Materials and Energy Balance in Metallurgical Processes

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Module No. # 01

Lecture No. # 28

Ironmaking Fundamentals

This lecture concerns iron making. It is typical example of application of reduction smelting unit processes as I have given you in the earlier lectures.

The objective of this lecture is material balance in iron making. Before I go straightaway into the material balance, I thought it to be appropriate to give you little bit of conceptual part of the iron making so that you are prepared for material balance and heat balance problem in iron making.

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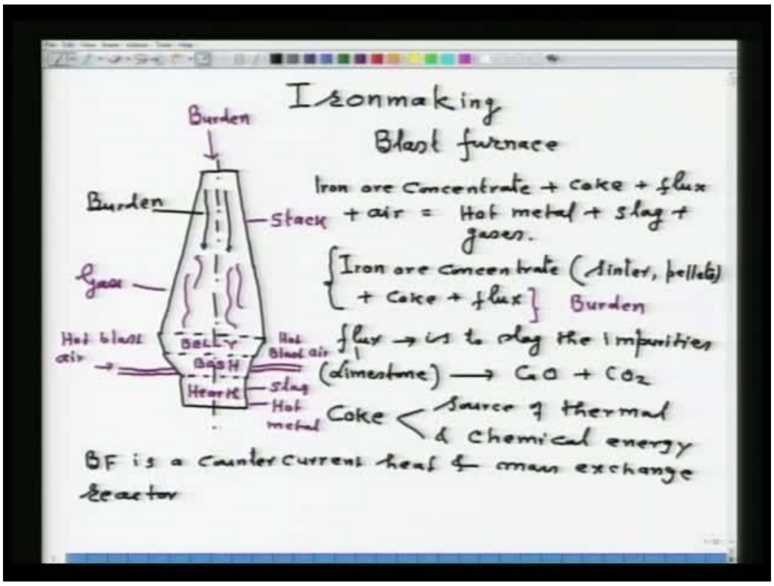

Now, as all of you know, the reactor in which iron is made is called blast furnace. So, as such this is the blast furnace iron making. On my left, this is the sketch, which I have drawn for blast furnace; I will come to that. Typically, what is done in iron making… I will again tell that my objective of this lecture is not to give you all aspects of iron making, but I will be giving that portion which is relevant for performing material in a heat balance operation.

In iron making, iron ore concentrate plus coke plus flux plus air results in hot metal plus slag and plus gases. A mixture of say - iron ore concentrate, which is typically used in the form of sinter or pellets plus coke plus flux; this mixture is called burden. The role of flux is to slag the impurities. That is, flux is added and mostly the flux is limestone that is added. Limestone decomposes to calcium oxide and CO 2. This calcium oxide reacts with the gangue minerals of the ore; that is, SiO 2 Al 2 O 3 and so on and helps in producing a slag.

Coke is a principle source of thermal energy and as well as chemical energy. As in the previous lecture on coke making, I have detailed what is coke making and so on. So, the carbon of the coke acts as a reduction of Fe 2 O 3 to iron. The combustion of carbon of coke also provides a thermal energy. So, coke is a source of thermal and chemical energy.

Now, let us come down to this charging sequence and how it is done. The burden is charged from the top and this portion (Refer Slide Time: 04:43) is called stack. This portion is called belly, this portion is bosh and this portion is hearth. Hearth has a tap hole for hot discharge of hot metal. Hot metal is heavier. On the top here is the slag. There is a tap hole for slag and hot metal.

This is hot blast air (Refer Slide Time: 05:25) and this is also hot blast air. That means the hot blast air is introduced through that tuyere, which is located at the periphery of the blast furnace. Now, what happens? As the burden descends, the direction of burden descend is downward, whereas the gases travel upward. This is the gases and this is the burden.

From the conceptual point of view, I will denote the blast furnace by B F. It is a counter current heat and mass exchange reactor. Needless to mention that in any counter current heat and mass exchange reactor, which consists of gas and solid, the permeability of the bad and the distribution of the burden is a very important issue.

For the smooth operation of the blast furnace, the upward rising gases should travel unhindered as well as they should transfer their heat in mass to the descending burden. I mean the transfer of mass by way of reaction of carbon with the oxygen of Fe 2 O 3. That is what so needless to mention about the importance of burden distribution that all constitutes a portion of iron making mean once we go into the detail. However, as material balance is concerned, we rather take it for granted that the there is a smooth movement of burden and gases.

