Biological process design for wastewater treatment
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Lecture 16
Reactor Hydraulics-II

Welcome everyone in this NPTEL course on biological process design for wastewater treatment. So we will continue from our previous lecture on reactor hydraulics, and we will try to learn new things regarding the reactor hydraulics. So, in the previous lecture, we learned that in terms of mixing patterns, there are few types of reactor.

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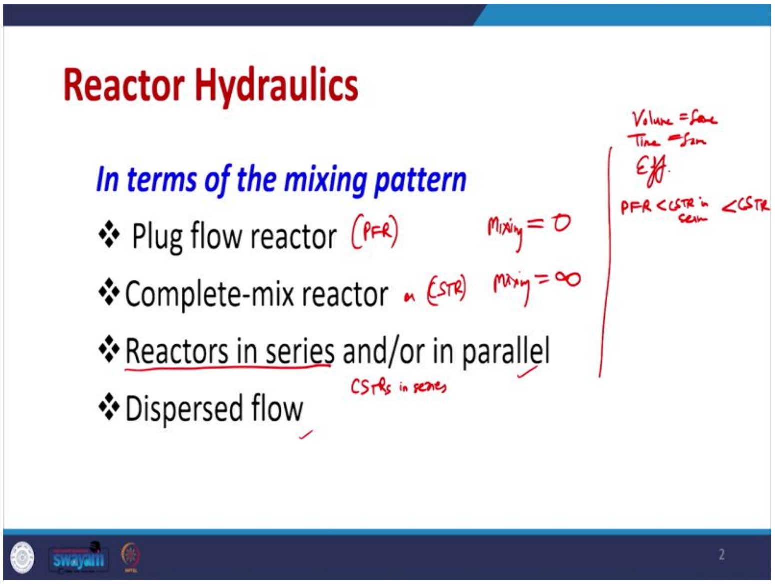

The one of the important reactor is called plug flow reactor or it is called PFR, there is another reactor which is called as complete mix reactor or complete mixed tank reactor and it is referred to as CSTR in general terms in reaction engineering etcetera, then we learned regarding the reactor in series and are in parallel that we are going to learn today but reactors in series we learned in the previous and that was more of CSTRs in series. So, we found out CSTR in series that was the learning that we did in the previous lecture. And today we will continue with other topics reactors in parallel dispersed flow.

Now, in the previous lecture, we also learned that in the plug flow reactor the condition is that, that we assume that there is no mixing, mixing is virtually 0, whereas, the mixing is very high and virtually infinite mixing for CSTR, efficiency wise if we try to find out for the same condition we solved one problem also, so we found that for if same volume of reactor volume is same for same volume of reactor and for same time of treatment same detention time, we found that efficiency followed the following pattern, that it was highest per PFR then it was a little lower for CSTR in series and then it was further lower for CSTR in general.

So, this was the idea that we obtained from the previous lecture. Now today we will learn regarding dispersed flow and CSTRs in parallel and some other concepts related to reactor hydraulics. Now disperse flow the mixing conditions in that dispersed flow reactor, disperse flow reactors are like in between the plug flow reactors and CSTR reactor. So, for any reactor we can find out a number which is called as dispersion number.

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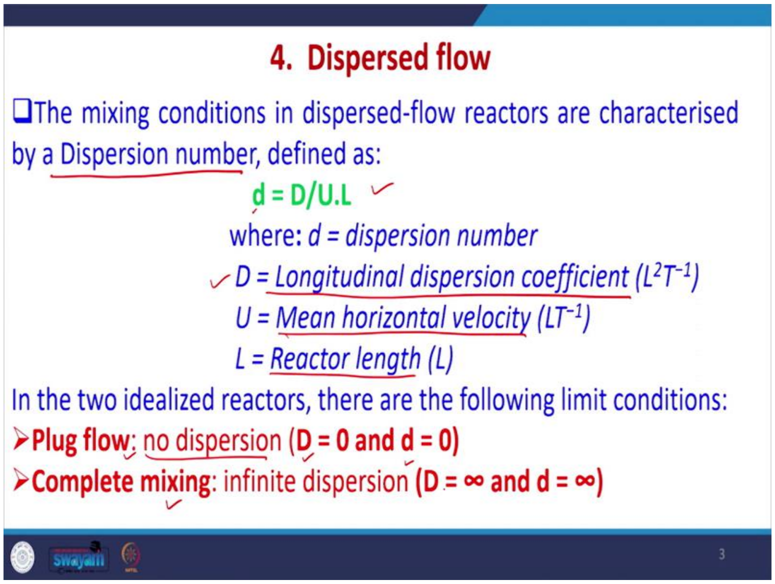

And if we can find out the dispersion number, we can tentatively identify the mixing conditions and we can define the mixing conditions, so dispersion number is called as D and it is defined as capital D/UL and capital D is longitudinal dispersion coefficient and then we have U is called mean horizontal velocity and L is called reactor length. So you can refer to any good book for understanding how the dispersion numbers are found out in chemical engineering.

And through this we can base upon the value or dispersion number that to idealize reactor that we learned in the previous lecture, the plug flow reactor and the complete mix in reactor, the CSTR we can for plug flow reactor since there is no mixing, so, there is no dispersion that means, the capital D is also equal to 0 and the small d is equal to 0 the dispersion number is 0 and the dispersion longitudinal dispersion coefficient is also 0.

For CSTR since infinite mixing was there so, that means there is infinite dispersion that means that capital D and small d both are equal to infinite value. So, this is there now, how the what are the factors that affect the dispersion in any other treatment units. So, this is also need to be identified. So, this depends upon number of parameters and these parameters are written here.

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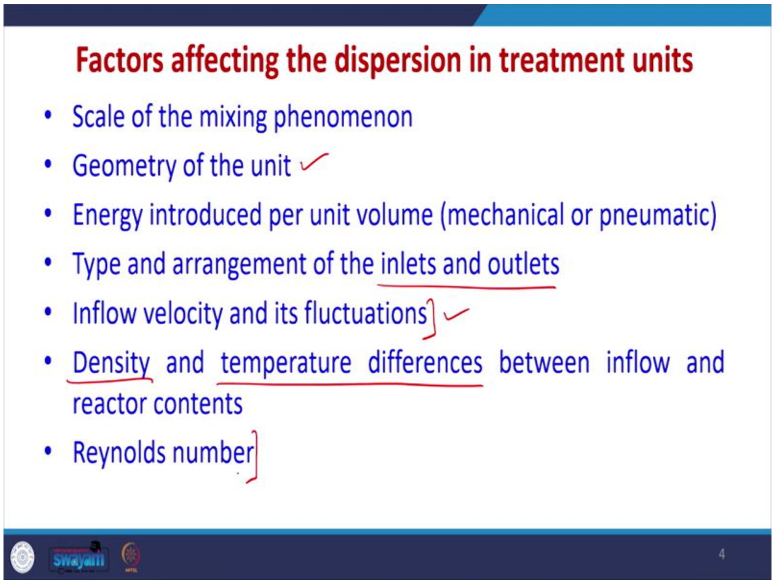

Now, these parameters may broadly be classified like depending upon the scale of what is the geometry of the unit, what are the different mixing things which are used. So, whether you we are using agitator or say some there is some dispersion of air etcetera, that means, if we are first and foremost geometry of the unit, so, whether we are using baffles or not. So, all these things are important, what is the length of the length and volume, all these are very important the geometry of the unit is very important with respect to determining the mixing or dispersion.

Then, second thing is that what is the scale of mixing, so, whether we are using agitator then what is the energy introduced per unit volume similarly, are we using some dispersion of air gas etcetera. So, again the energy introduced etcetera is very important then the type of within the geometry the type and arrangement of the inlet and outlet how is the inlet and outlet arranged inside the reactor. So, because these two things also introduce mixing inside the reactor, so depending upon that will be varied.

