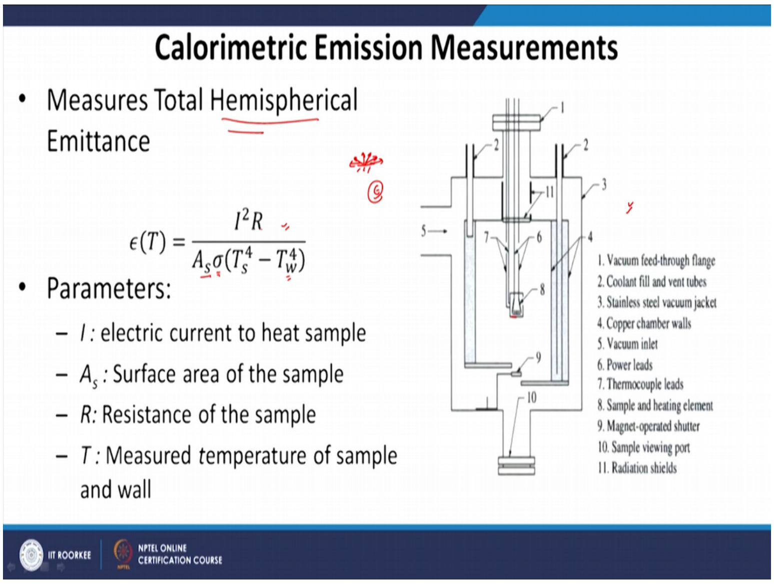

So, let us see how these devices can be used to measure the properties of plane surfaces. The first property that we are interested in measuring is hemispherical emittance. That means, the surface emits radiation in all direction. And this average emittance we want to measure. So, what we have is, there is a setup. The setup basically has many components. But the main component here is, there is a electric source.

The source basically heats the sample. So, there is a sample here which is heated electrically by measuring the current and the resistance of the sample, we can understand, we can calculate the amount of energy basically given to the samples. So, I square R is the amount of energy given to the sample. And in thermodynamic equilibrium, the amount of energy given to the sample should be = the amount of energy emitted by the sample through radiation.

Of course, that has to be vacuum, so that we can ignore the convective part of the losses. So, amount of energy given to the sample should be = amount of energy lost by the sample through radiation. And this is = A s times sigma, where A s is the surface area of the sample. Sigma is the Stefan Boltzmann constant and T s is the temperature of the sample which is measured using thermocouple.

So, we have to place thermocouples on the sample. And T w is the temperature of the wall. So, we have to put some thermocouples at the wall of the furnace. So, these 2 temperatures are measured. So, 4 quantities are measured, temperature of the sample and temperature of the wall, current and the resistance of the sample. So, once we have do that, we can use this formula to calculate the hemispherical emittance of the sample.

And this type of measurement where we use the energy balance; so, energy given is = energy lost, is called calorimetry. And this type, this experiment is basically calorimetric emission measurement.

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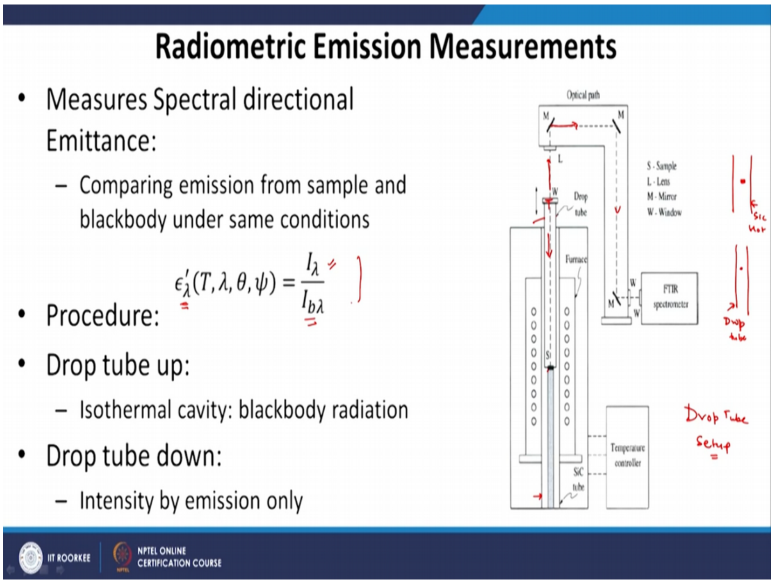

The second one is a radiometric emission measurements. Here we are directly basically measuring the intensity using some kind of detector. So, here the example that I am giving you is a special setup. It is called drop tube setup. So, this is a special setup that is used to measure the directional or spectral emittance, as well as it can use, it can be, the same setup can be used to measure the properties of gases as we will see.

