Thermal Physics
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Lecture - 56
Basic Concepts of Radiation

Hello and welcome back to the last week's lecture of this NPTEL course on thermal physics. Now up to previous week, we have been talking about classical thermodynamics, thermodynamic potential, thermodynamic processes, equilibrium. And also we have discussed phase transition, phase rule, all these things. This week we will be discussing something totally different.

We will be talking about radiation. Now what is radiation? What are the implications or what are the connections of radiation with thermodynamics, classical thermodynamics and how yeah and also what are the usefulness of different laws of radiation, we will see that during this segment.

Also towards the end, we will dedicate some time towards in the discussion of the third law of thermodynamics. Now let us start without any further delay.

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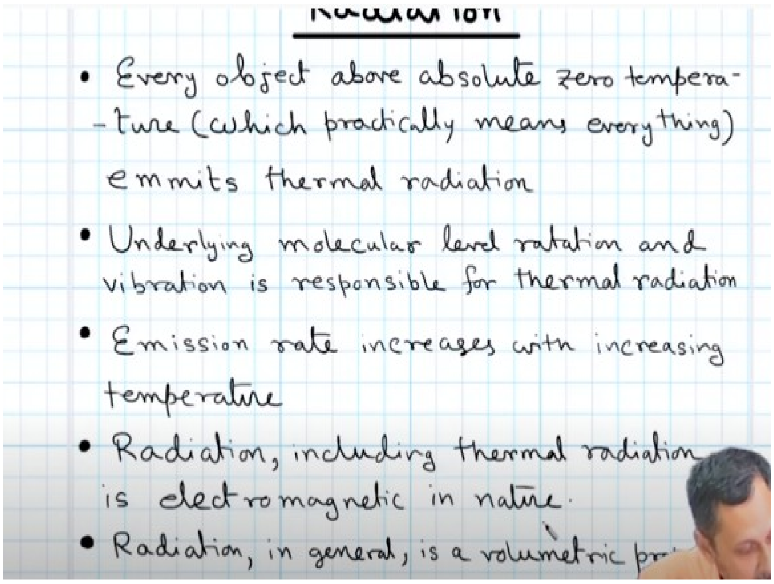

Now radiation means, that is every object above absolute zero temperature, that essentially means every object, because we will see, the one of the logical conclusion of third law of thermodynamics says that absolute zero cannot be reached by any finite number of processes. We will see, we will come to that towards the end of this week that means end of the course.

But when we say above absolute zero that essentially means, practically everything because nothing can be at absolute zero, emits something called thermal radiation. Now what is thermal radiation? Thermal radiation is certain amount of energy that get released from the surface of any object and the underlying, the source of this energy is underlying molecular level rotation and vibration.

For solids, we can realize that there should be only vibration, there is no rotation, underlying rotation. But for liquid and gas it could be vibration and rotation both. So the energy is emitted from the surface but the source of energy is inside the object itself. So it is there for the entire volume. This emission rate, what we talk about, what we are talking about the radiation rate that I would say it is a function of temperature actually.

We will see later on in a more formal manner that as the temperature increases, the rate of radiation also increases. There is a very famous law in the name of Stefan and Boltzmann called the Stefan-Boltzmann law that says this, that actually proves this phenomena. But even without that we can understand that if we are standing next to an hot object, we can feel some heat.

Like if we are standing next to a fire or if it is a very hot day and we are just outside on a you know maybe there is a courtyard where it is fully illuminated by direct sunlight, even if we are not inside into the sunlight, we can actually feel the heat coming and touching our skin. So that is what so that means typically temperature is we can actually feel the radiation by virtue of our senses, right.

So again, these are the laws, like every other branch of physics, radiation is also something that started off as an observational science, right. So there are certain properties that has been observed later on. So initially, it was only qualitative, later on it became quantitative and then it was formalized into mathematical laws, right. Right.

Now it was also proved later on that radiation including thermal radiation, I mean there could be thermal, I mean it could be non-thermal radiation as well. For example, this one, the radioactive radiation, X ray radiation. These are not exactly thermal radiation by nature. So we do not get gamma rays out of an object just by heating it. There has to be some sort of underlying radioactive process in order to get a gamma ray.

