Iron Making and Steel Making
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Module – 02
Lecture - 06
Overall Heat & Material Balance in Blast Furnace

Welcome this is the module-2 that is the week-2 and lecture number-6 – the first lecture of module 2. In the first three lectures of this module, we will cover the heat and material balance in blast furnace. In this lecture, I will cover the overall material balance with an example problem to demonstrate how to calculate the slag weight, ore weight as well as the volume of the blast furnace gas based on overall material balance.

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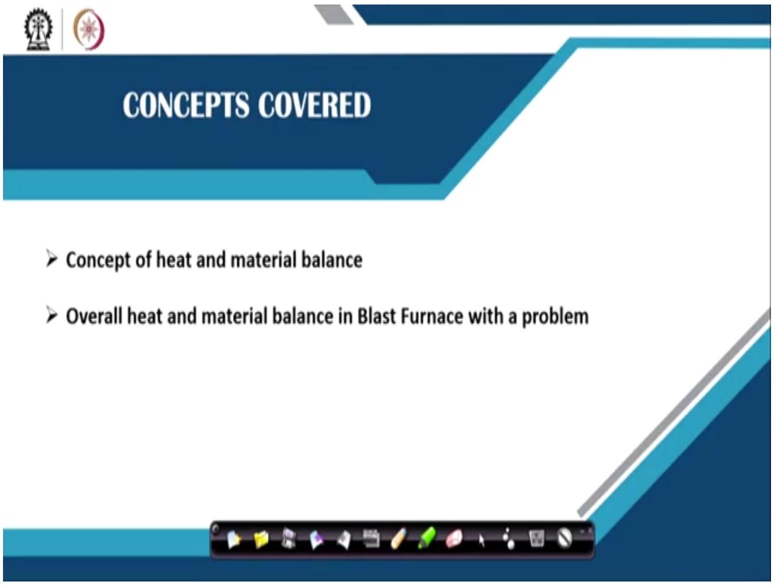

In this lecture we first discuss the concept of heat and material balance. What do you mean by the heat and material balance? We have to understand that this first.

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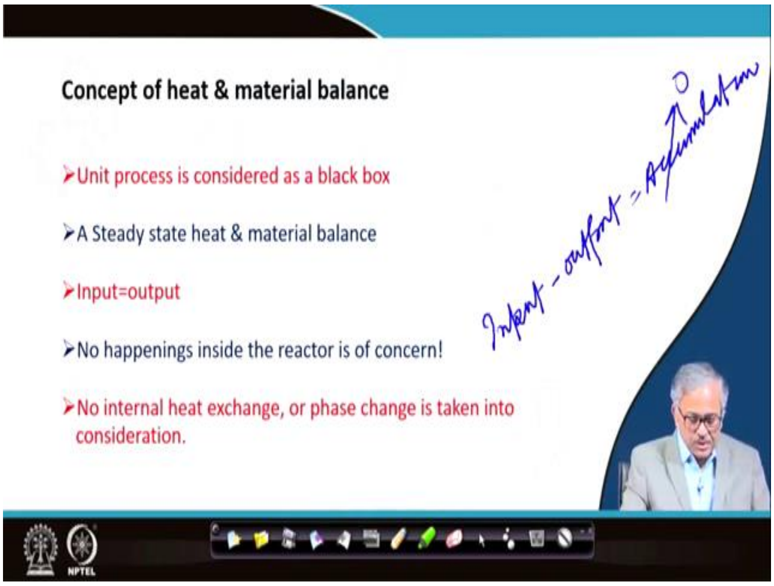

During macroscopic heat & material balance, the unit process is considered as a black box. You do not know inside what is happening, only we are concerned with the inputs and the output. Input is equal to output under steady state only. The general material balance statement is: $Input - output \pm generation/consumption = accumuation$. Without any source and sink in the system, and under steady state (No accumulation): $Input = output$. Anything unsteady we cannot consider here; because we are dealing with only the inputs and the outputs and finally we will equate the inputs to the output. Under unsteady state, when something is coming in, a part of it is accumulated in terms of increase or decrease in temperature or, concentration of the system and the rest get out of the system. In this balance we do not have any access to this accumulation and we do balance just by equating input to the output.