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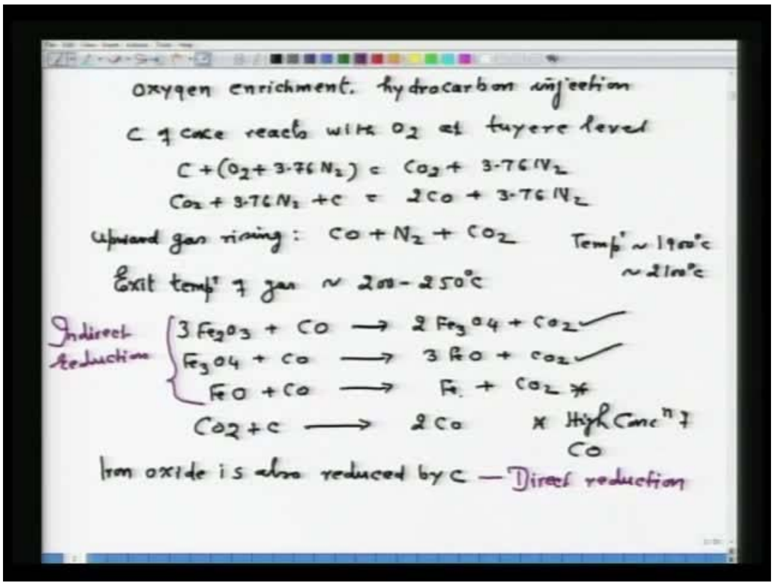

Through the tuyere of the blast furnace, sometimes the oxygen enrichment hydrocarbon injection is also done. As the burden descends, the gases travel up and the reaction between Fe 2 O 3 and carbon of coke or carbon monoxide, which is forming due to the reaction, the iron oxide gets reduced. So, as the burden descends, the carbon of the coke reacts at the tuyere level. Carbon of coke reacts with O 2 at tuyere level because the oxygen is available here. So, what happens is - C plus O 2 plus 3.76 N 2; that is, a 1 mole of air immediately forms CO 2 plus 3.76 N 2. This CO 2 plus 3.76 N 2 in presence of excess carbon forms 2 CO plus 3.76 N 2. So, the upward gas rising consists of CO plus nitrogen and plus carbon monoxide.

Now, as a result of reaction of carbon of coke with oxygen at the tuyere level, a temperature approximately around 1900 degree Celsius to 2100 degree Celsius is created. As the gases move and discharge from the top of the furnace, the exit temperature of the gas is approximately somewhere between 200 to 250 degree Celsius. So, you can imagine how efficient the blast furnace eases from the point of view of transfer of heat. So, the exit temperature of gas is around 200 to 250 degree Celsius. As the gases rising upward, what happens is the reaction between say 3 Fe 2 O 3 plus CO gives you 2 Fe 3 O 4 plus CO 2. Then, Fe 3 O 4 plus CO gives you 3 Fe O plus CO 2. Then, Fe O plus CO gives you Fe plus CO 2 and this reaction CO 2 plus C gives you 2 CO. So, these reactions are happening as the result of heat and mass exchange between the upward rising gas and downward movement of the burden.

One important thing to note: this reaction and this reaction (Refer Slide Time: 11:25) do not require very high percentage of carbon monoxide. So, they can offer towards the upper region of these stacks; whereas, the reaction Fe O plus CO is equal to Fe plus CO 2. This particular reaction requires high concentration of CO. At around 900 degree Celsius, the equilibrium concentration of CO in CO CO 2 mixture should be around 65 to 70 percent for Fe O to be able to reduce to iron. So, particularly, this reaction Fe O plus CO is equal to Fe plus CO 2 occurs at the point of stack and bosh region, where you have high concentration of CO. That is an important thing.

Now, in the reduction process, some iron oxide is also reduced by carbon. This reduction is called in direct reduction. This is endothermic in nature, whereas all these reactions are called indirect reduction. So, in the blast furnace, both indirect and the direct reductions are going on. Attempt is made such that the heat balance is there at every region of the blast furnace.

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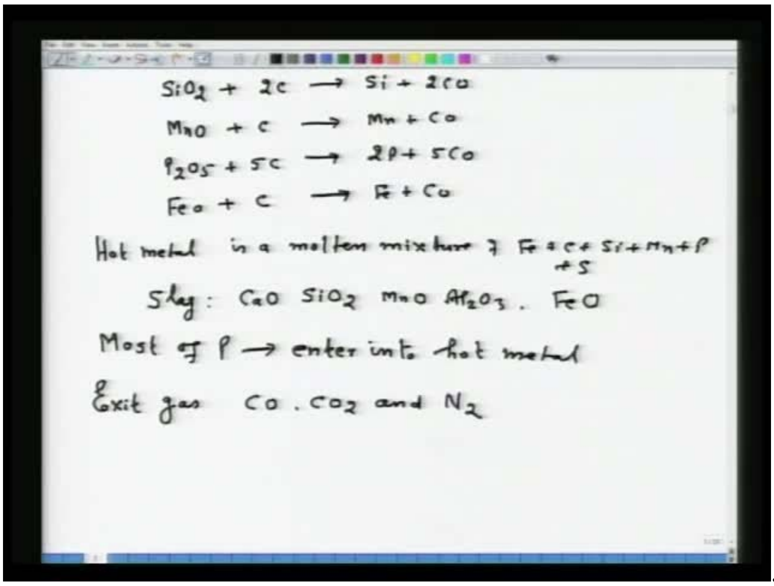

Some of the oxides, say for example, SiO 2, Mn O, P 2 O 5, and Fe O are reduced by carbon and they form silicon plus 2 CO; Mn O plus C forms Mn plus CO because they all take place at very high temperature. P 2 O 5 plus 5 C gives you 2 P plus 5 CO; Fe O plus C gives you Fe plus CO. So, all these reaction occur between the belly and the bosh region.

