Iron Making and Steel Making
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Module - 03
Lecture - 11
Aerodynamics in Blast Furnace - Part 1

Welcome. It is the module 3 and the 1st lecture on the Aerodynamics in Blast Furnace. And, I will require two more lectures to complete this aerodynamics in blast furnace.

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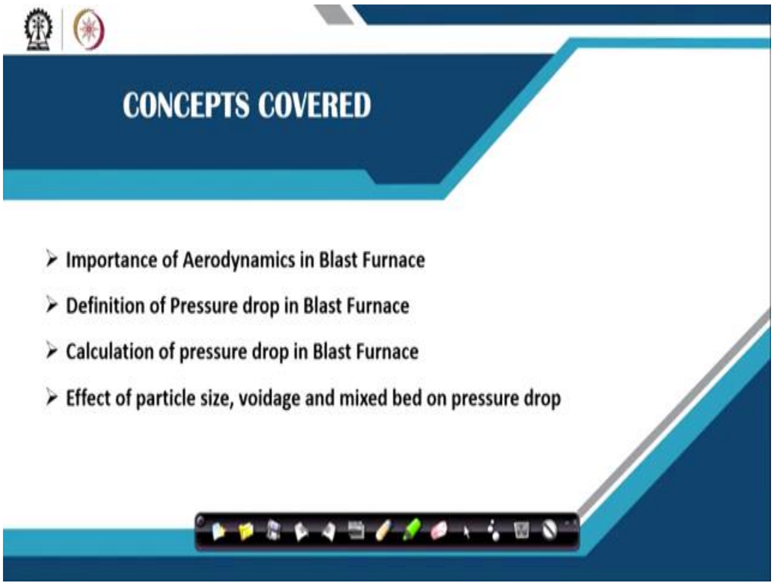

CONCEPTS COVERED

- Importance of Aerodynamics in Blast Furnace
- Definition of Pressure drop in Blast Furnace
- Calculation of pressure drop in Blast Furnace
- Effect of particle size, voidage and mixed bed on pressure drop

What is the importance of aerodynamics in blast furnace? That is the concept that will be covered here; that is the importance of aerodynamics in blast furnace. And what is the definition of pressure drop in blast furnace and how to calculate the pressure drop in blast furnace and, the effect of various parameters like particle size, voidage and mixed bed on pressure drop. So, these are the four items that will be covered in this lecture.

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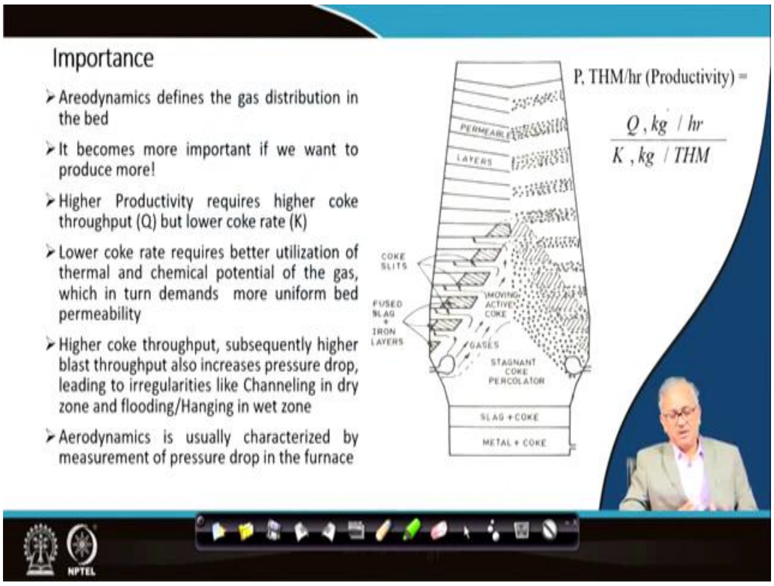

Importance

- Areodynamics defines the gas distribution in the bed
- It becomes more important if we want to produce more!
- Higher Productivity requires higher coke throughput (Q) but lower coke rate (K)
- Lower coke rate requires better utilization of thermal and chemical potential of the gas, which in turn demands more uniform bed permeability
- Higher coke throughput, subsequently higher blast throughput also increases pressure drop, leading to irregularities like Channeling in dry zone and flooding/Hanging in wet zone
- Aerodynamics is usually characterized by measurement of pressure drop in the furnace

P, THM/hr (Productivity) = $\frac{Q, kg / hr}{K, kg / THM}$

Aerodynamics defines the gas distribution in the bed and is a very important parameter in blast furnace. Because, for utilizing the gas potential, both the thermal and chemical potential, we need intense interaction between the gas and the solid, that is between the upcoming gas and the solid that is coming down. They should have a very intimate interaction such that the chemical and thermal potential of the gas is utilized to the maximum extent.

