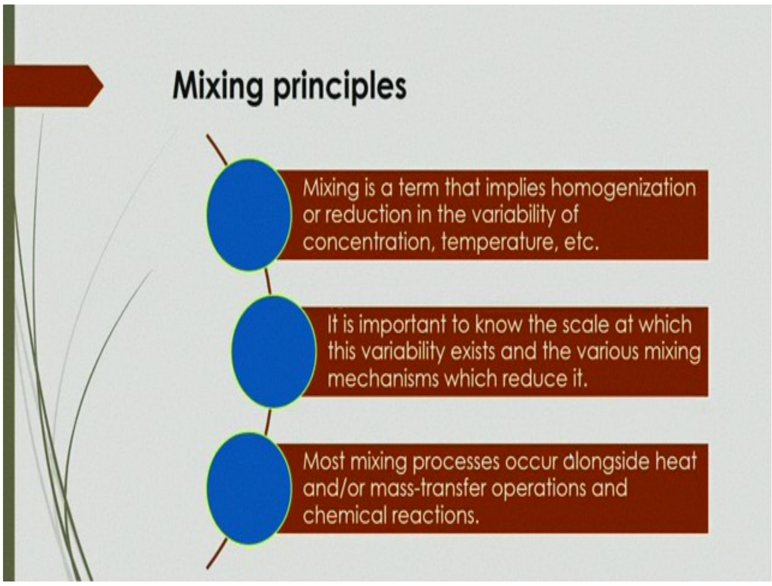
Chemical Process Intensification
Professor Dr. Subrata K. Majumdar
Chemical Engineering Department
Indian Institute of Technology Guwahati
Lec_05
Mechanism of Intensification by mixing

Welcome to massive open online course on chemical process intensification, so in this lecture will discuss something about mechanism of intensification, that is happen by mixing and in the previous lecture we have discussed the mechanism of intensification by some other means.

(Refer Slide Time: 0:54)



Mixing principles

- Mixing is a term that implies homogenization or reduction in the variability of concentration, temperature, etc.
- It is important to know the scale at which this variability exists and the various mixing mechanisms which reduce it.
- Most mixing processes occur alongside heat and/or mass-transfer operations and chemical reactions.

So, in this lecture take in to that mechanism of the intensification by mixing and you know that first of all, you have to know that mixing principles, what is that mixing? So, it will be the term of that implies homogenization or reduction in the variability of concentration, temperature, etc, that means, suppose system or we have actually discussed in the previous lecture regarding the mechanism of intensification by multiphase mixture and in that case to get into intensive mixing of those phases, you have to know the mechanism of mixing or phenomena.

Now, that mixing will happen based on what? Means that you are mixing a system in such a way that the concentration of the phases throughout the reactor or throughout the process system should be uniform, so that is why homogenization a term is coming, so mixing should be term where that homogenization of the system will be applied and another important feature of that mixing is that you have to reduce the variability of the concentration that means, throughout a reactor you have to get the concentration of the phases.

In oil in you know that uniform, so if you are intensity of the mixing will be a certain degree, so that your concentration will be distributed throughout the system uniformly and also not only that concentration distribution, there should be temperature also that you have to mix the system in such a way that suppose in a heat transfer equipment or some other reactive system where temperature is also one covering factor, so in that case you have to distribute the heat throughout this mixture in such a way that the distribution of the heat should be uniform.

So that is why mixing is a term that implies the homogenization of this concentration, temperature or is there any other, suppose hydrodynamic characteristics are there, how it can be actually homogenized into the system? Suppose there is a gas liquid mixture, however that you know that some certain chemical process is going on based on this gas liquid mixture or droplet or bubbles are forming there

So you have to distribute that bubbles or gases inside the liquid, in such a way that in all location of the system that bubble concentration should be uniform or droplet concentration should be uniform, so you have to mix the system in such a way, you have to use the gas distributor in such a way that all the locations or cross-sectional average variation of this concentration of this bubble number should be uniform.

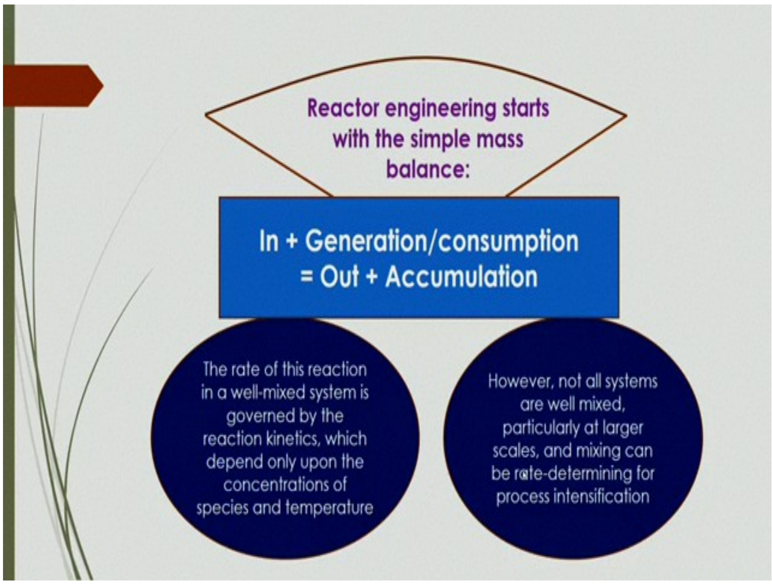
Also, it is important to know that the scale at which this variability exists and the various mixing mechanisms which reduce it, so in that case, you have to scale the processes in such a way that this variability where that like concentration, temperature or other if is there any variable, variables is there, so that mixing mechanism should be implied in such a way that or design in such way that reduction of this, you know, invariability or heterogeneity in the column.

