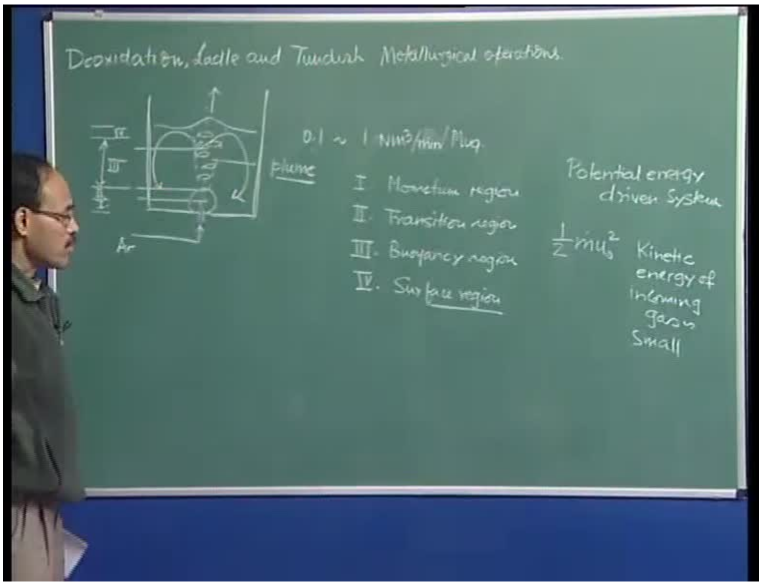
Steel Making
Prof. Deepak Mazumdar
Prof. S. C. Koria
Department of Materials Science and Engineering
Indian Institute of Technology, Kanpur

Module No.# 01
Lecture No. # 27
Deoxidation, Ladle and Tundish Metallurgy

(Refer Slide Time: 00:21)



Deoxidation, Ladle and Tundish Metallurgical operations.

0.1 ~ 1 Nm³/min/Mg.

I. Momentum region
II. Transition region
III. Buoyancy region
IV. Surface region

Potential energy driven System

$\frac{1}{2}\dot{m}u_0^2$ Kinetic energy of incoming gas is Small

Let me give you a picture of gas injection, a physical picture of gas injection through schematic of axis symmetric injection, so I have placed the nozzle at the central line, and this is the plume boundary, and this is the axis and this represents the wall of the ladle, the nozzle is placed at the central line along the access of symmetry, that is why it is an access symmetric gas injection. So, we have injecting organ through the nozzle.

Now, I have also mentioned to you that, the injected flow rate of organ through the central nozzle, where is over a wide range and it is substantially smaller than the flow rates of oxygen that we use for steel making or primary steel making processes, and I have given you value of about 0.1 to 1 normal meter cube per hour.

So, that is the kind of, this is normal meter cube per minute, but plug that is the range of fluorite which one uses, this is the list fluorite and this is the maximum fluorite. Now, under the ladle metallurgy gas injection operation, when we inject organ gas through a nozzle, for example typically a big gas envelope forms in the vicinity of the nozzle.

Now, this gas envelope it is typically hydro dynamically unstable, the fluid cannot really sustain, that big is a gas envelope. So, immediately above the gas injection nozzle, this big gas envelope typically devolves into its specter of spherical cam bubbles, and these bubbles are basically then rise due to their buoyancy, and then escapes to the surrounding.

So, the two phase mixture that we see at the center, so we have some liquid steel here, and disperse bubbles here and this is typically called as a plume. So, they injected gas given its buoyancy rises to the free surface, and as a result of which, it induces a turbulent circulatory motion of liquid steel in the system.

It is well known that this moving molten steel, it helps in homogenization of the bath, in terms of its chemical composition, in terms of its temperature, it raise in inclusion or glomeration, and also depending on in the position of the nozzle, whether it is too closely located to the wall or not, it can also create some preferential refractory, where particularly in the vicinity of the rising plume. In this case it is not significant, because it is going to be equidistance from both the walls.

Now, if you further look at the ladleand, the two phase region, it is basically divided into four different regions, and out of this four different regions; it is region one, typically is called the momentum region. So, here the momentum of the gas is substantially larger, and so it is this particular region, I am talking about the momentum region, immediately about this, this is a small little region and this is also known as the transition region, and the largest region, may be somewhere up to this or we can say that this is the region three and this region three is the buoyancy region, and finally we have region four, which is the surface of research region.

So, this is the way a typical gasteroid, in the plume developed in a gasteroid liquid system, gasteroid ladle is going to develop momentum region, transition region and surface region, all this three combines will barely take about 20 to 30 percent of the entire height of the reactor, on the other hand, this region the region three which is the buoyancy region, where we see nicely dispersed spherical cap bubbles, spherical cap because, the thermo physical properties of water provides us that kind of a region, where only spherical cap shaped bubbles are possible, tiny, very small spherical cap bubbles or ellipsoidal bubbles are not possible there, because we have the standard chart or nomograms available which gives us the shape of bubble, which are possible in various liquid system, in terms of e’twaun number reynolds number and so on.

So, this spherical cap bubbles which we see within the core of the liquid, and the equilibriums are their size are more or less governed by at the thermo physical properties, we have here a spectra of bubble, there is valences and descent equation of the bubble, and a dynamic size range develops within this system, and the mean size range here is governed basically by the thermo physical properties of the fluid gas liquid system, it is very little, that the nozzle or the orifice has very little role as far as the dynamics of this particular region is concerned.

That is why in ladle metallurgy steel making situation, we often say that at gas injection through or the nozzle dimensions, I would say that the nozzle dimensions are not critical to the characteristics of the plume, and the bulk recirculation which is produced.

So, therefore under ladle metallurgy gas injection operation we can say that, whether we inject gasses through a porous plug, whether we inject gas though a nozzle or a submerged wire, a porous recirculation produces are not going to be critical to the very nature of the gas injection devices.

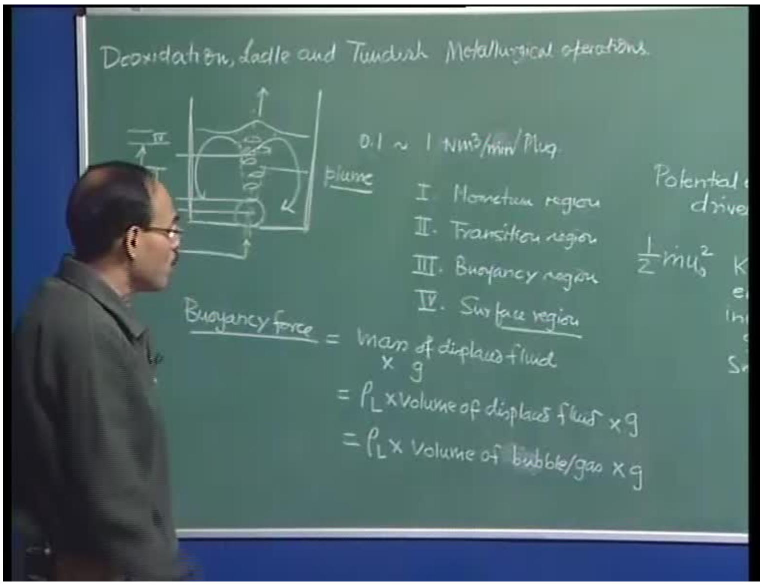
So, in this particular region 1 and 2, we will see some noticeable difference depending on the gas injection device, but boil in large, the plume region or the buoyancy region will be virtually in effected by the details of the gas injection nozzle and also the flow region.

Now, the system typically is driven by potential energy and not kinetic energy as we would normally anticipate, so it is a potential energy driven system, the kinetic energy of the injected gas and I would say that the kinetic energy of the injected gas, I can say half m dot u 0 square, in which m dot represents the mass flow rate, and u 0 represents the velocity or free stream velocity through the orifice itself, and this quantity which is the kinetic energy of the injected gas is extremely small.

How small in comparison to the potential energy, the kinetic energy is hardly 1 to 2 percentage, so that is why, we say that it is the buoyancydriven flow in gas stirred ladle system and not a kinetic energy.

For example an oxygen steelmaking converter, o b m where we have bottom blown oxygen steel making, where oxygen is going to be introduced through a bottom to air, that system is certainly not potential energy driven, they are the kinetic energy of the injected gas, there is a important role as per as the extent of flow recirculation is produced, because the gas injection rate at the flow rate is very large. Now, let me give you an expression of this potential energy, and then we will try to compare both values by putting some magnitude of free stream velocity, the mass flow rate etcetera.

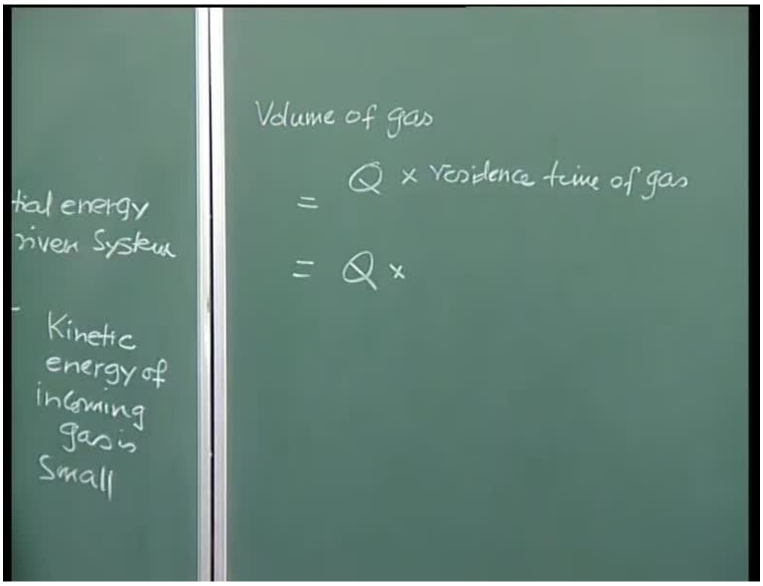
(Refer Slide Time: 08:43)



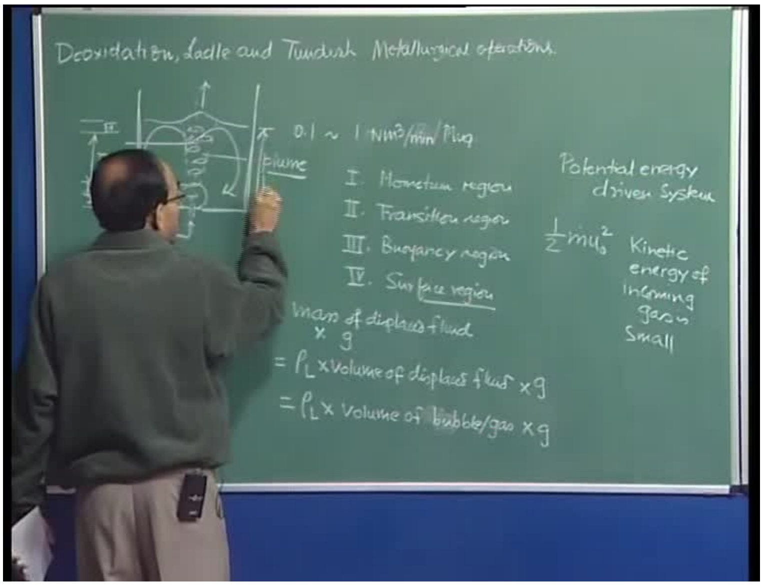
Now, we know that the buoyancy force by definition, the system is buoyancy driven and the buoyancy force, because of the presence of the gas bubble, by definition mass of displaced fluid, multiplied by the acceleration due to gravity, and this force is acting along the vertical direction. So, that is what is implied by this particular equation.

So, which I can say, is equal to rho liquid into volume of displaced fluid, what displaces the fluid, I have a bubble, so if in a small little volume element, if you imagine the presence of a bubble, so the bubble will displace some fluid and the buoyancy due to the presence of the bubble is equivalent to the mass of the displaced fluid multiplied by acceleration due to gravity, and I can now say by using continuity that this is equal to volume of displaced gas. So, whatever is the volume of the bubble or gas in that particular control volume. So, volume of displaced fluid is exactly equal to volume of bubble gas, this equality is termed as a principle of volume continuity.

