Fuel, Refractory and Furnaces

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Lecture No. # 30

Convection and Radiation Heat transfer, Role of Refractory

Today, I will be taking on transport phenomena and furnaces the role of convection and radiation in furnace design. Today I will be taking role of convection in furnaces. Now, some introductory remark, I had already given in my previous lecture, where I have said that convection heat transfer is associated with fluid motion. If you want to quantify the amount of heat transfer from one location to another, where motion of the fluid is involved? The first thing that, one has to do is to know, what is the velocity of the fluid? Unless you know the velocity of the fluid, you cannot quantified, how much amount of heat is transferred from one location to another location, when fluid is flowing?

So, accordingly in case of convective heat transfer, the fluid flow is most important. As I had already pointed out in my previous lecture that, if you want to predict or if you want to quantify the amount of heat transferred by convection then, there are two approaches. One approach is the differential approach or microscopic approach, in that you allow the fluid to flow through a volume element of delta x, delta y and delta z dimension, and then you do the energy balance and momentum balance. The whole idea of performing momentum balance is, to know the velocity and then, the equation of momentum balance is coupled with the equation of energy balance, in order to get the amount of heat transfer.

However, this is the most exact approach, but it requires a, very long computer calculations because the resulting equations cannot be solved analytically. They have to be solved by the use of numerical analysis, followed by computational calculations. However, in most of the engineering calculation, what is important is? How much amount of heat is being transferred, without going into much of the details about of the mechanism and so on, so far. So, for most engineering calculation purposes, it is sufficient. If, we can provide a quantified information about the amount of heat transfer and for that purpose, heat transfer coefficient.

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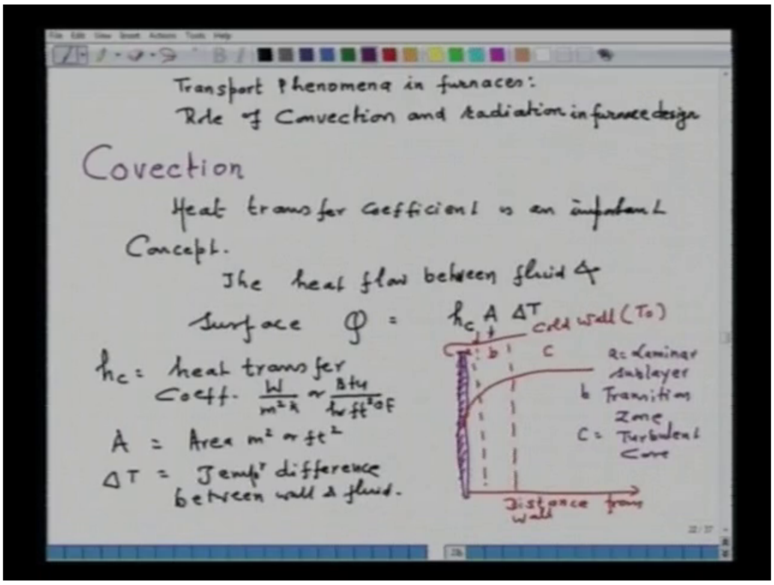

Is, an important concept. Now, according to this heat transfer coefficient the amount of or the heat flow say, between fluid and surface heat, that is equal to Q, that is equal to h c A into delta T. Where h c is the heat transfer coefficient, c is heat transfer coefficient and its dimensions are Watt per meter square Kelvin or it can also be express in terms of British thermal units upon, hour feet square degree Fahrenheit. A is the area either in meter square or in feet square and delta T is the temperature difference between wall and fluid.

Now, let us consider a temperature profile for a flowing fluid bounded by a cooler wall. That means, I will consider this is a cooler wall. Let us consider this is a cooler wall and the fluid is flowing in this direction, this is distance from the wall. So, as a fluid comes in contact with the cold wall so, let me say this is the cold wall at temperature T zero. So, as the hotter fluid comes in contact with this cold wall, it is at temperature T zero, which is very much lower than the hotter fluid, then the fluid immediately in contact with the wall, it its temperature decreases and as such the temperature profile will loop this particular way.

