Iron Making

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Lecture – 19
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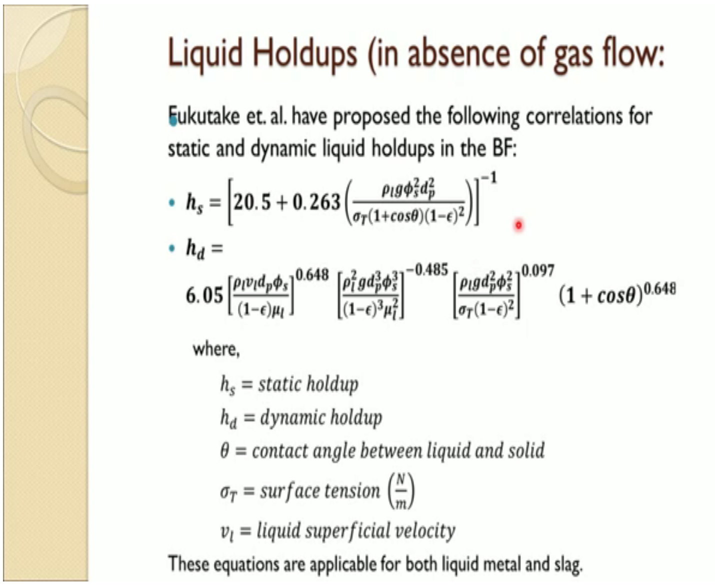

So it is quite difficult to quantify this liquid holdup especially at this high temperature. So, people have done the experiment again in the cold condition the way that now we saw in; this previous video. In the same way people have done the; experiment to quantify liquid holdup, static and dynamic using the room temperature experiment.

So, one of the researcher known as Fukutake and his team they did extensive experiments to find out the liquid holdup in various conditions and some of them resembling to the blast furnace. So, many types of liquid of different properties and packing they had used. And finally, they come up with these two correlation. So, hs is the static holdup of the liquid is equal to this. So, remember this liquid holdup, which we are discussing in absence of gas flow. As I mentioned previously, when gas flow is not there is still there is a liquid sitting in between the particle.

So, this is in absence of gas flow the a static holdup is represented by this correlation, where rho l is the liquid density, g is your acceleration due to gravity, phi s the shape factor, dp is the particle size, sigma T is the surface tension and theta is the contact angle between liquid and solid and epsilon is the void fraction in the packing. And similarly the dynamic holdup given why them is represented by this equation, again the same symbols are used, here vl is the liquid velocity, mu l is the liquid viscosity and all other terms we have already defined ever.

So, using this correlation one can get some idea about the liquid total liquid holdup once you add these two static and dynamic. So, you can know the total liquid holdup and you can modify your void fraction of the packed bed, and then you can calculate the gas velocity and liquid velocity, because that is the one which is important in calculation of heat and mass transfer and they those are the one which are going to get affected by these two parameter, and that is why they are very important.

So, these equation as such as I said why develop under cold condition, but they can be used for liquid metal and slag. Now, this is in absence of gas flow, but once we starts the gas situation changes as you have seen in the previous video, when the gas flow starts; how the liquid get displayed and not only get displaced, even the more static holdup it is sitting just in between the void, but the way Fukutake et al. have developed this correlation they do not have the side injection, they had the bottom injection.

So, where you do not see that sort of phenomena, still in absence of any other acceptable correlation; one can use this correlation for blast furnace till the further development takes place in this direction.

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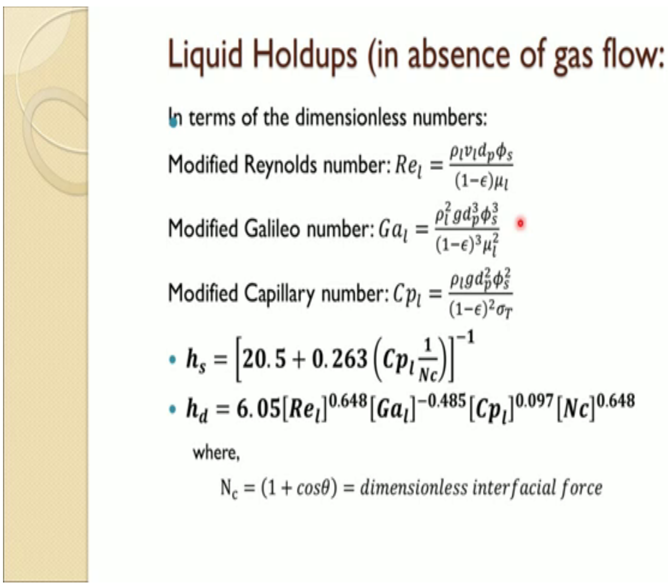