Now, if the arrangement is fixed, then what is the inflow velocity and its fluctuation these also causes a lot of variation in the mixing and thus in the dispersion number this is again very important, then the density and temperature difference between inflow and reactor content. So, if there is a lot of differences, there so certainly some mixing will be induced by the density difference and similarly, because of the temperature difference some mixing may be induced. Now Reynolds number is related to the flow pattern. So, depending upon the flow pattern other things overall Reynolds number will affect the dispersion inside the treatment units.

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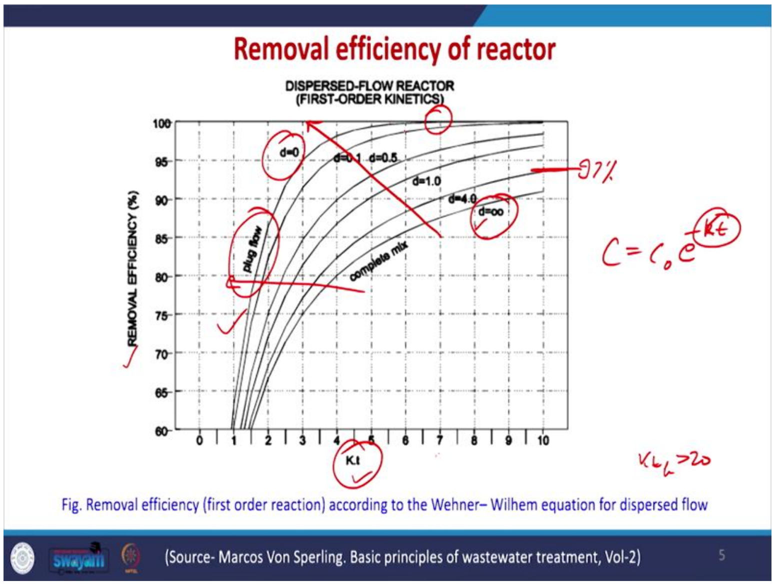

Now, in this graph, the effect of dispersion the D dispersion number is given for first order kinetics and we can easily see the y axis is represented by removal efficiency the x axis is represented by the Kt value which is related to first order because we have C is equal to C_0e^{-kt}. So, this kt is very important in terms of capital so, this kt value is written here and in terms of kt it is shown.

So, we can for any particular k value we can find out the and we can easily see here that as the value of d is decreasing or we can see from infinite value to 0 the efficiencies are increasing that means, as the value of d is increasing, the efficiency is decreasing. And as we are moving towards the no mixing condition, where there is no mixing between different plugs or piston types of fluid, then we do not we have very high efficiency. The moment from complete mix to plug flow reactor gives higher efficiency, this is the key point from this particular figure we can observe.

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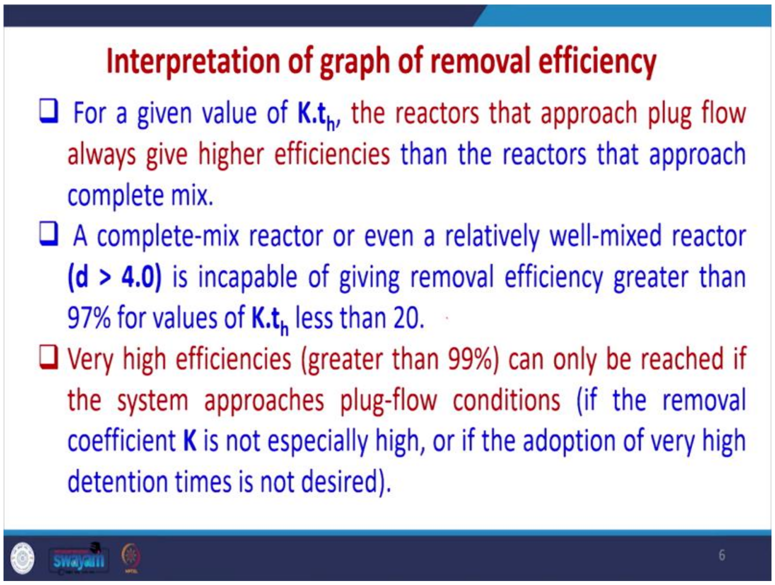

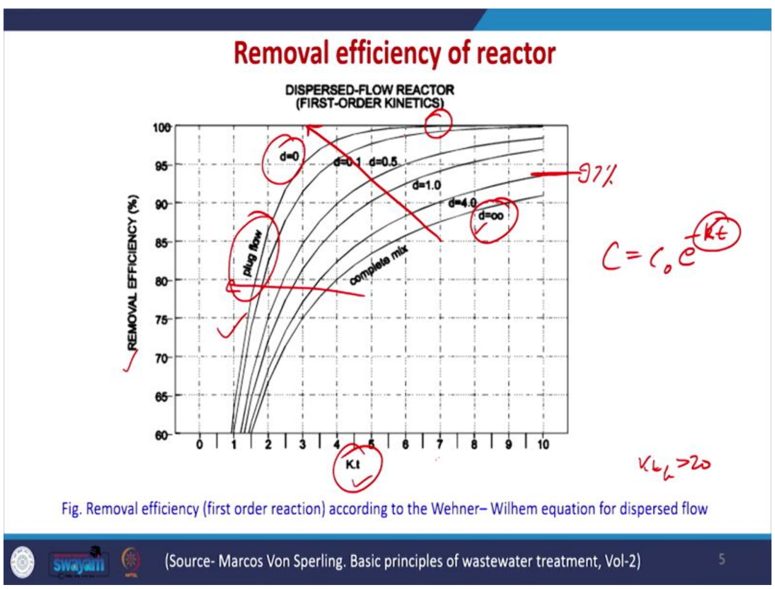

Going further interpretation of the graph with respect to the renewal efficiency for a given value of K^{th} the reactors that approach plug flow always give higher efficiency than the reactors that approach complete mix. Then a complete mix reactor or even a relatively well mix reactor is incapable of giving removal efficiencies greater than 97 percent for the values of K^{th} less than 20.

So, like we can see here that if 4 is also reached, we are reaching only 97 percent. So, we are not going higher than that, so that means, we can never achieve a good efficiency until unless we have K^{th} value very high, greater than 20 maybe, then we can go more than 97 percent otherwise, we can never go more than 97 percent, so this is very important, then, very high efficiency is greater than 99 percent can only be reached if the system approaches plug flow conditions.

And this is more true if the removal coefficient k is not especially high, or if the adoption of very high retention time is not being considered. So, we have to, there is no way out we have to go for like less than K^{th} Kt value less than 7. If we want to reach 99 percent we have to go for the this plug flow reactor there is no way out we cannot solve it. So this is the condition. So this is these are important interpretations with respect to flow pattern, mixing, dispersion number or plug flow use of plug flow or CSTR reactor.