It was used by Modest to measure the properties of the gases. Now, how does it work? So, here we have a 2 concentric tubes. So, this is 1 tube. The tube is made of silicon carbide. It is heated to the same temperature as the sample is heated to. So, when the sample is here. The tube, the second tube is basically the drop tube here. When the drop tube is up, the sample is basically inside the silicon carbide tube.

So, this is the silicon carbide tube. And sample is somewhere here. Both are at the same temperature. And we know that, when we have an isothermal medium, then the radiation coming out of that medium will be the = black body radiation. So, when the drop tube is up, the sample is surrounded by the silicon carbide tube. And the radiation coming out of this tube will be = the emitted radiation as well as reflected radiation.

And the intensity will be = black body intensity. Now, in the second part, what is done is, the drop tube is basically brought down, so that the sample is now exposed to cold drop tube. So, this is now cold. This is silicon carbide hot tube in the first part. And now this is basically the drop tube which is now cold. So, hot sample, but the tube is cold. So, this, in this case, the radiation coming out of the tube will be basically by emission only and no reflection component.

And that radiation is basically measured by the detector. And it is called I lambda. And how the radiation is measured by the detector? The radiation is basically coming out of the tube. There is a window here. Radiation travels all the way through mirrors. It is basically passed to FTIR. FTIR is basically a special type of detector which makes continuous measurements over a range of wavelengths.

So, there are many detectors that measure radiation at a given wavelength. But FTIR, the advantage of using FTIR; so FTIR is fast Fourier transform of infrared spectrometer. The using of FTIR is that we can measure the value of emittance over a range of wavelength in a single experiment. So, by taking the ratio of these 2 intensity measured, once when the drop tube is up, the second measurement when the top tube is down. And the ratio basically gives you the spectral normal emittance of the sample. And third experiment that I am discussing here is the reflection measurement.

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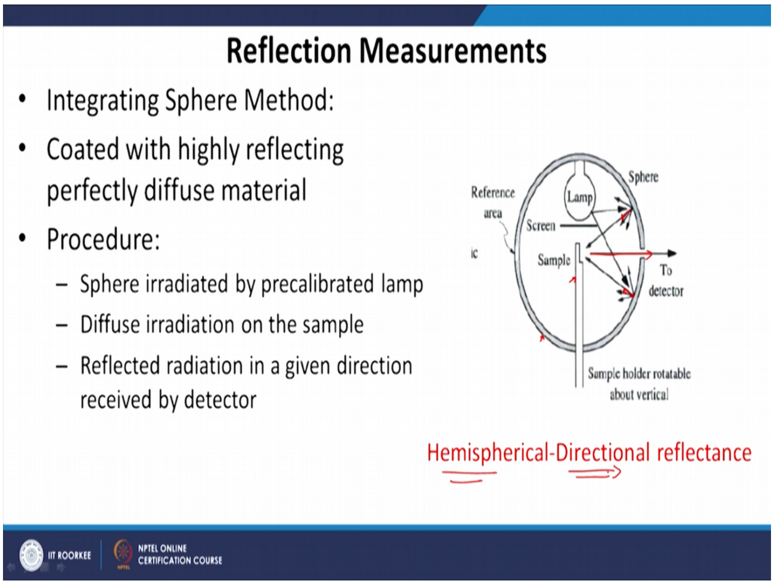

Now, reflection measurement, again there are various setups available. Here I am taking a very simple setup. This setup gives you hemispherical-directional reflectance. So, what we do is, there is a rod on which we put the sample. And what we have is a lamp. So, this may be a monochromatic length, monochromatic source if you want to measure spectral reflectance. Or it could be a black body source if you want to measure hemispherical to directional reflectance at averaged over all the wavelengths.

