Bioreactor Design and Analysis
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Lecture – 21
Mass Transfer in Bioreactors – Part 3

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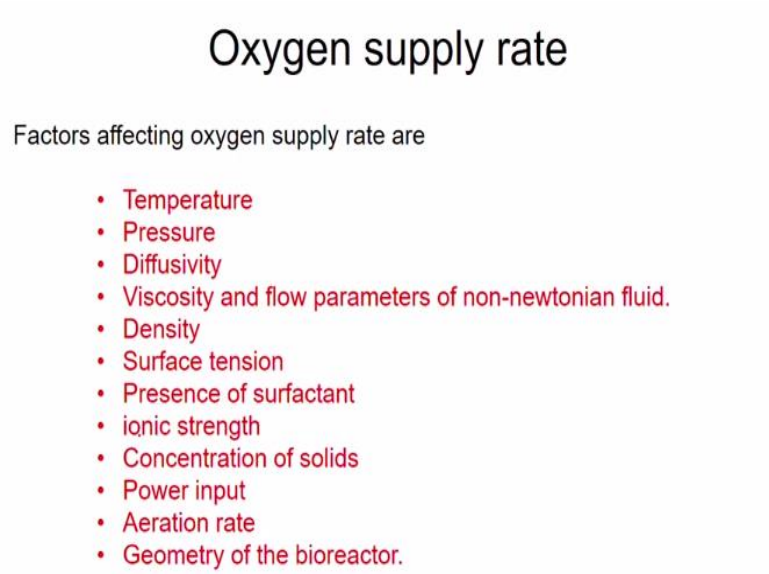

So, the factors in a fermentation system which affect the oxygen supply rate or the oxygen transfer rate this includes temperature, pressure, diffusivity, viscosity and flow parameters of non-Newtonian fluids. Like for example there are certain fluids which may become like fungal fermentations or plant cell fermentations that may behave at high cell densities and non-Newtonian fluids.

Then the density, surface tension, presence of surfactants, ionic strength of the medium, concentration of solids, power input, aeration rate and the geometry of the bioreactors. So, there are n number of parameters which can affect the oxygen supply rate or oxygen transfer rate.

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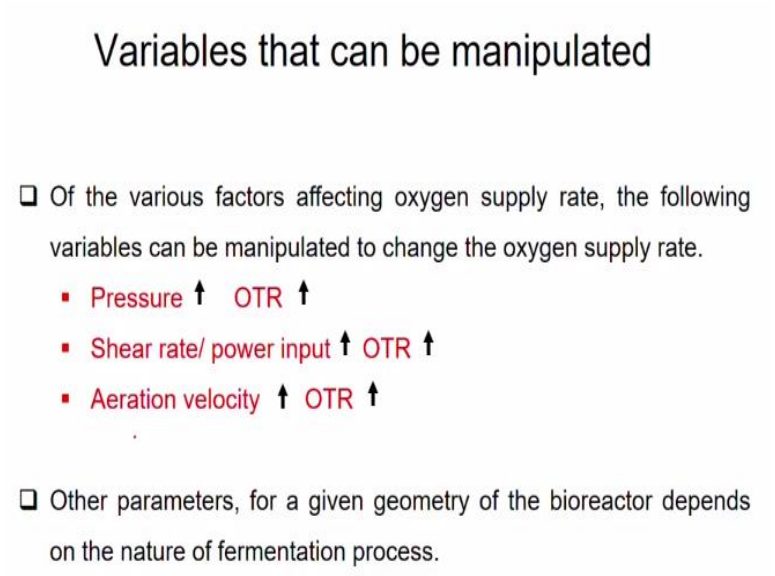

Now, generally what are the parameters which are manipulated or which are varied to make changes in the oxygen transfer rate in the reactor systems? So of the various factors which affect the oxygen supply rate, we generally bring about the changes in the following variables which are as shown on the slide here. We try to increase the pressure that will also increase the oxygen transport rate.