And how it can be ensured? It can be ensured, if we have a very uniform bed permeability across the cross section of the bed; that means, if the gas can pass through the cross section uniformly; then it will be able to interact with the most of the solid. On the other hand, if the gas passes through some channels of least resistance, then the solid particles those are in the regions where the gas cannot penetrate, will not participate in the gas solid exchange- both the heat and the mass exchange.

As a result, we cannot extract the chemical and thermal potential of the gas effectively. So, bed permeability is a very important parameter in blast furnace both in the solid zone and in the liquid region, or, the wet zone of the blast furnace. So, aerodynamics basically helps in predicting what type of gas distribution in a blast furnace we have or we can expect. And it becomes more important, if we want to produce more; that is if we want to increase the productivity then study of aerodynamics become more important, as will be explained now.

Productivity can be defined as the ratio of coke throughput, Q (amount of coke burning per unit time) to by the coke rate, K (amount of the coke used per tonne of hot metal produced). So, if you see the ratio, it simply gives you tonne of hot metal produced per hour; that is the productivity. So, P=Q/K.

Higher productivity requires the numerator Q to be high; high Q means I have to burn more coke per unit time; because if I burn more coke per unit time then only I can produce more; I can melt more amount of iron per unit time. So, Q has to be high and the denominator is the coke rate that has to be low; that is to produce 1 tonne of hot metal I must require minimum amount of the coke; then only I can increase the productivity; reducing coke rate also means making more space iron ore in BF.

Now, you see that if I am going to have a lower coke rate, it requires a better utilization of the thermal and chemical potential of the gas. Because, if I can utilize the gas most effectively; obviously, my coke rate will decrease. If I cannot effectively utilize the gas; that means, if gas partially bypasses through blast furnace without participating or without interacting with the solid, we are unable to utilize the potential of the gas effectively. In that case your coke rate will increase.

So obviously, lower coke rate requires your better utilization of the gas, better bed permeability and for that you need to study the aerodynamics. And, the higher coke throughput, on the other hand, requires higher blast throughput; or, in other words if you want to burn more amount of coke per unit time; and you have to supply more amount of air blast per unit time. Again, if you want to increase more amount of air blast per unit time, gas flow rate or the linear velocity of the gas in the blast furnace will increase and that will also increase the resistance to gas flow in the blast furnace. Because, it will increase frictional loss and the pressure drop in the blast furnace. And, high pressure drop in the blast furnace can lead to different irregularities in the blast furnace, mainly called the channeling. Channeling is a phenomena when the gas try to pass away through some selected channels in blast furnace.

Or flooding can take place in the wet zone of the blast furnace, where the liquid can be physically pushed up by the gas into the solid region. Up in the solid region, low temperature solid can make liquid to solidify, form an arc and solid boundary that may not allow the gas to pass at all. This is the condition of hanging; it is called that blast furnace refuses to take air.

So, these are the situation; that is if you want to increase the productivity, then channeling, hanging phenomena can happen; unless you take care of the aerodynamics in the blast furnace. That is why the aerodynamics is quite important in blast furnace.

And, aerodynamics is usually characterized by the measurement of pressure drop in the blast furnace and in any modern blast furnace you have number of probes which measure the pressure drop both in the radial cross section as well as in axial distance across the blast furnace. So, for any axial distance as well as radial cross section, you have the data of pressure drop and this distribution of pressure basically gives you an idea about the instantaneous aerodynamics in the blast furnace.

And, accordingly you can change your burden distribution, or you can change the raw material distribution, such that you can bring the furnace in a proper position or, in a good operating condition.

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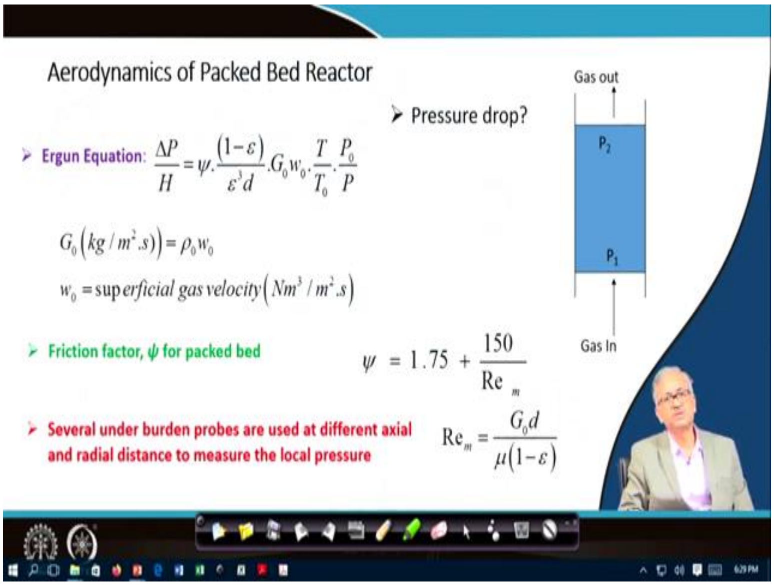

Aerodynamics of Packed Bed Reactor

- Pressure drop?