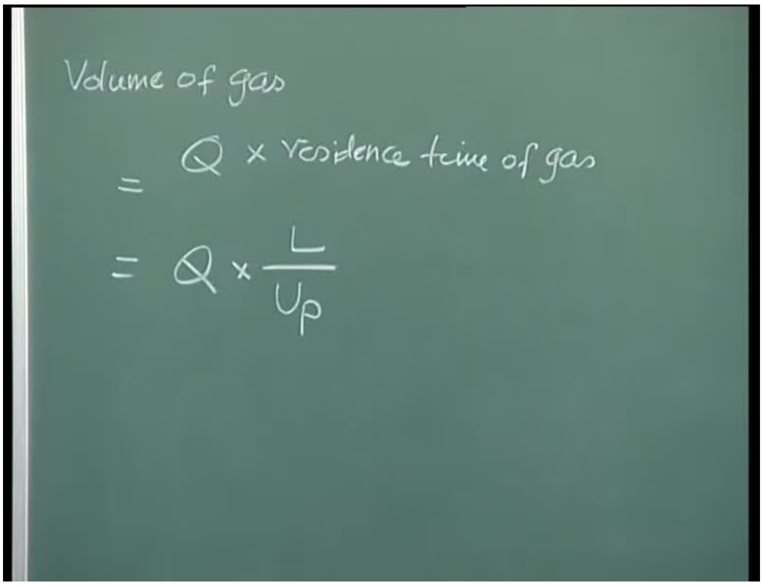
(Refer Slide Time: 10:23)



(Refer Slide Time: 10:47)



(Refer Slide Time: 10:54)



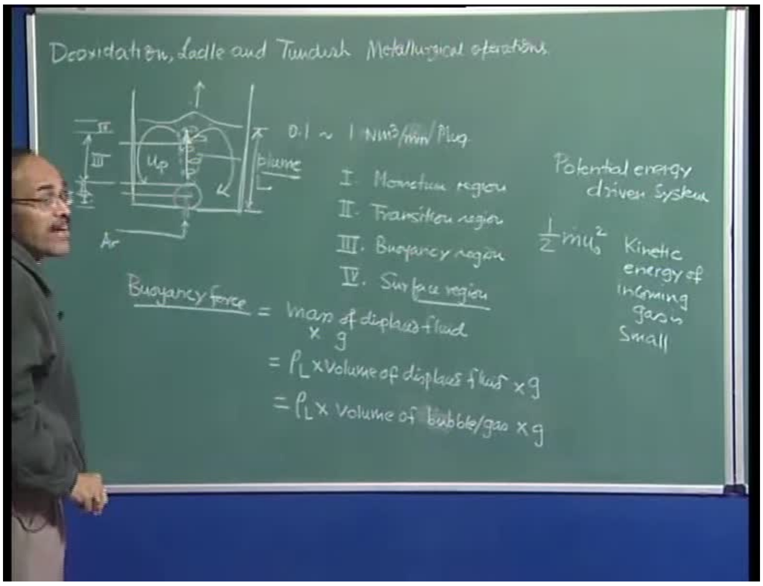
Volume of gas

$= Q \times$ residence time of gas

$= Q \times \frac{L}{U_p}$

So, now the volume of gas, how we can calculate, let see the volume of gas is equal to the volumetric flow rate of gas, multiplied by the residence time of gas, how long the gas spends within the plume, and if you do that and say that well, let this height be is equal to L, capital L which we call as a depth of liquid, in that case I would say this is equal to L divided by U sub p.

(Refer Slide Time: 10:58)



Deoxidation, Ladle and Tundish Metallurgical operations

0.1 ~ 1 Nm³/min/Plug

I. Momentum region

II. Transition region

III. Buoyancy region

IV. Surface region

Potential energy driven System

$\frac{1}{2}mu_0^2$ Kinetic energy of incoming gas is small

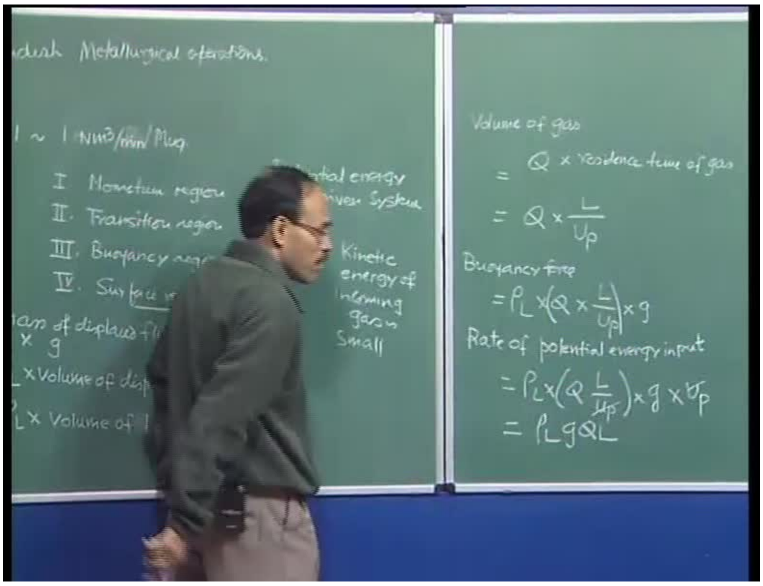
Buoyancy force = mass of displaced fluid × g

$= \rho_L \times$ Volume of displaced fluid $\times g$

$= \rho_L \times$ Volume of bubble/gas $\times g$

In which I can say that U sub p represents the rise velocity, I am going to talk about it in greater detail later on. So, U sub p essentially represents the rise velocity of the gas liquid plume or the gas liquid mixture.

(Refer Slide Time: 11:16)



So, L divided by U p represents the time, for which the bubbles spend within this system and multiplied by the volumetric flow rate gives us the volume of gas, this is meter cube per second, this is L divided by U p is equal to second, second seconds cancels outs. So, this quantity is equivalent to meter cube, and therefore this is equal to the volume of the gas.

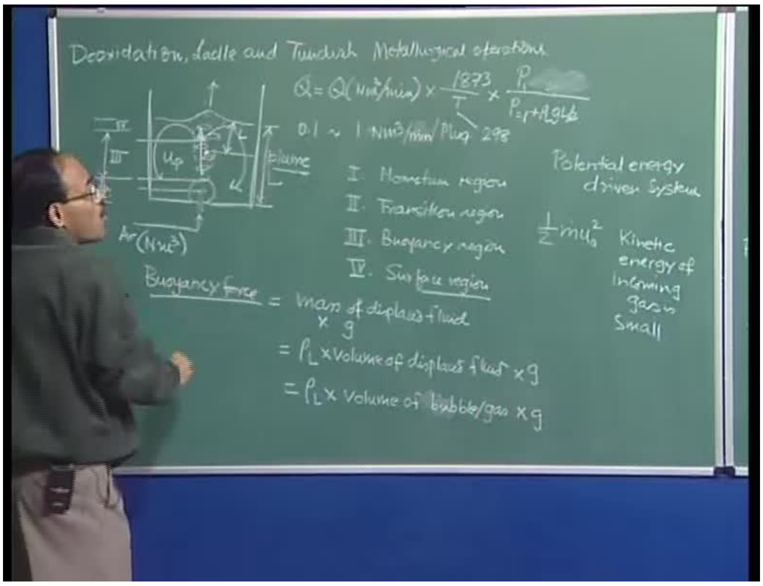
Now, if you substitute this here then what we get, therefore buoyancy force comes out to be rho liquid, then the volume of gas is equal to Q into L by U p, this is the term within the bracket represents the volume of the gas itself.

Now, if I say that, I want to now find out the rate of potential energy, potential energy input due to the bubbles, in that case what I am going to do, so the bubbles are rising with a certain velocity.

So if I multiply this with a velocity, I am going to get rate of energy input. If, I multiply with a displacement, I am going to get the work done, but on the other hand, if I multiply this with a rate of change of displacement, which is nothing but velocity, in that case I will get the rate of energy input and this is then going to be is equal to rho liquid multiplied by Q L by U p, and with what velocity the gases are rising as I have assumed here, the gases are rising with a velocity is equal to U p, so multiply this Up and therefore I get; this Up, this Up cancels out, this gives me rho liquid g Q L

So, the potential energy input rate to the gas stirred system, here is the density of the liquid multiplied by the acceleration gravity, this is the gas flow rate multiplied by the depth of liquid, before I proceed further I wish to know clarify about this gas flow rate.

(Refer Slide Time: 13:33)



Deoxidation, ladle and Tundish Metallurgical operations

$Q = Q(Nm^3/min) \times \frac{1873}{T} \times \frac{P_1}{P_1+\rho_L g L}$

298

0.1 ~ 1 Nm³/min/Plug

I. Momentum region
II. Transition region
III. Buoyancy region
IV. Surface region

Potential energy driven System

$\frac{1}{2} m u_0^2$ Kinetic energy of Incoming gas is Small

Buoyancy force = mass of displaced fluid × g

$= \rho_L \times$ Volume of displaced fluid $\times g$

$= \rho_L \times$ Volume of bubble/gas $\times g$

Now, we have injected the gas into the system at suppose some normal meter cube or the gas as it enters the system it undergoes thermal expansion, and also the gas will be injected at certain pressure, it is normal meter cube.

So, we have a normal pressure N T P normal temperature and pressure, but as soon as it enters here, the bubble is subjected to a very high prostatic head, one atmosphere plus the prostatic pressure, because of this much height of liquid which is L, and therefore as the bubble rises, its temperature at the gas develops into bubble, the temperature of the gas gradually increases from its injected temperature and also its pressure gradually gets decreased as it advances towards the free surface itself.

So, the gas temperature here could be 600 degree centigrade, the moment the gas temperature leaves here could be above 400 1300 degree centigrade, on the other hand here the total pressure, atmospheric plus prostatic pressure is very high and as the bubble rises thorough the liquid, the gas, the prostatic pressure afforded by the bubble gradually decreases.

So, as the bubble rises therefore we can anticipate that, because of the temperature increase, the bubbles volume is going to increase and also, because of the pressure increase, the bubbles decrease, because decrease in the pressure the bubbles volume is going to increase.

So, these pressure temperature effects are actually going to govern the net volume of the bubble, this is not the volume. Suppose, if I introduce a bubble which has a volume of, suppose hypothetically saying one normal meter cube at this particular point, as it is advancing or rising through the molten steel its volume is not going to be one normal meter cube. Its volume is going to be bigger than that, because of the combined effect of pressure and temperature. Therefore, in this analysis the gas flow rate that we use is reference to some main features of this system.

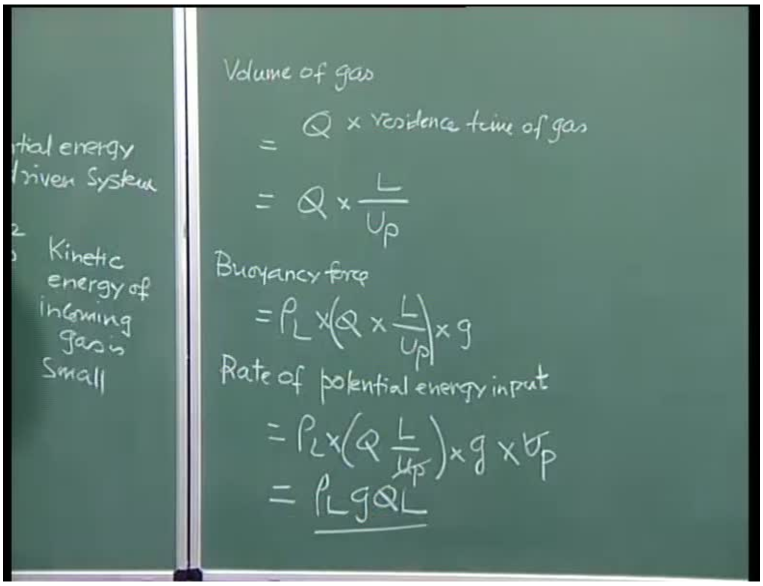
Now, we say that well whatever gas flow rate we are going to use, is actually Q in terms of normal meter cube per minute, and then multiplied by, and then we say it is equal to one atmospheric pressure. So, P is equal to 1 and this is equal to P plus, P 1 plus rho P L into, I have taken L by 2 to states specifically, that the pressure, reference pressure, because volume is not define unless I categorically mention the pressure and the temperature, and I am saying that well the gas in this system immediately attains the mean bath temperature which is 1873 degree centigrade, and this T is the normal temperature, so this is actually equal to 298, 273 plus 25 degree centigrade.

Normal temperature and pressure, so it is one atmospheric pressure, and this is going to be actually other way around, this is P plus 1 rho liquid g L by 2, because the volume is going to be inversely. So, this is the pressure we are talking about at the mid bath radius position, and this is the pressure, is the no corresponding to the normal pressure which is about one atmosphere.