We can increase the shear rate by increasing the power input thereby again improving the oxygen transfer rate which happens by the impellers because the higher the rotational speed, they will break down the larger bubbles into smaller bubbles, but this may also increase by increasing the shear forces. Then the aeration velocity directly increasing will also lead to increase in the oxygen transfer rate. Now, the other parameters for a given geometry of the bioreactor depends on the nature of the fermentation process.

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Equation for oxygen transfer rate

- In bioprocess, where oxygen transfer at the inter phase controls the overall oxygen transfer rate,

$$OTR = K_l a (C_L^* - C_L)$$

Where

OTR = oxygen transfer rate ($kg/m^3 \cdot s$)
K_l = mass transfer coefficient (m/s)
a = interfacial area between air bubbles and liquid (m^2/m^3)
C_L^* = Solubility of oxygen (kg/m^3)
C_L = oxygen concentration as measured in the liquid (kg/m^3).

So, as we have done it earlier, the oxygen transfer rate in bio processes when we assume that gas liquid mass transfer resistance is the slowest step or the gas liquid interface is the most crucial step affecting the oxygen transfer. Then, the oxygen transfer rate is defined as given here. Now, if this is so and if you need to determine the value of K l a as shown here, then we generally use two techniques.

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static method

- **In this method, first oxygen is stripped from the medium by sparing nitrogen**
- **Then air is sparged through the medium and the dissolved oxygen concentration is measured as a function of time, using an oxygen probe.**
- **Data of C_L against t (time) is collected and fitted to the equation given below to estimate $k_l a$.**

$$\frac{dC_L}{dt} = k_L a (C_L^* - C_L) \Rightarrow \ln\left[\frac{C_L^*}{(C_L^* - C_L)}\right] = k_L a\, t$$

One is called the gassing out technique, which is a static method. In this method, first the oxygen is stripped off from the medium by sparging in nitrogen and then, so which means that all the oxygen is being sparged off. Then air is sparged through the medium and the dissolved oxygen concentration therefore starts rising and it is then measured as a function of time using an oxygen probe in the reactor.

So, what we collect is the data of C L versus time. And now this data is fitted in the equation which we had shown earlier of OTR which is oxygen transfer rate. So, your OTR is nothing but dC L by dt the rate of oxygen transfer now why because here dC L by dt is the rate of accumulation of oxygen in the medium. So, because there are no cells present, so there will be no oxygen consumption. Therefore, the oxygen consumption term is not considered.

So, whatever oxygen is being transferred in the medium defined as the RHS here will be equal to the rate at which the oxygen is getting accumulated in the broth. So, now if we integrate this equation given here then it becomes a linear function as shown here. And if we make a plot of ln C L star by C L star – C L versus t, then the slope of that line can give us the K l a.

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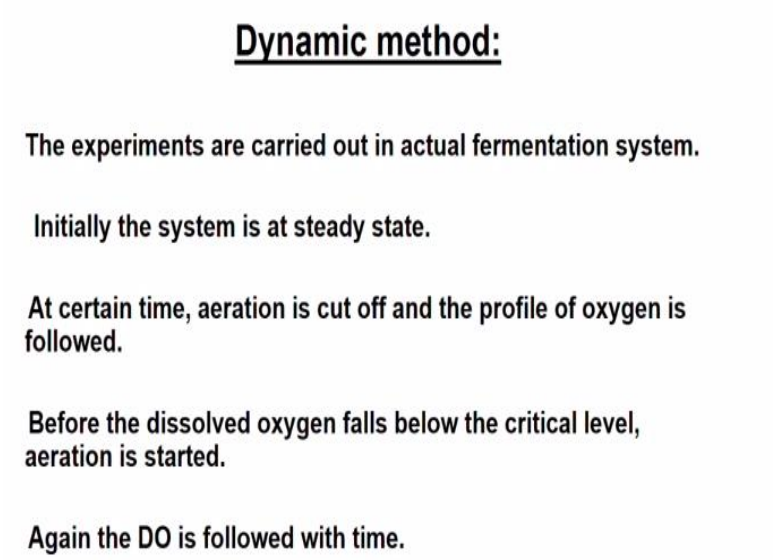

