Steel Making

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Module No.# 01

Lecture No. # 30

Deoxidation, Ladle and Tundish Metallurgy

When I was a student some 30 35 years back, we had nothing on Tundish Metallurgy, actually Tundish Metallurgy was not developed then, although continuous casting has made inroads in the area of steel making. But today Tundish has as I have mentioned already, occupied a preeminent position in the steel making circuitry, and this is because of the simple fact that in Tundish, we can overwhelmingly control the characteristics of steel in terms of its inclusion, in terms of its composition and temperature, and thereby produce the right kind of cast products through continuous casting.

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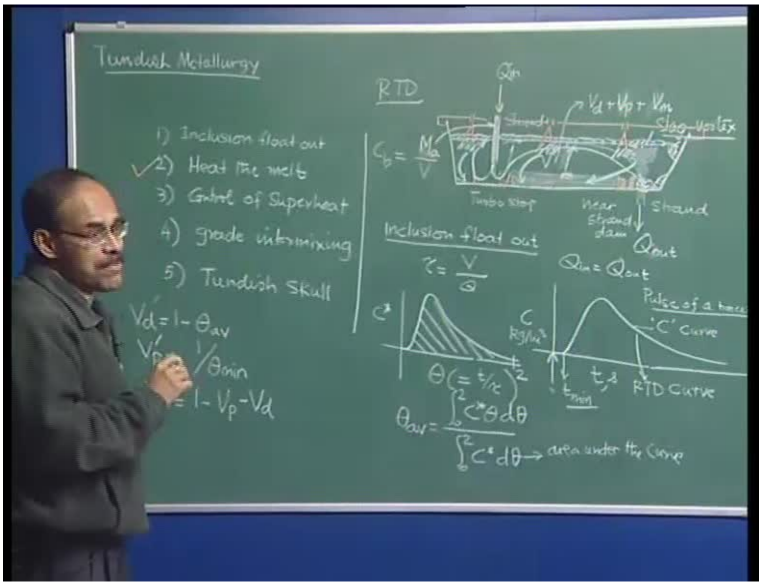

Now, let me draw again a simple single strand slab casting Tundish, I have already mentioned that while we have only a single strand in Tundish, slab caster Tundish, and multiple strand in bilateral bloom casting. So, this is our shroud and this is the strand.

Invariably, you will see that in slab and bloom casting Tundishes, there is a near strand damp, and the function of this damp basically is to prevent the initial metal, when the Tundish is getting filled up in the first heat itself or the lead heat, as it is termed in the industry.

So, we want to accumulate some amount of molten metal here and then the molten metal should spill over and enter the strand, and this helps us to prevent premature freezing, we of course have a turbo stop. In most of today's slab casting Tundish, because it produces, this is no more there, going to be have the turbo stop and instead we have the flow of metal goes, when the Tundish is completely a filled up. So, we can show the turbo stop like this, so that there is no confusion here, and this is the turbo stop, and this is our near strand dam.

Now, what are the issues in Tundish. The issues in Tundish are several; number one the foremost and the most important issue is the inclusion float out, and inclusion float out as I have told you already relies on the simple fact that the fluid coming into the Tundish, from the ladle, resides in the Tundish for some amount of time, before it goes out through the stranded self.

So, there is some time that the fluid is going to at the molten steel, is going to spend in the Tundish, and in that particular time of due stay or dual time, if we can somehow eliminate more and more inclusion that will be excellent, as far as the composition of steel is concerned.

Secondly, we would like to control, may be heat the melt to increase its temperature, if there is a significant drop of temperature during the previous processing steps heat the melt. We can also control super heat, this is of course one and the same thing may be, control in the super heat. Today, we all know that the super heat has a tremendous bearing on the quality of the cast products, the micro structure of the steel is controlled by super heat and also it is not desirable to have a large super heat in the continuous casting Tundish, because in that case you have to slow down the casting rate, because you would like to have some dwelling within the mold, before the material flows out that the mold otherwise what is going to happen, you are going to have a very thin shell.

So, larger is the super heat in the Tundish for a given condition in the mold, thinner is going to be the shell, and there is going to be a more hydrostatic pressure on the wall of the solidifying billet. So, the superheat has to be very properly controlled. Number 4 more important issues are like we have grade inter mixing, which is a also an important issue. What does grade inter mixing essentially implies, that this particular Tundish may work for 20 heats, 20 times we can do the ladle change over, but that 20 ladles may not have the same composition.

So, after five hits may be the composition is going to be changed, and as the composition is changed from grade a to grade b, in that case for some time we have, we will form billets or blooms or slab which are going to have composition neither of the previous grade nor of the former grade, but in intermix grade and that is what grade intermixing is a very important task, because intermix slab bloom or billet are often downgraded.

So, therefore economize the performance or to improve the performance of the cast shop, we want to have that as low a transition slab volume or mix slab volume or mix bloom volume as possible, and also we have Tundish skull which, this is a very important problem in today's steel plants, where they are trying to improve on the productivity and minimize specific energy consumption, because during the last heat when the lade Tundish is to be taken out for relining, so imagine the last heat and you have metal which is there in the Tundish and there is nothing is coming into the ladle, because that has to be the last heat, and then this interface goes down, and at some point what happens is I am going to discuss it, the slag vortexing will is going to start.

Just like the way when you open a tap in a sink, you must have seen that funnel vortex as formed, and this is the characteristics of drain vessels also, then ladles and Tundish through the strand or through the well in ladle, we have vortex formation or slag entrainment when the level of the metal really falls down to a threshold level.

If, this slag gets into the mold then we have lot of problem in terms of breakouts, in the mold and so on. Therefore, we really cannot, as the level drops down below a certain level, we cannot drain the molten metal, well we stop the casting and this much of molten material is going to be wasted.

Today, we would like to have that the residual volume of liquid or the skull, because this Tundish when it is going to be taken away for relining, this material will essentially solidify and manifest as scrap or skull, and this skull is going to be recycled back into the basic oxygen furnace for production of steel.

So, this is a very nice quality of steel that we have made by putting in lot of efforts, and now because we are forced to have some amount of liquid, so as a result of which what happens is that this is going to upset the yield of the plant, it is not a smart way to recycle back the steel which we have made with so much of care and spending so much of money.

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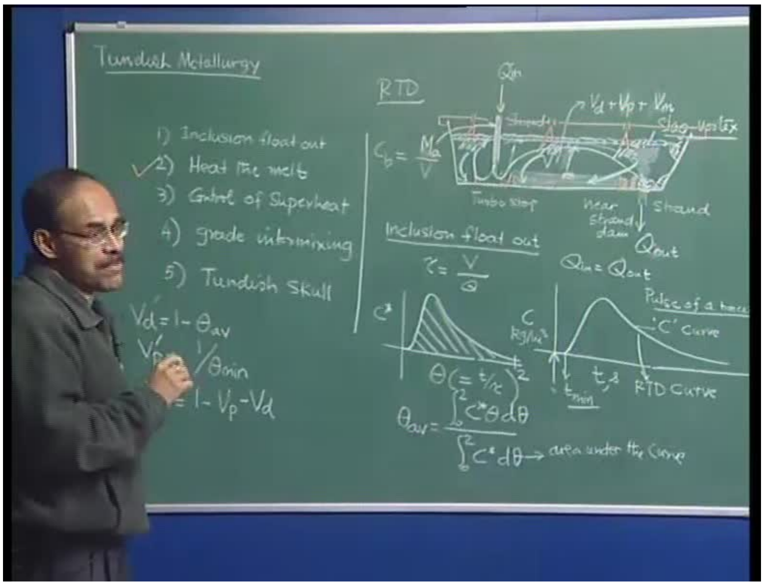

So, the target is that we have to have lesser skull volume, so this is also a very important issue in the Tundish itself, and now I am going to talk about one after another.