The temperature being very high, iron gets melted, and it absorbs silicon, manganese, phosphorus and sulphur that is present. Thereby, the formation of hot metal takes place and hot metal trickles down. So, hot metal is a molten mixture of iron plus carbon plus silicon plus manganese plus phosphorus plus sulphur. Carbon is also absorbed because carbon is present over there. This hot metal formation is accompanied by the formation of slag. So, slag is also found such that the gangue minerals are separated. Slag typically consists of Ca O, SiO 2, Mn O, Al 2 O 3. That means all other impurities of iron ore gets eliminated near the bosh region and all are in the fluid state. Both hot metal and slag trickles down into the hearth region and because of the density difference, the hot metal and slag are separated. In short, that is how the iron making in blast furnace is there.

Here some of the important point to note that all phosphorus enters into hot metal. This is typically because blast furnace iron making is under highly reducing condition. Therefore, all P 2 O 5 of the ore gets reduced to phosphorus and all phosphorus enter into the hot metal.

In this process of iron making, though the conditions are highly reducing, some amount of iron is oxidized. As a result, slag in addition to Ca O, SiO 2, Mn O and Al 2 O 3 also contain some amount of Fe O. However, the Fe O content is very less because of very high reducing condition; hardly, one percent or one and a half percent of Fe O you may find in the slag.

Now, about the exit gas - exit gas typically consists of CO, CO 2 and nitrogen. That is, in short, the blast furnace iron making is a burden descends downward. It comes in contact with the upward gases or upward mixture of gases. As a result of heat and mass transfer, iron oxide gets reduce to iron. The gangue minerals are slagged; all are fluxed nearby belly and bosh region. Iron melts and absorbs surrounding carbon silicon manganese phosphorus and hot metal forms. By virtue of the density difference between hot metal and slag, both are separated and hot metal and slag are tapped. So, from the material balance point of view, I presented a very brief overview of the iron making.

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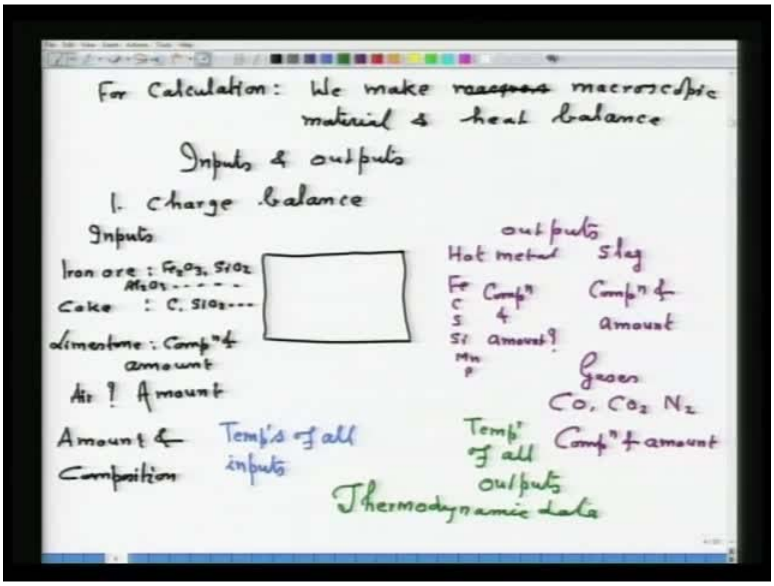

Now, let us see the material balance in iron making. For calculation purpose, we make macroscopic balance, macroscopic material and heat balance. By the term macroscopic material in heat balance, it is meant that we are concerned only at the inputs and outputs. That means here they are concerned only with the inputs and outputs; in between, what is happening does not come into the purview of the macroscopic balance. So, what is interested or what we want is a macroscopic material balance, where we are concerned with the inputs and outputs.

Here what will be our objective of this calculation? Say first you will like to calculate charge balance or example charge balance. We would like to know charge balance say if I again draw a material balance type of box. So, this is my reactor, here my inputs and here I have outputs.