There is another method called dynamic method because this will give you a better approximation of K l a because there will be culture growing inside the formentor system. So, it is much closer to a real situation. So, the experiments are carried out in actual fermentation system. Initially the system is maintained at steady state with respect to oxygen, then at some given time the aeration is cut off.

And what you will observe is the change in the oxygen profile with respect to time. Now before the dissolved oxygen levels falls below the critical oxygen, again the air is sparged in and the concentration of oxygen with respect to time is further noted till it reaches the steady state again.

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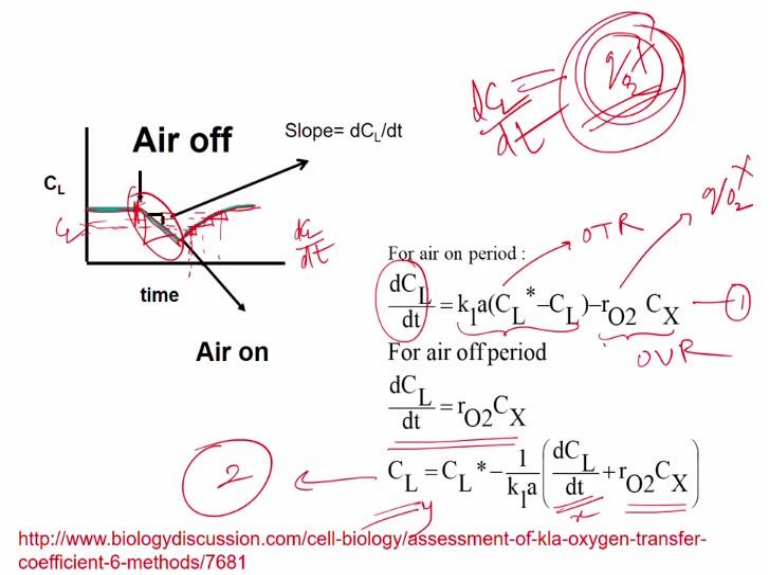

As shown on the slide here will be the trend which will be observed generally for C L versus time. So, till the arrow which is showing here as air off, it is a steady state with respect to oxygen. Once the air is cut off, so there will be a linear decrease assuming that during this experiment, there is no significant growth happening, so the X can be assumed to be nearly the same constant.

So, if q 0 is the specific oxygen demand q 0 O 2 and X is the biomass this will determine the oxygen demand or oxygen uptake rate. Now, during this phase when the air is cut off, there is only oxygen demand, but there is no oxygen transfer. So, the rate at which the oxygen in the bulk will be coming down as shown here will be linear as q 0 O 2 X is a constant. So, we can see it is a straight line and this slope can give us the value of the oxygen demand.

Before it goes below C critical, again the air is switched on and it will gradually raise to the steady state value. Now during this increase again data is collected for various C L N at different time points. Now at every such point on this plot, we can take a slope which will determine the dC L by dt at that time with the corresponding C L value and the time value. So, we will have such data with us. So, let us come to our continuity on mass balance for oxygen.

So, if you see equation one here, this is simple mass balance for oxygen transfer your dC L by dt stands for the oxygen accumulation rate. K l a times C L star – C L stands for the oxygen uptake rate, sorry oxygen transfer rate and r O 2 times C X where r O 2 is nothing

equivalent to your q O 2 which is specific oxygen demand and C X is nothing but your X. So, this stands for your oxygen uptake rate.