And here, we can characterize the different region, at this region is a, this is b and this is c. Now, the region a, is laminar sub-layer. Laminar sub-layer as you know, from the characteristic properties of fluid flow, as the fluid comes in contact with a wall, then the fluid in the immediate vicinity of the wall will have very low velocity. And its velocity will continuously increase as you move in the direction of the wall. So, b is transition zone and c is the turbulent core. So, fluid is flowing in this direction so, this is what the temperature profile of its flowing fluid, which is bounded by a cooler wall. Now as such we have to characterize now, the convective heat transfer.

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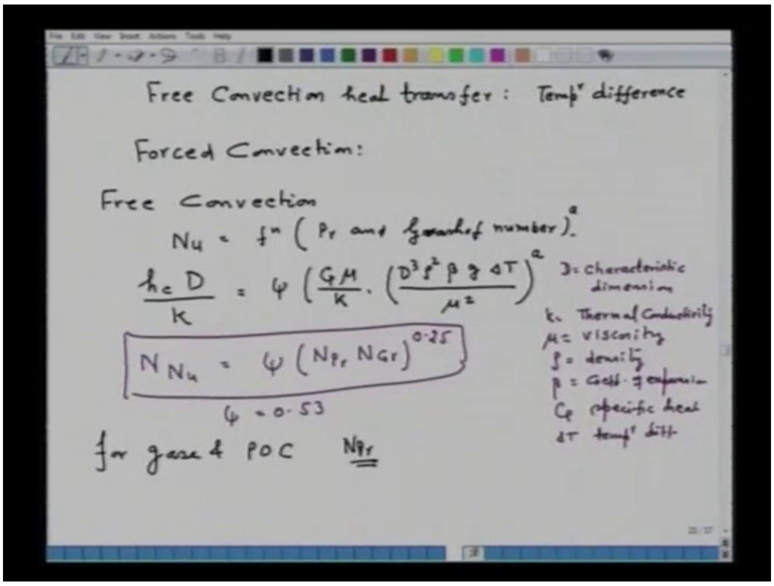

So, as such we have say, either forced, either free convection heat transfer and the free convection heat transfer is associated, because to the difference in temperature. So, here temperature difference is, temperature difference possess fluid to flow. Another mechanism is forced convection and in the forced convection, we possibly move the liquid for example, by pen by pump or in case of gas by blower by fan. So, here some sort of course, is applied for the movement of the fluid to occur so, this is in forced convection.

Now, both quantification of free a forced convection, it can be done in terms of heat transfer coefficient. The equation is such given Q, h c A into delta e; delta T. Now, here h c is the heat transfer coefficient. Now, just a little information about heat transfer coefficient remember, heat transfer coefficient is not a property of the fluid. Heat transfer coefficient is an empirically determine constant by way of experiment. That means, you have a cold wall, allow the fluid, hot fluid to flow and record temperature as the function of time and then invoke the equations to find out the heat transfer coefficient.

Therefore, heat transfer coefficient is very much empirically derived constant. It depends on, so many factors like, geometry of the surfaces like, temperature gradient. Whether it is a cube, whether it is a wall, whether it is a spherical shape everywhere, the heat transfer coefficient will have a different value. At what I wanted to say is that, that depending on the system under consideration for calculation of the heat transfer. You must search an appropriate empirical equation, to calculate the heat transfer coefficient. Otherwise you will be doing lot of mistake simply, because heat transfer coefficient is an empirically derived constant, is not a physical property of the system so, that an important thing.

So, now say heat transfer by free convection, in fact based on the result of several experiment empirically constant that, is heat transfer coefficient has been determine and it has been reported in the form of several correlation. For example, for free convection heat transfer coefficient, that is represented by Nussle number, that has been found to be a function of Prandtl number and Grashof number. Where Nussle number is say h c D upon K, that is equal to a constant Cp mu, that is the quanta number, upon K D cube rho square beta g into delta T upon mu square that is the Grashof number. And it is rest to the power some constant a, and the value of a, and g has to be determine by experiment.

Now, here D is characteristic dimension. Now, you must be careful for substitution of these values, characteristic dimension. Now, in this particular form, in which the equation is given, this is dimensionless. So, it does not matter whether you substitute the values in F P S system or S I system or M K system, but then if you choose, M K S and all value should be substituted in M K system in this particular formulation. K thermal conductivity of the liquid, mu is viscosity, rho density, beta is coefficient of expansion, C p specific heat and of course, delta T is temperature difference.

