# Convective Heat Transfer
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## Lecture - 57
## Experimental techniques – IR thermography

For doing this IR thermography let us begin with a problem which I am going to pose over here which is a problem from our research group ok. Where we will talk about the significance of the problem and why a new measurement technique was necessary for this ok.

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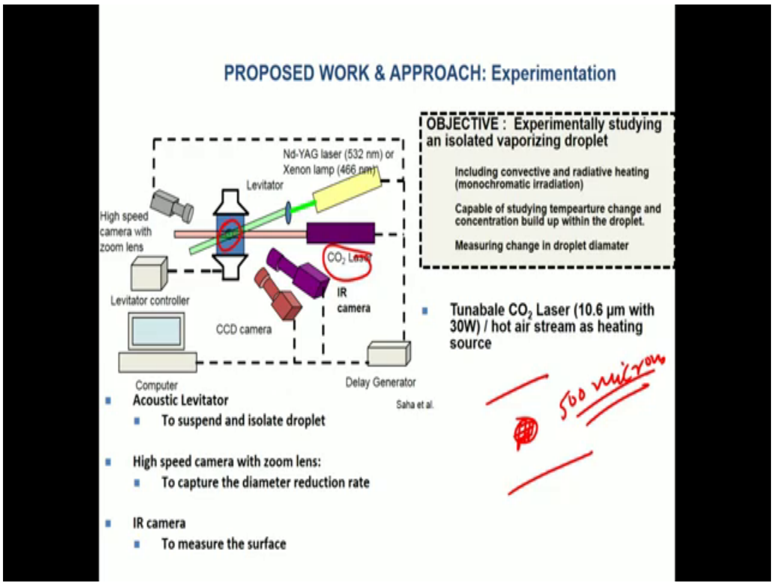


So, let us take the case as you can see on this in this PowerPoint presentation that in our group we needed to measure the temperature of a levitated droplet, that circle that I have marked inside that circle there is a green colored droplet that you can see. So, that green colored droplet basically is a levitated droplet; that means our droplet which is hanging from free space under acoustic pressure.

So, the main purpose of this exercise was how to measure what is the temperature inside or on the surface of this levitated droplet right. So, and this droplet was of the order of say 500 microns ok. We needed to know the temperature because you know using a lot of there could be a lot of things, but we really needed to know because this droplet was also heated by a laser and we needed to know the temperature of the levitated droplet.

Now this is looks like a very challenging task because your TLC would not work over here because you do not want to change the properties of the droplet ok. And the temperature range can be quite high so it is more than the range of the TLC's in certain cases.

So, the main idea was to devise a measurement technology by which we can actually measure the surface temperature of such a droplet. Now, in this particular case as measurement technique like IR thermography which is non intrusive emission based that can come in very handy ok; so that is what we are going to describe in the. So, just to give a pollute that in complicated situations like this you need a new technique which is called IR thermography.

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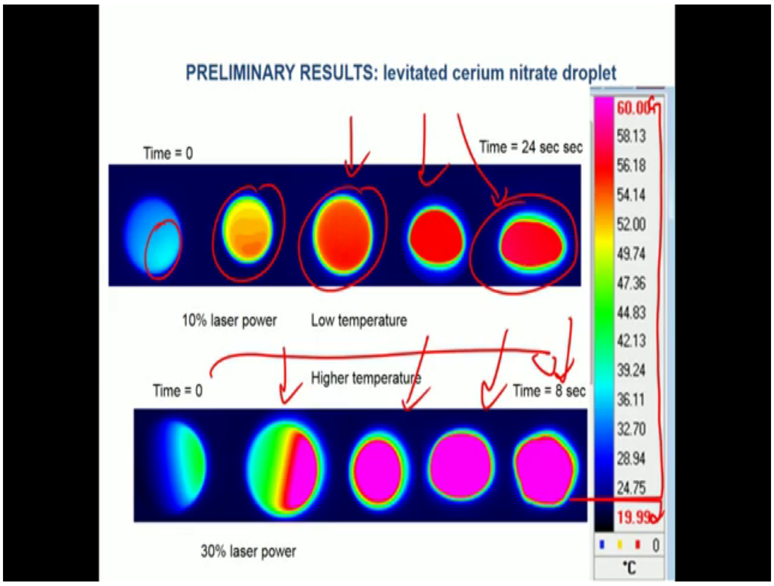


So, this is for example, what is the temperature that we measured if you look at it this is from our experimental data from my research group and you can see that we have a sufficiently fast acquisition from 0 to 8 seconds. You have quite a lot of images you have a sufficiently good resolutions on the temperature we can measure from 60 to 19 degrees correct ok. Now this is not possible with the TLC because a temperature band is usually very small right to begin with ok.

So, you can see how the temperature starts and how it grows, how it kind of equilibrates, and this is the droplet getting flattened and things like that. So, it is a global technique once again you can measure the surface temperature of the droplet, but you have to have some kind of a technique which measures this right.

So, once again IR thermography comes in very handy in this particular case basically IR thermography requires an IR camera infrared camera so that is the camera that you use basically to monitor the surface temperatures ok.

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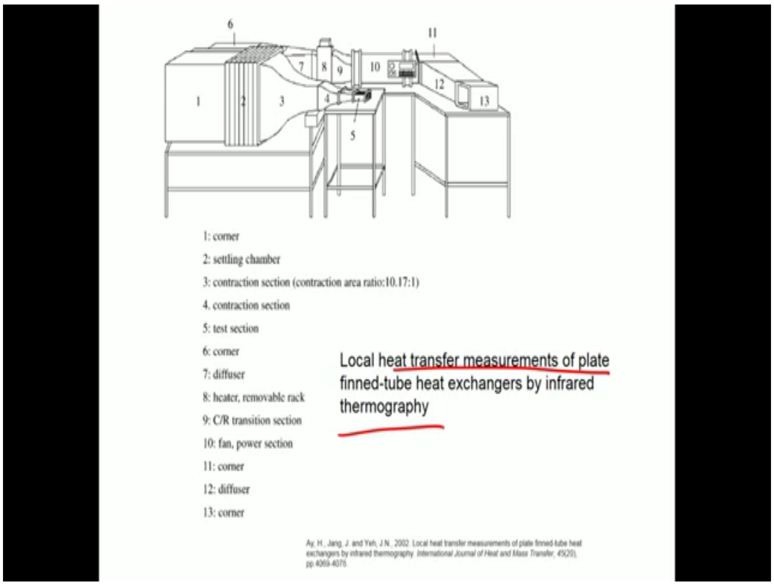


Now, other examples this is from our group there could be other examples like for example, this is a wind tunnel experiment. You want to measure the local heat, transfer between a plate, finned heat exchanger using infrared thermography that is one other kind of measurement that you might want to measure ok.