So, the liquid holdup in absence of, so in absence of gas flow still not in the meter, which you are observing in dynamic holdup these four actually they are nothing with like a Reynolds number, Galileo number; so one is a first one is a Reynolds number, second one is Galileo number, third one is Capillary number and the fourth one actually we call dimensionless interfacial force. So, this is your this one.

So, Reynolds number, Galileo number, capillary number and the dimensionless interfacial force number. So, if you represent in the non dimensional number, which are quite well known, then the equation you can write in those terms a static holdup is a function of Capillary and interfacial force; inverse of that and the dynamic holdup is a function of Reynolds number, capillary number interfacial force and inversely Galileo number. The and once you know this you can calculate the total holdup.

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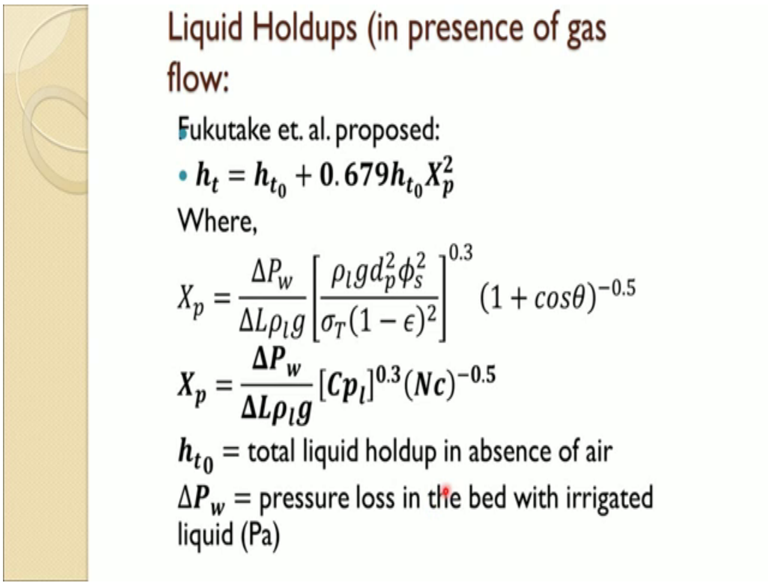

And in presence of gas flow they proposed this correlation, where h t is the total liquid holdup; which is nothing a combination of static and dynamic holdup, but in presence of gas flow, ht naught is again the total holdup, but in absence of gas flow. So, this is a total a holdup in absence of gas flow this is a total holdup in presence of gas flow.

So, in presence of gas flow total holdup is; in absence of gas flow total holdup plus this quantity, where Xp is nothing again a pressure drop, which is in the irrigated condition of waiting conditions, when the liquid flow is there the pressure drop under those condition and with this number which are nothing like capillary number and the interfacial force.

So, in terms of capillary number and interfacial force number this Xp is represent it in this form; ht naught is a total liquid holdup in absence of air and delta Pw is the pressure loss in the bed irrigated while liquid or in the waiting content liquid flow is there.