But all this radiation, let it be gamma ray, let it be X-ray, let it be IR, let it be microwave, these are thermal, I mean including thermal radiation, this is electromagnetic in nature. And radiation in general is a volumetric property. So that means, radiation is emitted from the, although we sense it from the surface only, radiation is there even inside the volume of an object.

And we will see later on that we in for a closed radiation I mean closed cavity radiation, we have to define the energy density per unit volume of radiation, okay. So let us take some example of radiation.

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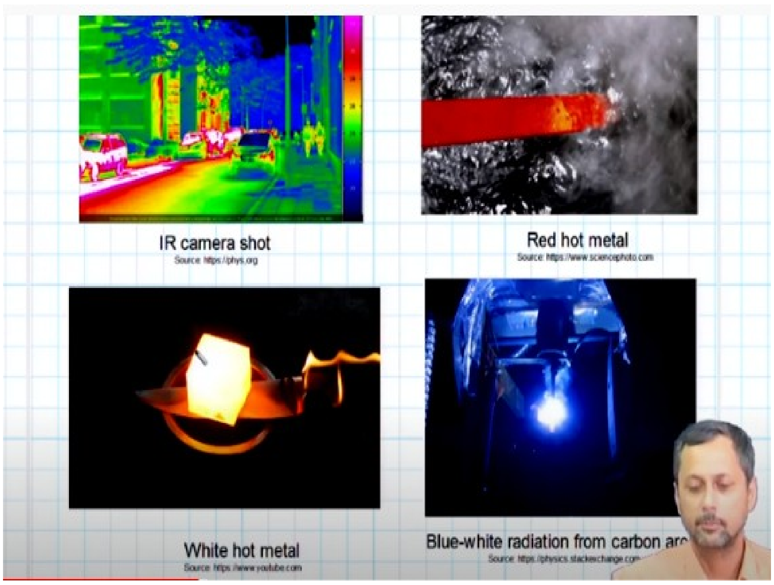

Every object is a possible source of thermal radiation. So if I just, if we just observe the IR, I mean shot, a normal shot, I mean it is a night vision actually. So street and some cars going, some people are moving, yeah. There is a lamppost here, there are buildings, trees, everything is there. It is a night shot why because you see the sky is dark. So there is hardly anything coming from the sky.

So that means it will tell you that it is a night shot, right. Now what do we have here? This is basically a thermal image, heat map. So actually it has been captured using a infrared camera. So even if we do not see things with our naked eye because, in the dark, because what we see these are actually reflected lights, it is not radiation as such.

When you look at me, what do you see or when you look at the screen okay, that is a different issue altogether, because the screen actually has some radian properties to it. But if you are talking to another person face to face, what you when you see that person what you see exactly is the light reflected from that person's face, person's body. But in that condition, there is no reflecting rays.

So our eye fail to see anything, but at the same time, as long as everything I mean every object as I have said mentioned already it radiates heat energy. Even in the dark an IR camera can sense the small I mean the heat radiation coming out of any object and this is exactly what we see through an IR camera, right? And here actually that can be converted to temperature.

So we see there is a temperature scale in degree centigrade is given to the right. The black is 18 degrees and the brightest one is the pink which is 32 degrees. We see this cars, the car tire which is hot actually. The road above which the car moves is hot. So that is why in this region we have very high temperature. There must be something up here. So that is why it is high temperature.

Tree is 20 degrees, buildings are 24 degrees like that. So these are typical IR thermal imaging captured by IR. Now this is something that we know exist and probably all of us have seen shots, pictures taken by IR camera. But for myself, I have never seen an IR camera myself. I mean, I have I do not know how it looks, I just know that it can capture thermal image.

But there are certain things that we have, we might have experienced. For example, if you have visited a blacksmith he is making something or a foundry some time in your life, you might have seen this type of red hot metal. This is a piece of steel, red hot steel, which is going inside water for certain processing. Anyway, so immaterial.

But what you see is a metal surface which is typically dark in color or maybe shiny but definitely not red, becomes red when it is hot. Not only that, a tungsten block can be white. I mean it is even hotter than the red one actually. So it becomes white almost. So this is called White hot condition. And this is a tungsten metal. Photo sources are given, so you can have a look.

