Thermal Operations in Food Process Engineering: Theory and Applications

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Lecture - 34
Heat Transfer by Radiation

After convection and conduction thoroughly done, now I would like to go for Heat Transfer under Radiation and this is lecture number 34. So, we are going to heat transfer by radiation, 'right". Now, let me tell beforehand that the importance, we have already said the importance of conductor a conduction, we have said importance of convection and the importance of radiation also we must say, 'right". It is that you if you have ever seen that a kitchen is also is one of the very important place to learn many things.

So, if you have ever seen that your mummy and others are making food and maybe doing some roti or bread or things like that and the plate on which it is being made, I do not know whether you have observed it or not that you do not have to touch the plate, but if you are nearby, then also you feel some heat, 'right". So, that heat you have not touched the thing, and there was no fan or nothing, you are very close to the plate and you observed or you faced or you felt that some heat is coming to you. How? Because this is possible when the temperature is very high that time the radiation takes place.

And when we go into the radiation in detail you will see that the normal our conduction convection we have seen that the deltas delta ts are all in terms of all in terms of normal T_c -T_h -T_c things like that. But here it will be in the time thumbs up power to the power 4, T_h^4, T_c^4, δT is that T_h^4-T_c^4, 'right". So, because of; that means, the higher the temperature more is the radiation, 'right". However, without saying much more let us go into the subject and we first look at what is radiation, 'right".

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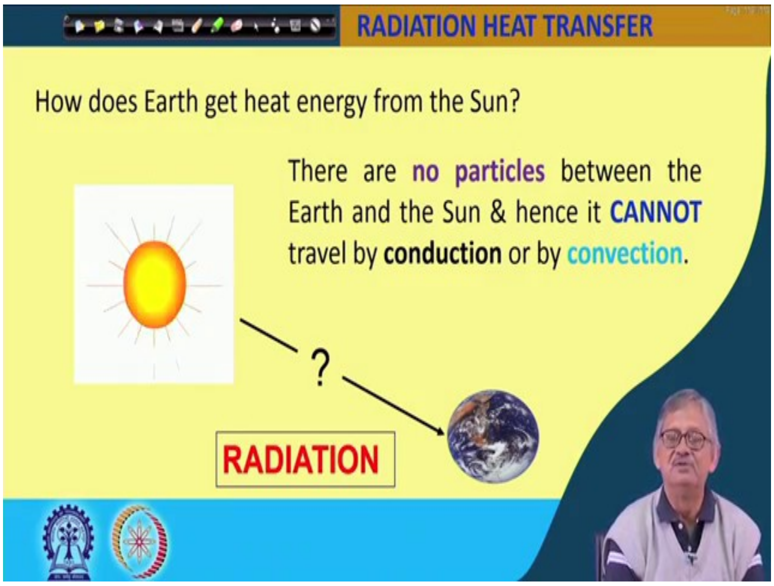

RADIATION HEAT TRANSFER

How does Earth get heat energy from the Sun?

There are **no particles** between the Earth and the Sun & hence it **CANNOT** travel by **conduction** or by convection.

So, radiation heat transfer is that how does earth get heat energy from the sun? ‘‘right’”. Sun is several lakhs kilometer away from earth. And yes, sun is so hot and this hot is coming to us we are getting in summer season you feel very hot, in the winter season you feel also cold, but still when there is a sun you feel a better. So, the sun is sending you that energy, ‘right”.

How it is happening? ‘right”. There are no particles between the earth and the sun and hence it cannot travel by conduction or by convection because you have seen for either conduction or convection you need to have some medium, ‘right”. But since between the earth and sun there is no medium, ‘right”. So, how it is being transmitted or how it is being sent? ‘right”. It is only by radiation, ‘right” the energy which is coming there is only by radiation because there is no medium, so no convection, no conduction, so only by radiation it is being transmitted from sun to the earth, ‘right”.