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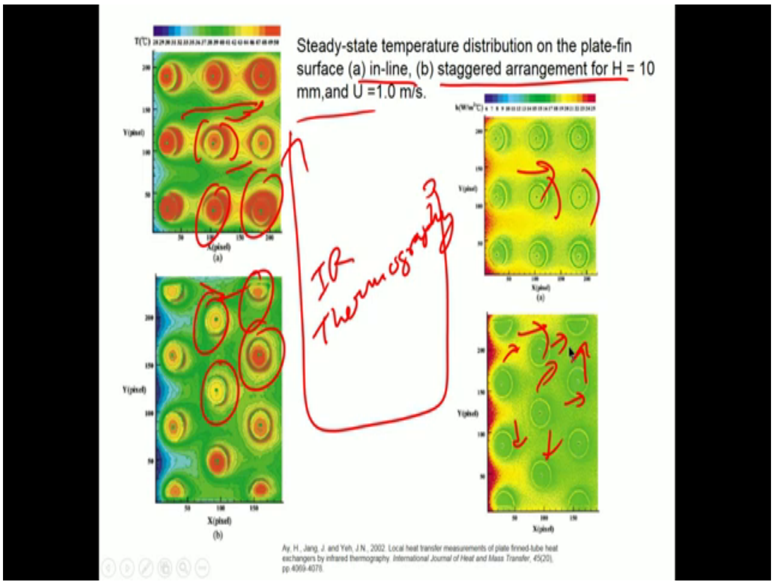


This is for example, in the steady state temperature distribution on the plate fin surface. So, you can see the temperatures right all these places these are temperatures you can see the linking between the two which is happening because of the flow right. So, there is a fore and aft asymmetry of the temperatures correct you can see the wake patterns very clearly right, but how each of these holes are dominating each other correct is not that so ok.

So, the steady state temperature distribution on the plate fin surface in time staggered arrangement, there are lots of arrangement all of these things done using IR thermography alright. So, IR thermography you are able to see this temperature distributions across different directions using this particular technique got it.

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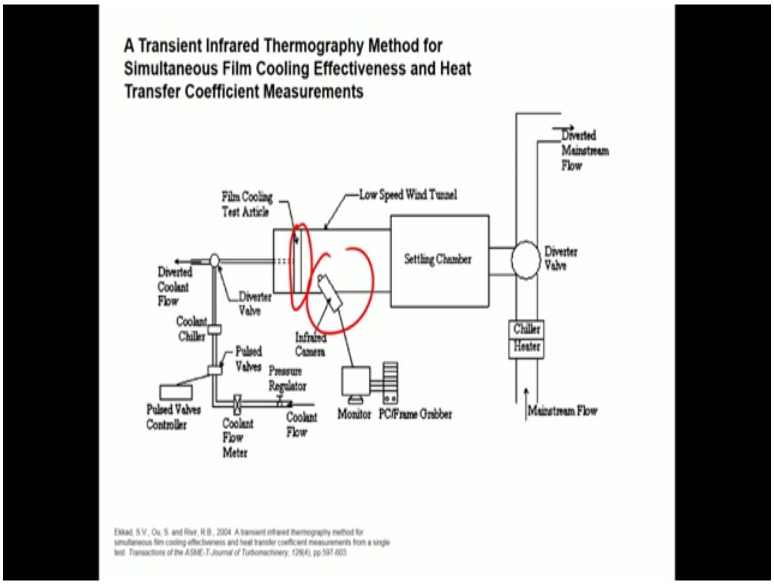


So, another thing could be a transient thermography measurement technique for simultaneous film cooling. Film cooling is what we use in the gas turbine plates right. So, for film cooling one uses this infrared camera and that the film cooling setup is right here and you can use it in a wind tunnel and you can measure what is the temperature ok.

Non intrusive and it does not require any probes give you the field measurement right can be used at very high temperature situations also where thermochromic liquid crystals may not be the right candidate to use ok. So, giving in mind that all these applications like which involves turbines, which involves simple droplets, which involves fins in heat exchangers, IR thermography is a very attractive technique to use correct ok.

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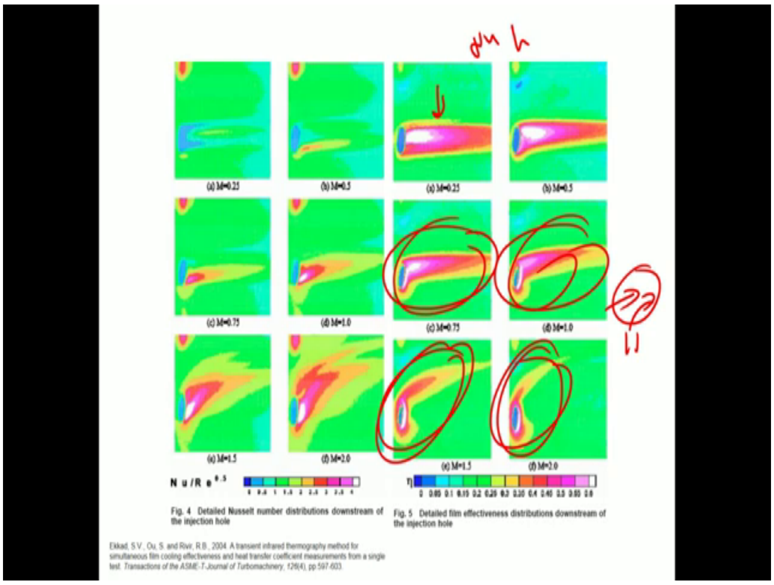


And this is for example, this is the film cooling holes and you can see that how the holes what is the temperature distribution across the holes for the different values of your momentum fluxes ok; that means, the film cooling there is a hole through which you actually inject fluid, and then there is a cross stream ok.

So, depending on the ratio of the two you get all kinds of you know the temperature profiles over here ok. So, all these things are very attractive you can get measurements with this kind of accuracy with this kind of a you know resolution which makes it a very attractive tool right to use in our measurements.

Because this is these are the measurements which will help you to calculate the Nusselt number right. These are the measurements which will enable you to calculate the heat transfer coefficient h right. So, these are important things because this is how you protect a gas turbine blade if you do not know the Nusselt number properly or you do not know the temperature distribution your blade will basically burn out right. You have to protect your blades and gas turbines are expensive propositions ok.