So this is a steel, this is a tungsten. And to your right, bottom right what you see here is actually a blue white radiation from carbon arc. So this is the arc that has been created inside vacuum between two carbon electrodes, solid carbon electrodes and we see this radiation is blue white in nature. There is a definite bluish tint. Now that tells you that thermal radiation can have a very wide range of spectrum.

We can have IR, we can have red, we can have whitish yellow, which is somewhere in the middle of the visible spectrum. We can also have violet blue or violet which is towards the high end of the, low frequency limit of the visible spectrum.

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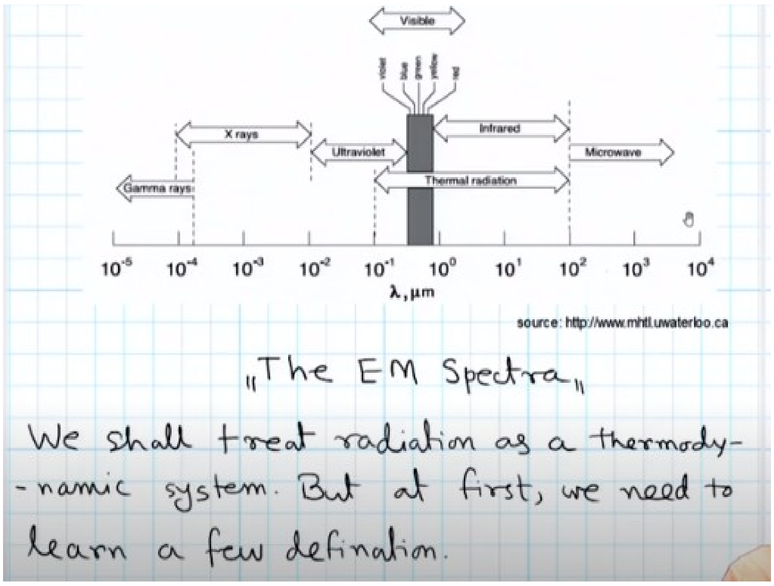

Now indeed this graph here actually shows you that thermal radiation is, I mean it can span from infrared to all the way into ultraviolet region. Now it does not mean that there cannot be thermal radiation in the microwave region okay, or there cannot be thermal radiation in the deep ultraviolet or you know higher x-ray region. It is also possible to have such radiation.

But typically these are very rare. Now in this chapter what we are going to do is we are going to treat thermal radiation as a thermodynamic system. But at first we need to learn few definitions before we can go there, okay. And also we will talk about little bit about the spectrum, the possible spectrum of a black body which covers entire the entire thermal radiation range.

There we will see that thermal radiation can have you know frequencies can be in the in this very small wavelength or sorry short wavelength and very long wavelength region as well, anyway.

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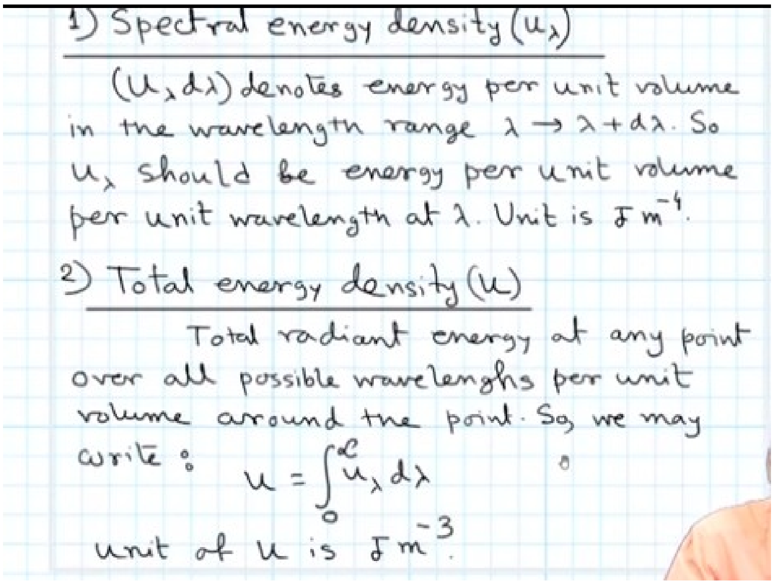

So let us move on. The first definition that we are going to learn is the spectral energy density. So that eventually is called u lambda. And u lambda d lambda denotes the energy per unit volume once again, because radiation is a volumetric property, per unit volume in the wavelength range lambda to lambda plus d lambda.

