

Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

Prof. Saptarshi Basu

Department of Mechanical Engineering

Indian Institute of Science, Bengaluru

Week – 12

Lecture - 56

Infrared Thermography – 2

All right, so we finished IR thermography in this particular class. So if you recall, we state that the received radiation power from a black body with a source temperature actually scales linearly with the response of the camera itself. So now we can write three collected radiation power terms. So one is the emission from the object, which is $\epsilon\tau W_{obj}$, where ϵ is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is T_{object} . All right.

So why are they multiplied by these two terms? If you look at the. In the previous drawing, you can see that this is the radiation it receives because it passes through the atmosphere. As it passes through the atmosphere, part of it is absorbed, part of it is reflected, and part of it is actually transmitted. So that is the part that we are calculating.

That is what the camera receives: the part that is actually transmitted, all right? All right, so then, of course, there is reflected emission from ambient sources. So whatever is reflected, a part of it that is not emitted, is the part that is reflected. So that when it passes through the atmosphere, it is given by this. Therefore, $1-\epsilon$ is the reflectance of the object. Ambient sources can have a temperature of T reflection.

The Measurement Formula



Assume that the received radiation power W from a blackbody source of temperature T_{source} on short distance generates a camera output signal U_{source} that is proportional to the power input (power linear camera).

$$U_{source} = CW(T_{source}), \text{ or with simplified notation: } U_{source} = CW_{source}$$

Should the source be a graybody with emittance ϵ , the received radiation would consequently be ϵW_{source} .

We are now ready to write the three collected radiation power terms:

1. **Emission from the object** = $\epsilon\tau W_{obj}$, where ϵ is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is T_{obj} .
2. **Reflected emission from ambient sources** = $(1 - \epsilon)\tau W_{refl}$, where $(1 - \epsilon)$ is the reflectance of the object. The ambient sources have the temperature T_{refl} .
3. **Emission from the atmosphere** = $(1 - \tau)\tau W_{atm}$, where $(1 - \tau)$ is the emittance of the atmosphere. The temperature of the atmosphere is T_{atm} .

The total received radiation power can now be written

$$W_{tot} = \epsilon\tau W_{obj} + (1 - \epsilon)\tau W_{refl} + (1 - \tau)W_{atm}$$

Now, emission from the atmosphere itself matters. So one minus tau is the emittance of the atmosphere. The atmospheric temperature, let's say, is $T_{atmosphere}$. You can see that all these things are now taken into consideration. You can see them all here.

So this is the $T_{atmosphere}$ temperature of one, which is basically the ambient temperature. The surroundings are okay, so the atmosphere has a certain temperature; there are three types of radiation that impinge on the camera surface. The total received radiation power can now be written as the sum of three terms. One term is definitely from the object. The other one is coming from the reflected emissions from the ambient sources.

And the last term comes from the atmosphere itself. Remember, $1 - \tau$ is the emittance of the atmosphere. And part of that emittance is actually transmitted through the atmosphere. And that is what actually reaches here.

Okay. So this is the total received radiation power that the camera gets to see. Okay. That is an incident on the camera. Okay. We can multiply each term by the constant C of the equation and replace the term CW products with the corresponding U .

So when you do that, C multiplied by W gives rise to a camera response or a signal. So the first term that you see is the $\epsilon\tau U_{obj}$. The second term is $1 - \epsilon\tau U_{refl}$. Then the third term is $1 - \tau U_{atmosphere}$. So, we are basically interested in the U_{obj} .

The Measurement Formula



We multiply each term by the constant C of Equation 1 and replace the CW products by the corresponding U according to the same equation, and get

$$U_{tot} = \epsilon\tau U_{obj} + (1 - \epsilon)\tau U_{refl} + (1 - \tau)U_{atm}$$

$$U_{obj} = \frac{1}{\epsilon\tau} U_{tot} - \frac{1 - \epsilon}{\epsilon} U_{refl} - \frac{1 - \tau}{\epsilon\tau} U_{atm}$$

This is the general measurement formula used in all the thermographic equipment. The voltages of the formula are:

- U_{obj} = Calculated camera output voltage for a blackbody of temperature T_{obj} i.e. a voltage that can be directly converted into true requested object temperature.
- U_{tot} = Measured camera output voltage for the actual case.
- U_{refl} = Theoretical camera output voltage for a blackbody of temperature T_{refl} according to the calibration.
- U_{atm} = Theoretical camera output voltage for a blackbody of temperature T_{atm} according to the calibration.

