Iron Making and Steel Making

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Module – 02
Lecture - 07
RIST Diagram based on overall heat and material balance

Welcome, this is the lecture 2 of heat and material balance and in this lecture we will discuss the RIST diagram based on overall heat and material balance in the blast furnace. First of all, we will develop the RIST diagram based on only oxygen balance that is the material balance and later on we will also add on the overall heat balance of the blast furnace.

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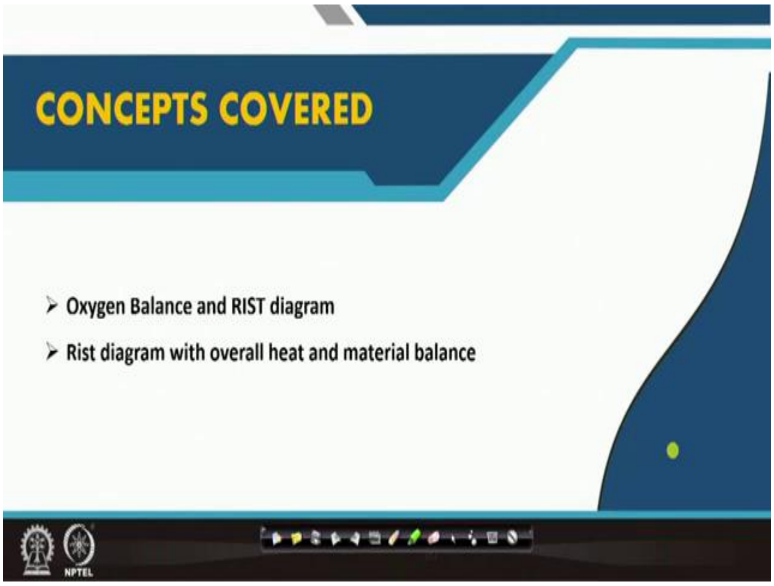

CONCEPTS COVERED

- Oxygen Balance and RIST diagram
- Rist diagram with overall heat and material balance

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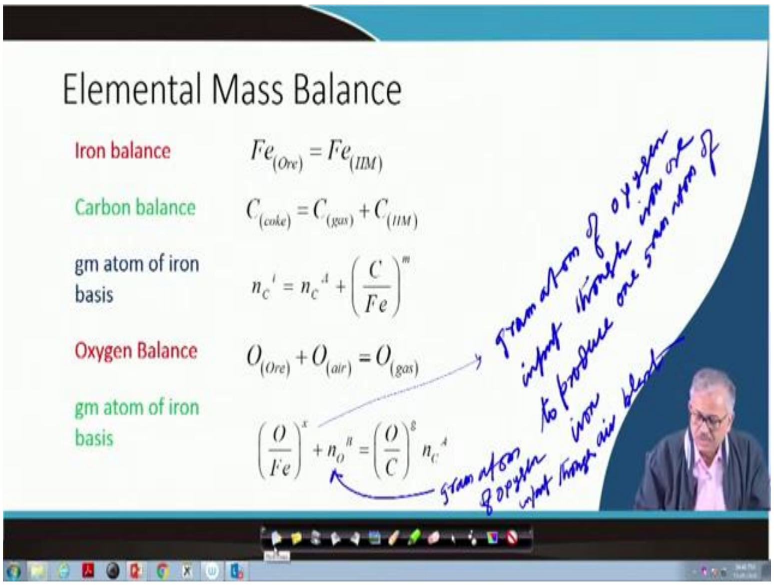

Elemental Mass Balance

Iron balance $Fe_{(Ore)} = Fe_{(HM)}$

Carbon balance $C_{(coke)} = C_{(gas)} + C_{(HM)}$

gm atom of iron basis $n_C{}^i = n_C{}^A + \left(\frac{C}{Fe}\right)^m$

Oxygen Balance $O_{(Ore)} + O_{(air)} = O_{(gas)}$

gm atom of iron basis $\left(\frac{O}{Fe}\right)^x + n_O{}^B = \left(\frac{O}{C}\right)^g n_C{}^A$

gram atom of oxygen input through iron ore to produce one gram atom of iron

gram atom of oxygen input through air blast

So, now before doing that material balance let us see the different elemental balance that exist in the blast furnace. We can first consider the iron balance. As we have discussed in last lecture that iron is coming to the blast furnace from the ore and it is leaving blast furnace through hot metal . Then consider carbon balance. Carbon is coming from the coke and the two sinks for carbon are there; are one is the blast furnace gas, another is the hot metal.

$$C_{(coke)} = C_{(gas)} + C_{(HM)} \tag{1}$$

In terms of one gram atom of iron produced thr carbon balance can be represented as:

$$n_C{}^i = n_C{}^A + \left(\frac{C}{Fe}\right)^m \tag{2}$$

Where n_C^i is basically total moles of carbon input through coke per gram atom of iron produced. Similarly, n_C^A represents the gram atom of carbon (called the active carbon) that joins the blast furnace gas per gram atom of iron produced.