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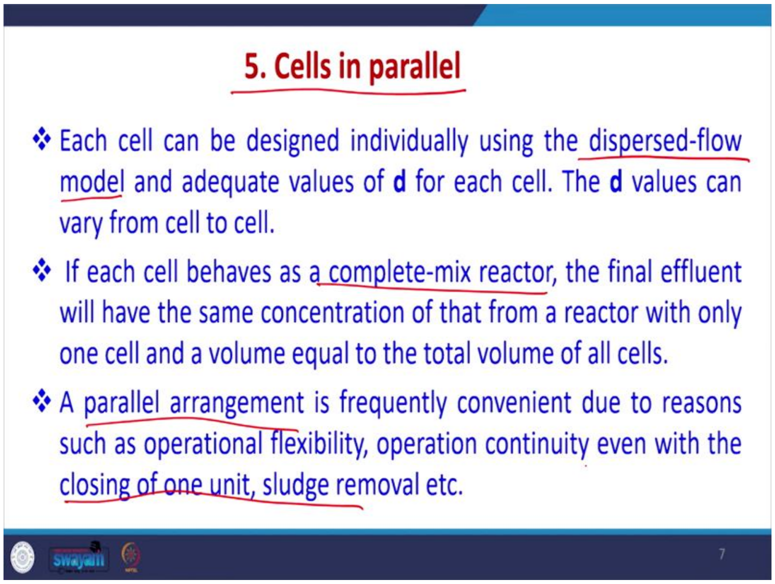

Now, we are going further can we use cells in parallel? Yes we can use cells already we have studied cells in series. So, we are going to learn a little bit regarding cells in parallel, so each cell can be designed individually using that disperse flow model and adequate values of D for each cell, the D values can be varied from cell to cell, so this is possible. If each cell behaves as a complete mix reactor that means, the D value is infinite.

The final effluent will have the same concentration as that from the reactor with only one cell and the volume equal to the total volume of all cells. A parallel arrangement is frequently convenient due to the reasons such as operational flexibility we can use one cell at a time or use all cells operational continuity even with closing of one unit and sludge removal, so, this is very important.

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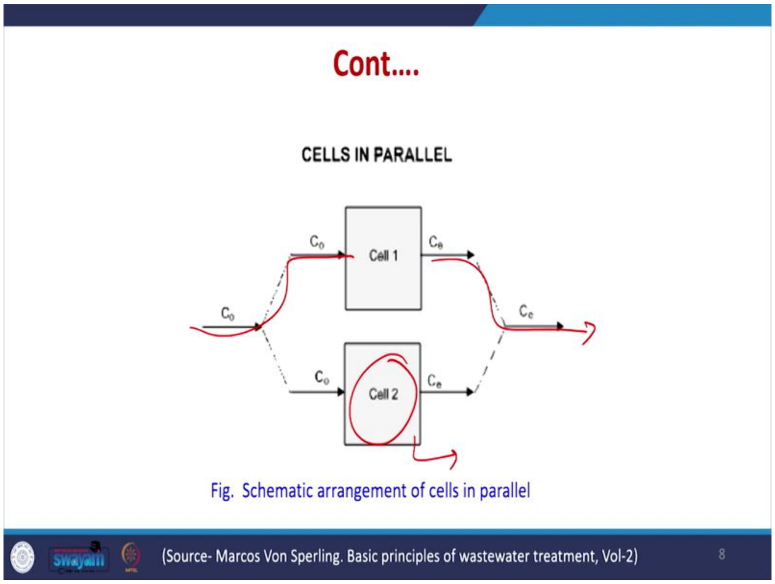

A parallel arrangement has lot of benefits that if suppose, we have these cells are there and these cells is out of order we are trying to remove the sludge out of this so, we can divert all the flow through this particular line and still we can treat the water our system will not be down otherwise our system will be down since we have to remove the sludge and then the water has to be accumulated beforehand somewhere so, that the treatment can be done later on. So, cells in parallel are always considered for better operation of the plant, cells in series and parallel for greater operational flexibility the arrangement of cells in series and in parallel is frequently used.

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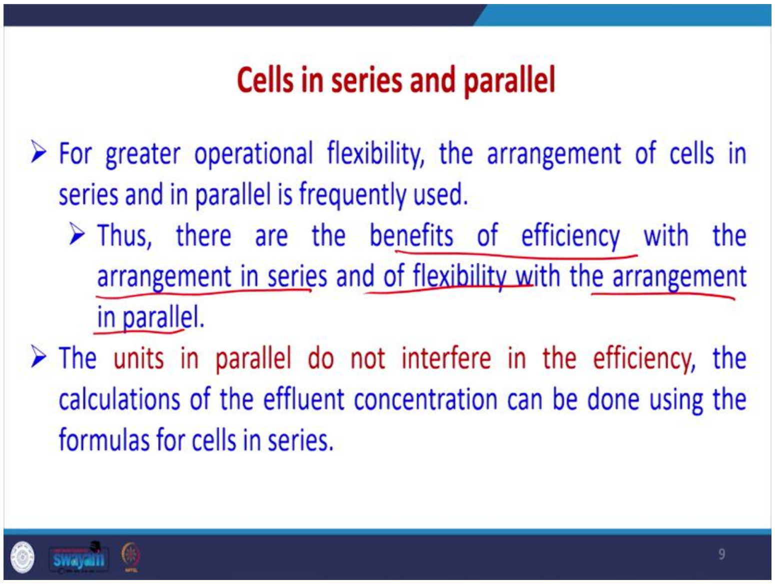

And thus there are benefits of efficiency with arrangement in series and our flexibility with arrangement in parallel. So, if we are arranging the cells in series that we are increasing the efficiency. Now, when we are arranging the cells in parallel, we are increasing the flexibility of operation which is very desirable in the case of wastewater treatment, because, we have to do a lot of cleaning operations after some time for biological reactors also like sludge removal and other things.

So, these for these operational be, it is more flexibility is also desirable along with the certainly the efficiency value, the units in parallel do not interfere in the efficiency and that calculations of the effluent concentration can be done using the formulas of cells in series.

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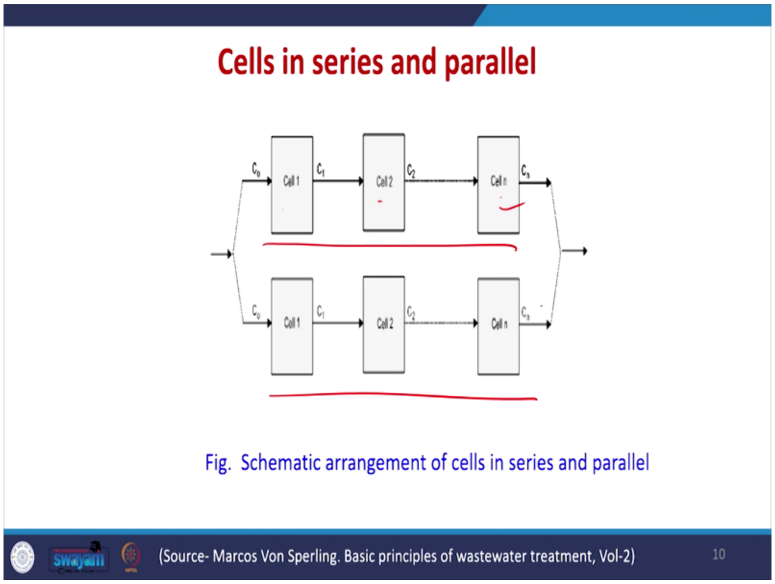

So, we can have like this type of structure where we have now, two cells in series and if any other cells is being cleaned or it is not in operation, the other one can be used. So, this type of arrangement is always possible and should be preferred for treatment of the wastewater in particular for biological treatment or for physio-chemical treatment also. So, we have cells 1 2 3 and number of cells in series and there are 2 such series. So, we are parallel series arrangement together.