So, you take this U object out, then you divide everything, and you rearrange the terms, basically.

$$U_{obj} = \frac{U_{tot}}{\epsilon\tau} - \frac{(1 - \epsilon)U_{refl}}{\epsilon} - \frac{(1 - \tau)U_{atm}}{\epsilon\tau}$$

So, this is the total formula that you get. Remember, the only caveat is that we assumed a linear response. We assumed that there was a linear response of the camera.

And we are interested in the new objects. This part is the one with which we are most concerned. The rest of the things, you total and all these things, somehow you have to account for this. So, this is the general formula used in all thermographic equipment. The voltages of the formula are U_{obj} ; U_{obj} is a calculated camera output voltage for a black body of temperature T_{obj} , which is a voltage that can be directly converted into the requested object temperature.

U_{tot} is the measured camera output voltage for the actual case. U_{ref} is the theoretical camera output voltage for a blackbody at temperature T-reflectance according to the calibration. And U_{atm} is again the theoretical camera voltage for a blackbody at temperature T-atmosphere according to calibration. You can see where these things are coming from now. The U_{obj} would ideally be the calculated camera output voltage.

For a black body with temperature T, that is what it is; that is what it should be because you have taken away the epsilon and tau terms. So, it is the actual calculated camera

output voltage if it were a black body with the temperature of T . That is the voltage that can be directly converted to the requested object temperature, no issues. Your total is the measured actual camera voltage that you are measuring. Right, because that is the total incident light that is falling on the camera.

Okay, so this is what you are actually seeing, and the other two reflectors, if these are pre-calibrated, that means for different black body temperatures, reflectance, and other things, if you knew what the camera output voltage would be, then these are provided to you by the manufacturer, for example. So, for example, you are working in an atmospheric temperature of 35 degrees Celsius. So it comes pre-calibrated with what the theoretical camera output voltage will be for this atmosphere, considering that the atmosphere is like a blackbody. What they do, they calibrate the camera for different blackbodies. Okay, and they give you a calibration sheet that you can enter.

That means when you say your atmosphere has a temperature of, say, 35 degrees Celsius or 45 degrees Celsius, whatever it is, the moment you enter the software package that comes with it, it automatically calculates the U -atmosphere. Then you also need to give what the T -reflectance or the temperature is. Once you give that, it will automatically calculate this as well, okay? So these two terms are automatically built into the software because when the vendor sends you the camera, he uses that camera and pre-calibrates it. That means he puts it in for different black bodies at different temperatures. And he calculates what the corresponding theoretical camera output voltage will be.

Once that is done, it will give you a sheet that you can use now. Right, so this is how it actually kind of works. Okay, so you understand that each of these terms, but this U total is the actual camera voltage that you are measuring. Okay, so this is, for example, a case where we, uh, did this; this is from our lab, where we measured the temperature. Of a polymer droplet, which was at around 900 kelvins.

Sample IR Thermography on Evaporating Droplet

(a)

Side view

Continuous CO₂ Laser

Polymer droplet (~900 μm)

Acoustic Levitator (100 kHz, 154 dB)

Beam dump

D_n

D_v

OBJECTIVE : Experimentally studying an isolated vaporizing droplet

- Including convective and radiative heating (monochromatic irradiation)
- Capable of studying temperature change and concentration build up within the droplet.
- Measuring change in droplet diameter

(b)

Top view

Laser light source ($\lambda = 540 \text{ nm}$)

