Iron Making and Steel Making
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Module – 07
Lecture - 35
Electric steelmaking

In this lecture we will discuss about the electric steelmaking. This is also one of the primary steelmaking in addition to the LD steelmaking. These are called primary steelmaking units because crude steel is made here at the minimum processing time, followed special refining with advanced techniques by secondary processing of steel in ladle, which is essential today and called the secondary steelmaking, or ladle steelmaking. We will discuss about secondary steelmaking later in details.

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CONCEPTS COVERED

- Features of Induction furnace
- Features of Electric Arc furnace (EAF)
- Modern developments in EAF

In electrical steelmaking category we have two types of furnace; one is called the induction furnace, where eddy current is induced into the object to generate heat and melt it. The second category is called the electric arc furnace, where electrical arc acts as a source of heat to melt the object and refine. There have been several modern developments in the electric arc furnace that we will also discuss.

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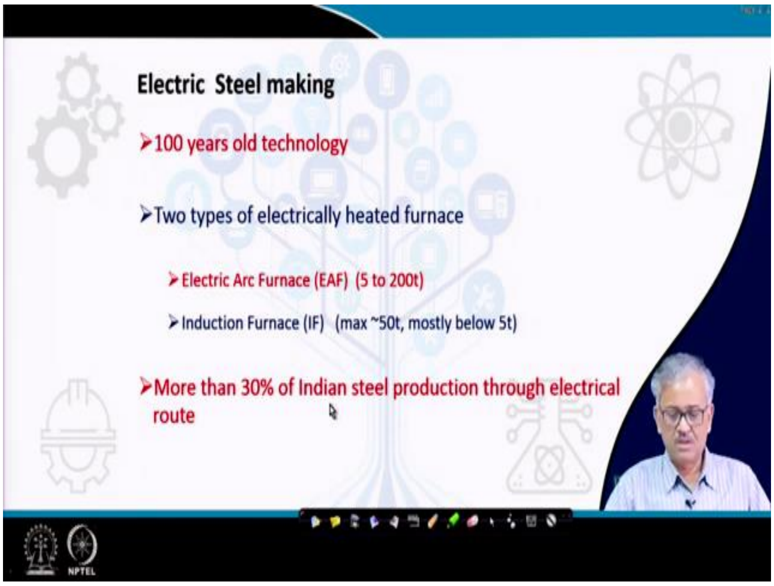

Electric Steel making

- 100 years old technology
- Two types of electrically heated furnace
  - Electric Arc Furnace (EAF) (5 to 200t)
  - Induction Furnace (IF) (max ~50t, mostly below 5t)
- More than 30% of Indian steel production through electrical route

Electric steelmaking is 100 years old technology. Capacity of electric arc furnace ranges from 5 ton to 200 ton depending on its use. Smaller capacity furnaces ranging 5 to 50 tons electric arc furnace are used in the small scale industry. Higher capacity electric arc furnace of 200 ton capacity is used even in the integrated steel plant today. Lots of modernization have made it suitable for large scale production. Since it is externally heated, it has the advantage of accepting any kind of charge mix of hot metal and cold charges like steel scrap and sponge iron.

Induction furnace are usually used in small scale industries with capacities less than 5 tons and its maximum capacity may be 50 tons. It is mainly used to melt selected scrap and produce the liquid steel of desired composition by adjusting the composition by alloying. Very little refining could be done in induction furnace. And, interestingly more than 30 percent of the Indian steel production is by the electrical route. Figure 35.1 shows the schematics of the induction furnace (IF).

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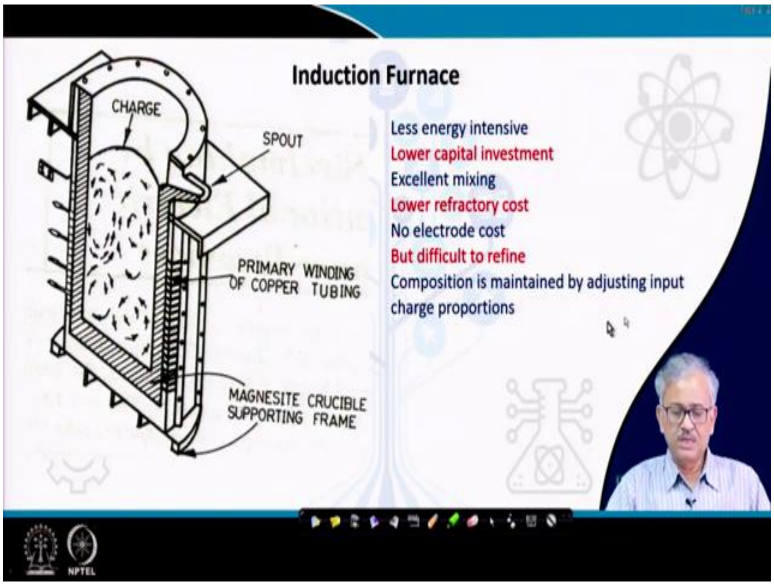

Induction Furnace

- Less energy intensive
- Lower capital investment
- Excellent mixing
- Lower refractory cost
- No electrode cost
- But difficult to refine
- Composition is maintained by adjusting input charge proportions