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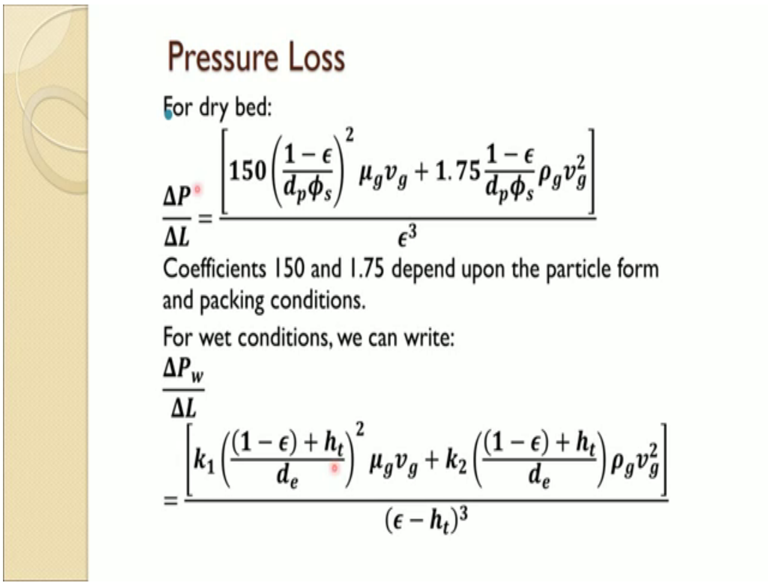

So, naturally one has to know then this; and for dry bed you already know about it, using the argon equation we have used this one many of the application previously, so for dry bed you can calculate the pressure drop per unit length using this argon equation, where coefficient are used 150 and this and this coefficient it is a depends on particle form and the packing condition.

However, in terms of the liquid flow condition the pressure drop is again given by the same equation, but in little modified way. When we say little modified way, because the in the dry condition the void fraction is the same everywhere, but when the liquid is flowing void fraction is reduced, because the liquid is occupying some of the a space in the packing. So, that has to be taken into care.

So, essentially what you are doing? You are adding that part of the liquid as a total holdup, wherever the void fraction term is coming. Otherwise there is no other difference and that takes care of the pressure drop, when the liquid is flowing in that and the d is defined as using this equivalent formula according to them.

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Where, d_e is defined as:

$$\frac{1-\epsilon+h_t}{d_e}=\frac{1-\epsilon}{d_p\phi_s}+\frac{h_t}{d_l}$$

d_l is the virtual diameter of a liquid drop given by:

$$d_l\sqrt{\frac{\rho_l g}{\sigma_T}}=6.828\left(\sqrt{X_p}-0.891\right)^2+0.695$$

k_1 and k_2 are estimated 140 and 1.7 respectively.

For two liquid phases, h_t is replaced by $(h_{ts}+h_{tm})$ and d_e is defined as:

$$\frac{1-\epsilon+h_{ts}+h_{tm}}{d_e}=\frac{1-\epsilon}{d_p\phi_s}+\frac{h_{ts}}{d_{ls}}+\frac{h_{tm}}{d_{lm}}$$

So, these define this way and, where dl actually is the virtual diameter of a liquid drop given by this formula. So, you can easily once you know that these properties are known to you can calculate it.

So, k 1 and k 2 in the waiting condition liquid flow condition this k 1 and k 2 while dry condition it is there and in this one; they are where estimated at 140 and 1.7 respectively. And this is if you are having a single liquid flow, but as you know in the blast furnace, you have two types of liquid: one the liquid iron and another is the liquid slag.

So, if you have a two liquid phases, then ht is replaced by the h ts. So, total holdup of slag total holdup of metal and d define in terms of same way as we did ever, but we include the another liquid here, and then dl also in the same way then one can calculate a pressure drop.

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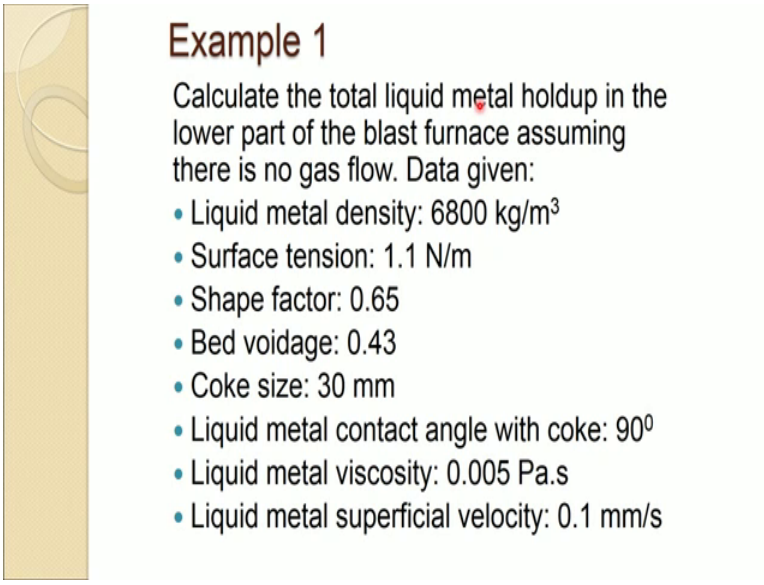