Beam dump

Infrared camera

Zoom Lens

High-speed camera

Continuous CO₂ Laser ($\lambda = 10.6 \mu\text{m}$, beam diameter = 3.3 mm)

Experimental Setup:

- Tunable CO₂ Laser (10.6 μm with 30W) / hot air stream as heating source
- Acoustic Levitator
 - To suspend and isolate droplet
- High speed camera with zoom lens:
 - To capture the diameter reduction rate
- IR camera
 - To measure the surface

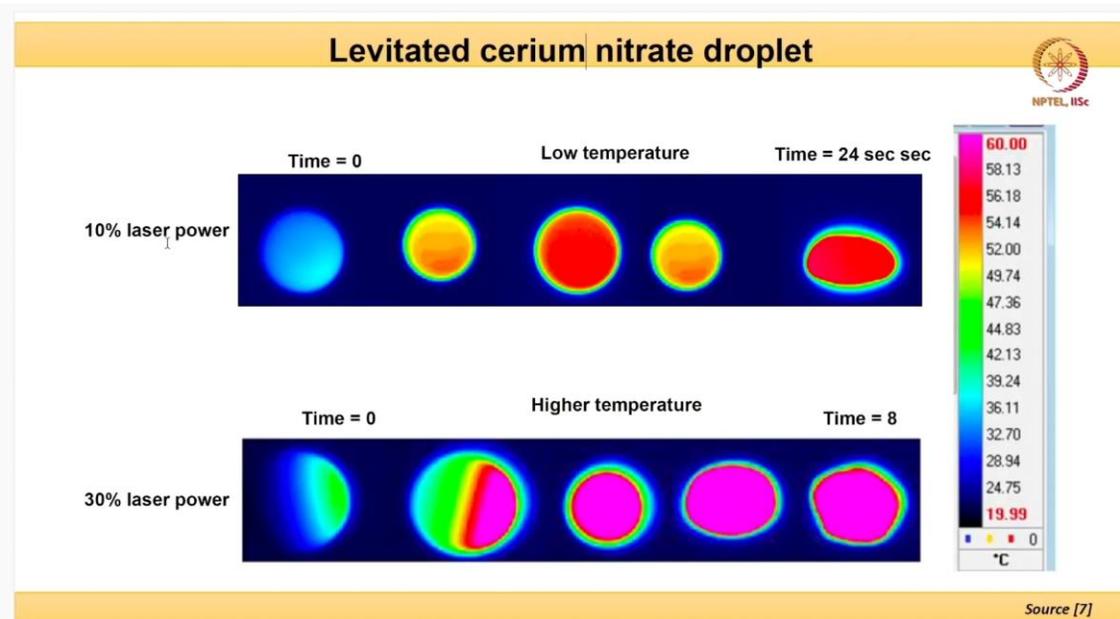


So, this is the droplet. This is how it is anchored. So this droplet is actually heated with a laser so that its surface temperature increases. Then you use an infrared camera. This is the camera that was shown in the previous slides. We monitored this particular droplet and tried to measure what the surface temperature looked like.

So the laser that is used to heat the droplet is also an infrared laser. It is about 10.6 micrometers with a 300 watt-hour. And there is an acoustic levitator in which it is suspended, and the droplet is suspended in an acoustic levitator so that it is kind of contact-free. And you use a high-speed camera with a zoom lens to simultaneously capture how the size of the droplet is actually reducing.

So, the IR camera is used to measure the surface temperature. Now, why is the high-speed camera used to measure the decreasing, the regressing? Because this can go to a much higher frame rate compared to the IR camera. So the IR camera is not essentially locked with the high-speed camera. So it cannot take images as quickly as a high-speed camera does. But from an IR camera, you can also measure the droplet size, so to speak.

So this is one sample of an IR thermography setup that we have. And this is what you see: if we forget about that, what is a cerium nitrate droplet? It's a droplet that has a certain composition variation, for example.



So this was with 10 percent laser power, as you see that it goes on in the time axis. So, as you know, the droplet slowly gets heated and finally reaches what we call a wet bulb kind of limit. You can see that initially you have variations in the surface temperatures; slowly and steadily, the temperature kind of equilibrates, and the droplet shows something like red, which is about 60 degrees or around 58 degrees Celsius.