- Ergun Equation: $\frac{\Delta P}{H} = \psi . \frac{(1-\varepsilon)}{\varepsilon^3 d} . G_0 w_0 . \frac{T}{T_0} . \frac{P_0}{P}$

$G_0 \left(kg / m^2 . s \right) = \rho_0 w_0$

$w_0 = \text{superficial gas velocity} \left(Nm^3 / m^2 . s \right)$

- Friction factor, ψ for packed bed

$$\psi = 1.75 + \frac{150}{\mathrm{Re}_m}$$

- Several under burden probes are used at different axial and radial distance to measure the local pressure

$$\mathrm{Re}_m = \frac{G_0 d}{\mu (1-\varepsilon)}$$

Blast furnace is a packed bed reactor, where basically you have lots of granules and gas is passing through the pores of the granules without shifting the particles; or, it should be a perfectly fixed bed reactor.

In In blast furnace, how do you define by the pressure drop? If you consider the blast furnace as a black box like a just a packed bed and its pressure at the bottom is P_1 at the top is P_2, then the pressure drop (ΔP) is defined as: $\Delta P = P_1 - P_2$;

We have seen that pressure drop can be measured by under burden probes; but if we want to understand how pressure drop varies with bed parameters, we can also calculate average pressure drop in blast furnace using Ergun equation as a function of gas voidage, particle size, gas velocity, height of the bed and fluid dynamic condition represented by empirical parameter called friction factor (see Equation 11.1)

$$\frac{\Delta P}{H} = \psi . \frac{(1-\varepsilon)}{\varepsilon^3 d} . G_0 w_0 . \frac{T}{T_0} . \frac{P_0}{P} \tag{11.1}$$

Where, H is the height of the blast furnace, ψ is the friction factor, ε is the gas voidage (fractional volume fraction of gas in the solid bed), d is the diameter of the particle, G_0 is the mass flux ($=\rho_0 w_0$), ρ_0 is the density at NTP and w_0 is the superficial gas velocity (Nm^3/m^2-sec; it is measured by dividing the gas flow rate by nominal cross sectional area), T, P are the temperature and pressure inside the furnace and T_0, P_0 are the normal temperature and pressure. The temperature and pressure correction of gas volume has been calculated using the gas law.

The genesis of Ergun equation is that the pressure drop across the packed bed is directly proportional to the mass flow rate and the linear velocity. And, the proportionality constant is called the friction factor. For flow through a pipe, you have some friction factor; for flow through a packed bed you have different friction factor. In case of the flow through a packed bed unlike pipe flow, gas passes through number of small tortuous channels and therefore the wetted surface area markedly differ from that of pipe flow, which depends on gas voidage and particle diameter. Basically, if you correlate your actual velocity through packed bed to the superficial gas velocity (defined as the ratio of volumetric flow rate to nominal cross sectional area of the cylindrical packed bed), voidage, particle diameter, you get the Ergun equation. The friction factor finally is calculated from empirical correlation, established through experimental data by Ergun. It is a universal correlation, defined by equation (11.2), and modified Reynolds number by equation (11.3).

$$\psi = 1.75 + \frac{150}{\mathrm{Re}_m}$$

(11.2)

$$\mathrm{Re}_m = \frac{G_0 d}{\mu(1-\varepsilon)}$$

(11.3)

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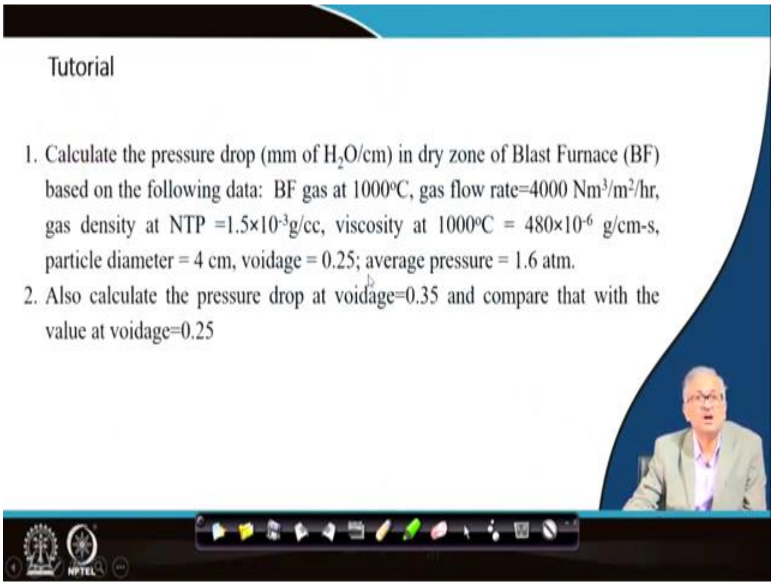

Tutorial

1. Calculate the pressure drop (mm of H_2O/cm) in dry zone of Blast Furnace (BF) based on the following data: BF gas at 1000°C, gas flow rate=4000 $Nm^3/m^2/hr$, gas density at NTP =1.5×10^{-3}g/cc, viscosity at 1000°C = 480×10^{-6} g/cm-s, particle diameter = 4 cm, voidage = 0.25; average pressure = 1.6 atm.
2. Also calculate the pressure drop at voidage=0.35 and compare that with the value at voidage=0.25

So, here is one example to show the calculation of the average pressure drop in a blast furnace. Blast furnace gas temperature, gas flow rate, gas density, viscosity at 1000 degree centigrade, particle diameter, voidage, average pressure are given.