So u lambda should be energy per unit volume per unit wavelength at lambda, at the wavelength lambda with an units of joules per meter to the power -4. Why, because if u lambda has units of joules per meter to the power -4, then u lambda d lambda will be in the units of joules per meter cube. That means, energy per unit volume, right.

Similarly, the total energy density, which is total radiant energy at any point over all possible wavelengths per unit volume around that particular point. So we may write, you know we can correlate this two and we can write u is equal to integration 0 to infinity u lambda d lambda where the integration is over all possible values of the wavelength.

Now obviously the unit of u will be joules per meter cube, because you see lambda, sorry u lambda has an units of joules per meter to the power 4. We are multiplying this with lambda once again, so the units will be joules per meter cube, right.

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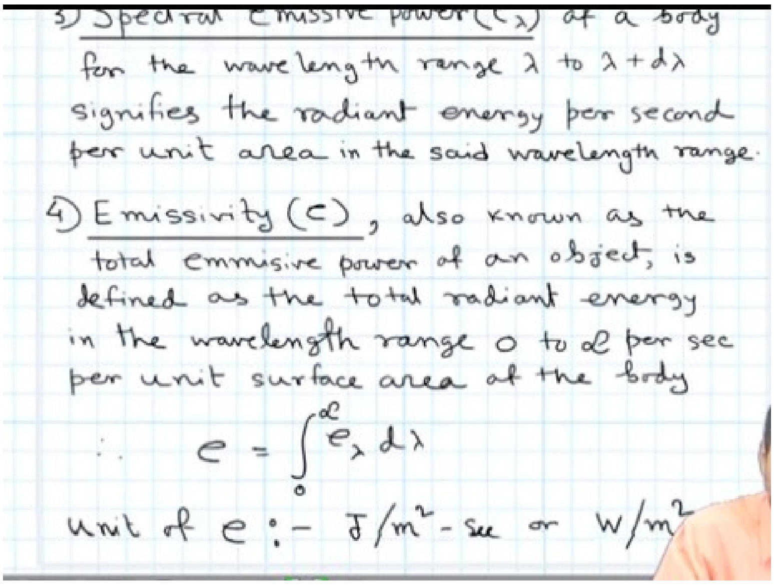

Spectral emissive power e lambda of a body for the wavelength range of lambda to lambda plus d lambda is defined as the radiant energy per second per unit area in the said wavelength range. So if the wavelength range in question is lambda to lambda plus d lambda e lambda is the amount of energy that is being radiated in this wavelength range per second per unit surface area, right.

Similarly emissivity, which is an integrated form of e lambda it gives you the total amount of radiation in I mean for all possible wavelengths and once again here the wavelength range I mean all possible wavelength of an object per unit area per unit time. So this will be e is equal to integration 0 to infinity e lambda d lambda where unit of e is joules per meter square per second.

So meter square because joules per energy, meter square because it is per unit surface area and second means it is per unit time. So we can write joules per second as watt. So we can simply write this as watts per meter square. Understand this that in both cases the integration limits as 0 to infinity here and here.

So that also tells us that although typically the thermal radiation falls inside this range, we can in principle have thermal radiation in this and this ranges as well. So this is your wavelength range of 0 and this is your wavelength I mean towards 0 and this is your wavelength towards infinity, okay.

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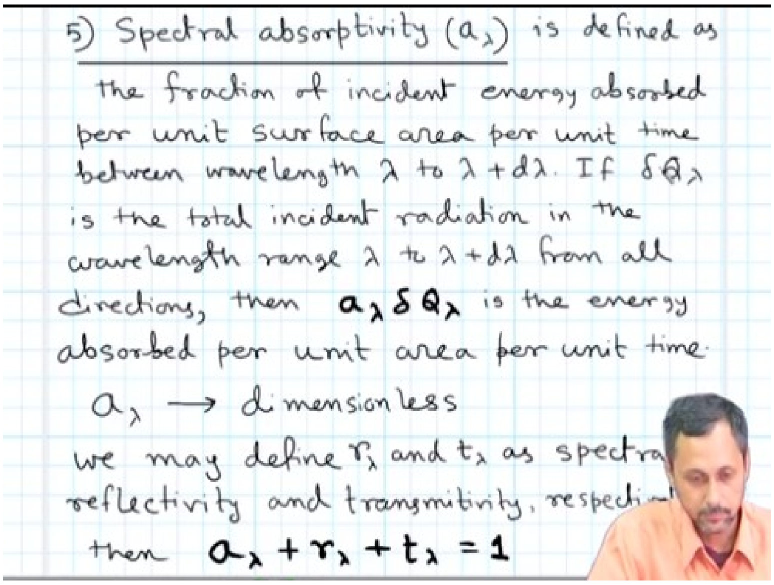