So, this term is equal to one atmosphere plus the corresponding atmospheric pressure translated in terms of the mid bath depth, which is nothing, so the gas flow rate that I am using in this particular formula, is therefore I will say with respect to or it is converted to the mean temperature and pressure of the liquid, mean temperature means is the 600 bath temperature, mean pressure means the total pressure at this particular point which is equal to one atmospheric pressure plus rho g L by 2.

So, if I use a corrected gas volumetric flow rate, which is reference to the mean temperature and mean pressure of the liquid, I am going to really experience the net potential energy which is supplied, if I work out the potential energy supplied on the basis of normal meter cube, it is going to be considerably under predicted, because my analysis would not have taken into account, the expansion of the gas volume, because of the reduction in pressure as well as increase in temperature itself.

(Refer Slide Time: 18:16)



tial energy
riven System

Kinetic energy of incoming gas is Small

Volume of gas

$$= Q \times \text{residence time of gas}$$

$$= Q \times \frac{L}{U_p}$$

Buoyancy force

$$= \rho_L \times \left(Q \times \frac{L}{U_p}\right) \times g$$

Rate of potential energy input

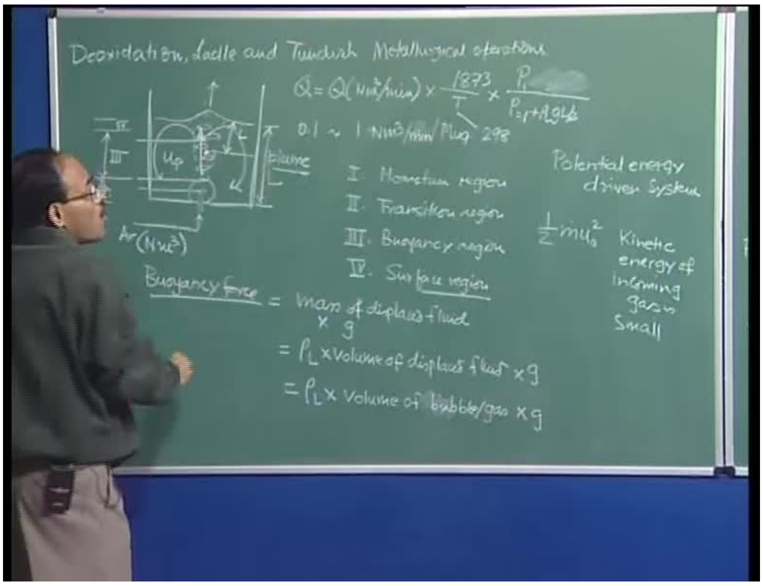
$$= \rho_L \times \left(Q \frac{L}{\cancel{U_p}}\right) \times g \times U_p$$

$$= \underline{\rho_L g Q L}$$

So, it is a very important point to note at this particular point, that the volumetric flow rate that is used in this formula is actually a gas flow rate which is corrected to mean height and temperature of the liquid.

Now, if we substitute the values, for example in industrial system rho liquid is 7000 k g per meter cube, g is equal to 9 point 81 Q, this factor will come out to be 65 to 6 times multiplication factor will going to come out here, and then we see that if we use one normal meter cube of flow rate per minute, this could be about 5 to 6 normal meter cube, L of the depth of the liquid in industrial system is about 3 meter, and if you substitute these values together with the potential energy values, we can immediately show that, indeed the kinetic energy applied by the gas, injected gas is barely one percent of the potential energy afforded by the rising bubbles to rise through the system itself.

(Refer Slide Time: 19:14)



Deoxidation, ladle and Tundish Metallurgical operations

$Q = Q(\text{Nm}^3/\text{min}) \times \frac{1873}{T} \times \frac{P_1}{P_1 + \rho_L g L_b}$

0.1 ~ 1 Nm^3/min/Plug 298

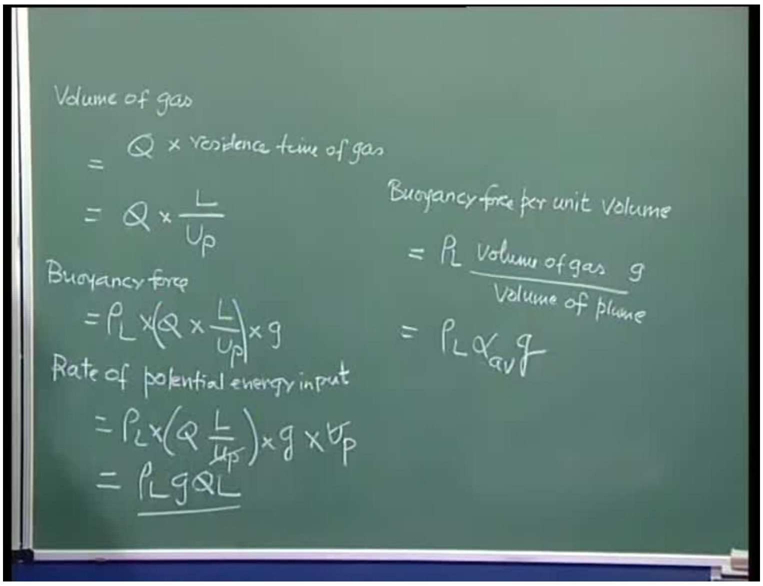
I. Momentum region
II. Transition region
III. Buoyancy region
IV. Surface region

Potential energy driven System

$\frac{1}{2} m u_0^2$ Kinetic energy of Incoming gas is Small

Buoyancy force = mass of displaced fluid × g
$= \rho_L \times$ Volume of displaced fluid $\times g$
$= \rho_L \times$ Volume of bubble/gas $\times g$

(Refer Slide Time: 19:24)



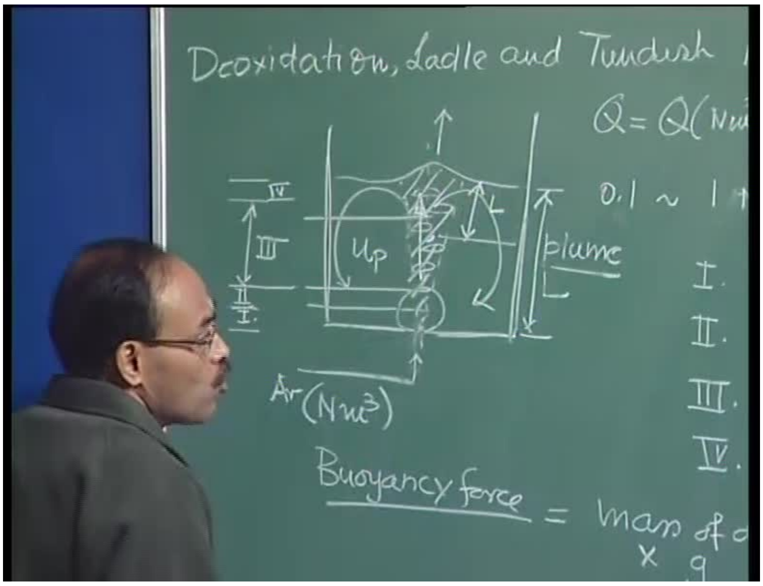
Volume of gas
= $Q \times$ residence time of gas
$= Q \times \frac{L}{U_p}$

Buoyancy force
$= \rho_L \times \left(Q \times \frac{L}{U_p}\right) \times g$

Rate of potential energy input
$= \rho_L \times \left(Q \frac{L}{u_p}\right) \times g \times v_p$
$= \underline{\rho_L g Q L}$

Buoyancy force per unit Volume
$= \rho_L \frac{\text{Volume of gas}}{\text{Volume of plume}} g$
$= \rho_L \alpha_{av} g$

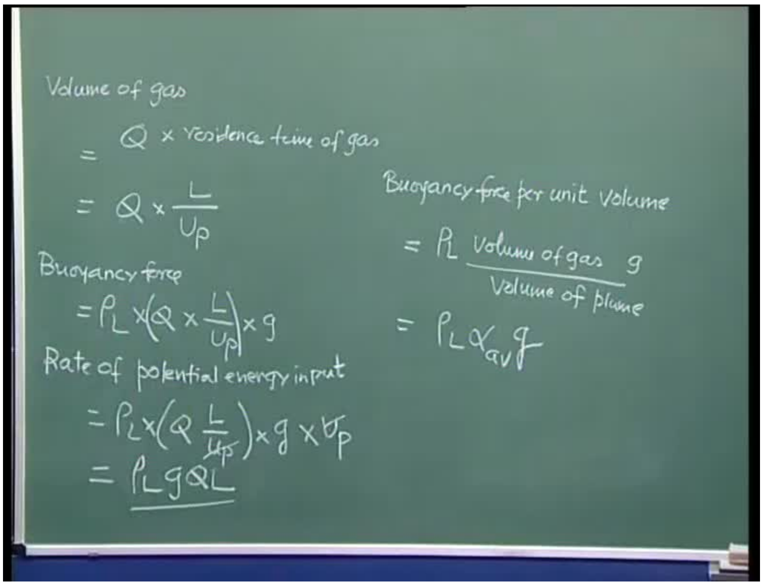
(Refer Slide Time: 20:05)



So, it is basically one can carry out simple expression, and one can on the basis of this show that it is a potential energy different system. Now, the buoyancy force per unit volume, I can also deduce buoyancy force per unit volume, per unit volume means per unit volume of the plume, so I have rho liquid, this is I have volume of gas and multiplied by acceleration due to gravity divided by volume of plume and this, in which alpha average represents the average gas fraction.

In fact, we have very high gas concentration at this particular point, may be 80 percent 90 percentages. On, the other hand we have disperse bubbles, here the gas volume fraction, because the plume expanse. So, we have the gas volume fraction continuously decreasing as the plume would expand towards the surface itself.

(Refer Slide Time: 20:39)



Volume of gas

$= Q \times$ residence time of gas

$= Q \times \frac{L}{U_p}$

Buoyancy force

$= \rho_L \times \left(Q \times \frac{L}{U_p}\right) \times g$

Rate of potential energy input

$= \rho_L \times \left(Q \frac{L}{u_p}\right) \times g \times v_p$

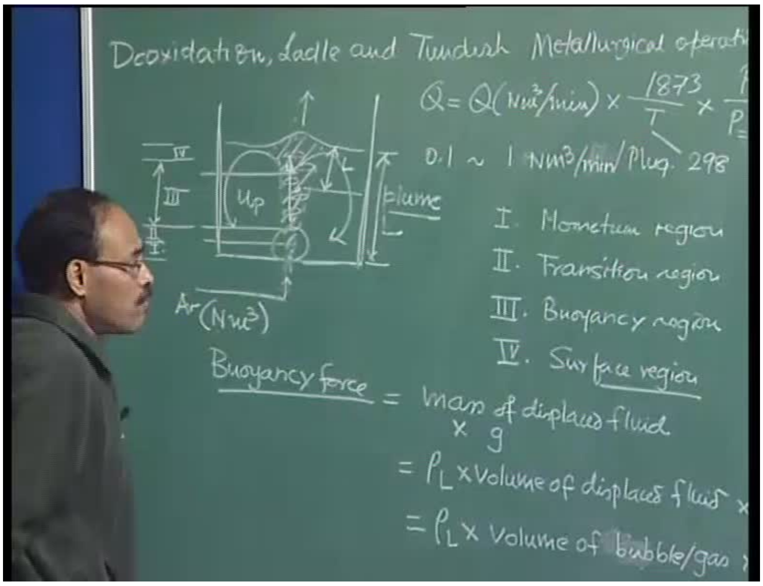
$= \underline{\rho_L g Q L}$

Buoyancy force per unit volume

$= \rho_L \frac{\text{Volume of gas}}{\text{Volume of plume}} g$

$= \rho_L \alpha_{av} g$

(Refer Slide Time: 20:43)



Deoxidation, Ladle and Tundish Metallurgical operati

$Q = Q(Nm^3/min) \times \frac{1873}{T} \times \frac{P}{P_=}$

298

0.1 ~ 1 $Nm^3/min/Plug.$

I. Momentum region

II. Transition region

III. Buoyancy region

IV. Surface region

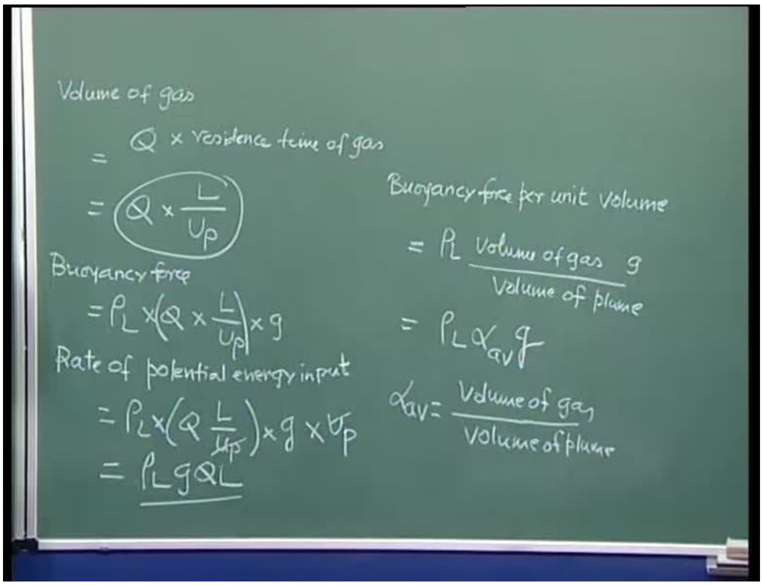
Buoyancy force = Mass of displaced fluid × g

$= \rho_L \times$ Volume of displaced fluid ×

$= \rho_L \times$ Volume of bubble/gas

So, there is a variation of gas volume fraction within the system, but we would say that we can average it out over the entire volume, and this alpha average, whatever I have shown towards the right is actually the mean gas volume fraction in the plume.