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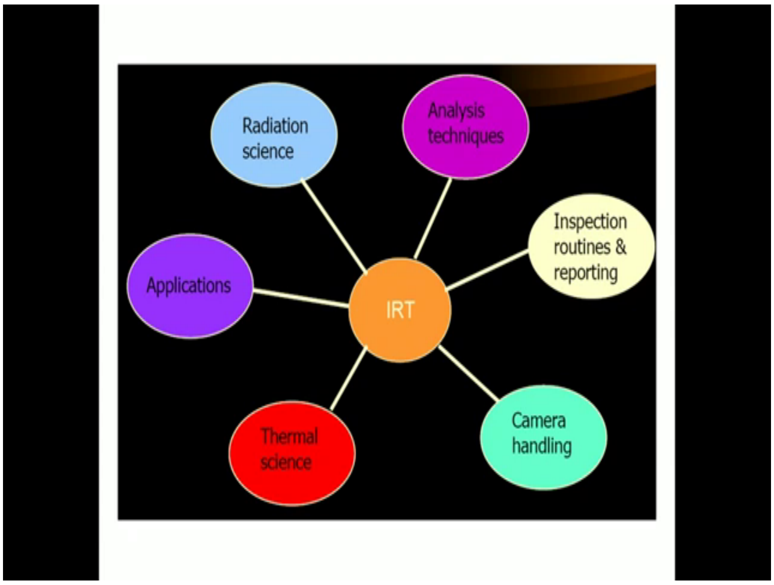


So, there are a lot of things that you have to you that uses the infrared technologies ok. There is the thermal science which we are doing, there is some inspection and routine things which you are not going to cover and there are other applications as well that uses this kind of a technique.

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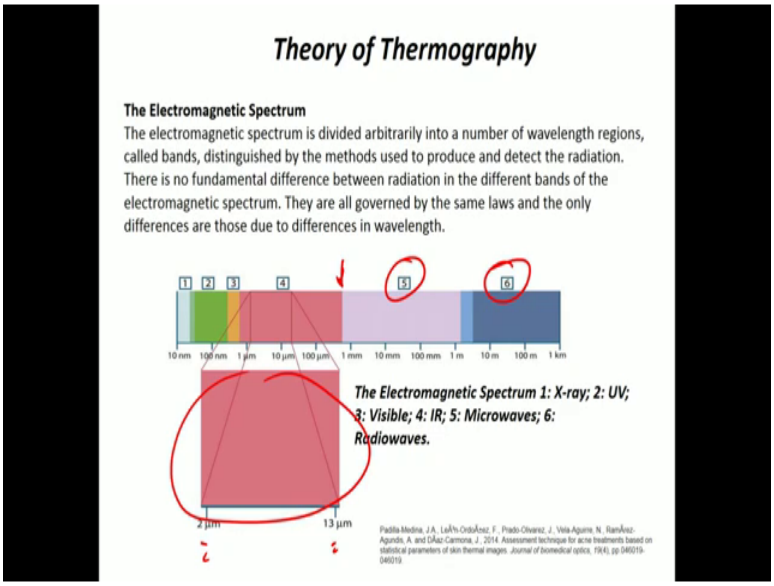


So, what is the theory of thermography over here because that is the most important part we have shown you a lot of examples where it can be used. Now let us look at what is the difference, how do we actually measure it? The electromagnetic spectrum as you already know is divided arbitrarily into a number of wavelength regions called bands right.

So, you can see bands 1, 2, 3, 4, 5, 6 right out of this one is basically the X-ray band right X-ray which is of the 10s of nanometers right. Then the second band is your UV; UV band which is of the order of as you can see 100 nanometer to ah close to in it is centered around 100 nanometer.

Third is basically you go to the visible region that is where we can see our human eyes can see you and me and everybody else ok. Then you go to the IR and IR is a very large band it starts all the way up to approximately close to 1 micron goes up and up and you can see that it ends somewhere there ok. Then comes the band of the microwaves and the 6th is the radio waves ok. So, this is the full electromagnetic spectrum whether last one extending up to kilometer right so this is based of the wavelength correct ok.

So, IR thermography basically deals with this anywhere between 2 micron to 13 micron is a good candidate, is a good IR band ok. This is where we take our measurements got it that is why it is called IR thermography; that means, which uses the IR band.

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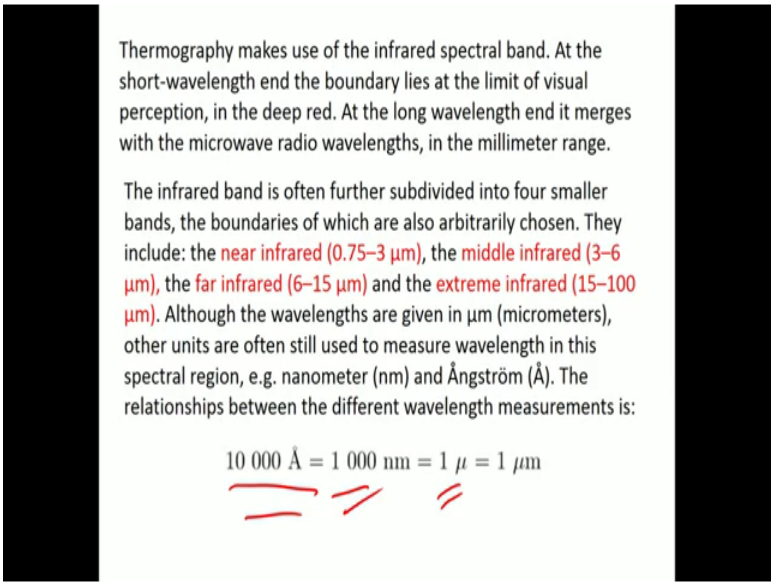


So, thermography makes use of the infrared spectral band ok. So, at short wavelength the boundary lies at the limit of visual perception and in the deep red. At long wavelength it merges with a microwave radio wavelengths, and it is in the millimeter range.

The infrared band is further subdivided into 4 smaller bands they are called near infrared which is 0.75 to 3 micron. This is some of the you know tunable diode laser based spectroscopes are carried out in this range 0.75 to about 3 micron, the middle infrared which is between 3 to 6 microns which is the middle band, far infrared 6 to 15 microns, and extreme infrared 15 to 100s of micron ok.

Although the wavelengths are given in microns the other units can be used it can be nanometers, it can be angstrom ok. The relationship is there 10000 angstrom is equal to 1000 nanometers equal to 1 microns, right this is the common conversion factor right. So, you should remember that there are 4 infrared bands near middle far extreme right progressively as you increase the wavelength. The infrared is by far is a very long spectrum before you go to the radio waves in the microwaves and things like that ok.

