Steel Making
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Module No. # 01
Lecture No. # 09
Modern Steelmaking I, Oxygen Steelmaking

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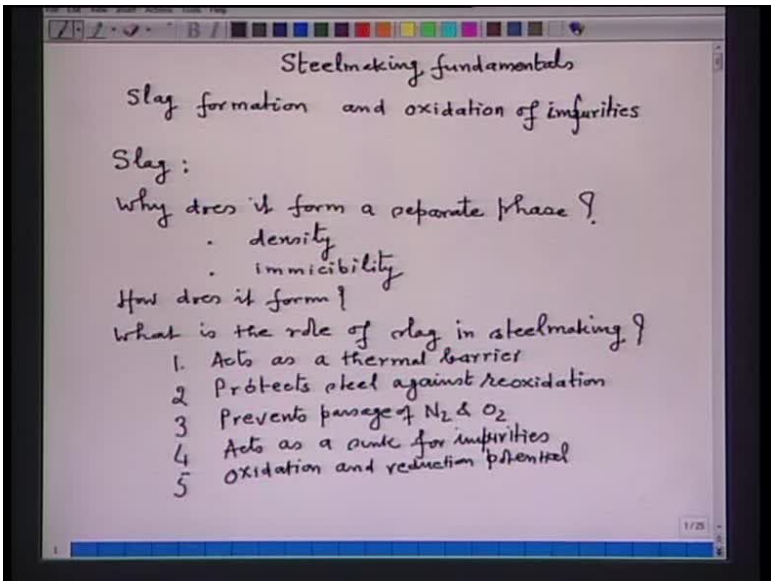

Steelmaking fundamentals

Slag formation and oxidation of impurities

Slag :

Why does it form a separate phase ?

- density
- immicibility

How does it form ?

What is the role of slag in steelmaking ?

1. Acts as a thermal barrier
2. Protects steel against reoxidation
3. Prevents passage of N_2 & O_2
4. Acts as a sink for impurities
5. oxidation and reduction potential

Today, I will be talking on steel making fundamentals. Now, what is steel making, in fact? A steel making involves removal of impurities through oxidation and slag formation, such that total iron content of slag and oxygen content of molten steel at turn down are minimum.

So, essentially steel making involves the turn down contents of iron in slag and oxygen in steel should be minimum. So, the fundamental comprises of slag formation and oxidation of impurities. Slag formation as you can also called as a slag making or whatever it is all the same.

So, what is a slag in fact? Slag is a generic name and in a steel making, it means, that it is a homogeneous liquid solution of oxides, sulfides, nitrites, but mostly slags in a steel making contains oxides and sulfides. When the slag is cooled and in the solid state, it consists of multi crystalline phases; so that is what in fact a slag means. Now, say why does it form a separate phase?

The reason is very simple. For your information, all the oxides, for example, FeO, SiO 2, MnO, Al 2O 3, m n s which constitute the components of the slag, their density is in between say 3 to 5 or 5.5, whereas molten steel as a density of 7 or 7.5. So, liquid slag is lighter than molten steel, and hence, it floats on the surface of the molten steel. This is number 1 reason, why it forms a separate phase? Say, number 1 reason is density of slag is smaller than density of liquid steel and second reason is that the oxides are invisible in molten steels; so second reason is immiscibility. So, density and immiscibility met the slag to appear as a separate phase in presence of liquid steel.

Now, another question comes, say, how does it form? In a steel making what is done? Hot metal? Hot metal contains carbon, silicon, manganese, phosphorous and iron and as oxygen is blown then, silicon is converted to SiO 2, phosphorous is converted to P 2 O 5, manganese is converted to MnO and some of the iron is oxidized to FeO.

So, because the steel making involves oxidation of impurities and except carbon all the impurities forms oxides and these oxides have density lower than molten steel; so it will float on the surface of molten metal during refining of hot metal twisting. So, it forms essentially, because we want to remove the impurities from hot metal and to get molten steel so that is how it forms. Now, what is the role of slag in a steel making? In fact, I will say this way, that make a slag, and slag will make your steel that is what the role of slag in a steel making.

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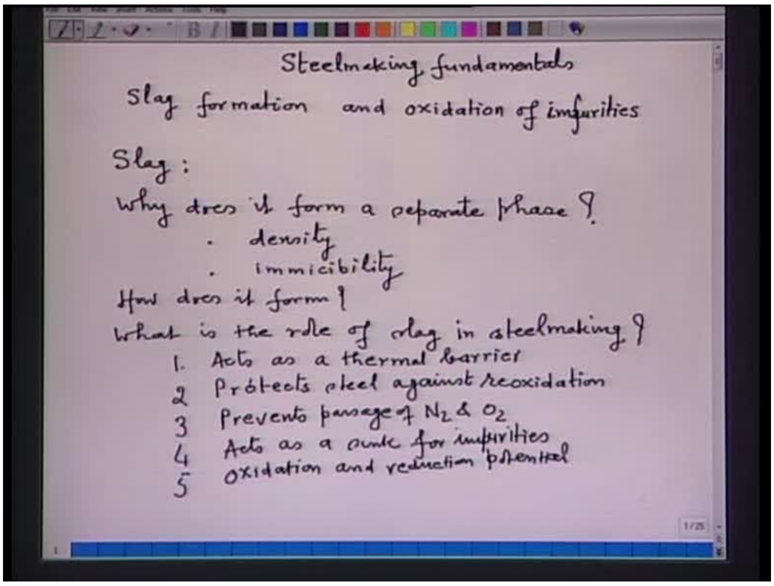

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If an operator does not know how to make a slag, he cannot make steel at all. So, the role of slag in a steel making can be said in just one sentence - make a slag and slag will make your steel. So, that is what the importance of slag, but besides this, there are several other importance of slag in the steel making.

First, slag acts as a thermal barrier what does it mean? Molten steel is covered by a slag and slag is a poor conductor of heat hence, it helps to restore or rather it helps to keep the heat within the molten bath and hence heat loses are minimum and therefore, we can call it acts as a thermal barrier. Second, it protects steel against re-oxidation. Now, imagine molten steel is uncovered and put in the atmosphere, then the iron oxidizes. Slag also protects steel against re-oxidation.

Third, slag prevents passage of nitrogen and oxygen from the gaseous phase to the molten bath. Because there is a slag cover and whenever the gas for example, nitrogen or oxygen from the atmosphere can be transferred only through the slag and in that way slag premains the passage of nitrogen and oxygen in the molten bath. Fourth, it acts as a sink for impurities, that means, when silicon gets oxidizes SiO 2, Mn gets oxidizes MnO, phosphorus gets oxidizes Fe 2 O 5, then they form a slag and by creating suitable properties in the slag, it acts as a sink for all these impurities, which are coming from the oxidation of the hot metal.