And, you have to calculate the pressure drop at two voidage levels; one at 0.35 and the other at 0.25; let us see the calculation procedure.

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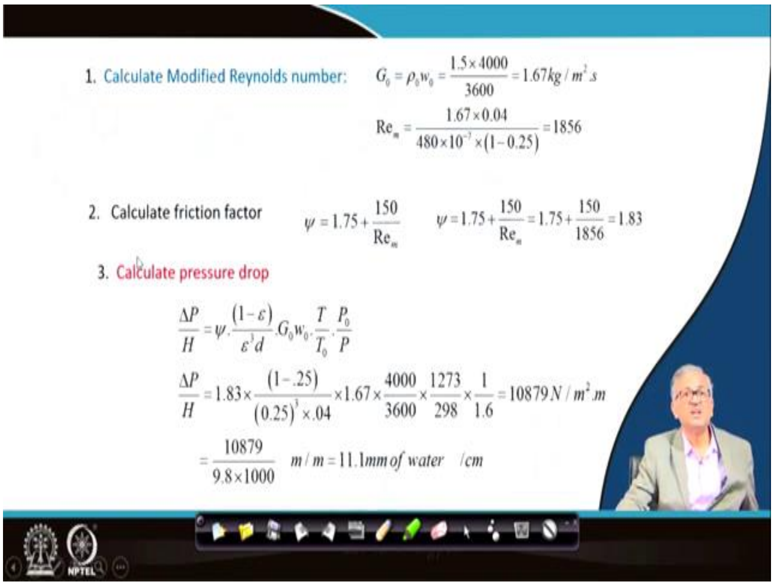

1. Calculate Modified Reynolds number: $G_0 = \rho_0 w_0 = \frac{1.5 \times 4000}{3600} = 1.67 kg/m^2.s$

$$Re_m = \frac{1.67 \times 0.04}{480 \times 10^{-7} \times (1-0.25)} = 1856$$

2. Calculate friction factor $\psi = 1.75 + \frac{150}{Re_m}$ $\psi = 1.75 + \frac{150}{Re_m} = 1.75 + \frac{150}{1856} = 1.83$

3. Calculate pressure drop

$$\frac{\Delta P}{H} = \psi . \frac{(1-\varepsilon)}{\varepsilon^3 d} . G_0 w_0 . \frac{T}{T_0} . \frac{P_0}{P}$$

$$\frac{\Delta P}{H} = 1.83 \times \frac{(1-.25)}{(0.25)^3 \times .04} \times 1.67 \times \frac{4000}{3600} \times \frac{1273}{298} \times \frac{1}{1.6} = 10879 N/m^2.m$$

$$= \frac{10879}{9.8 \times 1000} \quad m/m = 11.1 mm\ of\ water\ /cm$$

First you calculate the modified Reynolds number. Mass flow rate (G_0) does not depend on pressure and temperature and conveniently can be represented by mass flow rate at NTP, $G_0 = \rho_0 \times w_0$, where w_0, ρ_0 are the superficial velocity and density at NTP And, all units have been considered in SI units. So, G_0 is coming around to 1.67 kg per meter square second and then you can calculate the Reynolds number, as 1856. Then calculate the friction factor, which is coming around 1.83. Subsequently, you can calculate the pressure drop per unit length. Just put all the values and then you can find this value in Newton per meter square per meter of the bed height, which after conversion to water head, is calculated as 11.1 millimetre of water per centimetre of the bed. So, in a typical blast furnace the pressure drop is of the order of 10 millimetre of water per centimetre of bed, when the voidage in the bed is 0.25.

Here I have taken the voidage just 0.25 and I will not say it a very open bed and it is accompanied by a considerably higher pressure drop around 10 millimetre of water per centimetre of the bed.