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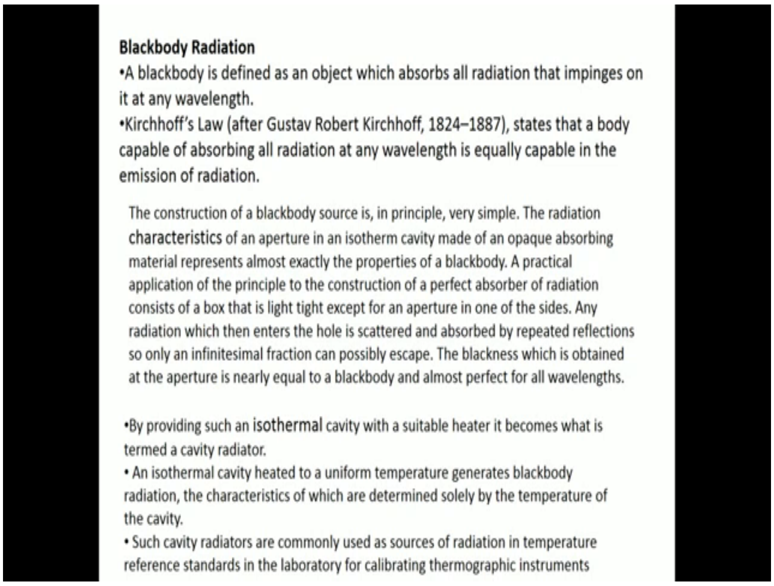


So, let us look at the simple problem of blackbody radiation. So, a blackbody is defined as an object which absorbs all radiation that impinges on it at all wavelengths right at any wavelength. There is a Kirchhoff's law which is basically Gustav Robert Kirchhoff states that a body capable of absorbing all radiation at any wavelength is equally capable in emission of radiation got it that was the Kirchhoff's law ok.

So, the construction why we are talking about the blackbody we will see in a little bit. The construction of a blackbody source is very simple, the radiation characteristics you know that you have an isothermal cavity right with a small aperture it is made of an opaque absorbing materials like the properties of a blackbody. So, normally we paint it with sooty color, a practical application will be the you know consists of a box that is light tight except there is an aperture on one of the site ok, and any radiation that enters the hole is scattered and absorbed by repeated reflections within the within that box ok.

So, the blackness which is obtained the aperture is nearly equal to that of a black body and it is almost perfect for all wavelengths. So, this is what is how you construct a black body. By providing such an isothermal cavity with a suitable heater it becomes what is called a cavity radiator alright.

An isothermal cavity when it is heated to a uniform temperature generates this blackbody radiation, the characteristics of which are determined solely by the temperature of the cavity. Such, such cavity radiators are commonly used as sources of radiation in temperature reference standards for calibrating thermographic equipments ok. So, you need a blackbody to basically calibrate.

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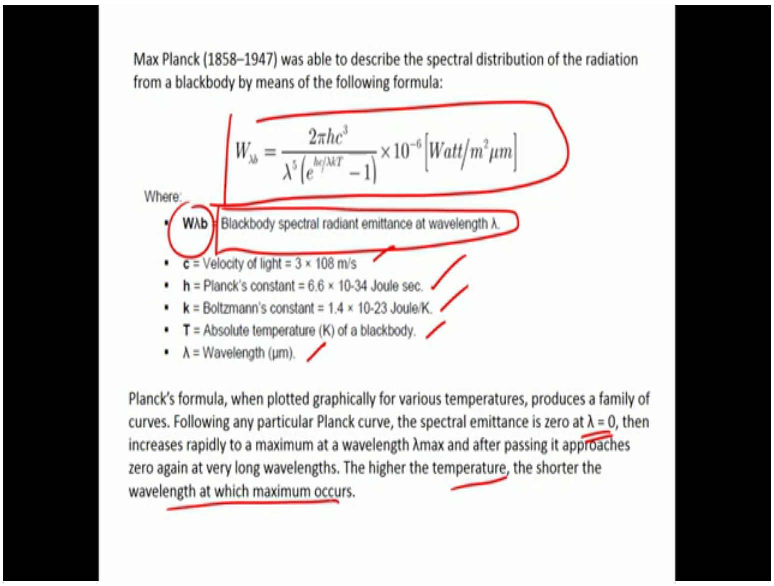


Now Max Planck we all know one of the 4 founding fathers of the quantum mechanics right was able to explain the spectral distribution of a blackbody radiation by means are the following formula ok. So, h was the Planck's constant, k was the Boltzmann constant, T was the absolute temperature, lambda is the lambda is the wavelength, c is the velocity of light, this is W alpha b or lambda b is the blackbody spectral radiant emittance at wavelength lambda ok.

You do not have to know a lot of radiation physics at this particular point, but you know that Planck was able to describe the spectral distribution of the radiation ok. So, when it is plotted graphically for various temperatures produces, a family of curves essentially that is what the Planck curve is right. So, the spectral emittance is 0, at lambda equal to 0.

Then it increases rapidly to a maximum which is called lambda max and after that it approaches 0 at very long wavelengths ok. Higher the temperature, shorter is a wavelength at which the maximum occurs. So, this is basically the blackbody spectral radiance emittance radiant emittance according to this Planck Planck's law.

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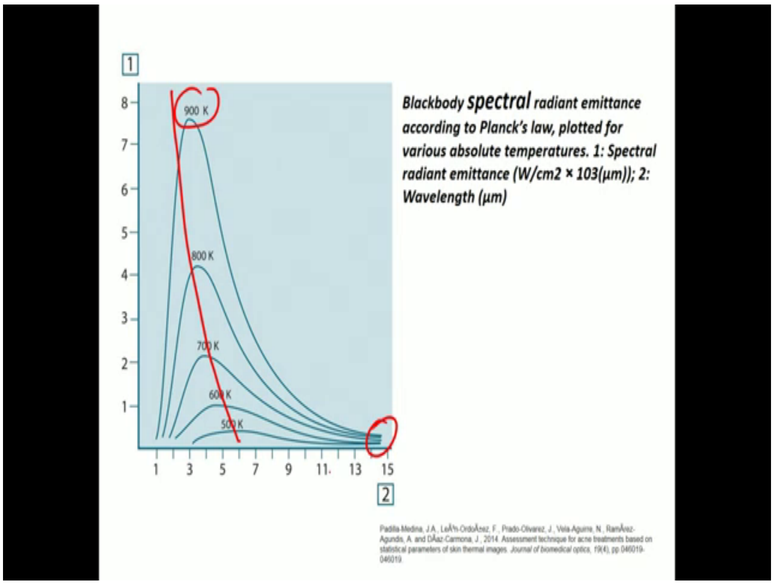


So, this is plotted for the spectral radiant emittance and the wavelength right. So, you can see that it is 0 then it peaks up and it peaks at a shorter wavelength as you increase the temperature. So, there is a shift like this right in the maximum and it again starts to become 0 at longer wavelengths got it ok. So, this is the blackbody spectral radiance pattern ok.