(Refer Slide Time: 20:52)



Volume of gas

$= Q \times$ residence time of gas

$= \boxed{Q \times \frac{L}{U_p}}$

Buoyancy force

$= \rho_L \times \left(Q \times \frac{L}{U_p}\right) \times g$

Rate of potential energy input

$= \rho_L \times \left(Q \frac{L}{\cancel{U_p}}\right) \times g \times U_p$

$= \underline{\rho_L g Q L}$

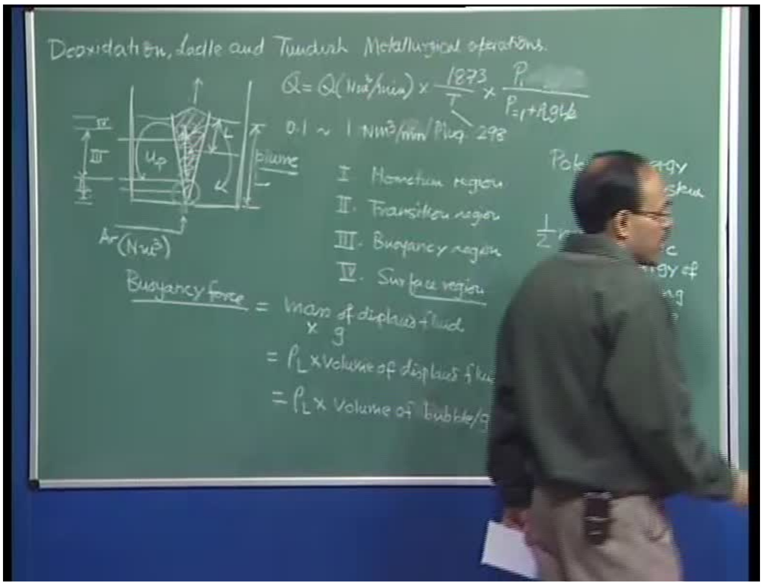
Buoyancy force per unit volume

$= \rho_L \frac{\text{Volume of gas}}{\text{Volume of plume}} g$

$= \rho_L \alpha_{av} g$

$\alpha_{av} = \frac{\text{Volume of gas}}{\text{Volume of plume}}$

(Refer Slide Time: 21:14)



Deoxidation, Ladle and Tundish Metallurgical operations.

$Q = Q(\text{Nm}^3/\text{min}) \times \frac{1873}{T} \times \frac{P_1}{P_{=1} + \rho_L g h}$

298

0.1 ~ 1 Nm³/min/Plug

I. Momentum region

II. Transition region

III. Buoyancy region

IV. Surface region

$\underline{\text{Buoyancy force}} =$ mass of displaced fluid $\times g$

$= \rho_L \times$ Volume of displaced flu

$= \rho_L \times$ Volume of bubble/g

Pot ergy

stem

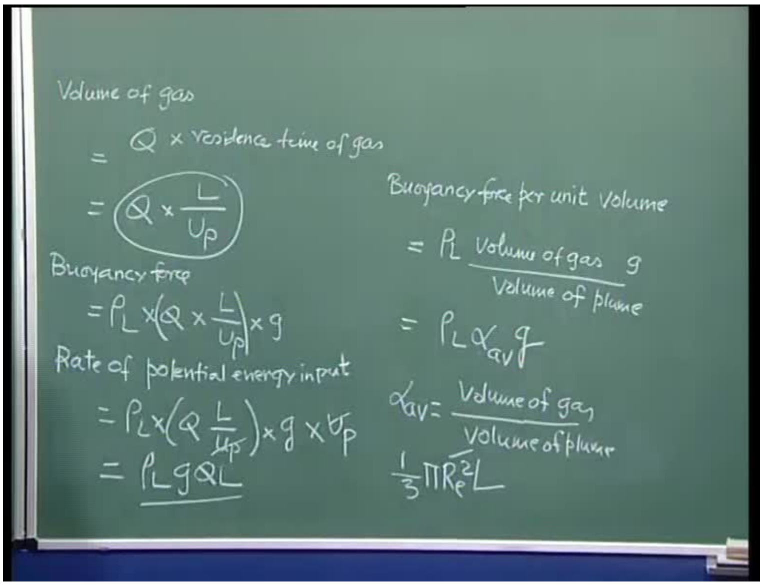
$\frac{1}{2}$

c

rgy of

ng

(Refer Slide Time: 21:20)



Volume of gas

= Q × residence time of gas

$= Q \times \frac{L}{U_p}$

Buoyancy force

$= \rho_L \times \left(Q \times \frac{L}{U_p}\right) \times g$

Rate of potential energy input

$= \rho_L \times \left(Q \frac{L}{\cancel{U_p}}\right) \times g \times \cancel{U_p}$

$= \underline{\rho_L g Q L}$

Buoyancy force per unit volume

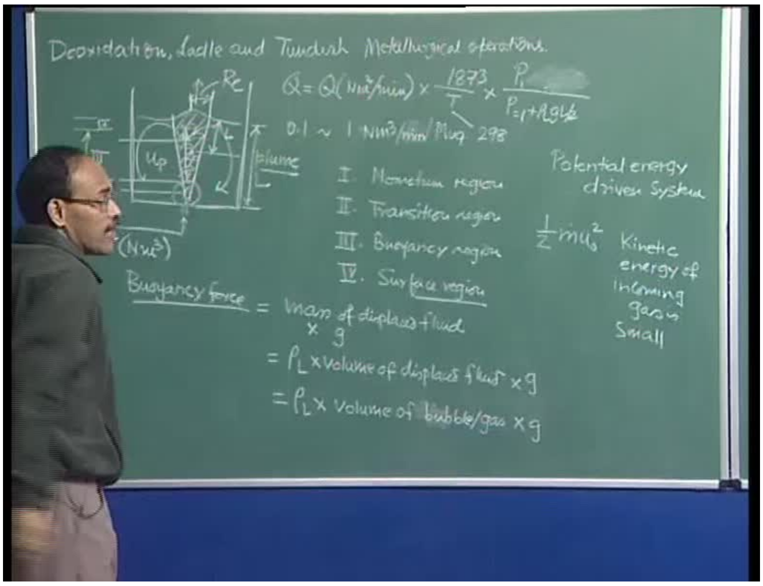
$= \rho_L \frac{\text{Volume of gas}}{\text{Volume of plume}} g$

$= \rho_L \alpha_{av} g$

$\alpha_{av} = \frac{\text{Volume of gas}}{\text{Volume of plume}}$

$\frac{1}{3}\pi R_e^2 L$

(Refer Slide Time: 21:27)



Deoxidation, Ladle and Tundish Metallurgical operations.

$Q = Q(Nm^3/min) \times \frac{1873}{T} \times \frac{P_1}{P_{=1} + \rho_L g L}$

T 298

0.1 ~ 1 Nm³/min/Mg

I. Momentum region

II. Transition region

III. Buoyancy region

IV. Surface region

Buoyancy force = mass of displaced fluid × g

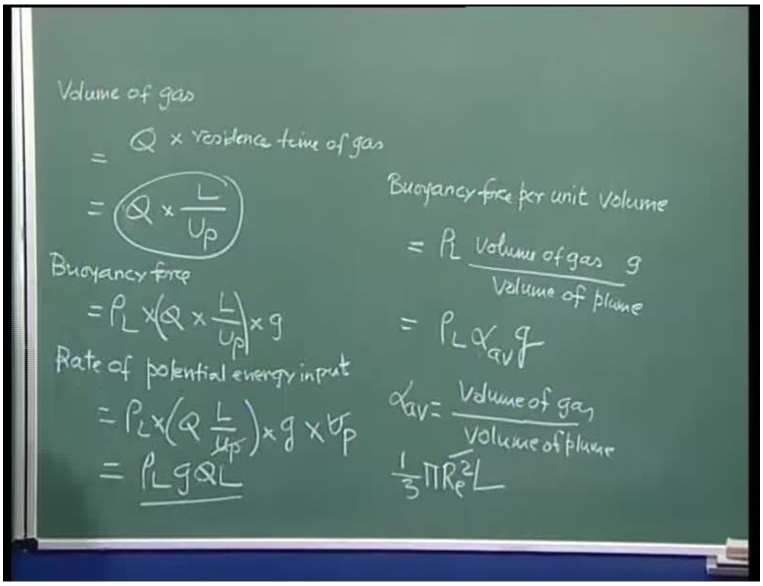
$= \rho_L \times$ volume of displaced fluid $\times g$

$= \rho_L \times$ Volume of bubble/gas $\times g$

Potential energy driven system

$\frac{1}{2} m u_0^2$ Kinetic energy of incoming gas is small

(Refer Slide Time: 21:36)



Volume of gas

= Q × residence time of gas

$= \boxed{Q \times \frac{L}{U_p}}$

Buoyancy force

$= \rho_L \times \left(Q \times \frac{L}{U_p}\right) \times g$

Rate of potential energy input

$= \rho_L \times \left(Q \frac{L}{U_p}\right) \times g \times U_p$

$= \underline{\rho_L g Q L}$

Buoyancy force per unit volume

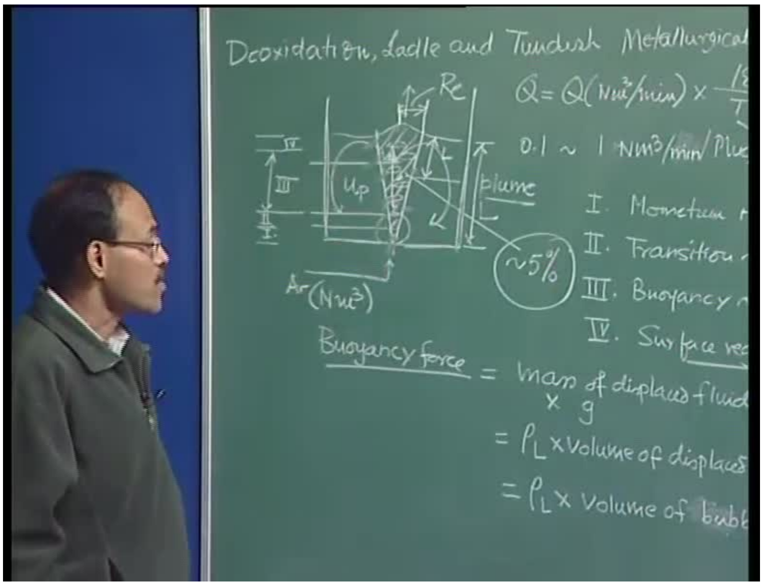
$= \rho_L \frac{\text{Volume of gas}}{\text{Volume of plume}} g$

$= \rho_L \alpha_{av} g$

$\alpha_{av} = \frac{\text{Volume of gas}}{\text{Volume of plume}}$

$\frac{1}{3}\pi R_e^2 L$

(Refer Slide Time: 21:45)