$\left(\frac{C}{Fe}\right)_m$ represents the gram atom of carbon that joins the hot metal per gram atom of iron produced .

Similarly, for oxygen balance the sources are: one is the iron ore, and the other is the air blast. The only sink for oxygen in the blast furnace is the blast furnace gas, where it leaves the furnace in the form of CO and CO_2. Therefore, the oxygen balance may be given as:

$$O_{(Ore)} + O_{(air)} = O_{(gas)} \tag{3}$$

$$\left(\frac{O}{Fe}\right)^x + n_O{}^B = \left(\frac{O}{C}\right)^g n_C{}^A \tag{4}$$

The equation (4), represents the oxygen balance in terms of gram atom of iron produced.

$\left(\frac{O}{Fe}\right)^x$ represents the gram atom of oxygen input through iron ore per gram atom of iron produced. For hematite ore (Fe_2O_3), this value is 1.5. You can always argue ore gangue is also a source of oxygen. But gangue mostly removed as slag. Some partial reduction of gangue may contribute to the oxygen in the blast furnace gas that we may consider separately. For the time being we are ignoring that for simplicity of the model.

n_O^B represents the gram atom of oxygen input through air blast per gram atom of iron produced. $\left(\frac{O}{C}\right)^g$ represents the exit gas composition in terms of atomic ratio of oxygen to carbon in the exit gas. n_C^A represents the gram atom of carbon leaving through the blast furnace gas per gram atom of iron produced (called the active carbon as it reacts with carbon forming its oxides, while carbon that dissolved in the hotmetal is called the inactive carbon). The product of two terms on the RHS represents the gram atom of oxygen that leaves the blast furnace gas per gram atom of iron produced.

The equation (4) represents a straight line. The intercept on y axis, represents $-n_O^B$. Positive y-axis represent the $\left(\frac{O}{Fe}\right)^x$, while the negative y-axis represent n_O^B. The slope of the line provides n_C^A, the carbon rate. The intercept of the line on x-axis for $\left(\frac{O}{Fe}\right)^x$ at 1.5, provides the exit gas composition in terms of atomic ration of oxygen to carbon, $\left(\frac{O}{C}\right)^g$.

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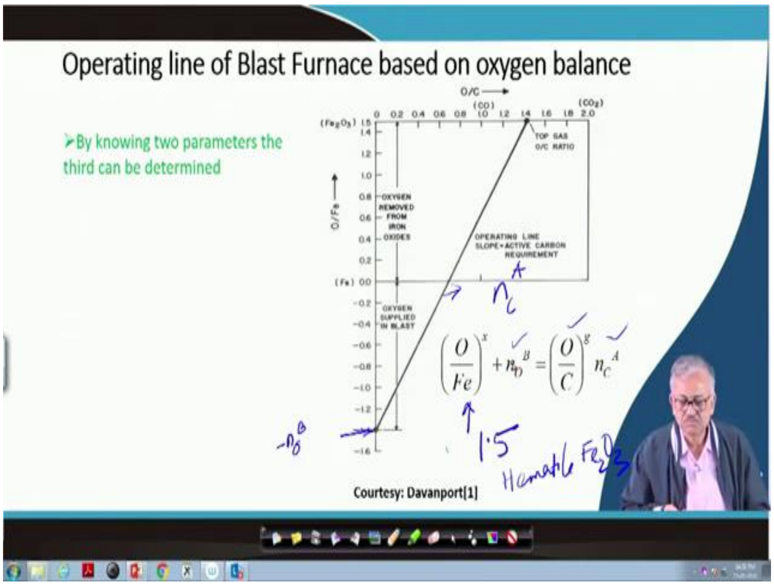

Operating line of Blast Furnace based on oxygen balance

- By knowing two parameters the third can be determined

$$\left(\frac{O}{Fe}\right)^x + n_O^B = \left(\frac{O}{C}\right)^g n_C^A$$

Courtesy: Davanport[1]

In equation (4), given that $\left(\frac{O}{Fe}\right)^x$ =1.5, we have three unknowns. We can vary two parameters to fix the third one, i..e, we have two degrees of freedom. So it is not a fully predictive mode, given the two parameters, we can estimate the other.