Now, in the blast furnace iron making, the input consists of iron ore of which the composition should be known. Also, input consists of coke of which the composition should be known. So, iron ore can have Fe_2O_3, SiO_2, Al_2O_3 and so on. Coke can have carbon. We should also know SiO_2 and other composition. So, their amount and composition should be known. Third input is limestone. What is the composition of limestone? Say amount of SiO_2, $CaCO_3$, Al_2O_3 and other composition and amount. Also, input consist of air and its amount. So, of this input side, the important is amount and composition.

In a macroscopic balance, we are only concerned in the input. At the output side, the output consists of for example, you have hot metal; hot metal composition say iron, carbon, sulphur, silicon, manganese and phosphorus. So, here again we are interested in composition and amount. Then, another output is slag; again we are interested in composition and amount. Third output is gases. Gases consist of CO, CO_2, N_2; composition and amount. So, when we say charge balance that means you should know for a given output of whichever way the problem can be formulated: for a given output, what should be the input; for a given input, what should be the output when sufficient number of variables are given?

What can be done here in order to calculate the macroscopic heat balance in addition to the amount? The important is the temperature at which the inputs are made into the furnace. The temperature of discharge that is also important to know. So, when you want to do the heat balance, then we should know temperature of all inputs: air, limestone, coke and iron ore. Unless you know their temperature, they cannot calculate the heat balance.

Here in the output side, we should also know the temperature of all outputs; it must be known. In addition, you should also know some of the thermodynamic data say heat of reaction, c p value and so on; whatever is needed. So, this is in short when we say charge balance; that is what is meant by charge balance.

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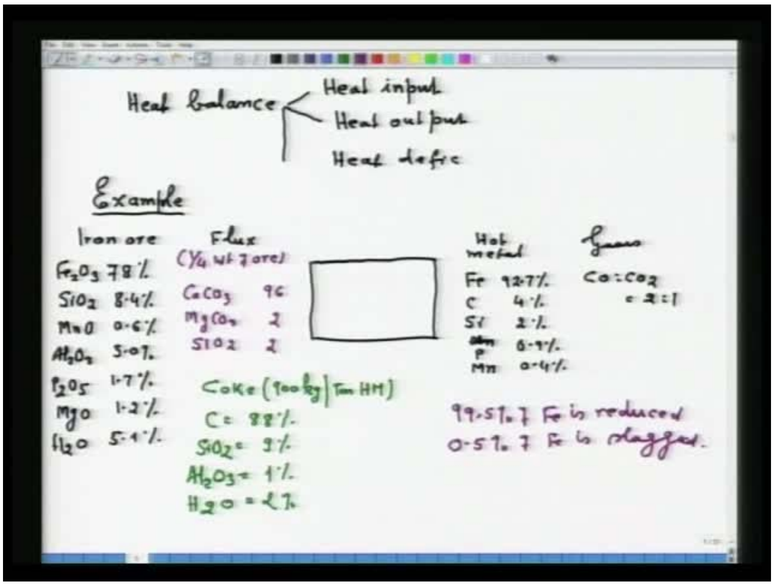

When we talk of heat balance, then we must know all heat input sources, all sources through which heat is input, and then all sources through which heat is out. The objective is to calculate heat deficit. Also, you would like to calculate the thermal efficiency of the process. That is how the scheme of charge balance and heat balance looks.

Now, let me illustrate a charge balance by taking a suitable example. This is the reactor say here I am charging iron ore, whose composition is Fe 2 O 3 - 78 percent, SiO 2 - 8.4 percent, Mn O - 0.6 percent, Al 2 O 3 - 5.0 percent, P 2 O 5 - 1.7 percent, Mg O - 1.2 percent and H 2 O - 5.1 percent. Then, flux is charged and flux amount is one fourth weight of ore. Its composition is Ca CO 3, Mg CO 3 and SiO 2; that is, 96, 2 and 2 respectively. Then, coke is charged 900 kg per ton of hot metal. 900 kg per ton of hot metal composition: carbon - 88 percent, SiO 2 - 9 percent, Al 2 O 3 - 1 percent and H 2 O is equal to 2 percent. This is all the input.

On the output side, we have hot metal. Hot metal composition contains iron, carbon, silicon, phosphorus and manganese. So, iron is 92.7 percent, carbon is 4 percent, silicon is 2 percent, phosphorus is 0.9 percent and manganese is 0.4 percent. Gases: CO is to CO 2 in this particular problem; that is equal to 2 is to 1. Also, it is said that 99.5 percent of iron is reduced. That means only 0.5 percent of iron is slagged.