So, what basically we have is, there is a cavity. This cavity has been coated with highly reflecting diffusely reflecting material. So, whatever radiation from this lamp falls on the cavity, it will be diffusely reflected and it will be pointed towards the sample. So, we see there, all the radiation basically is diffusely reflected towards the sample. And from the sample, some part of this will be reflected in the direction which will be going to the detector.

So, what we have is, the radiation, the sample is illuminated or irradiated from all directions; so, hemispherical. And only there is a slit in a given direction. So, we are measuring the radiation escaping in a given direction. So, this experiment gives you reflectance hemispherical-directional reflectance in a very simple way. Now, so this was all about measurement of properties of the surfaces.

Now, the how do we measure the properties of the gases. So, we were, we are interested in measuring absorption coefficient of the gases. Now absorption coefficient directly cannot be measured. Okay. So, we have to measure what we call transmission, transmittance. Okay. We pass a radiation through a gas sample. And whatever basically comes out of the sample, the transmitted part of the radiation is measured by the detector.

So, the properties of the gas is not measured directly. The other, the transmittance is measured, or transmissivity is measured. And from this transmissivity, we have to derive the values of absorption coefficient. So, absorption coefficient cannot be measured directly. So, that is the 1 part. So, here we have; now, we need to, we need to measure the properties of gas at various temperatures. So, we need a furnace. So, in this case, we have a furnace;

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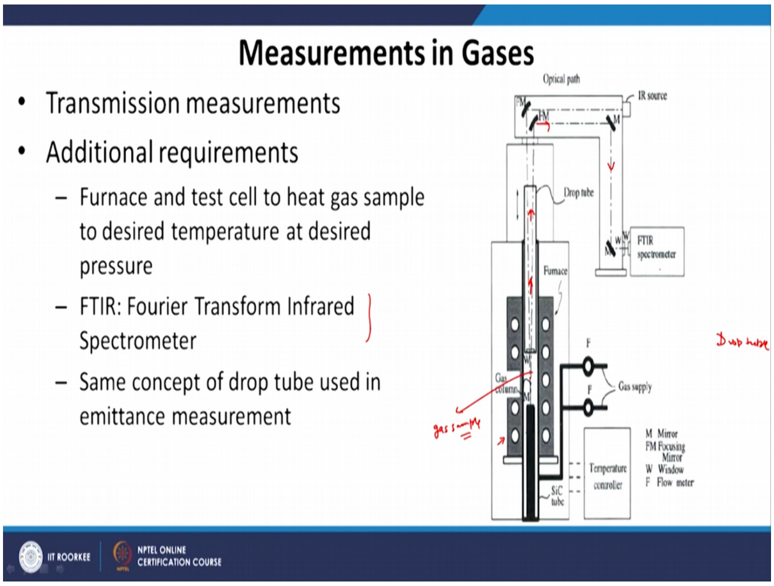

In which we have a gas sample. So, this is the gas sample here. Now the same setup, drop tube type setup is used. When drop tube is up, the radiation coming out is black, is equivalent to black body. When drop tube is down, the radiation coming out of the chamber, the gas chamber is basically the transmitted radiation. So, the ratio basically gives you the transmissivity. So, in this case we use FTIR, because we want to measure the properties along large number of wavelengths.

So, we use FTIR spectrometer. The same optical path as was discussed earlier is used. Radiation from this gas chamber travels in the direction through drop tube and then through mirrors it is reflected to the FTIR. So, this is how we can measure the properties of the gases. The main challenge in measuring the properties of the gases is that we should ensure that the temperature of the gas is uniform.

That means, the furnace is designed in such a way that the entire sample of the gas is at the uniform temperature. And when the drop tube is up, we take the reference spectrum. When the drop tube is brought down, the temperature of the gas may change. So, we have to take the readings very quickly. So, that the radiation, the temperature of the gas does not change. If the temperature of the gas changes in between taking the readings, then there will be sources of error.

So, drop tube is brought down. And the spectrum is taken. And the ratio of the reference spectrum and the actual spectrum gives you the transmissivity as a function of wavelength. So, we use FTIR and Fourier transform to find out the spectrum. So, these are some of the methods that we use to measure the properties of surface and gases. Now, there are heat flux measurements also required many times.

We are interested in measuring the heat flux. There are 2 types of heat flux. Normally in combustion applications we are interested in. 1 is total heat flux that basically comprises of radiative heat flux + convective heat flux. So, normally heat flux, normal heat flux case we can use to measure the total heat flux. But sometimes we are interested in measuring the radiative heat flux.