If you go to a slightly higher laser power, now you see a little bit of asymmetry because, remember, this is actually asymmetric heating. So this side of the droplet, because it's a radiative energy source, as we said, part of it is absorbed. So if you consider a droplet, the outer layer is like an onion. So, in the outer layers, the radiation gets absorbed as it moves in. So that's the reason you have this asymmetry in the droplet temperature distribution.

At 30% laser power, you can see that there is a significant difference, an initial asymmetry, but eventually the temperature becomes equilibrated because the motion of the fluid inside the droplet gradually addresses this. And this is, for example, the laser-induced evaporation of a polymer droplet. Now this is the polymer concentration. Forget about the nomenclature. This is once again done at different times.

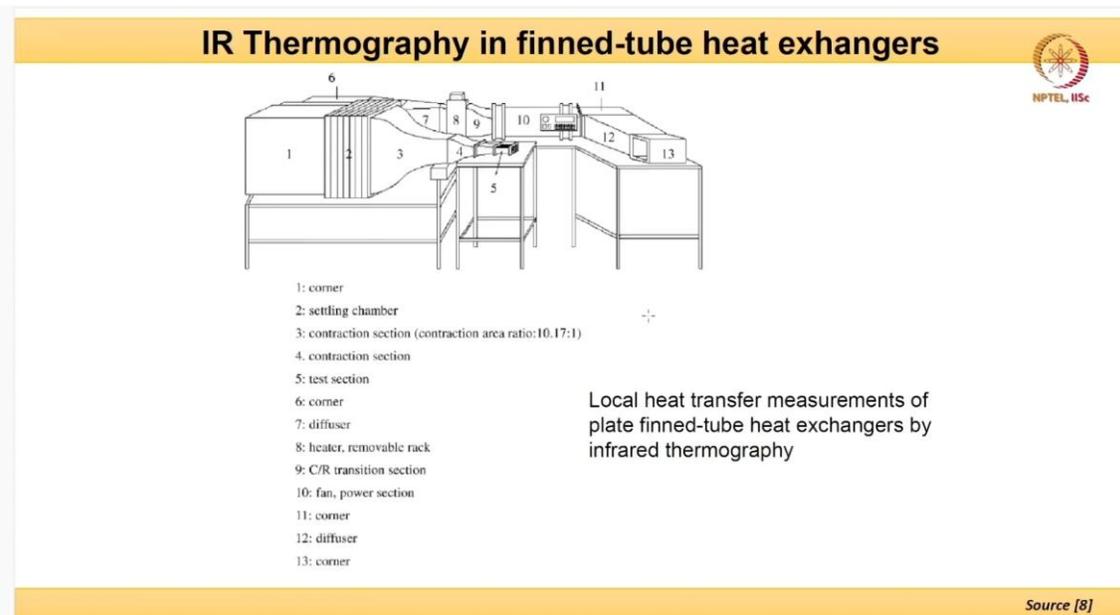
So this is time t equal to zero. And this is low temperature heating. It uses only 20% of the laser power. That means the amount of heat that you are dissipating is actually quite low. So you can see, once again, there is asymmetric heating. Now there is a compositional change within the droplet, and then it slowly becomes equilibrated; after

that, it starts to shrink in size, and the temperature rises to about 80 degrees Celsius.

Now, if you increase the laser power, the droplet, because of this asymmetric heating, actually deforms. You can see that there is a very strong temperature differential between the two sides of the droplet. And this is very illuminating. And the droplet bulges. Like this, slowly, and however, it kind of never equilibrates completely; the temperature goes very high at around 110 degrees Celsius or so, and you know there is a temperature differential of something right about eight or nine degrees even within a droplet, which is very small in size.