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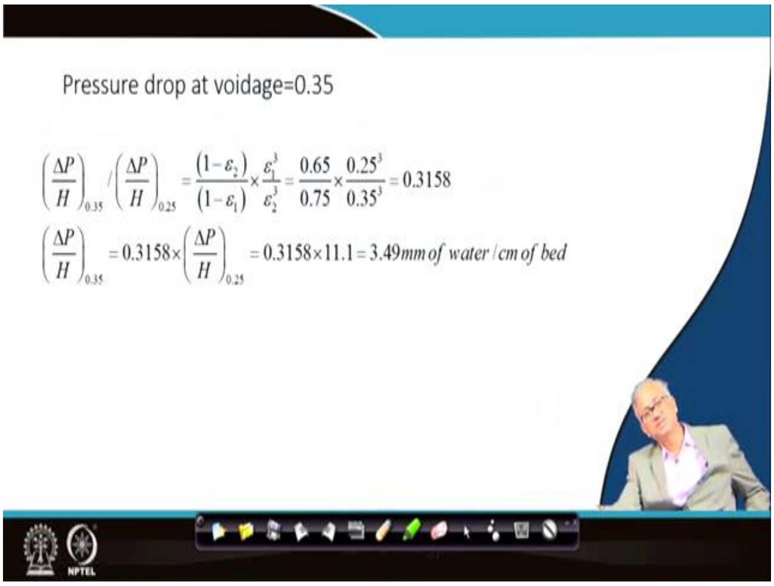

Pressure drop at voidage=0.35

$$\left(\frac{\Delta P}{H}\right)_{0.35} / \left(\frac{\Delta P}{H}\right)_{0.25} = \frac{(1-\varepsilon_2)}{(1-\varepsilon_1)}\times\frac{\varepsilon_1^3}{\varepsilon_2^3} = \frac{0.65}{0.75}\times\frac{0.25^3}{0.35^3} = 0.3158$$

$$\left(\frac{\Delta P}{H}\right)_{0.35} = 0.3158\times\left(\frac{\Delta P}{H}\right)_{0.25} = 0.3158\times 11.1 = 3.49\,mm\ of\ water\,/\,cm\ of\ bed$$

Now, if I want to calculate the pressure drop at voidage of 0.35 then you can simply do that using equation (11.4).

$$\left(\frac{\Delta P}{H}\right)_{0.35} / \left(\frac{\Delta P}{H}\right)_{0.25} = \frac{(1-\varepsilon_2)}{(1-\varepsilon_1)}\times\frac{\varepsilon_1^3}{\varepsilon_2^3} \tag{11.4}$$

Here basically I am ignoring the effect of voidage in calculation of the Reynolds number, which is also not very significant. Otherwise voidage and pressure drop is related by this and you can find that pressure drop at 0.35, as 0.32 times to that with bed voidage at 0.25.

So, pressure drop per unit length is very sensitive to the voidage.

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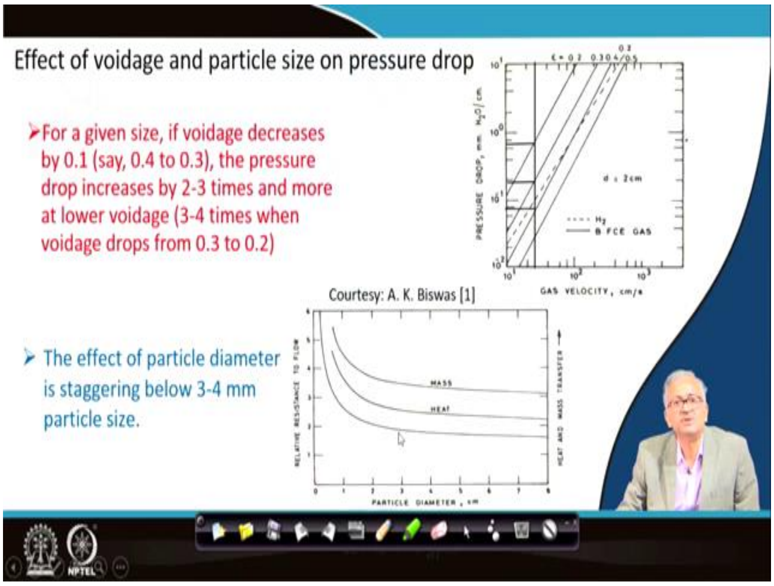

Effect of voidage and particle size on pressure drop

- For a given size, if voidage decreases by 0.1 (say, 0.4 to 0.3), the pressure drop increases by 2-3 times and more at lower voidage (3-4 times when voidage drops from 0.3 to 0.2)

Courtesy: A. K. Biswas [1]

- The effect of particle diameter is staggering below 3-4 mm particle size.

From the Figure (11.1), you can see some idea about the effect of voidage and particle size on the pressure drop.