And finally, no happening inside the reactor is of concern here. In a gas-solid reactor like blast furnace, the material can go under repeated heating and cooling by gas solid heat exchange and endothermic reaction; different types of phase formation, intermediate/metastable phases can form, CO and CO_2 can generate and consume through different reduction and carbon gasification reaction, and lot of internal phenomena can happen, all these things are not concerned. No internal heat exchange and phase changes are not taken into this consideration.

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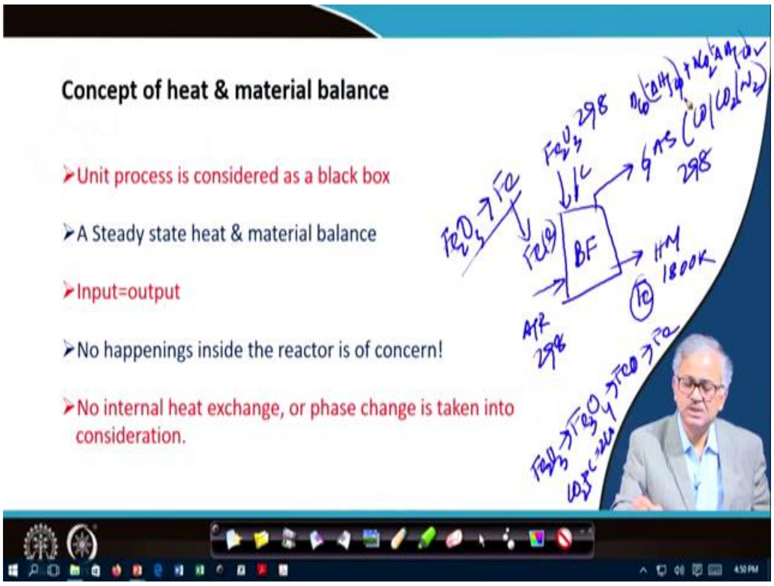

For example, if we just consider the blast furnace as a black box. What are the input? We have inputs like iron ore (consider pure hematite), coke (say pure carbon), air blast. And consider all inputs are at 298K. The outputs are hot metal (say pure iron at 1800K), and gas ($CO/CO_2/N_2$) at 298.

Now, inside the blast furnace lot of reactions are taking place. Hematite are undergoing reduction to iron through three sequential steps like $Hematite > magnetite > Wustite > Iron$. In the lower part of the furnace wustite is undergoing both direct and indirect reduction where CO_2 is being generated and CO is being consumed by indirect reduction of wustite and CO is being generated and CO_2 consumed by carbon gasifying reaction. While higher oxides are undergoing only indirect reduction where CO is being consumed and CO_2 released. So, lot of happenings are there; but what we finally see is that iron is being produced from hematite and certain amount of CO and CO_2 are coming out of exit gas.

So, all this inside happening I just ignore. What I am concerned is that Fe_2O_3 is in, carbon is in, air is in, iron is out and gas is out, and gas is CO and CO_2.

Siimilarly, for steady state heat balance: Demand = Supply. We can calculate the demand by calculating the heat of decomposition for final conversion of hematite to iron, and sensible and latent heat of iron. Similarly, final heat supply we can calculate by knowing the final mole fraction of CO and CO_2 in the exit gas and using heat of formation for these gases. So all internal conversions and associated heat effects are of not concern here.

So, we are not going inside the furnace what is happening there. So, we are basically concerned what are the inputs and outputs. So, from there I have to calculate what is the supply and what is the heat demand.