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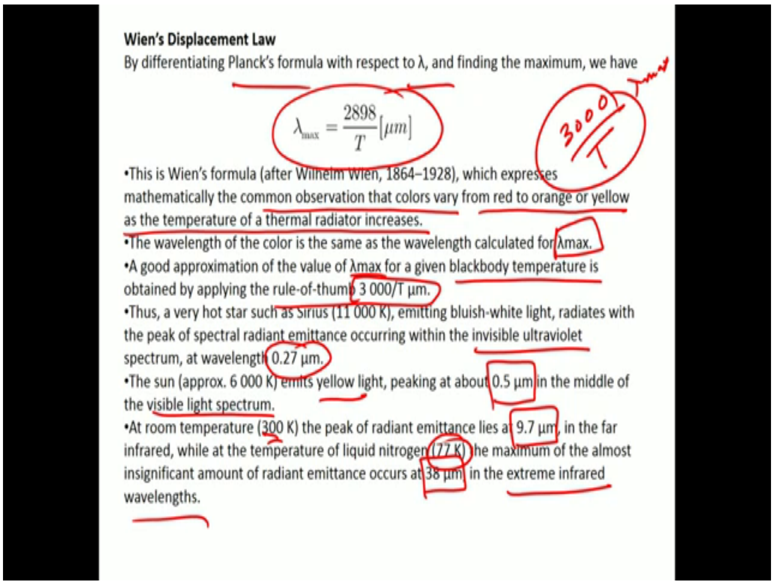


So, the Wien's displacement law was that by differentiating the Planck's formula with respect to lambda he was able to find out the maximum ok. So, this is Wien's formula which expresses mathematically the common observation, the colors vary from red to orange or yellow as a temperature of the thermal it increases. Because the lambda at which the peak happens actually changes.

The wavelength of the color is the same as a wavelength calculated for lambda max got it. So, the wavelength of the colour that it emit is the same as that right so good approximation of lambda max for a given black body temperature is applying the rule of thumb 3000 by T microns ok.

So, if you know the temperature so 3000 by T will actually give you whatever is a lambda max; that means, you would be able to see the colour whatever is the colour corresponding to that you should be able to see so that is a very hot stars such as Sirius which is 11000 Kelvin emits bluish white light ok, radiates with a peak spectral radiant emittance which occurs within the invisible ultraviolet at about 0.27 microns.

Sun however, which is about 6000 Kelvin emits yellow light, peaking around 0.5 micron in the middle of the visible light spectrum ok. The room temperature 300 Kelvin is the peak radiant emittance is about 9.7 microns ok. The room temperature that is the 300 where we are sitting right now is in the far infrared where as the temperature of liquid nitrogen which is at 77 Kelvin the maximum almost occurs at around 38 micron in the extreme infrared wavelengths.

So, these are some of the interesting stats right that whenever the temperature changes your peak wavelength changes and you can see that at room temperature it is 9.7 ok, nitrogen it is in the extreme infrared region where as sun is in the middle of the visible right, where as star like Sirius it is about 0.27 which is in the ultraviolet ok. So, these are some of the stats that we give ok.

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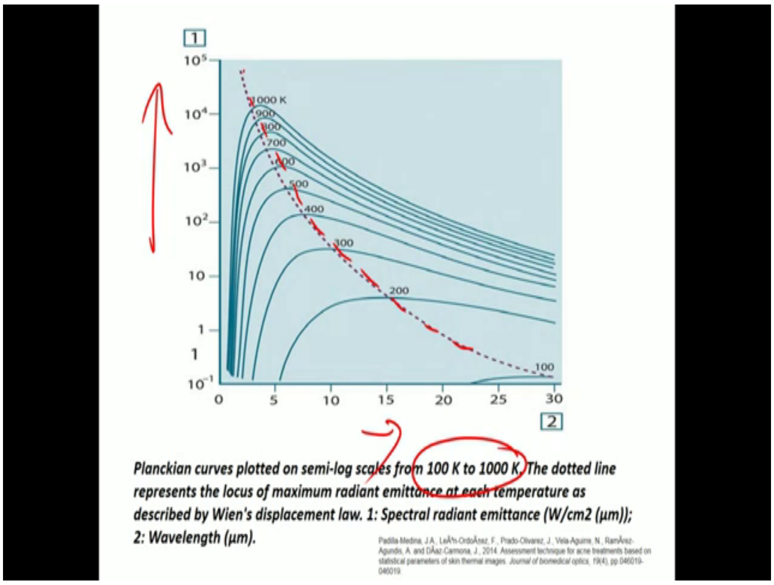


So, the Planck curves if you just plotted on a semi log scale from 100 to 1000 Kelvin the dotted line represents basically the locus right of the peak ok, described by the Wien's displacement law ok. So, this is once again the spectral radiant emittance and the wavelength that we have plotted over here ok. So, these are interesting things this is what we are going to use ok.

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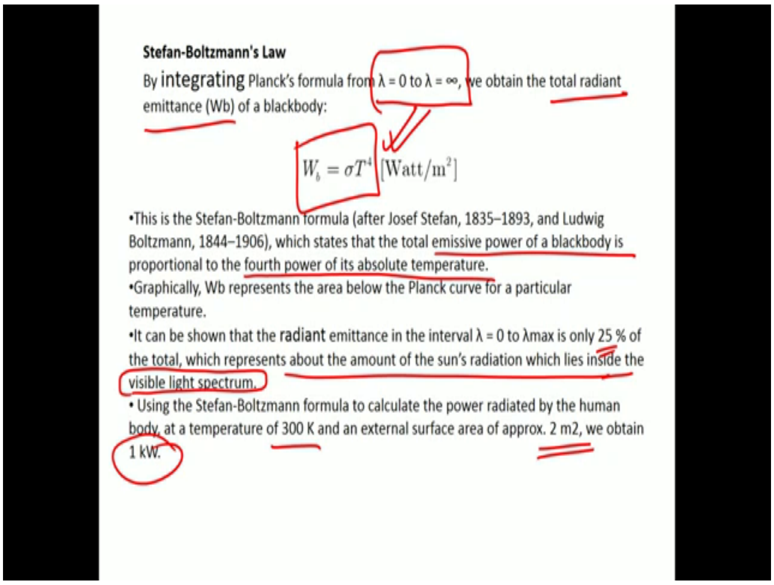


Then you have the Stefan Boltzmann law which you must have read in your radiation heat transfer that by integrating Planck's formula from 0 to infinity you obtain the total radiant emittance of a black body which is given by sigma T to the power of 4 where is where T to the power of 4 is the dependence. This is the Stefan Boltzmann formula which states that the total emissive power of a black body is proportional to the fourth power of its absolute power absolute temperature alright ok.