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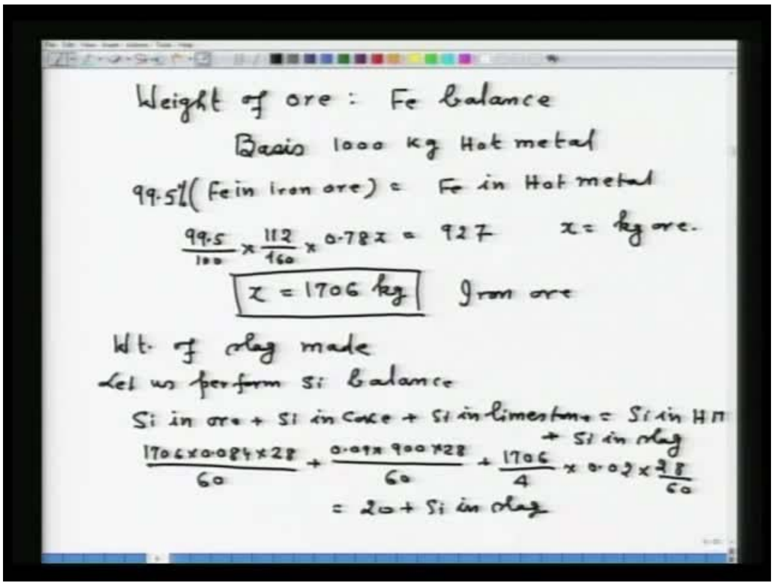

Now, you have to do calculations. First you have to calculate weight of ore. For that, we have to do iron balance. That is the first thing that you have to do.

First you select the basis. Basis is 1000 kg hot metal. If you do iron balance, we have noted in the problem that 99.5 percent of iron in iron ore; that is equal to iron in hot metal; that is 99.5 percent of iron in iron ore. So, if you do this calculation… because remember that for all iron, you have to see the source of input and source of output.

In this particular problem, iron is entering from iron ore and it is output; iron in hot metal and iron in slag, but it is given that 99.5 percent is reduced. So, our life becomes easier. So, which is straightaway 99.5 upon 100 into 112 upon 160 into 0.78 x. That is equal to 927, where x is the kg ore. Then, x is equal to 1706 kg. So, this is the amount of iron ore.

What I want to say is that if you want to calculate the amount of iron ore, the iron balance is the starting point. The next slag is not given. So, we have to calculate weight of slag matte. Here the concept is important. If you see the analysis, which is given in the problem, the slag will be consisting of SiO 2, Al 2 O 3, Mn O, P 2 O 5, Mg O, calcium oxide and so on.

Now, we have to calculate the weight of each constituent of the slag by making the elemental balance. Let us perform silicon balance. So, silicon balance; that is, silicon in ore plus silicon in coke; amount of coke is given to us; plus silicon in limestone; amount of limestone is also given. That will be equal to silicon in hot metal plus silicon in slag.

Choice is yours; you can do SiO 2 balance or silicon; it does not matter at all. So, if you do this particular balance, all that you have to put say for example, silicon in ore; that is, 1706 into 0.084 into 28 by 60; that is, silicon in ore, silicon in coke. 0.09 into 900 into 28 upon 60 plus 1706 upon 4 into 0.02 into 28 by 60 because limestone is one fourth of the weight of the ore. That will be equal to 20 silicon in hot metal plus silicon in slag. That is what we want to find out.

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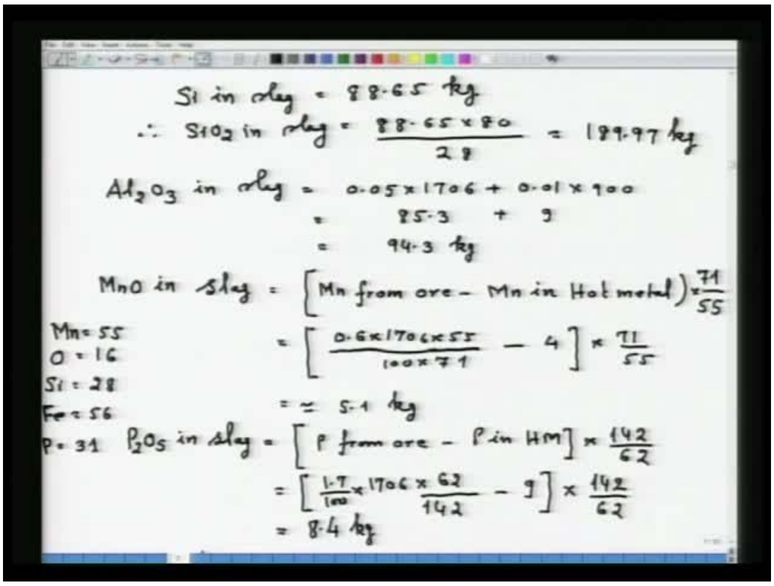

If you perform this calculation, we get silicon in slag equal to 88.65 kg. Therefore, SiO 2 in slag will be equal to 88.65 into 80 upon 28. Do not forget to covert SiO 2 because remember slag consist oxides; it does not contain any elemental. We have done elemental balance because of our convenience; you may do SiO 2 balance.