So, in measuring radiative heat flux we need to do something so that convective part of the heat flux can be eliminated. So, when do we have radiative heat flux in high temperature application and low gas velocity?

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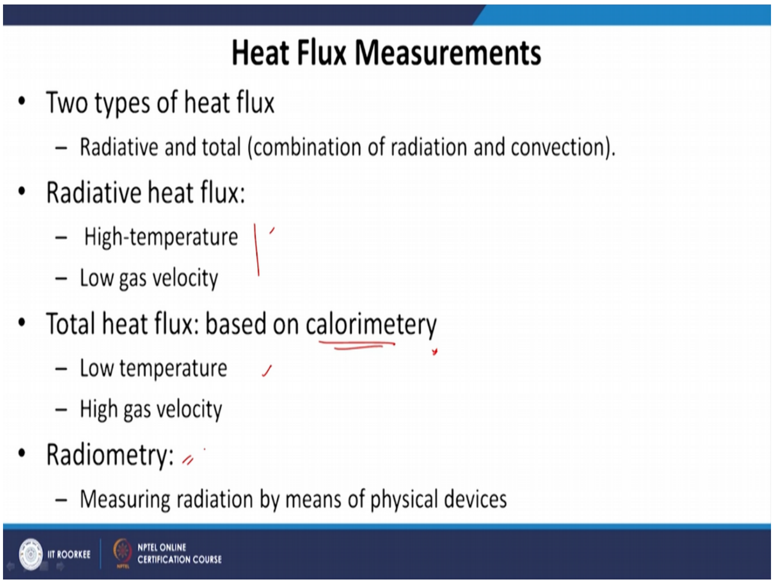

So, the gas velocity when low, the convective heat transfer will be very low. And in high temperature, radiation will be predominant. So, radiative heat flux needs to be measured. On the other hand, when we have low temperature and the velocity of the gas is high. Then mainly it is convective heat transfer, convective heat flux will be important. But some part will be radiative heat flux also.

So, in this case, radiation may be small fraction of the total heat flux. But we are interested in total heat flux. So, this total heat flux is measured based on the principle of calorimetry. And when temperature is high, gas velocity is low. We are mainly interested in measuring radiative heat flux. And radiometry is basically measuring radiative heat flux by means of some experimental devices. And the technique is called radiometry. So, radiometry is measuring radiative heat flux by some experimental mechanism.

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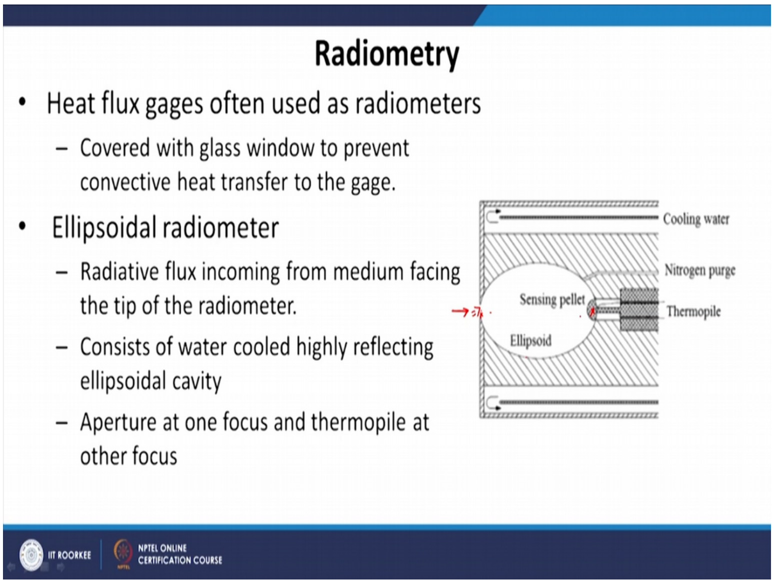

So, here I will give you a simple schematic for the radiative heat flux. This is a simple radiometric gage. Here we have basically a elliptical cavity. Here we have a glass window to prevent convective heat transfer. So, this is covered with a glass window. And radiation will enter into the cavity from here. So, from this cavity; now, this elliptical cavity basically has the focus, 2 focus.