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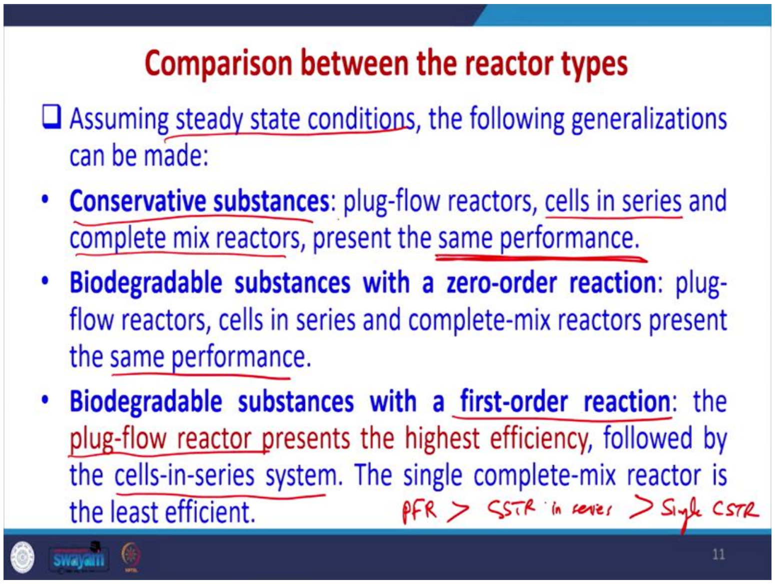

Now, comparison between the reactor types that we have studied till now, we have studied plug flow reactor, we have studied CSTR in series we have studied CSTRs, so, now, assuming steady state condition that means, when we are reaching the final condition, everything is totally at a steady state the following generalizations can be made conservative substances which do not decrease or for substances which are refractive in nature and which are not degraded inside the biological systems.

So, for these systems the PFR cells in series, CSTRs in series are CSTRs, they have the same performance that means, it does not affect whether which type of reactor we are using for conservative substances. Similarly, for biodegradable substances with a 0-order kinetics reaction kinetics, that means they are not dependent upon the concentration of the substance for these conditions, the again we have same performance, the PFR CSTR and CSTR in series they have same performance we have already studied this.

For biodegradable substances with first order kinetics, reaction kinetics, the plug flow reactor the PFR presents the higher efficiency that we have already seen, followed by cells in series. So, we have if CSTRs are in series, they will be having better performance as compared to single CSTR, which is the least efficient. So, this is the order we have PFR which is preferred then CSTR in series and then finally, the single CSTR. So, this is the overall pattern with respect to efficiency.

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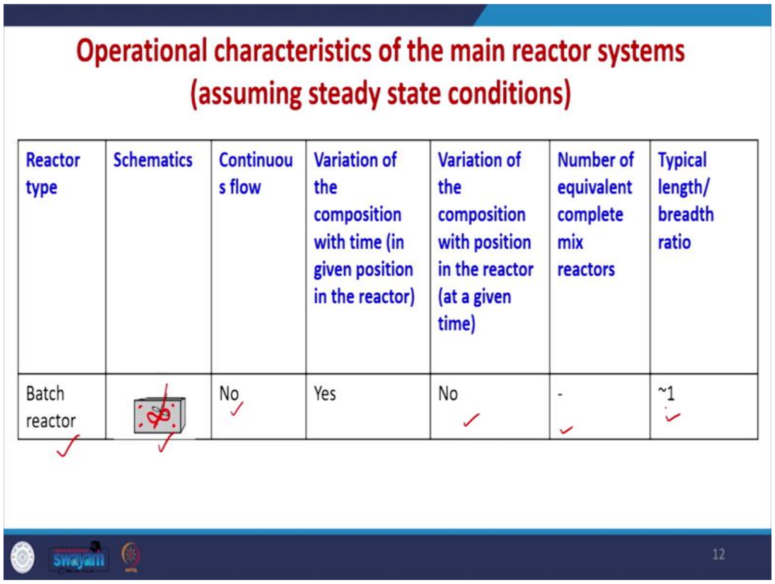

Going further, we will try to understand a little bit compare the operational characteristics of the main reactor systems. The first and foremost is the batch reactor. So, in the batch reactor, the we have like already the reactor will be filled and we have mixing which is happening inside the reactor. So, there is no continuous flow, because the reactor will be initially filled and after certain time of treatment maybe 5 hour 10 hour 5 days the effluent will be taken out the sludge will be removed.

So, we have no continuous flow, variation of the composition with time, yes, because initially the concentration will be high with time the concentration will decrease, variation of the composition with position in the reactor will there be a difference in concentration at any time? No, because we are assuming complete mixing condition. So, here also this is complete mixing, so, there is no variation in composition with position of the reactor. The number of equivalent complete mix reactor we cannot follow because this is a batch reactor not a continuous reactor and that typical length to breadth ratio are 1.

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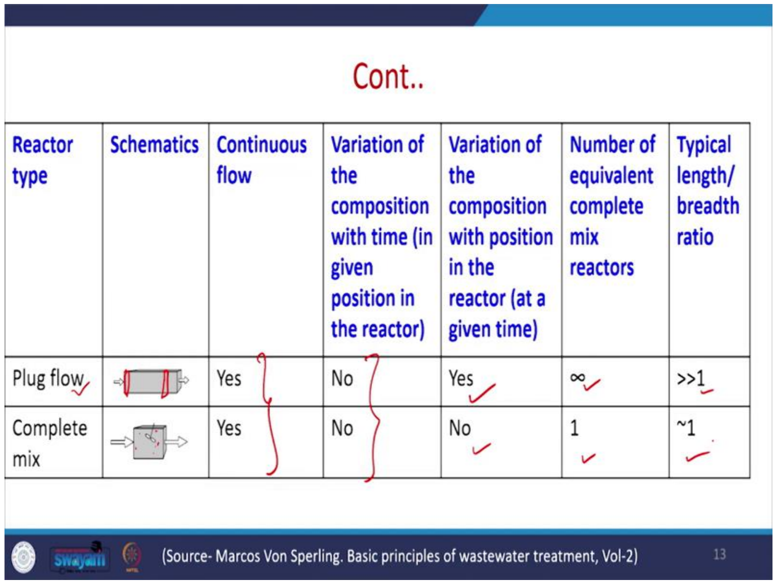

Reactor type	Schematics	Continuous flow	Variation of the composition with time (in given position in the reactor)	Variation of the composition with position in the reactor (at a given time)	Number of equivalent complete mix reactors	Typical length/ breadth ratio
Plug flow		Yes	No	Yes	∞	>>1
Complete mix		Yes	No	No	1	~1

Now, for plug flow in complete mix reactor, both are continuous flow reactor where the water to be treated is coming and after treatment it is going out. So, in both the case we have continuous flow so, these are not batch flow conditions these are called continuous reactors. Now, variation in the composition with time. So, there is no variation in the composition with time at any time for CSTR again it is well mixed so, it is no variation with time for this also though there is variation in the composition with position of the reactor, that means, the reactor here will be having different composition as compared to the reactant here, but with the time it will remain same.

So, that means there is no variation in composition with time for both the reactors. But yes for plug flow reactor there is variation in composition with position of the inside the reactor, but for CSTR there is no variation because it is a completely mixed tank reactor, the number of equivalent CSTR, so, if we have to model PFR with CSTR, so number of CSTR required are infinite whereas for complete it is 1, and typical length is much much higher as compared to breadth or diameter that means the typical length is much much greater than 1 for PFR and it is equivalent to 1, for in case of CSTR.

Now, we will try to have some mass balance, heat balanced approach etcetera in this lecture. So, for mass balance the we can always apply the mass balance to any reactor system or combination of reactor systems, we have already studied little bit of mass balance in an reaction earlier when we applied balances with respect to element, balances when we studied the Stoichiometry.