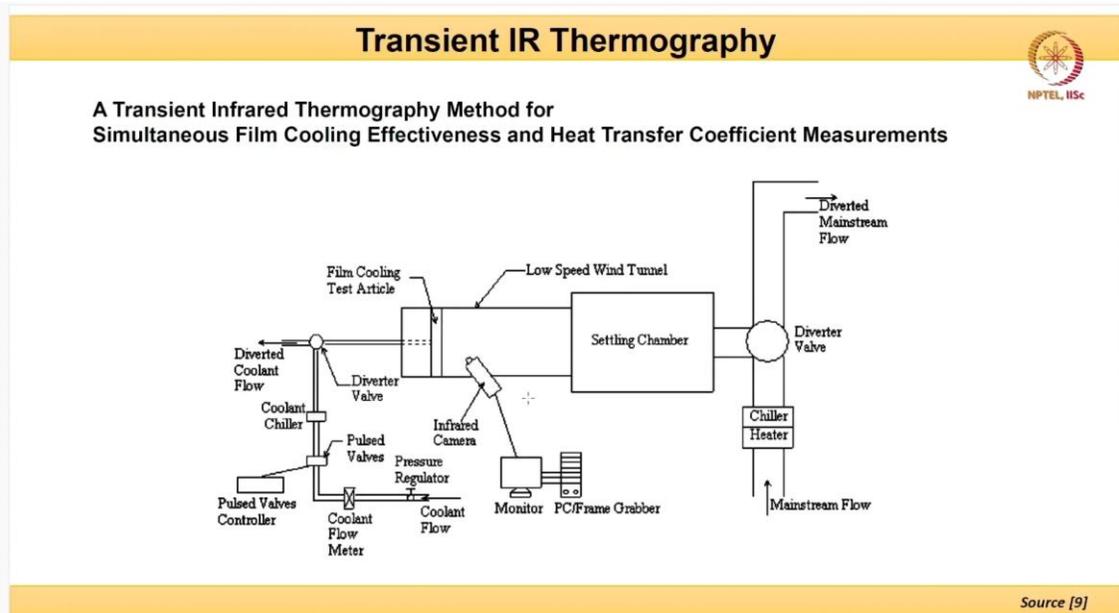
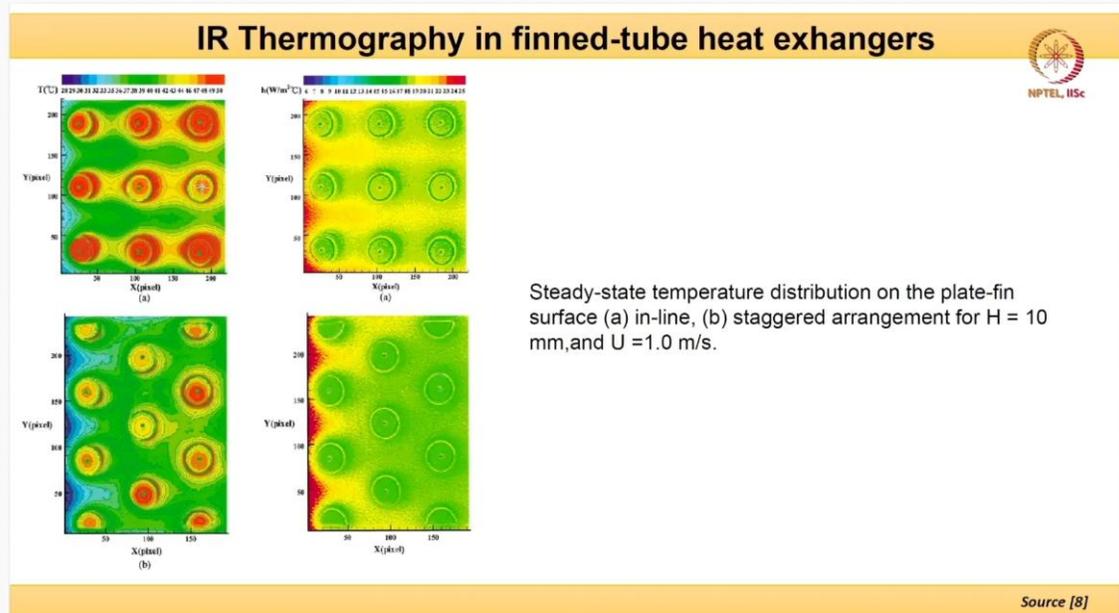
Remember, these droplets are some millimeter droplets to begin with, but this is illuminating that you can capture this level of detailing. Okay, from using an IR camera, you know, when there is asymmetric heating of the droplet. So this is quite good. I mean, this kind of shows that the system is actually powerful. It can actually do all this, you know, extremely nice measurements, even for very small droplet sizes.