So, this is 1 focus of the elliptical cavity and this is the second focus. On the first focus we have window and on the second focus we have the sensor or thermopile. So, radiation enters from here, through the window, so that convective heat transfer is eliminated. And once it enters here, it will be basically subjected to reflection or reflection from the surface of the elliptical cavity.

And it will focus on thermopile, which is the detector. So, 1 aperture is on the focal point of the ellipse another is the detector on the another focal point. So, whatever radiation enters from this cavity, after number of reflections it will focus on the detector. And this is how we can measure the radiative heat flux. So, this type of radiometers are used to measure radiative heat flux in number of experiments.

Lastly, we have infrared cameras. Infrared cameras are used to measure temperature without any contact. So, normally, to measure the temperature, thermocouples are used. But thermocouples, the advantage or disadvantages; although they are accurate, but they need to be sticked to the sample. Sometimes, sticking to the sample may actually create problems. It may disturb the surface itself.

And temperature measurement may not be accurate. So, infrared cameras are used in many applications to measure the temperature of the surface. Now, 1 thing you should basically here understand is that it is infrared camera, so it requires radiation in the infrared part of the spectrum. There is no visible part of the spectrum that is used. And normally you see in infrared cameras the color images.

And color is something identified by visible part of the spectrum. While infrared camera does not use visible part of the spectrum. So, what is the color coming from? What are, what does color has to do in infrared camera? In fact, most of the time, the image that is formed in infrared camera is monochromatic.

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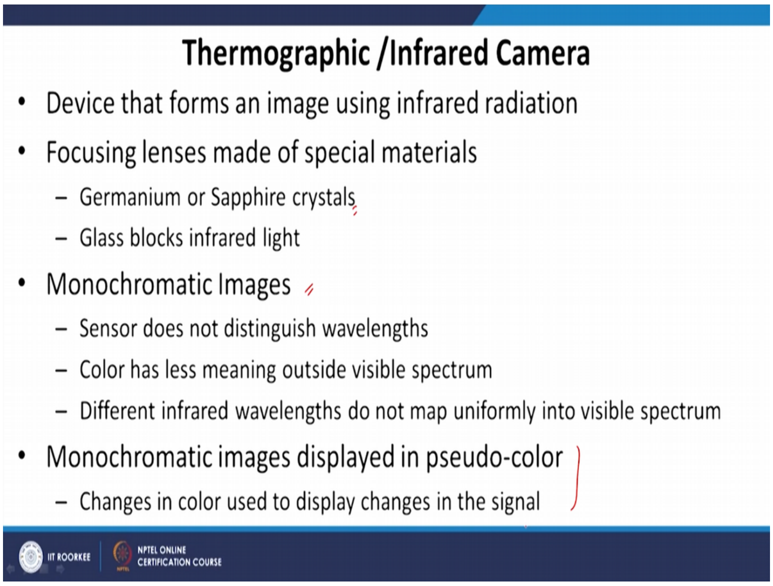

It is a single color. Because infrared cameras are not dealing with visible part of the spectrum, so there is no question of color coming into this thing. And the lenses and the images formed are monochromatic. Also, the lens that are made in these cameras are also not of glass. Because glass absorbs significant amount of radiation in infrared. So, you cannot make lenses of this camera from in, from glass.

Rather geranium, sorry germanium and sapphire crystals are used to make lenses of these type of cameras. Now, color does not have any meaning in infrared. So, mostly the sensor in infrared camera is monochromatic. And what you see, color is basically a pseudo-color. So, pseudo-color is basically used to display the intensity. Now, we have infrared camera. The sensor may be monochromatic.

But it gives you a different intensities at different wavelengths, is a function of color because of pseudo-color representation. So, pseudo-color representation is basically a representation of intensities at different wavelengths. So, different wavelengths have different intensity. And that is basically represented in the form of pseudo-colors, so that it gives you an idea, which part of the surface is hot and which part of the surface is cold. Okay.

So, wherever the integrated intensity over the wavelength is high, that will be shown as a blue or red. And wherever the intensity is low, that will be shown as yellow. So, we give pseudo-color. So, they are not the real colors. Because color does not have any meaning in infrared.