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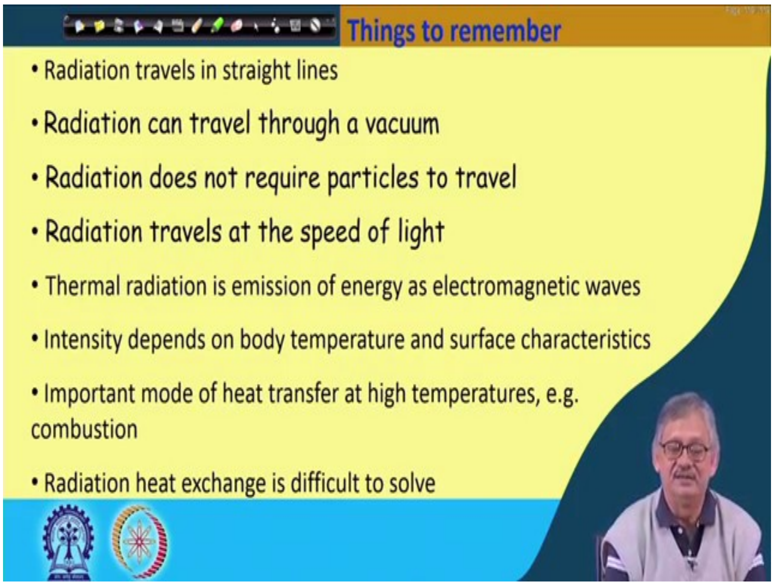

Things to remember

- Radiation travels in straight lines
- Radiation can travel through a vacuum
- Radiation does not require particles to travel
- Radiation travels at the speed of light
- Thermal radiation is emission of energy as electromagnetic waves
- Intensity depends on body temperature and surface characteristics
- Important mode of heat transfer at high temperatures, e.g. combustion
- Radiation heat exchange is difficult to solve

So, for this the certain things are to remember for radiation heat transfer, that radiation travels in straight lines. Radiation can travel through a vacuum also because the space is that where there is nothing no medium, but still it is propagating. Radiation does not require particles to travel. Radiation travels at the speed of light. Thermal radiation is emission of energy as electromagnetic waves. Intensity depends on body temperature and surface characteristics.

Important mode of heat transfer it is also an very important mode of heat transfer otherwise a had there been no radiation heat transfer, then earth would not have got so much energy from the sun, 'right". So, important mode of heat transfer at high temperatures for example, combustion etcetera, there as we said that it is to the power of 4, T^4, that temperature to the power 4, in that order the variations are. Radiation exchange is difficult to solve, it is not that easy that you can solve like conduction or like conviction also you can solve the problem so easily. It is more and more complicated.

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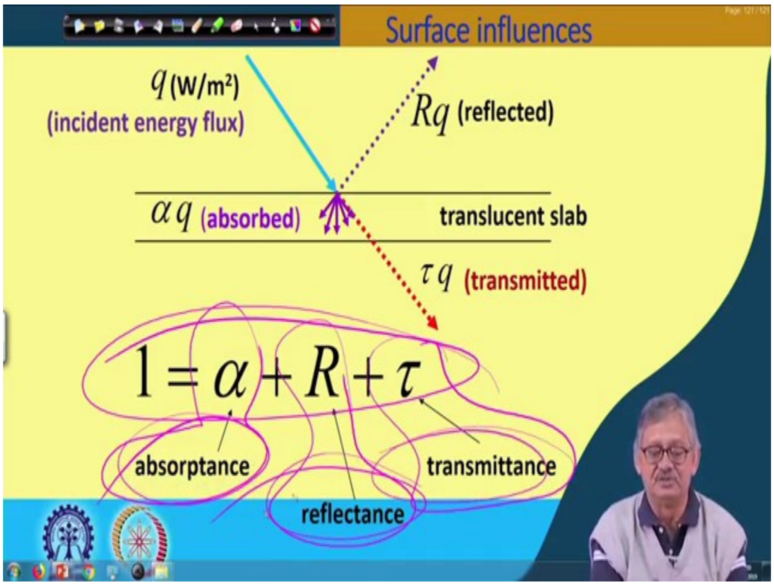

Surface influences

$$1 = \alpha + R + \tau$$

However, we must do some basics and show that when a radiation is coming that is incident energy flux like this, ‘right”, q W/m^2 that is the incident energy flux, and this is the surface which is a translucent slab. So, out of this when it is incident, then αq quantity is absorbed, Rq quantity is reflected, and τq quantity is transmitted, ‘right”.