Deoxidation, Ladle and Tundish Metallurgical

$Q = Q(Nm^3/min) \times$

0.1 ~ 1 Nm³/min/Plu

I. Momentum r

II. Transition

III. Buoyancy r

IV. Surface re

$\underline{\text{Buoyancy force}}$ = mass of displaced fluid × g

$= \rho_L \times$ Volume of displace

$= \rho_L \times$ Volume of bubb

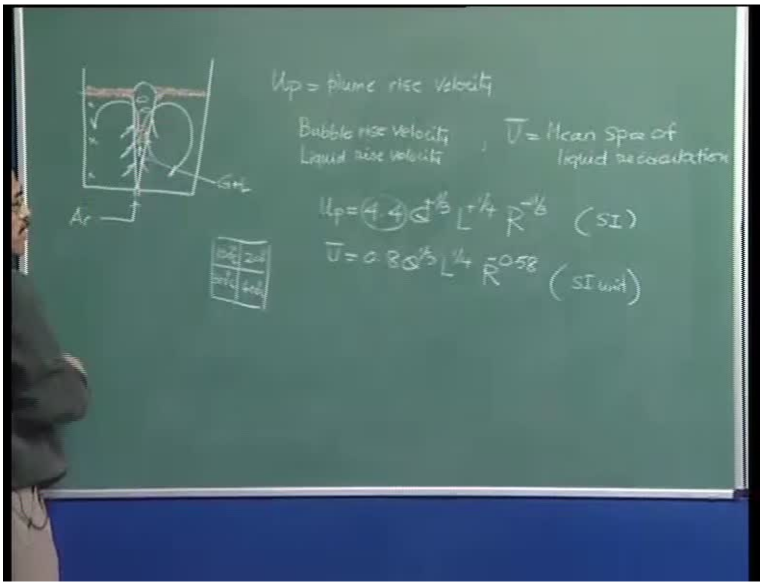
Now, this mean gas volume fraction in the plume, therefore by definition is equal to alpha average is equal to volume of plume, volume of gas and volume of plume. Now, volume of gas I have already given in the expression, and if I assume that well this plume is roughly chronicle in shape, in that case I can say this is going to be is equal to 1 by 3 pi R e square L, what is R e square, then R e square is exactly equal to the radius of the plume pi, and if I take the value of the volume of the plume as this one third pi R e square L, calculate the volume of the gas. On the basis of this formula, I will find out that the average gas volume fraction here is barely 5 percentage.

So, the very important deduction and a very important for us to remember, that the gas volume fraction within the 2 phase region is actually (()) very very small quality, 5 percent of this region is occupied by organ bubbles and remaining.

So, given this picture we can now conceptualize the gas injection phenomena, that it is like an unconfined jet, because the gas volume fraction is very small, it is rising through a very deep bath, the bubbles are not going to see the walls, they are located for away, so as if it is an unconfined liquid stream of bubbles which are rising through or a buoyant plume which is rising through, and the energy is transferred through the molten steel bath across the boundaries itself.

So, all along this because of the buoyancy itself, energy is going to be continuously transferred, the bubbles are going to give rise to their energy, give away their energy. So, the fluid, but they leave the system, the fluid will keep on recirculating, thereby generating a strong convection current in the system itself.

(Refer Slide Time: 22:55)



So, I have introduced a term which is the plume velocity, this plume velocity essentially implies the rise velocity of the gas liquid mixture, I have gas plus liquid here, so the average rise velocity of the gas liquid mixture.

In fact I have bubbles which rise there with certain velocity, and I have the liquid within the plume which rises with some velocity. So, I actually have a bubble rise velocity, bubble rise with their velocity, bubble rise velocity and I also have liquid rise velocity.

Typically, the bubbles rise faster, and the difference between the rise velocity of bubble and liquid is termed as the sleep velocity. So, the bubbles rise accelerate faster, rises faster, the liquid follows it, and together we can conceptualized of an average velocity of the gas liquid mixture, which we termed as an average, call it a plume rise velocity.

There is another important parameter, which is like we denote by mean speed of liquid recirculation, mean speed in the system, mean speed of liquid recirculation, which is presents like the average velocity in the system.

Now, for example I have an object, where I can have; say I divided into 4 segments, here there is 100 degree centigrade temperature, 200 degree centigrade temperature, 300 degree, and I say that well there is a difference in temperature, but nevertheless I can ascribe a average in this case, if all the control volumes are identical, it is 4 plus 3 plus 2 plus 1. So, sudden one thousand degree divided by 4, which is equal to 250 degree will be the average temperature.

Similarly, even though we may have different velocities here, we can give rise, we can ascribe a constant or a mean velocity to the system and this is denoted by U bar, and this is called the mean speed of liquid recirculation.

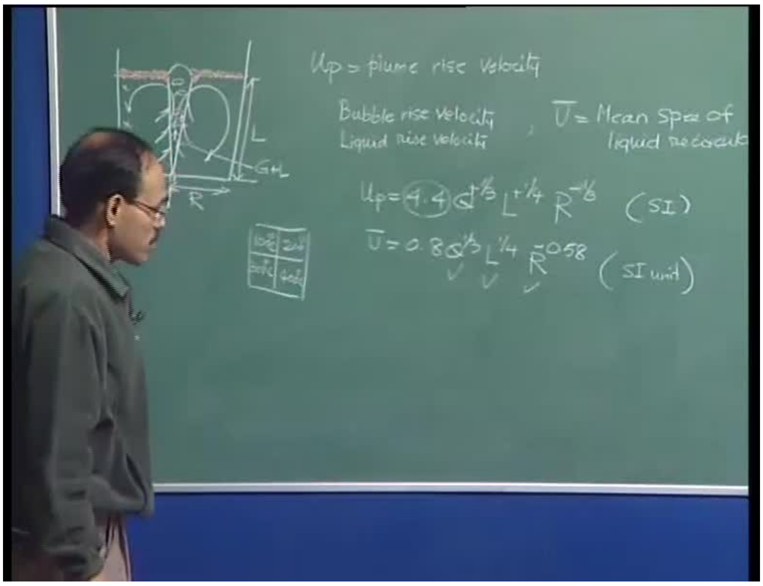
Now, we are talking of velocities scales or in a sudden here is that, it is important for us to know the scale of velocity in the system, because we would like to do some calculations, regarding allow dissolution, allow mixing, slag high area etcetera, and as I have mentioned inclusion floatation as well and as I have mentioned that steel making systems are basically mass transfer control systems.

So, therefore the convection current is going to assume predominance in such processes, so mixing mass transport, allow dissolution, temperature distribution, convective heat and mass transport everything is going to function of the velocity, and that is why we have to have some idea of the velocity here in the system, and then only we can conclude whether the organ stirred system really efficient or not in terms of its processing capabilities.

There are basically many equations people have derived, this is not within the for view of this course, but simple macroscopic equations which is available in the later lecture, for example the plume rise velocities given in terms of 1 by 3, and similarly this is an S I unit and mean speed of liquid recirculation, for example is given also Q raise to the power 1 by 3 L raise to the power 1 by 4, and r raise to the power minus 0 point 58.

Let us concentrate on U p, so this is a constant which comes out from various parameters; like what is the bubble diameter, what is the bubbles rise velocity, what were the properties of the system and so on. Q represents the gas flow rate, and as I have been the mentioning all the time, this is the gas flow rate corrected to mean height and temperature of the liquid.

(Refer Slide Time: 27:33)



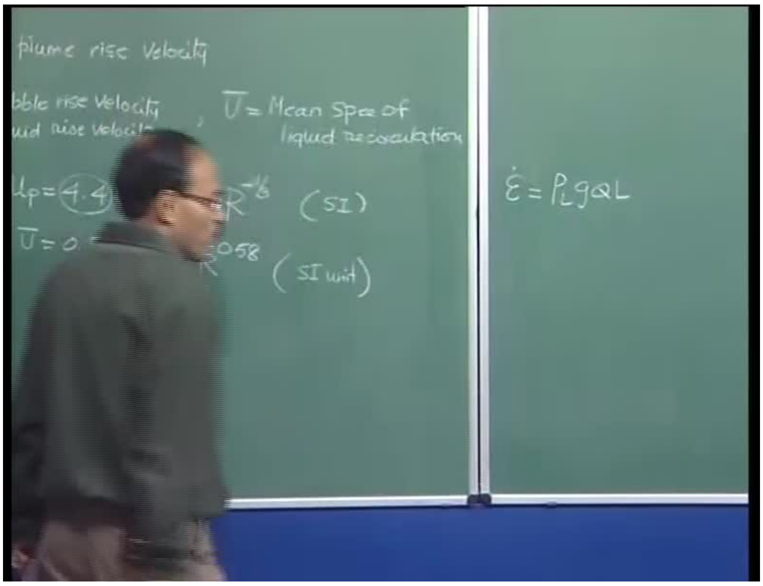
L represents the depth of liquid, which is basically this, and R represents as the formula suggests that the plume rise velocity or the average velocity, rise velocity of the bubble and the liquid mixture will increaseas hot power of the gas flow rate, it will increase also relatively weekly as depth of liquid, but it is going to decrease with a vessel radius.

Therefore, for a given flow rate and given liquid depth, the more is the diameter of the vessel and this is going to be the convection current or the plume rise velocity in the system.

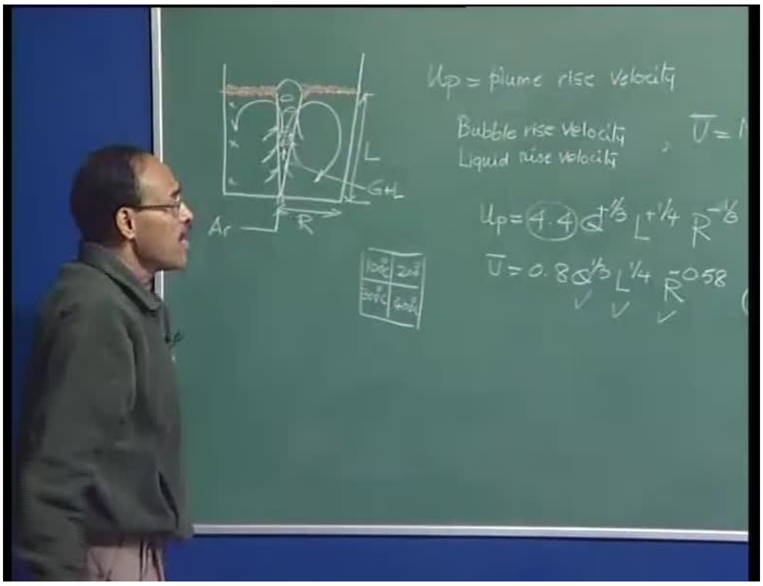
And same sort of a functional relationship one can see here, that both average velocity and liquid plume rise velocity are upset by any increase of the vessel radius. On the other hand by increasing the gas flow rate and liquid depth, we can increase the rise velocity as well as the mean speed of bath recirculation.

Now, typically these are under the ladle metallurgy steel making conditions, these correlations cannot be really applied to a very large flow rates situation, in which the gas injection rates are very large or the bath is extremely shallow or extremely tall vessel. So, these are not the conditions typical under typical ladle metallurgy condition only this equation hold good. Now, therefore a taller vessel is going to give rise to more convection current.

(Refer Slide Time: 29:05)

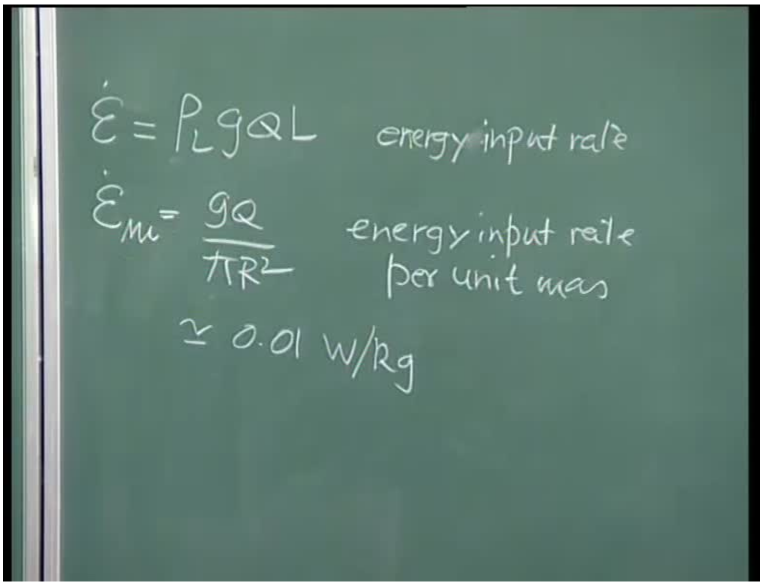


(Refer Slide Time: 29:32)



Now, imagine we have said that potential energy input rate, which is typically denoted by epsilon dot is equal to rho liquid g Q and L, and this tells us that, if we increase the gas volumetric flow rate, or if you increase the depth of liquid for any given system for lower list constant, the rate of energy supply is going to be increasing, and it is because of that more energy means, more rate of recirculation and that is being reflected in this particular formally as well.