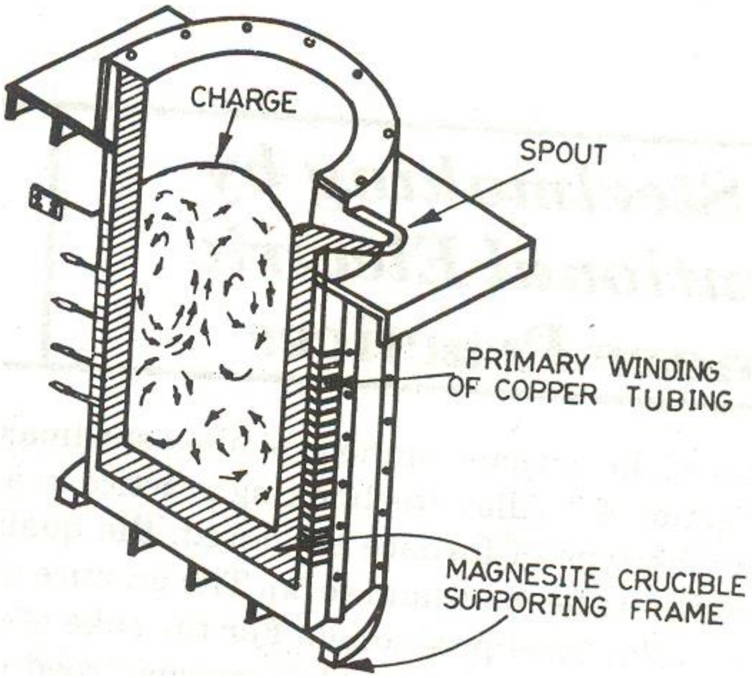

Figure 35.1: Schematics of Induction furnace [1]

There is a primary winding of copper coils, through which alternating current pass and produce an alternating magnetic field. This alternating magnetic field interact with the charge resulting in eddy current generation and dissipation in the scrap, which melts it.

Magnesite basic lining is used. Induction furnace less energy intensive compared to the electric arc furnace. Besides, lower capital investment and excellent mixing gives it an edge. Since not much refining is carried out and mixing is excellent, refractory cost is less; and no electrode cost are some other advantages. Major problem is that much refining could not be carried out; because slag being oxides, does not carry electricity much and consequently eddy current heating could not be achieved efficiently. A thin slag layer could be kept fluid by heat transfer from metal. If slag volume is large to accommodate large impurities, it would be difficult to maintain it fluid that facilitates impurity transfer.

So, in Induction furnace mainly selected scrap is melted and after little refining, composition is adjusted by adding ferro-alloys. Use of induction furnace is limited to foundry.

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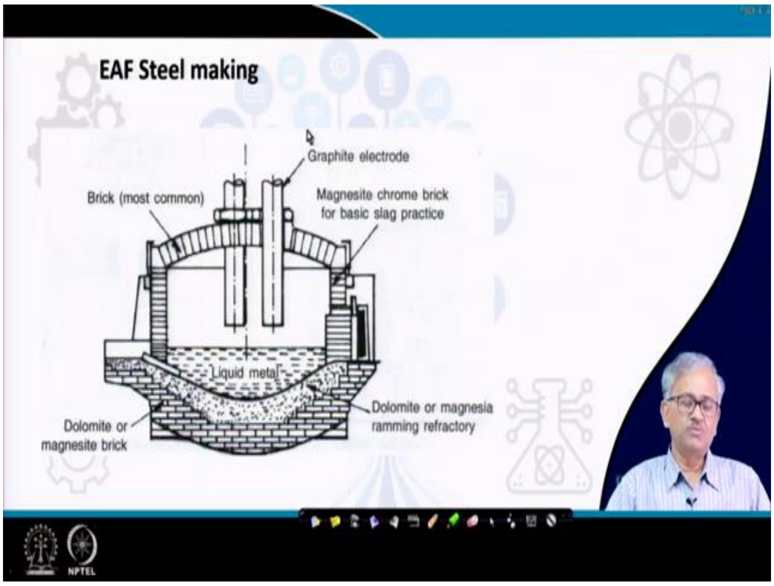

EAF Steel making

Now, we come to the electric arc furnace (EAF), which is most widely used and also lots of developments have taken place in the recent years. The schematics of typical EAF is given in Figure 35.2.

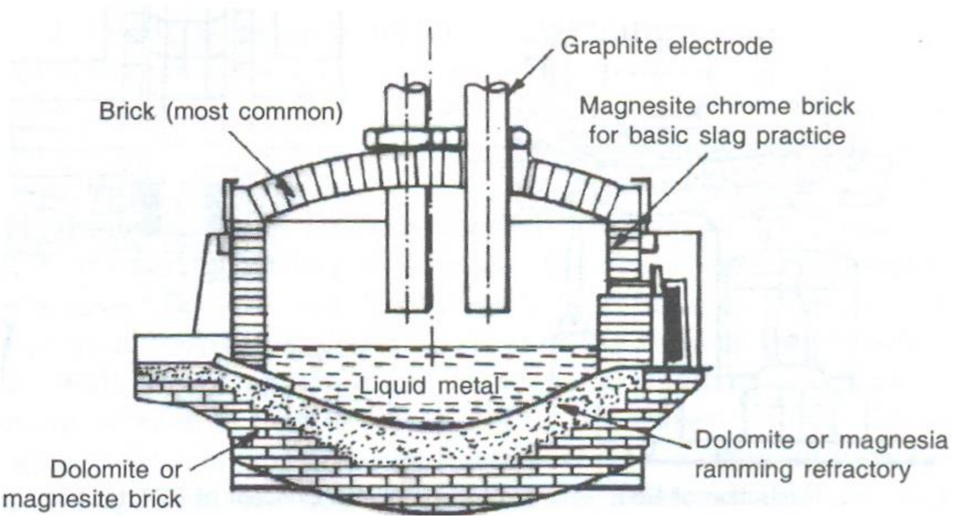

Figure 35.2: Schematics of Electric Arc Furnace (EAF) [1]

Usual refractory laying is observed. It is seen that over the permanent refractory lining of dolomite and magnesite bricks, there is a ramming monolithic wear lining of dolomite or magnesia. The tap hole, or spout is situated on the side wall, through which hot metal can be taken out by tilting the furnace. On the opposite side wall, the door is situated through which raw material is charged in the furnace.

Iron ore is used as oxidizing agent. Now-a-days oxygen lancing facility is also available. The roof is made of basic refractory bricks, through which carbon electrodes are inserted to make the arc over the charge.