Next is spectral absorptivity a lambda, which is defined as the fraction of incident energy that has been absorbed per unit surface area per unit time between wavelength lambda to lambda plus d lambda. If d of Q lambda is the total incident radiation in the wavelength range lambda to lambda plus d lambda from all direction then a lambda delta Q lambda is the energy absorbed per unit area per unit time, okay.

So this definition is something that we are going to discuss once again when we will be proving Kirchhoff's law, okay. And a lambda is a dimensionless constant. I mean sorry, it is a dimensionless number and we may define r lambda and t lambda for the as the spectral reflectivity and spectral transmissivity respectively.

Then for any radiation that is falling on any object, part of it will be reflected, part of it will be sorry, part of it will be absorbed, part of it will be reflected, and rest has to be transmitted. That eventually means, a lambda plus r lambda plus t lambda has to be equal to 1. Because if total energy delta Q is absorbed by a surface, sorry falls on a surface, the total amount that will be reflected plus transmitted plus absorbed by the surface should be equal to delta u lambda, right.

Once again this quantity is the change with wavelength. So we are not mentioning it explicitly, but as soon as we have this lambda as the, as long as we have this lambda as the subscript we have to understand that this is a property of a particular wavelength only. And that is not only for this quantities, but this is true generally for any quantity that will be discussed in terms of in the aspect of radiation, right.

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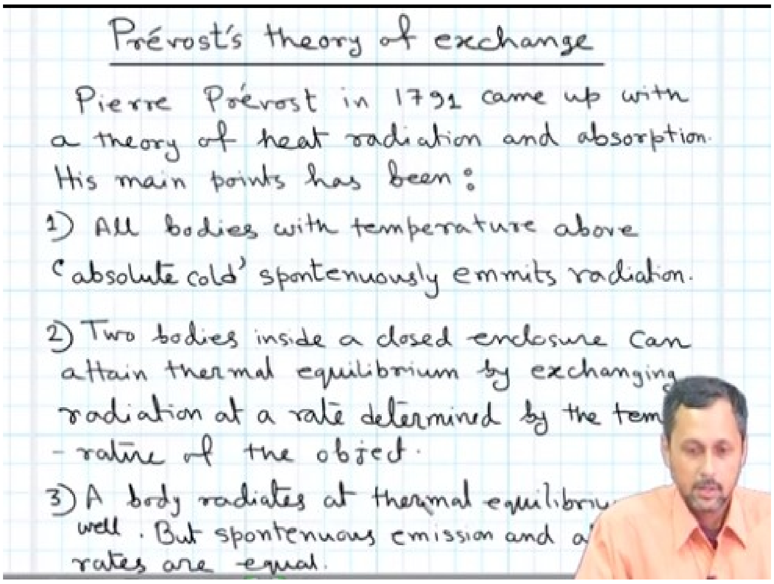

Now as I have said radiation like any other field has been observational field by itself, I mean observational field to begin with. So initial observation, people used to talk about heat radiation and cold radiation and so this is because if you are in front of, for example, inside a very cold room, you feel cold. So that means you as if the walls of this of that room is radiating cold radiation.

That used to be the thought. If you are in front of you know what you call a pile of ice that means you can feel the cold coming from that ice, okay. So it is like cold objects will radiate cold radiation and hot object, warm object will radiate hot radiation. So that used to be the concept. But around 1792 91 Prevost came up with his theory of exchange.

So what he said is all bodies with temperature above absolute cold, I am intentionally writing absolute cold because the term absolute zero was not defined at the year 1791. The term absolute zero was coined I think some 50 years after this around 1840 by, I think Lord Kelvin. But of course there was a concept that there exist an absolute cold, below which we cannot reach, okay.