Now, the first half of the experiment, which I am encircling here, the slope there will give us the oxygen demand of the culture which is your oxygen uptake rate. Now, oxygen uptake rate from the slope can be determined, so then this value is known a constant. And if you do the rearrangement here of equation 1, so after rearrangement we will reach to equation 2 and C L is unknown, rest all the factors can be obtained.

So dC L by dt is x here and C L is y. So, it is again a linear function and the rearrangement gives us the slope which is inverse of k l a.

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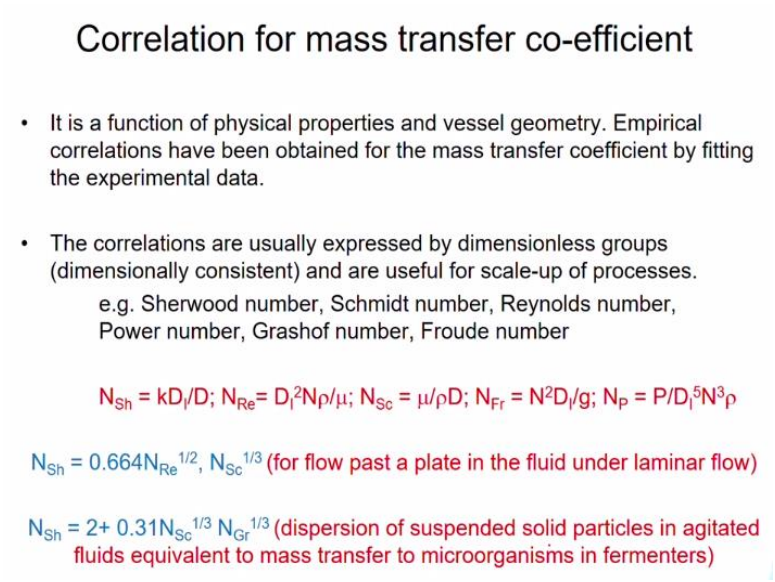

So, there are empirical core relationships also present for k l a determination. It is a function of physical properties and vessel geometry. So, the correlations are generally expressed by dimensionless groups or numbers and they are also used in scale-up of the processes. So, dimensionless numbers like Sherwood number, Schmidt number, Reynolds number, Power number, Grashof number and Froude number.

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- k_La is the critical parameter: volumetric mass transfer coefficient

$$k_La = k(P_g/V_R)^{0.4}(v_s)^{0.5}(N)^{0.5} \quad (1)$$

k, empirical constant; P_g, gassed power requirement; V_R, bioreactor volume, v_s, superficial gas velocity, N, rotational speed of agitator

- These correlations do not include effects of medium components on k_La
- Presence of salts, surfactants can significantly alter bubble size and liquid film resistance around the gas bubble. These factors can affect C* (oxygen solubility). Temperature and pressure also affects C* and k_La.

So, one such relationship here has been used to determine how k L a can be a function of various other reactor operating parameters like the gassed power requirement, the volume of the reactor, superficial gas velocity, the RPM of the impeller. So, your equation 1 is one such empirical relationship to determine volumetric mass transfer coefficient. Now if you notice these relationships they do not include the effect of medium composition.

However, presence of salts, surfactants they can also significantly alter the bubble size due to their effect on surface tension which forms the liquid film resistance around the gas bubble and thereby change the bubble size which changes the surface area for mass transfer and the thickness of the film changes then it is also impacting the mass transfer coefficient. Now, these factors then eventually affect the oxygen solubility at equilibrium, which is the C star value.

Similarly, your temperature and pressure it can also affect both the saturation concentration of oxygen which is your C star which is governed by the mole fraction of oxygen and also the pressure and k L a.

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Functions of an agitator

- Provide uniform dispersion of the gas bubbles.
- Produce small gas bubbles by breaking the large bubbles at the gas inlet by shearing with fluid velocity gradient.
- Maximize the retention time of the gas in the broth by driving the gas bubbles to the bottom of the bioreactor.
- Maintain uniform concentration of the nutrient throughout the bioreactor,
- Facilitates heat transfer and maintain uniform temperature throughout the bioreactor.