(Refer Slide Time: 29:41)



$\dot{\varepsilon} = \rho_L g Q L$ energy input rate

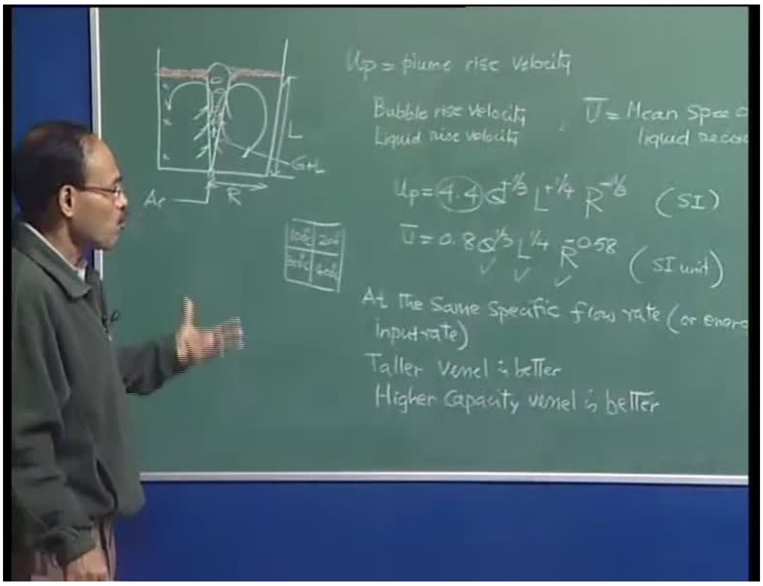
$\dot{\varepsilon}_m = \dfrac{gQ}{\pi R^2}$ energy input rate per unit mas

$\simeq 0.01$ W/kg

There is another term which is also important for us, which will use is the energy input rate per unit mass. So, this is energy input rate and this is energy input rate per unit, input rate per unit mass, and this is denoted typically g Q by pi R square, in which the ladle has been assumed to be perfectly cylindrical, so the volume is basically pi R square.

Therefore, rho L into pi R square L, so rho L is rho, rho L is going to be cancel out, L and L is going to cancel, out so g Q will remain in the numerator and on the denominator, we have pi R square and this value under ladle metallurgy steel making condition is basically of the order of 0 point watt per kg. That is thus weight of specific potential energy input rate to the system.

(Refer Slide Time: 30:54)



U_p = plume rise velocity

Bubble rise velocity

Liquid rise velocity

$\bar{U}$ = Mean Spe

liquid

$U_p = \boxed{4.4}\, Q^{1/3} L^{+1/4} R^{-1/6}$ (SI)

$\bar{U} = 0.8 Q^{1/3} L^{1/4} R^{-0.58}$ (SI unit)

At the Same Specific flow rate (or energ

input rate)

Taller Vessel is better

Higher Capacity vessel is better

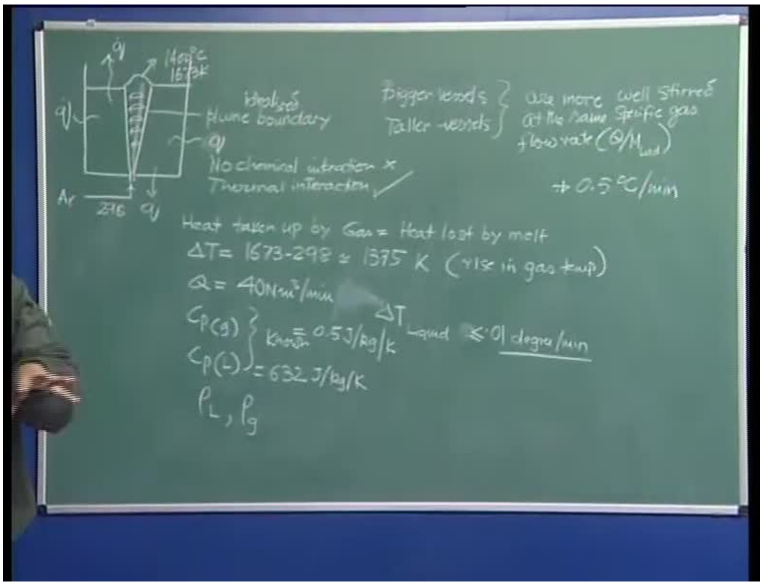
Now, for the same amount of specific potential energy input rate, on the basis of this equation I can show that well, there will be much higher plume rise velocity in system if they are taller and there will be more recirculation, if the system is going to be bigger capacity.

So, using this formally as well as this prescriptions, I can very well show that is for you to do this calculation, and so at the same specific gas flow rate, or energy input rate, same energy input rate, taller vessel is better, higher capacity vessel is better, better means in higher capacity vessel, the efficiency of stirring is going to be more intent stirring for the same amount of specific gas flow rate or same specific potential energy input rate, the taller vessel is also going to be better.

So, if you say that depth of liquid is higher that means the stirring is also going to be higher at the same specific volumetric flow rate or same potential energy input rate. So, this govern can vary easily shown.

So, I can say that a 500 ton ladle is going to be far more effective than a 200 ton ladle, for example at the same specific gas flow rate, also I can say that a vessel which is 2 point 5 meter depth is going to be more effective than a vessel which is only 1 point 5 meter depth at the same value of specific potential energy input rate.

(Refer Slide Time: 32:54)



No chemical interaction ×
Thermal interaction ✓

Bigger vessels }
Taller vessels } are more well stirred at the same specific gas flow rate (Q/M_{liquid})

$+ 0.5\ °C/\text{min}$

Heat taken up by Gas = Heat lost by melt

$\Delta T = 1673 - 298 \approx 1375\ K$ (rise in gas temp)

$Q = 40\ Nm^3/\text{min}$

$C_{p(g)}$ } known $= 0.5\ J/kg/K$

$C_{p(L)}$ } $= 632\ J/kg/K$

$\Delta T_{\text{Liquid}} \leq .01$ degree/min

ρ_L, ρ_g

Let us now examine the issue of gas liquid interactions in the ladle, typically because organ is injected, so we would say that there is no chemical interaction, because the solubility of organ in steel is negligible no chemical interaction. So, whatever interaction is possible in the system is basically thermal interaction.

So, this is significant for us thermal interaction, now there might be some miss conception at this particular stage saying that well an organ is introduced into the system at 298 and if it leads the system at close to 1400 or 1300 degree centigrade or 1673 kelvin, it might appear that, lot of heat is being taken out by the gas, because the gas is going to consume lot of heat from the metal and as a result of which I can give some kind of steel in effect on the metal itself, but simple calculation can show that the rate of temperature drop of the melt, because of this rise in gas temperature is really not significant.

For example if I write down the balance that heat taken up by gas is equal to heat lost by melt, this is a balance thermal balance equation under steady state condition, and if I now take that well delta t is equal to, say I have injected at, so it is about 16 73 minus 298, so roughly about 1375 kelvin.

If I say that the well my gas flow rate is something like; say 1 N m cube per minute per ton, in that case I would say, let me just do this one normal meter, 40 normal meter cube per, this is a typical arching flow rate, and then we can do the calculation that for this much of temperature, we know the specific heat of gas C P gas, and CP liquid molten steel, this values are known to us and we can plug in this values, what this energy balance equation, and then show that well for these kind of a temperature rise, rising gas temperature is going to introduce a delta T in liquid which is approximately is equal to or I can say less than equal to, and then a significant drop in temperature, simple calculation MCPDT I can do and write down the balance equation using the data, the gas specific heat can be obtained, the liquid specific heat also is known to us, which is about I think 632 joules per k g per Kelvin.

This is a value of I think point 5, I remember correctly, and if I substitute the value I should be able to find out that, because of this much and why is this difference occurring. The difference is occurring, because of the density of liquid is significantly smaller than the density of the gas.

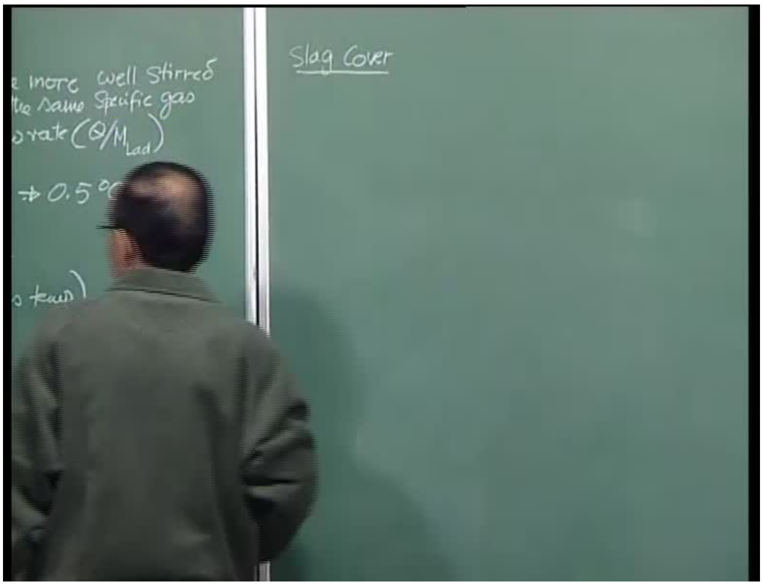
But it is 7000 k g per meter cube this is barely point 1 or point 2, and therefore this last difference actually does not cause in noticeable extent of temperature drop, so the gas even though it is going to be heated up to 1400 degree centigrade, it is really not going to take much heat from the melt itself.

In fact the heat loss through the free surfaces, I can say q, this is a standard notation, so all this through all this surfaces, heat is going to be lost and the loss of heat, this loss of heat through the surface of the ladle, free surface as well as the bounding walls through refractive line wall of the lade is going to cause actually noticeable amount of drop in the melt temperature itself.

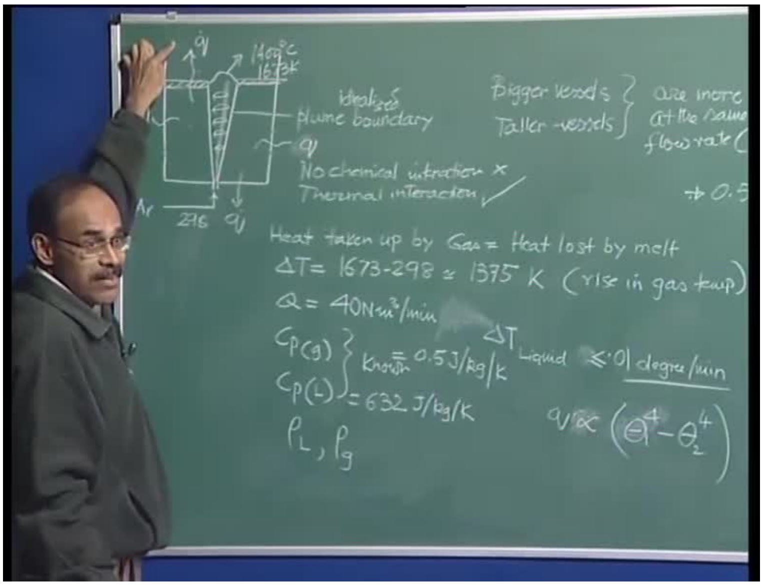
I think I have given you the value that actually for holding, due to this heat fluxes, prevalent through the wall, refractive wall well as the slag lined free surface, the drop in temperature of the melt is of the order of 0 point 5 degrees, which essentially means that if we gas stir a ladle for about 30 minutes, there will be 15 degrees of drop, because of loss of heat to the surroundings. On, the other hand in that particular time we may have point 3 degree drop, because of the heat which is consumed by the rising gas.

So, therefore we can conclude that the injected gas, even though it is cold and it is heated up to about 1400 degree centigrade due to its low density and low flow rate at the loss of heat is from the melt is going to be in significant in comparison to the loss, because of heat going out of the system to the surrounding through the free surface as well as the wall.