Hot metal does not contain any oxide. It contains only elemental form of the element. So, that is an important thing. So, that calculation gives you SiO 2 in slag; 189.97 kg. This is about the SiO 2 in slag. So, in calculating each component of slag, we have to do the balance. Similarly, we can do Al 2 O 3 in slag. Fortunately, here all SiO 2 3; charge from all sources enters into slag. We can directly do the Al 2 O 3 balance. So, Al 2 O 3 in slag will be equal to 0.05 into 1706; that is, Al 2 O 3 from iron ore; plus 0.01 into 900; that is, Al 2 O 3 in coke. So, that forms 85.3 plus 9. So, Al 2 O 3 in slag is 94.3 kg.

Now, a bit of patience and overall look of the problem is necessary. You should know from all sources as my experience said that while doing very fast calculation, you may forget one of the source. For example: Al 2 O 3 coming from coke is only 1 percent; you may forget this 1 percent. Then, the answer becomes wrong. So, here patience and the overall blick of the problem is required so that you know what is entering from which source and you taken into account. If you can do that, there is no problem in doing material balance.

Similarly, Mn O in slag. Find out Mn O in slag. Again you have to do input and output from all sources. So, Mn O will be equal to manganese from ore minus manganese in pig iron or manganese in hot metal. You may call pig iron also; it does not matter. This balance will go into the slag in the form of Mn O. So, we have to convert it into 71 upon 55. The molecular weight of manganese that I have taken is 55 or oxygen as usual is 16, silicon is 28, iron is 56. So, if you substitute all the value, manganese from iron ore will be equal to 0.6 into 1706 into 55 upon 100 into 71 minus 4 and that will be into 71 upon 55. That makes approximately around 5.1 kg. It is 5.08 or something. So, make it 5.1 kg. That is how we will calculate the Mn O in slag. Gradually we are building the amount of slag. Ultimately, the amount of slag will be the sum total of all that we have calculated.

Similarly, we have to calculate P 2 O 5 in slag. That will be again equal to phosphorus from iron ore minus phosphorous in hot metal multiplied by 142 upon 62. The molecular weight of phosphorus is 31. So, we do this (Refer Slide Time: 38:09) from iron ore: 1.7 upon 100 into 1706 into 62 upon 142 minus 9 multiplied by 142 upon 62. So, this will be equal to 8.4 kg. This is the amount of P 2 O 5 in slag.

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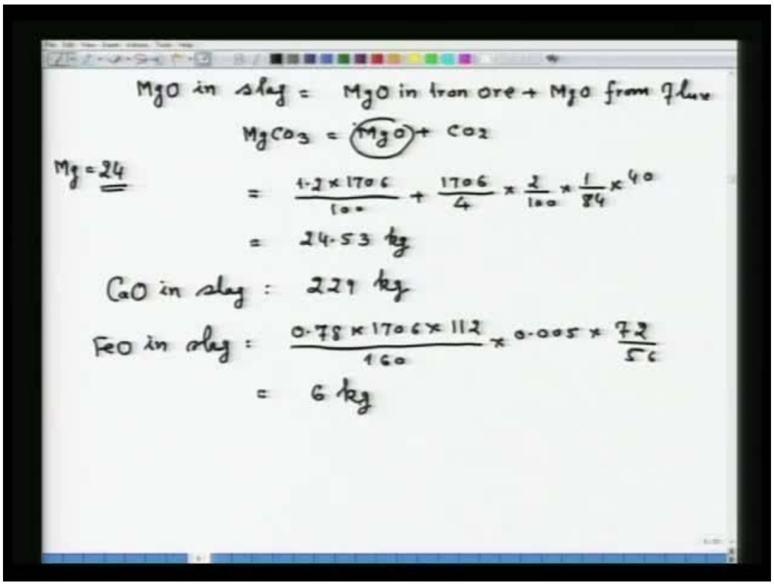

Similarly, we have to calculate MgO in slag because MgO is entering through iron ore. So, MgO will enter into the slag. So, MgO in slag will be equal to MgO in iron ore plus there is another source of MgO; that is, MgO from flux. These are the important things; all sources to be known. MgO in iron ore plus MgO from flux because $MgCO_3$ say the flux contain what? It contains $MgCO_3$. So, $MgCO_3$ will decompose to MgO plus CO_2. So, this MgO will enter into the slag (Refer Slide Time: 39:46). So, MgO in slag will be MgO in iron ore. That will be 1.2 into 1706 upon 100 plus 1706 upon 4 into 2 by 100 into 1 upon 84 into 40. So, that is equal to 24.53 kg. Here the atomic weight of magnesium is 24. So, we got that.

Now, we have to calculate calcium oxide in slag. It is very simple; the source is only calcium carbonate. If you calculate, it will become 229 kg. The problem also says 0.5 percent of iron is slagged off. So, there will be Fe O in slag that will be equal to 0.78 into 1706 into 112 upon 160 into 0.005 into 72 upon 56. So, that is equal to 6 kg.