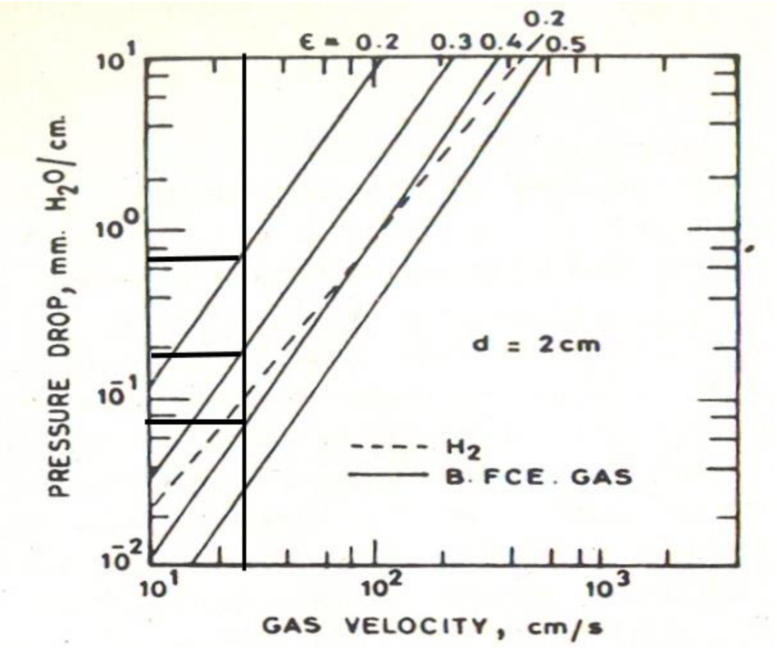

Figure 11.1 Effect of gas voidage on pressure drop (Courtesy: A. K. Biswas [1])

The constant gas velocity line (shown by solid vertical line) intercept the pressure drop lines at various voidage like 0.2, 0.3 and 0.4.   And, if you compare the pressure drop; say when the voidage is 0.4, pressure drop is 0.08 millimetre of water per centimetre of the bed. Now, when it is 30 percent voidage then the pressure drop become approximately 0.2

millimetre of water per centimetre of bed. So, you can find for a given gas velocity if the voidage decreases by 0.1 say 0.4 to 0.3, the pressure drop increases by 2.5 times. And the change becomes more staggering when the voidage is further low, that is if I want to go from 0.3 to 0.2 voidage, then this is around 3.5 times (0.2 to 0.7) . So, you can see there is a very significant effect of voidage on the pressure drop, especially at lower voidage.

And, for the effect of particle diameter, you can see particle diameter also has significant effect on the gas distribution. You can see relative resistance to the flow as a function of particle diameter in Figure 11.2.

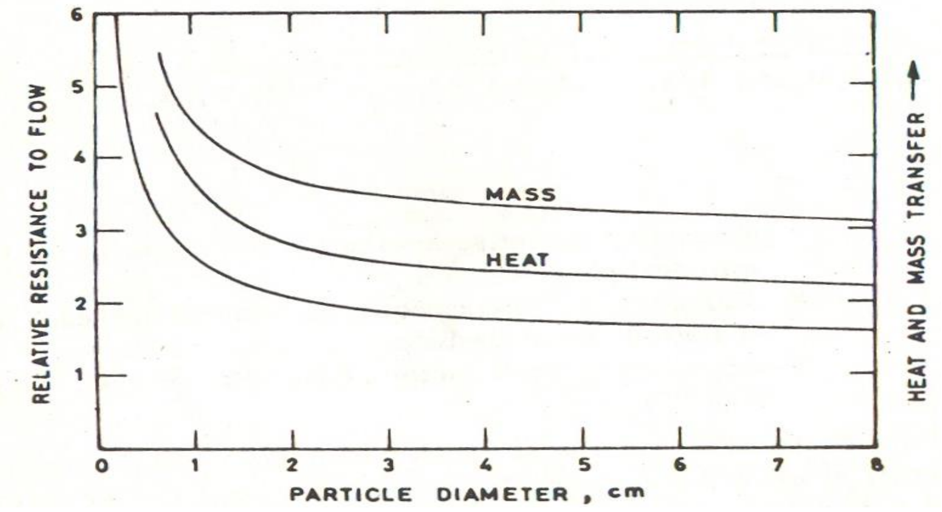

Figure 11.2 Effect of particle size on relative resistance to flow and heat & mass transfer (Courtesy: A. K. Biawas[1])

When the particle size is less than 3 millimetres, then you can see relative resistance to flow exponentially increases. Heat transfer, mass transfer resistances also increases exponentially. So, when the particle size below 3 to 4 millimetre, then the resistance become very high.

But, when the particle size is greater than 4mm, then particle size do not have much effect on the pressure drop. In the blast furnace we use particle size of the order of 20 millimetre to 40 millimetre size. So, that does not influence the heat and mass transfer; at least the particle diameter does not have much effect on the heat and mass transfer as well as on the relative resistance to flow. But of course, if the burden are not of higher strength and produces fines during descend, we should be cautious.