And most mixing process occur alongside heat and/or mass transfer operations and chemical reactions, so however mass transfer, heat transfer, reactive mass transfer even other chemical engineering processes of multiphase systems they are missing characteristics very important. So for mass transfer operation, you have to mix the system in such a way that, if you are getting that well mixed concentration or well mixed temperature distribution there, you can get the better mass transfer and also chemical reactions where, suppose slow reactions in that case, you have to mix the gas liquid system in such a way that the interfacial area should be well managed, well distributed through who is that mass transfer will be carried out.

Whereas in the fast reactions you see there may not be, you know the distribution of the bubbles or droplet in that case, you can use some other design at unit where the low residence time will be enough to get the better mass transfer operation, in that case, you have to develop the device in such a way that gas liquid, contact time will be less and there, you know that like channel based or micro reactor system where first reaction can be done based on this intensive contact and getting plug flow phenomena, that means they are only the interfacial phenomena where get the less residence time but the first reaction will be there.

So that is why, now you can say that mixing is one of the important hydrodynamic phenomena in any chemical engineering processes, where multiphase process systems are taking part on a particular process.

(Refer Slide Time: 6:49)



Reactor engineering starts with the simple mass balance:

In + Generation/consumption = Out + Accumulation

The rate of this reaction in a well-mixed system is governed by the reaction kinetics, which depend only upon the concentrations of species and temperature

However, not all systems are well mixed, particularly at larger scales, and mixing can be rate-determining for process intensification

Now, if we say that in any reactor that chemical engineering process are being carried out, in that case, you can use some reactor where that reactions will be carried out, so in that case reactor engineering starts with the simple mass balance where your reactions will be carried out, so in that case, suppose there is a reaction, so what should be the inlet in the reaction, reactor and if is there any generations or consumptions of the reactance whatever, actually allow to pass into a reactor.

So in that case inlet and the generation plus consumption whatever amount would be there, that should be balanced by the outlet concentration or outlet stream, amount of outlet stream and the accumulation if it is there in the process, so in plus, in means here inlet, stream amount of inlet and generation plus consumption is there any products is generated or suppose any reactant are consumed, so in that case, you have to take into account those terms and also that whatever stream is out, is coming out that you have to measure what the amount of stream is out, coming under also, if is there any accumulation is there, accumulation is possible where the inlet and outlet streams are not in a same measure.

That means here if inlet is greater than the outlet, then you consider should be some accumulation, if suppose outlet is greater than the inlet, then you can get the negative accumulation, so in this way you have to balance that reactive system in a reactor engineering by mass balance and the rate of this reaction in a well-mixed system is governed by the reaction kinetics, so in this case, the mixing phenomena is the important characteristics, where that rate of reactions will be depending on this degree of mixing.

So, rate of the reaction is in the well mixed system is governed by the reaction kinetics, which depend only on the concentration of the species and the temperature, so you have to distribute that temperature and you know that concentration of this reactance in the reactor in well manner. However, not all systems are well mixed, you can say, particularly at larger systems and mixing can be the rate determining for process intensification.

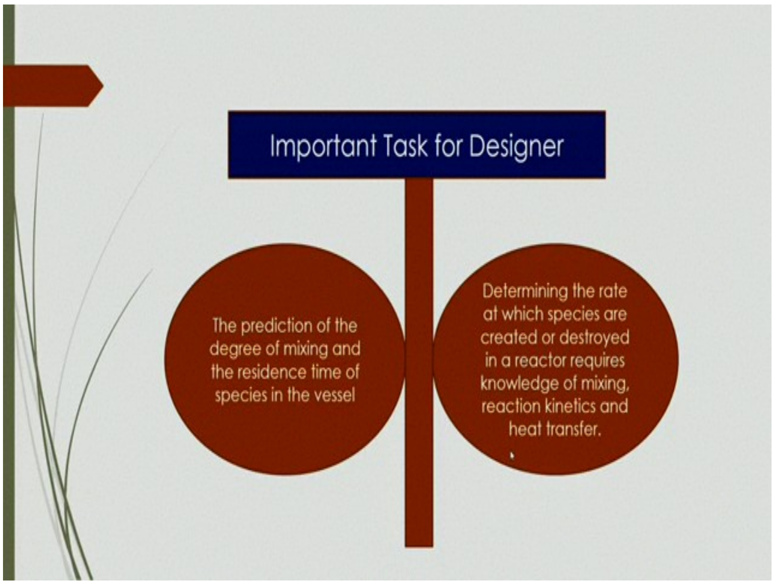
If suppose your system is wider in size, so that case you will see there will be a gas liquid mixing or gas liquid solid mixing will be there, but there will be a generation of circulation cell inside the reactor, so if you are mixing those systems in the reactor, you have to develop the system in such a way that there should be less back mixing, generally for reactive system, whereas for heat transfer systems back mixing sometimes it is advisable, whereas in reactive system, it should not be there and so the mixing is a rate determining steps or rate determining factors for the process intensification there and sometimes, you know this wider size reactor may sometimes give the less performance due to this back mixing of the fluid.

So there you have to use a mechanical provision so that, that you can reduce that back mixing, sometimes three-dimensional columns in such a way that your width and breadth should be less compared to the length and sometimes you have to design in such a way that there, you know that only there will be a width will be very less and length will be high, so that will be called pseudo-two-dimensional systems or two-dimensional unit where that you can reduce one directional mixing there, sometimes you know that if they are suppose three-dimensional mixing is there, so at least in two-dimensional you can reduce that your mixing, back mixing.

So you have to design the system in such a way that how can be actually optimize that mixing phenomena and also you will see that if suppose in their oxidation operation, gas solid reactions are there, where you know that adsorption is going on the solid surface, so if you are having the system in such a way or design the system in such a way, there will be back mixing of the solid particles, there may be a you know that less performance of the master transfer from the gaseous stream to the solid stream.

Because whatever adsorbent you are using as a solid particle that should be get back to the original position or circulated, so that due to that pressure differences, there may be a, you know that desorption as well as adsorption simultaneously happen, so there maybe the hindering of that you know, the performance of the mass transfer.