If you know the coke rate in a blast furnace and you know the gas composition, you can predict how much air blast you have to provide. And if you know the how much air blast furnace is taking and at which is the carbon rate, you can calculate the composition of the gas. So, this is simplest operating line based on oxygen balance.

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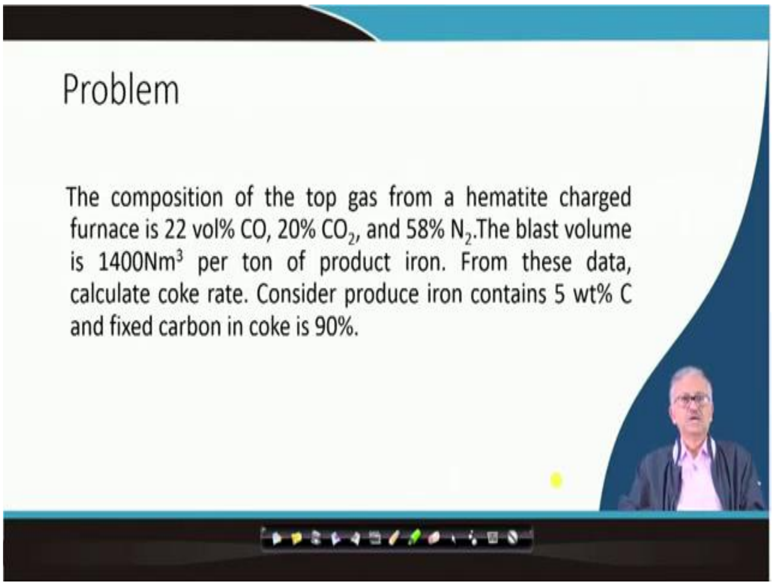

Problem

The composition of the top gas from a hematite charged furnace is 22 vol% CO, 20% CO_2, and 58% N_2.The blast volume is 1400Nm^3 per ton of product iron. From these data, calculate coke rate. Consider produce iron contains 5 wt% C and fixed carbon in coke is 90%.

Now, let us do a simple problem. The composition of the top gas from a hematite charged blast furnace is as 22 volume percent CO, 20 percent your CO_2 and 58 percent is nitrogen and the blast volume is also given. Now, from this data you have to calculate the coke rate.

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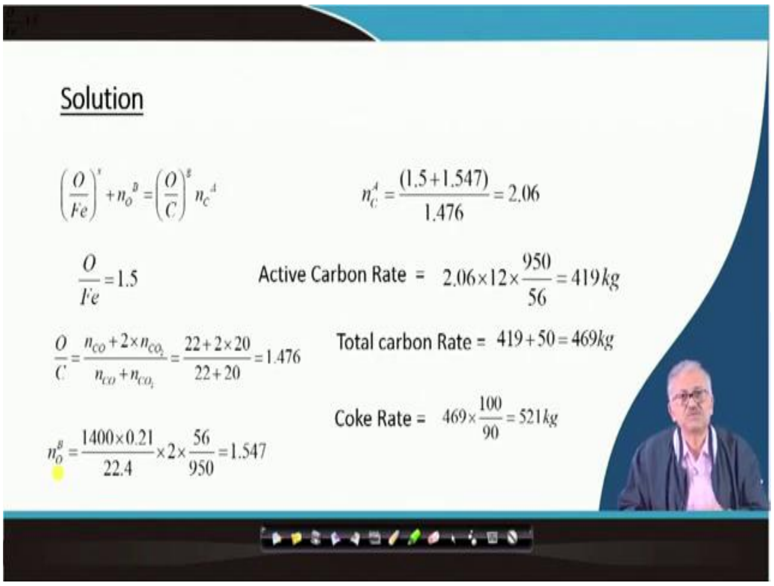

Solution

$$\left(\frac{O}{Fe}\right)^{s} + n_O^{B} = \left(\frac{O}{C}\right)^{g} n_C^{A}$$

$$\frac{O}{Fe} = 1.5$$

$$\frac{O}{C} = \frac{n_{CO} + 2\times n_{CO_2}}{n_{CO} + n_{CO_2}} = \frac{22+2\times 20}{22+20} = 1.476$$

$$n_O^{B} = \frac{1400\times 0.21}{22.4}\times 2\times\frac{56}{950} = 1.547$$

$$n_C^{A} = \frac{(1.5+1.547)}{1.476} = 2.06$$

Active Carbon Rate = $2.06\times 12\times\frac{950}{56} = 419\,kg$

Total carbon Rate = $419+50 = 469kg$

Coke Rate = $469\times\frac{100}{90} = 521\,kg$

Please note all the data are given per ton of hot metal produced. Therefore, to apply the equation (4), you need to convert the data per kg-mole of iron basis. So, blast rate per kg-mole of iron basis may be converted as:

$$n_O^B = \frac{1400 \times 0.21}{22.4} \times 2 \times \frac{56}{950} = 1.547$$

Please note that considering 5% carbon in hot metal, iron content in hot metal is 950 kg, or, 950/56 kg-mole.

