Steel Making
Prof. Deepak Mazumdar
Prof. S. C. Koria
Department of Materials Science and Engineering
Indian Institute of Technology, Kanpur

Module No. # 01
Lecture No. # 05
The Science Base of Iron and Steelmaking

In calculating the rate of convective heat transfer processes, what I have indicated that although, we have a governing differential equation which requires knowledge of heat flow, we will not generally solve those equations, particularly, when you are trying to address convective heat transfer between solid and liquid or vice versa.

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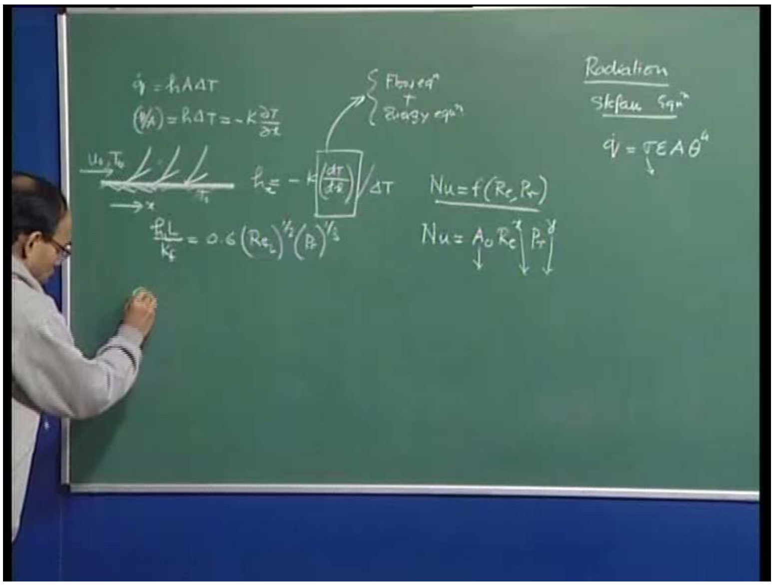

Instead, what we would like to do is to calculate the heat transfer coefficient and as I have shown you that the rate of heat flow is given in terms of a heat transfer coefficient and the delta T in which delta T is the driving force and the corresponding heat flux is q dot by A; this is minus K dT dx. So, this is the flux; this is heat transfer co efficient, differential temperature, thermal conductivity and the temperature gradient.

Now, as I have mentioned that in many classical situations, it is possible to solve the flow equation; it is possible to solve the energy equation - that is, the thermal energy balance equation. If you solve these two, for example, a classical scenario flow for a flat plate at which the plate is heated to a temperature of constant temperature of T 0 and the velocity is going to be V 0. Then by solving these equations applicable to this simplified boundary layer flow, one can calculate the temperature profile. So, at every point, you can may be calculate the temperature profile and then based on this temperature profile, you should be able to find out that what the slope of the line is.

Once you know the slope of the line, during the differential temperature, what is the plate temperature, here and the bulk temperature which is T sub b and you know the rising force, you should be able to calculate the heat transfer coefficient. So, heat transfer coefficient will come out to be minus K say, write it in terms of partial or ordinary, does not matter here in this case, the concept does not change and then have divided by delta T.

So, the driving force is known, wall temperature and the bulk temperature; bulk temperature is the temperature far away from this solid surface. So, this is the solid surface that I am talking about the flat plate. So, the bulk temperature is here; the bulk velocity or the free stream velocity is also here.

So, if we know the fluid flow equation, if you know the energy equation applicable to this, we can solve. Once we can solve, we can find out the temperature gradient. (Refer Slide Time: 03:13) So, this quantity will be known from the solution of this set of equations. Having known this, then I can multiply this newton thermal conductivity and I can divide it by the driving force and then I can obtain that what is the value of h. In this particular case, we can find out that will come out to be exactly. This is the flat plate for convective heat transfer correlation. So, this is the heat transfer coefficient - this is the plate average heat transfer coefficient which is because the slope of the line that is at every location. which is the function of This is the x direction and the slope varies at every location which means that the value of h also varies. So, this is called the local heat transfer coefficient and this is called h, the plate average heat transfer coefficient.

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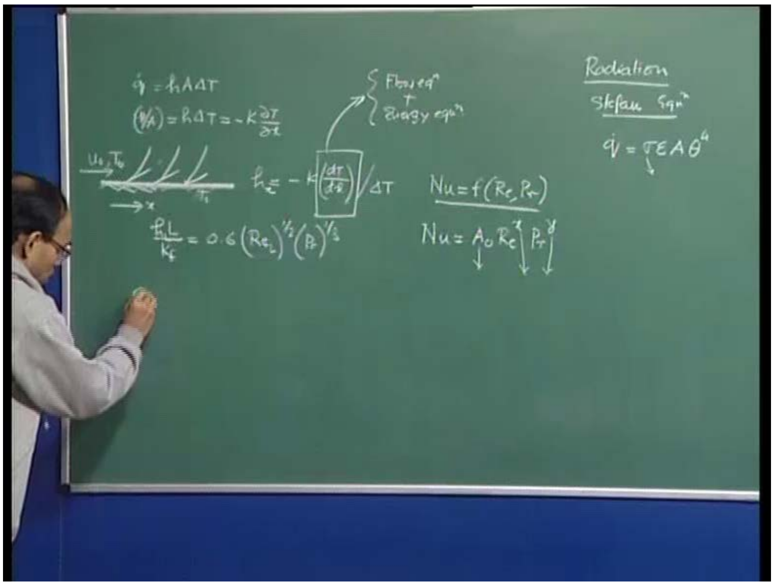

This correlation actually for such simplified scenario can be exactly derived by solving the applicable fluid flow and heat transfer coefficient, but as I have mentioned for complex scenario like those we encounter in steel making, you will not be able to solve these equations and derive this kind of a correlation exactly. So, what we are going to do? How we are going to have first convective heat transfer correlation is we are going to carry out experiments and based on that, we will determine that what is going to be the correlation.

For example, we can anticipate that this is going to be the correlation or we can say that the correlation could be something like Reynolds to the power x into Prandtl to the power y because that is what is expected from the few either most of the cases for forced convection this is the form of the correlation. If you Of course, it is a spherical geometry then as I have mentioned, we will add 2 preceding to this term.

Then the task would be to determine its 3 exponents, to determine exponents x and y and in order to determine the correlation and say that this is explicit from the correlation we have no option, but to carry out experiments in our laboratory and then provide a specific form of this particular generalized correlation.

So, this is for example, for many metallurgical scenarios - steel making process, we still do not know that what kind of a correlation exactly is applicable. So, we try to take correlations from the literature and make certain assumptions and try to obtain a firsthand estimate of the heat transfer coefficient, which may not truly be applicable. Also, one more important thing is that this sort of correlations are developed for flow of air over a flat plate, but in the case of steelmaking, we require correlations which we will be applicable to molten steel flows and as you all know, molten steel have largely different Prandtl number than with respect to the normal common fluid like air, water etcetera.

So, the characteristics of the boundary layer are going to be different because Prandtl number is a ratio of momentum diffusivity to thermal diffusivity. The characteristic of the boundary layer is a function of Prandtl number and we will anticipate that the characteristics of the boundary layer in molten steel system and air water systems in which the plane fluid is air or water is going to be somewhat different. So, there is some element of uncertainty when we apply this kind of a correlation in a straightforward fashion to steel making systems.

So I think enough is said about convection. We would now move on to the last mechanism of heat transfer, which is the radiation or the radiative heat transfer.

So, we know the rate law for heat conduction which is the Fourier's equation. Then we have rate law for radiation and that radiation is the Stefan's equation or the Stefan's law and it says that the heat flux or the rate of radiation heat flow is equal to sigma epsilon and if this is the weight of heat flow, then I will say that this is area into theta raise to four.

So, theta here represents the temperature, but this temperature is in the absolute scale. epsilon is the emissivity of the surface under consideration or absorptivity which is equal, A is the area and then sigma is the Stefan Boltzmann constant. As I have mentioned that radiation does not require a material medium; it is an electromagnetic wave basically. So, without a material medium heat can be transferred from one location to another location and this is precisely.

