Convective Heat Transfer
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Lecture – 56
Experimental techniques – Thermochromic liquid crystals

So, in this particular lecture we are going to take a small deviation and we have covered a lot of theory; we have done a lot of theoretical work lot of analysis using scaling arguments, using integral methods, also we have talked a little bit about that how you can solve certain things wholly numerically. But, at the same time as students one might get the feel that we hear a lot about this wall heat flux, wall temperature based on those parameters you calculate the Nusselt number and things like that, then how do you actually in real life measure some of these events, because the theoretical analysis that we have shown are mostly for canonical problems; that means, problems which are very simple in nature.

Now, real life as we when we started convection heat transfer we actually said that the real life is very complicated; that means, you get complicated situations like cavities, then gas turbine, blades, we considered many applications from small scale to very large scale and we saw that analysis becomes progressively ok, more and more on errors, when we actually deal with problems like that.

So, our idea over here now is basically to come up you know to give you guys a flavor that how do you actually measure this wall heat flux, how do you actually measure the flow ok, how do you actually measure the convective heat transfer coefficient right or the in other words the Nusselt number. So, there must be some measurements because all these numerical exercises that you do, need to have an experimental validation, right.

So, unless you have an experimental validation your numerical work does not make much of a sense, especially in complicated situations where no analytical solutions may exist, right. So, based on this here in this particular section of our lecture, we are basically going to cover you know a couple of techniques, basically one will be the thermo chromic liquid crystal base based techniques to measure heat transfer, the other one will be using IR thermography, that means, infrared thermography, ok.

So, there are lots of other techniques as well. You can use laser induced fluorescence also for example, to measure the temperature field, ok. It is possible to do that you can use the garden variety thermocouples also because in many applications you do need thermocouples like for example, when you want to measure the temperature you use thermocouples, but thermocouple do you guys already know.

So, there is not much to talk about thermocouple, that how a thermocouple responds and thermocouples mostly are point measurement techniques; that means, it will give you the temperature at a particular point in the field, they are not field measurement; that means, you do not get to see the temperature field across the whole domain, you get to see the temperature at a particular point in a particular domain, so, that is thermocouple.

And what thermocouple is extremely useful ok, but with time people have thought that why not go to some more sophisticated techniques which gives you more idea of the of the field like for example, you want to watch a movie, right. So, it is like in a movie that you want to see everything you just do not want to see a point right what is happening at a point, because that may not be the unique descriptor, you want the full spatial information how the temperature field is spatially varying, and things like that. So, thermocouple is we are not going to cover about that you can find out in any of your UG courses that you may have taken that what is a thermocouple.

The ancient form of measurement will be the thermo meter like for example, when you want to measure your fever how do you do it, you just insert a thermo meter under your armpit or under your tongue and you see that what is the temperature right. But that is a crude measurement technique because it is an equilibrium measurement it takes a lot of time to it to steady it out. So, essentially you do not get any fluctuations or anything like that,, but that is a very useful thing that you use at home. In home you do not use an IR thermography or any other sophisticated techniques, because it is not required, right.

So, the idea of any measurement technique is that, what is your requirement ok. Like for example, when you want to measure the body temperature, thermometer is an excellent choice you do not need anything else right, but when you try to measure for example, the temperature profile over a gas turbine blade, thermometer is not going to do because you are going to have a lot of fluctuations in the temperature field, near and on the blade. So, therefore, there the thermometer is not a useful instrument because it is response time is extremely large, ok. So, you are going to basically erase away all the fluctuations and you are going to get some kind of a you know misleading kind of a value ok.

So, we are going to take two interesting measurement techniques about which you may not have heard so far. So, first one of them if you look at it here is going to be the thermochromic liquid crystals applied to heat transfer that is the first technique that we are going to discuss. This is just going to give you a bird's eye view because it is not meant for an experimental engineering course.

But, this is just to give you an idea so that you can kind of correlate that all this t, q prime and all these things that we have heard so far, in the course that has got some meaning attached with it right there is some meaning attached with it. This is how you can actually physically measure the quantities right that is the most important part.

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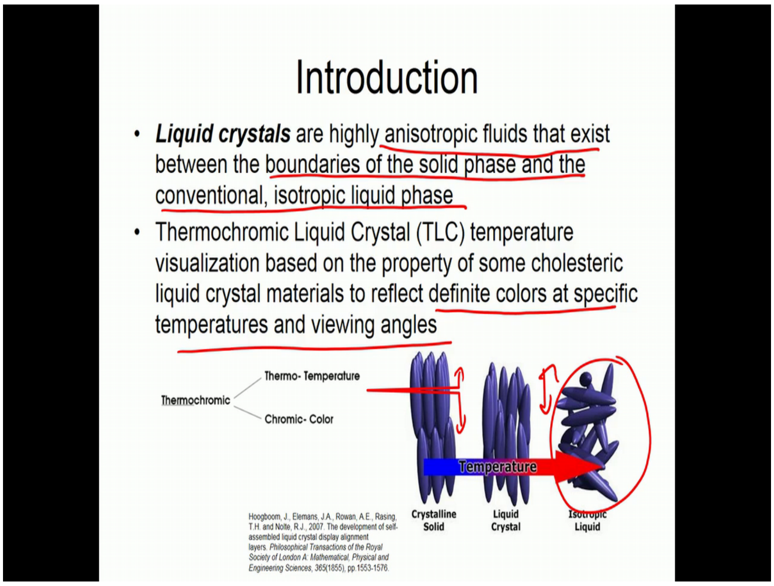

So, if you look at the slides now, you will find that what are liquid crystals? Now, liquid crystals is something that you already know, right. Liquid crystals you see it for example, in LCD TV's are usually made out of liquid crystals, right. So, liquid crystals are basically highly anisotropic fluids that exist between the boundaries of the solid phase and conventional isotropic liquid phase. It is neither solid nor liquid it resides somewhere in that boundary, right.