(Refer Slide Time: 12:34)



Important Task for Designer

The prediction of the degree of mixing and the residence time of species in the vessel

Determining the rate at which species are created or destroyed in a reactor requires knowledge of mixing, reaction kinetics and heat transfer.

Other important task for the designer is that the prediction of the degree of mixing and the residence time of their species in the vessel, so a certain reaction that sometimes depends on the residence times of the reactance, so you have to design the system in such a way that for a certain degree of mixing what should be the resistance time of the reactance that you have to predict or you have to estimate. So, by generating some models that you can predict the degree of mixing and the residence time and there are several methods to find out or estimate the degree of mixing, like you know that Tracer technique methods, even some other techniques also or they are available to find out that degree of mixing.

The Tracer technique mixing is one of the important technique by which you can predict the degree of mixing, like you know that you have to insert some Tracer in a reactor along with that, you know that liquid stream or fluid stream, you can say and then you have to collect the sample from the certain distance of that, you know reactor or at a certain position and after collecting that sample with respect to time you can get a certain profile of that concentration variations with respect to time and after that if you get this profile and compare with a certain model, like there is an important model, it is call tank in series model or excel dispersion model.

If you feed those concentration versus time data with that excel dispersion model, then you can get some parameters this will be actually expressed as that peclet number, so the by which you can calculate what should be the degree of mixing, the degree of mixing depends on that dispersion number or peclet number, dispersion number actually defined as one by peclet number, peclet number is actually gone basically is a, you know that as a function of fluid velocity and effective length of the fluid mixer which is lying in the reactor.

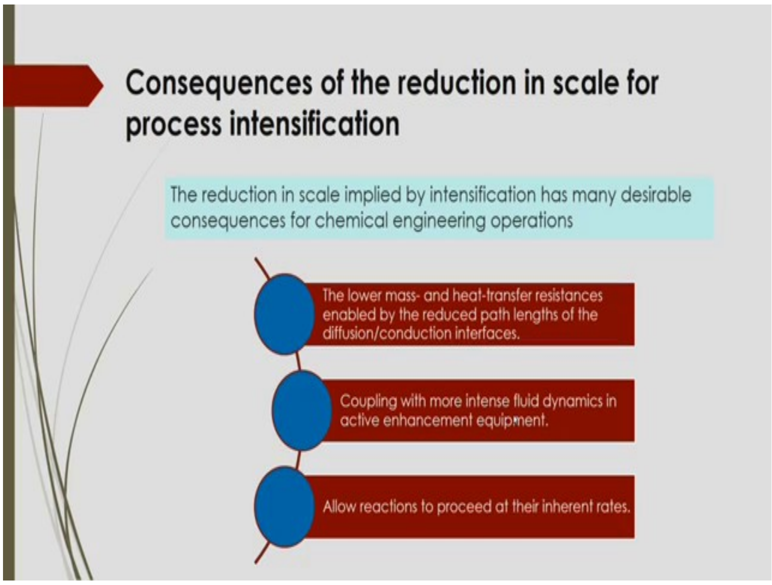
So to find out that the degree of mixing that you have to estimate the dispersion number, that means peclet number you have to estimate then one by Peclet number that will give you the dispersion number, if dispersion number is infinity, then you can say that your reactor fluid mixing will be well mixed and homogenized, whereas if dispersion number is going to 0, that means there will be a 0 mixing or it will be, you know that no mixing you can say and for infinity case, dispersion number if it is infinity then you can say the complete mixing or complete homogenization and based on that you can get that, you know that residence time of the distribution of the species in the vessel.

So, the designer actually finds out this degree of mixing as well as residence time of the species for analyses of the reaction for that particular process and also another important task for the designer is that what should be the rate of species which are created or destroyed in a reactor that requires for that particular reacting system to actually give the yield of the process.

So that depends on the mixing characteristics and also it will, you know that effect on the reaction kinetics, that means what should be the reaction is going on that some activation energy or temperature effect that will give you that kinetics of the reactions like, you know reaction rate constant or you can say that the activation energy of the system, how it will be there in the reaction system?

So that can be actually calculated based on this degree of mixing, so if you are having that more missing then you will get automatically the different value of that activation energy and the constant rate of reaction, so these are the important criteria for the designer to develop systems based on this mixing characteristic for the process intensification.

(Refer Slide Time: 16:56)



Consequences of the reduction in scale for process intensification

The reduction in scale implied by intensification has many desirable consequences for chemical engineering operations

- The lower mass- and heat-transfer resistances enabled by the reduced path lengths of the diffusion/conduction interfaces.
- Coupling with more intense fluid dynamics in active enhancement equipment.
- Allow reactions to proceed at their inherent rates.

And a designer, nowadays they are actually procuring the front devices based on this mixing characteristic and they are trying to reduce the size of the reactor, so in that case, reduction in scale is one of the important aspects for the process intensification. Now what happen when the scale is reduced for that process intensification, so the reduction scale implied by intensification has many desirable consequences for chemical engineering operations like the lower mass and heat transfer resistance enabled by the reduction path lengths of the diffusion or conduction interfaces.

So, if you are making the system in such a way that, suppose microchannel a based reactor, so in that case you will see that path lengths maybe a very small for the diffusion or the conduction through the interfaces, so in that case, you can get the lower mass and heat transfer resistances, so that your performance of the mass transfer operation and heat transfer operation will be enhanced.