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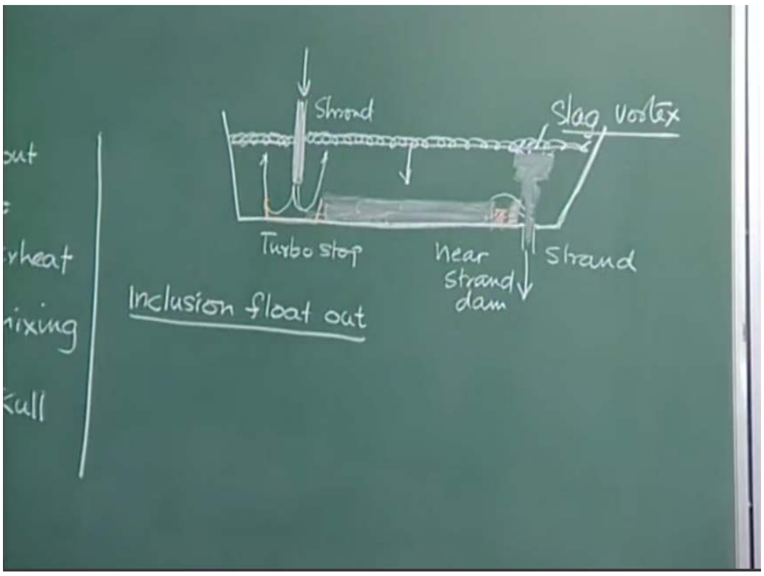

So, let us talk about inclusion float out, so imagine a Tundish which is completely filled, we have the slag layer here and then there is no slag vortex, because the bath height is too much now, so it is only when the bath height will fall to this level may be there is going to be some slag vortex. Since, so at this stage the Tundish is operated under steady state, the bath height is maintained constant and so is the casting rate, so the amount of molten metal which comes into the Tundish, is exactly equal to the amount of molten metal which goes out of the Tundish, and as a result of which we have a constant bath depth, this is known as the steady state operation of the Tundish.

Initially, when you fill the Tundish, when there is nothing in the Tundish, but we are filling it up with no nothing going out, the level of the metal goes up and the Tundish itself that is a transient mode of operation.

Similarly, when nothing is coming into the metal into the Tundish, and yet we are continue to casting the level is going to go down. Therefore, except for the lead heat or the first heat or for the last heat, most of the time you will see that the Tundishis going to be operated under steady state bath condition, and at that point the volume of the Tundish or the volume of the Tundish occupied by molten steel is going to be constant.

I have already told you that if Q represents, so the material balance or volume continuity requires that under steady state condition Q in is equal to Q out, and nominal residence time is equal to volume of the Tundish occupied by fluid divided by Q that I have already told you.

Now, imagine a fluid element which comes into the Tundish, so the fluid element goes like this may be, and then it spends some time and ultimately it goes out, another fluid element may follow a different path and it can come go like this, and it can go towards the free surface and then possibly behind the Tundish, it can again come here.

Obviously, this two path and the velocity of the particle or the rate at which they are approaching the strand are going to be different, so what I mean to say that if the particle follows this line, it will spend some amount of time, if the particle follows this line which is coming from the ladle follows this line, in that case it is going to spend different time.

So, all the particles in the Tundish do not spend the same amount of time as it dictated by the nominal residence time, in fact there is going to be a residence time distributions which essentially imply that the molecules of fluid which are coming or the atoms of fluid which are coming from the ladle, they each and every one are not going to spend same amount of time, but different amount of time, which is going to give rise to a residence time distribution.

Residence time distribution is a very well investigated subject, and well documented asked topic in chemical engineering literature and text books, and we also applied that residence time distribution in order to find out, whether the Tundish is good enough reactor for inclusion float out and so on.

Now, if we have intense amount of stirring in the Tundish, we can understand that there is going to be very little scope of inclusion float out, because the inclusions are very small particles, they have certain rise velocities or stokes rising velocities, which are also very small, inclusions having hundred micron, eighty micron size particles, I have very low rise velocities.

So in that case if you have a good amount of turbulence enchanneling in the system, perhaps the inclusion does not get a chance to float out. Therefore, for inclusion float out we require not too much of a mixing in the system, but rather then we require that there is going to be some amount of pluck flow or disperse pluck flow in the system, which is like acquires and flow moving gradually from the inlet strength, inlet region to the outlet region itself, that is the kind of a flow, that is going to give rise to inclusion float out, and whether we have mixed flow, whether we have pluck flow and that will follows from the theory of residence time distributions.

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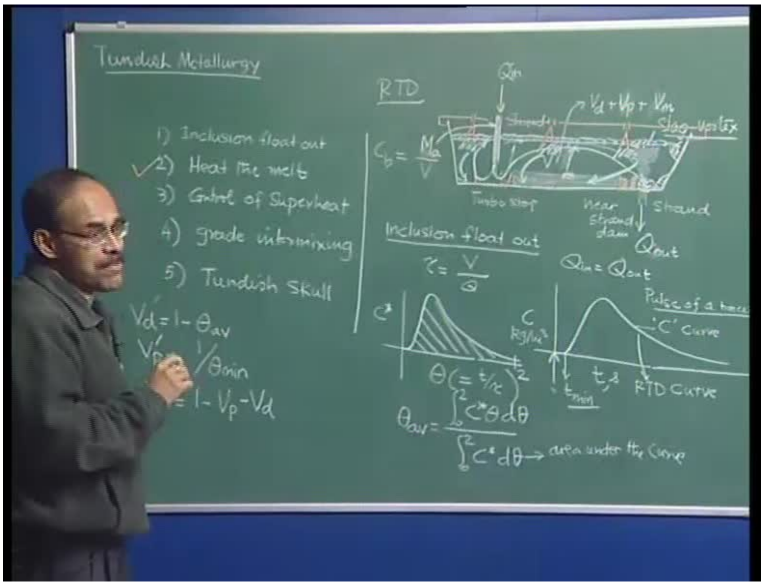

Now, how do you obtain residence time distributions in Tundish, therefore if we inject a pulse of a tracer into the shroud. So, you take a syringe and then inject, suppose you have a model operating and in that case into the shroud you can inject.

So, if you inject the material comes here infinite number of molecules, and then you are monitoring the concentration at this particular location, to find out that I know when I have injected the material at what time the molecules are going to go out, and then if you monitor the concentration versus time, you can see that well you have injected at 10 clock say, which is this time, but your deduction is not going to start at 10 clock, because the molecules are going to take some amount of time, before they can reach their response point.

So, concentration remains constant for some time, and then the concentration of the particle increases and then eventually decreases in an isentropic fashion. So, this curve that we have obtained by injecting a pulse of a tracer into the system is termed as the residence time distribution.

In metallurgical engineering literature and steel making literature people also call it as a C curve. On, the basis of this curve we can find out that what is in this Tundish, how much of well mixed volume is there or the extent of mixing flow is there, how much is the pluck flow region and also there may be some regions where the fluid is not at all moving, may be this corner or may be this corner, the fluid may not be moving, this may comprise of dead volume and actually the total volume of the Tundishare going to be comprised of the dead volume, plus plug volume, plus V sub plug and V m.

So, these are 3 different types of volumes, which comprise the total volume of the Tundish, and it is on the base by calculating or by knowing this residence time distribution, we should be able to find out that what are the each and every volume fraction.

Now, typically we can say that this concentration can be converted to a non-dimensional concentration versus a non-dimensional time, and what is that non dimensional time, this t is the dimensional time, this is in second, this theta is non-dimensional time no unit, this is concentration may be k g per meter cube, this is star has no dimension, it is dimensionless concentration, how do you obtain this from this. so, we divide this instantaneous concentration by the bulk concentration.

Bulk concentration means, the Tundish has suppose, V is the volume and I have injected V1. Therefore, I can say that the bulk concentration actually, V is the total volume we have added V addition divided by V, this is the trace of that we have injected into the shroud, so if we divide this we get a bulk concentration time and this bulk concentration, therefore will give us a non-dimensional time.

So, an amount of tracer, so it is mass of the tracer divided by the volume of the Tundish, mass of addition divided by a essentially implies addition, mass of addition divided by volume, so this will give you also k g per meter cube, so this is k g per meter cube if you divide this by C b then you get nothing here as an unit of C star.

Similarly, this is the time which is in second, this is the non-dimensional, this is the nominal residence time, so if you divide this, so this is actually equal to t divided by time. The, nature of the curve does not change only the extent of the height etcetera will change, so it will again remains the same, and on the basis of this skull, we can define what is known as a mean residence time theta average, and this is actually 0 to 2 C star d theta, and here 0 to 2C star theta.

So, you have to integrate the curve, what does this essentially implies, so the limit is 2, because it is believed that beyond the limit, beyond non dimensional time is equal to 2, the material does not flow out of the Tundish, it take immensely longer amount of time, so the integration from 2 to infinity really does not matter.

And what is this term, this term is nothing, but the area, so this is y d x, this is the area under the curve, and then if you can plot this, it determine the area under the curve, you can plot the area under the curve against theta and evaluate that what is going to be the denominator itself or numerator itself.

So, the area under the curve is equal to, this is the area under the curve. So, once you can determine theta average by definition now V d, I am not going to go is equal to 1 minus theta average.