The gas composition can be represented in terms of $\left(\frac{O}{C}\right)^g$ as follows:

$$\frac{O}{C} = \frac{n_{CO} + 2 \times n_{CO_2}}{n_{CO} + n_{CO_2}} = \frac{22 + 2 \times 20}{22 + 20} = 1.476$$

Now, applying equation (4), the n_C^A may be calculated as:

$$n_C^A = \frac{(1.5 + 1.547)}{1.476} = 2.06$$

Now, we need to convert the carbon rate per ton basis as follows:

$$2.06 \times 12 \times \frac{950}{56} = 419\, kg$$

Total carbon rate may be calculated by combining active and inactive carbon in hot metal as: 419 + 50 = 469kg/ THM. THM represent ton of hot metal.

Now coke rate (considering coke contains 90% carbon) = $469 \times \frac{100}{90} = 521$ kg/THM

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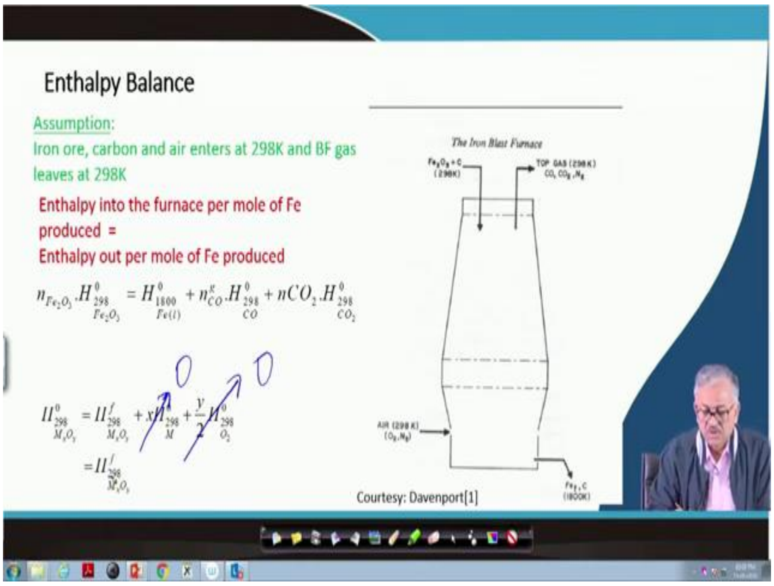

Enthalpy Balance

Assumption:

Iron ore, carbon and air enters at 298K and BF gas leaves at 298K

Enthalpy into the furnace per mole of Fe produced =
Enthalpy out per mole of Fe produced

$$n_{Fe_2O_3}.\underset{Fe_2O_3}{H^0_{298}} = \underset{Fe(l)}{H^0_{1800}} + n^g_{CO}.\underset{CO}{H^0_{298}} + nCO_2.\underset{CO_2}{H^0_{298}}$$

$$\underset{M_xO_y}{H^0_{298}} = \underset{M_xO_y}{H^f_{298}} + \cancelto{0}{x\underset{M}{H^0_{298}}} + \cancelto{0}{\frac{y}{2}\underset{O_2}{H^0_{298}}}$$
$$= \underset{M_xO_y}{H^f_{298}}$$

Courtesy: Davenport[1]

Now, we come to the enthalpy balance. If we do the overall enthalpy balance, it will introduce a fixed point in the operating line to ensure the heat balance requirement in the furnace. Thus it will reduce one degrees of freedom and we will move one step towards a fully predictive model that will require one further point on the operating line that will pin the straight line with the optimum coke rate.

First we will make some simplistic assumption to make the model simple enough to understand and at the same time providing the concept of heat balance and its implication on operating line. Let us consider that all solid feed at 298K and air blast also enters at 298K and the gas leaves as 298 K. Also assume hot metal is pure iron leaving at 1800K, i.e. at its melting temperature. Ore is pure hematite. Since elemental enthalpy is zero at 298 K, we do not have to consider sensible enthalpy input and output by carbon, oxygen and nitrogen. Thus only enthalpy input will be through pure hematite at 298K and enthalpy output will be through the enthalpy of hot metal at 1800K and enthalpy out through gaseous compounds like CO and CO_2. So, the enthalpy balance statement may be given as:

$$n_{Fe_2O_3}.\underset{Fe_2O_3}{H^0_{298}} = \underset{Fe(l)}{H^0_{1800}} + n^g_{CO}.\underset{CO}{H^0_{298}} + nCO_2.\underset{CO_2}{H^0_{298}} \qquad (5)$$