Fifth, slag also controls oxidation and reduction potential of slag. Essentially it is the FeO content, which decides whether this slag is oxidizing or reducing in nature.

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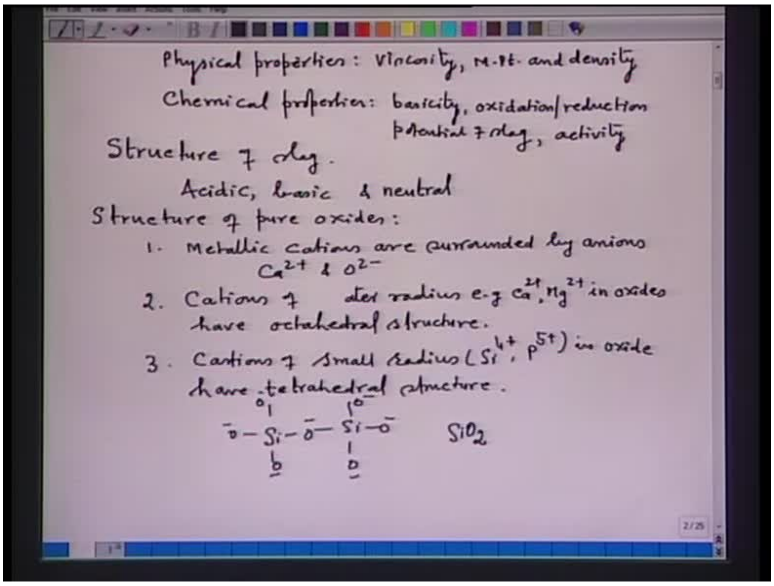

Physical properties: viscosity, m.pt. and density

Chemical properties: basicity, oxidation/reduction potential of slag, activity

Structure of slag.

Acidic, basic & neutral

Structure of pure oxides:

1. Metallic cations are surrounded by anions Ca^{2+} & O^{2-}
2. Cations of ater radius e.g Ca^{2+}, Mg^{2+} in oxides have octahedral structure.
3. Cations of small radius (Si^{4+}, P^{5+}) in oxide have tetrahedral structure.

$^-O-Si-O^--Si-O^-$ SiO_2

Relatively higher amount of FeO in the slag is called oxidizing; lower amount of FeO in slag that is a reducing slag. Typical example, blast furnace slag say 1 percent or even to that order of magnitude FeO, so they are called the reducing slag; whereas all steel making slag they have around 15 to 16 percent of FeO, so we can call them as a oxidizing slag.

So, for the above purpose, the slag must contain certain physical properties, and among physical properties viscosity, melting point and density are important; among chemical properties basicity, oxidation, reduction, potential of slag and activity of component of each of slag.

Now, these above properties are determined by a structure of slag. Now, slag in a steelmaking, they consist of acidic oxides, basic oxides and the neutral oxides. For example, SiO 2, P 2 O 5 they are acidic; Ca O, NgO, FeO, MnO they are basic; neutral Al 2 O 3, that means, Al 2 O 3 acts as base in the acid medium and acidic in a basic medium. So, let us consider the structure of pure oxides, some essential features oxides have cations and anions.

Now, one say metallic cations are surrounded by anions. If I have calcium oxide, then Ca 2 plus ions and O 2 minus ion; Ca 2 plus ions are cations and O 2 minus ions are the anions. Second important feature, cations have greater radius, for example, Ca 2 plus Mg 2 plus in oxides have octahedral structure, whereas cations of a smaller radius say Si 4 plus, P 5 plus in oxide have tetra hydraulic structure.

For example, if we take SiO 2, in the SiO 2 each silicon atom is surrounded by 4 oxygen ions and each oxygen ions is surrounded by silicon. For example, if I take this is the silicon, it is surrounded by 4 oxygen ions and each oxygen is surrounded by 2 silicon atoms. So, this structure repeats in three-dimensional and gives us the oxide like SiO 2, which is electrically neutral.

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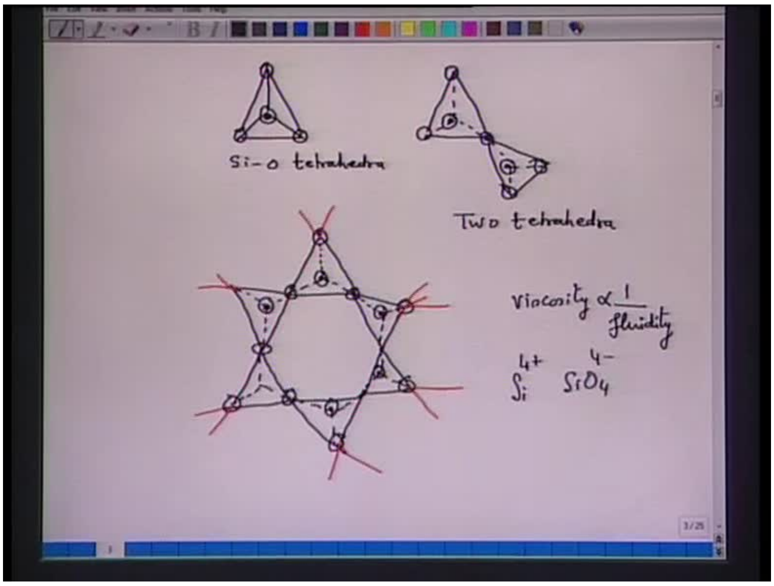

Now, another important feature is that in the acid slag, the tetrahedral network, which is present in three dimension, which is present in three dimension they are joint at the vertex. Now, with that I mean, for example, if this is the one tetrahedra of silicon oxygen tetrahedral, that is here oxygen, oxygen, oxygen, silicon and here is oxygen. Now, the two tetrahedrons, they are joined at the vertex. For example, if I take this one, this this so these are the two tetrahedral, they are joint at the vertex.

So, this is one oxygen, another oxygen, another oxygen, oxygen, oxygen, silicon, silicon and surrounded by the oxygen; so these are the two tetrahedra.

So, what is being said here is that cations in acidic oxides, they were lower radius and hence they follow the tetrahedral structure, that means, each tetrahedron is joined at the vertex and this particular structure is repeated in three dimension and hence, we get the electro neutral SiO 2.

So, a three dimension network will look something of this way, I will try to draw for you. So, this is a hexagonal network it forms, they are all the tetrahedron they are jointed at the vertex and so I am just showing the position of the ions. So, this is one oxygen, another oxygen, oxygen, oxygen, oxygen, oxygen, oxygen, oxygen, oxygen; this is one silicon, silicon, this is silicon, this is silicon and this is silicon and another oxygen over here, over here, over here, over here and over here.

And now in three dimensional, this will go further this way, further will be joined by another vertex. So, this is how in a three dimensional network, a silica structure looks like this. So, what we can imagine? At the melting point, the same type as structure prevails.