Thermochromic Liquid Crystal, visualization actually depends on some of the interesting properties which is called cholesteric properties of the liquid crystal, to reflect definite colors at specific temperatures and viewing angles, this is the most important part, right. How does this technique actually work ok? If you look at this particular example over here you will see this is a crystalline solid well arranged right this is a liquid crystal and as you go on increasing the temperature this is an isotropic liquid, ok.

So, there is some order in the case of a liquid crystal to begin with; and based on their structure they can actually reflect or reflect light at certain definite colors and at certain temperatures, ok. So, that property can be now used to perform certain meaningful tasks.

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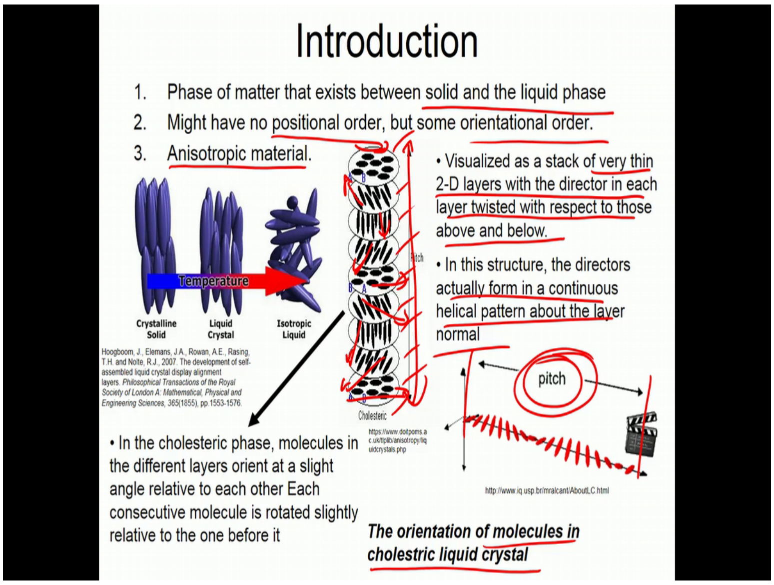

So, let us see, ok. This is part of the introduction. So, you can see the phase of the matter that exists between solid and liquid phase, it may not have any positional order, but some orientational order ok. So, there is some orientation, basic orientation that you will have is an anisotropic material ok. So, in the cholesteric phase the molecules in different layers.

So, these are the different layers if you look at it, right you see that these are different planes basically. They orient at slightly slight angle with respect to each other. The first layer has got a very different orientation from the second layer; the third layer has got in turn a different orientation than the fourth layer and so on and so forth, ok. So, there is a gradual change in the orientation of the arrangement as you go from layer to layer all right all right. So, in each constitutive layer the molecules are oriented slightly off with respect to each other, ok.

So, this is visualized as a stack of very thin 2-D layers with the director in each layer twisted with respect to the one that is above and below, right. So, this is like a stack, it is like a stack, it is like a 2-D stack of many layers right where each of the layer, the first layer is slightly twisted with respect to the one at the top another at the bottom, right. So, that is the most important part if you look at it ok. So, in this structure the directors actually form a continuous helical pattern which is called the pitch. So, if you take the director; that means, all these layers are at an angle right, this is this may be the angle for this, this may be the angle for this, this may be the angle for this, right this may be the angle for this, this is the angle for this, this is the angle, this is the angle, this is the angle, right.

So, if you plot kind of the directors, that means, the direction in which they are actually oriented if you plot them you will find that there is a repetitive pattern that actually emerges, and they are arranged in a helical pattern, ok. So, this particular repetition cycle is what we call the pitch, the directors actually form a continuous helical pattern about the layer normal ok.

So, the orientation of molecules in cholesteric liquid crystal is given like this. This is the pitch, ok, this is the pitch, this is what is called the pitch from here to here. This is the pitch right after that it returns back to it is original configuration, ok. So, understand it is like a slight twisting that happens and then again it goes back to it is original configuration, ok.

So, it has got a pitch because of mainly the ordering that it has at each of the individual layers, ok.

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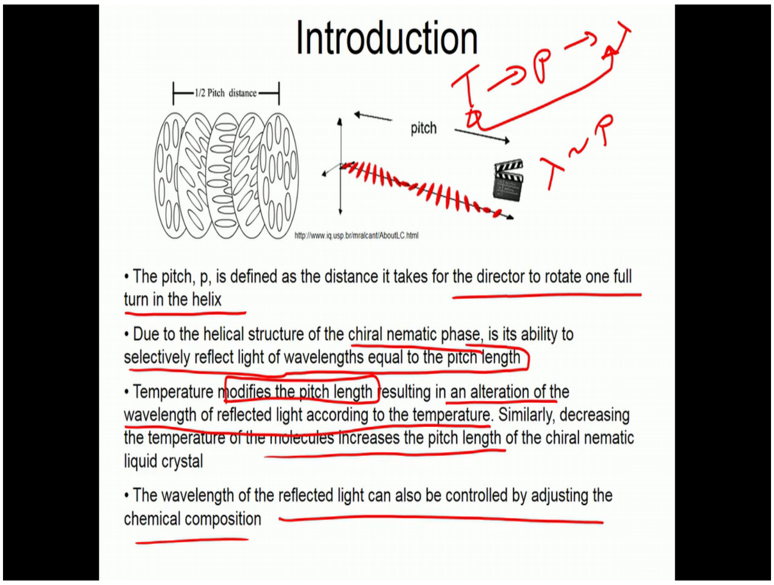