That means, the total is 1 which is α total q, ‘right” is $\alpha+R+\tau$ this time q, so it becomes 1 plus 1 is $\alpha+R+\tau$ out of which α is the absorptance, R is the reflectance, and τ is the transmittance, ‘right”. So, this is how the energy is getting transmitted out of which some are observed, some are reflected and some are also transmitted, ‘right”.

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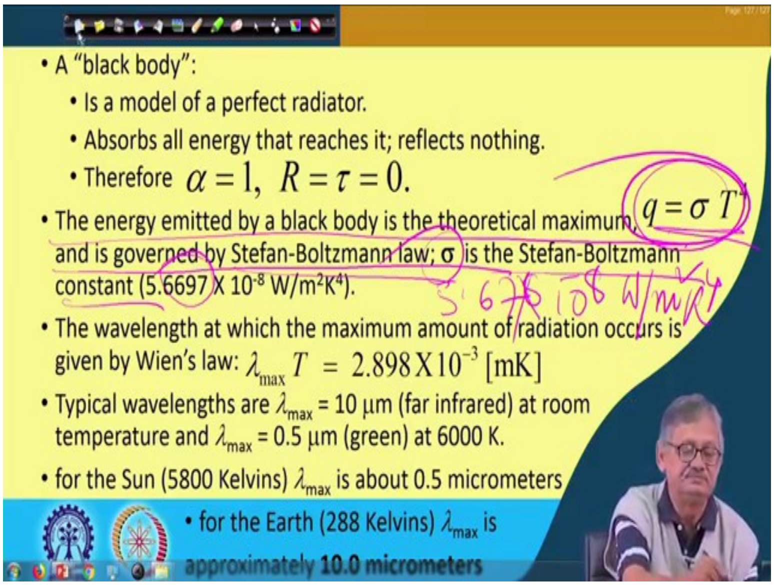

- A "black body":
  - Is a model of a perfect radiator.
  - Absorbs all energy that reaches it; reflects nothing.
  - Therefore $\alpha = 1,\ R = \tau = 0.$
- The energy emitted by a black body is the theoretical maximum, and is governed by Stefan-Boltzmann law; σ is the Stefan-Boltzmann constant (5.6697 X 10^{-8} W/m^2K^4).
- The wavelength at which the maximum amount of radiation occurs is given by Wien's law: $\lambda_{max} T = 2.898 X 10^{-3}$ [mK]
- Typical wavelengths are λ_{max} = 10 μm (far infrared) at room temperature and λ_{max} = 0.5 μm (green) at 6000 K.
- for the Sun (5800 Kelvins) λ_{max} is about 0.5 micrometers
- for the Earth (288 Kelvins) λ_{max} is approximately **10.0 micrometers**

$q = \sigma T^4$

$5.678\ 10^{8}\ W/mK^4$

So, if we look at a black body. A black body is a model of a perfect radiator which absorbs all energy that reaches it and reflects nothing. So, in the black body α is equal to 1, R is equal to τ is equal to 0. So, the previous slide which we had shown there this for a perfect black body, absorption is 1. So, α becomes equal to 1 because the reflectance is 0 and also transmittance is 0, nil. So, it becomes 1, α is 1 which is the quantum for absorption, 'right".

So, we can say that the energy emitted by a black body is the theoretical maximum that is q is equal to σT^4, 'right". So, $q = \sigma T^4$ and is governed by Stefan Boltzmann law, where sigma is the Stefan Boltzmann constant.

Generally, it is known as 5.67 not to this tune 5.6697, it is generally known as 5.67 maybe 8, 'right", 5.67 8 or 5.67 generally, 2 digit into 10^{-8} W/m^2.K^4, 'right". So, this is Stefan Boltzmann constant, so where it is denoted as $q = \sigma T^4$. So, this is the theoretically maximum which can be emitted by a black body, 'right".