Now, if it is known, that means, viscosity is inversely proportional to fluidity; lower fluidity, higher viscosity; higher fluidity, lower viscosity and fluidity is directly linked with the movement of the ions that are present in the liquid..

So, if the size of the ion is larger, then we require higher force; if the size of the ion is smaller, then we require the smaller force. That means if the size of the ions, which constitute the liquid is larger, then the viscosity will be very high and opposite is true that is when the ions are smaller, then the viscosity will be very low. So, the SiO 2 just at the melting point, it will consist of very large size of combination of cations and anions and hence, the viscosity of SiO 2 just at the melting point is very very high.

Now, if we want to reduce the viscosity, then one option we have. What we do? We go at very high temperature. So, at very high temperature what will happen, due to thermal dissociation, the bounds will be broken and we have ultimately at very high temperature a mixture, which contains Si 4 plus and SiO 4 4 minus.

Now, we have reduce the size of the ions, hence the viscosity will decrease and fluidity will increase, but this requires a very high temperature and such a high temperature is not possible in case of a steel making.

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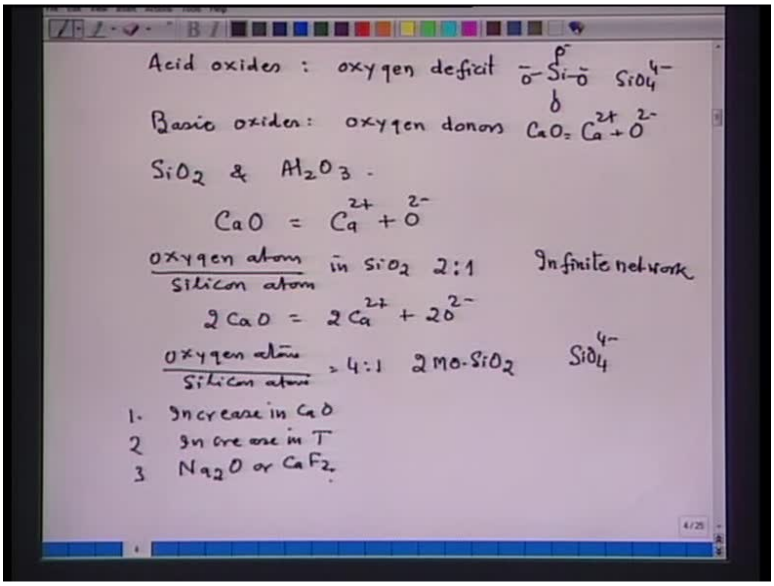

Acid oxides : oxygen deficit $\bar{O}-\overset{\bar{O}}{\underset{\bar{O}}{Si}}-\bar{O}$ SiO_4^{4-}

Basic oxides: oxygen donors $CaO = Ca^{2+} + O^{2-}$

SiO_2 & Al_2O_3.

$$CaO = Ca^{2+} + O^{2-}$$

$\frac{\text{oxygen atom}}{\text{silicon atom}}$ in SiO_2 2:1 Infinite network

$$2CaO = 2Ca^{2+} + 2O^{2-}$$

$\frac{\text{oxygen atom}}{\text{silicon atom}} = 4:1$ $2MO{\cdot}SiO_2$ SiO_4^{4-}

1. Increase in CaO
2. Increase in T
3. Na_2O or CaF_2.

So, now what to be done? Now, we also understand that acid oxides, in fact these acid oxides can also be considered as oxygen deficit. Because they are oxygen deficit, so they have a tendency to form a simple ions so called SiO 4 4 minus. So, remember acidic oxides, they are oxygen deficit that means they require additional ions to form complex ions. You will understand better, when I say basic oxides, they are oxygen donors.

For example, if I take calcium oxide, will give me Ca 2 plus and O 2 minus; so Ca 2 plus does not form that complex as silicon O 4 4 minus. So, basic oxides are oxygen donors and these, O 2 minus ions, they can move freely into the melt.

So, now, what can we do? If we want to reduce the viscosity of acidic oxides, that is only possible when we break all the four vertex of the tetrahedral, then the size of the ion will be smaller, energy required for the flow will be smaller and the fluidity of the slag will be very high.

So, considering that most important oxide in a steelmaking, they are SiO 2 and Al 2 O 3. Al 2 O 3 also behaves in a similar way. Now, let us consider an addition of calcium oxide. So, if you add calcium oxide what calcium oxide does? So, if you add calcium oxide, then calcium oxide dissociates to Ca 2 plus plus O 2 minus.

Now, you see, if I supplied 2O 2 minus, then I can break all the four tetrahedron, because the four vertex are joint by another four vertex. So, if I break all the four vertex, then I will get the ionic specific, which consist of SiO 4 four minus and this is only possible when I add 2 O 2 minus ions. Other way round, if I add 1 mole of calcium oxide, I am adding 1 mole of O 2 minus ions.

Now, this 1 mole of O 2 minus ions will break two vertex; if I add 2 O 2 minus, then it will break all the four vertex. So, if I make it for example, if I put it say total oxygen atom upon silicon atoms in SiO 2 that is 2 is to 1, if that is the case, then all the corners of tetrahedra are shared; all the tetrahedron all the vertex of tetrahedra in a three dimension will be shared; the size of the ion which will be allowable it is very high and hence viscosity of slag is very high.

Now, what I do? I know the basic that if I add 1 Ca O, I am putting 2 O 2 I am putting one O 2 minus ions, and one O 2 minus ions can break two vertex of the tetrahedron. So, what I do now? I add for example two Ca O, and 2 Ca O will give me 2 Ca 2 plus plus 2 O 2 minus, that means, now if I have this oxygen atom upon silicon atom ratio that is equal to 4 is to 1, that means, the composition will be 2 MO into SiO 2 or 2 Ca O SiO 2 in that case what will happen? All links are broken and the ionic species, which will be available after the addition of two moles of calcium oxide or two moles of any basic oxide, then I will have an entity in the slag which is SiO 4 4 minus and size of this entity is very small and therefore, the viscosity of the slag decreases drastically.

So that is what from the structural point of view the addition of calcium oxide it rather decreases the viscosity of slag. Now, between the ratio 2 is to 1 and 4 is to 1 for example you have the ratio 5 by 2 or 3 by 3 is to 1 or 7 is to 2, we had say we have 1 mole of calcium oxide, we had 1.5 moles of calcium oxide, 1.75 moles of calcium oxide.

So, in that order as you increase the amount of CO till you come to the ratio 4 is to 1 the viscosity will decrease and attain a minimum value at the ratio 4 is to 1. So, having understood the addition of calcium oxide on the structure of slag, now we can say that the progressive addition of calcium oxide till the formation of 2 MO SiO 2, there will be decrease in the viscosity of the slag. So, if we want to summarize, we can say that increase in Ca O, decrease viscosity of slag; increase in temperature, no doubt it also decreases viscosity of the slag.