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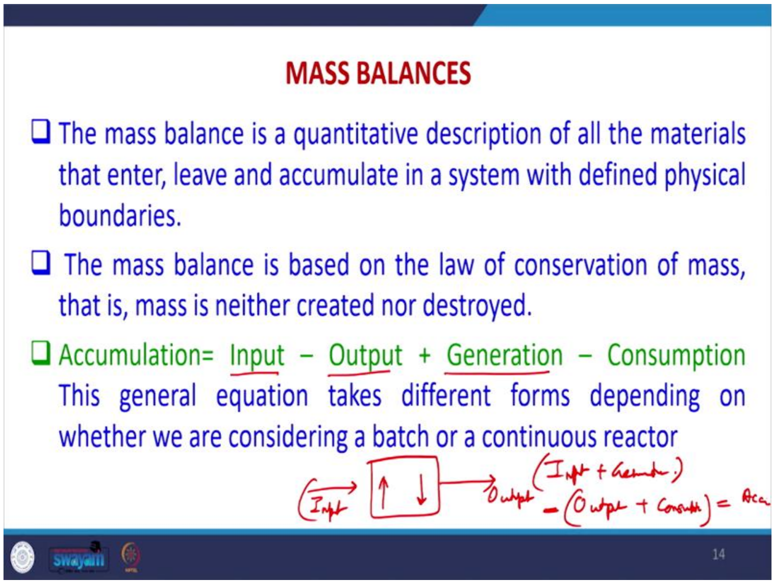

So the mass balance is an quantitative description of all materials that inter leave or accumulate inside the system within some defined physical boundary, the mass balance is based upon the law of conservation of mass that is, mass is neither created nor destroyed to under this condition input minus output plus generation. So, what we are doing that suppose this is our system boundary and there is some flow in and there is some flow out. So, we will try to see that the input plus there is a possibility that there is a generation of mass which is happening inside the reactor.

So, input plus generation, so there will be input plus generation which is there. Then we have output which is coming out and there is a possibility that some consumption of mass is also happening via some reaction. So, output this is one term this is output plus consumption because we are losing mass here, this is another and the difference between the two is what is getting accumulated inside the reactor. So, this is accumulation. So, this is the total balance.

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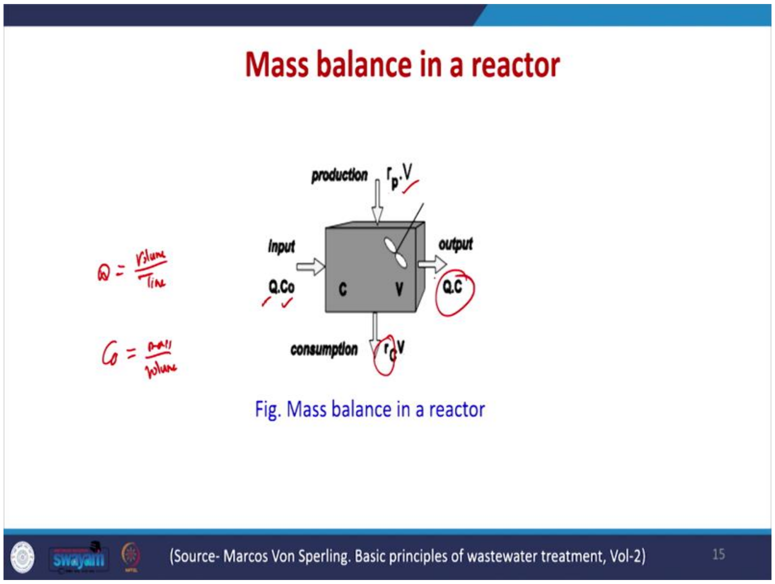

Now, if we try to write for this reactor which is given here, the reactor is having a concentration of C_0, initially, the flow rate is Q, the production is happening at the rate of rate of production is $r_P V$ and data consumption is r_C into V, this is their and output is QC.

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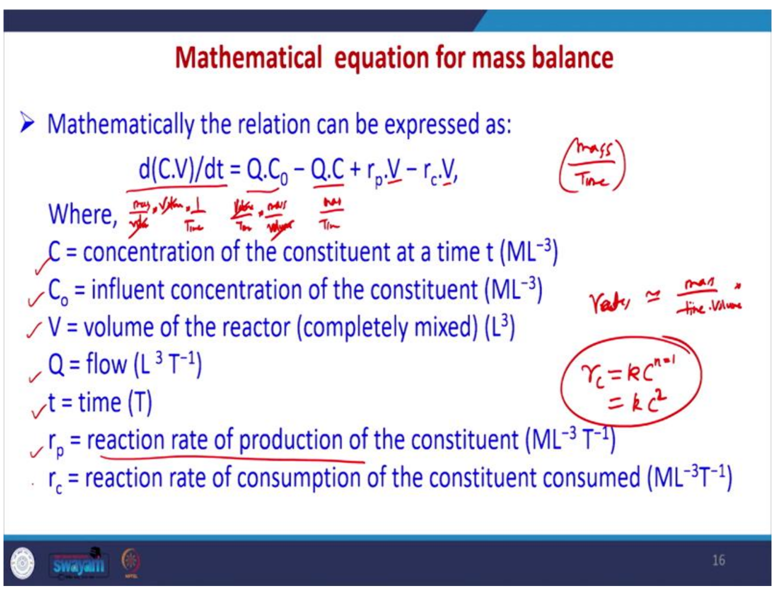
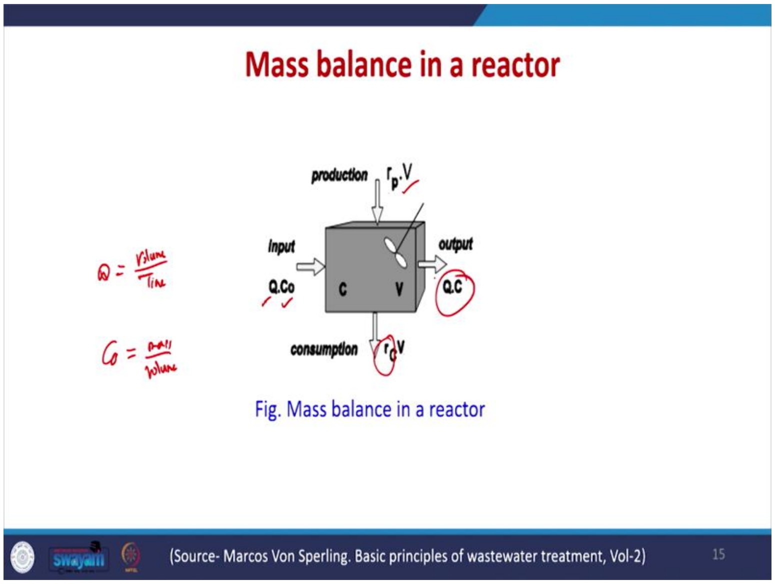


Mathematically the relation can be expressed as:

$$d(C.V)/dt = Q.C_0 - Q.C + r_p.V - r_c.V$$



So, if we write the mathematical equation, we can write, what is the mass here, if we assumed the C_0 is in some unit like mass per unit volume, which is correct and Q is the volume flow per unit time. And so, we are trying to write an equation where the overall unit is mass per unit time remember, for this equation, we are trying to write an equation with each of the term having the unit of mass per unit time.

So, Q into C_0, if you see volume per unit time or mass per unit volume. So, overall it is here if we write for Q, Q is the volume, this is volume per unit time and this is mass per unit volume, which is the concentrations, so volume volume goes off here mass per unit time same here for this also, which is outlet QC is the one which is going out. So, QC is mass per unit time again, r_P r the rate reaction rate of production, they have the unit like rate of production per unit time per unit volume. So, they generally the rates have the units the rates, the rates have the unit like this mass per unit time per unit volume, what is what is the rate of production of mass.