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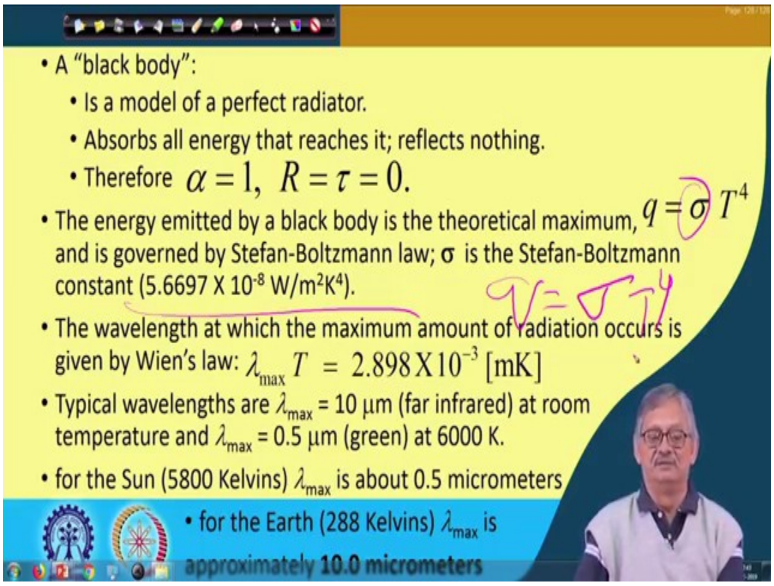

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$q = \sigma T^4$

The wavelength at which the maximum amount of radiation occurs is given by another law which is called Wien’s law, ‘right”; which is called Wien’s law. And this is $\lambda_{max}T = 2.898\times10^{-3}$ m.K, ‘right”, λ_{max} is meter T is in Kelvin. So, λ_{max} T is 2.898, 10^{-3} m.K.

Typical wave length are λ_{max} is 10 µm this is true for infrared at room temperature or far infrared at room temperature and ok, this is that. So, at room temperature and δ_{max} or λ_{max}, sorry λ_{max} is 0.5 µm that is called green at 6000 K, ‘right”.

For the sun which is at 5800 K λ_{max} is about 0.5 µm whereas, for the earth which is roughly 288 K, λ_{max} is approximately 10 µm, ‘right” is 0.5 µm for sun, whereas, for earth it is 10 µm, ‘right”.

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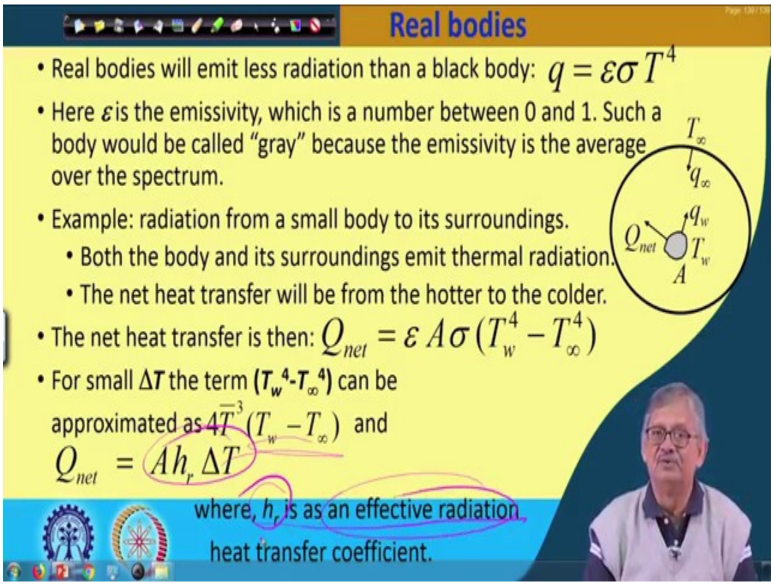