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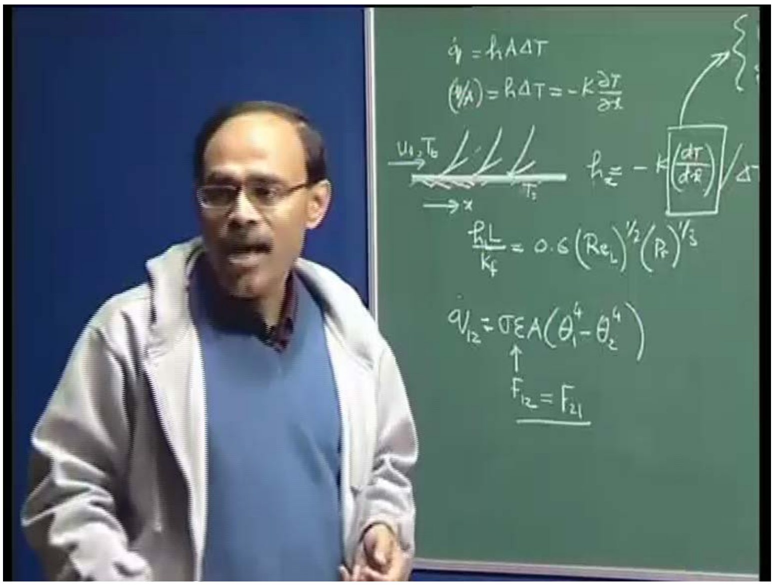

Now, if you are talking about radiation exchange between two objects, in that case, we would say that q 12 is going to be whatever heat one is radiating, an objective is radiating and it is going to be receiving some heat from the surrounding.

So, you can say that this is going to be equal to sigma epsilon A then theta 1 to the power 4 and theta 2 to the power 4. We must understand that while convective heat flux and conduction heat fluxes are proportional to temperature, the radiation heat fluxes are proportional to temperature raise to the power 4.

Now, this essentially tells us that as the temperature increases, the contribution of radiation is going to be extremely large. You imagine for example, solidified slab which is at a very high temperature may be surface temperature is about 1100 degree, 1000 degree centigrade and then you just keep it outside and on a normal day, you have breeze blowing over the slab. So, you have a convective heat transfer also and the radiation heat transfer also - radiation loss also and there you can see, if you are talking of this term this is going to be 1000 plus 273. So, there is going to be 1273 raise to the power 4 and the ambient temperature could be 25 degrees plus 273 which is 298 raise to the power 4 is the contribution of this term. It is enormous - the order of magnitude of this term is going to be enormous particularly at elevated temperature.

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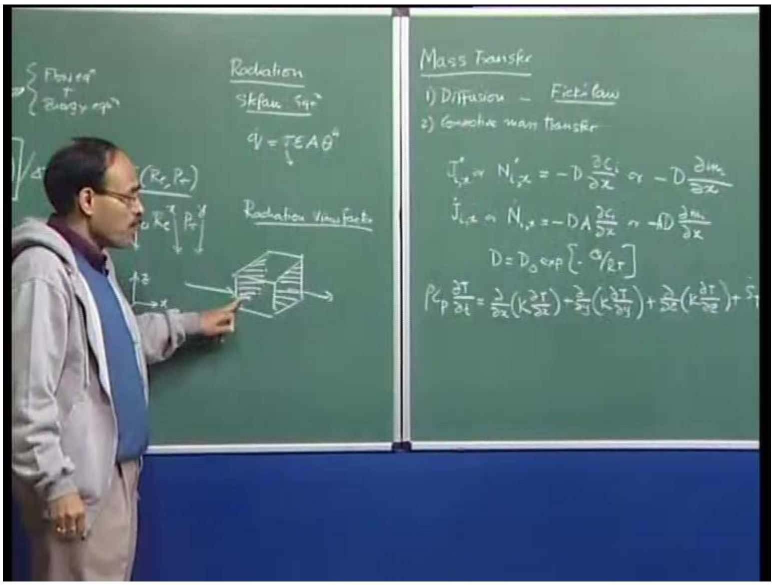

In radiation for example, one concept comes into the picture. There are many definitions like for example, a black body, you know what is a black body, what is a gray body etcetera. You know the Kirchhoff law in radiation and also reciprocity theorems. There are many such theories, which one has to know in order to do the radiative heat transfer calculations, but one important concept which comes to my mind is called the radiation view factor which is very important in calculation.

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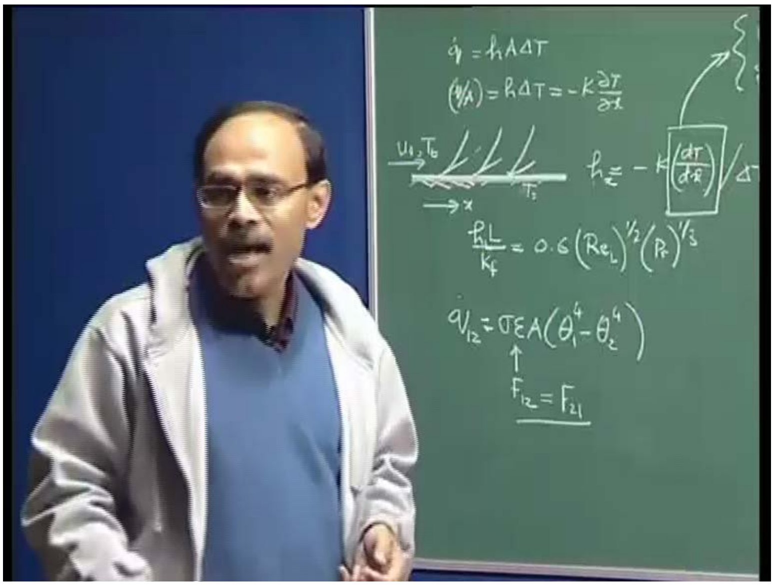

This expression essentially tells us that whatever radiation is given out by an object, it is received by the other object. So, 1 is receiving the entire radiation which is given out by 2 and therefore, we have written the net radiative heat exchange between the two objects 1 and 2 in this particular form.

But it may be the case that all the energy emitted by an object is not intercepted by the other object. For example, if you imagine that this board is an object and I am an object. (Refer Slide Time: 11:42) You know, I may be radiating energy in all directions and this particular board is going to be only getting the radiation which is going out from this particular surface. This radiation is going to be intercepted may be by the wall at the other end

So, a part of the radiation therefore, is going to be utilized, will be received by this and this brings us to a point where the view factor is to be determined.

For example, if you consider me, then this room is 1 object or I am there standing in the room or you imagine that the furnace is there and in the furnace, I have a solid ingot placed. Then the furnace is radiating energy in proportion to its absolute temperature raised to the power 4, but all these radiations are going to be intercepted by the solid object. Therefore, in this case, we can say that the radiation view factor is going to be equal to 1. On the other hand, the scenario just now I have said that I am standing here, the board is behind me.

So therefore, the radiation view factor within the board and me is certainly not equal to 1; it is going to be less than equal to 1 and therefore, in this particular case we have to introduce the radiation view factor in order F 12 and the reciprocity theorem says that F 12 this is equal F 21 and so on.

So I do not wish to go discuss radiation beyond this particular point, but as I said, it is very important in high temperature processes particularly in calculating heat losses etcetera. Conduction, convection and radiation are very important when you would like to address heat losses, when you would like to address melting rates of solids and so on.

You will see that I discussed deliberately the heat transfer a little bit more exhaustively because the flow of heat and mass are very identical, particularly, if you are talking of diffusive transport of material or mass diffusion. If you are talking of convective transport of mass, you will find that there is one to one similarity between heat transfer and mass transfer because we are talking about a subject of scalar transport, in this particular case and I have used the scalar quantity; mass is a scalar quantity. So, there is one to one similarity between the two.