Ok. Now, the pitch p is defined as the distance it takes for the director to rotate one full turn in an helix as it turns. So, it just takes the time for it to complete one full cycle in a spatial sense,. Now, due to the helical structure of the chiral nematic phase, is it is ability to selectively reflect light of wavelengths equal to the pitch length. So, whatever is a pitch length right this kind of crystals can actually reflect selectively reflect light, whose wavelength are equal to the pitch length, right. So, this 2-D layers right they as we said that they have a pitch. So, there is a helical pattern, right. So, that helicity actually repeats. So, once it takes one full rotation or one full turn in that helix after that it starts to repeat itself, right ok.

Now, that smallest block that one full rotation, that distance is called the pitch, right. Once we know what is the pitch of that particular system right it is the abilit it can actually reflect light of that particular pitch wavelength equal to that particular pitch, basically lambda is equal to that pitch all right. It can actually emit light reflect light of that particular wavelength, ok. Now, what happens is that when we change the temperature in such crystals right the pitch length changes right. As we change the temperature the pitch length actually changes, resulting in an alteration of the wavelength of the selected light accord reflected light according to the temperature, ok.

So, decreasing the temperature increases the pitch length whereas, increasing the temperature decreases the pitch length. So, that is the two things that actually happens, right. So, as you in decrease the temperature the pitch length actually increases; that means, the light that it reflects actually now has got a larger wavelength or a longer wavelength, and the pitch also changes when we actually increase the temperature. So, it goes the other way. So, it decreases.

So, the wavelength of the reflected light can be also adjusted by changing the chemical composition of this liquid crystals. So, you understand the basic thing, these liquid crystals has got some arrangement some order right these orders comes they are arranged in some kind of a helical pattern of course, the pitch is very small, ok. So, depending on this pitch depending on this orientation, ok, it is able to selectively reflect light of a certain wavelength, right. Because it is able to reflect light of a certain wavelength if you change the pitch you change the wavelength of the reflected light, right, it is a simple thing. So, that means, with temperature if the pitch changes then the wavelength of the reflected light will also change, right.

So, temperature leads to a change in the pitch leads to a change in the wavelength of the reflected light right. So, there is a connection between temperature and the wavelength of light that is reflected, right. So, this is what can be can be controlled also by using chemical composition.

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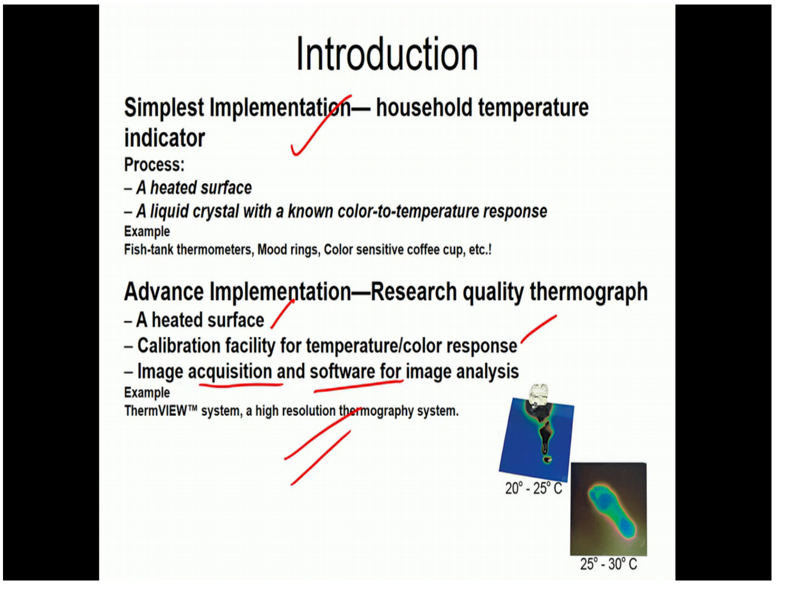

So, the simplest implementation of this ok, if you have seen and this is quite common in foreign countries, that you have this, what we call this mood rings, right. So, mood rings are basically rings that you wear in your finger. So, basically why it is called mood ring because if you are angry your body temperature changes the colour of this mood ring also changes. Similarly, if you are very depressed your body temperature changes therefore, the colour of your mood ring also changes, ok.

So, depending on your mental state if that leads to a change in your temperature in the body temperature this mood rings actually have this thermochromic liquid crystals. So, they are actually pitch changes they are colour changes as a result. By looking at your mood ring right people can make out that whether you are happy or you are sad or whatever, right.

Similar things you have in colour sensitive coffee cups, right. If you see in certain coffee cups you will see when it is hot it is red and as the temperature comes down, you will see a gradation in the colour, right. So, these kind of coffee cups also demarcates that when you are trying to pick up a coffee you know that it is red; that means, it is hot, ok. Similarly, when you are picking up something else, I mean when it is cooled down the colour will change to something else. So, just by looking at the colour you can kind of see that which one is hot which one is cold, right.

So, that is an interesting thing,. So, it is also used on heated surface, sometimes you know sometimes the doctors also use this thermochromic liquid crystals on your forehead to check the temperature. As it comes on to your forehead that it changes the colour. So, if you calibrate it well enough you would be able to make out that what will be the body temperature of yours, ok.