So, now I think after going through this probably it is the time we should concentrate on some application part or some example. So, you can get an idea how to calculate and what is the importance of this liquid holdups. So, here is one example calculate the total liquid metal holdup in the lower part of the blast furnace assuming, there is no gas flow.

So, that is we are remember we are doing in absence of gas flow. Data given liquid metal density 6800 kg per meter cube surface tension 1.1 Newton per meter shape factor 0.65 bed voidage 0.43; they are all usually the actual conditions of the blast furnace coke size and in the dropping zone it is above 30 millimeter, liquid metal contact angle with coke about 90 degree.

So, that is sort of we are at boundary of non waiting thing condition liquid metal viscosity is 5 into 10 to the power minus 3 Pascal second and liquid metal superficial velocity is a superficial velocity is point 1 millimeter per second.

So, you have to calculate that total liquid metal holdup. So, when we say total liquid metal holdup, so you have to calculate the a static liquid holdup and the dynamic liquid holdup in this condition. And in absence of gas flow, as we know the formula for that are these with the a static holdup and dynamic holdup in absence of gas flow; we can use these and most of the quantities are known, so let us do that.

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Solution:

Using the holdup correlations given by Fukutake et. al.:

- $h_s = \left[20.5 + 0.263\left(Cp_l \frac{1}{Nc}\right)\right]^{-1}$
- $h_d = 6.05[Re_l]^{0.648}[Ga_l]^{-0.485}[Cp_l]^{0.097}[Nc]^{0.648}$

Reynolds number of the liquid flow:

$$Re_l = \frac{\rho_l v_l d_p \phi_s}{(1-\epsilon)\mu_l}$$

$$= \frac{6800 * 0.1 * 10^{-3} * 30 * 10^{-3} * 0.65}{(1-0.43) * 0.005}$$

$$\therefore \boldsymbol{Re_l = 4.65}$$

So, using that holdup correlation, so what we have to do; we have to calculate Reynolds number, Galileo number, Capillary number, interfacial force. So, Reynolds number and packed way is given by this shape factor. So, density is given superficial velocity is given 0.1, particle size is given 30.

So, and the shape factor is also given 0.65, void fraction 0.43 and this is 5 into 10 to the power minus 3. So, the your Reynolds number of the liquid of the order of 4.65, which is quite low.

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Galileo number:

$$Ga_l = \frac{\rho_l^2 g d_p^3 \phi_s^3}{(1-\epsilon)^3 \mu_l^2}$$

$$= \frac{(6800^2 * 9.81 * (30 * 10^{-3})^3 * 0.65^3)}{(1-0.43)^3 * 0.005^2}$$

$$\therefore \boldsymbol{Ga_l = 726484062.4 = 726.5 * 10^6}$$

Capillary number:

$$Cp_l = \frac{\rho_l g d_p^2 \phi_s^2}{(1-\epsilon)^2 \sigma_T}$$

$$= \frac{6800 * 9.81 * (30 * 10^{-3})^2 * 0.65^2}{(1-0.43)^2 * 1.1}$$

$$\therefore \boldsymbol{Cp_l = 70.98}$$

$$\boldsymbol{Nc = (1 + cos\theta) = (1 + cos90) = 1}$$

And, so another sort of a laminar regime seems. And Galileo number again rho l gravity; suppose 9.81 particle diameter shape factor, void fraction and viscosity, that keeps you the Galileo number of 7.2 into 10 to the power 8. And capillary number similarly you get was by substituting all these quantity, which are already given, you get 70.98, and interfacial force is about 1.