So, the dead volume, this is the extent of dead volume V d meter cube, while this is dead volume fraction which is nothing, but V d divided by total V, so the dead volume fraction which is again dimensionless is going to be equal to 1 minus theta average, you have V plug which is equal to 1 divided by theta minimum, and what is that theta minimum, the minimum is the, this is the time which is called as the theta t minimum, the minimum time or the first time the tracer is located at this particular point following injection, so this is the time at which I have injected the tracer. On the other hand this is the point when the tracer has been detected at the nozzle.

So this time essentially represents the t minimum, and if you divide that t minimum by tau, what you get is theta minimum and the plug volume fraction is equal to this, and we know that the total volume fraction is equal to 1, some of the total volume fraction, therefore I can have that 1 minus V p minus V d should represent.

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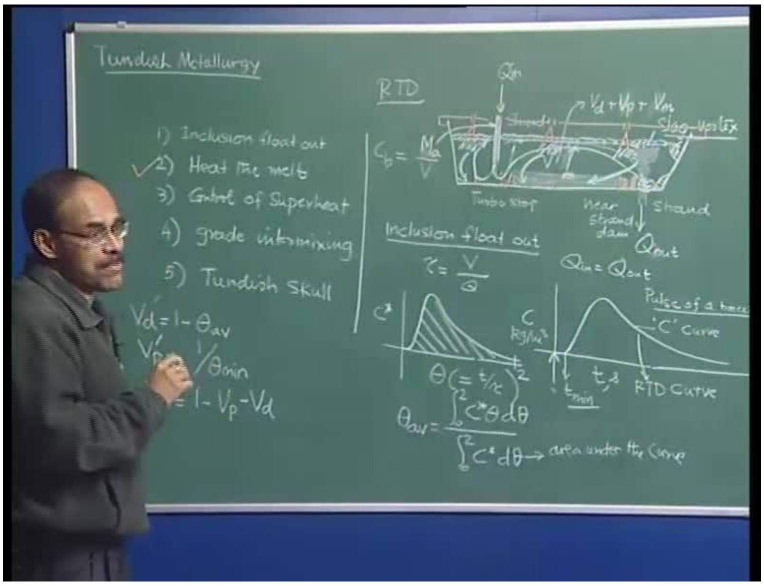

So, a Tundish with different kinds of furniture's may be I have a turbo stop, may be I have a near strand dam, or in other Tundishes I may have, not at a turbo stop not a near strand dam, but I have a dam here, we are here. So, I have a different flow rate, I have a different bath depth, I have a different geometry of the Tundish altogether, there can be lot of variations which are possible depending on the plant.

Therefore, we can say that in the Tundish itself, depending on its characteristics, we are going to have a different sort of a curve, this curve is not a universal curve, this curve is going to depend on the operating conditions, the geometry of the Tundish, the Tundish furniture's etcetera.

So, therefore accordingly; the theta average, theta minimum, its value will also be different for different Tundish systems, unless the result of which different Tundishes will have different dead volume fraction, plug volume fraction and mixed value fraction.

This essentially implies that different geometry Tundish under different operating conditions will perform differently, because a plug volume fraction is going to be different, for different Tundish system. Therefore, the inclusion floatation capabilities are also going to change with Tundishes inclusion floatation capabilities, are also going to change as a function of operating conditions and geometry itself, they are not going to be similar, because the characteristic residence time curve is a function of the Tundish operating conditions and Tundish geometry.

Now, as I mentioned to you that for example, if I want to, now inclusion floatation for the time being, let if you assume that inclusion floatation is not our objective, but we would like to say that we would like to heat the melt, because in the previous cases there has been quite a bit of drop in temperature, so we may apply what is known as the plasma heaters at various locations in the melt.

The Tundish as you all know is actually physically covered, the Tundish is physically covered, because we do not want any contamination of the melt with the ambient surroundings, therefore there can be holes here, there can be holes here through which the plasma heaters can be launched and we can heat here.

Now, if you want to heat up, in that case we would like to see that there is going to be good amount of mixing in the Tundish itself. Why, because heat is going to be restricted to this particular region, and I would like to see that this heat is going to be carried over everywhere.

I want the material to be uniformly heated, so the heat from this meniscus region must travel to the entire part of the liquid, and therefore we would like to see that in order to heat up the melt uniformly, we would like to have a good mixing flow in the system itself, but if you have good mixing flow, we understand that inclusion floatation are not going to be higher, because as I have mentioned larger turbulent flow, large intensity flow is going to cause some hindrance to the floatation of the inclusions which have very little rise velocity.

So, therefore the conditions which are needed in order to heating the melt uniformly, and the conditions which are needed to plot the inclusions in the Tundish cannot be met simultaneously. In one case that is in the case of former case, that is when you want to heat the melt uniformly, we will require large amount of mixed flow in the system or V prime m should be very large. On the other hand if you want to remove inclusion primarily from the Tundish, we would like to have that the plug volume fraction should be very large, so these two objectives cannot be maximized simultaneously.

So, one has to be sacrificed at the expense of others normally, if inclusion floatation is the major task in that case you can say that well, we will go for a larger plug flow volume and as little dead flow volume fraction as it is possible.

So, you go to the super heat again, super heat is a very important part in Tundish to control, Before I think I talk about superheat, let me just quickly mention once single point, we must understand that when inclusions are there, and these inclusions would like to float to the surface, so this is an inclusion here, and this inclusion is going to float to the surface.

The inclusion floats out gradually joins the slag, now typically it has been experimentally proved it with high temperature trails that, the inclusion goes and dwells in the slag for some amount of time before the slag actually physically captures.

So, the inclusion may develop liking for the slag or may not develop liking for the slag, so within the dwell time itself the inclusion can actually revert back to the flow system, if there is an intense fluid flow prevalent in the vicinity of the slag metal interface.

So, therefore the composition of the slag must be so adjusted in the Tundish, that they are good for the absorption of the inclusion that the inclusion will go dwell there and get absorbed, we do not want inclusions to be reentering, therefore the composition of the inclusion composition of the slag has to be tailor making.

Through plasma heating we can control superheat, particularly if the temperature is smaller, now most of the time as we will see that the Tundish is operated at a more than desirable temperature, particularly in those plants where there is not much of process control, then what people do is that pour molten metal into Tundish at a much higher temperature than is desirable, because there is going to be some amount of heat losses.

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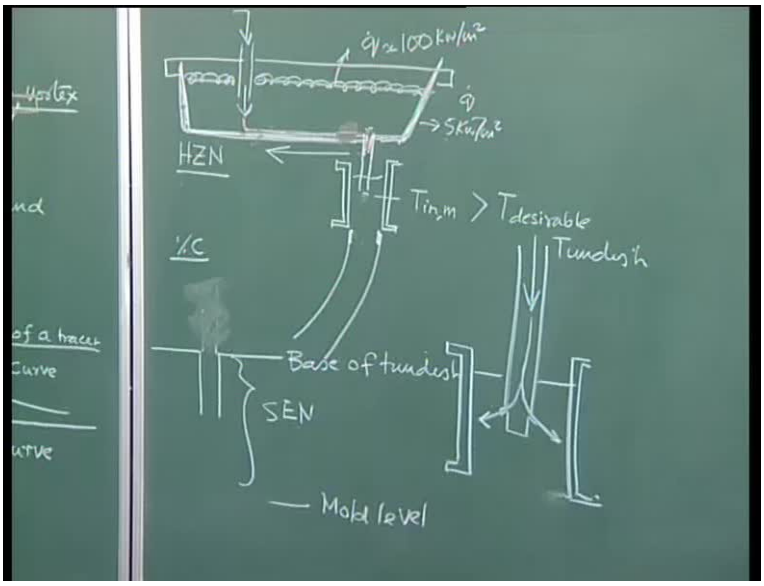

What is the extent of heat loss in Tundish. For example we can have, we look at this figure here and say single strand slab casting Tundish, operated under steady state condition. So, you have a heat flux operating here, which is of the order of 100 kilo watt per meter square, that is the kind of and we are talking about 5 kilo watt per meter square, so which is operating through.

So, through the walls of the Tundish, smaller heat fluxes are operating and, because these are refractory line walls, therefore extent of heat loss is not really appreciable, per meter square only 5 kilo watt is lost. On the other hand, Q the heat flux through the free surface can be 100 kilo watt per meter square.

And of course, these are not universal values, because whether you have a physical cover, whether you have a thick slag layer, all this is going to determine the extent of heat loss. Therefore, the value I have written there is 100 kilo watt is only an approximate which gives you an idea that significantly more amount of heat is going to be lost to the free surface, then it is through the wall as far as, but since, we have a large wall here, large surfaces here, the back surface is also there.