These are submillimeter droplets, for example. You can also perform IR thermography in pinned tube heat exchangers as well. So what happens here is that this is a pretty extravagant setup. But if you look at the test section, which is right around here at 5, this is where you want to measure the temperature. Local heat transfer is studied using IR thermography, and this is exactly where it is done.



It is not just for small droplets; the idea of showing this slide is that what I showed for

droplets was very small, and this is obviously pretty large. This is almost like a bellows, as it resembles the full heat exchanger assembly, making it highly versatile. Therefore, it can also take measurements in pinned tube heat exchangers. So it can measure these small droplets, and it can measure the asymmetry; it can measure these kinds of large-scale setups. This is the IR thermography on these pinned tube heat exchangers.

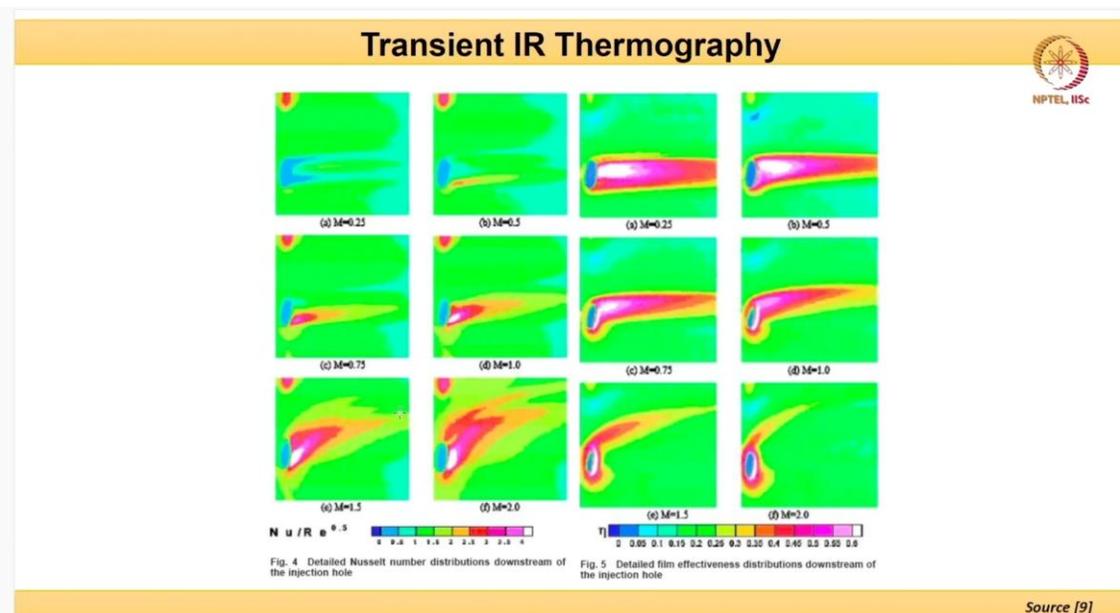


As you can see, you can also readily see the wakes. So this is like the temperature distribution. This is not the fluid flow distribution, but if you think that there is a certain

analogy between the two, you can see how the heat transfer, which is basically carried by the flow, essentially varies from different pins. So these are the different pins and how they vary with the different pins.

So as you can see, this is somebody else's data. So it is, you know, these are the best images that I could flush out from source eight. So you can see that in the aft, there is high temperature. Then it slowly decreases. Then it becomes high again.