Now, also Na 2 O or Ca F 2 decrease the viscosity of the slag to a larger extent as compared to when calcium oxide is added. Essentially it is because the Ca O and Ca 2 plus, it is two charges; so it will joint two SiO 4 4 minus ions. Na 2 O has single charge that is 2 Na plus and it will be able to joint only one SiO 4 4 minus similar is the calcium fluoride.

In the calcium fluoride F as also a one charge and it will replace oxygen or it may replace all the 4 oxygen and ultimately we may end up with the S i f 4 only. So that is the reason why Na 2 and f and calcium fluoride it decreases the viscosity at a drastically.

Now, as regards the role of alumina, now alumina also be as in the similar way, but alumina has a silica equivalents with that I mean 2 Al 3 plus can replace 2 Si 4 plus only when 1 Ca 2 plus is present so that is what the role of alumina.

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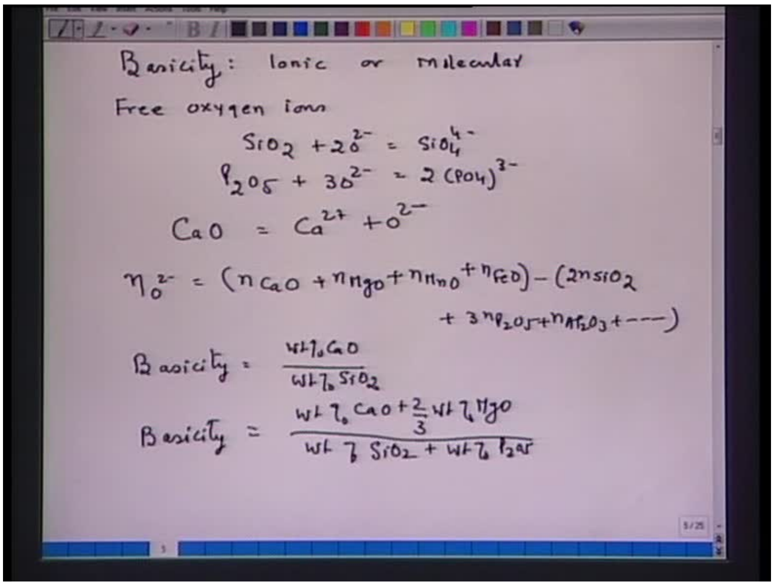

Basicity: Ionic or molecular

Free oxygen ions

$$SiO_2 + 2O^{2-} = SiO_4^{4-}$$

$$P_2O_5 + 3O^{2-} = 2(PO_4)^{3-}$$

$$CaO = Ca^{2+} + O^{2-}$$

$$n_{O^{2-}} = (n_{CaO} + n_{MgO} + n_{MnO} + n_{FeO}) - (2n_{SiO_2} + 3n_{P_2O_5} + n_{Al_2O_3} + ---)$$

$$\text{Basicity} = \frac{\text{wt\% CaO}}{\text{wt\% SiO}_2}$$

$$\text{Basicity} = \frac{\text{wt\% CaO} + \frac{2}{3}\text{wt\% MgO}}{\text{wt\% SiO}_2 + \text{wt\% P}_2\text{O}_5}$$

Now, coming back to the so-called basicity of the slag, now, basicity is another very important property. So, we can define either from ionic theory or from molecular theory. Now, from the ionic theory point of view, they can say let me know that most of the constituents or oxides in slag some oxide donors, some oxide takers.

So, when basic oxide I have read it, oxygen ions will be available and these oxygen ions they break the tetrahedron. So, any free oxygen ions available after satisfying the requirement of all acidic oxides that is called the index of basicity, that means, the presence of free oxygen ions is an index of basicity of a particular slag.

Now, with that I mean, for example, if I write SiO 2, it will take 2 O 2 minus ions to make SiO 4 4 minus; similarly, if I have slag which as P 2 O 5 that will take 3 O 2 minus ions to give us 2 PO 4 3 minus. So, if we further add oxygen ions, then probably the oxygen ions will be free.

Now, from where it will come? So, if I add calcium oxide, then it will give me Ca 2 plus plus O 2 minus. So, we can define, now a neutral slag is one, which contains enough O 2 minus ions so that each tetrahedron of acidic oxide is independent of each other.

So, we can quantify the free oxygen which is available per 100 gram on the slag that will be equal to n Ca O plus n MgO plus n MnO plus N FeO, because they are all oxygen donors minus 2n SiO 2, because 2 O 2 minus is required plus 3n P 2 O 5, because 3 O 2 minus is required plus n Al 2 O 3 plus so on.

So, any oxygen ions which is available after satisfying the requirements of all acidic oxide that will be free and we can consider the free oxygen ions is the index of basicity of the slag. But well, from the shaft flow of point of view it is very difficult to determine the free oxygen ions.

So, normally the shaft flow, the basicity is defined a very simple way weight percent of calcium oxide upon weight percent of SiO 2. Now, I suppose they are some other oxides are also present, for example, MgO is present or P 2 O 5 is present, then basicity is defined in terms of CO equivalent of NgO, that means, MgO is not that effective as compare to calcium oxide. In that case, basicity will be defined say weight percent Ca O plus 2 by 3 weight percent MgO upon weight percent SiO 2 plus weight percent P 2 O 5.

So, here what has been done? Now, suppose if the slag contains MgO also, then MgO is not that defective as calcium oxide it is only 66 percent effective hence that has been taken into account they are simply the index of basicity.

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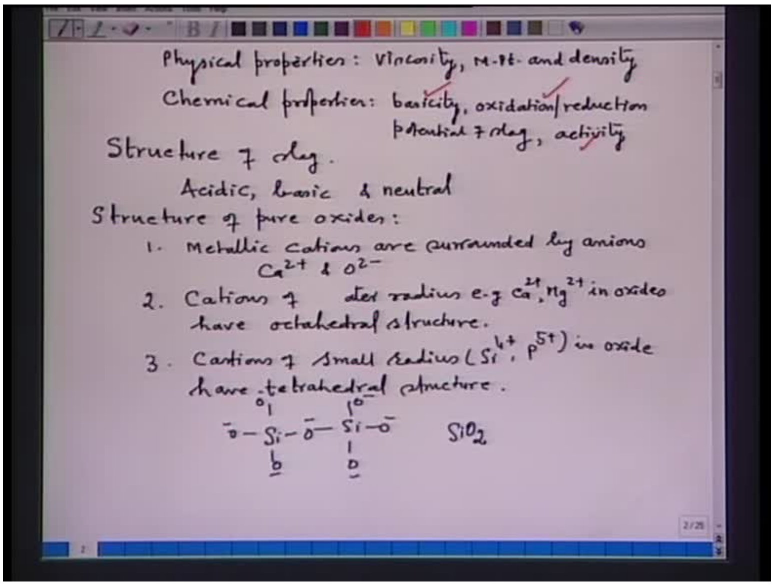

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Structure of pure oxides:

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3. Cations of small radius (Si^{4+}, P^{5+}) in oxide have tetrahedral structure.