So, there are different type of correlation available, the one which have using solving, some of the problem based on free or forced convection heat transfer. That will be say N N u that is equal to let us, put it the constant G and N p r into N G r, that is equal to 0.25. So, this is the correlation for free convection heat transfer. However, here and there the value of the exponent and pre exponent that, vary for example, the value of G that is equal to 0.53.

Now, some approximation can be made particularly for gases, which are moving in the furnaces. So, for gases and products of combustion, the prenatal number is almost the constant value and does not depend much on the temperature and pressure. Now similarly, we can substitute the other properties say, viscosity or thermal conductivity coefficient of expansion specific of that of air, because air and P O C they are closely related in their properties.

So, in order to calculate the values of heat transfer in the problem, which I am going to give you, we will be using the following approximated correlation. However, the exact value, you can search from the literature or from the book and use that value. What I will be doing now, if I substitute the other properties like, thermal conductivity, viscosity density, coefficient of expansion so on, they because air and P O C they closely relate.

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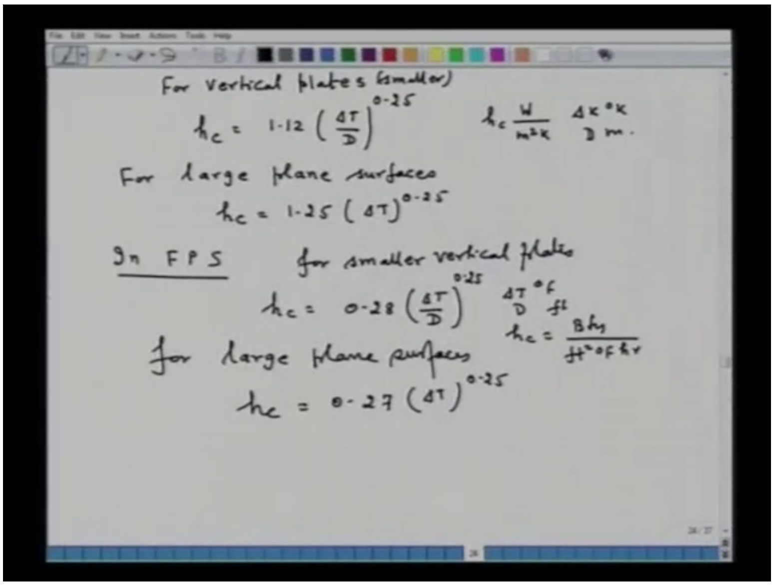

So I will be getting say, for vertical plates h c can be calculated from 1.12 delta T upon D raise to the power 0.25 now, mind you here, this is a dimensional equation. Therefore, h c it has to be substitute h c, you will get in watt per meter square Kelvin. So, delta T substituted in degree Kelvin and D in meter. Also for large plane surfaces, we will be using h c that is equal to 1.25 delta T whole to the power 0.25 this is for the large plane surfaces. Now, the same in F P S system, for vertical say for smaller vertical plates, this is also in the for vertical plates, smaller size then put it on a smaller size, h c that is equal to 0.28 delta T upon D.

Now, here delta T is in degree Fahrenheit, D in feet and h c you will be getting in B t u feet square degree Fahrenheit hour. For large plane surfaces h c that is equal to 0.27 delta T raise to the power 0.25 here is also 0.25. So, these are the equations, some of them depending on the geometry of the furnaces involved and depending on the calculation that will be useful for furnaces. These are the correlation for heat transfer coefficient, when there is free convection for example, the heat loss from the wall of the furnaces to the surrounding. That is the case of free convection then we will be making use of one of the correlation that, I will illustrate at the time of problem solving.