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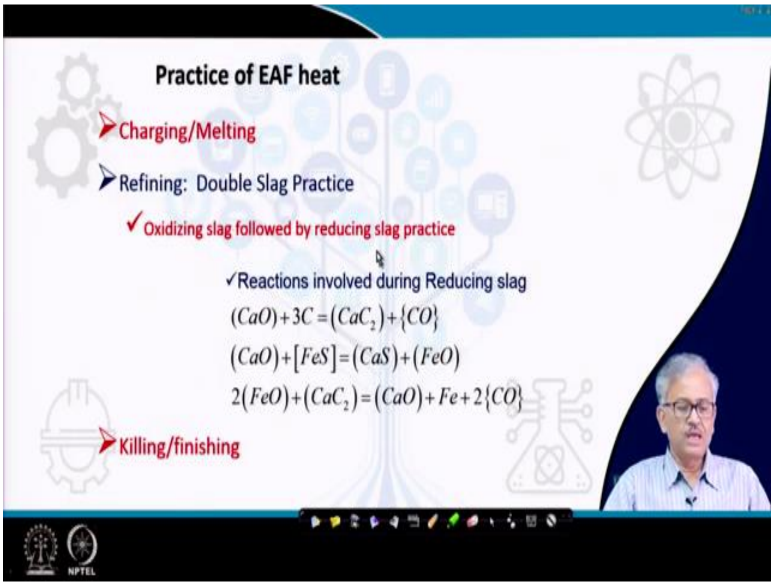

Practice of EAF heat

- Charging/Melting
- Refining: Double Slag Practice
  - ✓ Oxidizing slag followed by reducing slag practice
    - ✓ Reactions involved during Reducing slag

$$(CaO)+3C=(CaC_2)+\{CO\}$$

$$(CaO)+[FeS]=(CaS)+(FeO)$$

$$2(FeO)+(CaC_2)=(CaO)+Fe+2\{CO\}$$

- Killing/finishing

The process sequence are as follows: charging, melting followed by refining, killing and alloying. After charging the arc is struck over the charge and it starts melting. After melting refining starts. Usually double slag is made in EAF. First an oxidizing basic slag is made by adding iron ore (Fe_2O_3), CaO. Presence of iron oxide and temperature facilitates early melting of CaO and form basic slag. Impurities like C, Si, Mn, and P can be removed using oxidizing and basic slag. If impurities are high (in case hot metal is used), double oxidizing slag could be made by slagging off the furnace intermittently by tilting the furnace.

To remove the Sulphur, a fresh basic reducing slag is made after removing the oxidizing slag. To make reducing slag lime and carbon is added. Following reactions take place for de-sulphurization using the basic reduction slag.

$$(CaO) + 3C = \left(CaC_2\right) + \left\{CO\right\} \tag{35.1}$$

$$\left(CaO\right) + \left[FeS\right] = \left(CaS\right) + \left(FeO\right) \tag{35.2}$$

$$2\left(FeO\right) + \left(CaC_2\right) = \left(CaO\right) + Fe + 2\left\{CO\right\} \tag{35.3}$$

So, lime react with the carbon forming the calcium carbide and the CO gas. Lime also react with the sulfur in the hot metal forming the calcium sulfide and FeO. FeO in the slag is oxidizing. But FeO is not stable in reducing condition and it is instantaneously reduced by calcium carbide. This the advantage of EAF over LD, where a separate reducing slag could be made to remove the Sulphur.

Next operation is killing the bath; it means reducing the residual oxygen in the bath to a very low level before alloying. Killing is not required if you have already produced a reducing slag. After killing alloying is done to adjust the composition.

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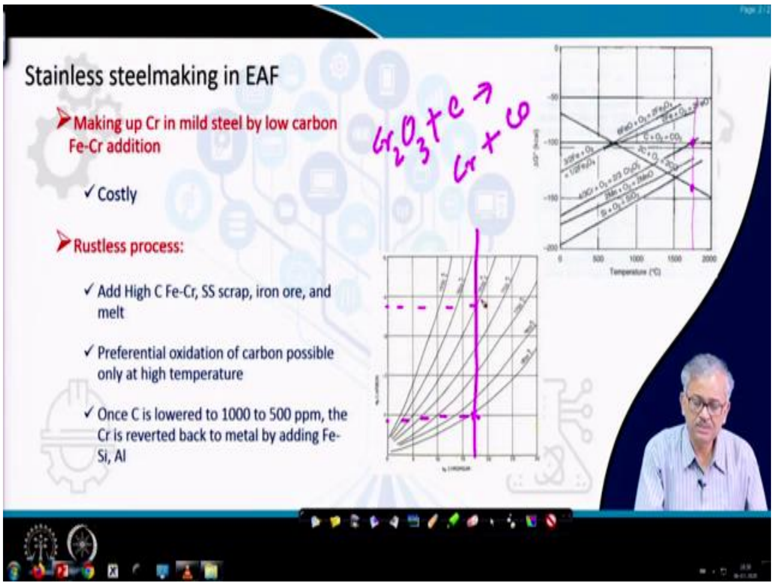

Stainless steelmaking in EAF

- Making up Cr in mild steel by low carbon Fe-Cr addition
  - ✓ Costly
- Rustless process:
  - ✓ Add High C Fe-Cr, SS scrap, iron ore, and melt
  - ✓ Preferential oxidation of carbon possible only at high temperature
  - ✓ Once C is lowered to 1000 to 500 ppm, the Cr is reverted back to metal by adding Fe-Si, Al

$Cr_2O_3 + C \rightarrow Cr + CO$

It is possible to produce stainless steel in EAF. Stainless steel is a low carbon high Cr, Ni alloy steel. Carbon is kept low in stainless steel to avoid its intergranular corrosion, also known as the phenomenon of sensitization. Because, in presence of plenty of carbon chromium forms carbide and precipitates at the grain boundary forming a galvanic couple between grain boundary and the grain, causing intergranular corrosion. In 304 stainless, carbon hardly exceeds 0.1wt%; while Cr and Ni are 18 and 8wt% respectively.

So, stainless steel making is nothing but making a very low carbon high alloy steel. There two ways to produce stainless steel: (i) produce a low carbon steel followed by addition of low carbon ferro-alloy, (ii) melt a high Cr, Ni, and carbon liquid iron and then preferentially remove carbon over chromium and nickel. Method (i) is straight forward but low carbon ferro-alloy are costly. So method two is preferred.