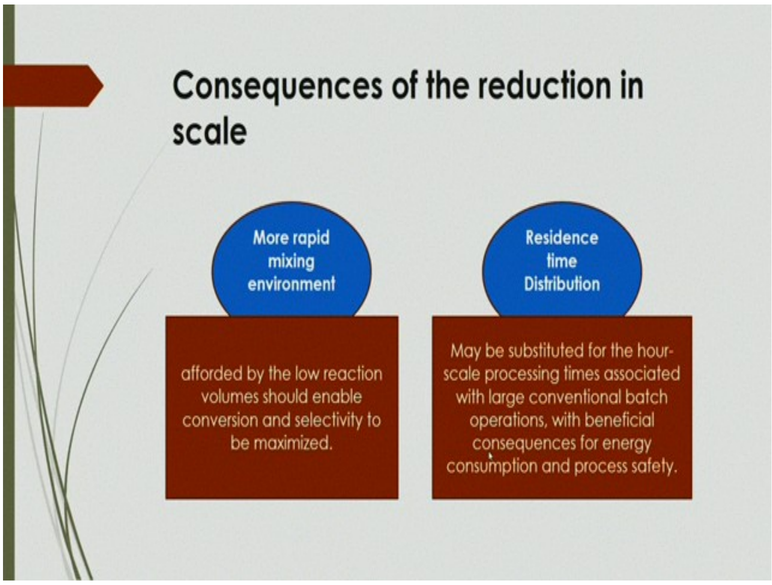
And also important factor is that coupling with the more intense fluid dynamics in active enhancement equipment where you can say that based on this mixing phenomena, you can intensify the equipment, you have to develop the equipment in such a way that, if you use suppose some baffles or some provisions, mechanical provisions inside the reactor to get reduce the back mixing of the system, then you can of course intensify the process of your chemical engineering operations.

So to get the intensification process you can use, sometimes you know some sheer producing a mechanical device or being used in the reactor or in a certain chemical engineering process equipment, where you will see sometimes statics mixers are being used, sometimes some bubbles, some you know that impeller systems are been used in such a way that whenever you are supplying some gas liquid or liquid-liquid system for extraction, you will see formation of the droplet, if you are rotating that impeller at high speed, you will see that you good at sheer effect, the formation of the fine droplets will be there and hence formation of the more interfacial area and you can get the more mass transfer, that means the extraction process will be there, more extraction phenomena you can get.

So more intense fluid dynamics, where you can get it by that mixing by making some, you know giving some provisions of mechanical devices to produce that more fluid particles like gas and liquid droplet inside that reactor to get the better mass transfer and heat transfer. Allow reactions to proceed at the inherent rates, also sometimes you will see if you are developing the systems or reducing the scale of the system in such a way that when, you know that getting the contact of that gas liquid system.

In the suppose microchannel systems, their gas and liquid flows out the, so you can get the more contact, more thin fins between that gas and liquid where you can get that more, you know that reactions at the interface and you can get the more reactive mass transfer which is happening in the particular chemical engineering process, so this can be produced just by the inherent, you know that properties to get the more reactive system or mass transfer system by reducing the scale of the unit.

(Refer Slide Time: 20:51)



Consequences of the reduction in scale

More rapid mixing environment

afforded by the low reaction volumes should enable conversion and selectivity to be maximized.

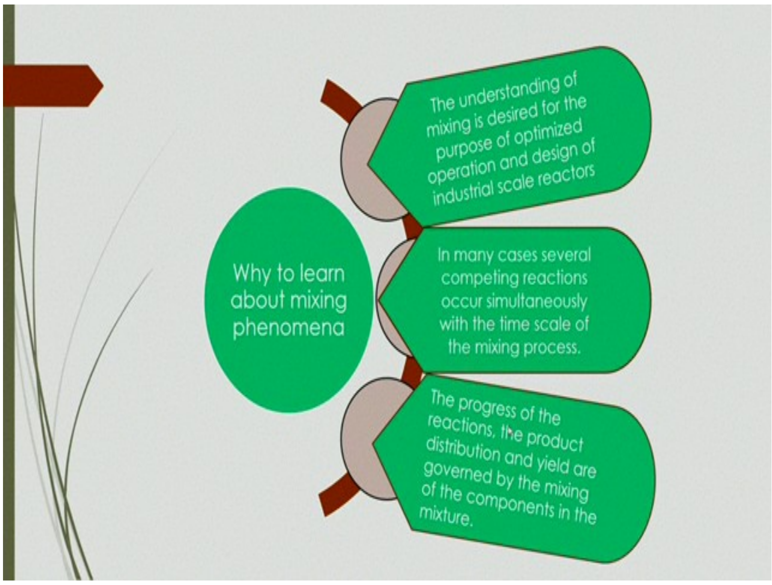
Residence time Distribution

May be substituted for the hour-scale processing times associated with large conventional batch operations, with beneficial consequences for energy consumption and process safety.

Also sometimes more rapid mixing environment also can be suggested for the process intensification like in that case if you are producing the rapid mixing environment that can be afforded by the low reaction volumes that should enable conservation as well as that conversion and selectivity to the maximized this process unit and also residence time distribution may be substituted for the hour scale processing times that will be associated with the large conventional batch operations which will be beneficial arrow, so consequences for energy consumption and process safety.

So, residence time distribution and the mixing environment are the two important design or parameters for the designer to actually have the mixing system to get the better mass transfer, to get the better way of reaction kinetics and also enabling the conversion and selectivity and also there will be some mode of application where that this scale reduction maybe helpful based on this mixing characteristic.

(Refer Slide Time: 22:07)



Why to learn about mixing phenomena

The understanding of mixing is desired for the purpose of optimized operation and design of industrial scale reactors

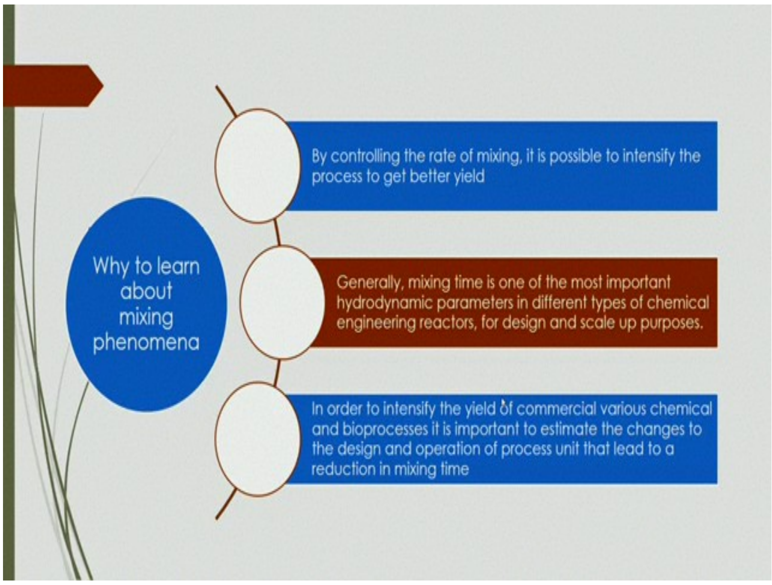
In many cases several competing reactions occur simultaneously with the time scale of the mixing process.