(Refer Slide Time: 39:11)



(Refer Slide Time: 39:18)

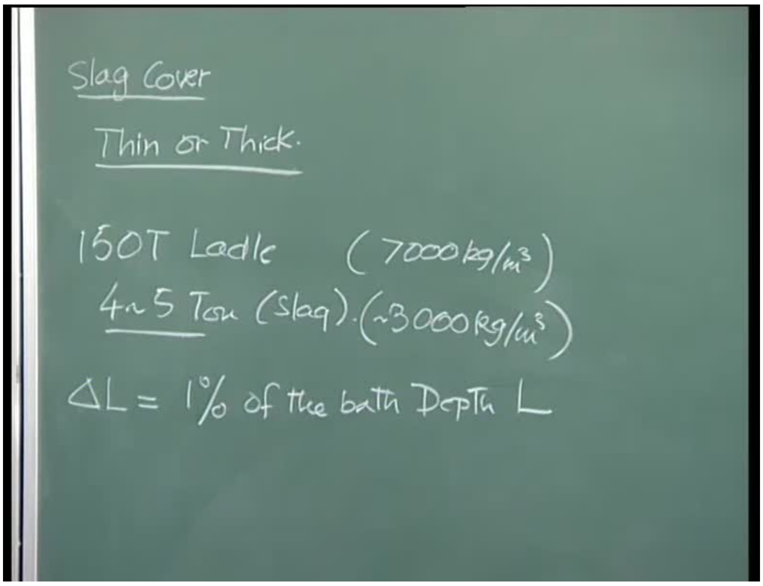


Now, we can talk about the slag cover in the system to minimize, therefore we have to have some kind of a slag layer here, otherwise if this surface is expose, the drop in temperature could be significantly larger, because this surface is at 1600 centigrade and that the radiation laws is proportional to delta theta rise to the power, I would not say delta theta, but say theta 1 to the power 4 minus theta 2 proportional to.

So, theta 2 may be the ambient temperature, theta 1 may be the surface temperature, the radiation heat flux is proportional to the temperature. So, the surface temperature if it is exposed could be 1873, and therefore you can imagine the extent of radiation heat loss if the surface is not exposed.

The slag layer basically that is two things; it provides a protective environment that the metal which is refined and quality is good, we have made lot of effort to produce a good quality steel here, and I continuously refining we would not like this metal to interact with the bulk here, so that deoxidation etcetera can take place and also we want to minimize the drop in temperature, and therefore we have to have some covering of slag at the free surface, and this slag as I have mentioned to you earlier is not an oxidizing slag, it does not contain f e o, it contains freshly prepare slag with some lime silica etcetera and so on.

(Refer Slide Time: 40:54)



Slag Cover

Thin or Thick.

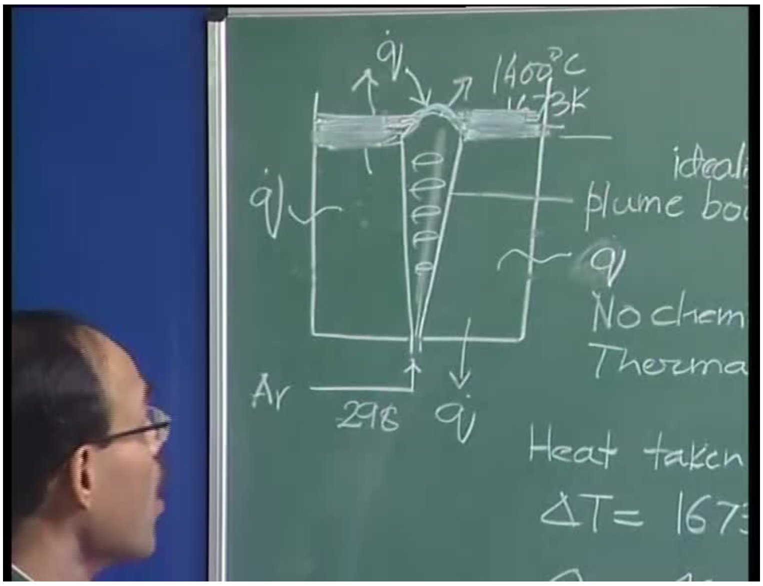
150T Ladle (7000 kg/m^3)

4~5 Ton (Slag). (~3000 kg/m^3)

ΔL = 1% of the bath Depth L

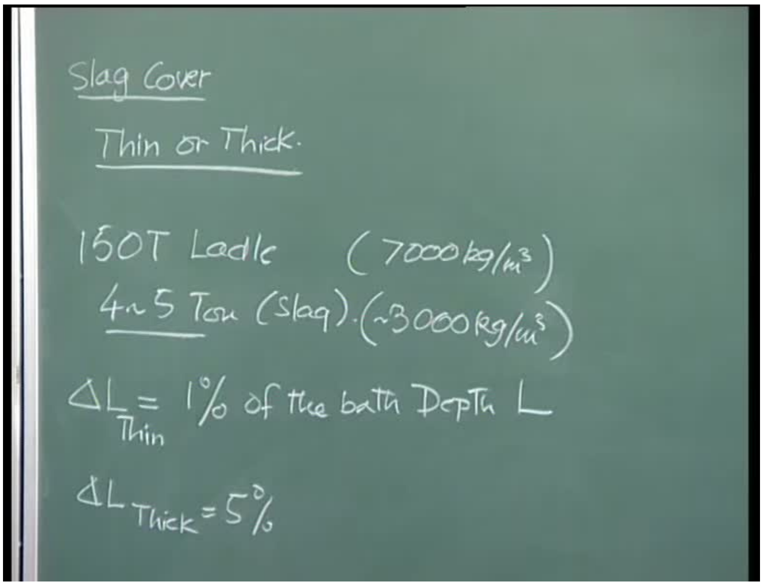
Now, basically the slag cover can be thin or thick and how thick is this slag cover this is barely maximum, if you look at 150 ton ladle for example, and the amount of slag is about 4 to 5 tons, this is the slag and if you convert them into their corresponding height taking into account, the density of steel which is 7000 kg per meter cube, and the slag density which is about approximately 3000 kg per meter cube depending on the density could be 2340, a typical density you can translate this into the corresponding height, and you can see that the thickness of the slag typically in industrial process is approximately maximum 1 percent of the bath depth L.

(Refer Slide Time: 42:12)



So, the thickness of the slag is very small, we are also like as I said that some covering this is an exposed plume high area, for example through which we can have lot of interaction with the environment, and it is possible for us to cover up this by increase in the thickness of the slag, if the slag is increase you can see that the slag high area, the exposed area can be really very small. So, I can show this by using a colored chalk here. So this now represents for example, the exposed area when your slag is really thick, so by using a thick slag, it is possible for us to cover a portion of the slag high itself, and thereby minimize the interaction of molten steel with the surrounding atmosphere itself.

(Refer Slide Time: 43:06)



Slag Cover

Thin or Thick.

150T Ladle (7000 kg/m^3)

4~5 Ton (Slag). (~3000 kg/m^3)

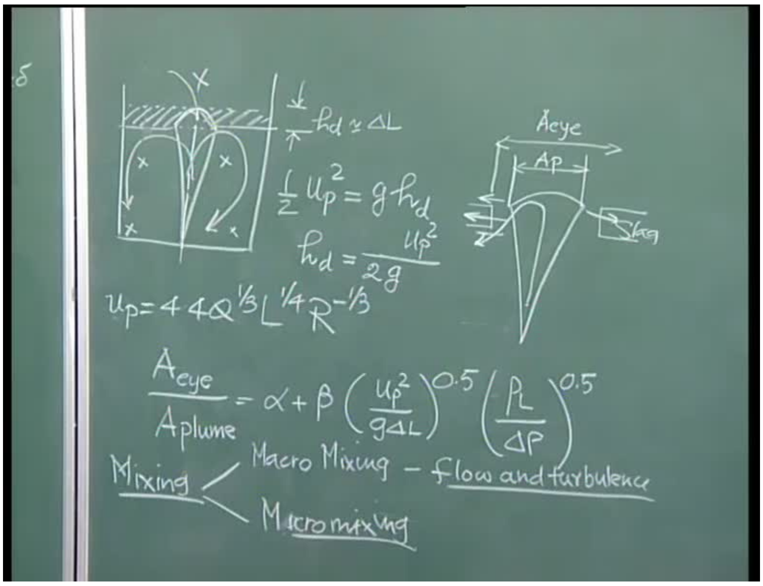
ΔL_{Thin} = 1% of the bath Depth L

ΔL_{Thick} = 5%

And, when you are talking of thick slag, the thick slag we are talking about this is thin, and thick slag we are talking about this approximation 5 percentage and that would tend to cover up.

So, thin slag as I have mentioned is barely 1 percent of the entire bath depth. On the other hand the thick slag is going to be about 4 to 5 percentage, but most of the industrial processes ladle metallurgy processes employ a thin slag.

(Refer Slide Time: 43:37)



Now, if i use a thick slag, for example I can show that it is possible under that condition to really cover up the entire plume high itself. So, this represents an extremely thick slag power by the plume high can be completely submerged under the slag layer itself, and this height we basically is, we say that this is the dome height h sub d or which is equal to now the delta sum L.

So, this is the high height or the dome height, and this dome height now becomes exactly equal to the thickness of the slag itself, and under such condition if you look at the figure the pi is now, the plume is now completely submerged and there is very little scope for the surrounding atmosphere to interact. No, this is now not possible, because the surface is totally covered.

So, under that condition we can see, we can also write that well this is the axis, and at this axis what happens the potential energy, because of the rising, if there is no gas injection this surface which is raised by h sub d will immediately fall down and entire bath depth will become.

So, the potential energy or lifting of this surface by an h d is exactly equal to, because of the kinetic energy of the plume, so we can say that half U p square is equal to. So, this is an expression energy balance, kinetic energy afforded by the plume is exactly equal to the potential energy, because of lifting of the surface by the, and therefore we can say that h sub d is equal to U p square, and Up expression of Up I have already given, Up is equal to 4 point 4 Q raise to the power 1 by 3 L raise to the power 1 by 4 and R raise to the power minus 1 by 3.

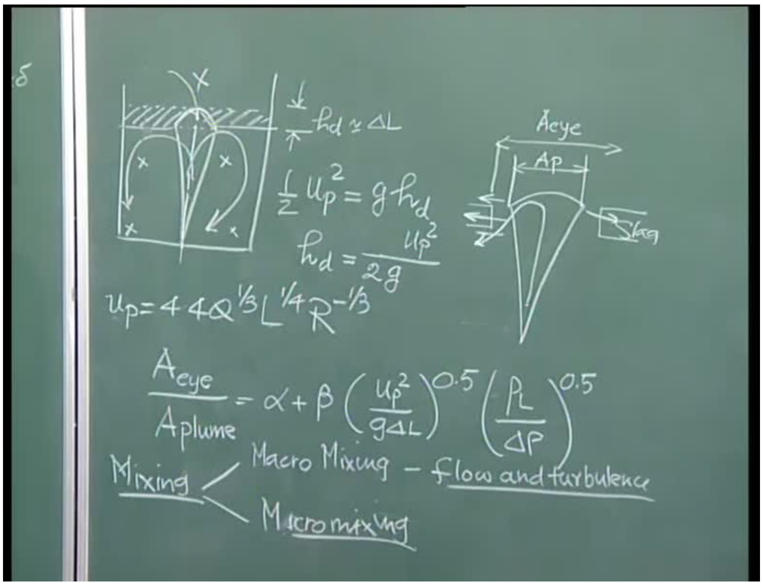
So, given the gas flow rate, we can convert it into the actual condition which is reference to our mean height and temperature of the liquid, we can use that depth of liquid in the system radius of the vessel, calculate the plume velocity in S I unit substitute it here, and then calculate that what is the dome height, and then set it to be equal to delta L and find out that what should be the thickness of the protective slag layer, which can really cover up the entire dome, thereby minimizing the chances of interaction between the melt and the upper ambient atmosphere.

Now, this slag high is a very important aspects of secondary steel making operation, we are gradually closing down now on various aspects of inert gas injection, the slag high area, for example is a potential sight of reoxidation and particularly towards the final stages of ladle rinsing operation, or organ stirring operation we want to homogenize the bath mix the bath, I am going to talk about mixing which is very important in the context of ladle metallurgy within a next few minutes.

So, during the final stage of ladle metallurgy operations when we are injecting the gas at a very slow rate or point one normal meter cube per minute per ton, under that condition we will really like to see that there is not much interaction with the atmospheric oxygen, we have to prevent the reoxidation which is the culprit for aluminum fading and formation of more oxide inclusions in the bath.

So, therefore to minimize that, we will have to have a process should be regulated in such a way that high area remains very small. Now, exposed high area, area of the plume, area of the eye to area of the plume is equal to, roughly is equal to we have a constant alpha, beta, then we have Up square by g delta L raised to the power 0 point 5 and then we have rho L divided by delta rho.