With this calculation, what message I want to give is that in this particular problem, you have to do the elemental balance or oxide balance; whichever way is convenient to you in order to get the total amount of slag. The most important thing is to see that you include all sources from where a particular element is in and all sources from where it is out.

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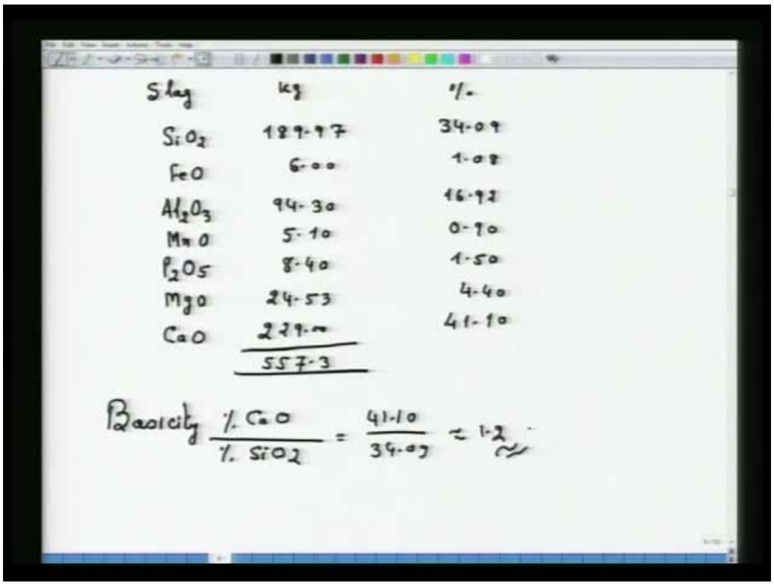

To summarize the amount of slag, the components are say we have: SiO 2, Fe O, Al 2 O 3, Mn O, P 2 O 5, MgO, and calcium oxide. These are the components. Their respective weights in kg: 189.97, Fe O - 6.00, Al 2 O 3 - 94.30, Mn O - 5.10, P 2 O 5 - 8.40, MgO - 24.53 and calcium oxide is 229.00. So, the total will give you around 557.3 kg. If we can calculate in percent, that will be 34.09, 1.08, 16.92, 0.90, 1.50, 4.40 and calcium oxide is 41.10. If you are interested, you can also calculate the basicity of slag. That is, percent Ca O upon percent SiO 2. That will be 41.10 upon 34.09. That will be approximately 1.2 around the basicity of that slag. This also can be done. So, this is about how to calculate the volume of slag.

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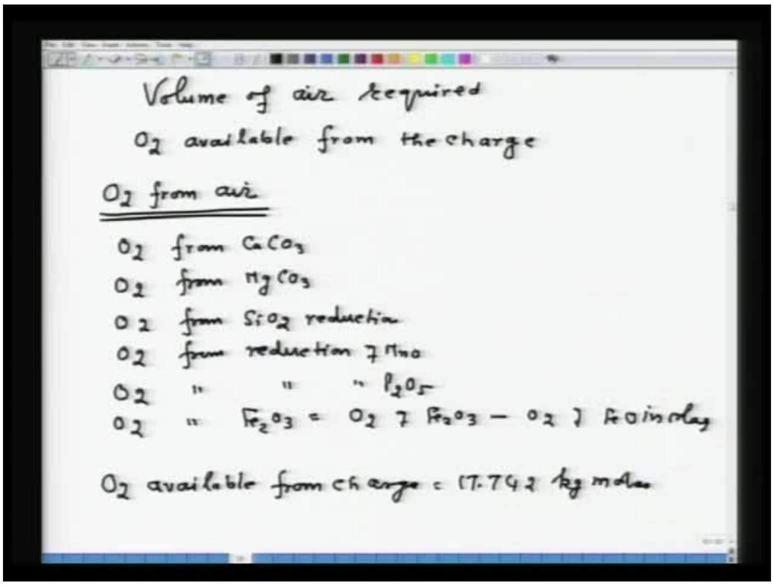

Next thing we have to calculate is the volume of air required. Now, you require air to combust carbon of coke. So, amount of air is important. In order to calculate the amount of air, you have to subtract the amount of oxygen, which is available in the charge. Here that means, you have to consider say oxygen available from the charge because SiO 2 reduce with carbon. You have S; you have silicon. That means some amount of carbon as already reacted with the oxygen of SiO 2. So, that much amount of oxygen, which is available from the charge, will not be supplied by air.