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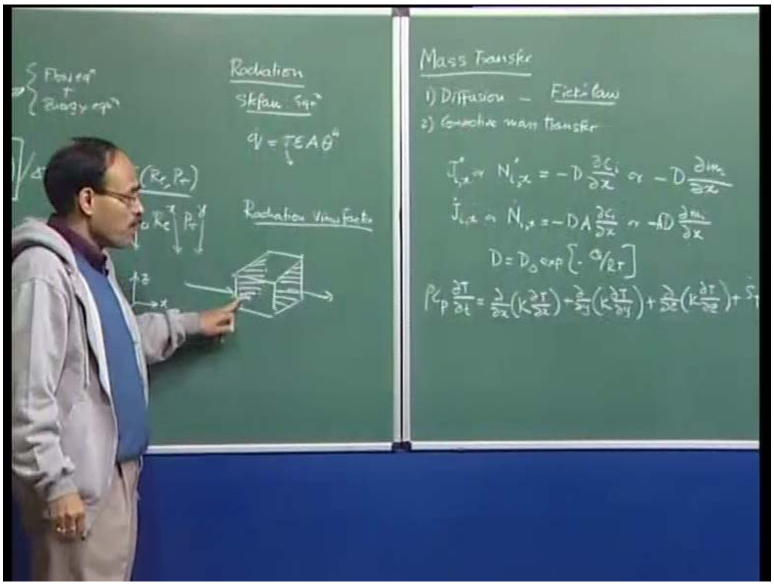

So, let us now talk about the relevance of mass transfer and once we have adequate knowledge of thermo dynamics, fluid flow, heat transfer and mass transfer, we can now calculate the rate of metallurgical processes and then we will move on to the metallurgical kinetics and that will be interesting. We will see how the concept of fluid flow, heat transfer and mass transfer are applied in order to calculate the rate of the metallurgical processes of steelmaking process.

Now, mass transfer is also extremely important in our case because we are talking about processing operations; we are talking about transfer operations where there are interactions among phases; there are interactions between metal and refractory; there are interactions between metal and slag and these interactions precipitate into mass transport and the driving force for the mass transport is actually concentration gradient. More accurately, it is the chemical potential gradient that gives rise to mass transfer and in many situations, for example, while we talk about steel making, you have a casting and then in the casting, you have lot of segregations sand casting lot of segregation which you know is a coring and you rotate the sand casting to a heat treatment furnace and after sometimes you get homogeneous structure because what happens, whatever has been segregated now, there are regions of higher concentration and regions of lower concentration. So, under the influence of heat, you are trying to diminish that concentration gradient and thereby, you are causing material to move from the region of higher concentration to a region of lower concentration.

You will be talking about mass transport in de-sulphurization, where you are concerned about transferring sulphur from metal to the slag. You would be talking about mass transport when you are doing kinetic degassing or vacuum degassing operations. How? Because you have dissolved gases in the melt and now you want to try to drive that dissolved gases into the ambient atmosphere. So, there is a transport of dissolved gases like nitrogen, hydrogen etcetera from the melt into the ambient. Here, we are talking about mass transfer.

So I can go on and on. Mass transfer is a basic characteristic and beyond mass transfer also, we will see that there are chemical reactions involved and I will completely isolate mass transfer from chemical reaction. Please do not confuse between chemical reaction and mass transport.

Chemical reaction means the combination bond making of bonds and breaking of bonds. These are the essential features of chemical reaction, but mass transport receives chemical reaction. First the material has to come to a place, the reactants have to come to a place and then the 2 reactants can collide with each other. Then the new bonds can form or bonds can be broken. So, mass transfer basically precedes chemical reaction; mass transfer also follows chemical reaction, when the products have to be removed from the side of the reaction.

Now the phenomenological law of mass diffusion: Again, we have diffusion as the mass transfer mechanism and convection; there is one to one similarity between mass diffusion and heat conduction. So, we had Fourier’s law in heat conduction, for diffusive mass transport, we have what is known as the Fick’s law. Fick’s law states that flux which could be mass flux denoted by J or molar flux. Flux of what? Flux of a species i, J is the mass flux, N is the molar flux of a species i. Flux is a vector quantity; so, I will specify in which direction. We can say this is equal to minus D and the net weight of transport we can say so the flux typically is denoted by this. So, I would say that J i x which is the net rate of transport or so C could be mass concentration or molar concentration you can say that it is either this or minus D, but we are talking about mass flux; we are talking about concentration in mass units. We are talking about molar flux; we are talking about concentration in molar unit. So, this is moles per centimeter cube or moles per meter cube. This could be mass per unit volume which is essentially is equal to density or dimensionally equal to density.

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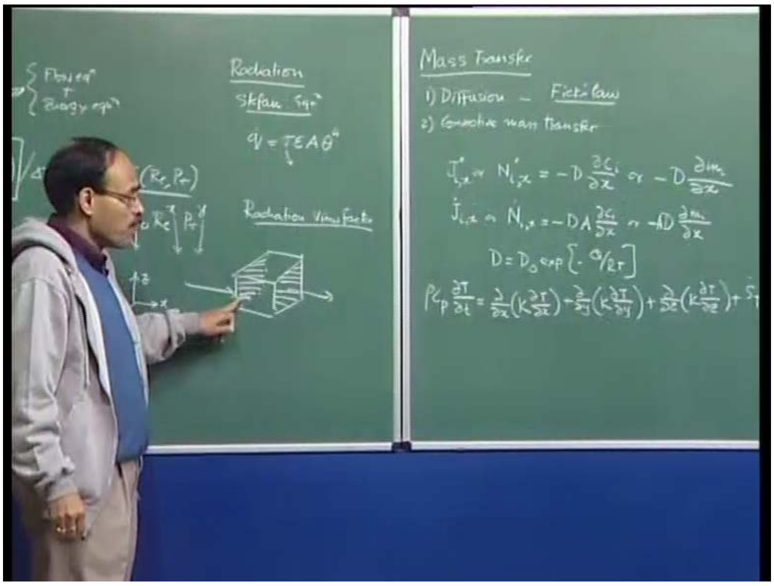

Therefore, this is going to be equal to nothing, but area. Fick’s law, we must understand that these equations we have expressed in terms of concentration, but in multi component system, the concentration is not the correct entity; the correct entity is going to be chemical potential because you may have read about the Darken’s experiment whereby, it was possible to transfer mass from a region of lower concentration to a region of higher concentration. It is because of a simple fact that a region of lower concentration actually of carbon, the activity of carbon was higher because of the solutal interactions.

So, superficially you see that mass is moving from a region of lower concentration to lower weight percentage value to higher weight percentage value, but in terms of activity or chemical potential, the lower concentration actually means or lower concentration actually is a higher activity or higher chemical potential and that is how, the driving force, more accurately speaking is not the mass concentration or mole concentration, but will have to have chemical potential or activity, while we are talking about only single component. For example, one single component which is diffusing, in that case, the concentration activity and concentration is at the minimum. So, there is no issue on that particular mass.

Now this equation, D is the diffusion coefficient and again this is like thermal conductivity; we have this diffusion coefficient which is the thermal attributed process and so, it follows a weight equation like exponential. So, the diffusion coefficient is a state property just like thermal conductivity, it depends on the temperature under consideration.

So, if you know the temperature, you will know the diffusion coefficient and to know the flux or the net rate of transport, what is needed is the concentration gradient. However, on a thumb rule, we will say that material moves from a region of higher concentration to a region of lower concentration.

There is one to one similarity between D and K. So, this is the molecular transport mechanism. Therefore, this is the only mechanism of mass transport within solid, but just like the way I said that in liquids both conduction and convection are going to be operative - convective heat transfer or conductive heat transfer. So, in liquid we will also see that material diffusion is there as well as convection is also there.

We must remember that there is no counterpart of radiation in mass transfer. It is well known that mass requires material medium to be transported unlike heat which does not require a material medium to transport.