So, let us see what are the functions of an agitator? We have seen during the introductory lecture that it can provide uniform dispersion of gas bubbles. It can produce small gas bubbles by breaking the large bubbles at the gas inlet by shearing with the liquid velocity gradient. Maximize the retention time of the gas in the broth by driving the gas bubbles to the bottom of the reactor.

So, your exhale movement can improve the retention of the gas bubbles. Maintains uniform concentration of the nutrient throughout the bioreactor and it also facilitates heat transfer and maintains uniform temperature throughout the bioreactor. So, it also disperses the gas bubbles to the walls of the reactor.

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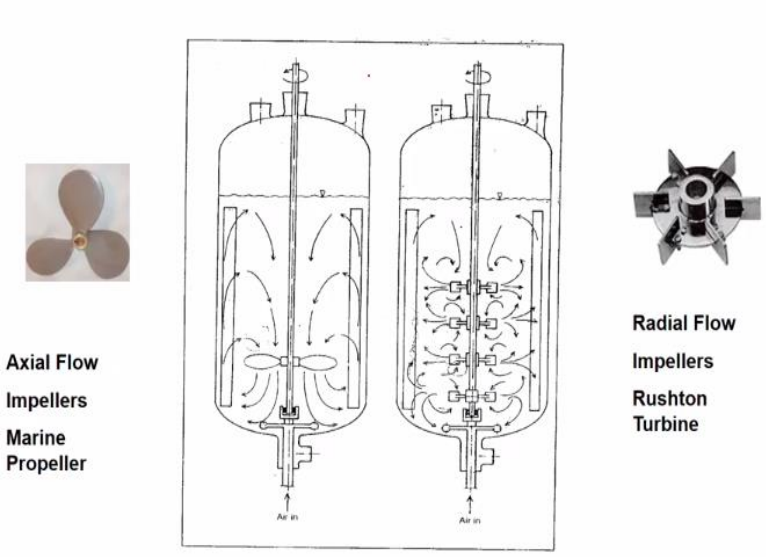

So, if you see on the slide, axial flow impellers have been shown here where the movement is parallel to the shaft and radial flow impellers have also been shown where the movement is perpendicular to the shaft. So, examples well known for axial impeller is marine impeller and for radial flow impellers mostly used are turbine or Rushton turbine impellers.

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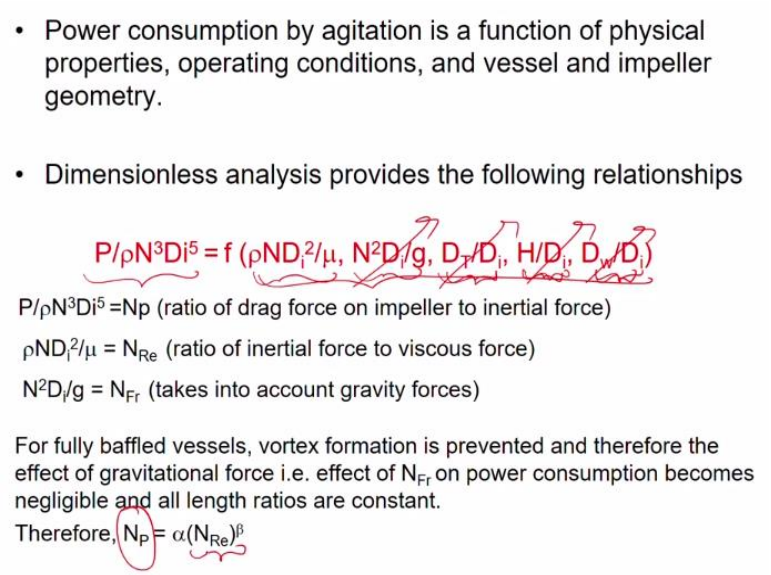

Now, for adequate agitation the power will be consumed by the impeller. So, how to determine the power consumption? This power consumption is found to be a function of various physical properties, operating conditions and vessel and impeller geometry. So, again dimensionless analysis is used to provide these relationships. So, if you see one such relationship it shows here that the power consumed by the impeller

Which is given here by the dimensionless number called as Power number is found to be a function of other dimensionless numbers which are in turn a function of various reactor and vessel geometry and the fermentation parameters like the first dimensionless number is the impeller Reynolds number. Then the second one is your Froude number which takes into account the gravitational forces.