The values were kind of predicted, but not exactly determined at that time. So what he said was all bodies with temperature above absolute cold, spontaneously emits radiation. And this is what I mean it was very counterintuitive at that time, because I mean sorry not very counterintuitive at that time.

But anyway he made this statement. So two bodies inside a closed enclosure can attain thermal equilibrium by exchanging radiation at a rate determined by the temperature of the object. So we have let us say, so the idea is we know that thermal equilibrium can be established by conduction and convection.

He said the thermal equilibrium can also be established by means of radiation alone if there is a closed chamber inside, let us say there are two objects which are placed side by side of two objects of different temperature. And if the place, the chamber is evacuated, even then if we give it long enough time, these two objects will reach a thermal equilibrium just by exchange of radiation between them, right.

A body radiates at thermal equilibrium as well. So even after a body reaches thermal equilibrium, let us say inside an enclosure, there are few objects and if we wait long enough according to Prevost's theory, they will reach thermal equilibrium. Now Prevost did not stop there. He continued saying that even after reaching thermal equilibrium, there will be still radiation.

But at the same time, it will also absorb radiation from the other sources, other possible sources. Each object or each part of the wall is inside a closed container is a possible source of radiation. Not possible, it is a definite source of radiation. So an object which will which is placed inside in a closed enclosure in thermal equilibrium will not only absorb radiation energy, sorry it not only emit radiation energy, but it will also absorb radiation energy at the same time.

But being at thermal equilibrium, the energy that has been absorbed and energy that has been emitted will be equal and will be equal to each other. So the net energy density or net energy of the body will not change with time. So these are the three very famous statement he made. And actually, this revolutionizes the field of radiation.

Prior to that, I mean people used to think of radiation in a very qualitative manner. But afterwards, after he came up with this statement, there has been numerous effort to quantify the concept of radiation, okay.

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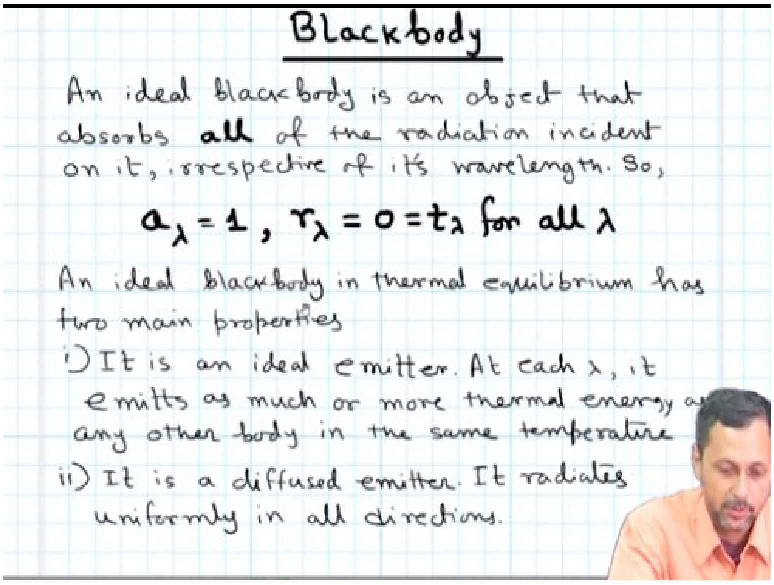

So let us go into another very important concept, which is called the black body. Now what is a black body? An ideal black body is an object that absorbs all the incident energy on it irrespective of its wavelength. So a lambda is equal to 1 and r lambda is equal to 0 is equal to t lambda for all lambda. So that means a black body, an ideal black body will absorb everything, will reflect and transmit nothing for all wavelengths lambda, okay.

So it is once again it is an idealized concept. But okay, I mean I am just giving you certain some more I mean some more concept about black body which can be proved in a systematic way if you if we go step by step. But it will just take a very long time to reach there. So and certain concepts nowadays, we are familiar with it even from our school physics.

So that is why I will just take I mean I will just point out the main findings or main properties of black body during the course of this lecture. And as and when required we will prove certain properties of associated with a black body. So an ideal black body also is a very good emitter. So and that can be proved. That is a direct consequence of the Kirchhoff's law actually.