So, however, these are the simplest implementation which does not require much of an effort advanced implementation which is that it is research quality thermograph; that means, whichever you are going to use to you know calculate the temperature right as as in the case of your Nusselt number, you need a heated surface, you need a calibration because the colour and the temperature calibration has to be done, right. Because you know the colour that is coming out and you know the temperature. So, a priori you need to have a calibration done, and you of course, need image accusation and other softwares and you need high resolution thermography images basically to visualize and make out that what these colors are actually telling you, ok.

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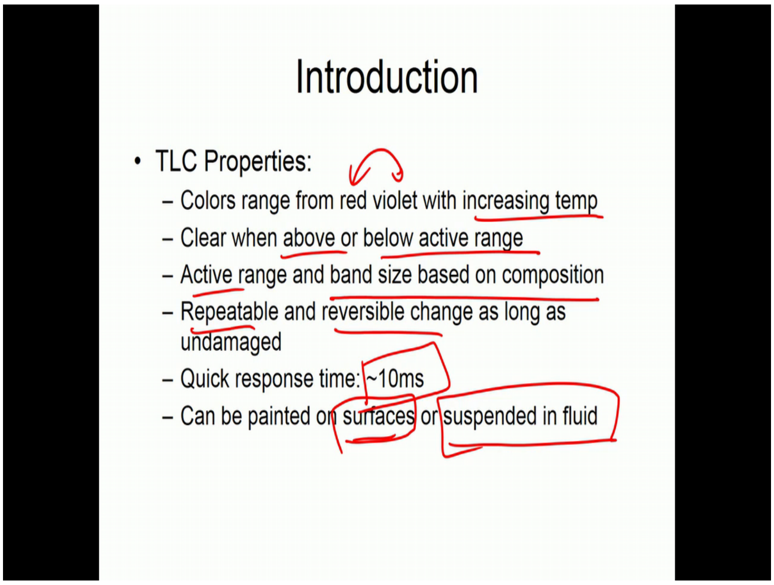

So, the TLC's the colour changes from red to violet with increasing temperature, some of the properties clear when it is above and below a certain active range. So, these TLC's has got active ranges. So, if your temperature is too high it will blank out, if your temperature is too low it will blank out.

So, only over a certain range that range could be 20 degree Celsius, range could be 30, could be 40 that is where it changes it is colour from red to violet with increasing temperature, ok. There is an active range and band range depending on the composition, ok. It is repeatable and reversible as long as it is undamaged; that means, once you take the temperature out the colour will return back to its normal, ok. So, you can again use it again and again. So, it is not a onetime, use and throw kind of thing.

It has got a quick response time of the order of 10 milliseconds, which makes it a very attractive proposition for certain experiments, not for all because 10 milliseconds still is a very high time if you are dealing with very turbulent flows and things like that, but for many applications 10 milliseconds can actually be a good thing to do. Can be painted on surfaces or suspended in fluid also; this is a very interesting point can be painted on surfaces means this will enable you to gauge the surface temperature, which is paramount importance when you are trying to find out your Nusselt number. You need to know your wall temperature, right. It can be also seeded in the flow; that means, you just seed it into the flow field and it will light up and show you the temperature of the flow field ok. So, you can actually do that also. So, there are both ways by which you can actually get this done.

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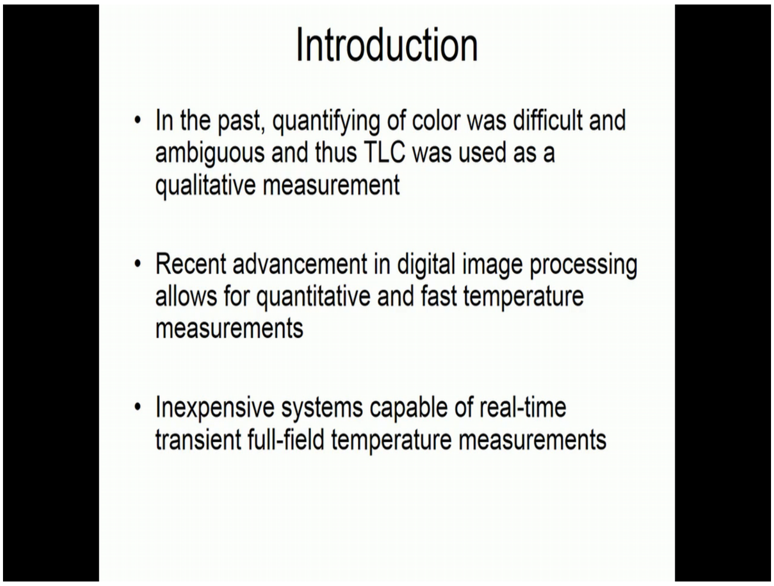

In the past, ok, quantifying the colour was difficult and ambiguous and TLC was used as a qualitative measurement only. That means, when we say red right when a human eye sees red, right you might want to ask what do you mean by red? Red is a very qualitative colour right what is dark red, darkish red, lightish red you can have we tend to grade it based on what our eyes can perceive, right, but you need more quantitative information than that right you need to know exactly what red are you talking about, right. So, recent advance in the digital image processing allows for quantitative and fast measurements, and inexpensive systems can be used basically all you need is a very high quality RGB camera, and the TLC crystals and the TLC sheet, that is it.