So, the overall contributions from the wall losses are not going to be significantly different from the free surface, because free surface is only one, but the walls are actually 5. So, it is per meter square, so the meter square, the area of the wall, summation of the area of the wall is significantly larger than the area of the free surface.

So, therefore even though you may find it to be 5, may be a similar, some total through the wall the extent of heat loss is going to be similar to what is through the free surface.

Now, so if you pour molten metal typically at a high temperature, because people think that there is going to be lot of temperature heat loss in the Tundish itself and also there is a, you do not want premature freezing here in this part, then the material comes in the lead heat the material flows, so the Tundishis not filled up.

So, the material enters the Tundish and it flows, and if there is too much of a heat loss, in that case by the time the material goes here, it will lose so much of heat that it can actually solidify here, which can create problem.

So, as to prevent this, to prevent premature solidification, what we will do is, they pour in molten metal or the metal in ladle is significantly over heated or overrated to some extent at least to compensate for heat, this heat loss such that the material can flow uniformly and then can flow out through the exit nozzle itself.

Now, as a result of this, because the process control is not tight enough, in that case what happens is, that we may land up with material into the mold, which is having mode temperature then it is desirable.

So, here we can have then relatively high temperature, because to compensate for this heat loss, we have done arbitrarily increase the temperature by 20 or 15 degrees, and as a result of which material entering the Tundish ladle entering the mold, this is a continuous casting mold. So, material entering the mold may now have a somewhat larger temperature.

So, here T inlet mold is actually more than T desirable, and as I have mentioned that more is the temperature here, lesser will have to be the casting speed, because you have to keep the molten metal in the mold for some amount of time, before its flows out of the mold, because we want that you have a reasonable amount of shell thickness at this particular point, otherwise there is going to be a breakout, because of or bulging, because of higher hydro dynamic pressure, steel has an extremely large density.

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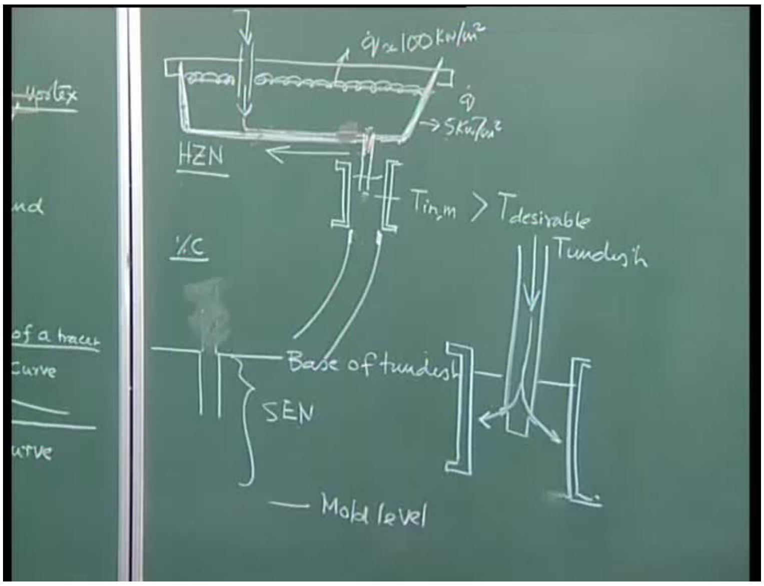

So, therefore you were talking of one meter, you can imagine that the Ferrostatic pressure here is going to be tremendous, and the shell is thin and the thickness of the shell I repeat again is a function of the temperature itself.

The cast composition and the cast microstructure is intricately related to the temperature of the metal, and it is well known now, that smaller is the superheat, the better is the quality of the cast product, by the by what is the definition of the superheat, so if the steel has a melting temperature which is a function of carbon and other composition, so the temperature over and above the liquid as temperature is termed as the extent of superheat. So, we are talking about superheat, desirable superheat here, to the range of 15 degrees to 20 degrees that is perhaps ideal.

So, now if you have too large a temperature here, well we do not want any premature solidification, then how can how it is possible for us to deliver molten metal into the Tundish, into the mold correctly.

So we can have in between the two, what is known as a hollow jet nozzle technology, this is a patented technology actually, so what I am saying here is that, well we will pour more continue to pour molten metal at a higher temperature in order to prevent any premature solidification, but at the same time we would like to have this temperature not to hide in the desirable range.

So that means if the temperature here is higher than required, and if you want a reasonable superheat here, the heat must be removed between the mold and the Tundish itself, and how this is facilitated, this is facilitated by using a technology which is known as a hollow jet nozzle, it is a patented technology, and how does it looks like.

So we have a stream which is coming from the Tundish, and then we have, this is the base of the Tundish, this is I would say like this, this is the base of the Tundish, and this is a nozzle this is base of the Tundish, so the SEN this is the between the mold, and this is the mold level. So, this is actually the SEN, submerged entry nozzle, but connects the Tundish to the mold is SEN, so the design of the SEN is going to be now changing, typically the SEN in slab casting, how does the SEN look like, SENs are basically a tube with ports here to feed in molten metal and it goes like this.

So, this is the mold level, this is the mold and this is the level, and that is how from the Tundish the material comes in from Tundish, the material enters and in a slab caster, it is material if this comes here and it goes out like this, it goes out like this and that is how a material is going to be actually delivered in Tundish in the mold.

So, this conventional SEN design is going to be now altered, if we have to control the superheat within the mold and the Tundish, and this hollow jet nozzle technology, this is basically a heat extraction device.

So as I said that this is high temperature, this is we want, its significant drop in temperature here, so we have to eliminate heat between the Tundish and the mold.

So therefore we have to have a heat extraction device, so the hollow jet nozzle that is employed between the ladle Tundish and the mold in order to remove heat or lower the superheat in the melt is basically a heat extraction technology, I am going to draw it now and to show it to you.

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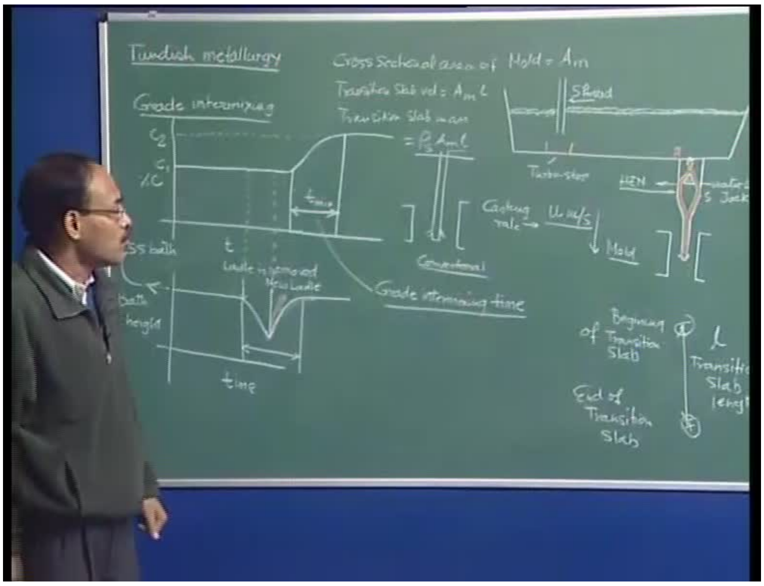

So, let me now draw the hollow jet nozzle to show you, how the s e n design actually is changed, in order to facilitate extraction of heat, so it looks likes, this is the slab casting Tundish, this is the mold c c mold, and then we have the hollow jet nozzle actually goes something like this.

That is how, so that has become now the design of the SEN, typically what is the design of the SEN between this and this, we have the SEN is actually, this is the conventional design of the SEN, and this is the hollow jet nozzle.

So, this is conventional and this is the hollow jet nozzle, so this is a refractory baffle molten steel, what happens is molten steel comes from the Tundish, it impinges here and then it flows like this that is the way it flows.

This is a water cooled steel jacket, and as the molten steel comes here, it impinges on this baffle, and it flows like an umbrella around the wall or the periphery of this hollow jet nozzle, and because the hollow jet nozzle is water cooled, so there is a circulating water, so lot of heat gets removed, and by controlling the surface area of contact, by controlling the flow rate of water, we should be able to control the heat extraction rate and there by deliver molten metal at this particular point under correct temperature, even though the material here is going to be substantially overheated, so the superheat can be controlled by this new technology very effectively.

Let, us talk about now the great transition phenomenon, grade intermixing, we have talked about inclusion floatation, we have talked about heating of the melt, we have talked about superheat, and it is importance and how to control superheat, and last but one let us talk about grade intermixing.