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Now, static holdup is given by:

$$h_s = \left[20.5 + 0.263(Cp_l)\frac{1}{Nc}\right]^{-1}$$

$$h_s = [20.5 + 0.263(70.98)]^{-1} = 0.0255$$

And dynamic holdup by:

$$h_d = 6.05[Re_l]^{0.648}[Ga_l]^{-0.485}[Cp_l]^{0.097}[Nc]^{0.648}$$

$$h_d = 6.05(4.65)^{0.648}(726.5 * 10^6)^{-0.485}(70.98)^{0.097}(1)^{0.648} = 1.2477 * 10^{-3}$$

Therefore, total holdup would be:

$$h_{t_0} = h_s + h_d = 0.0255 + 1.2477 * 10^{-3} = 0.0267$$

So, once you now all these non dimensional quantity, now you can substitute them into the correlation static holdup you put that, so you get about 0.0255 meter cube per meter cube. Remember this unit with respect to the packing volume and dynamic holdup you get 1.2 into 10 to the power of minus 3. So, if you look at this, you can see the dynamic holdup once is usually in these conditions in the blast furnace; they are one order magnitude lower than you are a static holdup of the liquid.

So, static holdup of the liquid; that is the liquid which is in between the particle and by capillary forces in this; it is quite a lot then you are the dynamic holdup, which is flowing through the void spaces. So, therefore, the total holdup would be a reason of a static holdup, which is 0.0255 and the dynamic holdup 0.00124 that gives you 0.0267 meter cube per meter cube.

So, this is that your total holdup of liquid in the blast furnace and this would be constituting almost 5 percent void fraction it would be occupying this space. And even a 5 percent a space, when it is reduced it is going to change your case velocity and other parameter substantially and; that is why these importance of this liquid holdup. Now, this is actually remember in absence of gas flow.

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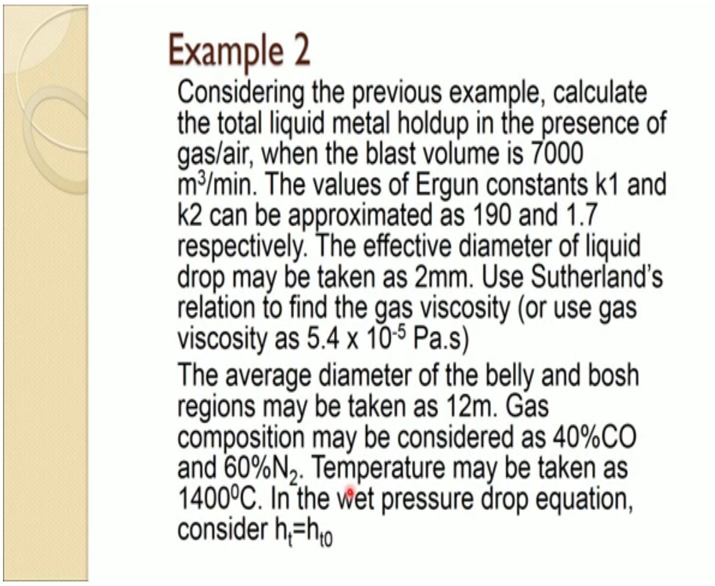

Now, let us do the same example, in presence of gas flow; what happens; so this is the second example, which is more talking about liquid flow, in presence of gas flow. So, considering the previous example, calculate the total liquid holdup in the presence of gas air, when the blast volume is 7000 meter cube per minute. The value of Ergun constant k 1 and k 2 can be approximated as 190 and 1.7 respectively. The effective diameter of liquid drop may be taken as 2 millimeter.

So, already the t l is given here. So, use Sutherland's relation to find the gas viscosity. It is an important, if you have read in your undergraduate heat or momentum transfers; you would be quite familiar with this Sutherland relation by which you can calculate the gas viscosity, who do not know that they may use the gas viscosity as 5.4 into 10 to the power minus 5 Pascal second.