So it is an ideal emitter and for each lambda, it emits as much or more thermal energy as any other body in the same temperature. So that means at a given temperature and given wavelength a black body is the best emitter among any all other possible objects. Similarly, okay so this is one concept that probably we will be proving, that will come out as a natural consequence of Kirchhoff's law, which we will be covering within this lecture itself.

And secondly, it is a diffused emitter. Diffused emitter means a black body radiates in all directions. So although we have just started saying that black body is a idealized, is an object which absorbs everything, we have made two statement regarding the emission of the black body. Because that is what is more interesting.

We will see later on that black body radiation, it is not only the field of, I mean it is not only the field of thermodynamics that benefited from black body radiation, but also the field of quantum mechanics has been immensely you know supported or I should not call it I mean probably or I would say the black body radiation played a key part in the development of old quantum theory, right.

So we talk about black body as an ideal emitter, but mathematically speaking, a black body is defined by this simple relation. Now it is just a natural consequence, thermodynamic consequence that if something is a very good absorber, if it has a lambda is equal to 1, it will be a very good emitter as well as we will see later.

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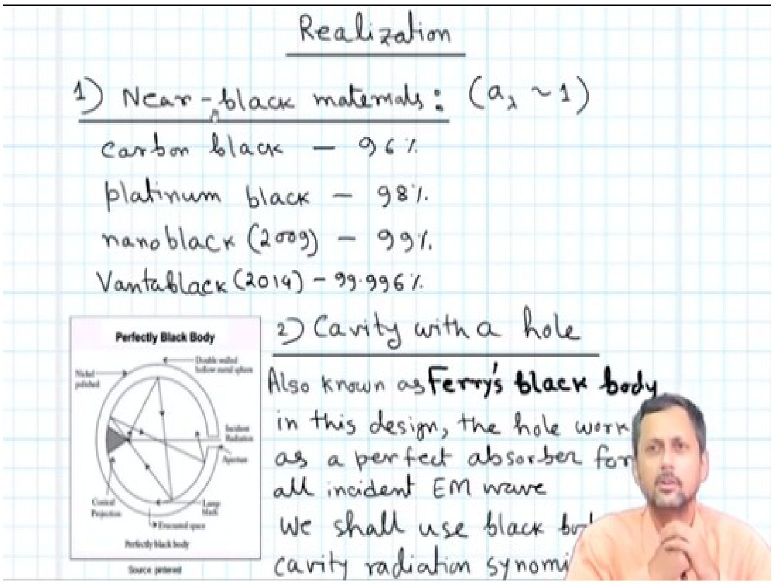

Now how to realize a black body? A black body is an idealized concept because no object can have 100% absorbance or you know absorbance cannot be equal to 1 at any given wavelength. Now there has been search for material which has very high absorption power. For example, I mean very familiar material to us which is carbon black. Now what is carbon black?

Carbon black is when we have a candle light burning. Sometimes we see our mom our mother will complain that our gas stove is not working properly and all the utensils is becoming you know black underneath. So this is nothing but so there must be some sort of a blockage in the passage of you know passage of the gas and due to some incomplete burning lot of carbon deposits are being processed, so is generated.

And those carbons it deposits are nothing but carbon black. So there are I think there are certain local names for it, I am not familiar to those. But we call it carbon black and this is precisely what we get if we just take a, you know piece of metal and place it on a candle flame. So if we keep there for some time, a spoon let us say for some time, one minute or so we will see there is a black coating.

So that black coating is nothing but carbon black. Now carbon black has a absorptivity a lambda is equal to 96% and that is across wavelength. And that eventually means the carbon black is also a good emitter. Okay, I will come to that later on. Platinum black, similarly similar to carbon black, they can be processed platinum powder called platinum black which is 98%, I mean it absorbs 98% of radiation of all wavelength that falls on it.

Nano black, which was developed in 2009 by a group of Japanese scientists, it has 99% nearly 99% absorbance. And there is a material called Vantablack, which is actually I think, patented product of a company from Surrey, UK which has an absorption power of 99.996% as has been measured, right. So you can actually search for this and there are many interesting pictures and videos available from their official website that this material actually looks really, it can do wonders, anyway.