So, grade intermixing basically, suppose you have a ladle and the material is coming and is flowing through the Tundish, so if I measure the concentration here, say in terms of carbon concentration and if I plot it, in that case I will see that well this is the percentage carbon, and this is the time percentage carbon remains constant, because the same grade of steel is being cast, it is composition is uniform, so if I take samples and keep on analyzing those samples as a function of time, I will see no variation. So, this is the composition of the said steel.

Now, as soon as I remove this ladle, for example and bring in so the turret looks like what, the turret looks like one ladle is there from which molten metal goes down into the Tundish, another little is behind that ladle about 180 degree, at an angle of 180 degree diametrically opposite. So as soon as this ladle is going to be the ladle at the front, suppose you are there, so you are looking at in this direction, so the ladle at the front is exhausted, the turret undergoes rotation, and this ladle is brought in and material from this particular ladle now starts to go into the Tundish.

So, now when you withdraw this ladle, so for this particular time when there is no material flowing out flowing into the Tundish, so this particular Tundish is exhausted, and it undergoes rotation like this. So, for some time we will see that no material is coming into the Tundish, and as a result of which, what happens is the bath of the Tundish is going to go down, see if I look at it the bath height, again another figure bath height versus time, then I can say that well the bath height remains initially constant, and then at certain point of time the bath height starts to fall.

And I can understand that this is the time I am talking about that my ladle is removed, ladle is removed, but the casting is still continuing, as a result of which I am monitoring the concentration and you see this is the point here, as I would say that the same composition of steel is still being recorded even though the bath is falling, because there is no material coming in.

Now, at this particular moment which is this, I bring in the new ladle and start to pour in molten metal from the new one. Now, the composition is a different composition, it is a different percentage C, so this represents C1 and we say that the new grade has a composition of C 2, which is suppose say higher than C1.

Now, so once I start, if we bring in the new ladle the bath is going to rise immediately, the bath can be made to rise very steeply or can be made to rise slowly, depending on the process performance, we do not want to lose time also we do not want to have too much of a slag emulsification.

So, if we try to pour in molten metal at a too faster rate, in that case may be the refractory damage is going to be there. On the other hand if we pour it too slowly in that case what we are going to see is the rise of the bath a rise in the bath level is not going to be significantly larger, and as a result of which the casting rate may hamper.

So, somewhere in between, not a very high rate not a very small rate, but with a reasonable rate we should be able to start filling the ladle, and now we filled the ladle, bring in the ladle, open the ladle and bring the bath height to the original level itself, this is my steady state bath depth.

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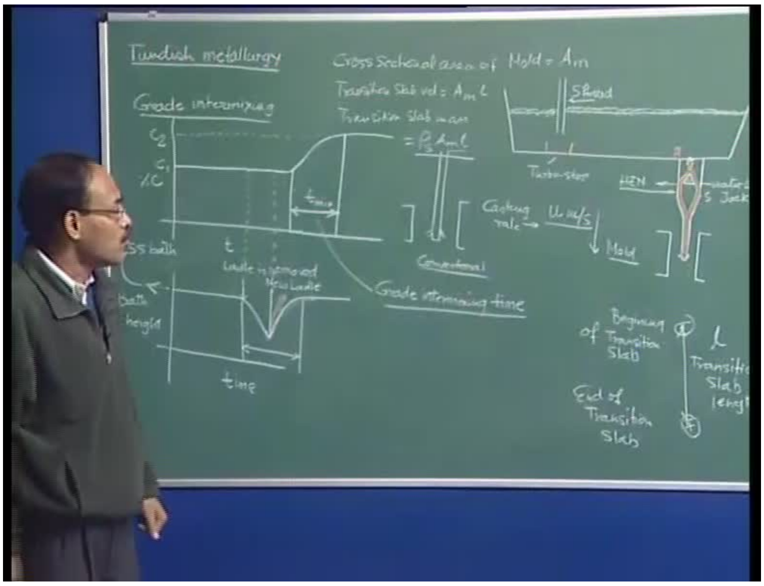

So, this is the time I have brought in a new ladle, and after I open the new ladle, the bath height increases and then I bring it to the original level as is shown here.

So, this is the time for which the bath is fast decreasing, and then it is increasing. So, bath depth fluctuates from the steady state level.

Now, look at the concentration here, so I have brought in the new ladle, open the new ladle here, but still I am not going to see that the concentration has changed, because the material I have brought in the ladle here, open the ladle, but it is going to take some amount of time before my probe can detect it.

So, the casting is going to still go here continue beyond this for some amount of time, and then gradually it is going to increase and then ultimately it is going to go like this, and this is the new composition that I am talking about the C2 composition.

Therefore, as you can see that I have concentration remaining constant here, and then the concentration changing, percentage carbon changing. So, for some duration, therefore what is that duration, it is this particular duration we are talking about. For this particular duration, the composition is neither C1 nor it is C2, but the composition of the slag which comes out will have an intermediate composition.

Initially, it is going to be closer to C1, finally it is going to be closer to C2, but nevertheless during this particular time, we are going to have slabs of mixed composition which we may not be able to sell to the customer.

So, this time duration is called grade intermixing time, at this grade intermixing time, actually if I know the casting speed u meters per second is my casting rate, then I can multiply the transition time, grade intermixing time with the casting speed and get the length of the slab, which is going to have composition neither corresponding to C 1 nor corresponding to C2, and therefore the length of the slab now if I know the cross section of the slab.

For example the slab may be 1500 millimeter long wide, and 200 millimeter width, so I know the cross section, so if I multiply that length with this cross sectional area I am going to get the volume of slab corresponding to this grade intermixing time, and I can convert that volume into mass of steel and then say that well, the mass of the transition slab volume, mass of the transition slab is actually so many tons.

So, by knowing this I should be able to t mixing, I should be able to pin point that from where to where, this point to this point that the transition length is going to occur, it is by knowing this particular graph, I should be able to find out the beginning of the production of the transition slab and end of the production of. So, this is beginning of transition slab and this is the end of transition slab. So, this is called the transition slab length.

If I know the transition slab length l, and if I know the cross sectional area of the mold, suppose is A sub m, in that case transition slab volume is equal to A times m into l, transition slab mass is equal to rho steel into A m l.

So, therefore the cracks of the problem is to be able to generate this curve, based on which I can identify this point, I can identify this point, I can identify the transition slab length and as a result of which I can find out what is the amount of transition slab mass, and then make an assessment that when you do grade inter mixing, how much of material we are losing, because as I have mentioned the transition slab or transition bloom are often downgraded.

What does that mean that, because I cannot sell it to the market or maybe I can sell it, but at a lower price, I cannot get the premium for transition slab, I can have to sell it at a reduced, much reduced price or worst come worst that transition slab is going to be charged back into the basic oxygen furnace or e a f as solid steel scrap.

So, therefore the objective in the steel industry, is to control Tundish flow, is to control the casting rate in such a way that the transition slab volume or transition slab mass is going to be as low as possible, if the Tundish and slab mass is going to be higher, in that case imagine the number of heat is, this is particularly relevant for analogous steel plant, while your casting only two heats of a given grade of steel, ball bearing steel, the next to heat is going to be free cutting steel, and the in the following 2 grades could be some other kinds of steel.

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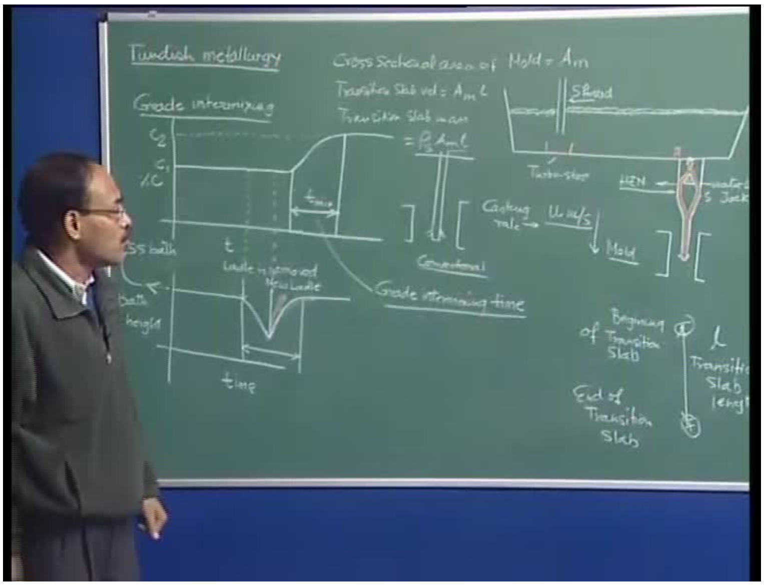

So, if you are changing frequently the grades, and then you are using the same Tundish, so you can imagine that how much of rejection is going to be there, therefore in small plants, alloy steel plants; grade intermixing is a very important problem, because it has tremendous influence on the economics of the steel plant.