So, that means, we have to multiply together by volume to get the unit of mass per unit time. So, that is why the rate of production and rate of consumption both are being multiplied together by V and also like for rate of consumption, it is possible that if it is being followed by first order kinetics, it can further be written as like rate is equal to rate of consumption is equal to Kc depending upon the order here is assumed to be 1, if it is first order.

If it is second order we can write Kc square, so, these terms will depend upon further but general balance can be written like this and whatever is the difference this is getting accumulated. And for this case also we can easily see, its unit is again mass per unit time because the concentration is there. So, concentration is mass per unit volume, we have volume which is at the top then we have the time. So, again we can see the overall unit is mass per unit time.

So, this is how the mathematical equation for mass balance can be written and here the C is the concentration of constituent at any time t inside the reactor and then C_0 is the influent concentration with the volume, k is the flow rate, t is the time RP and RC are the reactant rate of production and consumption of the constituent. So, this is possible so, we can write the overall balance like this.

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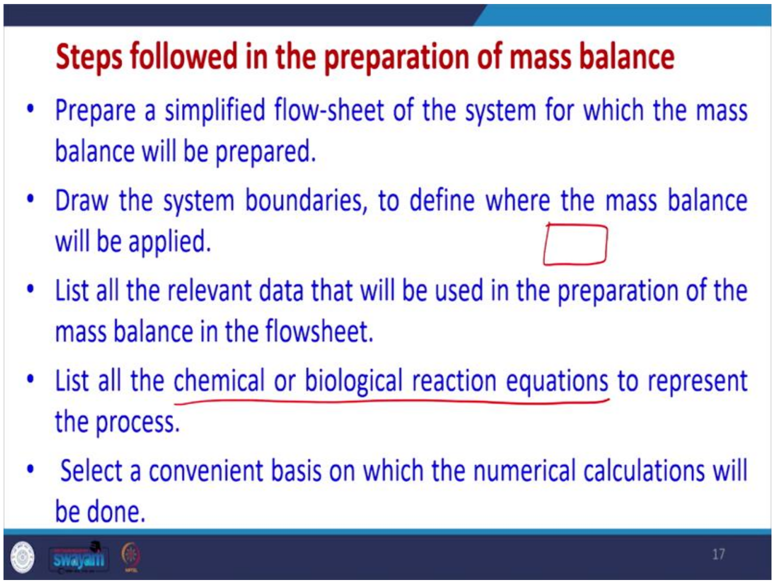

So steps, that have to be followed in preparation of mass balance equation, prepare a simplified flow sheet of the system for which the mass balance has to be prepared are made. Draw system bound is to define where the mass balance will be applied. So, we always should know what are the system boundaries that we are applying, it is possible that we can have two reactors together inside the reactor system boundary.

And list all the relevant data that will be used in the preparation of mass balance in the flow sheet list all the chemical and biological reaction equations to represent the process and select the convenient basis on which the numerical calculations will be done. So, everything will be followed when we will be now be studying different types of treatment systems like activated sludge process or tickling filter or any of the other reactor.

So, these mass balances are very important. Then within the mass balances there are two consideration because we have accumulation term in one case, the steady state condition accumulation is assumed to be 0. So, we are at a steady state, in the dynamic state we have accumulation.

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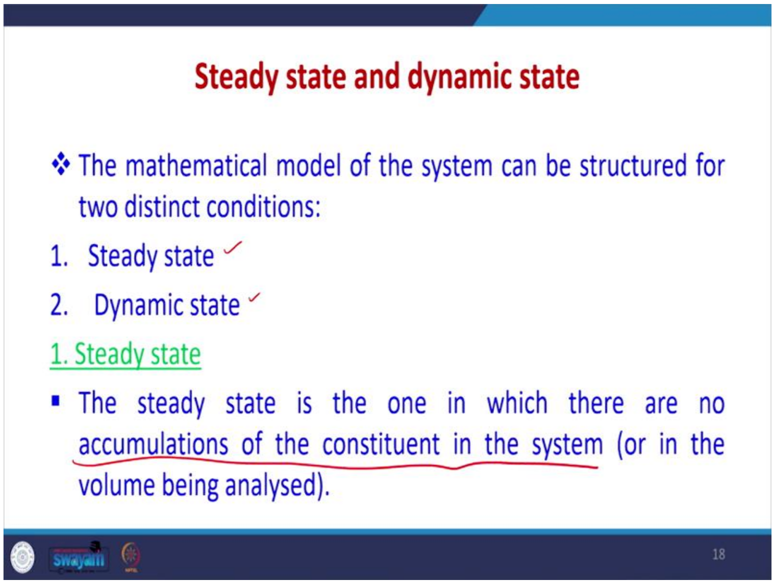

The mathematical model of the system can be structured for two distinct conditions one is steady state and another is called dynamic state. Now, in the steady state there is no accumulation of the constituents is in the system or in the volume being analyzed.

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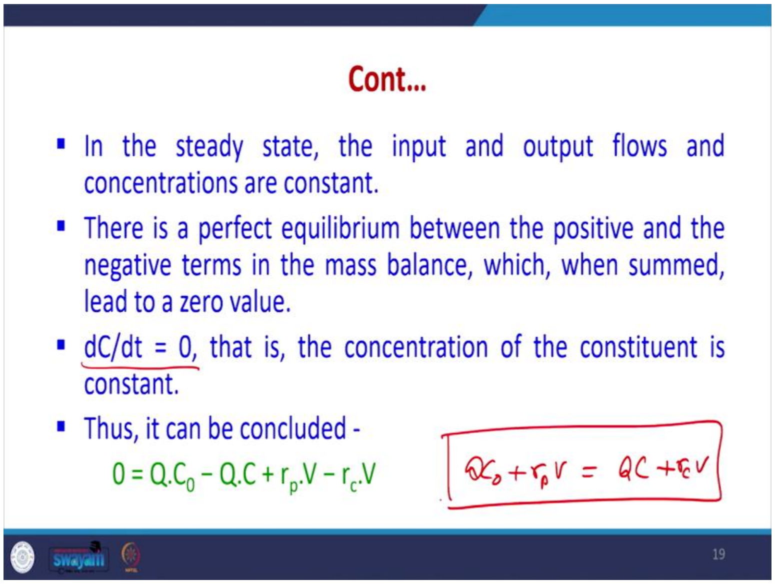

dC/dt = 0, that is, the concentration of the constituent is constant. Thus, it can be concluded –

$$0 = Q.C_0 - Q.C + r_p.V - r_c.V$$

So, overall that in the steady state the input and output flows and concentrations are constant, there is a perfect equilibrium between the positive and the negative terms in the mass balance, which when summed up lead to a 0 value that means, we have dC/dt is equal to 0 and that is the concentration of the consequence is constant. So, if we assume earlier equation, this will be the condition. So, we have now QC_0 plus r_PV which is equal to QC plus r_CV. This is a condition with respect to a steady state.