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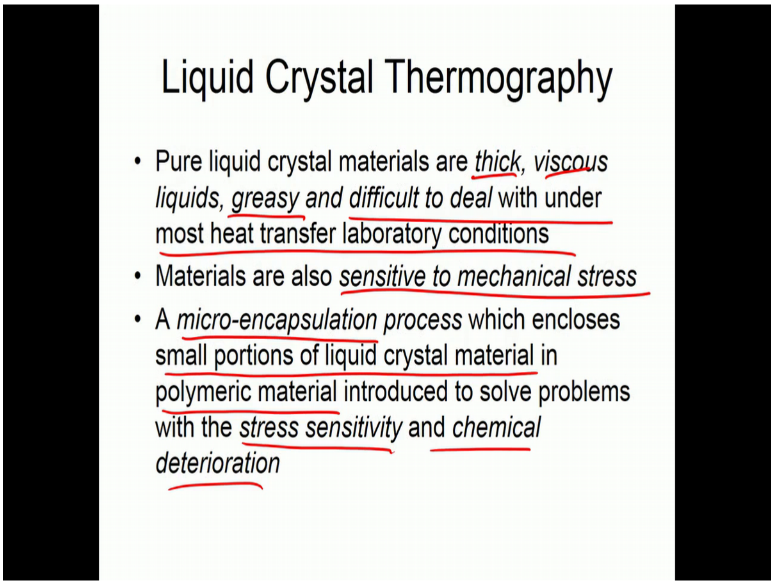

So, pure liquid crystal materials are thick, viscous, greasy and it is very difficult to deal with under most heat transfer conditions, ok. See these materials are also sensitive to mechanical stress, right. So, micro encapsulation is a procedure by which it encloses the small portions of the liquid crystal material in a polymeric polymeric polymeric shell ok, through it actually solves the problem of stress sensitivity and chemical deterioration, ok.

So, there has been lot of work if you ask any polymer person or chemical engineers ok, they will show that how this encapsulation process actually happens for liquid crystal and how they can be actually used to you know use it in common heat transfer applications. Because, as we say pure liquid crystals are thick, greasy viscous type of fluids which are not very conducive to the measurements that we are dealing with.

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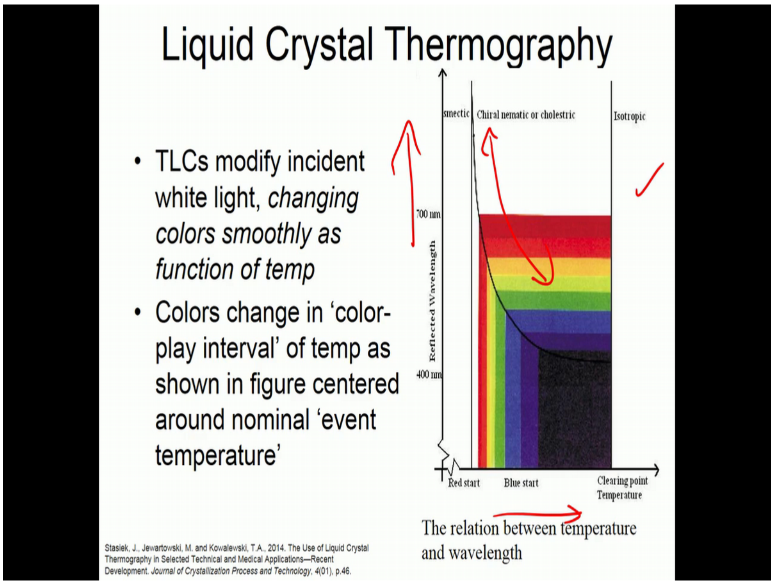

So, let us look at a sample graph. So, this is for example, the reflected wavelength, this is the temperature, this is the relationship between temperature and wavelength, ok. So, the TLC is what it does, it modifies the incident white light. So, you are going to shine white light on this particular TLC coated object right and the colour changes smoothly as a function of temperature that is it that is what happens, right. So, you shine white light, it selectively reflects particular colors which is what you see.

So, the colour changes in colour play interval is shown in the figure ok, in this particular figure you can actually see it where you can see that is a highly non-linear process by the way. You can see that nature of that graph is not a linear graph, graph that you slowly move on in that in the in the colour spectrum, right. So, it is a non-linear graph as you can see from the nature, right it goes from violet all the way up to blackish and violet from red to violet and then black ok, but the depending on, but it is varies in a non-linear fashion, right. So, that is what it is, right.

So, and the range is somewhere between anywhere between 700 to 400 or 350 in that nanometer range, that is where the change actually happens, right. So, this is a sample colour spectrum depending on temperature we know that, what is the colour that it actually reflects right, ok.

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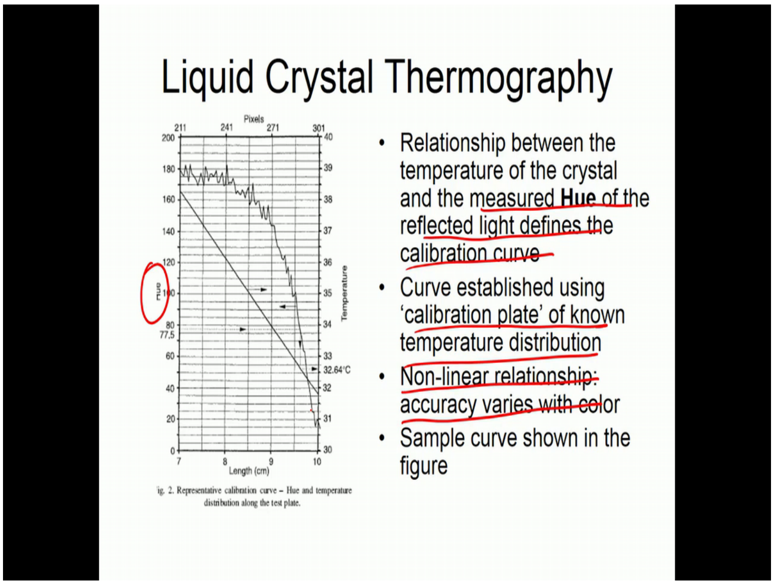

So, the relationship between the colour and the and the and between the temperature of the crystal and the measured hue of the reflected light defines the calibration curve, ok. So, this is the hue, ok. The colour established using calibration plate of known temperature distribution, as I said is a non-linear relationship accuracy varies with colour, and this is one of the sample curves that we have shown, ok.