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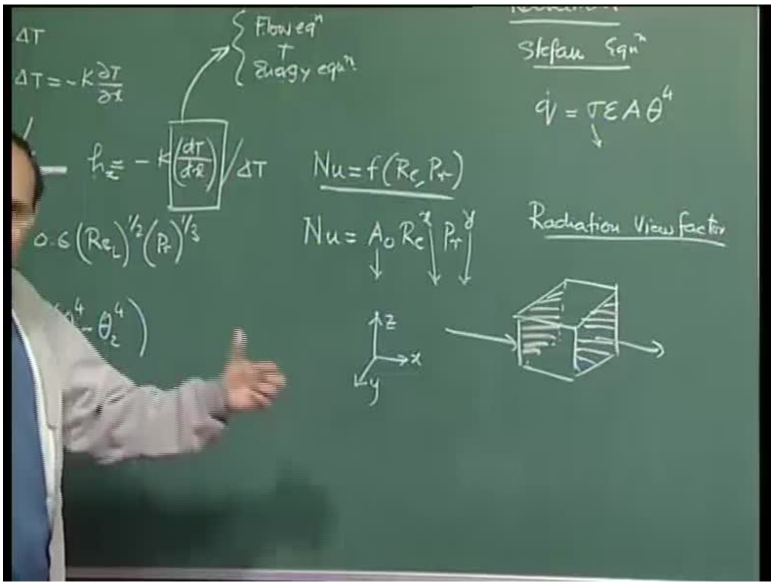

Now, using this basic phenomenological description of diffusion or Fick’s law, we should be able to do a control volume analysis, which we have done already in the context of mass transport or diffusion and do a balance amount of mass or material coming in through the control volume and amount of mass leaving through the control volume in all 3 directions z, x and y plus the net rate of mass generation, which could be because of chemical reaction taking place between two species. This could be the net rate of accumulation of mass in the system.

So, a similar equation which I have written earlier, if you remember what I have done, I wrote the corresponding heat conduction equation. (Refer Slide Time: 23:36) So, that is the expression which I wrote in the previous lecture - the conduct energy balance within a solid object unsteady state. So, the net rate of accumulation of heat is equal to net flux of heat in the x direction, y direction, z direction due to conduction plus the net rate of heat generation.

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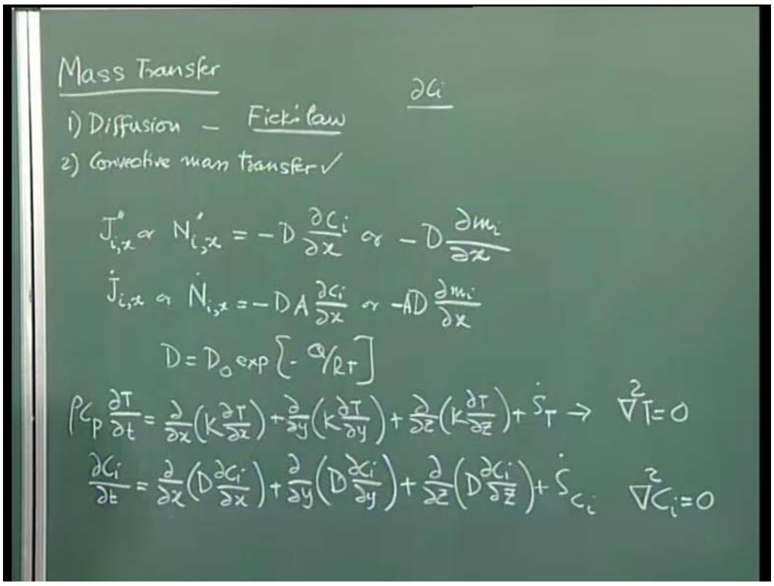

Mass Transfer

1) Diffusion – Fick's law

2) Convective mass transfer ✓

$\frac{\partial C_i}{}$

$$J''_{i,x} \text{ or } N''_{i,x} = -D\frac{\partial C_i}{\partial x} \text{ or } -D\frac{\partial m_i}{\partial x}$$

$$\dot{J}_{i,x} \text{ or } \dot{N}_{i,x} = -DA\frac{\partial C_i}{\partial x} \text{ or } -AD\frac{\partial m_i}{\partial x}$$

$$D = D_0 \exp\left[-Q/RT\right]$$

$$\rho C_p\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) + \dot{S}_T \rightarrow \nabla^2 T = 0$$

$$\frac{\partial C_i}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial C_i}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial C_i}{\partial z}\right) + \dot{S}_{C_i} \quad \nabla^2 C_i = 0$$

There is a one to one similarity now. I can say that the corresponding mass equation could be. So, there is as you see, one to one similarity between mass diffusion and heat conduction; see replace K by D, replace T by C sub i and you get the same equation. Note that, if I take K divided by rho C p, that becomes the thermal diffusivity which is synonymous to mass diffusivity and both of them have unit as meter square per second.

So, if you can write one equation, you should be able to write other equation. Also, the simplified form of this, just like the way I have told yesterday. Well, we can say that this is equal to 0 for constant thermal conductivity under steady state condition with no heat source term. The equation boils down to this - divergence at Y is equal to 0. Similarly, this equation will also. For steady state case, that means, this derivative is 0, no mass source term and constant diffusion coefficient, this will also falls down which is nothing, but the popular Laplace equation.

So, if you can solve this equation now, you should be able to find out what is the concentration gradient, what is the concentration field. Having known the concentration gradient, we should be able to find out the fluxes or we should be able to find out net rate of transfer by multiplying the former with the relevant area through which mass diffusion is taking place. Just like the way these equations require boundary conditions that means at the surface of the object, you have to have flux of temperature provided. Similarly, for this also in the 3-dimensional domain, you have two values of xs; you have six different phases; you are considering a 3-dimensional domain; mass transport eliminates y and z.

So, you have domains x is equal to 0 and x is equal to l; y is equal to 0 and y is equal to b and z is equal to 0 and z is equal to h. So, there are 6 bounding surfaces and all these bounding surfaces, you have to specify what is the value of C i in terms of either its absolute value or in terms of flux.

So, given the initial condition, given the boundary conditions, in terms of either mass flux or concentration profile, you should be able to solve this equation. If you solve this equation, you will know C is a function of concentration, as a function of distance. Once we know concentration as a function of distance, we can evaluate the derivative and find out the corresponding mass flux along x, y, z direction.

Now, coming to convection, again we have the same kind of an equation that we have seen in the context of heat transfer. When you try to calculate convective mass transfer rates Let me just tell you one thing. So, diffusion - why we are going to calculate diffusion? Rate of diffusion would be relevant just like the way I gave you an example of ingot heating to explain the relevance of heat conduction. So, mass diffusion could be completely relevant or you know totally controlling the mass flow. For example, flow of carbon in a core structure or in a casting.

So, within any solidified object, if there is a concentration in homogeneity and you are trying to move this from one location to another location, getting the homogeneous structure in that case, you can see that within the solid, the flow of material from one point to another point is going to be purely by diffusion.

On the other hand, when you talk of convective mass transfer, that means, the mass transfer is now aided by fluid motion and whatever I said about convective heat transfer yesterday is going to be totally applicable to convective mass transfer as well. Therefore, in order to calculate the convective mass transfer rate, it is understood, I repeat again, we will require the fluid flow to be known first. So, having obtained the flow, our objective could be to calculate the mass transfer rates and the convective mass transfer equation will exactly look the same as we have done in the case of a

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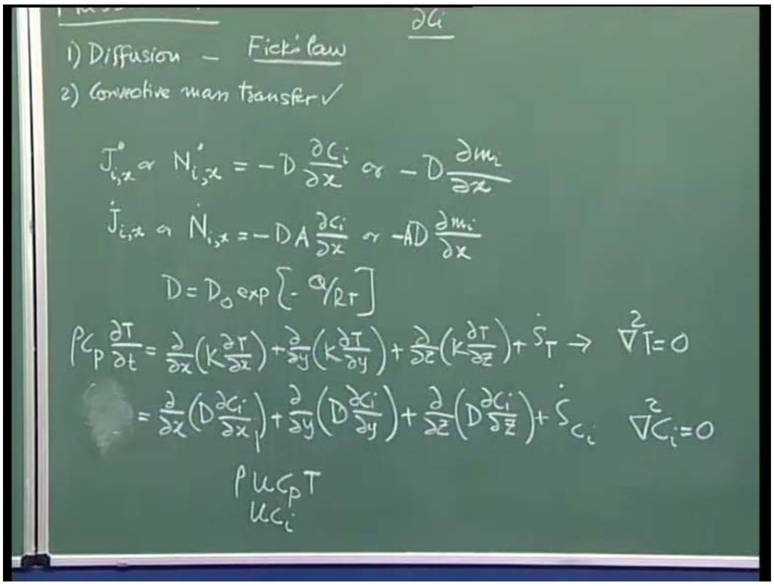