Since elemental enthalpy at 298 is 0, the standard enthalpy of a compound at 298 K may be given as its heat of formation, as follows:

$$\begin{aligned} H^{0}_{\substack{298\\M_xO_y}} &= H^{f}_{\substack{298\\M_xO_y}} + x\cancelto{0}{H^{0}_{\substack{298\\M}}} + \frac{y}{2}\cancelto{0}{H^{0}_{\substack{298\\O_2}}} \\ &= H^{f}_{\substack{298\\M_xO_y}} \end{aligned} \tag{6}$$

So, equation (5) can be re-written as:

$$n_{Fe_2O_3}.H^{f}_{\substack{298\\Fe_2O_3}} = H^{0}_{\substack{1800\\Fe(l)}} + n^{g}_{CO}.H^{f}_{\substack{298\\CO}} + nCO_2.H^{f}_{\substack{298\\CO_2}} \tag{7}$$

Rearranging the terms of equation (7), it can be written in terms of heat demand (D) and heat supply (S) as follows:

$$\begin{aligned} & H^{0}_{\substack{1800\\Fe(l)}} + n_{Fe_2O_3}.\left(-H^{f}_{\substack{298\\Fe_2O_3}}\right) = n^{g}_{CO}.\left(-H^{f}_{\substack{298\\CO}}\right) + nCO_2.\left(-H^{f}_{\substack{298\\CO_2}}\right) \\ & D = S \end{aligned}$$

The LHS represent the demand terms and it consists the sensible enthalpy of liquid iron at 1800K and the heat of decomposition of Fe_2O_3. The RHS represent the supply term that consists of heat supplied by oxidation of carbon to CO and CO_2.

Let us calculate the demand term. The first term (the sensible enthalpy of liquid iron at 1800K) includes the sensible enthalpy for heating solid iron at 298 k to its melting temperature at 1800K and its latent heat of fusion = $40\frac{kJ}{kg-mole.K} \times (1800 - 298)K + 15000\frac{kj}{kg-mole} = 60080 + 15000 = 75{,}080\frac{kJ}{kg-mole}$

In the supply term, the gas composition has to be represented in terms of $\left(\frac{O}{C}\right)^g$ to make it compatible to the material balance equation given by equation (4), such that both the equation may be combined. Now, moles of CO and CO2 in supply terms may be converted in terms of $\left(\frac{O}{C}\right)^g$ as follows:

$$n_{CO}^{g} = n_{C}^{g}.X_{CO}^{g} = n_{C}^{A}.\left[2-\left(\frac{O}{C}\right)^{g}\right];$$
$$n_{CO_2}^{g} = n_{C}^{g}.X_{CO_2}^{g} = n_{C}^{A}.\left[\left(\frac{O}{C}\right)^{g}-1\right]$$

(8)

Now, putting the values for heat of formation of for CO and CO2, the supply term may be given as:

$$H_{\substack{298\\CO}}^{f} = -111,000 kJ/kg-mole; \quad H_{\substack{298\\CO_2}}^{f} = -394,000 kJ/kg-mole$$
$$S = n_{C}^{A}.\left[283,000.\left(\frac{O}{C}\right)^{g} - 172,000\right]$$

(9)

Noting D = S, equation (9) may be written as:

$$D = n_C^A\left[283{,}000.\left(\frac{O}{C}\right)^g - 172{,}000\right]$$

(10)

Now, heat balance equation (10) may be combined with material balance equation (4), by eliminating the common term, $\left(\frac{O}{C}\right)^g$ from these equations as follows:

$$\left(\frac{O}{Fe}\right)^{x} + n_{O}^{B} - \frac{D}{283,000} = n_{C}^{A}.\frac{172,000}{283,000}$$
$$\left[\left(\frac{O}{Fe}\right)^{x} - \frac{D}{283,000}\right] - \left(-n_{O}^{B}\right) = n_{C}^{A}.\left(\frac{172,000}{283,000} - 0\right)$$

(11)

The equation (11) is written in the form: $y_2 - y_1 = m(x_2 - x_1)$, indicating the equation of a straight line passing through two points (x_1, y_1), (x_2, y_2). The point (x_2, y_2), represent a fixed point on the operating line, called the thermal pinch point:

$$H \equiv \left\{ \frac{172{,}000}{283{,}000}, \left(\frac{O}{Fe}\right)^x - \frac{D}{283{,}000} \right\}$$