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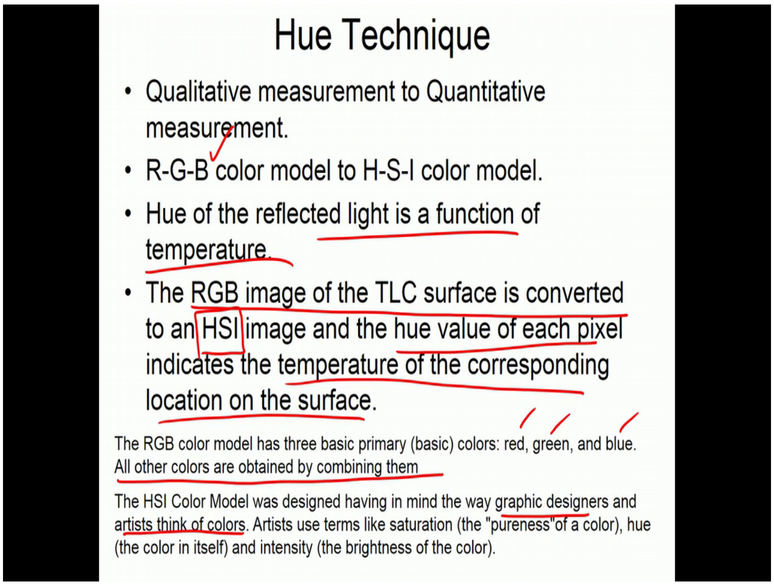

So, the qualitative measurement to quantitative measurement what we want to do is basically you want to go from a R-G-B type of model; R-G-B is the red, green and the blue channel that any cameras will have to an H-S-I kind of a model, ok. So, that. So, in the HSI colour model the hue of the reflected light is basically a function of the temperature.

So, the RGB image is first converted to an HSI image and a hue value of each pixel indicates the temperature of the corresponding location, understood? So, first you get an RGB image you convert that to the hue format and the hue at each pixel, the image that you take has got this pixels right, so, that is the lowest resolution or the or the minimum spatial resolution that you can get. So, there if you calculate the value of the hue that will correspond to the temperature of the surface, ok.

So, RGB basically what it has is that it has got three primary colors red, green and blue all this color all other colors are obtained by combining by just mixing these colors. HSI model was designed keeping in mind the graphic designers and artists think of colour, ok. So, artists use terms like saturation right I just call the pureness of a colour, right, hue the colour itself and intensity is the brightness of the colour. This is what an artists would actually use, that is why it is called HSI model ok. So, hue is the colour in itself, saturation is the pureness and I is basically the brightness of the colour, ok.

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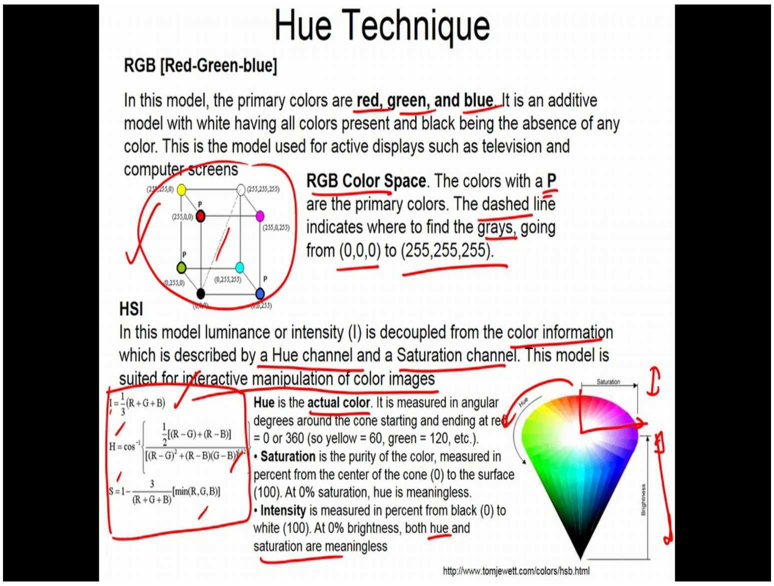

So, the RGB or the red, green, blue in this model the primary colors are red, green and blue it is an additive model; that means all other colors are basically added. So, in the RGB colour space if you look at that say for example, the colour with a P are the primary ones ok, the dashed lines the dashed lines indicates where to find the grays going from 0, 0, 0 all the way up to 255, 255, 255, this is the range that we have, ok.

Now, in the HSI model in the model luminous luminance or intensity is decoupled from the colour information, which is depicted by a hue and saturation channel, ok. This model is suitable for interactive manipulation of the colour images, all softwares actually do it. So, hue is the actual colour, it is measured as an angular degrees around the cone starting and ending at red. So, this is how the hue is actually. So, like a cone. So, this one was like a like a cube ok, this is like a cone. So, hue is basically the angle. So, you start from red, end that red and you pass through all this kind of colour.