1) Diffusion – Fick's law

2) Convective mass transfer ✓

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$$= \frac{\partial}{\partial x}\left(D\frac{\partial C_i}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial C_i}{\partial y}\right)+\frac{\partial}{\partial z}\left(D\frac{\partial C_i}{\partial z}\right)+\dot{S}_{C_i} \quad \nabla^2 C_i = 0$$

$$\rho u C_p T$$
$$u C_i$$

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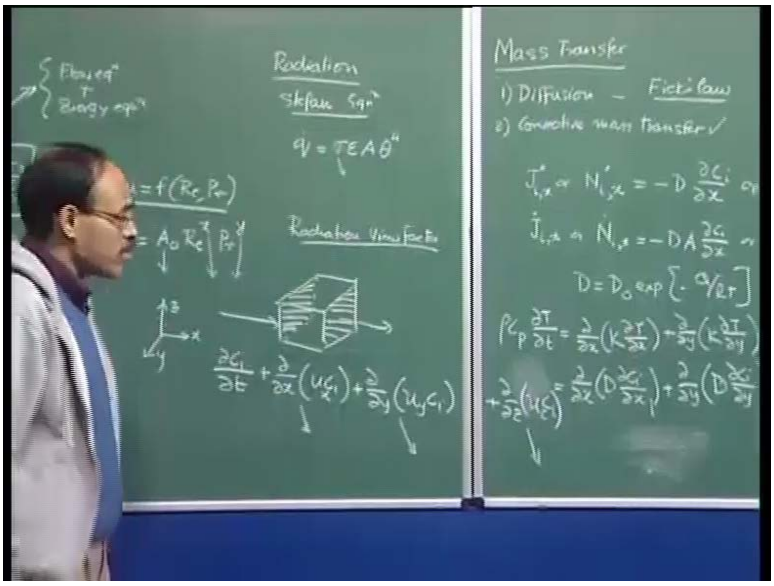

$$\frac{\partial C_i}{\partial t}+\frac{\partial}{\partial x}(u_x C_i)+\frac{\partial}{\partial y}(u_y C_i)+\frac{\partial}{\partial z}(u_z C_i) = \frac{\partial}{\partial x}\left(D\frac{\partial C_i}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial C_i}{\partial y}\right)$$

Mass Transfer

1) Diffusion – Fick's law

2) Convective mass transfer ✓

For example, yesterday whatever I wrote and today, the concentration, once you put in the convection term here, what we are going to see, the left hand side will look like, let me just erase this and then this is going to be easy. So, I can write it like this, If you remember whatever I had written. So, this is the original term and this is a diffusion flux. So, I have made a net flux expression and I said that along x direction, mass is flowing not purely because of diffusion and because we are talking of convective mass transport, mass is flowing because of convection also and the net flux was expressed that, within this bracket, I get this term minus the convective flux. which was something like For heat transfer, I said that this term looks something like this and in the case of mass transport, it is going to look something like u into C i.

So, therefore, we can say that, we bring this term here, you can look at your notes and then look at appreciate the similarity and say, the first order derivative and then we have u into C i, this is u x and in the y direction, we have u into u y into C i and then in the z direction you have u z into C i and then we have this particular expression. This is no more relevant; I just wanted to explain it to you.

So, these are the convective fluxes and in the previous lecture, when I wrote the corresponding heat flow equation, first equation I wrote was that. I brought in another term here and then in the second step, I transported this term with a negative sign to the left hand side and this is the convection along the x direction; this is the convection along the y direction; this is the convection along the z direction and more specifically, convective mass transport along x direction, convective mass transport along y direction and convective mass transfer along z direction.

So, the same sort of an equation we have - 3 terms from convection, 3 terms from mass diffusion, 1 source term and 1 unsteady term. So, we have 4 terms on the left hand side, 4 terms on the right hand side and exactly the same equation, as you would encounter in the case of convective heat transfer.

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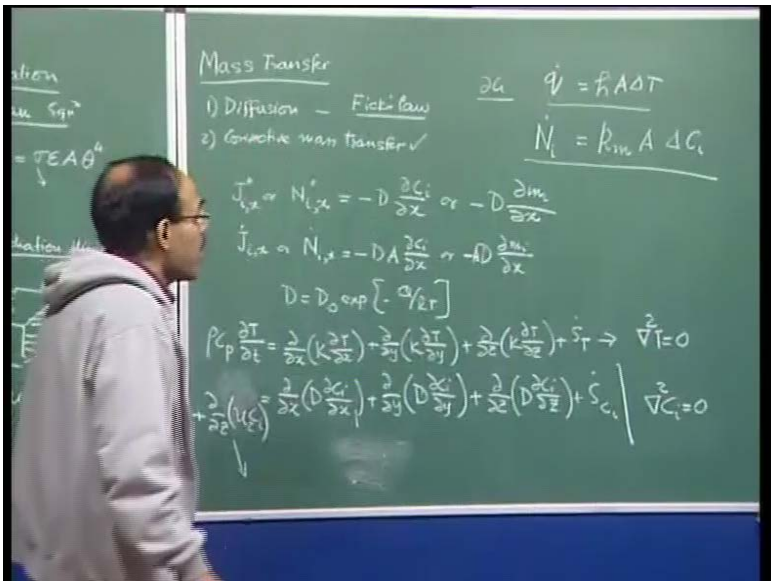

So, the same logic states that for every problem, we are not going to solve this kind of equation. We need a much more simplified approach and again there is one to one analogy between heat and mass transport and it is say that Well, we can say that mass transport is a first order process and therefore, you have a mass transfer coefficient and that mass transfer coefficient is k m and this k m multiplied by area multiplied by the driving force delta C i essentially gives us the net weight of transport.

Just like the way I said that the net weight of heat transport is equal to heat transfer coefficient into the area through which heat is flowing and multiplied by the temperature differential which drives the heat transfer, in the case of mass transport, you can see the similarity. So, the heat flux was q dot and then this is equal to h into A into delta T.

So, that was the rate of heat flow and now, N i represents rate of the mass flow and this k m represents the mass transfer coefficient. h is the heat transfer coefficient; k m is the mass transfer coefficient. h was a function of fluid flow; k m is also a function of fluid flow.

So, therefore, k m cannot be known unless and until, we have idea about the fluid flow. Indirectly to such expressions, we incorporate or through k m, we incorporate the influence of fluid flow in the system itself. In convective mass transport therefore, the main objective for calculation of mass transport rate boils down to the calculation of the convective mass transfer coefficient. If we can somehow calculate k m, in that case, delta C i will be known to us and this is a very interesting concept of thermodynamics really comes there in order to find out what that delta C i and I am going to explain to you subsequently, when we talk about metallurgical kinetics. The area which is relevant to transport will be always known to us and therefore, we should be able to calculate without much difficulty, the rate, provided we know convective mass transfer coefficient.

Now, just like the way we had a pre-convective heat transfer and post-convective heat transfer, we have pre-convective mass transfer and post-convective mass transfer. So, because of solutal concentration gradient, just like the way because of thermal gradients we have density difference in the system, which precipitates into some kinds of a loose convection current which we call as pre-convection.

Now, in the case of mass transport also if you have concentration gradients in a fluid and that concentration gradient can precipitate in density differential and again this density differential can induce some kind of a weak motion in system.

So, this is called solutal convection. Now if you have both pre-convection heat transfer and pre-convection mass transfer because of the temperature difference as well as because of concentration difference, we call that convection as thermo solutal convection. For example, the continuous casting; if you go towards the lower part of the bloom or the billet, where there is actually no stirring effect felt of the material coming through a c n, there, whatever flow you are going to see - heat flow that would be basically due to your thermo solutal convection because there is going to be temperature differential in the fluid as well as concentration difference in the system.