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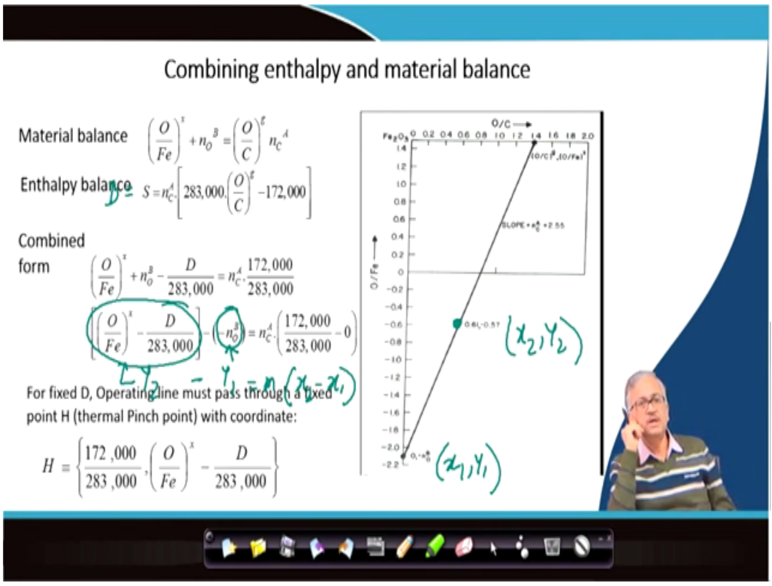

Combining enthalpy and material balance

Material balance $\left(\frac{O}{Fe}\right)^x + n_O{}^B = \left(\frac{O}{C}\right)^g n_C{}^A$

Enthalpy balance $D = S = n_C^A \cdot \left[283{,}000 \cdot \left(\frac{O}{C}\right)^g - 172{,}000\right]$

Combined form $\left(\frac{O}{Fe}\right)^x + n_O^B - \frac{D}{283{,}000} = n_C^A \cdot \frac{172{,}000}{283{,}000}$

$$\left[\left(\frac{O}{Fe}\right)^x - \frac{D}{283{,}000}\right] - \left(-n_O^B\right) = n_C^A \cdot \left(\frac{172{,}000}{283{,}000} - 0\right)$$

$$y_2 - y_1 = m(x_2 - x_1)$$

For fixed D, Operating line must pass through a fixed point H (thermal Pinch point) with coordinate:

$$H \equiv \left\{ \frac{172{,}000}{283{,}000}, \left(\frac{O}{Fe}\right)^x - \frac{D}{283{,}000} \right\}$$

Putting the values for D, we get the H point as (0.6,- 0.57).

Imposing a fixed point on the operating, it reduces one degrees of freedom. Out of three parameters if we choose one parameter, the other two parameters get fixed. If I choose coke rate then the blast rate as well as gas composition get fixed. If I choose the blast rate, the coke rate and the exit case composition get fixed. So, I have still one degrees of freedom and the model is still not fully predictive. Now, there can be several operating lines but all need to pass through the thermal pinch point H to ensure the heat balance requirement of the furnace.

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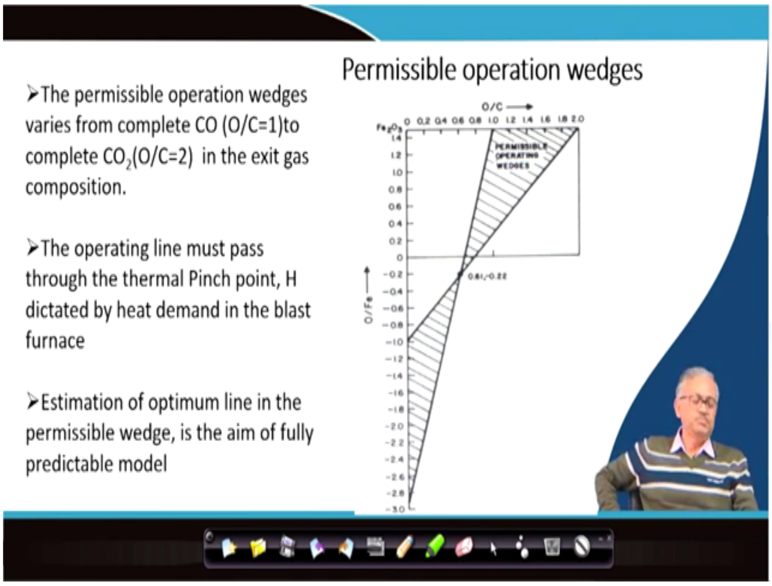

Permissible operation wedges

- The permissible operation wedges varies from complete CO (O/C=1)to complete CO_2(O/C=2) in the exit gas composition.
- The operating line must pass through the thermal Pinch point, H dictated by heat demand in the blast furnace
- Estimation of optimum line in the permissible wedge, is the aim of fully predictable model

As shown in the figure, you can see that under this condition you can have range the operating line. The permissible operating range is shown by the hatched line with point H as the pivotal point.