If you are casting primarily plain carbon steel, so in that case it is not such a big deal, because we should be able to sell, if your casting point 14 percentage carbon in point 28 percentage of carbon, you will always find a buyer which will take that intermediate composition of carbon, but it is not true because you are particularly making alloy steel plants.

So, therefore how do you understand this, how do you generate this curve, this is a very important issue, this can be done by modeling which I will be discussing through a few lectures or demonstrating through a few lectures, it is by mathematical and physical modeling, it is possible to generate this curve corresponding to a specific Tundish operation, and thereby we can make prediction and optimize the process, such that the Tundish and slab volume is going to be minimum.

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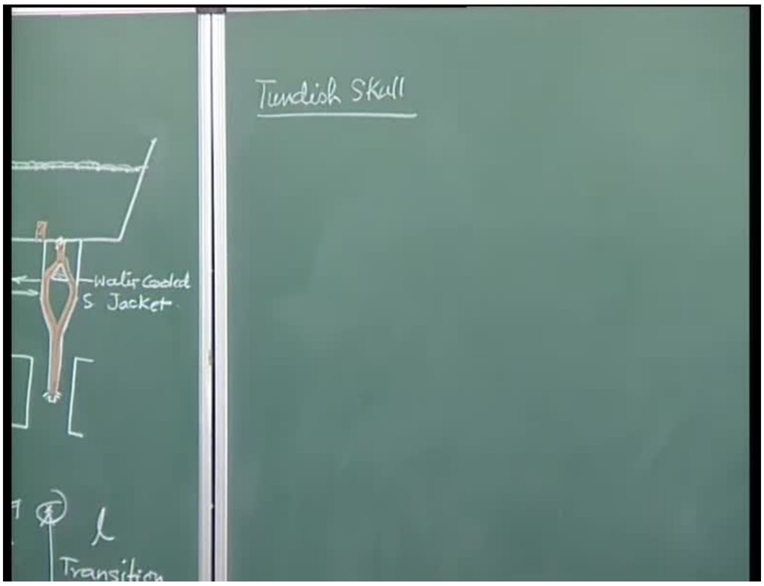

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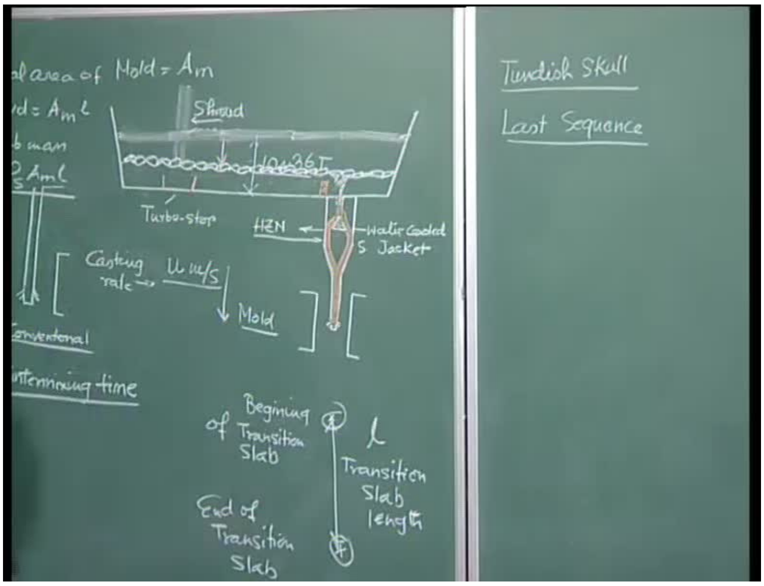

Now, the last topic; last but one that is the Tundish skull, and before we must remember that the casting rates are different for different processes, they depends on the number of strength, they depend on the cross section of the product and so on.

For example, if we are talking of bloom caster, bloom casting per strand, your casting rate could be 800 k g, 900 k g or at the most 1 ton, if we are talking of conventional slab casting, the casting rate per strand is going to be about 3 tons per minute, we are talking about 1200 m m wide slab.

If we are talking of thin slab casting, your casting rate could be about 5 tons, 6 tons per minute through a single strand.

So, therefore the velocity of steel through the Tundish strand is going to be significantly different, depending on the product that you are going to produce through continuous casting, bloom casting is low close to 1 ton, conventional slab casting is 2 to 3 tons per minute, and then thin slab casting could be about 5 to 7 tons per minute.

So therefore the velocities are going to be different in different Tundish systems. Now, if the velocities are higher here, for given cross sectional nozzle diameter, in that case you can imagine that the flow rate, if the flow rate is very high in that case there will be tendency to form vortex as a draining the slag layer, because as I have mentioned that you can see the funnel vortex particularly, when you are draining a sink, you have kept the water open, and then the water is draining out and more is the velocity of water from the tap, you can see more intense is going to be the tendency of the creation, of the rotational funnel vortex in the system.

So, similarly in the Tundish also, as this the flow rate casting rate increases dramatically, in that case there will be a tendency for the slag layer to be drawn, and particularly this is going to be prominent, when we have the slag metal level going down.

So the skull formation is basically an issue at the last sequence, the sequence is a very common word in industry, and sequence essentially means a series of heats in the Tundish.

So, it is called sequence casting one after another, ladle is coming in one ladle with x, some composition then the next ladle with different composition, so we have sequence casting essentially implies, it is not that casting of one heat, but several heats may be of different composition through the same casting, so imagine the last cast last sequence, so the ladle is going to be finally removed, there will be no more ladle, and last sequence basically is the sequence, when the Tundish demands relining, that the Tundish has undergone so much of wear and tear that we are really not in a position to use it any further.

Therefore, before it is taking for relining, so the last heat if you conceptualize the ladle from the ladle material is coming down, this is the last ladle, so the material in the ladle is going to be exhausted, and as the material in the ladle is going to be exhausted nothing comes in into the Tundish, and as a result of which the Tundish bath depth the Tundish goes down.

So at the moment, this stops coming from the ladle, nothing comes in. Now, this is a scenario, this is the instant at which the material does not flow from ladle, we have about 28 depending on 10 to 28, may be 10 to 36, I have seen so much of material, this is the mass of Tundish, mass of steel in a Tundish, so this much this could be in a say bloom casting Tundish or this could be in a thin slab or a slab casting Tundish, huge slab casting Tundish, they can count it about 36 tons of material.

So, the moment molten steel from the ladle is stopped, we have about 36 tons of steel remaining, and now the casting goes on and the objective is to salvage the entire amount of steel out, in the form of solidified product.

But now as I have mentioned already, that as the left depth of the liquid falls down as a surface descends, why the surface descends, because nothing is coming out, only thing material is being drawn from the Tundish, therefore the bath depth really decreases, and as the material drops down, and immediately above the nozzle there is a formation, so imagine that the material now has this level, so the slag is here, I can remove this, the bath depth has descended to this particular level.

There comes an instant, when you will have funnel vortex formation, the rotational, the tedious influence of the nozzle is what we are going to see in terms of funnel vortex formation above the nozzle, and this vortex is known to entrain the upper slag into the mold itself.

And as I have mentioned, the intensity with which this vortexing is going to occur will depend on the casting rate, in thin slab casting mold, thin slab casting process, where the casting rate is significantly larger the vortex may be is extremely intense, and may be forming at a greater height.

On the other hand in a bloom casting Tundish, where the flow rate is very small this may be forming at a much reduced bath depth itself, so the characteristics of vortex formation will depend on the continuous casting process itself.

But, nevertheless; whether it is bloom casting, whether it is slab casting, whether it is thin slab casting, you are going to see that some amount of funnel vortexing is going to generate at some instant of time, when there may be still five tons or seven tons of material left.

So we have started from 36 tons of material in a slab caster, and we will see that by the time, the material falls to about 5 to 7 tons of, 7 ton level, intense amount of funnel vortex can form which can entrain the deleterious upper face slag into the mold, it is at that instant of time that the casting has to be stopped.