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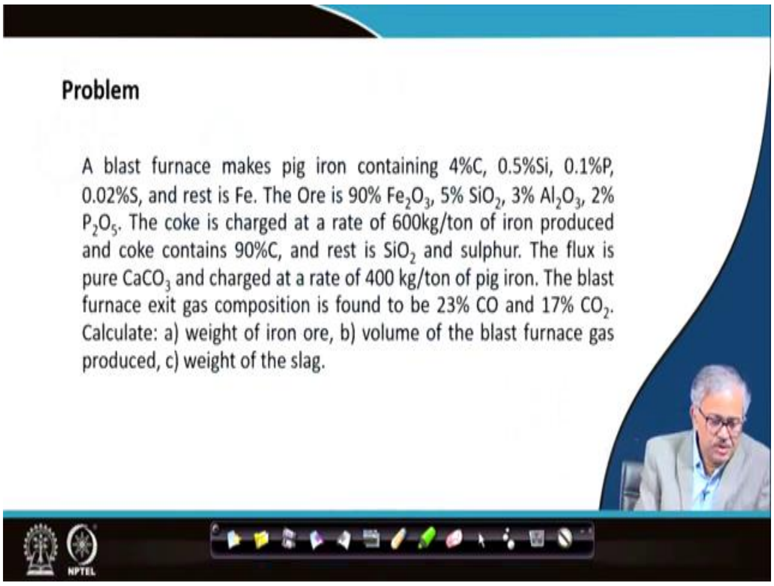

So, I think this is simply clear. So, now, let us demonstrate the overall material balance by using an example problem. As par the problem stated in the slide, a blast furnace makes pig iron, and the pig iron composition is given as 4% carbon 0.5% silicon, 0.1% phosphorus, 0.02 % sulphur, rest is iron.

And ore composition is also given an ore is 90 % Fe_2O_3. It is quite good kind of ore, 90% Fe_2O_3 means total iron is 63 percent, because Fe_2O_3 contains 70 % iron 30 % oxygen from stoichiometry. The ore further contains 5 % SiO_2, 3 percent Al_2O_3, 2 % P_2O_5.

The coke rate is given this is 600 kg per ton of iron produced, and coke contains 90 percent carbon, and rest is silica and sulphur. The flux is pure calcium carbonate and it is charged at a rate of 400 kg per ton of pig iron. Blast furnace exit gas composition is given as 23 % CO, 17 % CO_2, and rest is nitrogen. Now, we have to calculate the weight of iron ore, volume of the blast furnace gas produced and the weight of the slag. So, it will be a simple overall material balance only.

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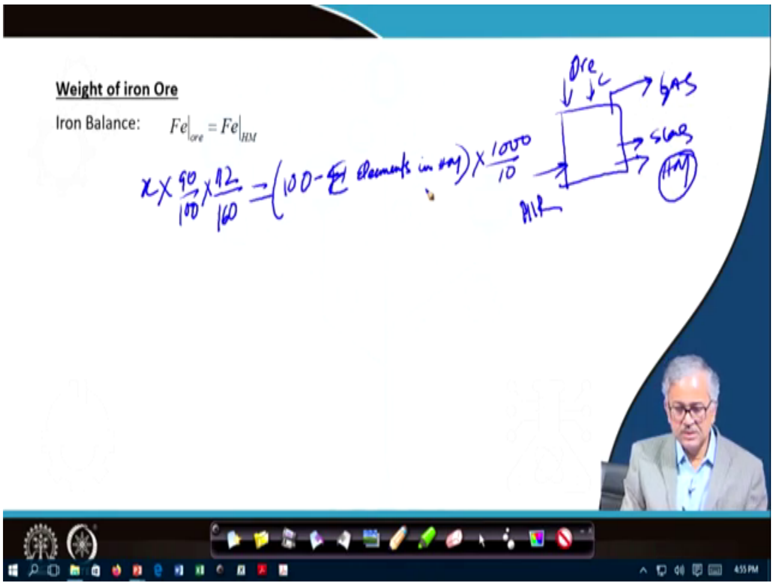

So, let us see how will attack this problem. First we have to calculate the weight of the iron ore; it is very simple. If I want to calculate the weight of the iron ore, what I have to do? I can simply do the iron balance. For Iron balance we need to find the source and sink for iron.