The maximum slope and carbon rate will be obtained when the exit gas is fully CO, or O/C =1. This corresponds to a hypothetical 100% direct reduction in blast furnace. Similarly the minimum slope or minimum carbon rate is obtained when the exit gas is fully CO_2, or O/C=2. This represents a hypothetical situation of 100% CO utilization through indirect reduction. As we have seen maximum thermos-dynamical efficiency is obtained at maximum indirect reduction of 46% corresponding to % CO utilization of 85%. Therefore, to fix the optimum carbon rate we need to consider the wustite equilibrium, which is the topic of next lecture.

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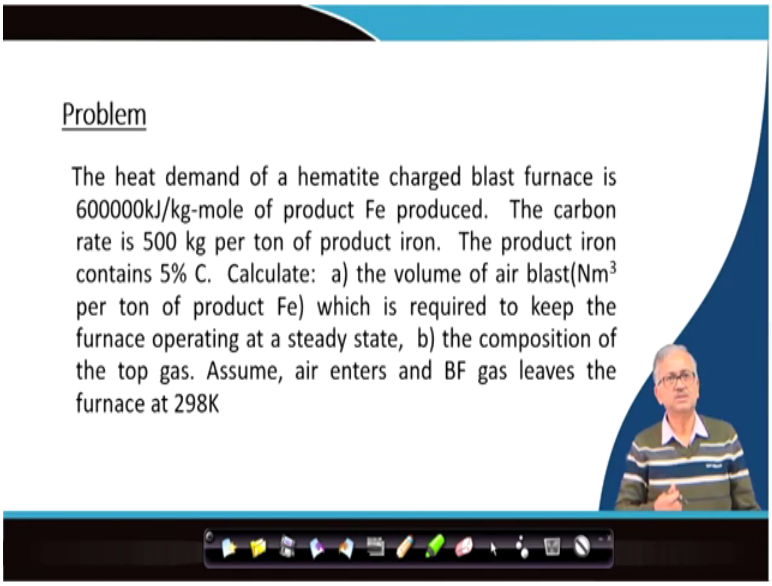

Problem

The heat demand of a hematite charged blast furnace is 600000kJ/kg-mole of product Fe produced. The carbon rate is 500 kg per ton of product iron. The product iron contains 5% C. Calculate: a) the volume of air blast(Nm^3 per ton of product Fe) which is required to keep the furnace operating at a steady state, b) the composition of the top gas. Assume, air enters and BF gas leaves the furnace at 298K

Now, let us solve one problem simple problem based on operating line with heat balance and a thermal pinch point on the line.

The heat demand of a hematite charged furnace is given as 600,000 kJ per kg mole of product iron produced. The carbon rate is 500 kg per ton of iron, and the product iron contains 5 percent carbon. We need to calculate the volume of the air blast,which is required to keep the furnace operating in steady state and the composition of the top gas.

The solution for blast volume:

$$H \equiv \left(0.6,\left(\frac{O}{Fe}-\frac{D}{283000}\right)\right)$$

$$H \equiv \left(0.6,1.5-\frac{600000}{283000}\right)$$

$$H \equiv (0.6,-0.62)$$

$$n_C^A = \frac{(500-50)}{12}\times\frac{56}{950} = 2.21$$

$$\mathit{Blast\ Rate}$$

$$2.21 = \frac{n_O^B - 0.62}{0.6}$$

$$n_O^B = 1.95$$

$$\mathit{Blast\ volume} \quad = \frac{1.95}{2}\times\frac{950}{56}\times 22.4\times\frac{100}{21} = 1760 \quad Nm^3$$