The average diameter of the belly and bosh regions may be taken as 12 meter. Gas composition may be considered as 40 percent CO and 60 percent nitrogen, which is a typical sort of composition in the drop in zone. Temperature may be taken as 1400 degree Celsius. In the wet pressure drop equation, consider ht equal to ht naught.

So, this is a simplification to simplify this equation and you will observe here this ht term is coming in the pressure drop term. And if you look at your total holdup equation, it is this pressure drop term constitute the part of Xp which is coming here.

So, the total holdup term is coming both the side, which creates the problem means the equation has to resolve numerically with trial and or trial and error to find out the total holdup and due to that region especially for this example for the dry wet for the wet, where for this pressure drop, this ht which is appearing here it is saying it can be taken as the total holdup of liquid in absence of air and then you can easily solve the total holdup.

So, let us see how do we go with it. Now, you need also the gas velocity which is not given, but the volume is given. So, you can probably with this volume and with this time it as you may be able to calculate the superficial gas velocity.

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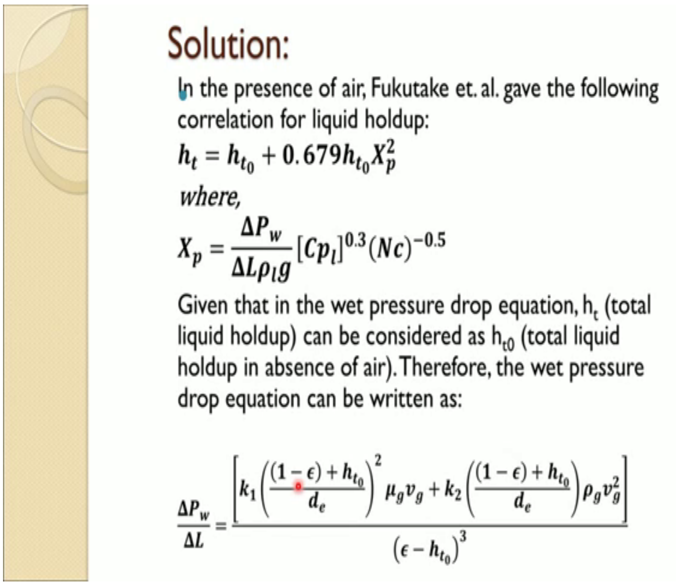

So, let us see, so here in presence of air, this is the correlation and where, Xp in terms of non dimensional number is given this. And as you can see given that in the; liquid condition pressure drop equation, ht total liquid holdup can be considered as ht naught total liquid holdup in absence of air.

Therefore, the wet pressure drop equation can be written in this form, where we have substituted total holdup in presence of gas by total holdup in absence of gas.

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We need gas viscosity, μ_g and gas superficial velocity, v_g, to calculate the wet pressure drop.

To find the density and viscosity of the gas:

Composition: $\mathbf{40\%CO\ and\ 60\%N_2}$

At 273K, 1mol of gas occupies 22.4dm^3

Therefore,

$$\rho_g = \frac{((0.4+0.6)*28)}{22.4*1000}\frac{273}{1673} = 2.04*10^{-4}\frac{\text{g}}{\text{cm}^3} = \mathbf{0.2\frac{kg}{m^3}}$$

Gas viscosity is calculated using Sutherland's formula:

$$\mu = \mu_0 * \left(\frac{a}{b}\right) * \left(\frac{T}{T_0}\right)^{\frac{3}{2}}$$

Where,

$a = 0.555T_0 + C$

$b = 0.555T + C$

$\mu = viscosity\ at\ temperature\ T\ (^0R), cp$

$\mu_0 = viscosity\ at\ reference\ temperature\ T_0\ (^0R), cp$

$C = Sutherand's\ constant$

So, when we make this simplification which of course, is given in the example in the; we can our task become much more easy. So, we need now the gas viscosity. So, gas viscosity is coming into picture here, ht naught we have already calculated in the previous examples, so we do not have to in absence of air, but what we need? We need gas viscosity and the gas velocity superficial. So, these two things we will do it. So, means the case superficial gas viscosity and gas superficial velocity vg, to calculate the wet pressure drop.