In EAF preferential decarburization is carried out at high temperature, called the rustless process. First, high alloy iron melt is prepared by melting high carbon ferrochrome, steel scrap, chromite ore. So in the melt you have both high carbon and high Cr and nickel. Then carbon is preferentially removed over chromium at high temperature. Thermodynamically CO is more stable than chromium oxide at high temperature. Figure 35.3 shows that thermodynamic condition favoring preferential decarburization at high temperature.

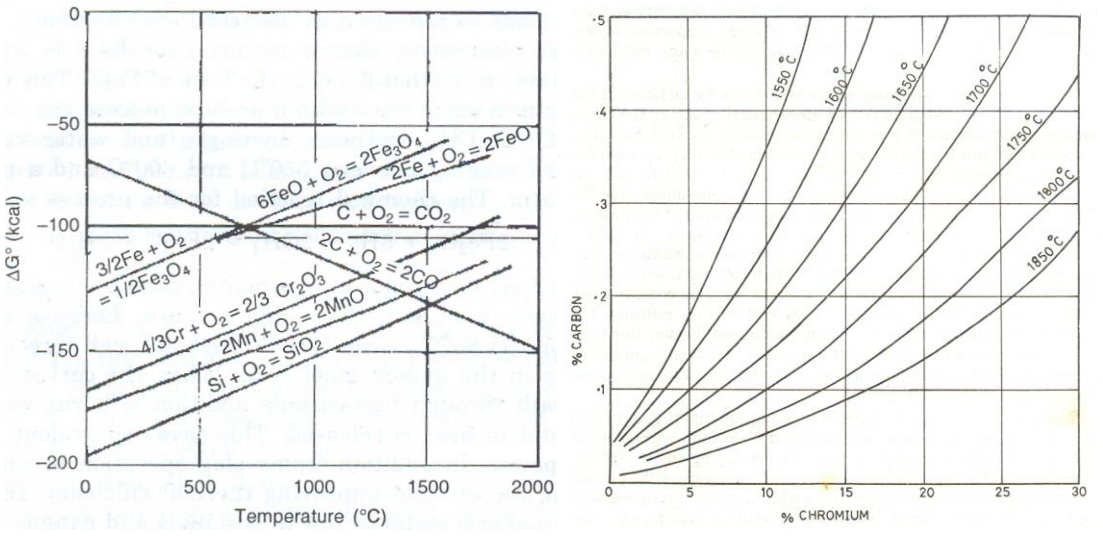

Figure 35.3 (a) Ellingham diagram showing stability of CO over Cr_2O_3 under high temperature, (b) showing at a particular chromium level in the bath, dissolved carbon decreases with increase in temperature[3].

Ellingham diagram in figure 35.5 clearly shows that CO become much stable compared to Cr_2O_3 at high temperature say, 1850^{o}C. Also the figure 35.3(b) shows that at 1850^{o}C, carbon level could be brought down to less than 0.1 wt% by maintaining 18% chromium in the bath. So after treating the bath at 1850^{o}C, carbon can be reduced to desired level. Obviously, due to kinetics of the process, some chromium will also be oxidized and join the slag, which is further reduced back to the bath by adding ferrosilicon, as silica is more stable than chromium oxide (Equation 35.6).

$$2Cr_2O_3 + 3Si = 3SiO_2 + 4Cr$$

(35.6)

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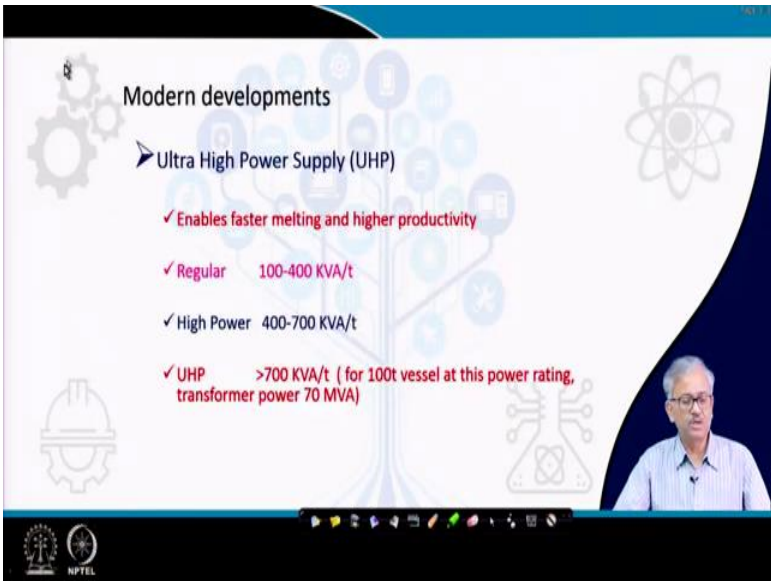

Modern developments

- ➢ Ultra High Power Supply (UHP)
  - ✓ Enables faster melting and higher productivity
  - ✓ Regular 100-400 KVA/t
  - ✓ High Power 400-700 KVA/t
  - ✓ UHP >700 KVA/t (for 100t vessel at this power rating, transformer power 70 MVA)

Now, we will discuss some recent advances in EAF. The first development in EAF is the ultra-high power supply (UHP). Regular specific power supply ranges from 100 to 400 KVA per ton; while high power supply ranges in 400 to 700 KVA per ton. And ultra-high power greater than 700 KVA per ton. This represents specific power input. So, for 100 ton vessel with ultra-high power supply, the transformer power could be greater than 70 MVA. High specific power supply means higher energy input per unit time, indicating faster melting of scrap and higher productivity.