To find the source you need to check all the inputs you have. What are the inputs? Iron ore is an input; flux is an input; coke is an input; air blast is an input and out of which only the iron ore contains the iron, so only source of iron is iron ore. So, iron is coming from the iron ore.

What are the sink for iron in the blast furnace? Let us see what are the outputs? Outputs are blast furnace gas, hot metal and slag. Out of these output only hot metal only contains the iron. You may argue for iron in slag. But, in the blast furnace slag does not contain any iron, because of the presence of reducing atmosphere in the furnace and it is highly unlikely that you can find some iron in the slag. So, it is you can safely assume that iron is only passing through the hot metal. So, whatever the iron coming in by ore, all the iron going through the hot metal; so that is the simple iron balance.

Now knowing the source and sink we can write the iron balance as follows:

$$Fe|_{ore} = Fe|_{HM}$$

If we assume, x kg of iron ore is used to produce one ton of hot metal, then iron balance can be rewritten as:

$$x \times \frac{90}{100} \times \frac{112}{160} = \frac{95.38}{100} \times 1000$$
$$x = 1514 kg$$

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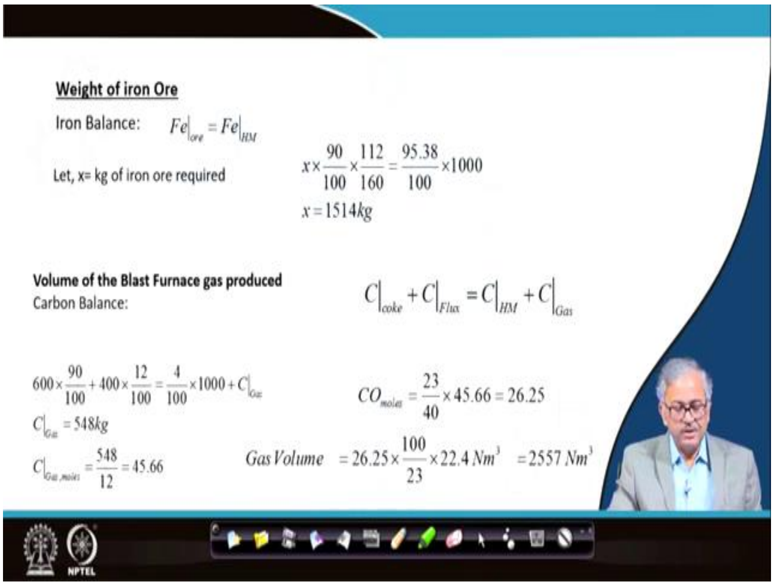

Next is the volume of the gas produced. Now if you want to calculate the volume of the blast furnace gas produced, how you can do that? There are two ways: one is through nitrogen balance; because whatever nitrogen enters through the air, same amount of nitrogen comes out through the exit gas, because there is no sink for nitrogen in the blast furnace; in other words it does not take part in any reactions inside So, you can do the nitrogen balance; but problem is that in this problem we do not have any information about the air blast, i.e the volume of air blast etc.

So, another way we can calculate, if I know that is the moles of CO, CO_2 produced finally in the exit gas. That is possible to calculate though carbon balance and exit gas composition, where all the resources are available in the problem.

The carbon balance can be written as:

$$C|_{coke} + C|_{Flux} = C|_{HM} + C|_{Gas}$$

Carbon is coming through the coke, a part of the carbon also come through the flux. Flux here means the calcium carbonate, which on decomposition gives CO2, which is a source of carbon. There is no other source of carbon. And carbon is leaving through the hot metal as dissolved carbon in iron and rest of the majority carbon goes through the gas.

$$600 \times \frac{90}{100} + 400 \times \frac{12}{100} = \frac{4}{100} \times 1000 + C\Big|_{Gas}$$

$$C\Big|_{Gas} = 548 kg$$

$$C\Big|_{Gas,moles} = \frac{548}{12} = 45.66$$

So, the carbon balance yields the moles of carbon that leaves through the exitgas. And since I know the volume percentage of CO in a CO, CO_2 mixture, then I can calculate the partitioning of carbon between CO and CO_2. I can calculate, how much moles of CO and CO_2 will be produced, so that is the thing I am going to do.