Saturation is the purity of the colour measured as percentage from the center of the cone to the surface, ok. At 0 percent saturation the hue is basically meaningless of course, that is at the center. Intensity is measured in percent from black to white at 0 percent brightness both hue and saturation are actually meaningless. So, brightness is basically the height. So, you understand. This is like a cone the angle of the cone this particular rotation basically designates your hue, the center to the edge distance is basically governs your saturation right, while the distance from the top to the apex of the cone is basically what designates your brightness, right. So, this is like a cone type of a model and this is the conversion factor and what is the intensity hue and saturation how they are related to the RGB.

So, remember RGB is a basically an additive kind of a model right with 255, 255, 255 being the maximum, ok. So, it has got basically three channels. HSI model on the other hand operates on like a cone type of a framework, and the relationship between RGB and HSI are given in that particular fashion right what you see at the left. So, you can see that intensity is one third of R plus G plus B, ok.

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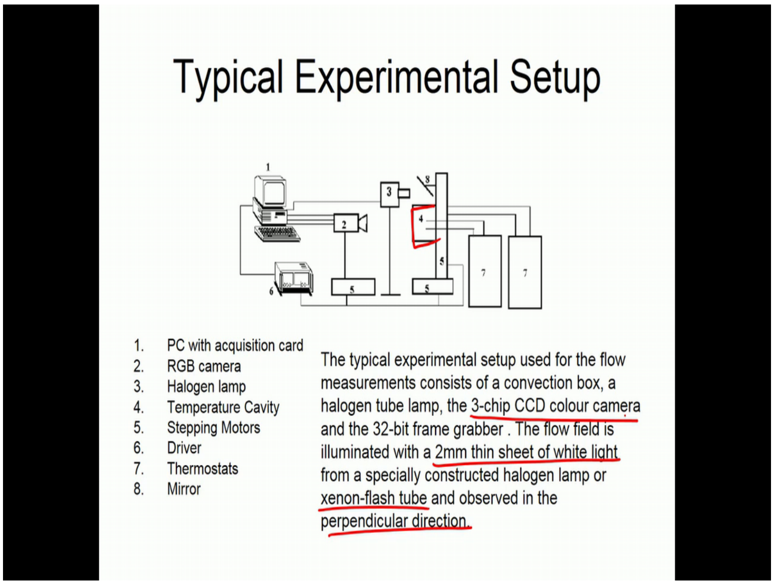

So, let us look at a very typical experiment. So, now, you know that you get the colour, you can get the hue, you can get all those things and you can calibrate with the temperature, so, you know how to how this calibration thing works, right. So, let us look at a very typical experiment, ok.

So, this measurement is inside a convection box ok, the temperature cavity, this is where you want to measure the temperature and the flow field is illuminated with a 2 mm sheet of white light halogen light or xenon-flash lamp and these are observed in a particular direction, it has got a 3 chip CCD camera and 32 bit frame grabber. These are all technical details you do not need to know that much, ok.

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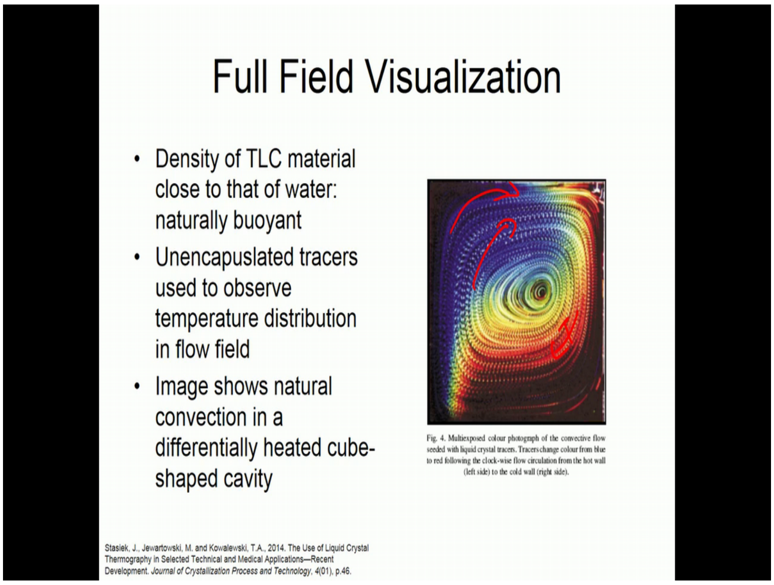

So, if you look at the density of the TLC material so, if you look at this kind of a flow this is like a natural buoyant flow, that you can see in this particular picture now, if you can see. So, this one is that you can see the rotation that is you can see how the full flow field is actually working, at the same time you can see the colour ranges. So, here it is red, here is more bluish, right. So, you know the image shows natural convection and here you have used unencapuslated tracer particles, and you can actually see what the flow field and the temperature actually looks like.

So, in one shot you get the information about the temperature as well as about the flow field in one single snapshot, right. So, you know what the temperature is red to blue so, we can say what which one is hot which one is cold right, ok. At the same time you can also see the direction; that means how this flow field actually happens. So, with the thermocouple you would have never got this kind of a thing.