The progress of the reactions, the product distribution and yield are governed by the mixing of the components in the mixture.

Now, main problem is that why to learn about this mixing phenomenon? Basically that understanding of the mixing is desired for the purpose of optimized operation and the design of industrial scale reactors and also in many cases you will see that there should be a simultaneously competitive several reactions that occur and in that case you will see simultaneously the timescale of the mixing process as well as that, you know that degree of mixing are very important factors to give you the competitive reactions phenomena and optimize system to develop that particular reaction system.

And the progress of the reactions, the product distribution and yield are the governed by the mixing of the components in the mixture is the very important aspects where that your knowledge of mixing is important, so how this reactions are being progressed and how the product are being distributed and yield are governed by the mixing of the components in the mixture that is required to know based on this mixing phenomena, also you can control that degree of reactions, extent of reactions or extent of mass transfer or heat transfer by controlling the rate of mixing.

(Refer Slide Time: 23:40)



Why to learn about mixing phenomena

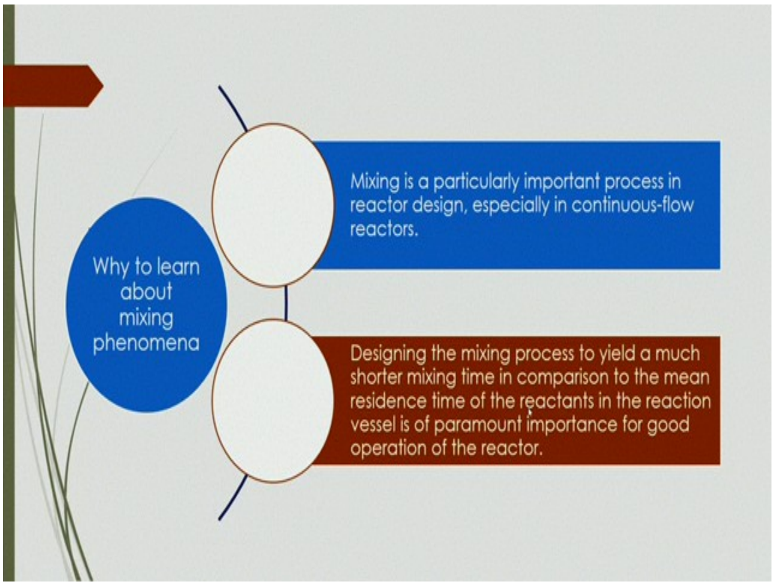
By controlling the rate of mixing, it is possible to intensify the process to get better yield

Generally, mixing time is one of the most important hydrodynamic parameters in different types of chemical engineering reactors, for design and scale up purposes.

In order to intensify the yield of commercial various chemical and bioprocesses it is important to estimate the changes to the design and operation of process unit that lead to a reduction in mixing time

In that case, it is possible to intensify the process to get the better yield, generally mixing time is one of the most important hydrodynamic parameters in different types of chemical engineering reactors, for the design and the scale up of the unit and also process and also to intensify the yield of the commercial various chemical and bioprocesses, it is important to calculate or estimate the changes to the design and operation of the process unit that lead to a reduction in mixing time, so you have to design the operating unit in such a way that your yield of the reaction should be optimized, based on this reduction and mixing time.

(Refer Slide Time: 24:34)



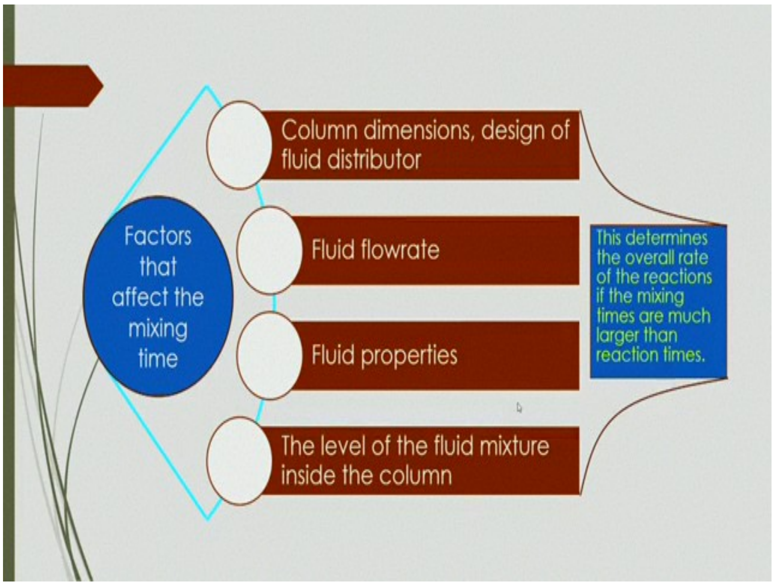
Why to learn about mixing phenomena

Mixing is a particularly important process in reactor design, especially in continuous-flow reactors.

Designing the mixing process to yield a much shorter mixing time in comparison to the mean residence time of the reactants in the reaction vessel is of paramount importance for good operation of the reactor.

And also mixing is a particularly important process in reactor design, especially in continuous flow reactors and designing the mixing process to yield a much shorter mixing time in comparison to the mean residence time of the reactants in the reaction vessel, and in that case, it is a paramount importance for the good operation of the reactor, so we have to know the mixing phenomena for the design of the reactor, where this reaction kinetics, reactive mass transfer and heat transfer can be optimised. Now what are the factors those are actually affecting the mixing time? Generally, there are several variables that effect on that mixing time or degree of mixing there, generally we can categorise these variables in four types.