Real bodies

- Real bodies will emit less radiation than a black body: $q = \varepsilon\sigma T^4$
- Here ε is the emissivity, which is a number between 0 and 1. Such a body would be called "gray" because the emissivity is the average over the spectrum.
- Example: radiation from a small body to its surroundings.
  - Both the body and its surroundings emit thermal radiation.
  - The net heat transfer will be from the hotter to the colder.
- The net heat transfer is then: $Q_{net} = \varepsilon A\sigma(T_w^4 - T_\infty^4)$
- For small ΔT the term $(T_w^4 - T_\infty^4)$ can be approximated as $4\overline{T}^3(T_w - T_\infty)$ and $Q_{net} = Ah_r\Delta T$

where, h_r is as an effective radiation heat transfer coefficient.

So, with this some preamble of our blackbody, let us now go to the real bodies, 'right". So, real bodies are those which emit less variation than a blackbody where q is $\varepsilon\sigma T^4$. So, the quantity of heat which is emitted is $\varepsilon\sigma T^4$. ε is the emissivity which is a number between 0 and 1. Such a body would be called gray because the emissivity is the average over the spectrum, 'right". You see air from the T infinity q infinity is coming, ok, net is capital Q, q watt is being transmitted at T wall and area is A.

So, for this we have given that example, radiation from a small body to its surroundings like this is both the body and its surroundings emit thermal radiation, both the body and its surrounding. The net heat transfer will be from the hotter to the colder; obviously, if this is hot than the other then it will be from there or if it is hot than the other then it will be from there, 'right".

So, the net heat transfer is then $Q_{net} = \varepsilon\sigma(T_{wall}^4 - T_\infty^4)$. From small or rather for small ΔT this term $T_w^4 - T_w$, T_∞^4 can roughly be approximated as $\Delta\overline{T}^3(T_w - T_\infty)$. And in that case Q_{net} can be related as $Ah_r\Delta T$, where ΔT $h_r \times \Delta$ T, where h_r is an effective radiation heat transfer coefficient and ΔT is the temperature difference, 'right". So, h_r is an effective radiation heat transfer coefficient.

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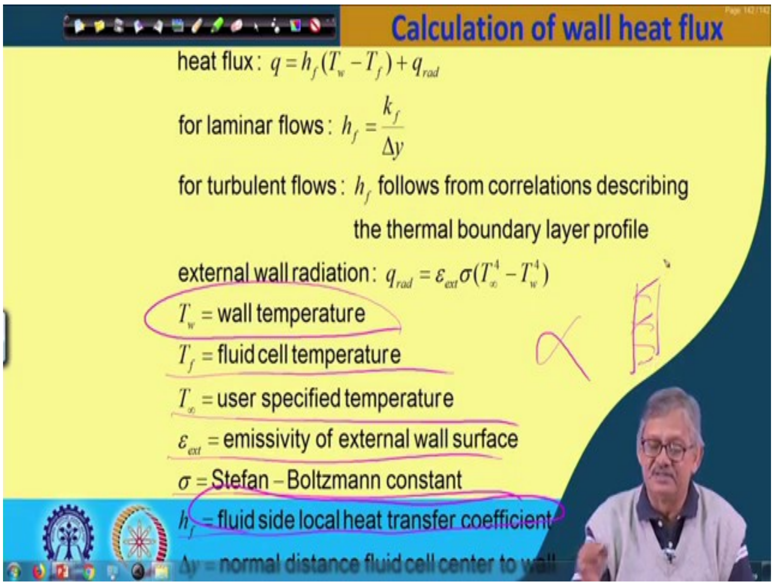

Calculation of wall heat flux

heat flux: $q = h_f(T_w - T_f) + q_{rad}$

for laminar flows: $h_f = \frac{k_f}{\Delta y}$

for turbulent flows: h_f follows from correlations describing the thermal boundary layer profile

external wall radiation: $q_{rad} = \varepsilon_{ext}\sigma(T_\infty^4 - T_w^4)$

T_w = wall temperature

T_f = fluid cell temperature

T_∞ = user specified temperature

ε_{ext} = emissivity of external wall surface

σ = Stefan – Boltzmann constant

h_f = fluid side local heat transfer coefficient

Δy = normal distance fluid cell center to wall

So, if this is known then let us go for calculation of wall heat flux. So, if we want to find out the wall heat flux, then heat flux q is $h_f \times (T_w - T_f) + q_{radiation}$ and for laminar flows h_f is $k_f/\Delta y$, for turbulent flows h_f follows from correlations describing the thermal boundary layer profile.