So, to find the density and viscosity of the gas density is not given, so at that temperature we have to find the density of the gas and this we have done previously in many of the examples. So, there should not be a problem as you know one mol of gas occupies 22.4 decimeter cube. So, rho g is given with the fraction we know of this and both of them are having molecule of 8, 28 so and you know the 1400 degree, 1673 degree Kelvin, your density of the gas comes above 0.2 kg per meter cube at 1400 degree Celsius.

Then rho g is obtained; what we need the gas viscosity. Now Sutherland formula is actually this for the gases. So, using this formula a, b these are the constant and where C is the Sutherland constant and for these particular cases we can get these values from the books of those constant.

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For CO:

$C = 118, T_0 = 518.67^0 R, \mu_0 = 0.01720 cp$

For N_2:

$C = 111, T_0 = 540.99^0 R, \mu_0 = 0.01781 cp$

Calculating for given temperature and composition,

$$\mu_g = 0.4\left(0.0172 * \left(\frac{0.555 * 518.67 + 118}{0.555 * 3011.4 + 118}\right) * \left(\frac{3011.4}{518.67}\right)^{\frac{3}{2}}\right) + 0.6\left(0.01781 * \left(\frac{0.555 * 540.99 + 111}{0.555 * 3011.4 + 111}\right) * \left(\frac{3011.4}{540.99}\right)^{\frac{3}{2}}\right)$$

$$\therefore \mu_g = 0.4(0.055) + 0.6(0.054) = 0.0544 cp$$

$$\therefore \boldsymbol{\mu_g = 5.44 * 10^{-5}\ Pa.s}$$

And once we substitute into this equation so for CO: C equal to 118, T naught in (Refer Time: 24:44) similarly for nitrogen is 0.111 one what the (Refer Time: 24:49), then the mu naught viscosity at a temperature is given, so we then we can calculate for the given temperature, what would be the this viscosity.

So, 0.4 it is a CO, fraction 0.6 is the nitrogen fraction and based on these values, which are given above and putting into this formula and we are constant these are the temperature, if we do get viscosity of the gas is about 0.0544 centipoises.

And that is also given those who do not and know about the Sutherland formula, they can directly take this value 5.44 into 10 to the power minus 5 Pascal per second so, but this is quite easy is you are having a quite a lot variation and you do not know you can easily calculate the viscosity of the cases using this Sutherland formula, which is quite reliable I am getting the value is at higher temperature.

So, now you got the mu g, you got the rho g you still need a superficial gas velocity for that. So, for superficial gas velocity you already know the blast volume which is about 7000 meter cube per minute; so in meter cube per second it would be this.

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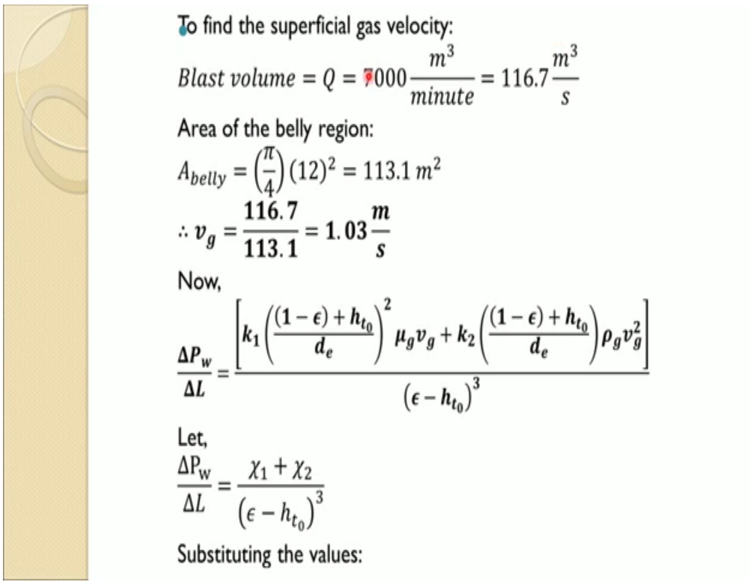

Now, the average diameter of the belly and blast region is given, which is about 12 meter. So, using that, we can get the area of the belly region. So, that comes around 113 meter a square.