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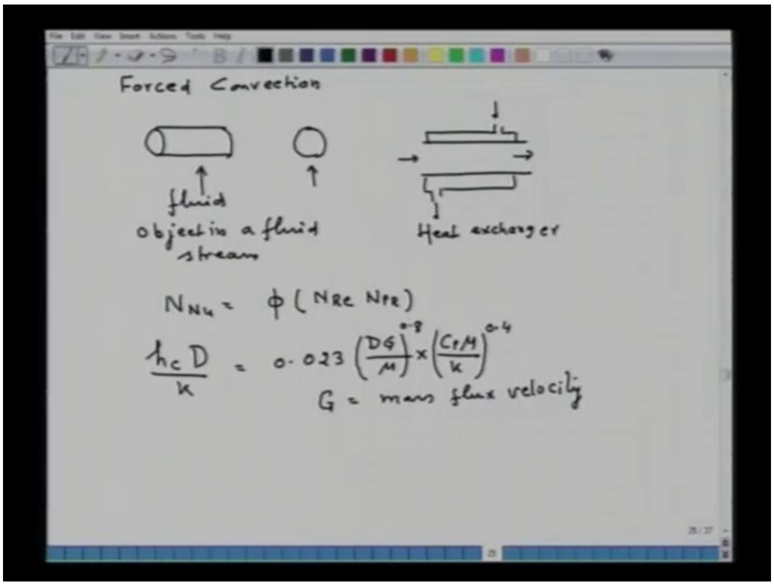

Now similarly, for force convection heat transfer, there could be several case, for example, you have a cylindrical object or a sphere, where fluid is moving or fluid is striking this For example, object in a fluid stream. These are the example of force convection heat transfer, another example you can think of is that of the heat exchanger say here, fluid in here fluid out, hot fluid in hot fluid out, this typically an heat exchanger. Similarly, regenerator recuperator they are all cases of force convection heat transfer and heat transfer by force convection, the correlation is an Nussle number, that is equal to a function of Renaults number and Prandtl number. Now, the Renaults number is entering because the liquid is moving.

So, the correlation which will be using h c upon into D upon K, that is equal to 0.023 D G mu, which is the Renaults number into C p mu upon K, this raise to the power 0.4 and this is raise to the power 0.8. So, that is the correlation, we will be using here, G is the so called mass flux velocity. So, this is what? The co-relation will be using for the determination of heat transfer by forced convection. So that is what, the evaluation of heat transfer by free or forced convection for example, in case of free convection, the heat loss from the furnace wall. For forced convection suppose, the hot gases are flowing in a duct or hot gases are flowing in the heat exchanger.

So, these are all the examples of forced convection heat transfer as related to furnace, the application of these equation we will see, when I solve the problem. So, I will, this I want to proceed the next mechanism.

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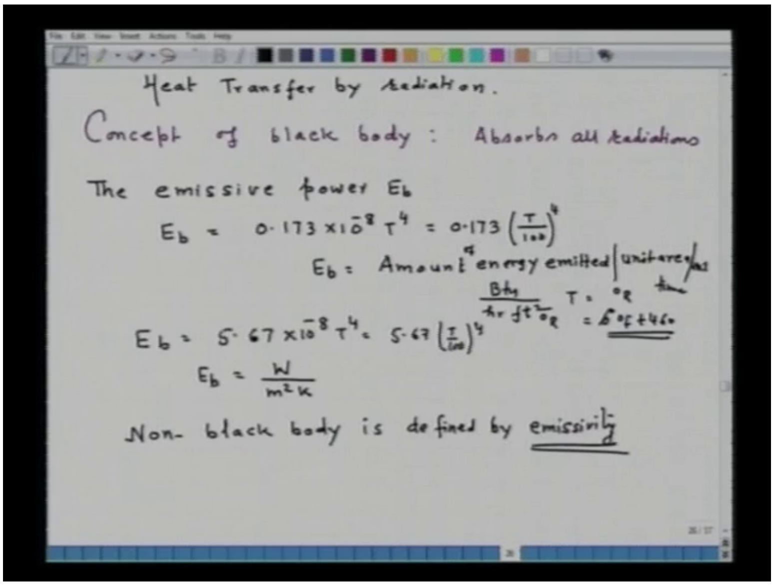

That is the heat transfer by the radiation. Now, as we know, the energy is continuously radiated or emitted from the surfaces of all bodies, in the form of electromagnetic waves of various wave lengths. So, that is in fact, the mechanism of heat transfer, where electromagnetic waves of various wave lengths are involved depending on the temperature of the hot bodies. So, about hot bodies, is always emitting the radiation. Now, the rate of radiation of heat from surface, it increases with the forced power of the temperature. That means heat loss or heat emitted by radiation is proportional to the forced power of temperature.

Therefore, at high temperature, the heat transfer by radiation is a very, very important mechanism of heat transfer, because the heat is being loosed or gained depending upon, what you are dealing? It is the forced power of the absolute temperature and the famous Stefan's Boltzmann law is that, it relates the emissive power of the black body, with the absolute temperature. Now, before that the concept now, in radiation heat transfer the concept of black body is important.