(Refer Slide Time: 25:36)



Factors that affect the mixing time

Column dimensions, design of fluid distributor

Fluid flowrate

Fluid properties

The level of the fluid mixture inside the column

This determines the overall rate of the reactions if the mixing times are much larger than reaction times.

Like you know that first one is like dynamic variables in that case flowrate is called the dynamic variables, so if you are increasing the flowrate you can get the more mixing and, in that case, there may be that mixing will be there, there may be internal circulation of the fluid mixing, so that you can get the more residence time of the fluid particles. So dynamic variables like flowrate is one of the important factors.

Then you can say a geometric variable like you know that, if you are using any reactor, what is the size of the reactor? And if you using some catalyst particles for a particular reaction, in that case what should be the, you know the size of the catalyst particles, if you reduce the size of the particles you can get more interfacial area of the particles and then you can get more, you know that mass transfer, sometimes some adsorption processes if you are getting more, you know that porous material and finer porous materials then you can get more mass transfer because of the more interfacial areas of that solid particles.

So in that case the size of the particles and also size of the reactor, if you are making that reactor sizes wider, then you can get more, you know that internal circulation of the fluid particles that is radial distribution of that reactants would be more, so in that case, sometimes it may hinder the reaction performance, but some physical processes it may be actually suitable, like heat transfer processes for uniform distribution of the heat, you can suggest that more, you know radial mixing, more internal circulation of the fluid, a system inside the reactor that may enhance the heat transfer operation.

So that geometric variables you can say the reactor size, reactor relent is also important and catalyst size, sometimes you will see in a particular reactor, sometimes gas distributors are or liquid distributors are being used for, you know that supplying that gas as a dispersed phase of bubbles or distributing the liquid as a dispersed phase of droplet, in that case, the distributor whole size, distributor, you know that pour size should be optimized in such a way that you can make more finer droplet or more finer bubbles just by making that whole size or (())(28:20) size of the, you know that distributor, so that is why the distributor whole size is also one of the most important factor for this mixing time on mixing processes there.

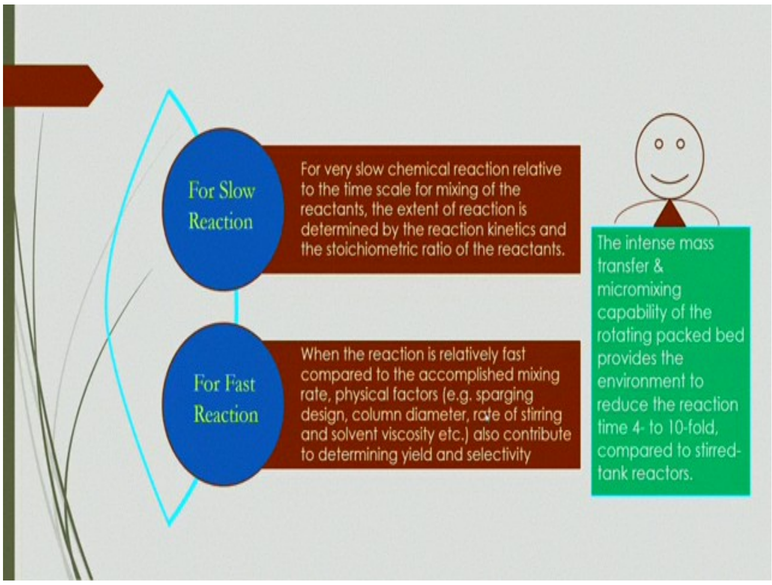
Another important variable is called fluid properties. You know that whatever fluids are being used for that particular processes like you know liquid, you are sometime use, being used, sometimes you know the solvents are being used, sometimes you know only slurry systems are being used, so in that case what will be the physical properties of those systems? Like what is the density? What is the viscosity? What is the you know that concentration of the system, so those are actually some, you know that factors which will affect this mixing time as well as degree of mixing.

And also the level of the fluid mixture inside the column that is height of the mixing, mixture, that is fluid mixture inside a column that is also an important because there are one important factor is that pressure, hydrostatic pressure will be, you know changing as well as that to get you know the excel dispersion of that system that depends on mixture height as well as to get the more residence time for that species you can actually elongate the unit or you can produce that level of the fluid mixture high inside the column.

Generally, for fluidization system, fluidised bed system, you know pneumatic fluidised based system, they are you know that level of the fluid mixture should be high to get that segregation of that dens region and the free-board region there, so that is why fluid mixture height is one of the important phenomena.

Now, this determine the overall rate of the reactions if the mixing times and the degree of mixing if you know, based on these factors and much larger than the reaction times the overall rate of reactions will be there, based on these factors of, those are affecting the mixing time as well as degree of mixing.

(Refer Slide Time: 30:35)



For Slow Reaction

For very slow chemical reaction relative to the time scale for mixing of the reactants, the extent of reaction is determined by the reaction kinetics and the stoichiometric ratio of the reactants.

For Fast Reaction

When the reaction is relatively fast compared to the accomplished mixing rate, physical factors (e.g. sparging design, column diameter, rate of stirring and solvent viscosity etc.) also contribute to determining yield and selectivity

The intense mass transfer & micromixing capability of the rotating packed bed provides the environment to reduce the reaction time 4- to 10-fold, compared to stirred-tank reactors.

Now, let us consider some phenomena for the slow reactions and the fast reaction. For very slow chemical reaction that is relative to the time scale for mixing of the reactants, the extent of reaction is determine by the reaction kinetics and the stoichiometric, you know proportions of the reactants there.