Then it slowly decreases. So there is a certain amount of asymmetry, which predominantly comes due to the flow asymmetry. So you were able to capture this kind of detail, which is not possible with a thermocouple. For example, if you insert a thermocouple here, you will disturb the flow. And at the same time, whatever temperature you get, maybe just this red or just this yellow, but you will not get the field. This field is vitally important because it tells you that if you plot the streamlines on top of it, then you will get a very good idea of how the fluid transport and the heat transport are actually happening in conjunction with each other.



You can also find out what the heat transfer coefficient is for this pinned heat exchanger, which is what you need for practical applications. So you can also determine this film cooling effectiveness. So what film cooling effectiveness is, is that you have a low-speed wind tunnel, you have a film cooling article, and then basically you have the coolant flow through that. And you use an IR camera to see how heat transfer is happening with the coolant flow. So how efficient is the coolant flow? You know, that is what is measured.

This is from source 9. Once again, this is a film measurement. So we have shown droplets, we have shown pinned fins, and we are also now showing that if you do it in a low-speed wind tunnel, the film thickness is actually very important. Okay, and this is what the corresponding results look like. So if this is, these are the holes, these are the film cooling holes, this is how the temperature distribution actually looks for different flow rates, we can do a very detailed analysis. This is the Nusselt number divided by the Reynolds number to the power of 0.

5, and this is color coded, but the Nusselt number calculation comes from the temperature and the heat transfer coefficient, therefore. Therefore, this is how this data looks. Amazing clarity. It gives you the field measurement without being constrained by a thermocouple sticking somewhere and making guesses. So, this will actually give you the temperature at the top of the film.

So that is what you should be able to look at clearly. So these are kind of the sources from which different things are taken. Some of it is our work, while some of the work comes from other people's efforts, of course. So the work comes from Srinath Eker, from the film Cooling Effectiveness, and also from the work of Jaina Iya. But there are certain things that we want to mention at this particular point. We have come to the close of the lecture; therefore, IR thermography is based on a certain amount of calibration and a certain amount of details that you get from the camera signal and how you calibrate it.

You also have to key in—uh, this is what I forgot to mention—you also have to key in this epsilon and tau; these are parameters that you need to. Uh, you know, putting atmosphere is normally pre-calibrated, so these things are already there unless you want to do it in a different atmosphere. But normal atmospheric conditions are given. Epsilon is something that you have to enter, so when you operate an IR camera, you have to enter that this IR camera has this object with an emissivity of whatever. So that is something that you need to know, because if you do not know that, then you will have an error in your temperature measurement, as it is very sensitive.

These things are all pre-calibrated and entered for you. So, and this is also, you know what the blackbody temperature is going to be. So it is kind of, once you know all these parameters, okay, these are all pre-calibrated, this is something that you know, uh from your actual measurement this epsilon is something that you are entering, tau is already pre-existent, so when you do all these things you know your new object moment, you know your new object from the calibration curve, you know your t object. Now this can be done from pixel to pixel because the simple reason is that you know IR cameras. You can do pixel to pixel if your object has a surface with varying temperature. And that is

exactly what we captured here, for example, surface-varying temperature.

Or in the later part, this surface varies in temperature. So naturally, that is the USP of doing this. So at each point, it can actually do this. So it is pretty sensitive in that particular way. So at each pixel resolution, it can do this. But also at the same time, because it actually registers a certain amount of radiation, the pixel resolution is not all that great compared to the normal CMOS cameras that you use for high-speed imaging.

And also, the frame rate cannot be as high as that of IR cameras or high-speed cameras, so to say. So there's a certain amount of calculated risk. There is always a certain amount of error, especially if the ambient conditions are very fluctuating, for example. If it is showing fluctuations, for example, if it's a hot day and it's showing buoyant plumes, then it's a plume that is occurring; you can see that in the desert.