Now, we can also define a sort of a free calcium oxide iterative sometimes you called excess base. I will call for example as we have seen in case of ionic nature of the slag that free oxygen ions is index of basicity and that free oxygen ions can take part in the reaction. Similarly, free Ca O is an index of basicity, in the sense that that free Ca O can take part in the reaction.

Now, we define for example, say a basic slag is 1 with neutralizes all the acid components of the slag normally in a steelmaking, we have for example SiO 2, n P 2 O 5 or the acidic oxide.

So, in order to define free Ca O, for example, if I consider Ca O SiO 2 system, if I consider Ca O SiO 2 system, then free Ca O will be available only when the requirement for SiO 2 is completely met. With that I mean that when the compound 2 Ca O SiO 2 has been formed then and then the excess Ca O will be available that means that excess Ca O now can take part in the reaction.

So, if I want to define for example, in kg kg free Ca O that will be equal to kg Ca O added minus 100 and 12 upon 60 kg SiO 2. Now, since 60 kg SiO 2 needs 112 kg of calcium oxide from where this equation comes. Now, for example if I take 100 ton hot metal, say if I take 100 ton hot metal 1 percent silicon, then silicon is equal to 1000 kg SiO 2 will be 2143 kg and then, the free Ca O in kg that will be equal to kg Ca O minus 112 upon 60 into 2143 that what does it mean?

That means that free Ca O in slag will only be available when added amount of Ca O is greater than 112 by 60 into 2143. Now, this comes say kg Ca O minus approximately 4000 kg calcium oxide. So, only that Ca O which is which comes after subtracting this amount is the free Ca O and that can take part in the reaction, for example for the removal of phosphorus.

Now, if you also consider phosphorus into our discussion, then free Ca O again in kg that will be equal to kg Ca O added minus 112 upon 60 into kg SiO 2 minus, say now we have say 142 kg P 2 O 5, it needs 168 kg of calcium oxide; we are considering the compound three Ca O P 2 O 5 so that will be minus 168 upon 142 P 2 O 5 in kg.

So, if I put it this way, this will be kg calcium oxide minus 1.86 kg SiO 2 minus 1.183 kg P 2 O 5. So that is what the concept of free calcium oxide in the slag and it also consider that free Ca O will you can also call it to be the activity of calcium oxide in the slag.

Now, this is what a very important thing to understand the concept of free Ca O in this slag. Now, here its will be noted that if P 2 O 5 forms the function of time, then accordingly the free calcium oxide in the slag will also vary. We have seen basicity, we have seen oxygen direction potential of slag, now we have to consider the activity of slag. Now, say activity of slag component.

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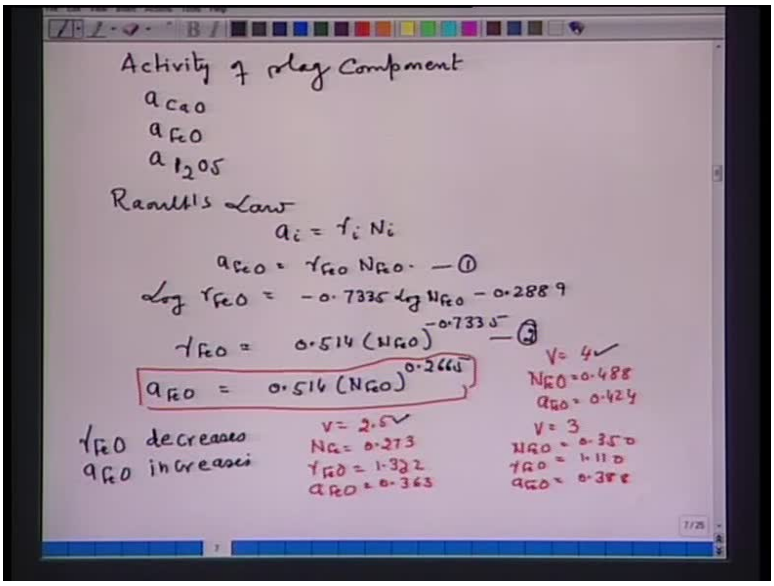

Activity of slag Component

a_{CaO}

a_{FeO}

$a_{P_2O_5}$

Raoult's Law

$$a_i = \gamma_i N_i$$

$$a_{FeO} = \gamma_{FeO} N_{FeO} \quad — ①$$

$$\log \gamma_{FeO} = -0.7335 \log N_{FeO} - 0.2889$$

$$\gamma_{FeO} = 0.514 (N_{FeO})^{-0.7335} \quad — ②$$

$$\boxed{a_{FeO} = 0.514 (N_{FeO})^{0.2665}}$$

γ_{FeO} decreases

a_{FeO} increases

$V = 2.5$ ✓

$N_{FeO} = 0.273$

$\gamma_{FeO} = 1.322$

$a_{FeO} = 0.363$

$V = 4$ ✓

$N_{FeO} = 0.488$

$a_{FeO} = 0.424$

$V = 3$

$N_{FeO} = 0.350$

$\gamma_{FeO} = 1.110$

$a_{FeO} = 0.388$

Now, what activity means, activity is the effective concentration that particular oxide will be active or will be available for reaction when it is free in nature so that is what the most important.

Now, from a steelmaking point of view, we are looking for example activity of calcium oxide, because calcium oxide is a component, which makes slag basic, which forms compounds is SiO 2 and P 2 O 5. So, it should remain free, then we are also looking for activity of FeO, because activity of FeO determines oxidation and reduction potential of slag, say availability of oxygen from slag to metal that will depend upon what is activity of FeO that is what is the free FeO content of the slag, then we are also looking for activity of P 2 O 5. Now, since activity of P 2 O 5, we want that activity of P 2 O 5 should be very very low, because we want to remove phosphorus phosphorus will form P 2 O 5.

So, if its activity of P 2 O 5 in the slag is very high, the phosphorus will revert back to the metal and that is what we do not want it. So, conceptually what we can say, that the activity of any component it depends on its mole fraction and activity coefficient.

Now, the slag it follows Raoult’s law, because they are concentration is more than one percent. So, Raoult’s law is obeyed and according to Raoult’s law activity of any component that is equal to activity coefficient into mole fraction of that component.