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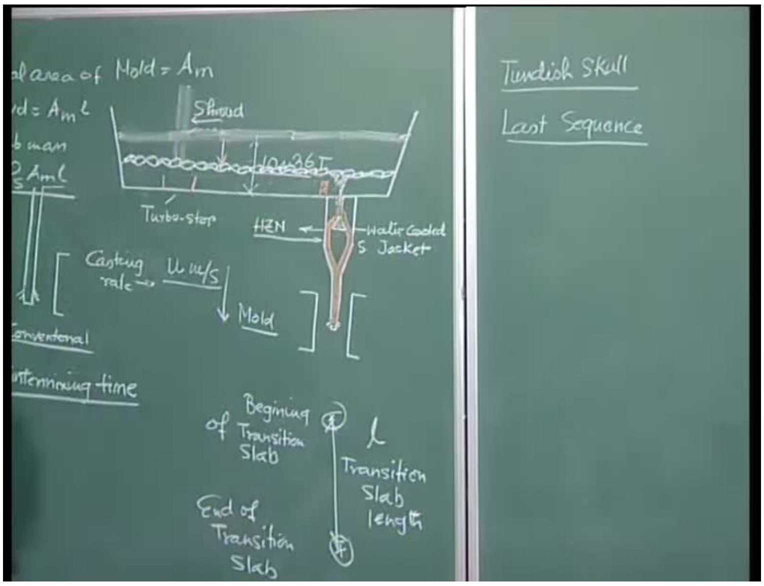

If you do not stop the casting, what happens; slag will be entrained and this slag which are oxides, they are going to make steel weaker and as a result of which we can have innumerable problems, and nobody is going to buy that steel which will contain lot of entrained slag particles itself.

So, the moment slag starts to be entrained into the mold, it is at that point that we say the casting of this particular sequence is over, the Tundish is going to be removed now, ladle has already been removed, and fresh sequence is being prepared and that particular mold as I have mentioned, we may have 5 to 7 tons of steel left in the Tundish itself.

So, the Tundish is taken out from above the continuous casting mold, it is left aside to cool, and this the 5 to 7 tons of material which is left here, now solidifies in the Tundish itself and this is known as the Tundish skull.

So they are hammered basically out of the Tundish, so the Tundish is now broken, the refractory is to be relined, then the skull is going to be salvage by physically breaking apart the refractory lining of the Tundish, and the skull is going to be now taken and recharged back into electric arc furnace as well as, every plant very meticulously weighs that skull, because they want to find out that what is the yield from the Tundish, so much of material they have charged into the Tundish, and how much of billet or bloom they have formed, and this amount of Tundish skull really gives the plant an idea of the yield in continuous casting Tundish just themselves.

So, there is now considerable interest to minimize Tundish skull, and this can also be maneuvered to certain extent by controlling the geometry of the Tundish itself.

So you have to understand, that how does the slag vortexing at a fundamental level, that what controls the slag vortexing, and once you understand that aspect, you should be able to design the Tundish in such a way that, the residual level of liquid at which slag vortexing will take place will really get reduced.

So, the Tundish geometry can be altered with suitable or fundamental knowledge, and once you can alter that, you will have vortex formed in the Tundish, not when there is seven tons of material, but there may be just 2 or 3 tons of material.

So, it is possible to salvage out a reasonable proportion of a residual liquid by altering the design of the Tundish and casting practice to some extent, I must tell you that, when you change a ladle and bring in ladles of different composition particularly in grade intermixing, in that case if the level goes down to lower level before you bring in the fresh ladle in that case also we may have premature vortex formation. Also, because one ladle is removed, so the bath depth is going to down, so at that when little change over takes place, we have to ensure that the level of the metal should not go down to that level which will cause a significant amount of slag vortexing or noticeable amount of slag vortexing.

So, great transition operation has to be very carefully done, so that the level of the material is adequate, so that there is no scope for slag entrainment itself, also we must remember that in the transition slab blank, it is now well known, that more is the level of liquid, more is the transition slab volume.

So, therefore in that this is considerable interest, to reduce the level to certain threshold level, and then opened the fresh ladle, but it is not all as possible, because we want to take precaution that we do not want to have slag entrainment, otherwise it is going to jeopardize the casting process, so as a result of which what happens is, we open the second ladle when the bath is in a comfortable level itself, but that again gives rise to a longer or a larger transition slab volume.

So, the level of the liquid and the transition slab volume, these are to be optimized simultaneously that we do not like to have slag entrainment, at the same time we would not like to have also a larger transition slab volume, so the curve has to be this particularly the rate at which the molten metal is fed into the Tundish, the level of the residual liquid at this have to be really optimized in order to take care of Tundish skull as well as the intermix slab volume.

Tundish skull is relevant particularly in the case of last sequence, grade intermixing is going to be relevant when you are changing ladle change over, but the point I would like to mention or I would like to emphasize that in grade intermixing also, there is a there may be a possibility of slag entrainment.

Particularly, if you have brought the level to too low a level, brought the level of steel to too low a level before you can open the new ladle itself, so that need not happen there , so you have to have lot of experience, the operators have to have lot of experience in order to control the opening of the ladle prevention of Tundish, prevention of too much of slab formation and as well as prevention of slag entrainment into the mold.

Now, I would like to say a few things about melt level control, and give you some idea about the kind of automation and process control that is being done today in steel mill shop.

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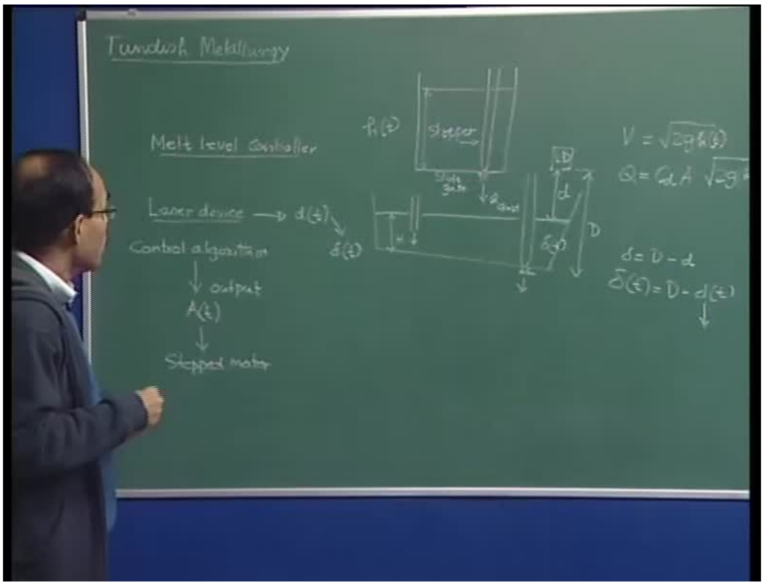

We have seen that there is a ladle, and as I have mentioned that either there could be a stopper rod to control the flow or there could be slide gates nozzles, and then similarly we can have in Tundish also a stopper rod or we can have the Tundish also a slide gate.

So, this is our slide gate so these are the two flow control devices, in today’s modern steel making plants you will find only slide gates and no stopper rod, because it is difficult to control and it does not give a continuous flow of molten metal stream.

So, now the issue is as I have mentioned that, well the material enters here, I can say I should have drawn this ladle somewhere here, so the material enters here, and this you can imagine that the height of the liquid here, is a function of time. On the other hand except for the initial period of filling and the final stages of draining, as I have mentioned already, this height in the Tundish remains constant throughout the process.

Now, as the time as the height decreases, normally for a constant diameter we would expect that the flow rate of molten steel through the Tundish, through the ladle nozzle will also vary.

So, the height decreases from Bernoulli’s equation that, the velocity is equal to square root 2 g h in this case I would say, so the velocity through the nozzle is going to be a function of time, and because height is a function of time.

But, the diameter when you have a stopper rod or a slide gate nozzle is not constant, so the volumetric flow rate is equal to we have a discharge coefficient, and then multiplied by the area of the nozzle into 2 times g square root t.

So, this is the area of the nozzle, and this area of the nozzle is dynamically adjusted in accordance with the height of the bath, such as to get a constant flow rate, exactly the same thing happens in the Tundish also, we get a constant flow rate here by maintaining a changing diameter, as the height decays the diameter is enlarged either by opening the slide gate or by lifting the stopper rod, in order to get a constant flow rate into the Tundish.

Similarly, we have to match the nozzle diameter here also, such that whatever is coming in is exactly what is going out, but the issue is how do you control this diameter, so this diameter has to be the diameter of the opening, the diameter of the opening here has to be adjusted with time, this has to be adjusted continuously with time, on the other hand once this reaches steady state this will assume a constant value,

The issue is how do you maintain a constant bath diameter, and how do you maintain a constant flow rate here, so we have small process control here, which we say as a melt level controller, that is there in steel and the purpose of this melt level controlling or melt level controller is to supply molten metal in the downstream reactor at the constant rate.