In order to calculate the volume of air, it is necessary to calculate the oxygen available from the charge. For that say in this problem, oxygen from Ca CO 3 will be available. Oxygen from Mg CO 3 will be available; then, O 2 from SiO 2 reduction, because silicon is forming and silicon is entering into metal; then, oxygen from reduction of Mn O and oxygen from reduction of P 2 O 5. Oxygen from Fe 2 O 3 and that will be equal to O 2 of Fe 2 O 3 minus O 2 of Fe O in slag. So, that is how all these calculations have to be made. Then, if we do that for example, oxygen from Ca CO 3, I think you can calculate these things. If you do that, in this problem, total oxygen available from charge comes around 17.742 kg moles. That much is the amount of oxygen available from the charge.

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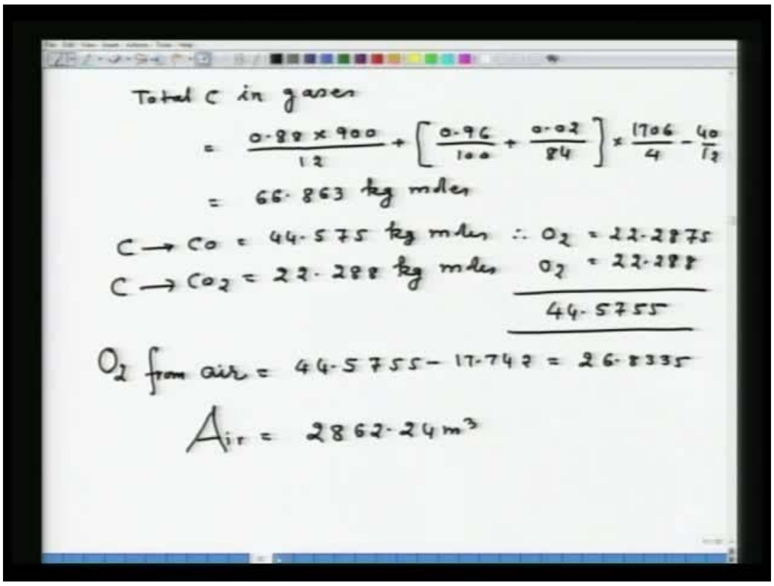

In order to calculate the amount of air, we have to find out total carbon in gases. Total carbon in gases will be equal to 0.88 into 900 upon 12 plus 0.96 upon 100 plus 0.02 upon 84. This is carbon from Ca CO 3 and from Mg CO 3 into 1706 upon 4 and minus 40 upon 12; that is carbon in pig iron.

We get the total carbon in gases and it comes around 66.863 kg moles. Now, CO : CO 2 ratio given is 2 is to 1. So, C to CO will be equal to 44.575 kg moles and C to CO 2 will be equal to 22.288 kg moles. Then, here we find out O 2 required for 44.575 moles of CO. That will be equal to 22.2875 and O 2 require to form CO 2; well C plus O 2; CO 2 is 22.288. So, total amount of oxygen that you require to supply is 44.5755.

Remember: this oxygen is available at the tuyere for the carbon to combust. So, O 2 from air would be 44.5755 minus the one which is available from the charge; you have calculated 17.742. That will be equal to 26.8335 kg moles. Therefore, amount of air will be 2862.24 meter cube. That is how you will be calculating the amount of air.

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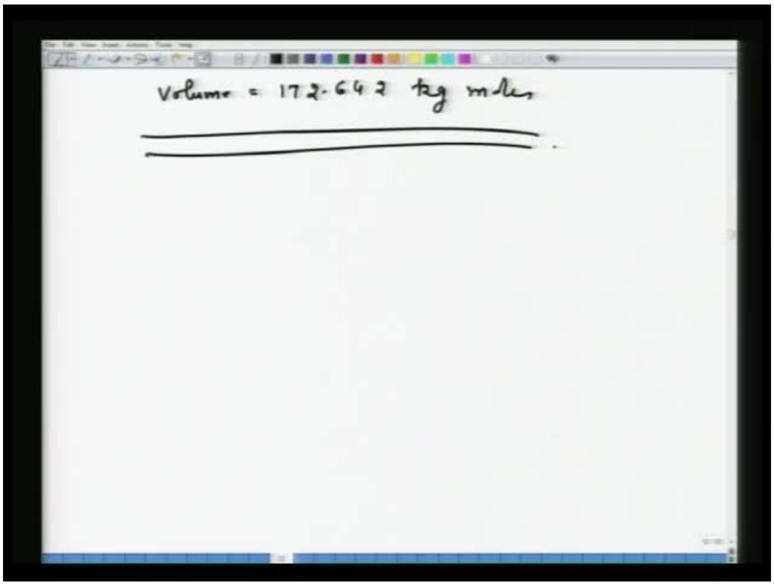

The last thing, which is left is, the volume and percentage composition of blast furnace gas. In order to calculate the volume of gas, we have already calculated CO CO_2. All that we have to calculate is nitrogen. So, if you do… We have to add H_2O. So, volume of gas will be equal to 172.642 kg moles. That makes the calculation of charge balance complete.