Now, activity of FeO I enough said when we are considering free Ca O, then let us take it activity of FeO, which is a very important component for a steelmaking. So, activity of FeO that is equal to gamma FeO into N FeO. Now, log gamma FeO is equal to minus 0.7335 log N FeO minus 0.2889.

Now, if I write, for example gamma FeO that will be equal to 0.514 N FeO to the power minus 0.7335 and if I write now activity of FeO, that means, this is my equation number 1; this is my equation number 2; now if I combine equation 1 and 2, then I get activity of FeO that will becomes equal to 0.514 N FeO to the power 0.2665.

So, this equation one can calculate the activity of FeO. Now, for example if I take v ratio that is the basicity ratio equal to 4, then I consider say, for example, I take N FeO that is equal to 0.488 and I determine activity from here, then the activity of FeO it comes equal to 0.424 and similarly, if I take v is equal to, for example, 3, then N FeO that is equal to

0.350, I determine gamma FeO that comes equal to 1.110, then I will be calculate activity of FeO that is equal to 0.388.

I take another example, I take v is equal to for example, 2.5 I calculate N FeO that is equal to 0.273, then gamma FeO that is equal to 1.332 and activity of FeO that is equal to 0.363. Now, what this calculation means? Now, this calculation means that in a Ca O SiO 2 system, if basicity of the slag as defined by weight percent Ca O upon weight percent SiO 2 it increases, then gamma FeO decreases and activity of FeO it increases.

As you see from here that if the v ratio is 2.5 to 4, if you go then the gamma FeO at v is equal to 2.5 was 1.332 and at v is equal to 3 gamma FeO becomes 1.110 and for v is equal to 4 gamma FeO can be calculated to the value of 0.87. So, the gamma FeO decreases and as a consequence of decreasing gamma FeO activity of FeO increases.

Now, so that is what the important consequence of this particular calculation that increase in the v ratio, that is increase in the basicity increases the activity of FeO and that one can understand also, that means, if we consider Ca O FeO SiO 2 system, then in Ca O FeO SiO 2 system as we increase the amount of calcium oxide, then the FeO becomes free and hence its activity increases so it is logical also. Now, the next thing that I will come now, the important property is the slag forming.

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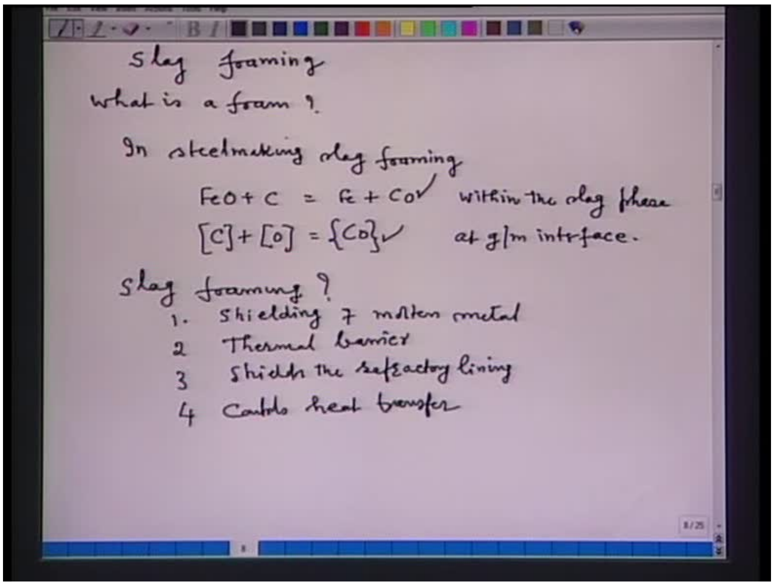

slag foaming

what is a foam ?

In steelmaking slag foaming

$FeO + C = Fe + CO$ ✓ within the slag phase

$[C] + [O] = \{CO\}$ ✓ at g/m interface.

slag foaming ?

1. Shielding 7 molten metal
2. Thermal barrier
3. Shields the refractory lining
4. Controls heat transfer

Now, what is a form? Form in fact is a dispersion of gas bubbles in liquid. A liquid is set to be forming when gasses could not escape through the liquid and as a result the height of the liquid it increases.

Now, even this definition now in a steelmaking, slag forming occurs due to the following reaction: one reaction is FeO plus C that is equal to Fe plus CO. Now, this reaction this reaction occurs within the slag phase.

Another reaction is carbon in metal plus oxygen in metal that is equal to CO gasses phase and this reaction occurs at gas metal interface. Now, when the CO bubble, which is forming by this reaction or by this reaction, they are unable to escape through a layer of slag, then what will happen? The slag will foam that is bubbles will be entrained and the height of the slag will increase.

So, the important point in case of foaming of this slag is that, gas bubble should be interrupt, easy escape of CO bubble when it is not there, then slag is set to be foaming in nature.

Now, the question is, a slag foaming desirable valid to some extent? Yes, because when the slag foams and with the droplets are entrained, then the interfacial area increases and the rate of reaction is also very fast. Now, in another advantages are also of the slag foaming. The first advantage is that the shielding of molten metal against reoxidation shielding of molten metal.

Second slag forming also acts as a thermal barrier; it shields the refractory lining, particularly in electric arc furnace steelmaking. Fourth, it controls heat transfer from post combustion flame to the metal bath.

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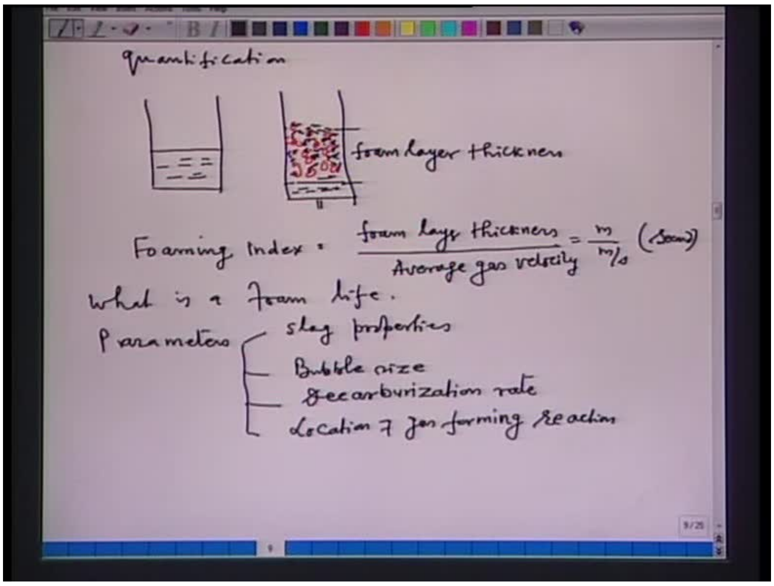

quantification

Foaming Index = $\frac{\text{foam layer thickness}}{\text{Average gas velocity}} = \frac{m}{m/s}$ (seconds)

what is a foam life.