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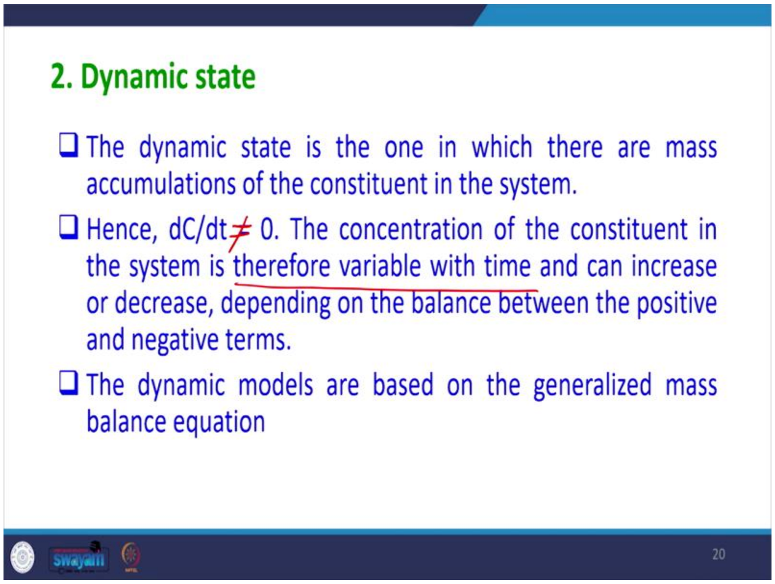

Now, in the dynamic state is the one where there are mass accumulations of the consequent inside the reactor. Hence, dC/dt is not equal to 0 sorry this is dC/dt is not equal to 0, a concentration of the constituents in the system is therefore variable with time. So, we are assuming since dC/dt is not equal to 0 that means, the concentration is changing with time, can increase or decrease depending upon the balance between positive and negative terms. The dynamic models are based on the generalized mass balance equation that we use.

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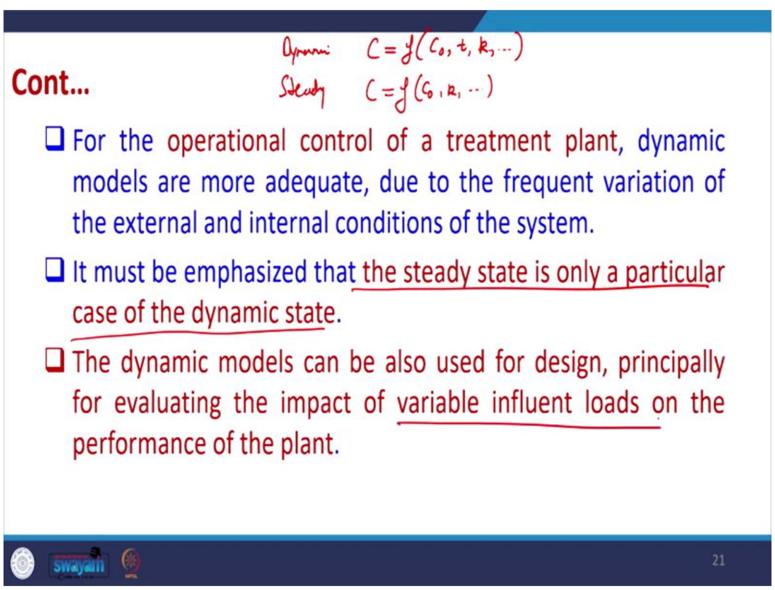

For the operational control of any treatment plant for better understanding that dynamic models are more adequate and due to they have frequent variation with respect to external and internal condition of the systems. So, we always try to analyze the dynamic model initially during the starting how the system is behaving at the steady state how the system is behaving. So, that means, that the steady state is only a particular case of the dynamic state. So, if we try to solve the initial equation, so, if we try to we have all the concentration values etcetera.

So, far dynamic state it is possible that we can have a profile which is a function of certainly initial concentration, time, some other parameters also like degradation rate constants, etcetera but at steady state will be funding that at the steady state the C value will be a function of concentration k etcetera only, now the time variable will be will be gone, because the steady state has been reached, the dynamic models can be used for design principally for evaluating the impact of variable influent loads on the performance of the plant, so, this is possible.

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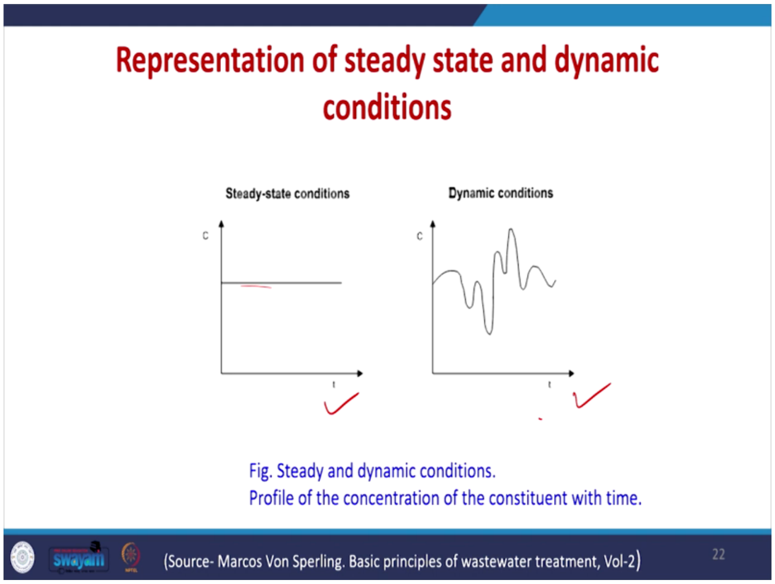

If we try to represent this the steady state will be a straight line with time there will be no fluctuation whereas in the dynamic condition will be the concentration may vary like this. So, this is the profile of the concentration with constituents for different constituents with time. So, we can represent like this.

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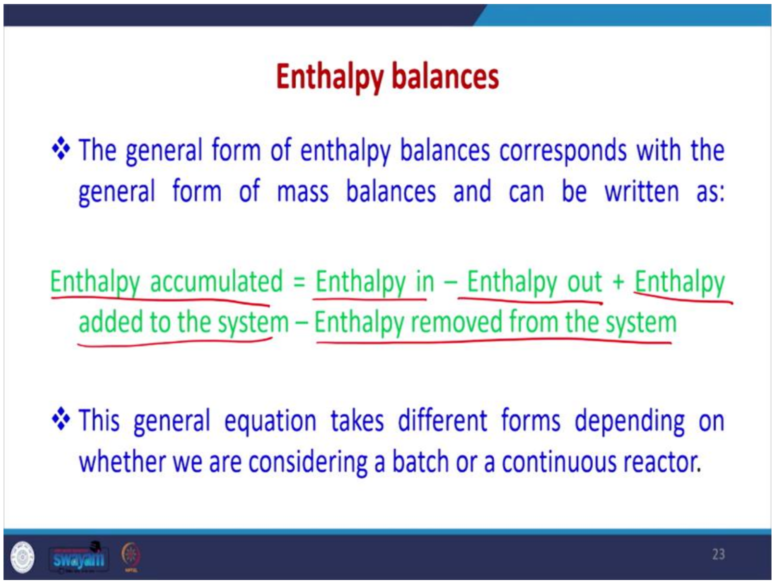

Similarly, to mass balance we have to apply enthalpy balances also. So, many times we have to consider that what is the energy input what is the enthalpy input etcetera. So, general form of the enthalpy balance corresponding with the general bar form of mass balance can be written as the enthalpy accumulated in is equal to enthalpy in minus enthalpy out plus enthalpy which is added to the system or generated or enthalpy removed from the system. So, this is same as the mass balance equation only thing that in place of mass we are writing enthalpy.