Now a black body it absorbs all radiations, that fall on it and reflect non. So, according to Stefan's Boltzmann law, the emissive power of a black body say, E b. Then we can say E b, that is equal to 0.173 into ten to the power minus eight T to the power four or you can also write down 0.173 T upon 100 raise to the power four. Where E b is the amount of radiant energy emitted per unit area. So, E b is the amount of energy emitted per unit area that is in fact, it is a flux and per unit time, that is a flux.

So, in this formed this e b the dimensions are B t u per hour feet square. Now, in this equation T has to be substituted in degree ranking, that is equal to degree Fahrenheit plus 460, that point is to be remember. Now, in M K S system, E b that is equal to 5.67 into ten to the power minus eight T to the power four, that is also equal to 5.67 T upon 100 raise to the power four. Now, here E b that will get in watt per meter square kelvin so, these are the say, basic equation for the rate of emitting or the emissive or the amount of energy emitted per unit area and also per unit time.

So, an important thing in case of radiation is that, black body is an idealized concept, just to represent an, understand and quantifying the amount of energy radiated per unit time per unit area. In fact, the behavior of all non-black bodies is rather is defined by term called emissivity. So, emissivity is an important concept in case of radiation, which defines the amount of energy radiated per unit time, per unit area of any surface that is what the important of concept of emissivity.

Now, so far we have consider the amount of energy radiated for one body. Now, let us consider the heat exchange, because in fact the amount of heat which is radiated by one body, it will fall on another body. That body gets heated up, it will also emit radiation and the first body also receives the radiation which is emitted by the other body. So, what I taking about is, what we are interesting is, the rate of heat exchange between any two surfaces A 1 and A 2, which are black in nature.

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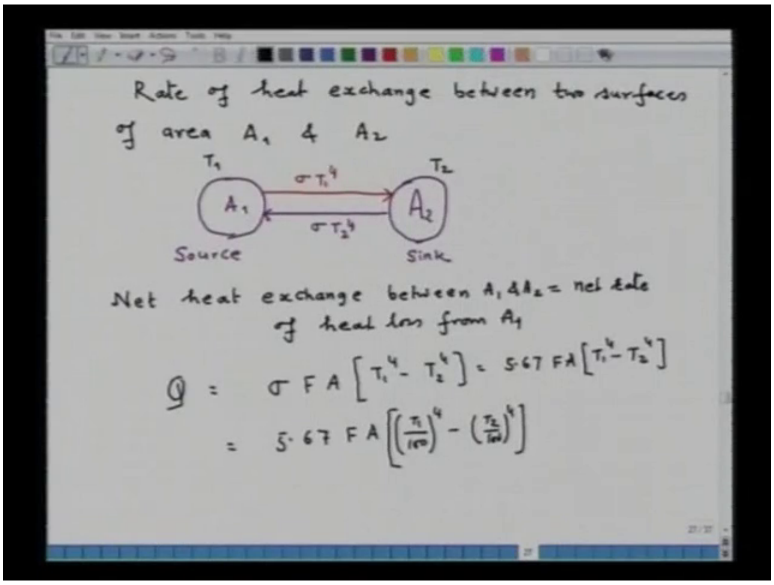

So, what we are interested in fact, the rate of heat exchange between two surfaces say of area A 1 and A 2. So, let us call, this is surface area A 1, this is area A 2. Now, what will happen? A 1 is a source and A 2 is a sink, let me put, A 1 is a source and A 2 is a sink. So, what A 1 will do? A 1 will emit the radiation, that radiation will strike the surface A 2 the amount of energy radiated per unit time per unit area by area A 1 that will be equal to sigma T 1 to the power four. Now, after a while, what will happen? A 2 will be heated up, A 2 will also be begin to radiate, and A 2 will also radiate, and it will fall on A 1. What is emission rate of emission? Sigma T 2 the power four.

So, net heat exchange between A 1 and A 2 that will be, equal to net rate of heat loss from A 1. A 1 is the source and A 2 is the sink. So, what a amount of heat A 2 will be receiving? Heat will also emit so, the net heat exchange in between A 1 and A 2. What we are? We are expressing in terms of rate of heat loss from the surface A 1, which is the source. So Q which is the rate of heat loss that is equal to now, one more thing is important for the radiation, which is not in any other mechanism for example, conduction or convection.