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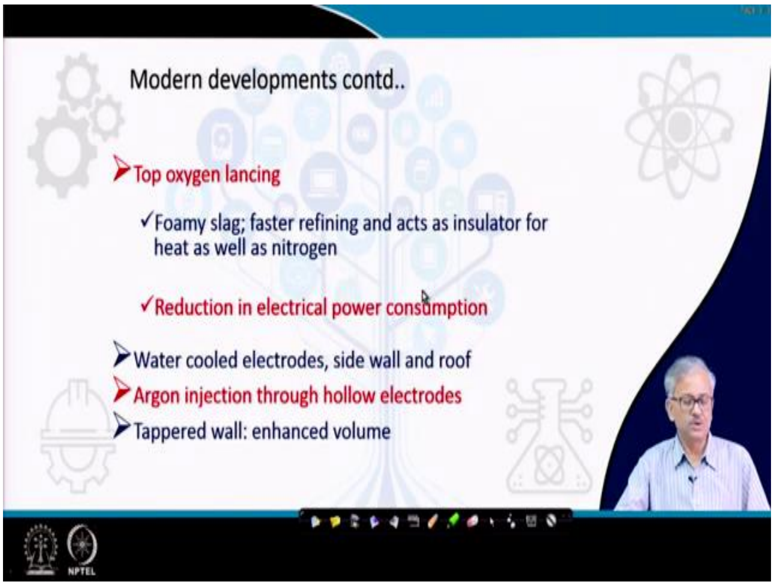

Modern developments contd..

- ➢ Top oxygen lancing
  - ✓ Foamy slag; faster refining and acts as insulator for heat as well as nitrogen
  - ✓ Reduction in electrical power consumption
- ➢ Water cooled electrodes, side wall and roof
- ➢ Argon injection through hollow electrodes
- ➢ Tappered wall: enhanced volume

The second development is the top oxygen lancing. The benefits of oxygen lancing are i) foamy slag practice, where you can produce a foamy slag by lancing oxygen in presence of excess carbon and promoting decarburization, and foam/emulsion formation. In emulsion, refining kinetics become faster; and secondly foam makes an insulating barrier restricting heat loss that reduces electricity consumption. Foam also restricts atmospheric interaction. Nitrogen dissolves faster at the high temperature near arc tip through atomization and dissolution of nascent nitrogen; foam restricts the nitrogen access to the arc tip.

Third development is water cooled electrode sidewall and roof that increases the lining life. Fourth development is argon injection through the hollow electrode that helps in bath stirring, improving heat and mass transfer, and removing stratification leading to process efficiency and reduced specific energy consumption.

Tappered wall increased the volume of the furnace, increasing productivity.

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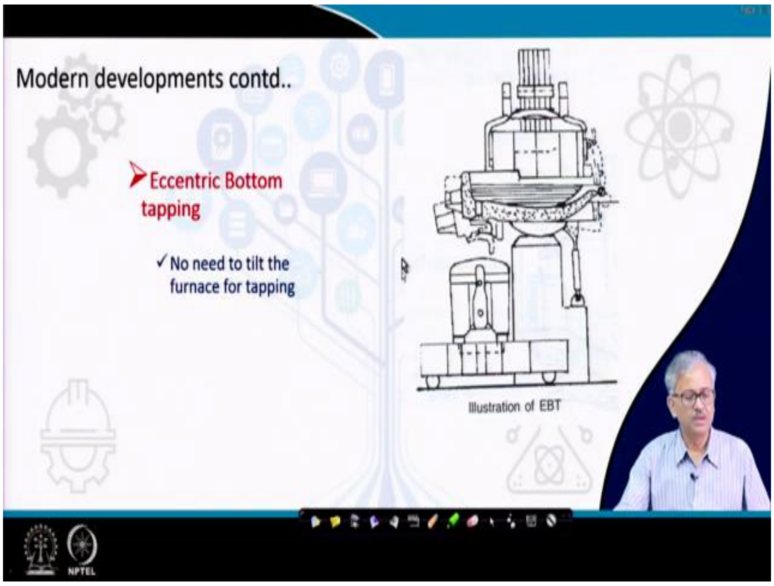

Modern developments contd..

- Eccentric Bottom tapping
  - ✓ No need to tilt the furnace for tapping

Illustration of EBT

Eccentric bottom tapping, allowed direct tapping without tilting the furnace, reducing time of operation and manpower.

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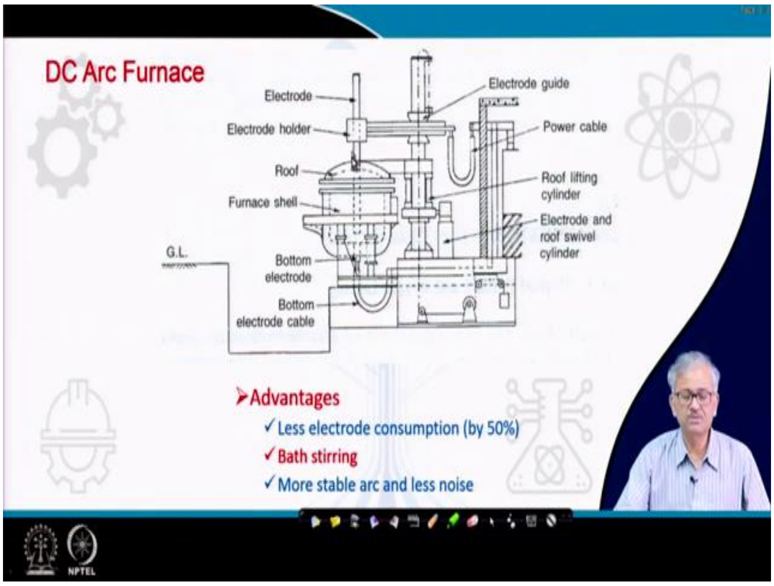

DC Arc Furnace

- Advantages
  - ✓ Less electrode consumption (by 50%)
  - ✓ Bath stirring
  - ✓ More stable arc and less noise

Another development is the DC arc furnace. With DC arcing the electrode consumption is reduced by 50 percent. In case of alternating current, there exists skin effect that allows electron concentration on the surface of the electrode, which heats up the surface; subsequently surface gets oxidized and erode faster. Another advantage of DC arc is excellent bath stirring due to fixed polarity; unlike in AC where polarity changes and induced flow direction due to electromagnetic interaction (Lorenz force) also changes frequently, diminishing the strength of stirring.