$$CO_{moles} = \frac{23}{40} \times 45.66 = 26.25$$

So, the exit gas volume you can simply calculate, because since you know the volume percentage of CO in the gas, as follows:

$$Gas\,Volume \quad = 26.25 \times \frac{100}{23} \times 22.4\, Nm^3 \quad = 2557\, Nm^3$$

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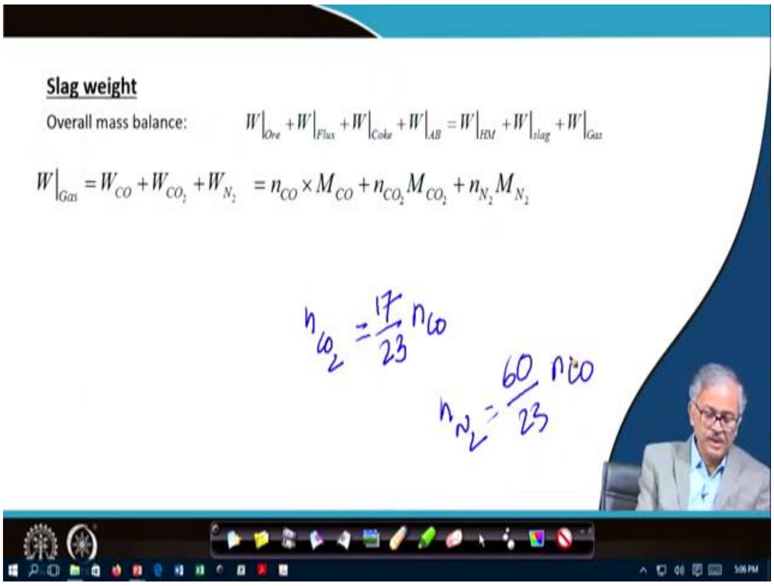

Now, the slag weight to be calculated. There are two ways you can calculate it; one way is by analyzing and calculating the amount of slag constituents separately and adding them together. The other way is to do the overall material balance.

If you go by the first way, then you need to identify the sources of slag constituents and resources for calculation of their amount. Slag will contain CaO, SiO_2, MnO, P_2O_5, CaS and those are being sourced from ore gangue and coke ash and flux. In the present problem, resource for Sulphur calculation is limited, because exact amount of Sulphur in its source, i.e., coke is not defined. It is told that total amount of silica and Sulphur in coke is 10%; no explicit mention about Sulphur is made.

Therefore, we can try overall material balance. There are two ways to can estimate slag weight by overall balance.

The first approach: Ore gangue, coke ash and flux are the source of constituents of slag. A part of the oxides coming from these sources are reduced and join metal phase. Therefore, by substracting the oxide equivalent of elements in hot metal from the total weight of ore gangue, coke ash and oxides from flux we can get the slag weight.

So, Let us calculate how much silica, P_2O_5 and Sulphur are lost to hot metal:

$$= \frac{0.5}{100} \times 1000 \times \frac{60}{28} + \frac{0.1}{100} \times 1000 \times \frac{141}{62} + \frac{0.02}{100} \times 1000 = 13.18kg$$

Total gangue coming from ore $= 1514 \times 0.1 = 151.4\ kg$

Total ash coming from coke = 600×0.1 = 60 kg

CaO coming from flux = $400 \times \frac{56}{100} = 224kg$

So, slag weight =151.4+224+60-13.18=422.2 kg

And other way is that is the overall mass balance.