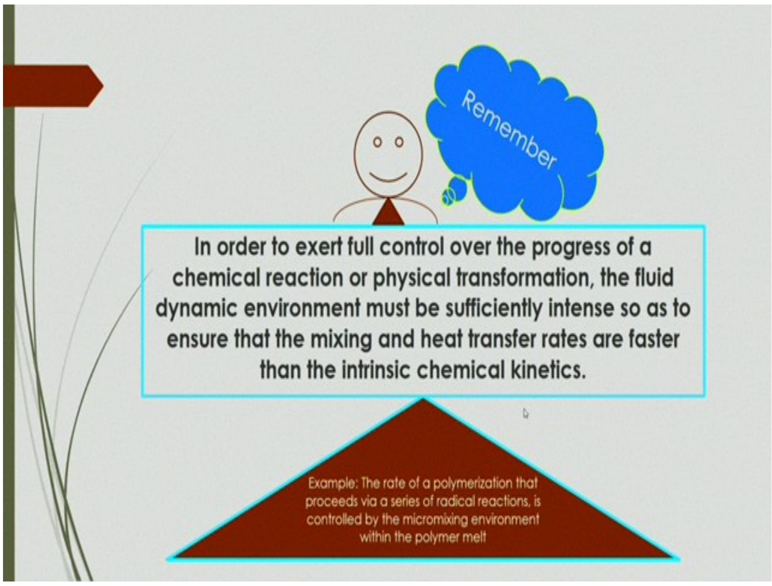
And when the reaction is relatively fast, in that case mixing rate, physical factors like sparging design, column diameter, rate of you know stirring, solvent viscosity, that is, those are different, you know dynamic, you know that geometric, physical property variables and also some other variables is the, sometimes there is thermodynamic variables also very important there, pressure and temperature.

So those factors will be actually considered for these fast reactions there to optimize this reaction. And the intense mass transfer and micro mixing capability of the rotating packed bed provides the environment to reduce the reaction time that is 4 to 10-fold compared to the stirred tank reactors, that is why you will see that why this for the process intensification this, you know that micro mixing or micro reactors are being actually developed.

Because it gives this higher mass transfer and also sometimes you see if we develop some rotating packed bed as a process intensification unit, than how this rotating packed bed provides the good and environment of reacting systems, where that you can reduce the reaction time 4 to the 10-fold that is compared to the stirred tank reactor.

So that is why nowadays stirred tank reactors are now actually less important than this, you know rotating packed bed reactors. Of course, every reactor has some pros and cons but sometimes some stirred tank reactors will be more easier to operate, whereas rotating packed bed may not be easier to offer it and also the investment cost will be higher compared to that stirred tank reactors will be there.

(Refer Slide Time: 32:45)



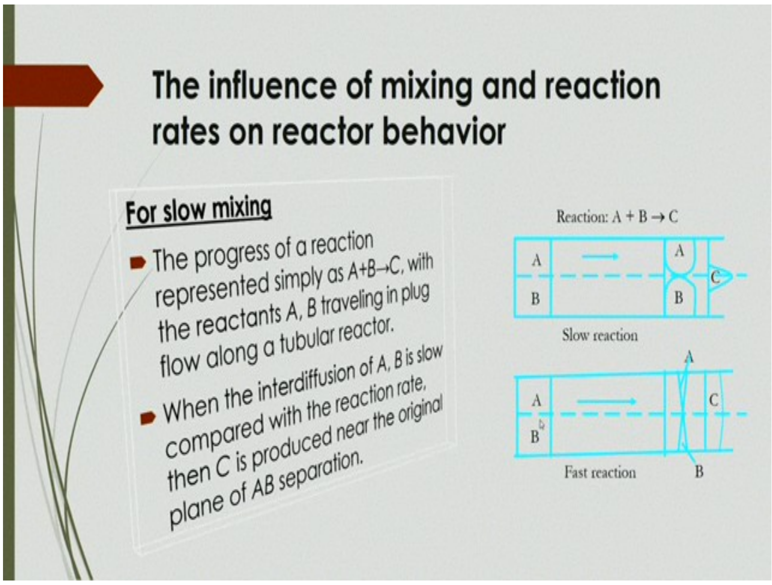
In order to exert full control over the progress of a chemical reaction or physical transformation, the fluid dynamic environment must be sufficiently intense so as to ensure that the mixing and heat transfer rates are faster than the intrinsic chemical kinetics.

Example: The rate of a polymerization that proceeds via a series of radical reactions, is controlled by the micromixing environment within the polymer melt

Now you have to remember that in order to exert full control over the progress of a chemical reaction or physical transformation, the fluid dynamic environment must be sufficiently intense, so that the mixing and the heat transfer rates are faster that will be compared to the, you know that other systems, then the intrinsic chemical kinetics.

So in that case, you have to remember this that control over that reacting system based on the mixing phenomena, example, rate of polymerization that happens via a series of, you know that radical reactions and in that case that can be controlled by the micro mixing and environment within the polymer, you know melt, so this is one of the important examples where that, you know, you can control this polymerisation reaction based on this micro mixing environment.

(Refer Slide Time: 33:50)



The influence of mixing and reaction rates on reactor behavior

For slow mixing

- The progress of a reaction represented simply as A+B→C, with the reactants A, B traveling in plug flow along a tubular reactor.
- When the interdiffusion of A, B is slow compared with the reaction rate, then C is produced near the original plane of AB separation.