What section of the radiation, of the source is sink by the surface or by the sink, only that particular section will be heated up, with this, what I want to say? That if the source is A 1, which is emitting radiation in all the direction. If the sink A 2 tends the, only a fraction of radiation, then the so, then that fraction of radiation in case of radian, in case of heat transfer by radiation. That means the geometrical arrangement of the two surfaces is the most important, while describing or while quantifying the heat transfer by radiation.

Because if, you use a common sense in radiation that portion will be heated up, which is seen by the radiating flux? Which is arriving from the source? So that is here, the rate of heat transfer or heat loss, it is defined in terms of sigma, where sigma is the Stefan's Boltzmann constant, into F into A T 1 to the power four minus T 2 to the power four or that is equal to 5.67 into F into A T 1 to the power four minus T 2 to the power four. Or we can also, write down 5.67 F into A T 1 upon 100 to the power four minus T 2 upon 100 to the power four. So, that is the heat exchange between the two surfaces A 1 and A 2.

Now, here you must have all the variables are known to you, T 1 is the temperature of the source, that is for example, this is T 1 is a temperature of source and T 2 is a temperature of the sink A is a area of the source and F is a dimensionless composite factor.

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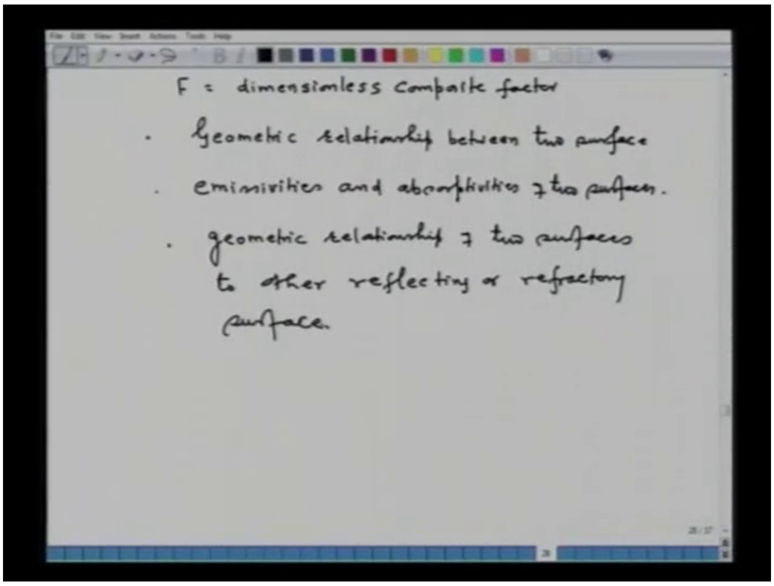

F is dimensionless composite factor and for your information, it is a evaluation of F that is the most important part in case of heat transfer by radiation. Now, this F it takes into account, the geometric relationship between two surfaces that is, how the source and sink are arranged? Whether sink is bigger source is smaller, source is bigger sink is smaller or source is inclined and all sort of configuration that we can think of. That is taken into a account by a so called dimensionless composite factor, as it also takes into the account emissivities and absorptivities and of two surfaces. And it also, takes into account the geometric relationship of two surfaces to other reflecting or for example, refractory surface.

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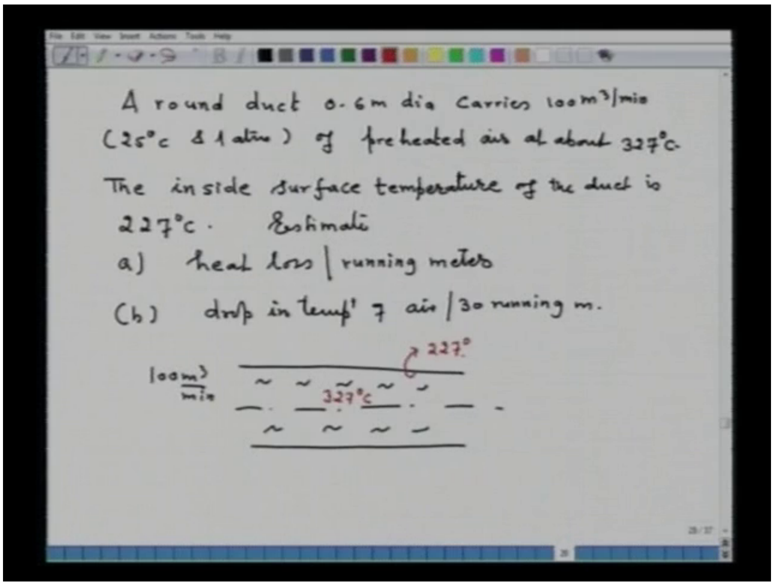