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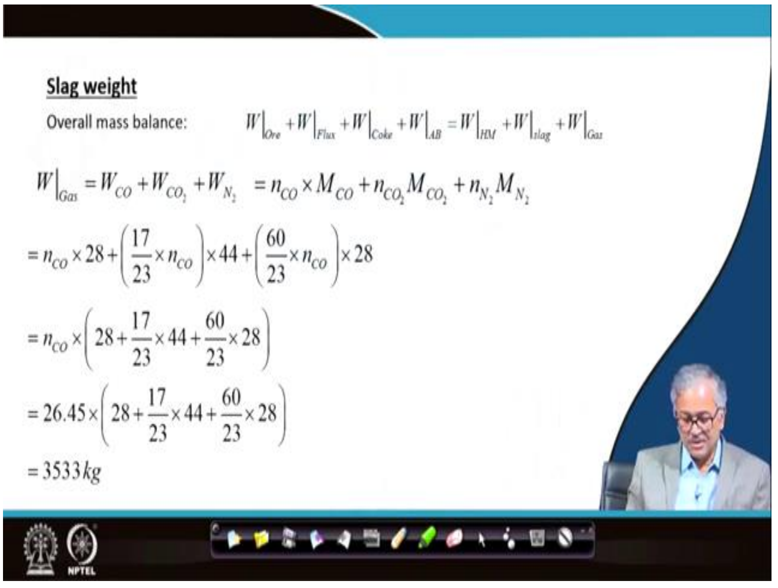

In second approach, overall mass balance statement can be written as:

$$W|_{Ore} + W|_{Flux} + W|_{Coke} + W|_{AB} = W|_{HM} + W|_{slag} + W|_{Gas}$$

Weight of the gas can be calculated as follows:

$$W|_{Gas} = W_{CO} + W_{CO_2} + W_{N_2} \quad = n_{CO} \times M_{CO} + n_{CO_2} M_{CO_2} + n_{N_2} M_{N_2}$$

$$= n_{CO} \times 28 + \left(\frac{17}{23} \times n_{CO}\right) \times 44 + \left(\frac{60}{23} \times n_{CO}\right) \times 28$$

$$= n_{CO} \times \left(28 + \frac{17}{23} \times 44 + \frac{60}{23} \times 28 \right)$$
$$= 26.45 \times \left(28 + \frac{17}{23} \times 44 + \frac{60}{23} \times 28 \right)$$
$$= 3533\,kg$$

Weight of air blast may be calculated as:

$$W|_{AB} = W_{N_2} + W_{O_2}$$

$$= n_{N_2} M_{N_2} + \frac{21}{79} n_{N_2} M_{O_2}$$

$$= n_{N2} \left(M_{N2} + \frac{21}{79} \times M_{O_2} \right)$$

$$= n_{CO} \times \frac{60}{23} \left(M_{N2} + \frac{21}{79} \times M_{O_2} \right)$$

$$= 26.45 \times \frac{60}{23} \times \left(28 + \frac{21}{79} \times 32 \right)$$

$$= 2519\,kg$$

Finally, slag weight from overall material balance:

$$From \quad overall \quad mass\,balance$$
$$W|_{Ore} + W|_{Flux} + W|_{Coke} + W|_{AB} = W|_{HM} + W|_{slag} + W|_{Gas}$$
$$1514 + 400 + 600 + 2519 = 1000 + M|_{Slag} + 3533$$
$$M|_{Slag} = 500\,kg$$

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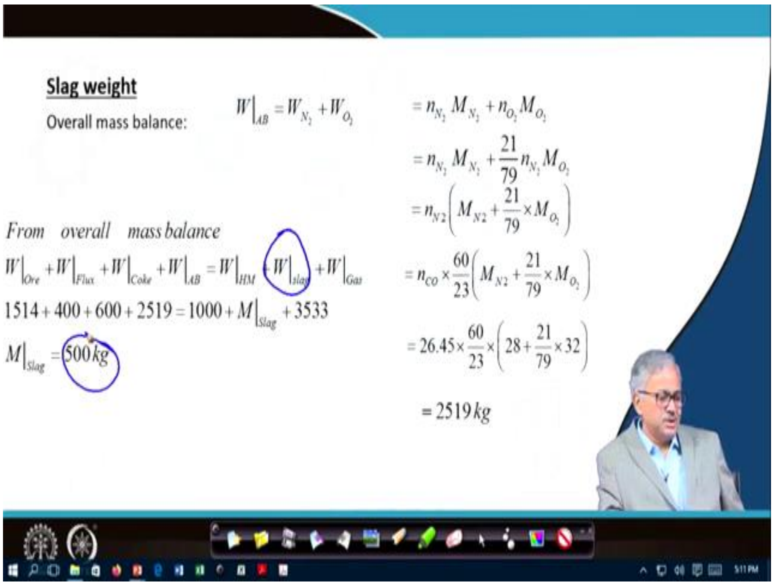