The Reynolds number we all know it is the ratio of the inertial forces to viscous forces and then rest of these are relating the geometrical parameters to the power consumed. So, now if you noticed D T which is the tank diameter to the impeller diameter D i, H is the height of the tank, D i is the impeller diameter, D w is the width of the impeller and D i is the impeller diameter.

So, these ratios D T by D I, H by D i, D w by D i these are generally governed by thumb rules and they can be assumed to be constant. So, we can neglect these and for fully baffled vessels the vortex we will assume there is no vortex formation. So, further the effect of gravitational forces which is the Froude number on power consumption also becomes negligible. So, this is further neglected and because as I said earlier the length ratios are constant. So, now effectively the Power number is found to be a function of the Reynolds number.

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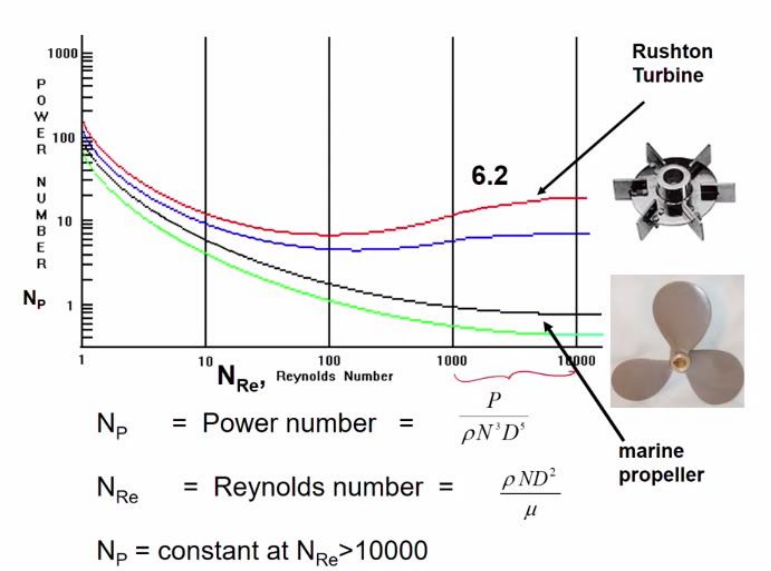

So, for different kinds of impellers if a correlation is drawn with the change in the Reynolds number how the Power number changes as shown here in a plot you can observe the different profiles. In most of these cases in the turbulent region where the Reynolds number is beyond 1000 or 10,000, the Power number is found to become constant.

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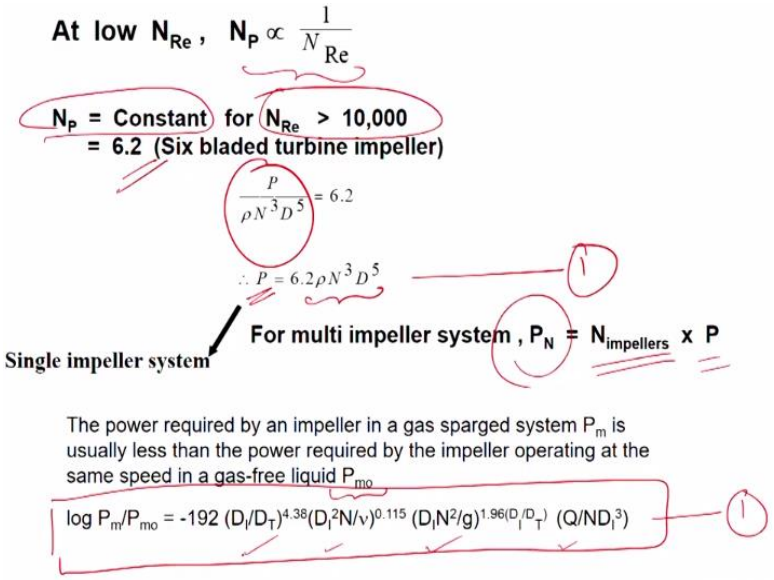