So, let me illustrate by a problem say, a round duct 0.6 meter dia carries 100 meter cube per minute, express at 25 degree Celsius and 1 atmosphere pressure of pre heated air at about 327 degree Celsius. The inside surface temperature of the duct is 227 degree Celsius. Now, estimate (a) heat loss per running meter and (b) drop in temperature of air for 30 running meter. So, this is typical, the gas is flowing in a duct, it has certain velocity, because its diameter is given 2.6 meter, a gas is flowing at the rate of 100 meter cube per minute.

So, if I want to represent the problem so, this is the duct and it is carrying say, 100 meter cube per minute of gas at this temperature here, is given to us 327 degree Celsius. This inside temperature of the duct is given to you, 227 degree Celsius. So, the gases flow heat transfer will occur, because of the difference in temperature. This is a typically a problem of forced convection heat transfer, because the gases are flowing at a particular speed. So, depending on its speed, heat transfer or heat loss from the pre heated air will occur and that you have to estimate. Now, immediately say question of heat transfer by forced convection.

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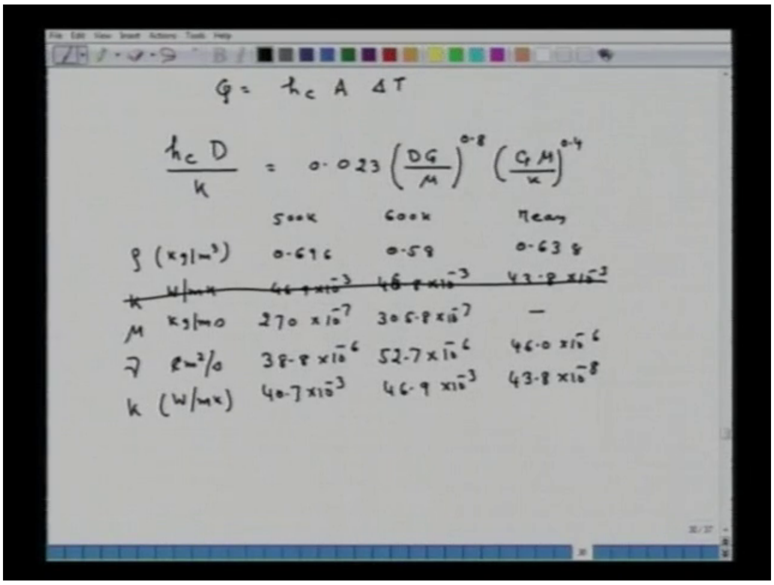

So, we know that, the heat transfer that is Q, that is equal to h c A into delta T. h c is the heat now, h c is the heat transfer coefficient so, the value of heat transfer coefficient can be determine. Just now, I illustrated the correlation K, that is equal to 0.023 D G mu raise to the power 0.8 C p mu, upon K raise to the power 0.4. So, through this correlation K, that is equal to 0.023 D G mu raise to the power 0.8 C p mu upon K raise to the power 0.4. So, through this correlation, we can find out the value of heat transfer coefficient.

Now, what is required here? In evaluating the properties of the fluid that is flowing here, in this example is air, one has to use the properties at the mean temperature of the fluid. So, here the temperature is 500 Kelvin and 600 Kelvin. So, we will take the properties, for example, we have to find out the properties I am giving you say, density, thermal conductivity, viscosity and kinematic viscosity. So, density is in kilo gram per meter cube, K watt per meter Kelvin mu kilo gram meter per second and kinematic viscosity in meter square per second.