So, if we divide this our blast volume with this blast area, we can get the superficial gas velocity, which comes around 1 meter per second. So now, we come back to the pressure drop equation in liquid flow condition k 1 is already given to us, k 2 is given to us, rho g we have calculated, mu g we have calculated, v g we have calculated, what we need now; we have to calculate all these all other things are given to us.

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Using $\frac{1-\epsilon+h_{t_0}}{d_e} = \frac{1-\epsilon}{d_p\phi_s} + \frac{h_{t_0}}{d_l}$

$$\chi_1 = 190\left(\frac{1-0.43}{0.03*0.65} + \frac{0.0267}{2*10^{-3}}\right)^2 (5.44*10^{-5})(1.03)$$

$$\therefore \chi_1 = 19.3$$

$$\chi_2 = 1.7\left(\frac{1-0.43}{0.03*0.65} + \frac{0.0267}{2*10^{-3}}\right)^2 (0.2)(1.03)^2$$

$$\therefore \chi_2 = 654$$

$$\therefore \frac{\Delta P_w}{\Delta L} = \frac{19.3+654}{(0.43-0.0267)^3} = 10264.17\frac{N}{m^3}$$

Now,

$$X_p = \frac{\Delta P_w}{\Delta L \rho_l g}[Cp_l]^{0.3}(Nc)^{-0.5}$$

$$X_p = \frac{10264.17}{6800*9.81}[70.98]^{0.3}(1)^{-0.5} = 0.552$$

So, taking this one as x 1 or kappa 1 and this quantity as kappa 2, we can calculate separately and of course, the de which is coming here, which actually we have defined before.

So, in de what we have done here; again we have assumed the total holdup which was there in the equation in a presence of case we have substituted that total holdup with in absence of gas. So, ht naught and this is given and quite reasonable that for pressure drop equation in liquid or metal flow we can use this for simplification. So, same thing we have done here, and which is nothing in this and once we use those and dl of course, actually is given.

So, we directly substitute as you know the dl is given here, yes; effective diameter of liquid drop may be taken as 2 millimeter. So, all the parameters are known here. now the x 1 is this; so 191 minus 0.43 plus ht naught is 0.0267 and de with that we put it, so it comes and do all other quantities or velocity and other thing viscosity kappa 1 is 19.3.

Similarly, kappa 2 is your this k 2 is 1.7, 0.43, 0.026 rho g, vg squares and d. So, this is all your rho g, vg is square tl, ht naught. So, this comes into that; so kappa 2 you get 654. So, once you know by putting this kappa 1, kappa 2, here and this quantity over here you get the pressure drop which is about this Newton per meter cube.

So, now once we got the pressure drop we can easily calculate our Xp. So, Xp is nothing delta P w pressure drop divided by rho L g and multiplied with a capillary function and interfacial force inverse of heat. So, we already we have calculated these values. So, we are just simply substituting those and that gives us X p 0.552.

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Now,

$$h_t = h_{t_0} + 0.679 h_{t_0} X_p^2$$

$$\therefore h_t = 0.0267 + 0.679(0.0267)(0.552)^2$$

$$\therefore \boldsymbol{h_t = 0.0322}$$

And now this Xp we can put in the total liquid holdup equation which is nothing as we have seen the total liquid holdup in presence of air is equal to total liquid holdup in absence of air plus this term. Now, Xp we have calculated total holdup in absence of gas, we already know from previous example. So, once we put these quantities all together we get the total holdup 0.0322.

So, you can see there is a substantial increment in the total holdup in presence of gas than in absence of gas, which means it will further reduce your point as permeability of the bed in the blast furnace and further it will affect the operation of the blast furnace.

And remember this just we have done based on the matter flow we have not taken into consider in the consideration the select flow. If we take consideration of the select flow which is more in volume this could be much higher and that certainly is going to affect voidage in the lower part of the blast furnace and that is going to affect finally, a big perform are the performance of the blast furnace and that is why; this liquid holdup are important to understand the correct aerodynamics of the blast furnace or the gas velocity.

So, we one can calculate in a proper way the heat and mass transfer, which are occurring in the blast furnace.