So, graphically it represents the total area under the Planck's curve because that is what you have indicated any take any of this plunks blackbody spectrum you have integrate it out the total area under the curve is basically what we are writing over here. It can be shown that the radiant emittance in the interval from 0 to lambda max is only 25 percent of the total which represents about the amount of suns radiation which lies in the visible light spectrum.

So, this is an also another interesting fact that from 0 to lambda max lambda max on peaks around the visible right. So, in that region you get only 25 percent there is a long tail of the distribution. So, sun emits a lot of radiation in the infrared and higher up ok. So, using Stefan Boltzmann formula to calculate the power radiated by a human body at 300 and external surface of approximately 2 meter square, we obtain it is about 1 kilowatt correct. So, these are some interesting facts, but this is an important thing that the total emissive power that is emitted by a black body ok.

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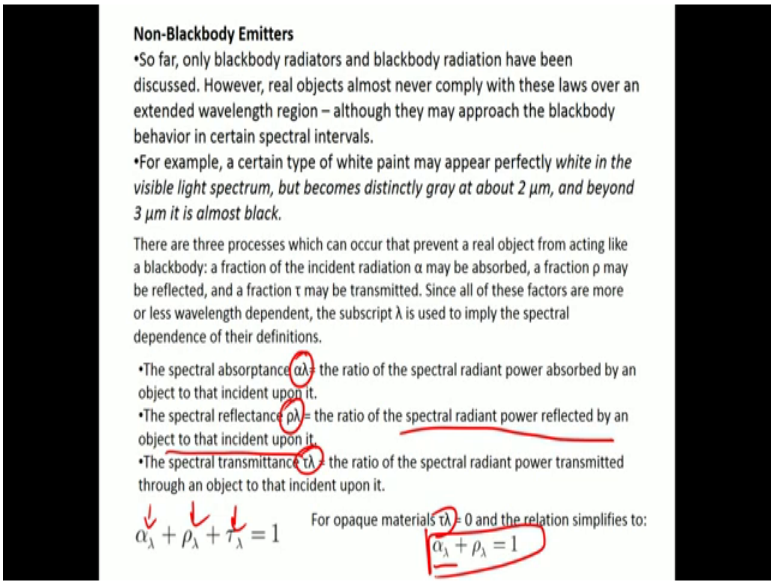


But however, we have non blackbody emitters mostly right so far only blackbody emitters and blackbody radiations have been discussed. However, your real objects never comply with these kind of laws, they might approach the blackbody behavior in certain intervals. For example, a certain type of white paint may appear perfectly white invisible white light, but become distinctly gray at 2 micron and beyond 3 micron it is almost black alright.

So, there are 3 processes which can occur that prevent a real object from acting as a blackbody ok. So, blackbody is very idealistic it does not happen it does not exist ok. So, a fraction of the light that is incident, incident radiation may be absorbed let us call that alpha, a fraction called rho maybe actually reflect it, and a fraction tau may be transmitted.

So, there are 3 mechanisms absorption, reflectance, reflection, and transmittance. Since all of these factors are more or less wavelength dependent the subscript lambda is used to imply the spectral dependence of their definitions. So, the spectral absorptance which is alpha into lambda the ratio of spectral radiant power absorbed by an object to that incident upon it the spectral reflectance is this rho into lambda. The ratio of the spectral radiant power reflected compared to the one that is incident upon it and the spectral emittance transmittance is basically whatever power is transmitted.

So, you know the coefficient of all these summation of all these things would be equal to one because it is a fraction it has to be because there is no other way the energy can go, for opaque materials your transmittance is basically 0. So, you basically have absorbance or reflectance the relation simplifies to something like this got it.

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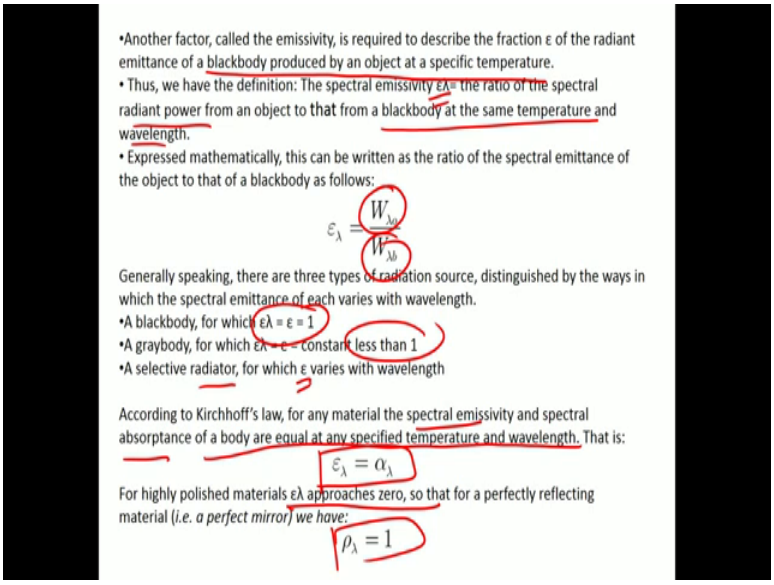


Now another factor which is called emissivity is required to describe the fraction of the radiant emittance; emittance of a blackbody produced by an object. So, we have the definition the spectral emissivity is a ratio of the spectral radiant power to that from a blackbody at the same temperature and wavelength ok. So, basically you are comparing the blackbody with the real body. So, expressed mathematically you are basically writing it as this divided by the blackbody.

So, generally speaking there are 3 types of radiation sources a blackbody whose emissivity is equal to 1, and gray body whose emissivity is less than 1, and a selective radiator where this emissivity varies with the wavelength there are all kinds right.