So at 500 D G Kelvin and 600 Kelvin so, density is 0.696, here it is 0.58, here it is 46.9 into ten to the power minus three, here it is 43.8 into ten to the power minus three, here it is 43.8 into ten to the power minus three, here it is 227 into ten to the power minus seven, here it is 305.8 into ten to the power minus seven, here it is 38.8 into ten to the power minus six, here it is 52.7 into ten to the power minus six. So, the mean value in take, say density becomes 0.638, here it is 43.8 into ten to the power minus three now, here this value is 46.8.

So, mu we do not need because I took the kinematic viscosity so, it is 46.0 into ten to the power minus six. I write once again, the value of K that is K, which is watt per meter Kelvin. The value of K is 40.7 into ten to the power minus three and here it is 46.9 into ten to the power minus three so, the mean value, 43.8 into ten to the power minus eight. So, that is what, we know all these values now, what we have to do? We will substitute in the formula to determine the heat transfer coefficient.

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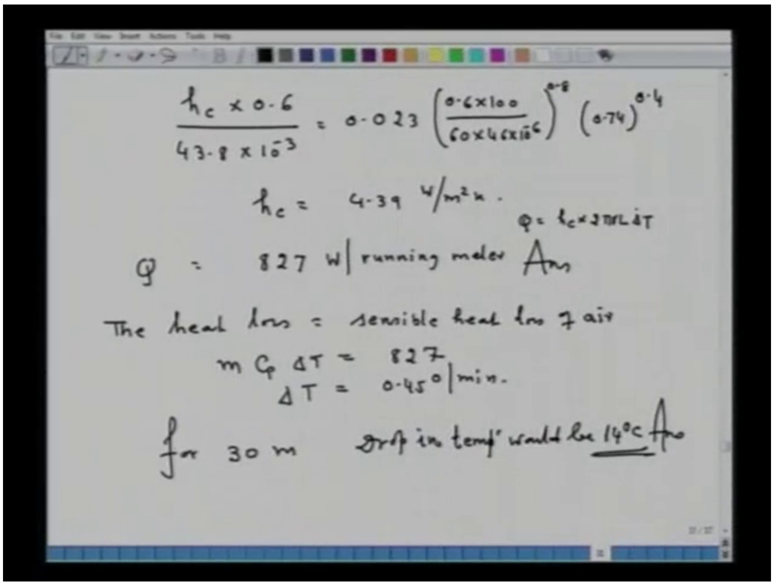

So I will just do for you so, that h c into 0.6 six divide by 43.8 into ten to the power minus three, that is equal to 0.023 0.6 into 100 upon 60 into 46 point, to ten to the power minus six or 0.8 and quantal number is 0.74 so, 0.74 raise to the power zero point four. So, if I solve the equation, I will be getting h c, that is equal to 4.39 watt per meter square Kelvin. Now, if I want to find out the Q, which is the heat loss per running meter. So I have to multiply by area, that is the pi d L so, that will be heat loss will be equal to 827 watt per running meter. You can find out Q, that will be equal to h c into 2 pi into 2 pi r L into delta T. So, you can find out from this.

Now, next we have to find out, what is the drop in air temperature for thirty meter; for thirty running meter? Because the drop in temperature is important suppose, you are integrating the a flow of air with some furnace, which is using pre heated air, then it is important for you to know, what is the drop in temperature? So, in fact this heat loss, which is 827 watt per meter, is in fact, the sensible heat loss by air, is it not? Because air is flowing at certain speed and in 1 meter length, it is loss around 827 that means it is loss is sensible heat.

So, heat loss is equal to the sensible heat loss of air so, once you know this, we can see, m C p delta T, that is equal to 827 and from here, we can determine delta T, that is equal to 0.45 degree per minute and for 30 meter the drop in temperature would be 14 degree Celsius. So, this is the answer and here, this is the answer. So, you see now, how easily one can estimate the heat loss in case of forced convection heat transfer. Now similarly, other type of problems can also, be taken by utilizing the concept of heat transfer coefficient.

Now, remember the concept of heat transfer coefficient is easy to perceive, but the most important thing is to find a suitable correlation. If you are unable to find the suitable correlation, then the values which you will be calculating, that will not be representing to the problem under consideration. The most important thing in utilizing the concept of heat transfer coefficient is only, selecting an appropriate correlation to estimate the heat transfer coefficient. I will repeat once again, because heat transfer coefficient is not a property of the system. It is an empirically derived constant and its value must be carefully determine, through using a suitable correlation, that is suiting or that is rather representing the problem under considerations.