Besides, DC arc is more stable and mitigate noise.

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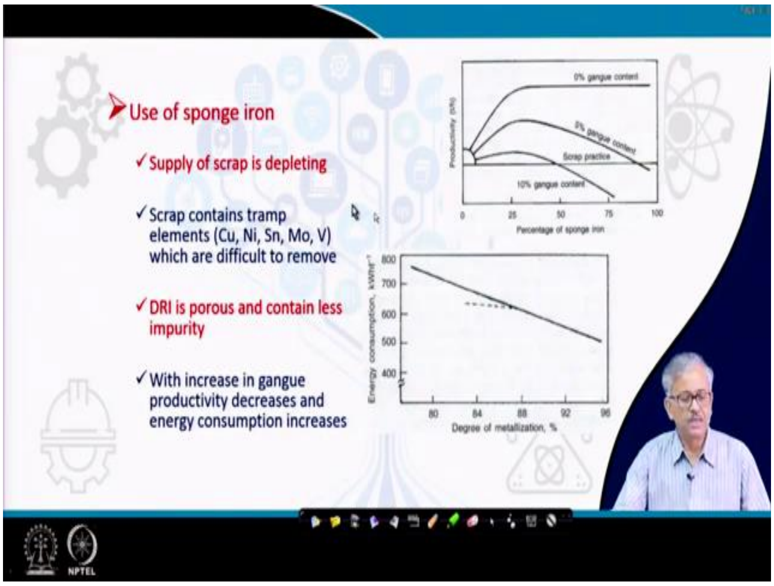

- Use of sponge iron
  - ✓ Supply of scrap is depleting
  - ✓ Scrap contains tramp elements (Cu, Ni, Sn, Mo, V) which are difficult to remove
  - ✓ DRI is porous and contain less impurity
  - ✓ With increase in gangue productivity decreases and energy consumption increases

Then use of sponge iron in EAF. Scrap is depleting with the advent of the continuous casting due to process integration. Direct reduced iron, or sponge iron is also emerging as a coke free alternative to conventional blast furnace ironmaking. Besides, sponge iron does not contain trump element, which are difficult to remove. Besides it is porous that ensures faster dissolution. So, sponge iron are being used progressively in EAF. Sponge iron also contain very low impurity since it is produced in solid state. But depending on metallization it may contain FeO in various amount.

If the gangue content of the sponge iron including FeO increases, slag volume increases, and yield as well as productivity decreases. Figure 35.4 (a) shows the percentage of sponge iron could be added depending on its gangue content.   It is found that sponge iron with 5% gangue can be admitted upto 75% and sponge iron with 10% gangue can be admitted upto 50% without sacrificing productivity that could have been achieved with only scrap melting. Energy consumption also increases with degree of metallization in sponge iron. Higher FeO in sponge increases slag volume and energy consumption (Figure 35.4(b)).

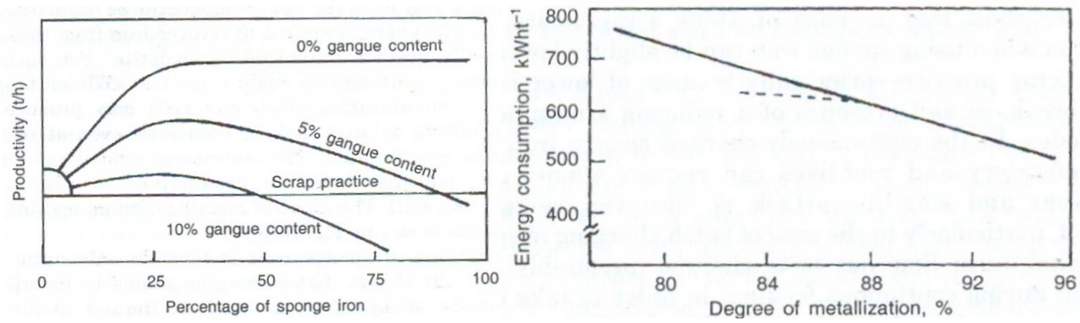

Figure 35.4: (a) Effect of gangue content in the sponge on its productivity, (b) energy consumption versus metallization[3]

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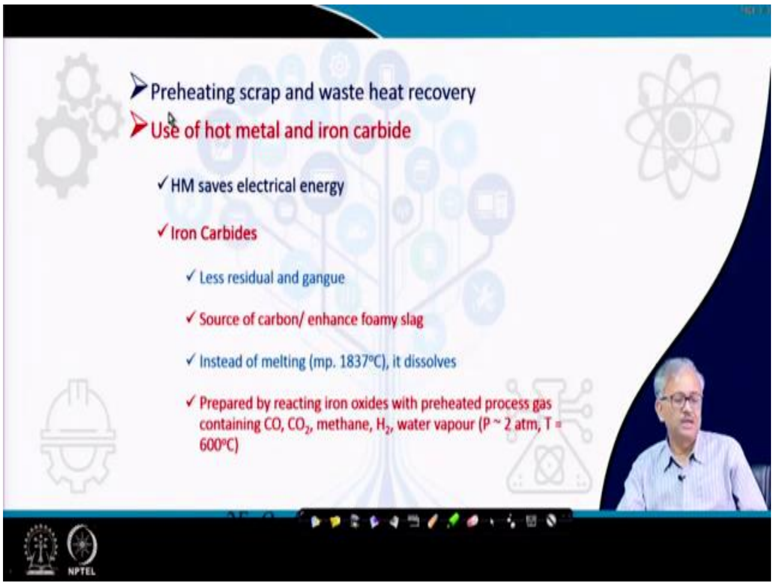

- Preheating scrap and waste heat recovery
- Use of hot metal and iron carbide
  - ✓ HM saves electrical energy
  - ✓ Iron Carbides
    - ✓ Less residual and gangue
    - ✓ Source of carbon/ enhance foamy slag
    - ✓ Instead of melting (mp. 1837°C), it dissolves
    - ✓ Prepared by reacting iron oxides with preheated process gas containing CO, CO_2, methane, H_2, water vapour (P ~ 2 atm, T = 600°C)

Arrangements with enclosed channel for countercurrent waste gas and scrap movement for waste heat recovery and preheating of scrap has also been introduced, which saves energy and reduces specific energy consumption.