So, according to Kirchhoff's law for any material with spectral emissivity and spectral absorptance are equal at any specified temperature and wavelength. So, basically this emissivity and absorptions are basically the same at any particular wavelength alright. For highly polished surface this actually approaches 0, so, you have actually reflectance all the way it is like a mirror like a perfect mirror that if you if you if you think about a mirror that is exactly what it is ok.

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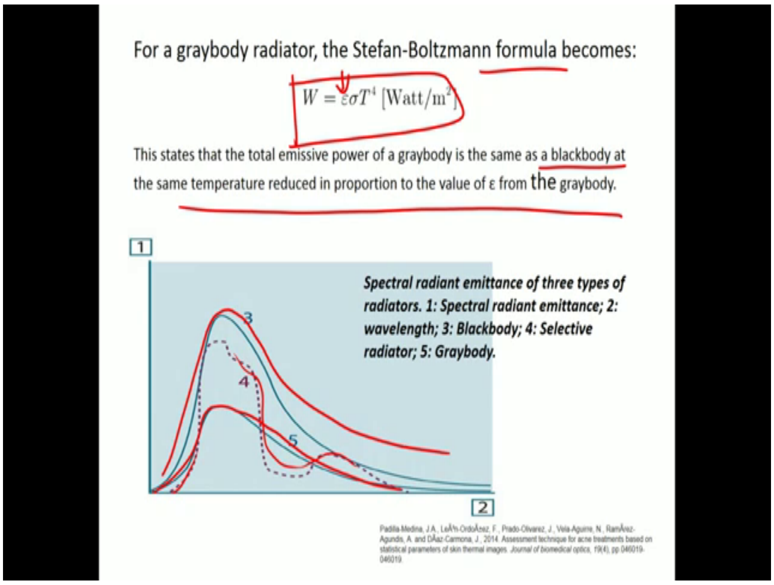


So for a gray emitter the Stefan Boltzmann formula now becomes something like this. So, you now have the emittition emissivity attached with it right. So, this states that the total emissive power of a gray body is the same as a blackbody at the same temperature reduced in proportion by that factor which is the emissivity which is epsilon right.

So, you can see that one is basically the spectral this; these are the 2 axis's ok, 2 is basically the wavelength ok, 3 is basically the blackbody. So, this is our blackbody ok, 4 is basically selective radiator. So, you can see that it varies with wavelength and then the gray body which is what we have done over here is basically a scaled down version of the blackbody every everywhere it is reduced by that particular factor with no selectivity with respect to wavelength.

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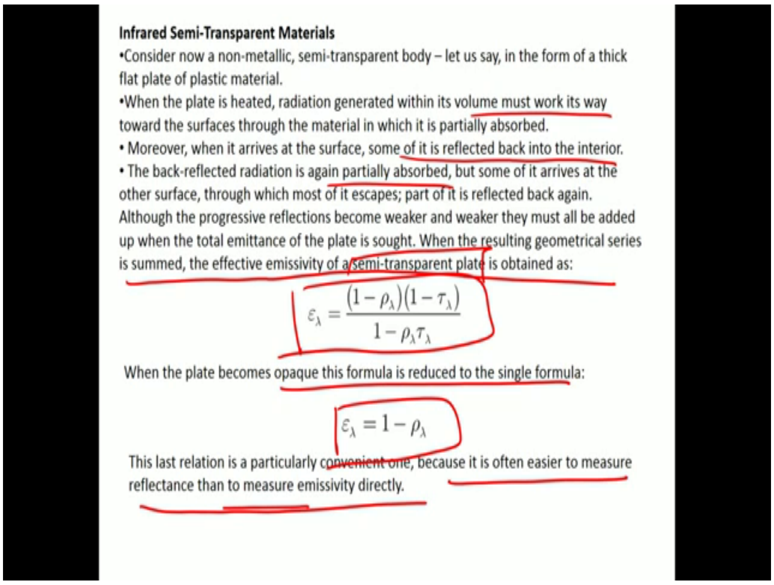


So, infrared semi transparent material now consider a nonmetallic semi transparent body let us say in the form of a thick flat plate of plastic material; when the plate is heated the radiation is generated within the volume moreover when it arrives at the surface some of it is reflected back ok.

So, what happens is that the back reflected radiation is once again partially absorbed some of it arrives at the other surface, some of it escapes. So, progressive reflections becomes weaker and weaker they must be added when the total emittance of the plate is sort right. So, when there when the resulting geometric series is sum the effective emissivity of a semi transparent plate is given by this particular form we are not going through the math, but you can if you want you can do it ok.

So, here the plate becomes opaque when this formula reduces to something like this right ok. So, the last relationship is particularly convenient because it is easier to measure reflectance than to measure emissivity directly ok. It is just a measurement wise, it is an easier way to do ok.

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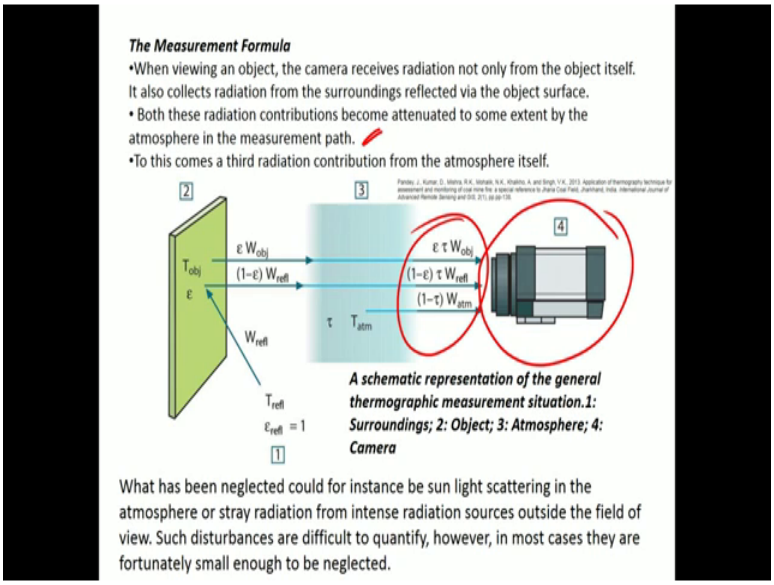


So, the measurement formula what IR cameras would normally use is that this is our camera, this is the camera which we would use to measure the temperature of any surface that is what IR camera have been used, this is what we have been doing on the droplet surface, this is what we have been doing on the film cooling holes.