External wall radiation is like this $q_{rad} = \varepsilon_{external}\sigma(T_\infty^4 - T_w^4)$, where T_w is the wall temperature, T_f is the fluid temperature, T infinity that user specified temperature or surrounding temperature.

$\varepsilon_{external}$ is the emissivity of external wall surface, σ is the Stefan Boltzmann constant, h_f is fluid side local heat transfer coefficient, and Δx normal distance fluid cell center to the wall, fluid cell center from the fluid to the wall, 'right". The distance that is Δx or Δy, in this case we have used delta y, 'right". So, h_f into = $k_f / \Delta y$.

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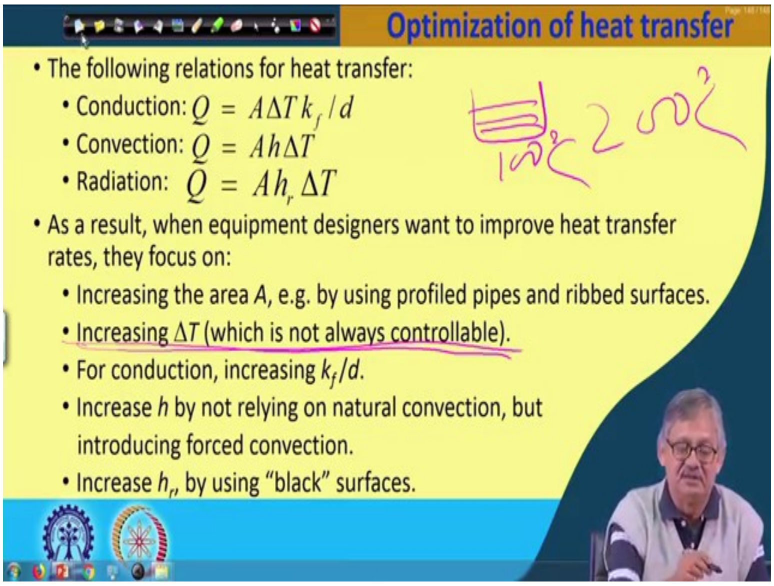

Optimization of heat transfer

- The following relations for heat transfer:
  - Conduction: $Q = A\Delta T k_f / d$
  - Convection: $Q = Ah\Delta T$
  - Radiation: $Q = Ah_r \Delta T$
- As a result, when equipment designers want to improve heat transfer rates, they focus on:
  - Increasing the area *A*, e.g. by using profiled pipes and ribbed surfaces.
  - Increasing ΔT (which is not always controllable).
  - For conduction, increasing k_f/d.
  - Increase *h* by not relying on natural convection, but introducing forced convection.
  - Increase h_r, by using "black" surfaces.

So, from these basic relations we go to the optimization of heat transfer. Like, the following relations for heat transfers are optimized like, if it is conduction then it is $A\Delta Tk_f/d$, 'right" that is for conduction. If it is convection, then $Ah\Delta T$ and if it is radiation then $Ah_r\Delta T$, 'right". This is more or less optimization of the heat transfer for 3 modes of heat transfer, $A\Delta Tk_f/d$, $Ah\Delta T$ and $Ah\Delta T$ $Ah_r\Delta T$, 'right".

So, as a result when equipment designers want to improve heat transfer rates they focus on either increasing the area A. For example, by profile pipes and ribbed surfaces which we have done by extension of area that is by fin, 'right", that fin heat transfer also we have done, 'right". Increasing ΔT which is not always controllable, it is not that when you are cooking suddenly your temperature is 100 °C, suddenly you thought it is taking time let me make it 200 °C not visible, 'right". So, this control is beyond you.