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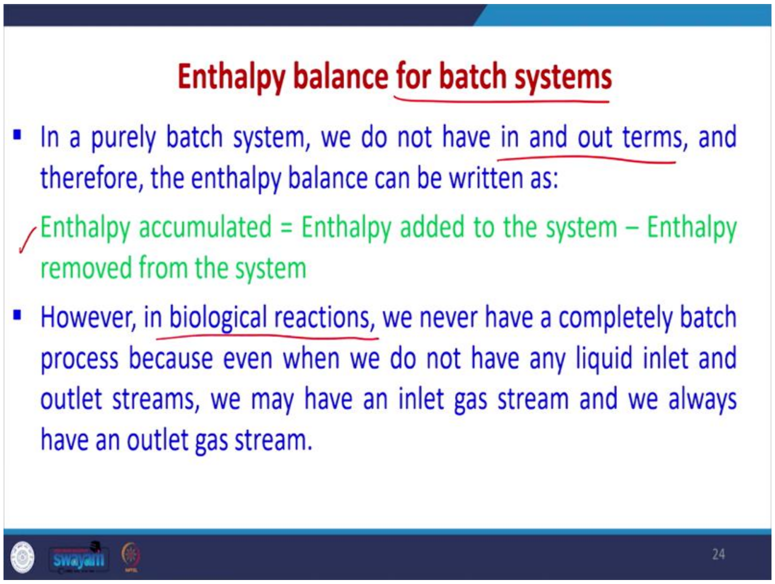

Now, for batch systems enthalpy balance for batch system in purely batch system, we do not have in and out terms, there is no in and out term, and therefore, the enthalpy balance can be written as enthalpy accumulated is equal to enthalpy added to the system minus enthalpy removed from the system. However, in the biological reactions, we never have completely batch process, because even when we do not have any liquid inlet and outlet streams, we may have an inlet gases stream and we also have can have an outlet gases stream. So, this we have to remember.

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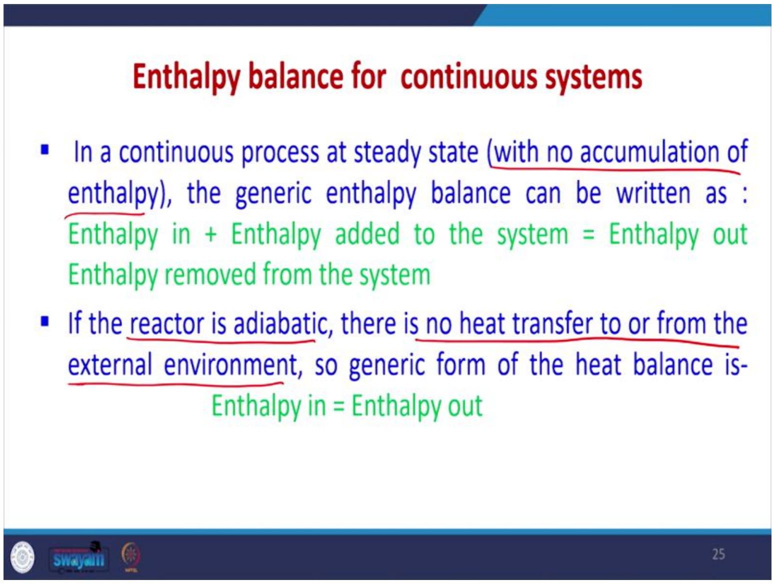

Now enthalpy balance for the continuous system with no accumulation when there is no accumulation of enthalpy the generic term will be enthalpy plus enthalpy added to the system is equal to enthalpy out plus enthalpy removed from the system. so, this is there. When the reactor is adiabatic. So, there is no heat transfer to or from the external environment that means adiabatic there is no exchange of any energy, heat energy or other energies. So, enthalpy in will always be equal to enthalpy out. So, these are the different conditions with respect to enthalpy balance.

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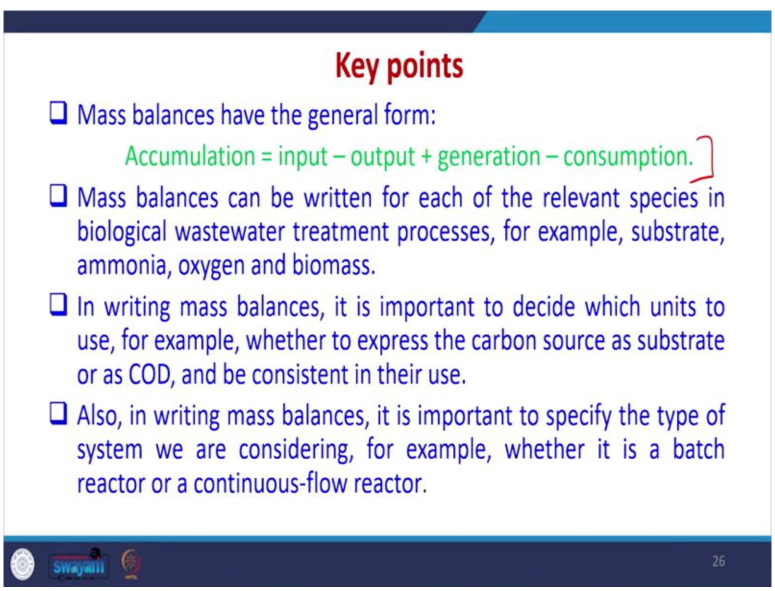

So, there are a few key points that will summarize before ending this lecture. So, mass balance can have general this formula mass balance can be written for each of the relevant species in the biological wastewater treatment processes. For example, for substrate for ammonia, oxygen, biomass, any of the things in writing the mass balance, it is important to decide which units have to be used.

So, we have to appropriately designed the units and we have to be consistent for the use the same units all across all the terms inside the mass balance. Also, when writing the mass balance, it is important to specify the type of system we are considering for example, whether it is batch reactor or continuous flow reactor, so depending upon that the mass balance equation may change.

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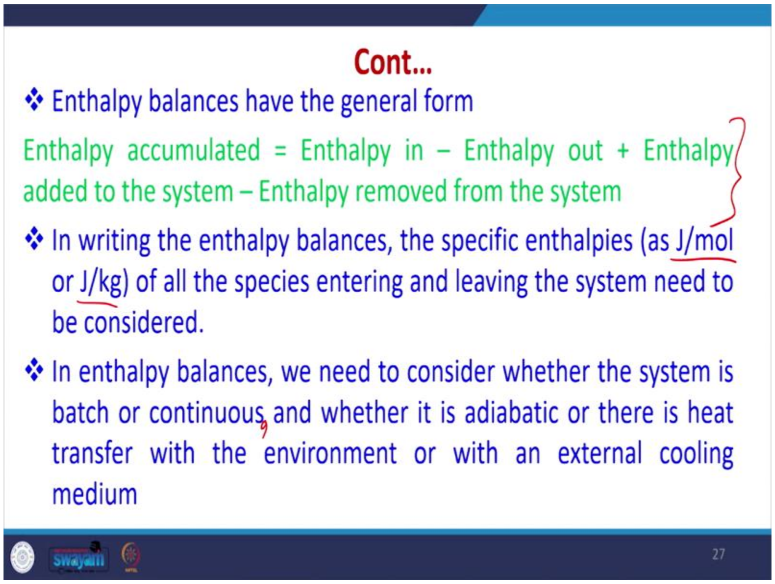

Similarly, enthalpy balance has the general form of this which was written, in writing the enthalpy balance the specific enthalpy such as joule per mole or Joule per kg of all the species entering and leaving the system need to be considered, we may have to refer to either better books related to where the this thermodynamics etcetera is considered better we have to refer to these books for better understanding.

In enthalpy balances we need to consider whether a system is batch or continuous, whether it is adiabatic or there is a heat transfer with the environment or with external cooling medium. So, all these considerations have to be done in writing the enthalpy balance. So, we this will end that today's lecture we have already we studied the regarding the reactor hydraulics, we understood that there is lot of importance of dispersion number, the mixing and we found out that plug flow reactor is one of the better reactor, if where the dispersion or the mixing is 0.

So, dispersion numbers with 0 always give better efficiency as compared to higher dispersion numbers which is like infinite for the CSTR. We also learned regarding the mass and heat balance and these will be applied later on when we will be studying the different wastewater treatment units in detail. So, thank you very much.