Use of hot metal (HM) saves energy as it does not require melting besides it contains some superheat. Use of HM allows charge mix (sponge/scrap/HM) depending on inventory that makes the process economic.

Iron carbide also a very good feed to the electric arc furnace. Because, it does not contain any impurity, gangue. It does not melt rather carbon diffuse out of it leaving pure iron that that also dissolves in liquid bath. Since it is a source of carbon, the formation of foamy slag is facilitated by using it.

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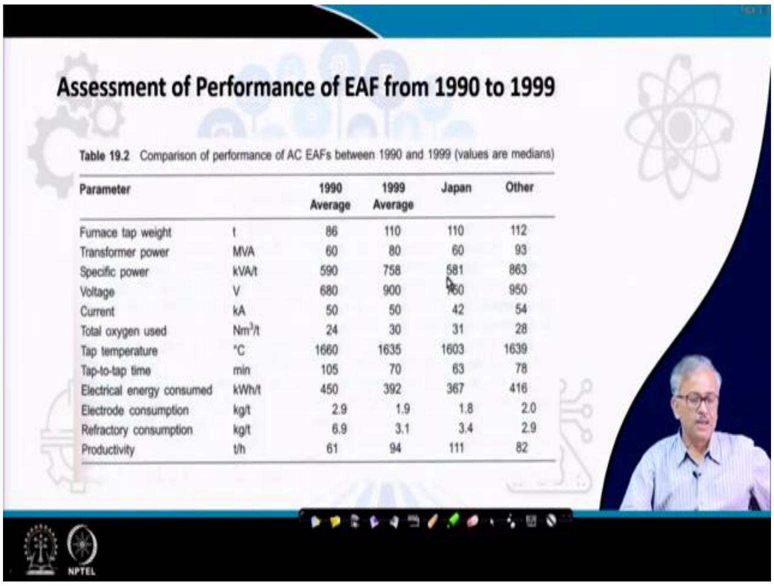

Assessment of Performance of EAF from 1990 to 1999

Table 19.2 Comparison of performance of AC EAFs between 1990 and 1999 (values are medians)

Parameter		1990 Average	1999 Average	Japan	Other
Furnace tap weight	t	86	110	110	112
Transformer power	MVA	60	80	60	93
Specific power	kVA/t	590	758	581	863
Voltage	V	680	900	750	950
Current	kA	50	50	42	54
Total oxygen used	Nm^3/t	24	30	31	28
Tap temperature	°C	1660	1635	1603	1639
Tap-to-tap time	min	105	70	63	78
Electrical energy consumed	kWh/t	450	392	367	416
Electrode consumption	kg/t	2.9	1.9	1.8	2.0
Refractory consumption	kg/t	6.9	3.1	3.4	2.9
Productivity	t/h	61	94	111	82

Table 35.1 presents the assessment of performance of EAF during 1990 to 1999, when significant advances had taken place in EAF.

Table 35.1 Comparison of performance of AC EAFs between 1990-1999 [1]

Parameter		1990 Average	1999 Average	Japan	Other
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Refractory consumption	kg/t	6.9	3.1	3.4	2.9
Productivity	t/h	61	94	111	82

The table shows that the specific power input (KVA per ton) has increased from 590 to 758 during this period, which increased the melting rate and productivity increased from 61 t/hr to 94 t/hr. The specific electrical energy consumption (kWh/t) decreased from 450 to 367. Decrease in energy consumptions are due to various process improvements like foamy slag practice by oxygen lancing, which improved from 24 to 30 Nm^3/t. Besides inert gas injection through hollow electrode improved mixing, kinetics, time of refining, yielding energy savings. Refractory consumption (kg/t) decreased from 6.9 to 3.1, due to use of better cooling arrangement. Electrode consumption (kg/t) decreased from 2.9 to 1.9, due to use of DC arc and electrode cooling.

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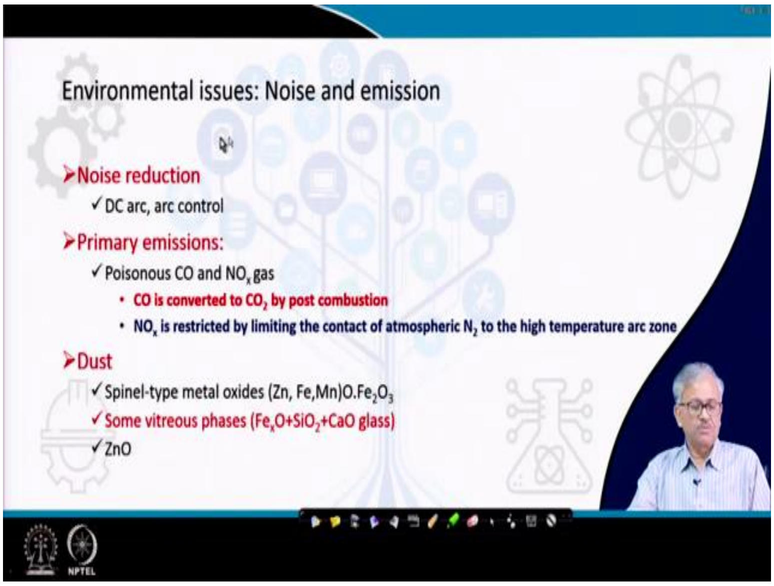

Environmental issues: Noise and emission

➢Noise reduction

- ✓ DC arc, arc control

➢Primary emissions:

- ✓ Poisonous CO and NO_x gas
  - CO is converted to CO_2 by post combustion
  - NO_x is restricted by limiting the contact of atmospheric N_2 to the high temperature arc zone

➢Dust

- ✓ Spinel-type metal oxides $(Zn, Fe,Mn)O.Fe_2O_3$
- ✓ Some vitreous phases (Fe_xO+SiO_2+CaO glass)
- ✓ ZnO

And finally, I will talk about some environmental issues. Noise has been reduced significantly by using DC arc that produces stable arc. Post combustion of CO saves electrical energy and also diminishes poisonous CO emission. NO_X emission can be limited by using foamy slag practice that restricts direct contact of nitrogen at arc tip. EAF dust contains spinel type metal oxides, some vitreous phase and ZnO. Depending on galvanized scrap used, ZnO amount could be high and could be recovered.