At lower Reynolds number, your Power number is said to be inversely proportional to the Reynolds number. And when Power number is constant is the case if you see here beyond 10,000 it becomes constant. So, if you see at a very low Reynolds numbers it is can be considered as a linear drop, and therefore it is said that the Power number is inversely proportional to the Reynolds number.

And at N Re in the turbulent region greater than 10 to the power of 4, your Power number becomes constant for a given type of impeller. Like for example, for 6 blade turbine impeller, this number becomes 6.2**.** So, Power number is given by an expression here, where P is the power consumed, N is the RPM, D is the diameter of the impeller and rho is the density of the broth. So, then the power consumed by the impeller at the given reactor operating parameters can be determined.

This is for a single impeller. So, if there are more number of impellers, then this power consumed can be multiplied with the number of impellers to give the total power consumed by that system. Now, the power consumed by the impeller in a gas sparged system will be lesser than the power consumed in an ungas system. Because to reach to a particular homogeneity, the gas sparging also helps in the mixing. So, the net power consumed therefore is less.

So, net power required by the impeller operating at the same speed in a gas free liquid, let us assume it is at P m0, so then the correlation given here at the bottom is generally used to relate the gassed and ungassed power requirement with the functions of aeration number, Froude number, Reynolds number and your linear ratios of your length ratios where it is D i by D T, D T stands for the tank diameter and D i is the impeller diameter.

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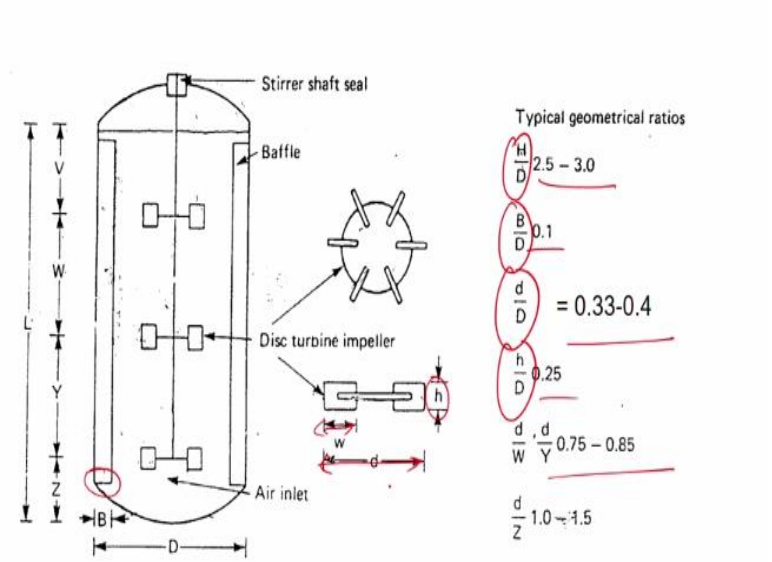

So, as I said earlier the linear length ratios generally they follow thumb rules. So, here these are some thumb rules given for reference, you can make note of it. In the given schematic you can see capital D stands for the tank diameter, small d stands for the width of the baffle. Your L is the length of the reactor or height of the reactor. Small h is the height of the impeller, w is the width of the impeller and d is the diameter of the impeller. So, these linear dimensions or linear lens have been related as constant ratios.