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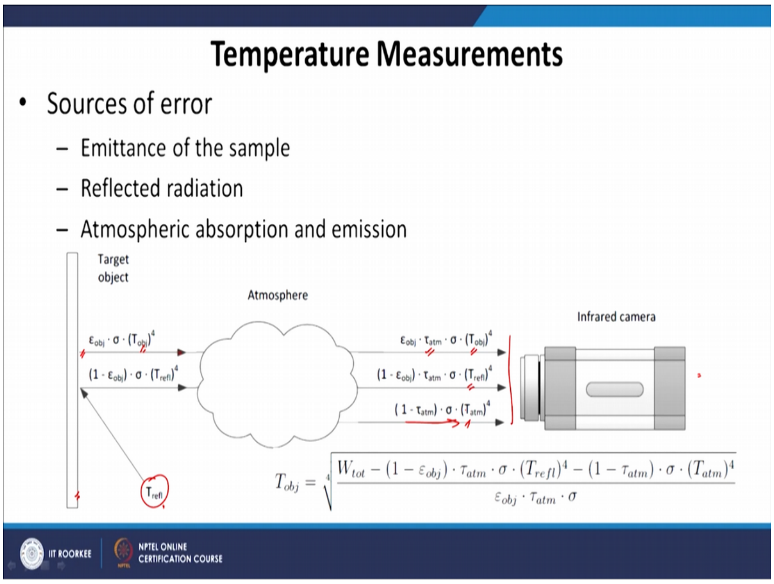

So, this is a simple setup. Suppose this is the surface you want to measure the temperature of, we use infrared camera. We focus this camera onto the surface. Now, there may be number of sources of error. Radiation coming from the surface definitely will pass through the medium. Let us say you are measuring the temperature of the surface of the furnace. Then the gases in the furnace will definitely absorb the radiation.

So, the radiation coming from the surface will be undergoing attenuation by the transmission factor tau of the medium. And then, there may not be a single surface in the furnace, there may be multiple surface. So, reflected part of the radiation will also be coming into play. So, some part of the reflected component that is coming from walls which are away from the wall on which you want to measure the temperature.

So, the radiation coming from the side walls after reflection also reaches the camera. And then, finally, radiation from the gas also reaches the camera. So, 3 components of the radiation are reaching the camera. And you have to compensate for that. So, you want to measure the temperature of the object. But actually what you are measuring is, not only the radiation coming from the object, but also the reflected part of the radiation and also the radiation from the gas.

So, these 3 components are basically coming. So, you have to compensate for this in the camera. And normal the infrared cameras that are basically come, they come with different compensation mechanism.

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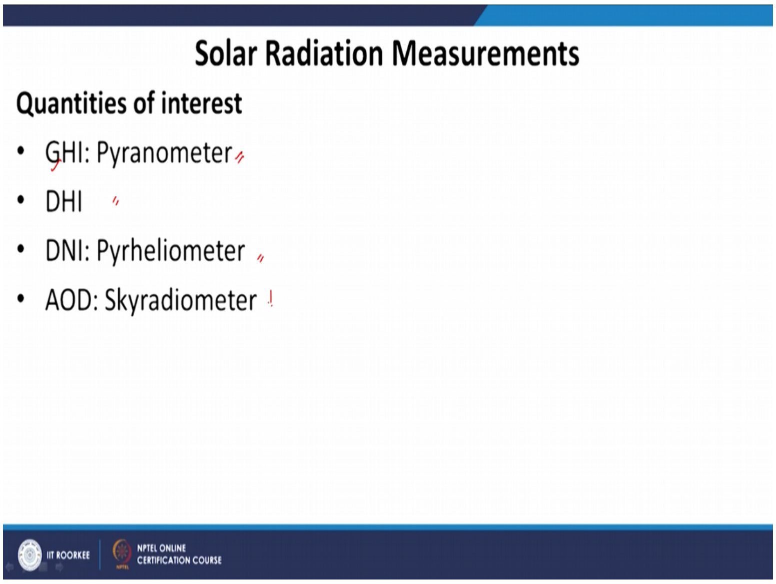

Solar radiation is also require measurement. For many applications, if you want to set up a solar power plant, you need to have some idea about the intensity of radiation, solar radiation at different locations. So, again in this category, we have number of measurements required. We want to measure global horizontal irradiance, that is total amount of energy coming on a flat surface normal.