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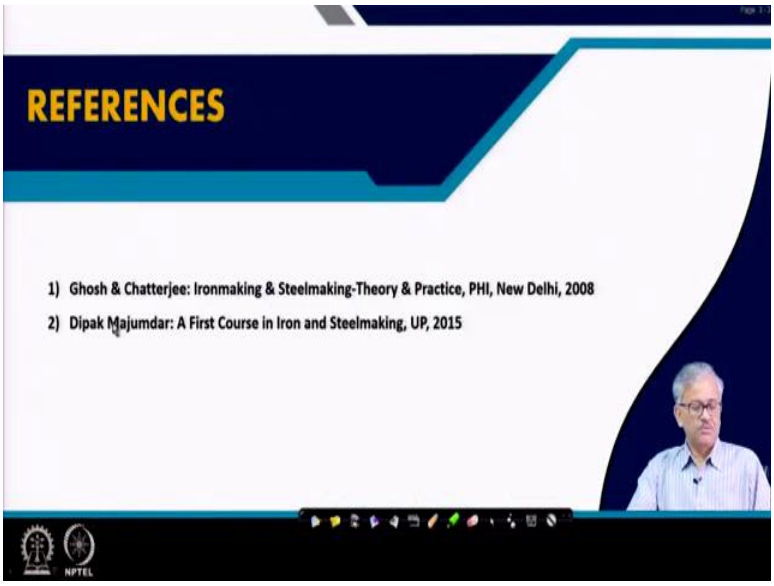

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1) Ghosh & Chatterjee: Ironmaking & Steelmaking-Theory & Practice, PHI, New Delhi, 2008
2) Dipak Majumdar: A First Course in Iron and Steelmaking, UP, 2015

And, the references are mentioned in the slide above. The reference 3 is missing:

[3] R H Tupkary: Modern Steelmaking, Khanna publishers.

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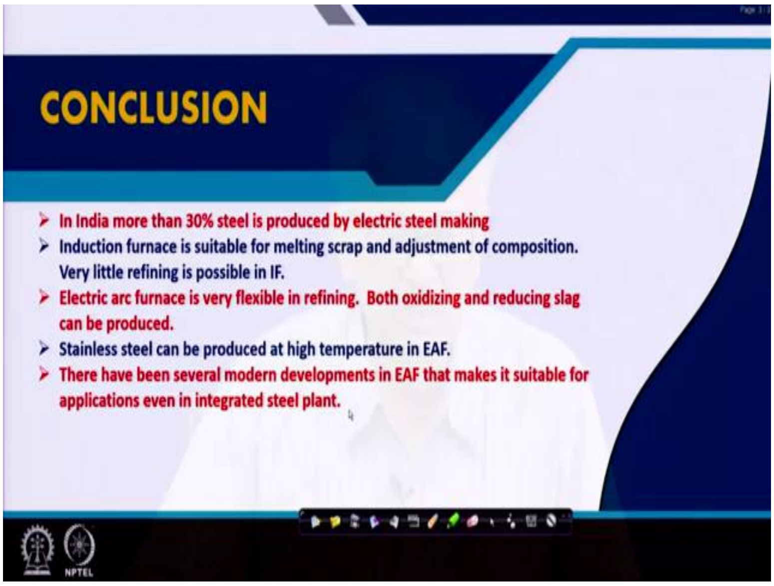

CONCLUSION

- In India more than 30% steel is produced by electric steel making
- Induction furnace is suitable for melting scrap and adjustment of composition. Very little refining is possible in IF.
- Electric arc furnace is very flexible in refining. Both oxidizing and reducing slag can be produced.
- Stainless steel can be produced at high temperature in EAF.
- There have been several modern developments in EAF that makes it suitable for applications even in integrated steel plant.

Conclusion: In India 30 percent steel is produced by electric steel making. Induction furnace is suitable for foundry use in melting scrap, adjustment of composition with very little refining. Electric arc furnace is very flexible for refining, where both oxidizing and reducing slag can be produced. It can produce wide range of alloy steel including stainless steel (by preferential carbon oxidation at high temperature).

There have been several modern developments in the electric arc furnace that makes it suitable for application even in the integrated steel plant.   Advantage of EAF in integrated steel is that it can accept various charge mix (scrap/sponge iron /hot metal) depending on inventory.

Some of the modern developments include ultrahigh power supply that increased the melting rate significantly. Foamy slag practice by oxygen lancing improved kinetics, restricted heat loss and atmospheric interaction. Water cooled refractory, inert gas injection through hollow electrode, tapered furnace, eccentric metal tapping are some other developments. All these development reduced the specific electrical energy consumption.

Sponge iron has emerged as a solid charge in EAF; because it is produced in a coke free alternative route, has faster dissolution rate, does not contain tramp elements. It has been found that sponge iron containing 10% gangue can be used upto 50% in charge mix without sacrificing productivity.

Iron carbide is also an excellent raw material that does not contain any impurity, tramp element and dissolves in the bath. It is suitable for foamy slag practice as it is a pure source of carbon.

Arrangements has also been made for waste heat recovery and scrap preheating towards energy savings.

Emission of dust, CO and NOx is a major concern for EAF. NOX reduction is also possible using foamy practice. CO post combustion also saves electrical energy as well as reduces CO emission.