So, when viewing an object the camera receives radiation not only from the object itself, but also from the surroundings reflected via the object surface right so it all contributions from all kinds. So, both this radiation contributions becomes attenuated to some extent by the atmosphere or by the measurement path right. So you can see all kinds of things that are happening there is reflection, there is emission, there is all kinds of things which actually reaches the camera right ok.

So, what has been neglected for instance could be the sunlight scattered or stray radiation from an intense radiation source outside the field of view such disturbances are difficult. So however, most cases they will be kind of small also, but if you are not sure in your case you have to do a controlled experiment that you have to do it in a controlled room environment where all these extraneous sun lights and other things are not there right.

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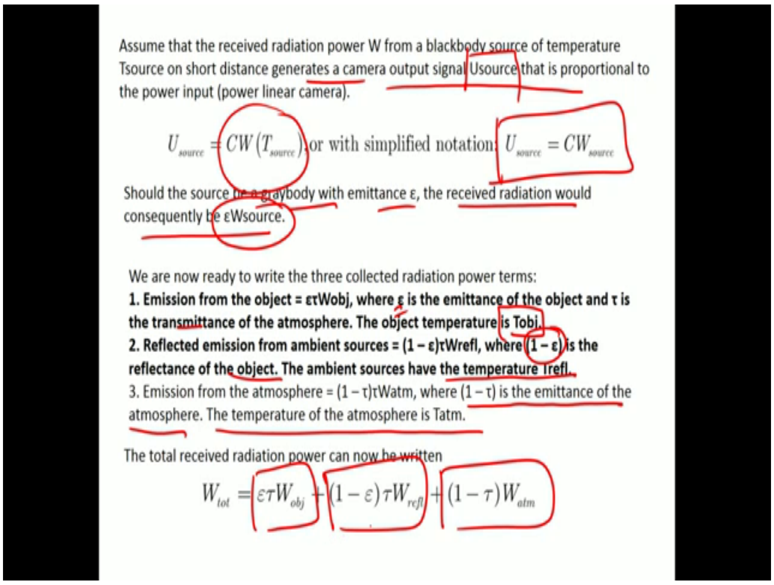


So, assume that the received radiation power W from a blackbody source of temperature of T source on a short distance generates a camera output which is U source that is proportional to the input power right. This is U source this is with respect to the input power should the source be a gray body with emittance the received radiation would consequently be epsilon into W source alright.

Now you are ready to write 3 collective collected radiation power terms emission from the body right which is epsilon tau W object, this is the emittance, this is the transmittance of the atmosphere right ok. The object temperature is T object ok. Now the reflected radiation from ambient sources is one minus epsilon tau W reflectance, where this part term is the reflectance of the object ok, the ambient sources have the temperature T reflect.

Now emission from the atmosphere which is 1 minus tau into tau W atm, Where 1 minus tau is the emittance of that atmosphere. The temperature of the atmosphere is T atm. So, the total radiation that is received is basically some of this object, some of this radiation, some of the atmosphere right. So, you have 3 terms basically the total radiation that is the total power that it receives is basically a sum total of all these quantities this is what the camera sees right.

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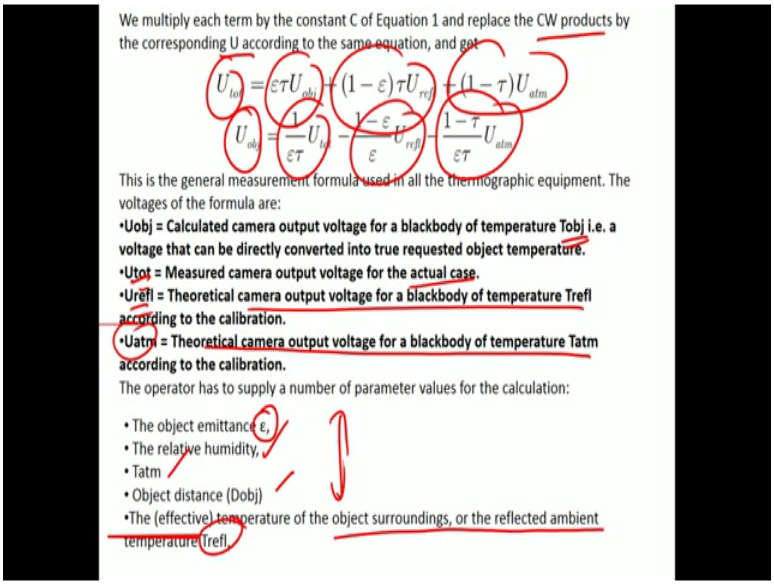


Now, we multiply each term by the constant and replace the CW products by the corresponding U, so your U total is somewhere like this right. So, the U object is something like this because you have to calculate the U object ok.

So, the new object is the camera calculated camera output voltage for a black body temperature of T object, T U total is basically for the actual case ok, U reflectance is the theoretical camera output for a blackbody of temperature T reflectance and U atmosphere is basically the theoretical camera output voltage for a blackbody of temperature T T atm according to the calibration.

Now the operator whoever is working on the camera has to supply the object emittance that is why in IR camera you will see this term specifically appearing you have to specify the relative humidity, you have to specify the temperature of the ambient, you have to describe the object distance sometimes that is pre done because you are focusing a camera ok.

The effective temperature of the object surroundings or the reflected surrounding temperature T reflectance, if you give all these terms we can calculate what will be the temperature ok. So, once that is done you once you are able to isolate what is the camera output voltage using these parameters.

Because you know you need to know the temperature few things most of these things are readily available to you. Because object emittance you can measure the beforehand the relative humidity is something that is already given the T atmosphere is something that is known in the environment that you are working, and the object distance is something that is also known.

So, the effective temperature and combining all these terms you can now come to a generalized expression in which you say that this will be my camera output voltage and how is it actually related to the corresponding T source right, T source or T object so that the that you should be able to now see you recalculate from this particular expressions ok.

So, we have covered a long distance from black body to gray body and how to calibrate how to do the exercise and then how to formulate the U source, and then ultimately it will give you our temperature. Other than that it is just an emission signature so you have to convert that to a temperature through this method.

So, IR cameras can be fast they can go up to about 300 FPS, it can be more in these days, they have a good spectral resolution, good spatial resolution as well and they are very handy because they just depend on these radiation signatures to calculate the whole thing ok.

So, here we have given you ideas about 2 systems TLC and IR thermography; obviously, these are bird eye bird eye views and there are lot of complications ok. It is not that simple, but this is just to give you an idea that how things can be measured ok, and how things are practically measured so that your computational models can be actually validated.

Thank you see you next class.