So, it is a, basically you measure by pyranometer. Then diffuse horizontal irradiance and direct normal irradiance. So, diffuse horizontal irradiance is the component of solar radiation which is subjected to scattering and that reaches the surface. It can also be measured by paranometer. Then direct component of radiation is measured by pyrheliometer. And sometimes we also need the information about the dust and aerosols in the climate, so that we can guess an idea, how much radiation will be subjected to scattering and attenuation by these particles.

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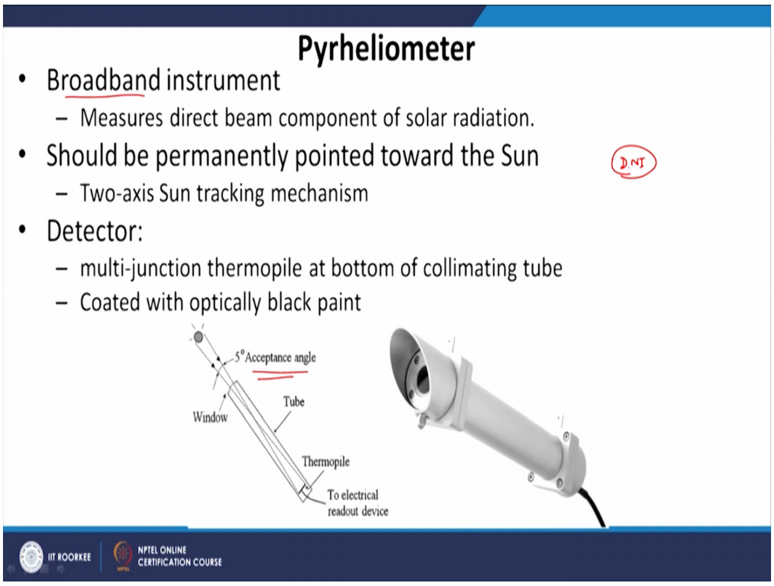

So, this is a pyrheliometer used to measure broadband for DNI. This measures DNI, direct normal irradiance. And because it measures direct irradiance, it accepts radiation within small acceptance angle. Okay. So, radiation is accepted inside the pyrheliometer within a small angle roughly 5 degree. Okay. So, that means, diffuse part of the radiation is not entered in inside this instrument.

It measures only the direct part and integrated over all the wavelength. The sensor is a broadband sensor. It takes all the wavelengths and integrate over those wavelengths and gives you total amount of DNI integrated over all the wavelengths. Okay. And because sun angle changes from time to time, it will be different angle in the noon, it will be different angle in the evening.

So, this pyrheliometer also needs to be pointing towards the sun all the time. So, it has to be on a tracker. That mean, there should be a sun tracker on which this instrument should be mounted. So, that it always points to the sun and we can measure DNI accurately.

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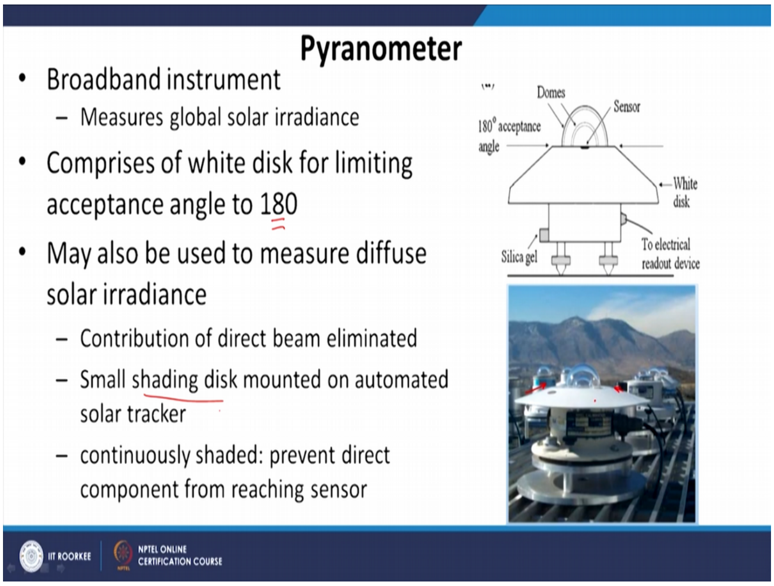

Then we have paranometer. Paranometer is simple device. It is also a broadband device that gives you spectrally integrated diffuse, as well as global horizontal irradiance. In this we have a disc as is shown here also. So, it accepts radiation in the entire solid angle of 2 pi. Now, some radiation from the ground may also come at grazing angles. So, for that, this white plate has been given. Okay.