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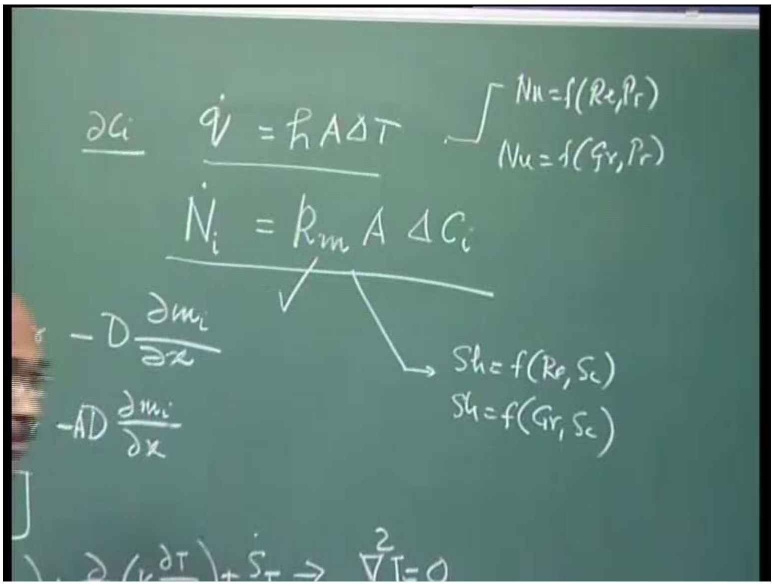

So, if we have force convection heat transfer, here we have Nusselt’s number as a function of Reynolds number and Prandtl number for force convection and Nusselt’s number is equal to function of Grashof’s number and Prandtl number in the case of free convection.

Similarly, we have in the case of mass transport, we have in place of Nusselt’s number what is called as Sherwood’s number, a function of Reynolds number and Schmidt number and Sherwood’s number as a function of Grashof’s number and Schmidt number this is called appendable; the material Grashof's number and this is the thermal Grashof's number; so, there is some difference between the two.

So, it boils down to, in convective mass transport that we have to have a correlation and based on that correlation, we should be able to calculate the corresponding Sherwood's number because we assume that the flow will be known to us and once we know the flow, we know the Reynolds number and once you know the Reynolds number, Schmidt number is equivalent to Prandtl number; only thing is in Prandtl number, we have thermal diffusivity and in Schmidt number, you have mass diffusivity.

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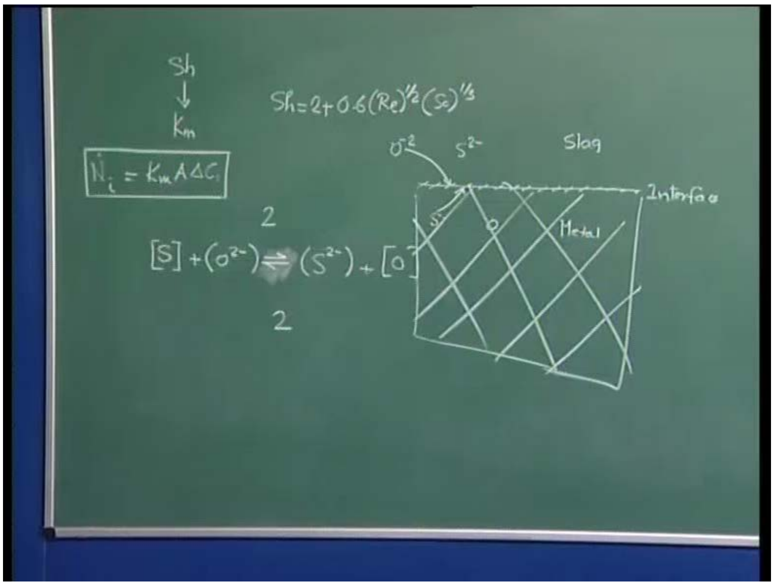

So, if we know Reynolds number, that Schmidt number is known. If a correlation is available, you will be able to find out what that Sherwood's number is equal to and once you the Sherwood's number, you will be able to find out that what is the mass transport coefficient and once you know the mass transfer coefficient, the task is now simple and you will multiply that mass transfer coefficient with area, you get the net rate of transfer. This now needs to be explained a little bit that how we obtain the differential concentration which is driving the mass transport in the system.

Now, there is lot of analogy between heat and mass transport. Therefore, many a times the correlation which is derived for some simple situations in heat transfer, they can be applicable in a straightforward fact manner to mass transport also.

For example, I have given you the Ranz-Marshall correlation for heat transfer. Similarly, Ranz-Marshall correlation for mass transport is, which is valid for laminar flow for a spherical geometry. So, you can see the analogy between heat and mass transfer, you know the similarities between thermal and concentration boundary layers and the similarities between correlations.

So, for every situation in mass transport therefore, we need not have to have a correlation. If a heat transfer correlation is available, we can convert that or make the correlation applicable to mass transport also. Alternatively, if you do not have correlations available for a given situation, we have no option, but to go back and carry out experiments and derive the coefficients.

Now, let us look at the mass transport and chemical reaction on which the concentration differential really is on the basis of which, concentration differential is estimated.

Suppose, let us look at a flux metallurgical process, a mass transport process. Suppose, we have an interface and this interface slag is here and metal is here. Suppose, we have So, this I say slag because I am going to use S and I say here, we have sulphur in the metal and eventually, we have sulphur 2 minus in the slag. So, we have oxygen 2 minus in the metal and what happens is that we get oxygen. So, how does the reaction What does this imply? This implies for example, calcium oxide.

So, this is the slag metal reaction which I can represent as S in metal plus O 2 minus in slag and if I consider the equilibrium for a moment and then I write S 2 minus in slag. So, this is the chemical reaction and now, if you look at it, this reaction essentially implies that this is phase 1 - metal; this is phase 2. So, it is a heterogeneous chemical reaction and this heterogeneous chemical reaction now takes place at these boundaries.

In order that the reaction takes place in the phase boundaries, we would like to have sulphur from the bulk moving to the metal. We have to have oxygen ion meeting slag material. Then a chemical reaction takes place and once the chemical reaction takes place, sulphur moves to the slag and oxygen moves to the metal.

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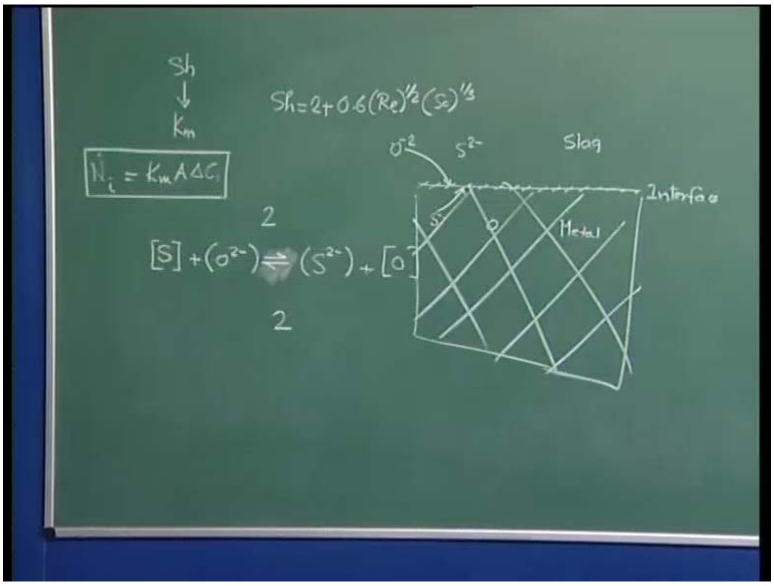

Now, you see the desulphurization can be clubbed into 4 different kinetic steps. So, we are gradually getting into the subject of metallurgical kinetics and then you will see the relevance that how can you calculate these terms?

So, let us remember this. We will discuss kinetics, get back to here and then do the rate calculation to explain the matter better to you. So, the entire process of desulphurization is comprised of 4 different mass transport steps - mass of sulphur transfer from bulk to the interface, oxygen ion transfer from the bulk of slag to the interface. Then these are the 2 mass transports steps. Once these have occurred, then the chemical reaction takes place and after the chemical reaction, again sulphur from the interface is moved into the bulk of the slag and oxygen is moved from the interface to the bulk because if we allow oxygen and sulphur to accumulate at the interface, then what is going to happen? The reaction is going to come to a halt; the reaction will not proceed.

So, what we are talking about now is not equilibrium, but continuous transfer of sulphur. So, the continuous transfer of sulphur essentially, as I have mentioned are comprised of 5 different kinetic steps of which 4 are mass transfer, transfer from bulk to the interface or moving from the interface to the bulk and one is the chemical reaction. So, these are called the individual kinetic steps and the rate of the desulphurization is going to be a function of the rate of the individual kinetic steps. What does that mean? That this mass transfer of sulphur from the bulk to the interface will also have some rate; maybe, it is a convection which is taking place. So, I will find out what is the rate of transport of this. I will have to calculate the flux - convection flux or convection plus diffusion.