Now, typically for example in Tundish, we have a device called laser device that device is going to monitor what that device is going to monitor, for example we may have a laser gun here and that is going to monitor this particular height, so this is suppose a laser gun L d or a laser device, at this laser device, tracks determines that what is the distance which is suppose say, this is the d, and we already know that this much, what is the total distance of this, this is already known to us, we have position the laser the laser is at a some distance from the base of the Tundish, this distance is known to us so which basically we would say.

So, therefore the melt level bath which is we can say delta is equal to capital D over capital D minus d. Note, that this delta is a function of time, this D is a constant and this d is also a function of time, because the melt level can fluctuate.

So, the laser device would be able to find out, depending on the response laser is going to get from the melt surface, so this is the input into the laser device and then the laser device produces an output, and this goes to what is known as a control algorithm.

So, laser device determines, what is d sub t, it calculates what is delta sub t, which is instantaneous thickness, and now we have a control algorithm which may be simple empirical equation, of which may be Bernoulli’s equation, and based on that you see now I want a constant flow rate, I know already suppose what is the flow rate which is coming into the Tundish.

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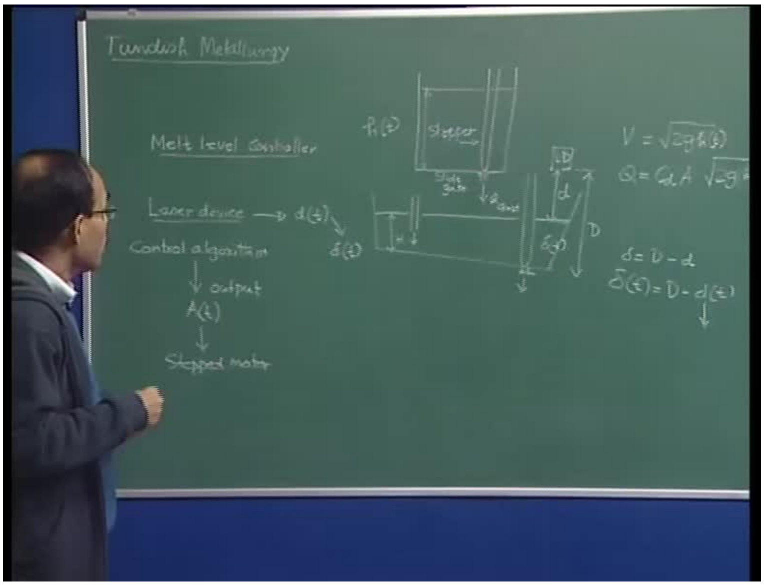

So, I will set that to be the flow rate here, and since I have already determined h sub t through a laser device, it gives such me an opportunity to calculate a and accordingly adjust the

So, the call to control algorithm is going to make an output, and that output is nothing, but A sub t, and then there is going to be a step motor, and this step motor actually is going to either close this aperture slide gate.

Slide gate the name essential it, as it is a gate valve, but you just slide it then it gets closed, you take it away it opens, so the motor, step motor can then adjust the nozzle diameter, in accordance with what is the response desired response, over which is being produced on the basis of the control algorithm.

So, the laser device will give me the bath depth, the bath depth is going to be fed into a control algorithm for a given flow rate, the control algorithm will yield the necessary area and then that particular area will be created by using a step motor, and it is in this particular way we can maintain a constant bath depth for a given flow rate.

So, as you see in order to control the melt level in the Tundish, we require a sensor and that sensor here, is the laser device we require a control algorithm, and it is being done dynamically, so this type of simple process control in steel making shop which we call as a dynamic control of themelt shop dynamic control of the Tundish bath depth, and this is a very simple control algorithm, and control process, controller melt level control procedure that I have illustrate.

But, there are much more sophisticated control algorithms which are available in B O F shop, which are available in continuous casting house where most of the processes, the fluctuation of the mold or the decarburization rate in oxygen steel making converters, they are been controlled and everywhere we will see that extensive process control is being applied either on an off line fashion or on an online fashion, this is the way it is being done within the process itself.

The melt level can fluctuate and accordingly the response will be produced, and the nozzle is going to be adjusted, so this is done dynamically with the process, and therefore it is an online process control which will be necessary for us in order to regulate the bath.

So, I will not like to discuss anything on Tundish metallurgy, so we come to the conclusion of our discussion on ladle and Tundish metallurgy, and quickly I will now like to summarize that part, we have done in ladle and Tundish metallurgy, basically the ladle and Tundish metallurgy are applied in order to profoundly influence, the quality of steel and also we have seen the productivity of steel as well.

Now, when you talk of quality of steel, basically it is in terms of achieving the right composition, it is in terms of achieving the correct temperature, it is in terms of achieving the correct cleanliness, and these are the main motto of the secondary steel making processes, and it starts following the taping operation, first what we have done, we have seen Deoxidation and then subsequent to the Deoxidation, we have talked about inert gas margin and I have already mentioned to you that, inert gas margin is very important, because we would like to now create stirring in the process.

So, all along one thing in secondary metallurgy is central, and that is the inert gas stirring, so all through the duration of secondary steel making, we will have gasses injected from the bottom either 1 or 2 porousplugs.

Now, following inert gas stirring, we can go for arcing process where we can increase the temperature which is the ladle furnace, which increase the temperature of the bath. We can also do alloy addition and compensate for heat loss and alloying etcetera through the arcing, and following ladle furnaces, we can go for vacuum degasing, and subsequently we can go for inclusion modifications through injection metallurgy and so on.

I have also mentioned to you very categorically that more and more secondary steel making operations, you are going to incorporate in your steel making circuitry, the amount of effort is going to be increased and as a result of which, the cost of the final steel produced is going to be increased.

So, today the trend is to carry out primary steel making or mostly decarburization in the oxygen steel making temperature, and then tap the molten metal and carry out all these operations in ladles, and once you have set the correct temperature, correct cleanliness, correct composition you are all set to cast molten steel through continuous casting.

Then comes Tundish which we have traditionally seen is a baffle vessel, but now whatever I have discussed in the last few lectures, we have seen that well there is a lot of scope to improve the quality of steel further in the Tundish, and also insured defect free cast products coming out of the continuous casting process.

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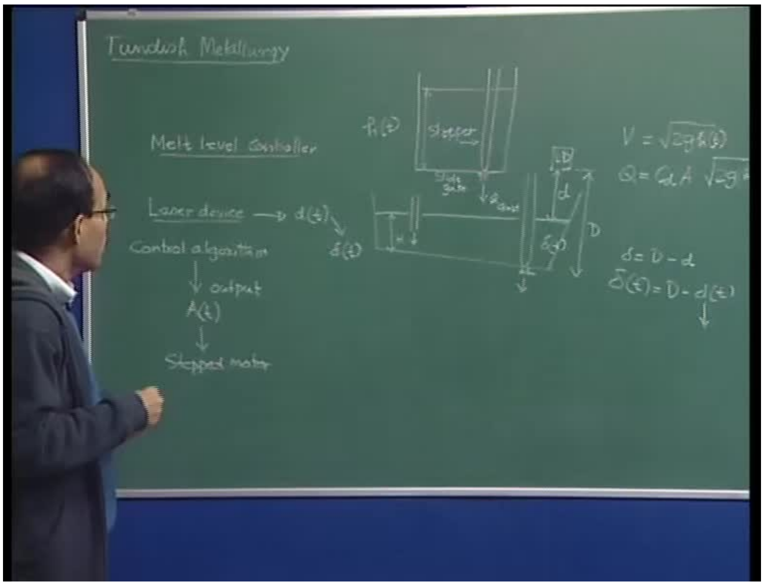

In that context, I have enumerated many things starting from your inclusion modification or inclusion floatation in Tundish, I have talked about your after inclusion modification or inclusion floatation, I have talked about your temperature control or heating through plasma heaters, I have also talked about super heat control, I have also talked about Tundish skull and also grade intermixing and all these things.

So, there is lot of scope in Tundish metallurgy, also I mean Tundish; we need not look at Tundish just like a distributer to two different molds, no it is not like that anymore, we have lot of scope there, and there in Tundish what really we can do or maneuver the operations by controlling the design of the Tundish, introducing furniture’s store, such an extent that the productivity and the quality of steel can be significantly enhanced.

The conclusion part of this lecture what I have done is, I have tried to show you that how the melt level is controlled through slide gates or stopper rod by using a simple control algorithm and a sensor, and this gives you an idea about the simple process control which are available there.

Nobody has to do anything this kind of, there are computers, there are sensors available and it is being done absolutely automatically, no man power is needed and this gives you some flavor of a simple or perhaps the simplest example of dynamic control process control in terms of the melt level control in Tundish, and ladle that I have discussed. Now, I am going to move on to the next topic.