(Refer Slide Time: 43:37)



$h_d \simeq \Delta L$

$$\frac{1}{2} u_p^2 = g h_d$$

$$h_d = \frac{u_p^2}{2g}$$

$$u_p = 4.4 Q^{1/3} L^{1/4} R^{-1/3}$$

$$\frac{A_{eye}}{A_{plume}} = \alpha + \beta \left(\frac{u_p^2}{g \Delta L}\right)^{0.5} \left(\frac{\rho_L}{\Delta \rho}\right)^{0.5}$$

Mixing
- Macro Mixing – flow and turbulence
- Micromixing

The density differential and the plume raise velocity determines the ratio of the eye to the ratio of the plume, because you can always see that sometimes you can see that the slag is here, the slag for example is here, and the plume is somewhere, the slag is pushed to such an extent that actually this is the eye area that we are talking about, and this is the area of the plume that we are using in this particular formula.

So, there are two areas here, and this tells us that the eye is actually and A P, so because the flowing liquid, radial flowing liquid, the liquid goes like this, it comes like this, so it has been able to push this slag layer, it is the slag layer, it puts this slag layer and as a result of which we are creating a bigger appending then actually the area exposed.

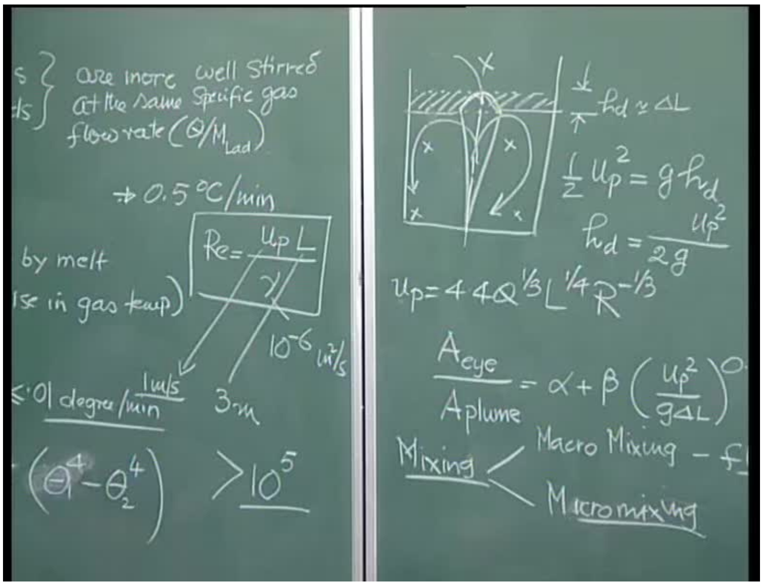
Therefore, we can say that the eye area is bigger than the plume area under that particular condition and we can have an equation like this, which tells us that the thickness of the slag layer, the plume rise velocity and the density of the slag are critical parameter in determining, that how much of area is going to be really exposed, and thereby we can say that whether there is going to be significant amount of reoxidation or not the system.

What are the late objectives of inert gas stirring, is to enhance mixing in the system, as I have mentioned that we would like to induce velocity all the time, we want to transport sub a species from one position to another position, and facilitate reactant reaction between the various species. We can also think of transporting the product, moving the product from the reaction sights, and all these are going to be aided by a strong convection current which is going to be prevalent in the system.

We also may have we have different temperatures at different regions, and we may do gas stirring obviously, for example as I have said you there is no more heat loss to the surface, the temperature here is going to be cooler than the temperature here, temperature in the center, temperature here is going to be cooler than the temperature here, and say as a result we may have some thermal stratification in the system, and we can remove that thermal stratification by gas stirring, so which does some amount of thermal mixing.

Similarly, we can say we may have some inclusion difference differential counts in the system, and we can have gas stirring, and the gas stirring is going to give rise to some uniform inclusion distribution system. So, material mixing and thermal mixing at important objectives of gas stirring, and when we talk of mixing we must understand that mixing are basically macro mixing, and micro mixing in engineering term; in engineering we always talk about macro mixing not micro mixing, micro mixing means mixing at the molecular level, but in engineering applications we are not really concerned with micro mixing, we are concerned about macro mixing. What are the mechanisms of mixing, the mixing is aided macro mixing is basically due to flow and turbulence.

(Refer Slide Time: 52:01)



I must mention at this particular stage that, the flow which is induced in the system even though the flow rate may be small, gas injection rate may be small even though the velocity scalar velocity may not be significantly high, but the flow which is induced in gas stirred ladle system is highly turbulent.

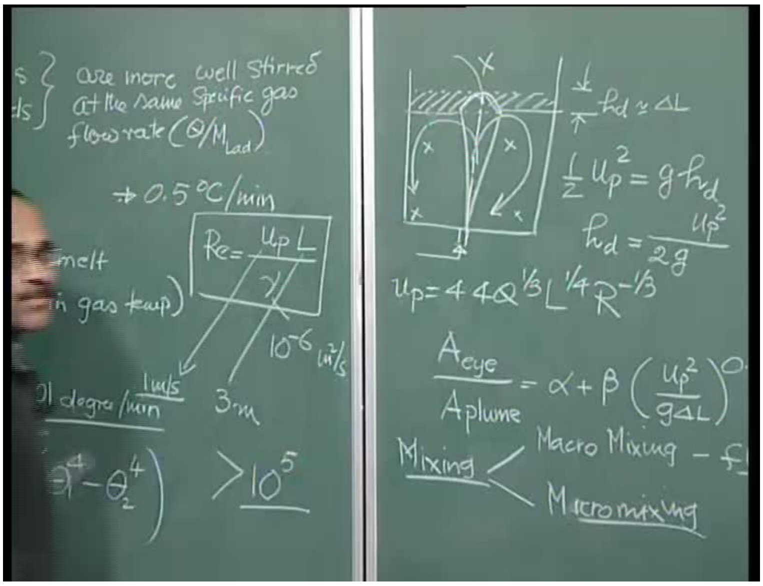
Based on what I make this opposition, if I calculate on the basis of say a reynolds number in the system, then the Reynolds number, then say how it is defined, it is defined in terms of the kinematic viscosity in the denominator and then we have characteristic velocity, if I take that to be is equal to U P and then a characteristic length scale, if I take that to be the depth of the liquid.

Now, if I calculate this substituting the values of a relevant industrial size ladles, for example the kinematic viscosity in S I unit is of the order of steel, is of the order of 10 to the power minus 6 meter square per second.

This depth of liquid typically mould 3 meters and under ladle metallurgy steel making conditions in steel processing ladles, the value of U P is of the order of 1 meter per second.

So, if you substitute these values then I am going to get a Reynolds number, a dimension less number and that number is going to give me the ratio of the inertial to viscose forces, and this is going to come out to be much larger 10 to the power.

(Refer Slide Time: 53:47)



This is the velocity that is on the basis that is due to the potential energy supplied to the system and I should not calculate the Reynolds number based on the orifice velocity, because the orifice velocity is in significant as far as the stirring in the system is concerned a more representative velocity is U P.

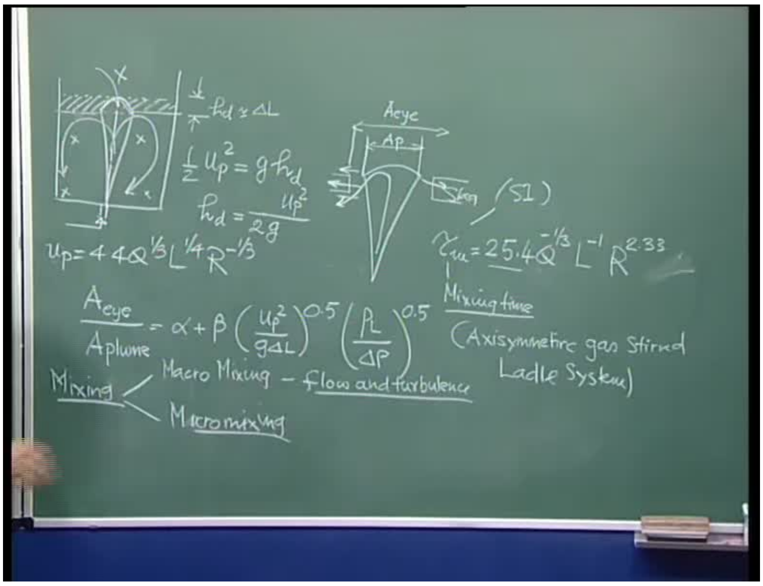
Similarly, I should not calculate reynolds number based on the diameter, because the energy input to the system is governed by the depth of liquid in the system, so on the basis of this I can therefore say that the viscose force is 10 raise to the power 6 times smaller than the inertial force, and a high reynolds number 10 raise to the power 5 times smaller than the inertial forces.

So, therefore I can say that, since the reynolds number is going to be greater than 10 raise to the power 5, we can conclude that the system is inherently a turbulent, so the large size of the steel processing vessel, the smaller kinematic viscosity of steel precludes low reynolds number or laminar flows, therefore it is an important understanding at this stage there, in most of the steel making vessels the fluid flow or molten steel motion that we are going to see, that are going to be basically turbulence, and as the turbulence aids in heat and mass transfer.

If there is more turbulent means fluids can jump from one point to another point, and along with them they can take heat, they can take mass and therefore aid in more mass transport and heat transport, and therefore macro mixing in industrial ladle system is, because of the flow which is we are talking about the mean flow or the convection current that we see, and also on top of that turbulence plays a major role as for as mixing is concerned.

Now, just like the way I have given you an equation, I will come back to this equation and I would like to mention that these are constants for example, and these constants are not yet determined specifically for industrial systems, because it is so difficult to make a realistic measurements of eye area and plume area, industrial system itself, but we do carryout some modeling studies and laboratory, and based on laboratory some laboratory skill work particularly cold model work, we have some values of alpha and beta, but for actual industrial system, the exact values of alpha and beta at this stage are not known with any certainty.

(Refer Slide Time: 56:04)



$h_d \simeq \Delta L$

$\frac{1}{2} u_p^2 = g h_d$

$h_d = \frac{u_p^2}{2g}$

$u_p = 4.4 Q^{1/3} L^{1/4} R^{-1/3}$

(SI)

$\tau_m = 25.4 Q^{-1/3} L^{-1} R^{2.33}$

Mixing time

(Axisymmetric gas Stirred Ladle System)

$\frac{A_{eye}}{A_{plume}} = \alpha + \beta \left(\frac{u_p^2}{g \Delta L} \right)^{0.5} \left(\frac{\rho_L}{\Delta \rho} \right)^{0.5}$

Mixing < Macro Mixing – flow and turbulence; Micromixing

So, similarly based on models also we have derived equations for mixing, and the mixing time is typically for an axis symmetric gas stirred ladle system. For example now you see the exponent on L and R changes drastically, for example plume raise velocity as the velocity would increase the mixing time is going to go down time, this is the mixing time, time to attain a given degree of homogeneity.

So, if efficiency of mixing is very high, I can say that mixing time is small if efficiency of mixing is very small, I can say that the mixing time is going to be larger, so the time to reach a certain degree of homogeneity, how much mixed, 99 percent of it is mixed or 95 percent of it is mixed, so I can say that 95 percent mixing time or 99 percent mixing, it is a constant and this equation is again in S I unit is 2 raise to the power minus 1 by 3.

So, an increasing gas flow rate will increase in velocity, but decrease in mixing time, because as the intensity of flow increases, the efficiency of mixing increasing as a result of which mixing time goes down.

Similarly, a vision is more tall the deep is liquid is very deep in that case there is going to be more energy input rate, so there is going to be a more stirring, so as a result of which I can expect that the intensity of mixing is going to be large, and as a consequence I would say that the mixing time is going to be shorter, and similarly when the velocities are proportional to R raise to the power minus 2, minus 2 point 3 etcetera; in this case you see that the exponent on R is positive, which essentially tells that a bigger diameter vesselfor a certain flow rate Q and certain liquid depth L is not conducive for shortening mixing or enhancing the efficiency of mixing.

Now, this correlation which I have shown here is an imperial correlation, and it is found to be valid for axis symmetric gas stirred, so there is a single plant located at the center of the vessel, and for that particular case with negligible amount of slag there is no slag layer, here you see I do not have any prandtl like this, so I would said in that sense of any slag this is the correlation which people have found to work, again I repeat that this correlation, this sort of a correlations are really derived from module studies, because it is so difficult to carry out high temperature experimental observations in steelmaking operation.