The solution for gas composition:

$$2.21 = \frac{1.5 + 0.62}{\left(\frac{O}{C}\right)^{g} - 0.6}$$

$$\left(\frac{O}{C}\right)^{g} = 1.6$$

$$n_{CO} = n_C^A \times X_{CO} = n_C^A \times \left(2 - \left(\frac{O}{C}\right)^{g}\right) = 1.72 \times (2 - 1.6) = 0.688$$

$$n_{CO_2} = n_C^A \times X_{CO_2} = n_C^A \times \left(\left(\frac{O}{C}\right)^{g} - 1\right) = 1.72 \times (1.6 - 1) = 1.032$$

$$n_{N_2} = n_O^B \times \left(\frac{1}{2}\right) \times \left(\frac{79}{21}\right) = 3.67$$

$$n_T = 0.688 + 1.032 + 3.67 = 5.39$$

$$Gas\,Composition: \quad \%CO = \frac{0.688}{5.39} \times 100 = 13\%$$

$$\%CO2 = 19\%, \%N2 = 68\%$$

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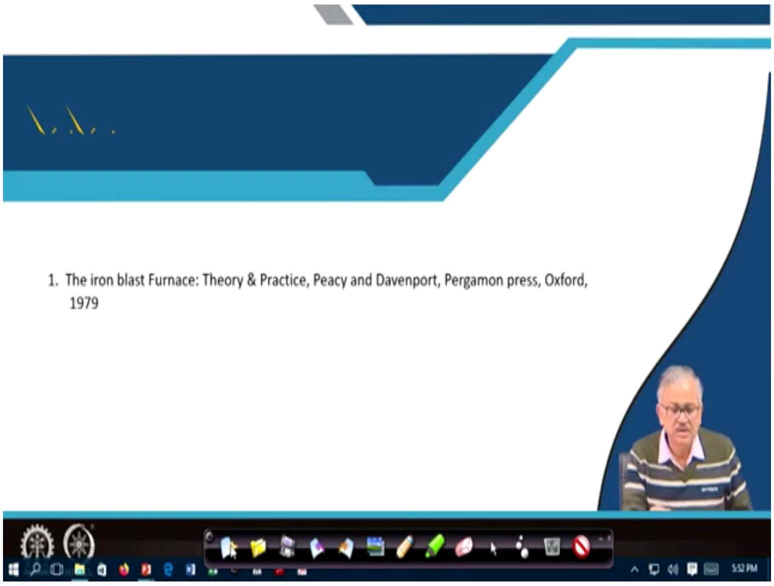

1. The iron blast Furnace: Theory & Practice, Peacy and Davenport, Pergamon press, Oxford, 1979

You can consult the book of iron blast furnace theory and practice by Davenport.

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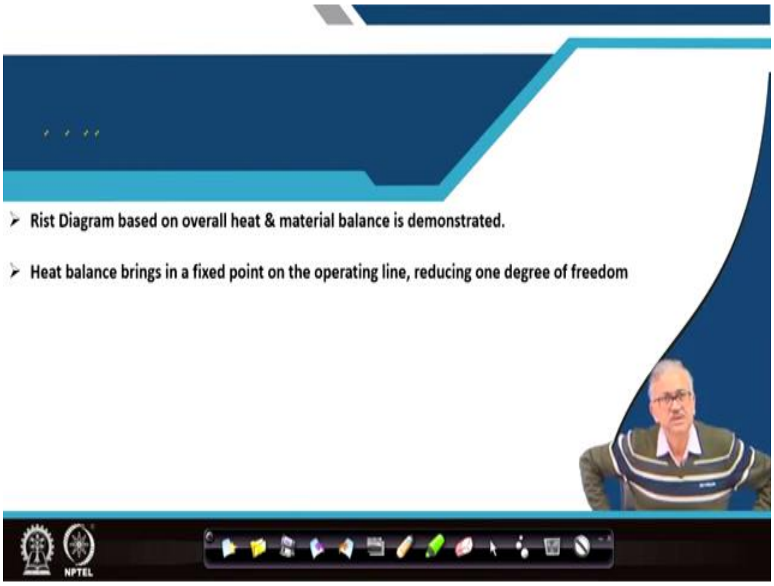

- Rist Diagram based on overall heat & material balance is demonstrated.
- Heat balance brings in a fixed point on the operating line, reducing one degree of freedom

The operating line described is also known as the RIST diagram, after the name of te author who first penned down such operating line based on heat and material balance.

We have seen that based on oxygen balance we get the simplest operating line, where we have two degrees of freedom. In other words, if we choose two parameters, the third operating parameters get fixed, i.e, we can predict third parameter if we know the other two operating parameters. If we just introduce the overall heat balance of the furnace along with material balance, a new fixed line appear on the operating line, called the thermal pinch point, that satisfy the heat requirement of the furnace. Due to this fixed point on the operating line, one degrees of freedom is eliminated. Now if we choose one parameters, other two operating parameters are fixed. In other words if we know one operating parameters, we are able to predict the other two parameters. In the next lecture, we will bring in another fixed point on the operating line considering wustite equilibrium, which will make the model fully predictive- that means all three operating parameters could be predicted for a fixed charge to the furnace.

Thank you.