Such discrepancy between two methods may be due to slight inconsistencies between the input, output data. Otherwise both values need to be same.

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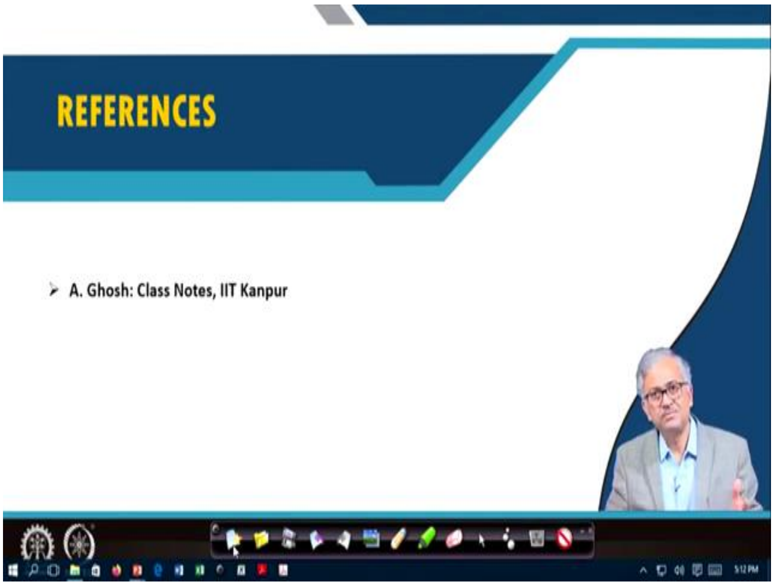

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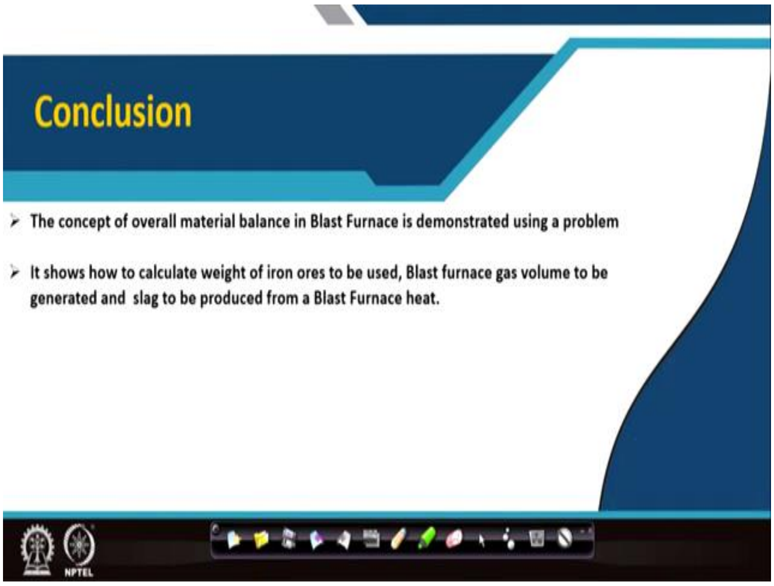

So in this lecture, I have tried to prove the concept of heat and material balance and subsequently, using an problem example, I have demonstrated how to calculate the important parameters like slag weight, gas volume and weight of iron ore based on overall material balance.

Thank you very much.