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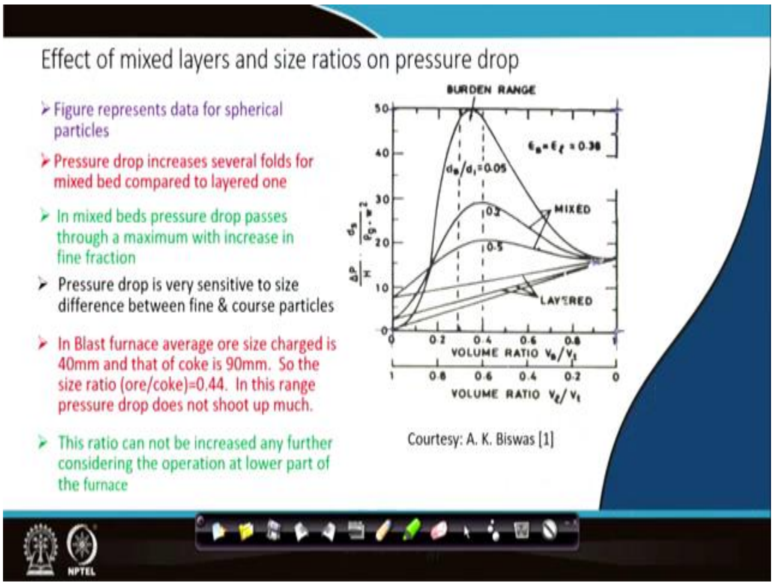

Effect of mixed layers and size ratios on pressure drop

- Figure represents data for spherical particles
- Pressure drop increases several folds for mixed bed compared to layered one
- In mixed beds pressure drop passes through a maximum with increase in fine fraction
- Pressure drop is very sensitive to size difference between fine & course particles
- In Blast furnace average ore size charged is 40mm and that of coke is 90mm. So the size ratio (ore/coke)=0.44. In this range pressure drop does not shoot up much.
- This ratio can not be increased any further considering the operation at lower part of the furnace

Courtesy: A. K. Biswas [1]

Now, we see the effect of mixed bed. It is very important because in the blast furnace we charge alternate skips of coke, ore and limestone. But, eventually you can find that the near the coke and ore interface there is a mixed layer formation. Figure (11.3) depicts the data are from a laboratory scale mixed bed and the layered bed experiments.

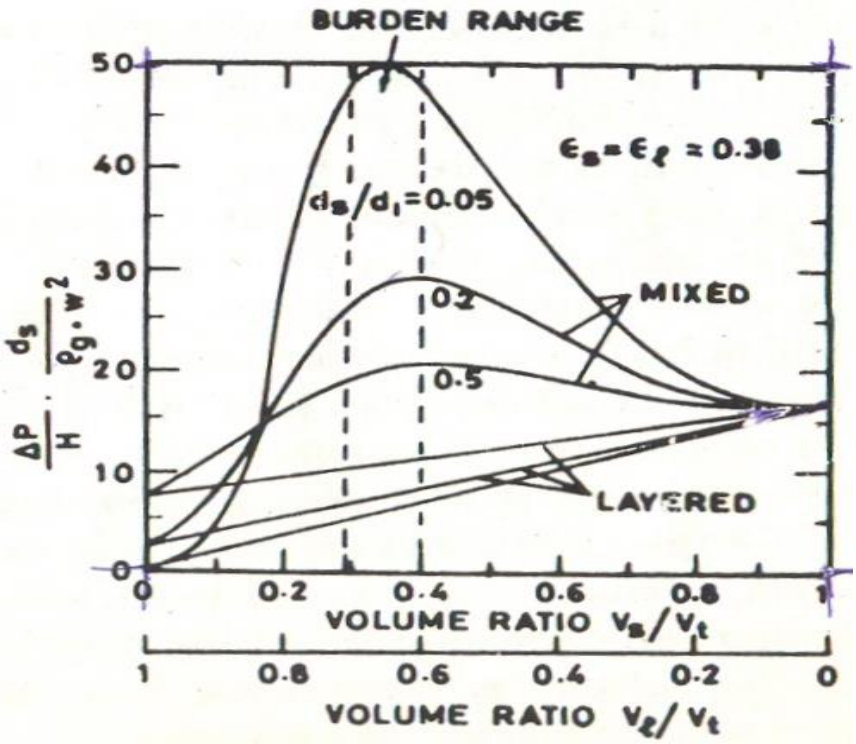

Figure 11.3 Effect of mixed bed on pressure drop (Courtesy: A. K. Biswas[1])

In the figure above, the dimensionless pressure drop in a fixed bed has been plotted against the fine fraction. It shows that if you increase the fraction of the fines how the dimensionless pressure drop changes in a packed bed reactor. So, what you can find? When it is a layered bed; meaning you have one layer of fine and then one layer of coarse, then one layer of fine, then one layer of coarse with a very sharp interface. In a fixed laboratory scale bed you can maintain it because the particles are not moving down. When the particles are moving then they mix up; but otherwise in laboratory fixed bed formation of layered structure is possible. It is seen if you have a layered structure then if you increase the volume fraction of the fines, pressure drop increases as you increase the fines; but it linearly increases. However, when the fine and the coarse are mixed up then you can find there is a shooting of pressure drop at certain volume fraction of the fines. It is found that in a mixed bed the pressure drop suddenly shoots up when the fine fraction is 30 to 40 percent. So, this is a very important observation from here.