The Measurement Formula



We multiply each term by the constant C of Equation 1 and replace the CW products by the corresponding U according to the same equation, and get

$$U_{tot} = \varepsilon\tau U_{obj} + (1 - \varepsilon)\tau U_{refl} + (1 - \tau)U_{atm}$$
$$U_{obj} = \frac{1}{\varepsilon\tau} U_{tot} - \frac{1 - \varepsilon}{\varepsilon} U_{refl} - \frac{1 - \tau}{\varepsilon\tau} U_{atm}$$

This is the general measurement formula used in all the thermographic equipment. The voltages of the formula are:

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- U_{atm} = Theoretical camera output voltage for a blackbody of temperature T_{atm} according to the calibration.

So there are refractive index variations. So when we do the shillery, that will be the thing that is important. But in those cases, when this is time-varying quite a bit, and when the atmospheric temperature is not exactly fixed at all times, it is varying, time-varying. At that time, it poses a little bit of a difficulty, especially if the variation is too fast. For example, if there is a turbulent plume in front of your object. In those cases, the accuracy of the measurement actually decreases quite a bit.

So, you have to be careful. All we are saying is that when you use these methods, you have to be very careful. Surface curvature effects also come into the picture because not all radiations come, and you cannot collect all the radiations uniformly, so that is one

other point of concern for this. However, if your IR cameras are manufactured in such a way that some of them are pre-calibrated to the normal setting where there is not a turbulent plume, if you want to measure the surface temperature of something, you should be able to do that. However, you cannot do it, for example, in a highly fluctuating environment like in a turbulent flow. For a turbulent flame, it is simply not possible; it's too onerous to calculate the temperature in those kinds of systems.

We have to utilize film cooling, a pinned heat exchanger, and droplets' surface temperatures in applications like batteries or thermal management tools. In those cases, I think this will be highly useful, but it would not be useful in all cases. That is what the whole point of it is. So whenever there is turbulence and other types of things, the simple methods that we kind of talked about here may not be all that applicable. But you understand that it all depends on the blackbody radiation, how you collect the radiation, and what the contributors to this radiation are.

And we also gave you a little bit of a primer on blackbody, non-blackbody, Wings' displacement law, Planck's constant, and stuff like that. And we also talked about the IR thermography spectrum. The electromagnetic spectrum peaks around these temperatures; you know IR is actually quite useful because it peaks at that particular wavelength, in the dark, so to speak. However, the signal becomes weak, as we know, as the temperature goes down.

That is also a problem. But it still has a very wide variety of applications, so to speak. It has many things that it can do. It's highly effective, as these kinds of images actually show. So it can give unprecedented resolution on the heat transfer calculation.

Further readings are suggested. So you can read a few research papers. These are all research papers. You can also look at Alden's lectures on molecular spectroscopy. That is for absorption spectroscopy, as well as for IR thermography, to a certain extent. And once you do all those things, you should have a very good idea of what type of things we are actually dealing with. So the methodology, last I want to mention before we end this lecture, is that it's a non-intrusive method.

Therefore, we don't need anything to poke the flow or poke the system with. Your thermocouples and other devices are point measurements. So they will not pick up any spatial variations. It might pick up the temporal part, but not the spatial part. IR thermography, obviously, if you have a very rapidly varying temperature, cannot measure that at such a high FPS. It has got reasonable resolution, but not very high resolution so that you cannot resolve at the same level as your normal CMOS 4K cameras do, for example.

So there are certain limitations, but still, it's a field measurement. And because it's a field measurement, it has a lot of utility. In the community. So I think we should end our lecture here. And so, IR thermography is something that is here to stay.

And you can read more research papers. You can look into more details about the camera. FLIR is one company that manufactures IR cameras regularly. You should look at those.

An IR camera has different ways. It has volometer-based techniques and other things. We are not covering this particular series of lectures. It is more about the fundamentals and how they are measured. So, time permitting, we also provide a small video snippet, which will show you what kind of IR cameras actually exist, what technology that means, the hardware part of the IR camera, and how they sense the signal. How do they respond to a certain level of radiation? Okay, so we will see you in the next class.