So, that is why increasing ΔT is not normally controllable, but increasing the surface area A, yes as and when you need you can do it, 'right". And we had said also in the fluid heat transfer that there is a parameter by which heat that is justified then only you can do, 'right". For conduction increasing k_f/d that value if you can increase. So, more the value up for a given d, more the value of k_f you have more conduction conductive heat transfer.

Increasing h by not relying on natural convection, but introducing forced convection we also saw that compared to natural convection or free convection forced convection has more heat transfer, ‘right”, the rate is a much much higher and increase h_r by using black surfaces. So, this is how we can optimize the heat transfer in 3 modes that is the conduction, convection and radiation.

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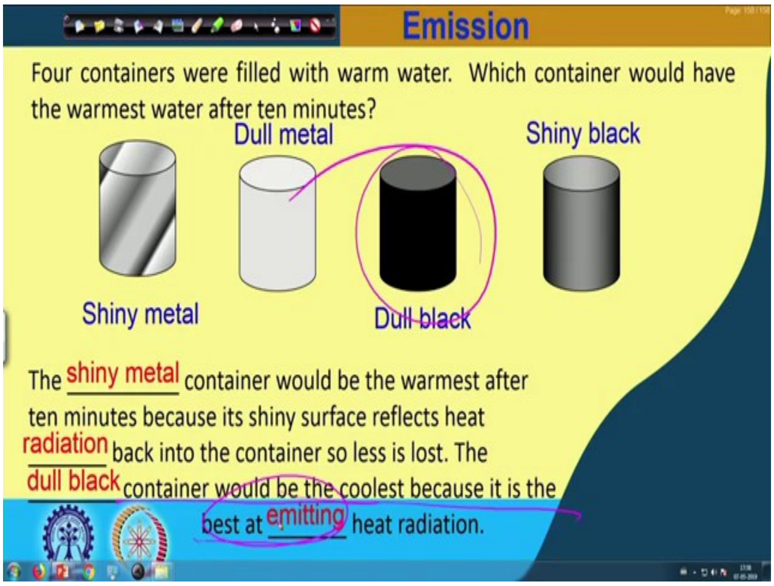

Emission

Four containers were filled with warm water. Which container would have the warmest water after ten minutes?

The shiny metal container would be the warmest after ten minutes because its shiny surface reflects heat radiation back into the container so less is lost. The dull black container would be the coolest because it is the best at emitting heat radiation.

Now, we have said earlier one term that epsilon or emissivity, ‘right”. So, that emissivity or emission how can we measure or to have some idea, let us look into this. Those 4 containers were filled with warm water, which container would have the warmest water after 10 min? One, shiny metal container with shiny metal, container made of dull metal, container made of dull black and container made of shiny black.

The question is which container would have the warmest water after 10 min all other conditions remaining identical. You have a container which that is made of shiny metal or a container the same size everything same, container content everything same is dull metal, then container with dull black and container with shiny black, which one is the one that will have the maximum temperature or a warmest temperature or condition of water which one will have? ‘right”.

So, the answer is the shiny metal container would be the warmest after 10 min. The shiny metal container would be the warmest after 10 min because its shiny surface reflects heat radiation back into the container. So, less is lost, ‘right” and the container with dull black would be the coolest, with dull black will be the coolest because it is the best at emitting heat radiation, ‘right”.

So, it is the best at emitting heat radiation. So, we have seen that we have taken if; that means, radiation is also a function of the material, ‘right” that we have given and once we have seen that some radiation is occurring or internal, ‘right”, so that is becoming the warmest, that is the shiny metal. That is why you will see in most of the cases; the walls are getting highly policed highly shining so that the reflection or radiation is taking place very well. That depends on the case to case how what you want to do the utilization, ‘right”.

So, with this let us complete this initial class of the radiation, subsequently we will also go into a little detail to find out the emissivity etcetera. Let us see how we are proceeding.

Thank you.