So, there is a rate of net rate of transfer 5 kg moles of sulphur per second to the interface. Similarly, I have a rate of transport for this, I have a rate for chemical reaction also - forward reaction. So, all the 5 steps that I have just now mentioned they are all associated with their individual rate which essentially and this is called the intrinsic rate of each of the kinetic process.

So, for example, now, I gave this example in the class room that suppose, you are a student, you stay in your hostel and your hostel is quite far away, you have a bicycle. So, to attend to the class at 8 o clock suppose, you get up at 7 30. You take 5 minutes to brush up, another 10 minutes to have your breakfast and then another 10 minutes to bike down to the class room to get there, 5 minutes before time - so, 10 plus 10 plus 5.

These are the time taken for the 3 individual steps and the total time that you take to reach the class room from your hostel is a summation of all these activities. Similarly, the overall rate of desulphurization there, here we are going to see is the summation of the rate of four mass transport steps during the metal phase, during the slag phase plus.

Now, it may be possible that the rates are not comparable. Some rates are very high; some rates are very slow. Now, the slow step is going to control the rate of the process because these kinetics steps are all operating in series. What do I mean? That if I stop one of the kinetic step and kinetic step means individual step - transfer of sulphur from bulk to the interface; this is one simple kinetic step.

So if I stop one of these 5 steps, any of the 5 steps, the process of desulphurization or you know the mass transfer of chemical reaction which essentially is desulphurization will come to a standstill. So, when the processes are connected in series, individual kinetic steps are connected in series, it is the lowest step that is going to determine the rate.

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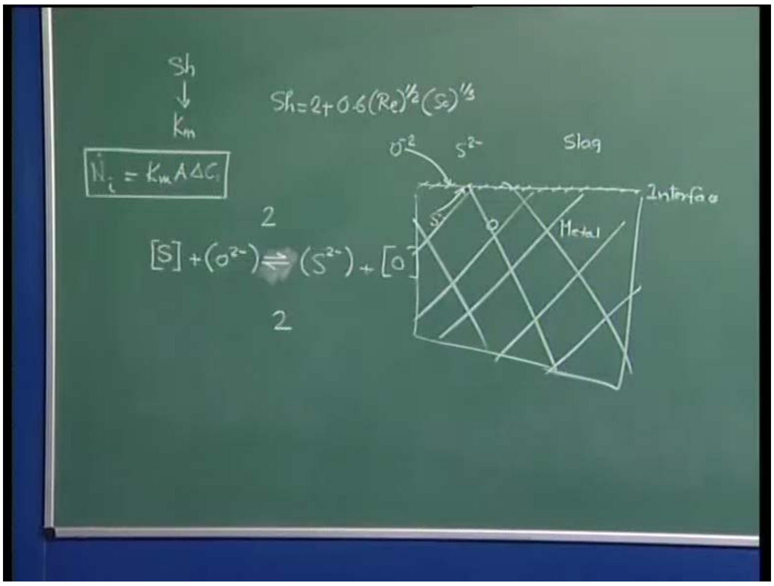

For example, I go back to the class room problem and now I say that you take 2 minutes to brush your teeth, get freshen up and dress, 5 minutes to have breakfast and then 20 minutes to bike down from your hostel to the class room. That means, they are at these activities the efficiency with which you carry out these activities are not same. The biking takes much longer time than eating your breakfast or getting up from the bed itself.

Therefore, I can say that look, now if you can buy a motor bike and then you should be able to reach the class much faster. So, if you are biking, you use a motor bike and in that case, maybe you should be able to reach the class room in about just 2 minutes of time and then we say that now my rates are comparable; one is 2 minutes, second is 5 minutes and with a motor bike also it is 2 minutes. So, in 9 minutes I should be able to get to my class.

But alternatively in the previous case, if bicycling takes 15 to 20 minutes, in that case, you can say that you know, this is the slowest step and this is the reason why I am getting late to the class. I cannot possibly be more efficient in terms of brushing my teeth or you know, getting dressed up or eating breakfast, but if I can somehow expedite my travel time from the hostel to the class room maybe, I could be able to reach the class in time.

So, therefore, when the steps are connected in series, the slowest step determines the rate and in metallurgical kinetics, often we are concerned with determining the slow kinetic step. Now, it is not necessarily that the rate of a process is going to be controlled by one single kinetic step.

So, if I can identify per say that out of this 5 steps, only one is rate limiting. This could be either a mass transfer step or a chemical reaction. Forget about mass transfer in metal or the slag we are not talking about it, but essentially the nature of the desulphurization process gives us 2 types of kinetics step - mass transfer and chemical reaction.

So, when mass transfer and chemical reaction both control the rate, that means, the individual intrinsic rate of these processes are identical; then we say that it is a mixed control scenario. So, the possibilities are three; either the process could be mass transfer controlled or the process could be chemically controlled. When you say chemically controlled, it means the mass transport steps are very fast than the chemical reaction itself. small or our third possibility is that both mass transfer and chemical reaction can be rate limiting and they control the rate.

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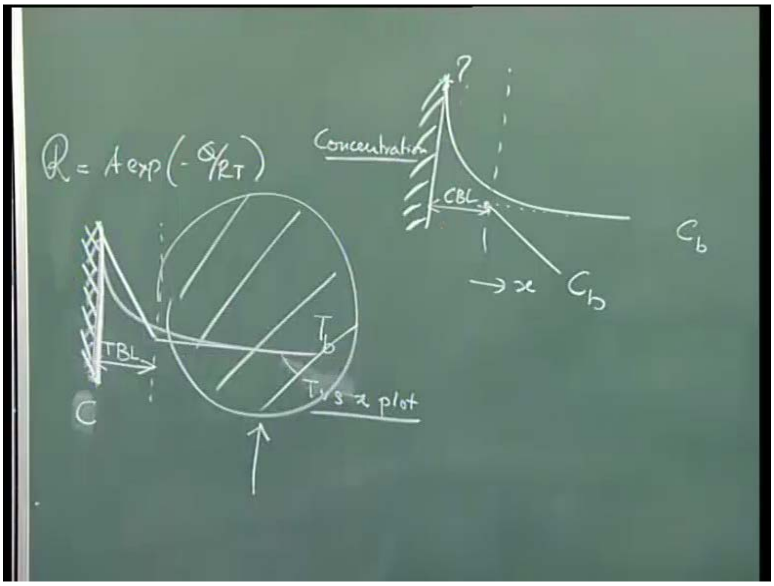

Now, rate of chemical reaction: Let us now generalize the subject. The rate of chemical reaction at elevated temperature follows what kind of a law? Arrhenius rate flow. A exponential. Therefore, this tells us that as temperature is increased, the rate of the chemical reaction increases.

Therefore, rate of a chemical reaction So, we have 2 mass transport step before this chemical reaction, 2 mass transport steps after this chemical reaction and now, we are looking at just this 1 step and we conclude that look, based on the Arrhenius rate flow, we can expect that the rate of the chemical reaction under steel making condition, where temperature is 1873 kelvin could be really very fast. If the rate of a chemical reaction is very fast, what does that mean? That means, the process will tend to reach equilibrium very fast and therefore, we can say that under that condition, as a thumb rule, we can say that chemical reactions could be operating under equilibrium condition because the rate of the chemical reaction is fast. Does that mean there are no exceptions? Yes, there are few exceptions, where chemical reaction even at high temperature is rate limiting, but that is beside the point.

So, now we have, the moment we say that chemical reaction is rate limiting and then we have 4 different mass transfer steps and out of that, if I say that look, I do some analysis, there are kinetic analysis based on which I can say that well, it is not the mass transport in the metal phase which is important, it is mass transport in the slag phase that is much more important.

So, all the mass transport, I can say that everywhere, there is no mass transport here. The moment I say that mass transport in the metal phase is not rate limiting, it is very fast what does that mean? That means, if the mass transfer is very fast there is no concentration gradient of sulphur in the metal itself; there is no concentration gradient of oxygen in the metal itself because mass transfer is very fast. That means, everything is very well mixed. Whatever is coming into the metal, it is immediately getting mixed. Therefore, we have a homogeneous concentration here.