Parameters
- slag properties
- Bubble size
- decarburization rate
- Location of gas forming reaction

Now, how can slag forming be quantify quantification? Now, for example, if you take a bath, here is a liquid, here is the liquid and then, if we allow the gas to flow and this is now the liquid is here. So, these are the gas bubbles of different sizes and this is again the slag layer, because slag was so viscose, they did not allow the gas bubble to escape from the system, as a result slag has foamed and this particular thickness we call as a foam layer thickness.

So, now, we can define foaming index. We can define for example, foaming index that is equal to foam layer thickness upon average gas velocity average gas velocity. So, if this is in meter, this is in meter per second, then the foaming index comes in seconds. Low foaming index, means gas can escape easily or residence of the gas bubble in the slag is small, hence the slag will be of lower foaming index. Higher foaming index means the escaping of the bubbles is delayed and hence slag will foam.

So, again one can also say that is smaller size of the gas bubble cannot easily escape as compare to larger size of the bubble, that means, the gas bubble also play an important role. And in relation to a steelmaking then the gas bubbles they are formed and the slag metal interface, then do not have sufficient chance to grow and such slag may foam much as compare to the reaction when C plus O occurs at the gas metal interface.

Now, at the gas metal interface, the gas bubble a sufficient time to grow, they become bigger sizes and they can easily escape through the slag I mean this is just a common sense here. So, now, in this relation what is the foam life? Foam life is directly proportional to foaming index; lower foaming index, lower foaming life; higher foaming index, higher foaming life.

Now, the parameters that control the foaming, there one is the for example, slag properties, then bubble size, then the decarburization rate higher or lower decarburization rate, because decarburization is the reaction, which generates carbon monoxide and then, location of gas forming reaction.

In fact, double size and location of gas forming reaction, they are little bit interrelated that is, if the location of the gas reaction- gas forming reaction- is at the slag metal interface, then an effect the gas metal interfaces as I already I explained.

A lower decarburization rate and higher decarburization rate- higher decarburization rate more amount of carbon monoxide would evolved and at the slag is not sufficient viscous then it will not allow CO 2 escape through the slag layer.

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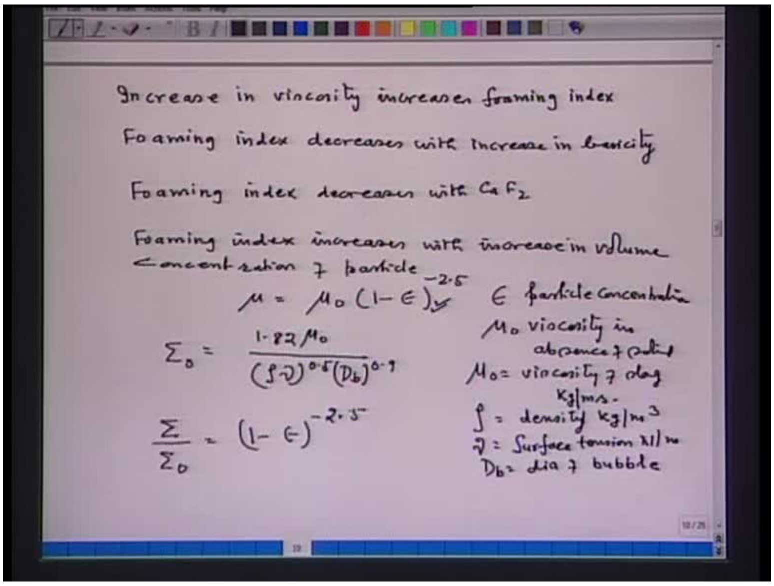

Increase in viscosity increases foaming index

Foaming index decreases with increase in basicity

Foaming index decreases with CaF_2

Foaming index increases with increase in volume concentration of particle

$$\mu = \mu_0 (1-\epsilon)^{-2.5}$$

ϵ particle concentration

μ_0 viscosity in absence of solid

$$\Sigma_0 = \frac{1.82\,\mu_0}{(\rho\sigma)^{0.5}(D_b)^{0.9}}$$

μ_0 = viscosity of slag kg/ms.

ρ = density kg/m^3

σ = Surface tension N/m

D_b = dia of bubble

$$\frac{\Sigma}{\Sigma_0} = (1-\epsilon)^{-2.5}$$

Now, about slag the properties, I will summarize some of these slag properties. Effect of slag properties increase in viscosity, increases foaming index, then foaming index decreases with increase in basicity of slag; foaming index decreases with Ca F 2 addition calcium fluoride, because it decreases the viscosity of the slag.

Now, foaming index increases with increase in volume concentration of particle with increase in volume concentration of particle. Now, why it does so, can you imagine? Because more particles are there in the slag, the viscosity of the slag increases a non-account of which the foaming index increases.

Now, the viscosity of a slag which is entering by the solid particle that is equal to mu is equal to mu 0 1 minus power minus 2.5, where epsilon is the particle concentration volumetric particle concentration, mu naught is the viscosity in absence of particles in absence of solid particles.

So, foaming index can be quantified as follows: foaming index sigma 0 that is equal to 1.82 mu naught upon 0.6 diameter of the bubble raise to the power 0.9. Now, here mu naught is the viscosity of slag, I am writing once again in the absence of solid particles so that has to be substituted in kilogram per meter second, then rho is the density of slag it has be substituted in kilogram per meter cube. This is the surface tension and it has to be substituted in Newton per meter, then Db is the diameter of bubble the dia of bubble.

Now, if I want to know the foaming index in the presence of solid particles, then what I can do? I can substitute the value of mu 0 from this particular equation and I get the foaming index in presence of solid particle. If I divide by foaming index in the absence of solid particle that will simply come out to be 1 minus epsilon raise to the power minus 2.5.

So, effectively what it says that the foaming index increases with increase in the volume concentration of solid particles. Now this I can illustrate by a simple problem.