So, this white plate has been given, so that the radiation coming into this dome comprises only the radiation coming from the sky in angle 180 degree. And no radiation coming from the down, from the earth surface is basically accepted in this. It measures entire amount of radiation that is received. That means, DHI as well as DNI. And that is why it is called GHI instrument. This is a paranometer that measures global horizontal irradiance.

But with special care, the same instrument can be used to measure DHI also. All we need to do is, we have to block the direct component. And for that, shadowband is sometimes used. So, small shading disk that basically rotates that blocks the direct component of the radiation can can be mounted on this instrument. And direct component can be blocked. And the same instrument can be used to measure DHI as well. And the final instrument is a skyradiometer.

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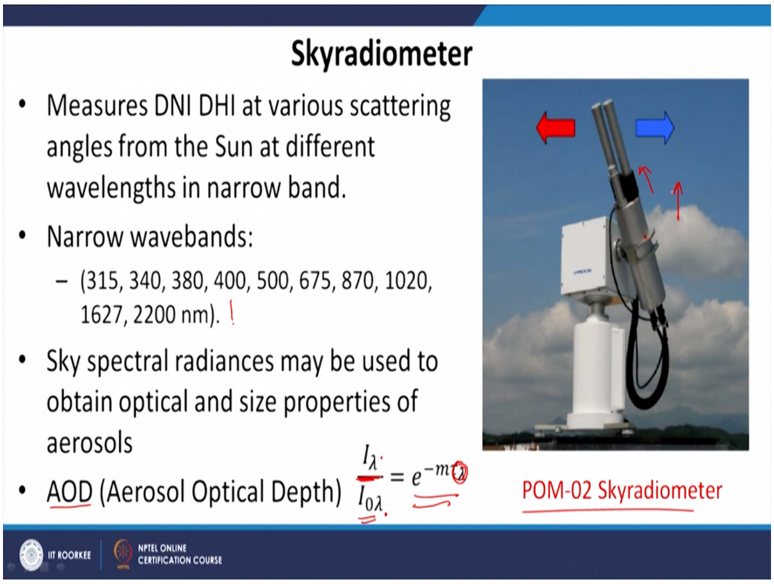

The good thing about skyradiometer is, it is a narrow band instrument compared to paranometer and pyrheliometer which are broadband instrument. They measure spectrally integrated radiation. This particular instrument is a narrow band instrument that measure radiation in small narrow bands. Okay. So, for example, this is a POM-02 Skyradiometer measured by a Japanese company.

It measures radiation in different narrow bands. Okay. And there are large number of narrow bands. So, the advantage of these type of instrument is, it basically gives you liberty to determine various factors that absorb radiation in a more accurate way. For example, there are dusts, aerosols that absorb radiation in specific wavelength interval. So, if you want to quantify the presence of aerosols and dust in the atmosphere, we have to make narrow band instrument, narrow band measurements.

Because GHI and DNI cannot give you accurate idea of the presence of this aerosols in the atmosphere. So, there is a parameter called aerosol optical depth, that is basically used to quantify the presence of aerosols in the atmosphere. What it basically means is, it gives you the aerosol optical depth tau lambda at a given wavelength as a ratio of intensity, actual intensity i lambda and I 0 lambda.

I 0 lambda is the intensity of solar radiation on top of the atmosphere. So, radiation intensity outside the atmosphere, radiation intensity at the ground surface and the ratio of the 2 basically is the attenuation or transmission. And in this transmission, what we have is aerosol optical depth. And m is the air mass. So, m is the air mass depending on the angle. This instrument can measure radiation at many angles.

It can measure radiation in this angle, as well as in the normal direction. So, if you are want to measure the properties of aerosols in a given direction, you have to take into account the variation of air mass m versus the angles. So, thank you. This was the last part of this course. In this lecture we discussed the concepts of experimental techniques as applied to combustion and solar energy.

So, various techniques are used to measure the relevant quantities, the heat fluxes in a spectral variation of the properties. And the properties of plane surfaces and gases. We end this course here. I am sure you get benefited from the content covered in this course. Thank you.