But this is these are modern. You see this nano black and Vantablack, these are pretty modern in that way. So in the early days, and I am talking about black body I mean theories, which has been developed over like 200 years back or maybe at least 100 years back. So on those days, there are different devices that acted as ideal black body. One such device is Ferry's black body which is basically a hollow sphere, okay.

And there is a double walled sphere, outer world is, outer wall sorry. There is a vacuum that is maintained inside this wall. And there is a small tiny opening. Just opposite to this opening there is a sharp feature on the wall. And what is the role of this sharp feature? Any incident radiation that comes in cannot be reflected back directly.

So instead it will fall on this angle and it will randomly getting reflected inside this inside the cavity. Now the inner side of the cavity is coated either with this carbon black which is lamp black carbon black is essentially the same thing or platinum black which will keep absorbing you know high percentage of light after every on every reflection.

And eventually after few 5, 6, 7, 8 reflections almost everything 99.99% is absorbed. So nothing is coming out of it. And the outer wall is nickel polished so that the radiation loss is minimal because, if something is very good reflected that means it is not absorbing anything and we will see later on if something is not absorbing it will not also not emit that much, okay.

So that is Kirchhoff's law by the way. Now this one acts as a black body. But please remember only the opening of this is it behaves like an ideal black body, this tiny opening, if a radiation falls on this surface, nothing happens, it will just be reflecting out, okay. So this tiny opening is your black body, this entire thing is the cavity inside which helps to create this ideal black body, I mean create this black body, okay.

And if the whole system is warmed now, it is put inside a furnace, this tiny hole itself it will radiate energy which will be which can be called the black body radiation, okay.

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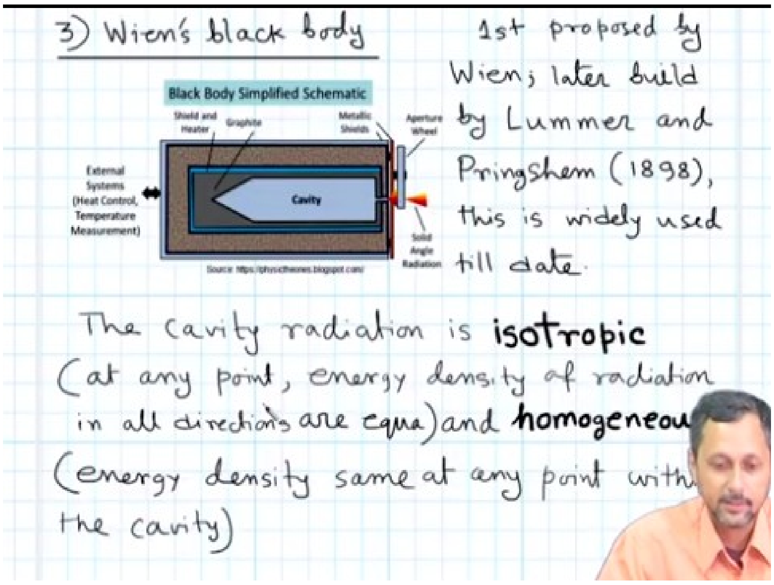

So there is another type of construction that is called the Wien's black body. It was first proposed by Wien and later built by Lummer and Pringsheim in 1898. So this is a slightly different construction, where we have a cavity, a platinum cavity and this is actually a metallic shield outside. There is a heater outside through which we can actually control the amount of heat that is being generated.

Now this heat it will be absorbed by this, by the sidewalls and a tiny amount can be taken out by adjusting this slit over here, this aperture here. So if we open this aperture a tiny amount might or might be coming out. So this is also another type of instrument that has been used for as a black body in a laboratory.

The cavity radiation and now for the rest of this discussion we will be using black body and cavity radiation, these two words synonymously, okay. So this cavity radiation is isotropic. That means, at any point the energy density of radiation in all directions are equal. So it should be l here, equal and homogeneous as the energy density is the same at any point within the cavity.

So what I mean to say is if I choose any arbitrary point here or here or here and the energy density at this points will be equal. Similarly, if I take any point, place a surface at that point at any possible direction, the total energy that is that will be incident on this surface will be equal. So these are the two properties which are called isotropic and homogeneous, okay.

So we will be we will stop here for today's lecture. Next lecture we will be talking about something called the Kirchhoff's law and other properties of this black body radiation. Till then thank you.