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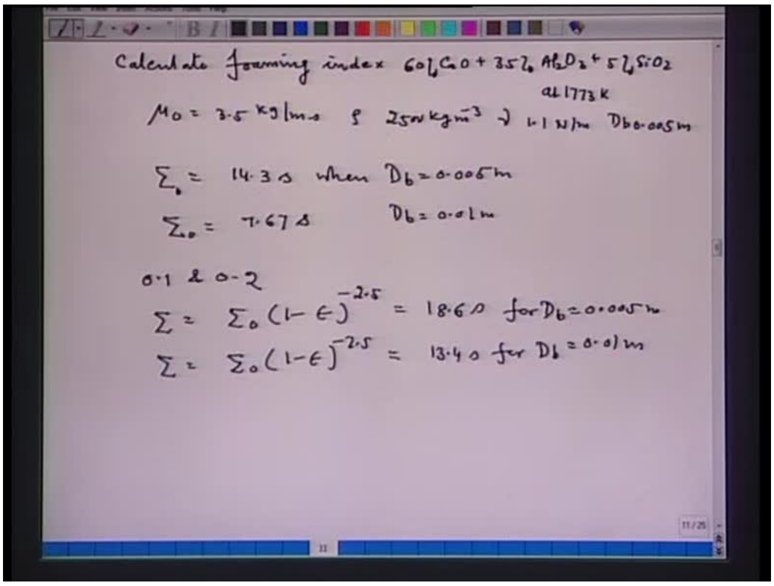

Calculate foaming index $60\%\ CaO + 35\%\ Al_2O_3 + 5\%\ SiO_2$ at 1773 K

$\mu_0 = 3.5\ kg/m.s$ ρ $2500\ kg\,m^{-3}$ γ $1.1\ N/m$ $D_b\ 0.005\ m$

$\Sigma_0 = 14.3\ s$ when $D_b = 0.005\ m$

$\Sigma_0 = 7.67\ s$ $D_b = 0.01\ m$

0.1 & 0.2

$\Sigma = \Sigma_0(1-\epsilon)^{-2.5} = 18.6\ s$ for $D_b = 0.005\ m$

$\Sigma = \Sigma_0(1-\epsilon)^{-2.5} = 13.4\ s$ for $D_b = 0.01\ m$

Now, for example, let us calculate the foaming index of slag, which is 60 percent calcium oxide plus 35 percent Al 2 O 3 plus 5 percent SiO 2 at 1773 kelvin. Now, this temperature in this calculation is not important, because I am giving you the properties. So, this is in the absence of solid particle, the viscosity mu 0 is 3.5 kilogram per meter second density 2500 kilogram per meter cube surface tension 1.1 Newton per meter.

And let us consider diameter of the bubble 0.005 meter as a typical example. Now, if I substitute all the values and I keep foaming index that comes to 14.3 second when diameter of the bubble is 0.005, when diameter of the bubble that is equal to 0.005 meter.

Suppose, I take now diameter of the bubble is 0.01 meter raised all the properties of the same, then the foaming index in the absence of solid particle it comes 7.67 seconds. Now, you see that is the increase in the diameter of the bubble, it decreases the foaming index. Now, if the slag contains, for example 0.1 and 0.2 volume friction of solid particles, then I can calculate sigma that is equal to sigma 0 1 minus epsilon to the power minus 2.5 and that comes 18.6 second when diameter of the bubble that is equal to 0.005 meter.

Now, this has to be compared with 14.3 seconds. Now, increase in solid concentration, it increases the foaming index. Now, same thing I can illustrate for diameter of the bubble 0.01 so this will come sigma that is equal to sigma 0 1 minus epsilon to the power minus 2.5 and that will come 13.4 second for diameter of the bubble equal to 0.01 meter.

So, what it illustrates? Increasing the diameter of the gas bubble, it decreases the foaming index; increasing the volume concentration of particle, it increases the foaming index.

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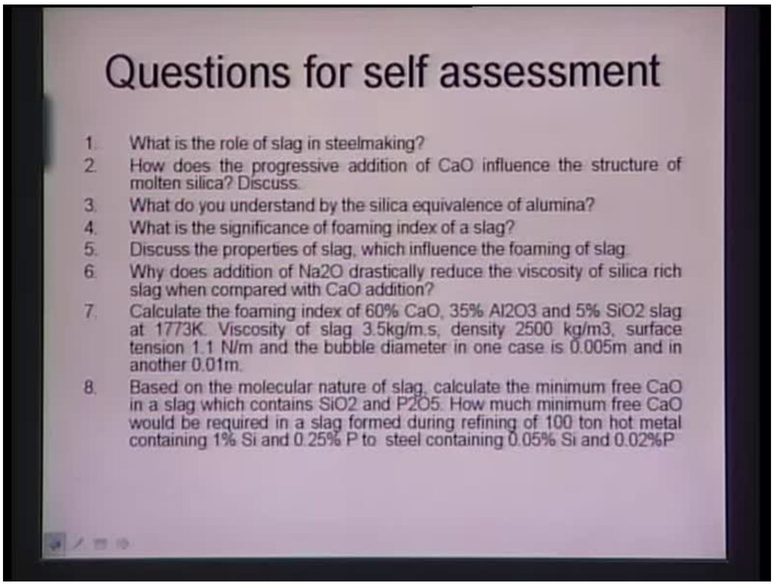

Questions for self assessment

1. What is the role of slag in steelmaking?
2. How does the progressive addition of CaO influence the structure of molten silica? Discuss.
3. What do you understand by the silica equivalence of alumina?
4. What is the significance of foaming index of a slag?
5. Discuss the properties of slag, which influence the foaming of slag.
6. Why does addition of Na_2O drastically reduce the viscosity of silica rich slag when compared with CaO addition?
7. Calculate the foaming index of 60% CaO, 35% Al_2O_3 and 5% SiO_2 slag at 1773K. Viscosity of slag 3.5kg/m.s, density 2500 kg/m3, surface tension 1.1 N/m and the bubble diameter in one case is 0.005m and in another 0.01m.
8. Based on the molecular nature of slag, calculate the minimum free CaO in a slag which contains SiO_2 and P_2O_5. How much minimum free CaO would be required in a slag formed during refining of 100 ton hot metal containing 1% Si and 0.25% P to steel containing 0.05% Si and 0.02%P

So, that is what I have to say. So, here are the questions for self-assessment. So, I have framed around 8 questions for you for self-assessment, I just read very fast.

So, what is the role of slag in steelmaking? How does the progressive addition of calcium oxide influence these structures of molten silica? What do you understand by the silica equivalence of slag of alumina? What is the significance of foaming index of a slag? We have already discussed.

Discuss the properties of slag, which influence the foaming of slag? That already I have listed. Why does addition of Na 2 O drastically reduce the viscosity of silica rich slag when compared with calcium oxide addition? This already I have explained, because Na 2 O is a single charge.

Now, calculate the foaming index. Though, I calculated for you can again recalculate and also you can procure the different slags and find out the different properties and you can categorize the slag with reference to the foaming index.

Last question is based on the molecular nature of slag, calculate the minimum free Ca O that is required, which contains SiO 2 and P 2 O 5. How much minimum free Ca O would be required in a slag formed during refining of 100 tons of hot metal containing 1 percent silicon and 0.25 percent of phosphorus to a steel containing 0.05 percent silicon and 0.02 percent phosphorus? Remember, you have to subtract that amount of silicon and phosphorus, which is going to a steel, rest will be captured by calcium oxide.

So, good luck for solution of the problem. Now, the next slide, they are the reference for your further reading; there are few references are here.