The pressure drop increased by several folds for mixed bed compared to layered one. In mixed bed the pressure drop passes through a maximum with increase in the fine fraction. And, the maximum attains at around 30 to 40 percent of the fine fraction. And, pressure drop is also very sensitive to the size difference between the fine and the coarse particle; you can follow the different ratio of small to big particle ratio (ds/dl) in the diagram above. So, when there is a huge difference between the fine and the coarse particle size (say 0.05 in the diagram), then you can see staggering increase in the pressure drop. And, when the diameter ratio is 0.2 then there is an increase, but not staggering. And, when it is 0.5 then the effect is further lower. In blast furnace average ore size is around 40 millimetre and average coke size is 90 millimetre and in that case your ore to coke size ratio is around 0.44, which is not likely to increase the pressure drop even in mixed bed. But during burden descent if the burden are not strong enough they may generate fines and might create such adverse situation; therefore attention should be given of the quality of the burden.

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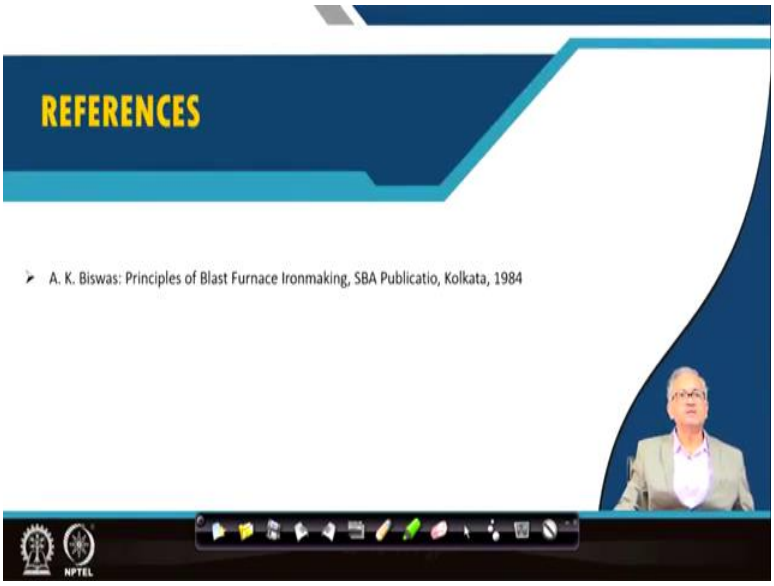

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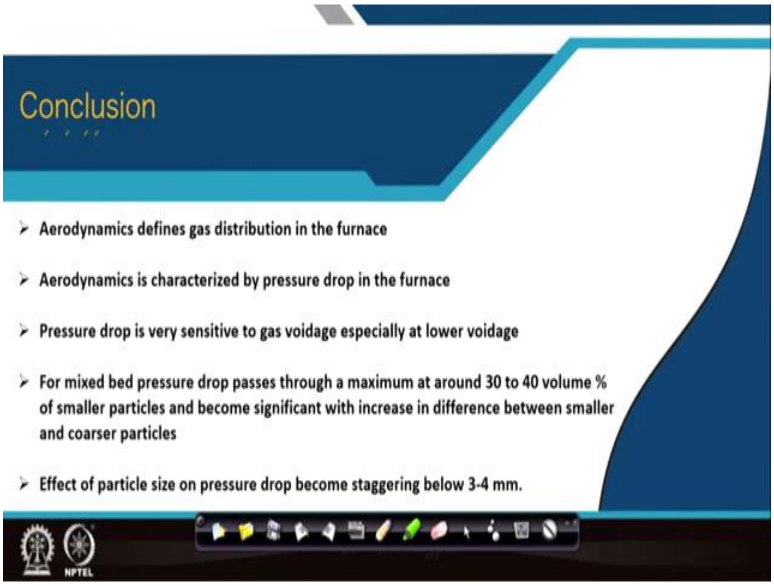

Conclusion

- Aerodynamics defines gas distribution in the furnace
- Aerodynamics is characterized by pressure drop in the furnace
- Pressure drop is very sensitive to gas voidage especially at lower voidage
- For mixed bed pressure drop passes through a maximum at around 30 to 40 volume % of smaller particles and become significant with increase in difference between smaller and coarser particles
- Effect of particle size on pressure drop become staggering below 3-4 mm.

I have referred only one reference and that is of A. K. Biswas.

What are the conclusion? Aerodynamics is characterized by the pressure drop in the furnace and pressure drop is very sensitive to the gas voidage, specially at lower voidage. And, for mixed bed the pressure drop passes through a maximum at around 30 to 40 volume percent of smaller particle and become significant with increase in size difference between the small and the coarse particle. But, fortunately in the blast furnace the size difference between ore and coke is not very high, where the pressure drop can be alarming.

But poorer quality burden can produce significant fine during descend through blast furnace and might cause such difficult situation.

Effect of particle size on the pressure drop becomes staggering below the 3 to 4 millimetre. This also put on restriction on the quality of burden in blast furnace.

In the next lecture we will consider about the channeling and flooding; two major irregularities in the blast furnace that take place.

Thank you very much.