So, the moment we make these assumptions, we can make certain idealizations and then we can say that the interface concentration is equal to the bulk concentration or the bulk concentration is the

Let us quickly look at this scenario. For example, Now, heat transfer For example, I have a solid surface. It has a temperature of T sub 0 and this is a fluid flowing T sub b. We know that ahead of a solid liquid interface. So, the fluid is flowing like this. We have a thermal boundary layer. This is called TBL; this is your thermal boundary layer. So, this temperature is equal to T zero. The thickness of the boundary layer basically is defined at where the temperature becomes almost equal to 99 percent of the bulk temperature.

Now, basically, what we see that heat is being transferred from the bulk to the solid surface and I can now split it into 2 parts. one is This is the boundary layer. This is not the boundary layer; this is the thermal boundary layer and this is T versus x plot.

So, heat is going to be transported now from the bulk to the surface and I can split it up into 2 different parts. I can say look, heat is transferred from the bulk to the interface and from the interface into the thermal boundary layer. Now, the moment I say this, I can say that the rate of heat transfer is controlled by I can make this assumption that there are 2 steps which controls the rate of heat transport; transport in the bulk phase as well as transport within the boundary layer. It is true also for mass. Same example I could have given in the context of solid liquid mass transport also. Now, if I say that look, I will make an idealization not 2 steps control the rate, I will say that the rate is controlled by mass transport within the boundary layer because the boundary layer gives the largest resistance; the velocity is very small here; velocity is very large here.

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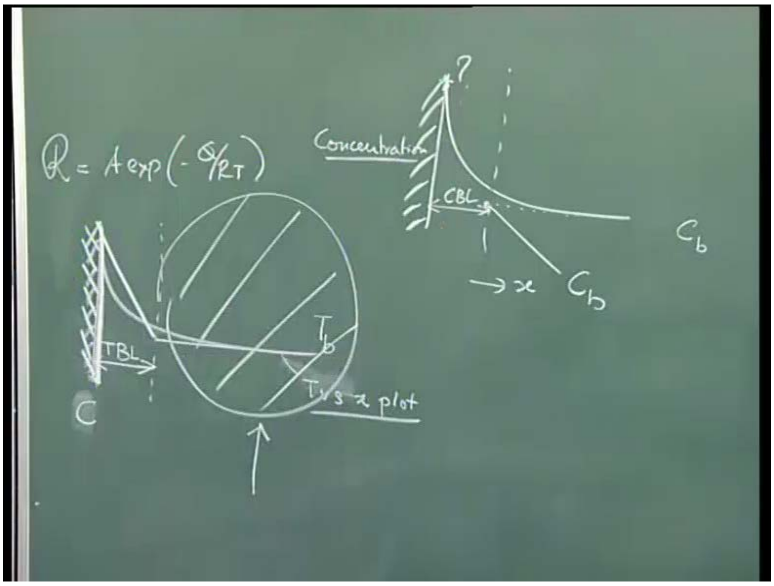

So, there it boils down to saying that heat transfer from here to the edge of the boundary layer is almost instantaneous. It boils down to that there is no temperature gradient and that is why we always think, if you remember that when you determine the rate of the process, you may have calculated that temperature far away from the interface. What is that? That is the bulk temperature and the driving force for temperature is the surface temperature and a temperature which is far away from the solid surface. (Refer Slide Time: 52:57) This temperature is far, far away.

But this temperature actually prevails up to the edge of the boundary layer because of the simple fact that we have made an assumption that the transport of heat within the bulk is instantaneous and that there is no concentration; there is no temperature gradient; the largest gradient really occurs within the boundary layer itself.

So, the actual curve is then idealized in this particular fashion and we see that between the edge of boundary layer and the bulk, there is no drop and that is how we determine the temperature also. Now, we are going to see that how this concept boils down to, in the case of a mass transfer.

Now, suppose I have a solid here which is dissolving into liquid. Instead of T 0, now I say that look, this is C here concentration and C is in the solid and this solid gets into C or I can say this dissolves. There is a fluid which is flowing past the solid surface. This is the solid surface and there is a fluid which is flowing past the solid surface. So, C from the solid is continuously getting dissolved into the fluid. This is the reaction. C in the solid phase gets into C and where this reaction is taking place? (Refer Slide Time: 54:17) This reaction is taking place in the edge of the solid or the solid liquid interface, which is this particular line. It is here that it is taking place.

So, the overall rate of the dissolution of this plate or overall rate of C transport to the liquid will be, first the chemical reaction has to take place and then the fluid has to remove that and that is going to be distributed in the bulk itself. So, I can say that well, this is the solid and similarly, I can have a concentration layer, concentration boundary layer developing. So, this is the CBL - concentration boundary layer. This is the distance x and this is the concentration.

Therefore, now we can say that look, far away from the interface, it is the bulk concentration, but this bulk concentration I can assume it to prevail up to this particular interface. I have made this assumption that within the bulk, the concentration there is no concentration gradient and mixing is very rapid. It is true because in the bulk, the level of agitation is far intense than it is near the wall itself. Therefore, the driving force of concentration becomes, this is C b is known, but what is this concentration here? So, that determines the driving force for concentration, which I have used in this particular expression.

Now, I will assume that the rate of dissolution - the rate of solid from the solid going into the liquid depends on, the rate of mass transport depends on the rate of this chemical reaction plus the transport of the species through the boundary layer plus the transport from the boundary layer to the mass, but the third step does not exist. The transport is determined by only 2 steps - the rate of the chemical reaction at the interface plus the transport across the boundary layer.

I apply my judgment of high temperature kinetics and if I say that look, if the process is occurring under high temperature, in that case, I can say this equation will be close to equilibrium and if this equation is close to equilibrium, therefore, the rate of mass transport is going to be dictated totally by the rate of boundary layer or transport to the boundary layer itself.

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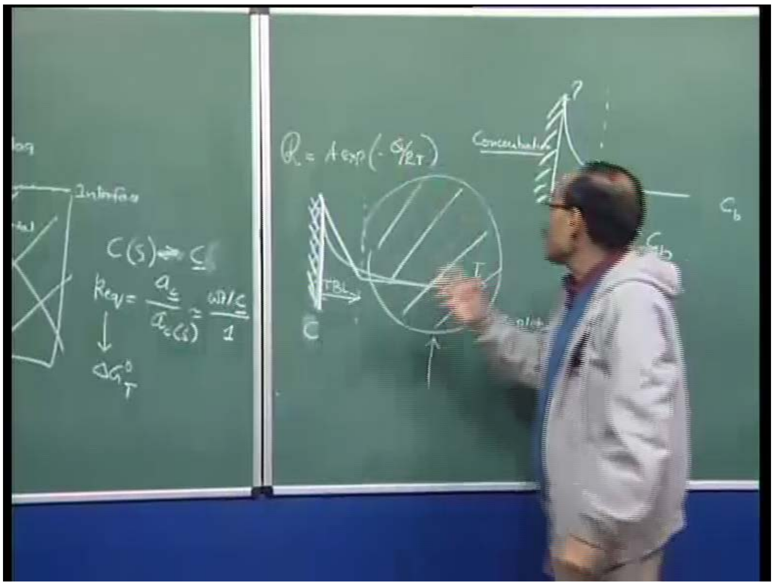

Now, the moment I say that this chemical reaction is at equilibrium, we can apply our knowledge of thermodynamics and say we can write down that, k equilibrium is equal to activity of C in the phase and then activity of C in the solid. If I know now, k equilibrium from my delta G naught value at that particular temperature, I should be able to find out or if it is a dilute solution, I can say that weight percentage of C divided by activity of solid phase - this is the pure solid phase, then we say this is equal to 1.

So therefore, if you know delta G naught because delta G naught value will be known may be from Ellingham diagram type of diagrams or from thermodynamic data book. So, knowing the temperature, I will be able to calculate delta G naught is equal to minus RTln k, k equilibrium will be calculated and this weight percentage of carbon at the interface, this concentration will be known to us.

So, while in the case of heat transfer, we are going to determine the surface concentration by using some kind of a pyrometer or thermo metric devices. In the case of mass transfer, often the interfacial concentration is going to be determined through thermodynamic considerations.