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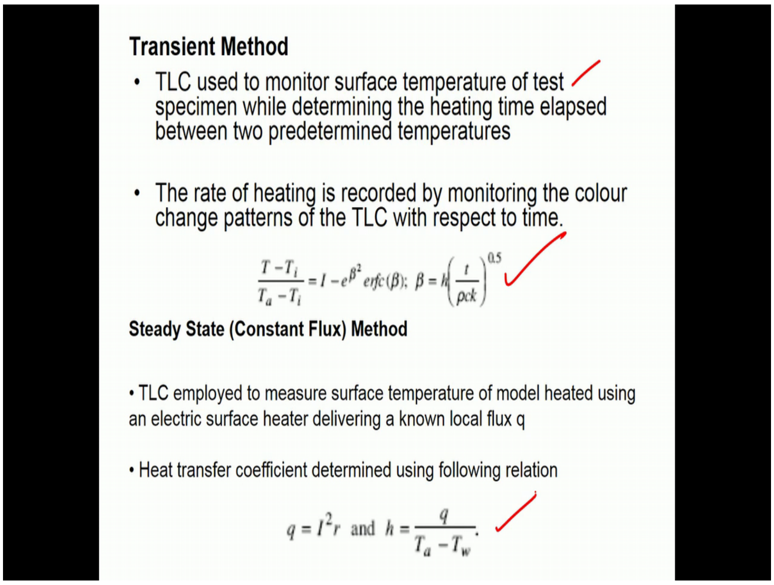

The transient method the TLC is also used to measure the surface temperature of a test specimen while determining the heating time. So, that means, you can record the rate of heating ok, by monitoring the colour change pattern. So, you just take pictures of the colour then you convert that to a temperature and you can find out what will be the temperature history, right. You can also use the steady state method; that means, you want to measure the surface temperature, using say a local heat flux. So, if it is a constant heat flux kind of a situation right, you want to measure what is the surface temperature. So, you can also use a very similar method like this, ok.

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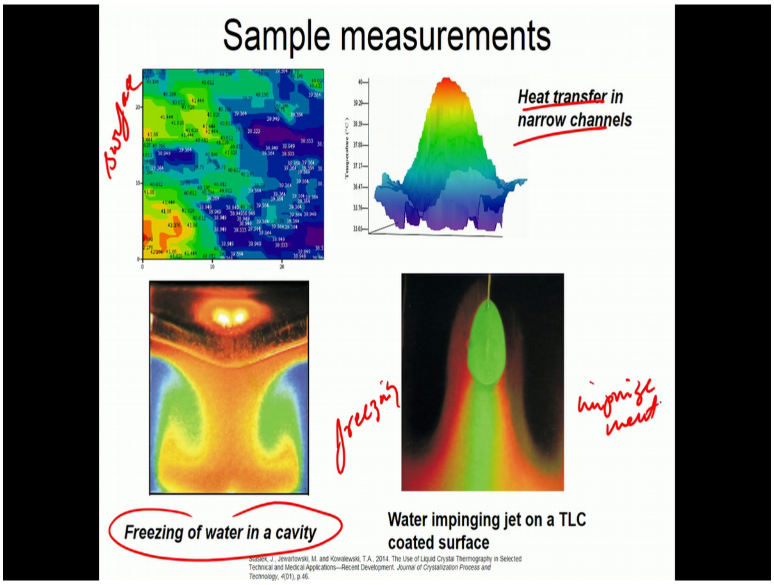

So, these are more sample data say for example, this is a surface where TLC, TLC sheets have been pasted and you can see the temperature distribution, you can see all the temperatures ok, marked out. So, with very good resolution you have been able to get. This is heat transfer in narrow channels ok; this is for example, water impinging on a TLC coated surface this is freezing of water in a cavity.

So, you can see all kinds of things has been captured using the TLC based technique. Right from surface temperature all the way up to freezing all the way up impingement ok, got it.

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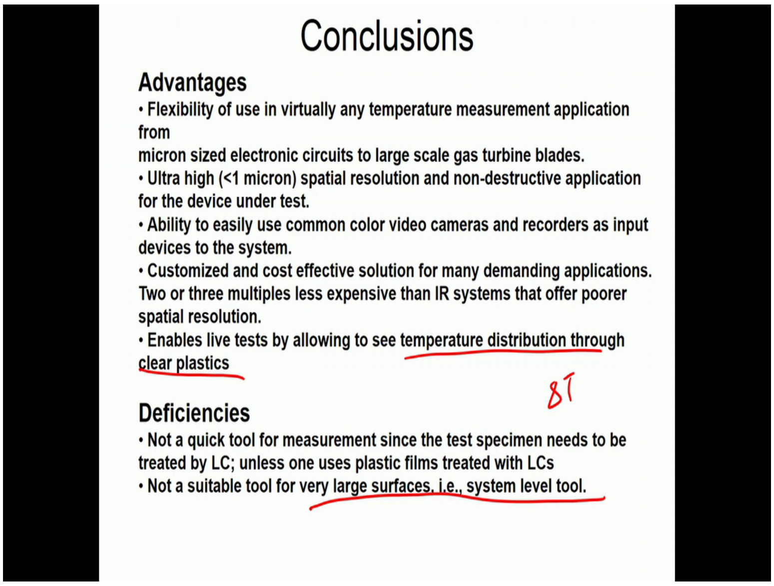

So, advantage is that flexibility of use in virtually any temperature measurement, and it has got ultra high less than a micron order spatial resolution, non destructive in nature, you can use common colour cameras; that means, DSLR cameras and other things can be useful and it is a low cost things, low cost than any other system that we can do ok, enable life test, but you can see the temperature distribution also, right.

That there are certain deficiencies as well, it is not a very quick tool because the you know the response time is still about of the order of 10s and 100s of milliseconds and for very large surface or with very large temperature differentials if the delta T is very large this cannot be used because the band of operation is actually normally very restricted 20 to 30 degree Celsius.

So, in the next class what we cans we will look at is another measurement technique which is called IR Thermography.