Reaction: A + B → C

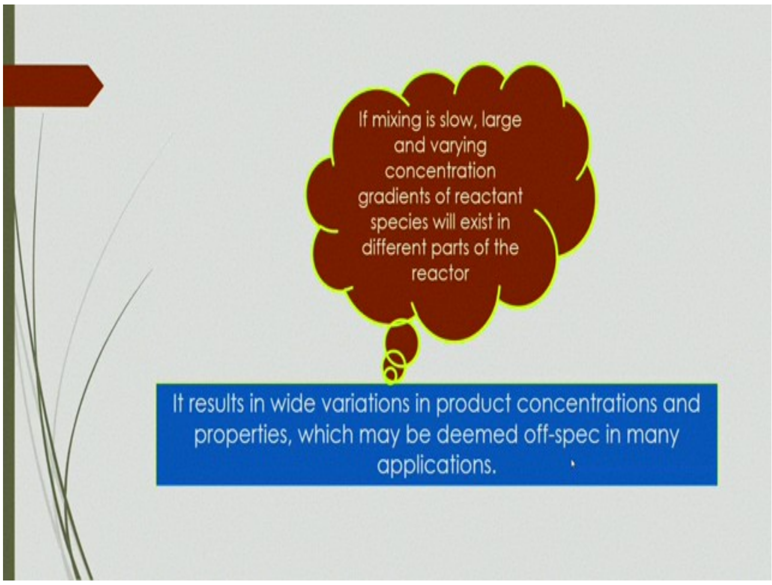
Slow reaction

Fast reaction

Now the influence of mixing and the reaction rates on the reactor behaviour, how this low mixing actually progress of reaction that represented here at this simple diagram, like there is a reaction A+ B will give you C, with the reactants like A and B that will travel in a plug flow along a tubular reactor, whereas you can say that in this slow mixing there will be a certain diffusion that inter-diffusion will happen between this A and B and we should be very slow compared to the reaction rate, then C is produced near the original plane of the A and B, that is AB separation there.

So for the slow reaction which is the mechanism, that progress of reaction that will be represented by this A+ B to C reactions, where that reactants A and B should be travelled in a plug flow or tubular reactor, so in that case microchannel based reactor for this process intensification are important, in this case, the inter-diffusion of this A, B should be very slow compared to the reaction rate, that is happen to the other unit.

(Refer Slide Time: 35:06)

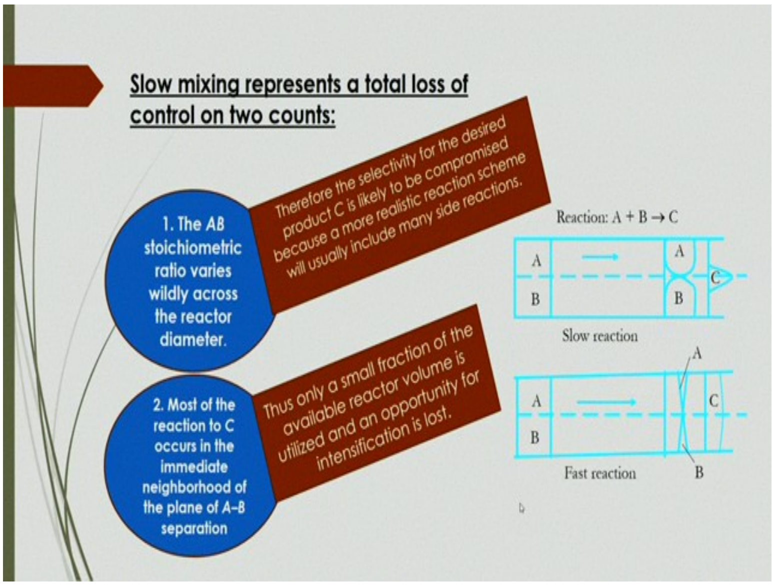


If mixing is slow, large and varying concentration gradients of reactant species will exist in different parts of the reactor

It results in wide variations in product concentrations and properties, which may be deemed off-spec in many applications.

And if the mixing a slow, large then varying concentration gradients of the reactants basis will exist in the different parts of the reactor, so that is also to be remember that, how you are optimizing the system based on this mixing, whether it is slow or fast, so if results is wide variations in the product concentrations and properties, that may be deemed off-spec in, you know many applications, so that is you have to remember the mixing is whether slow or fast according to that you have to intensify the process and also develop the process unit.

(Refer Slide Time: 35:49)



Slow mixing represents a total loss of control on two counts:

1. The AB stoichiometric ratio varies wildly across the reactor diameter.

Therefore the selectivity for the desired product C is likely to be compromised because a more realistic reaction scheme will usually include many side reactions.

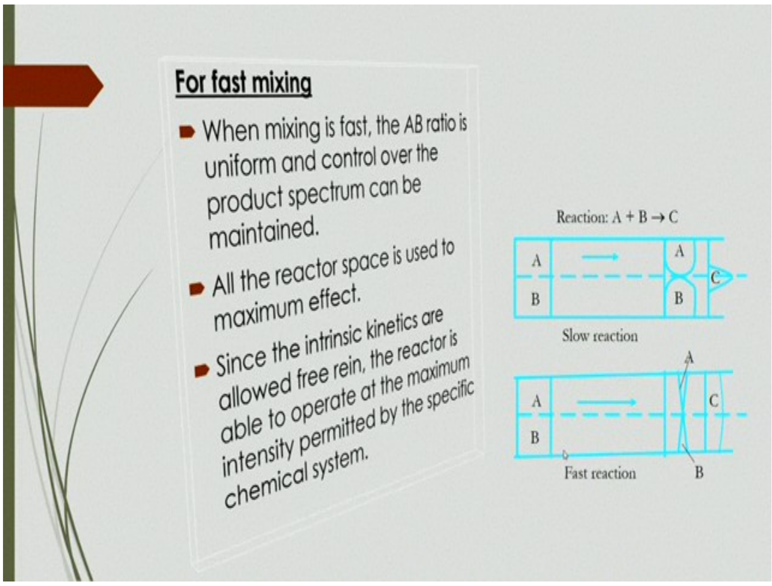
2. Most of the reaction to C occurs in the immediate neighborhood of the plane of A–B separation

Thus only a small fraction of the available reactor volume is utilized and an opportunity for intensification is lost.

And slow mixing that represents a total loss of control on the two counts, like one is that suppose there is AB reactions, that AB stoichiometric ratio, that will vary widely across the reactor diameter, therefore the selectivity for the desire product C is likely to be compromised because you know that more realistic reactions scheme that will usually include many side reactions there.

And another point is that the most of the reaction, that is give you that C in the immediate neighbourhood of the plane of this A and B separation as shown here in the figure. In this case, hence only a small fraction of the available reactor volume will be utilized and opportunity for the intensification will be lost, so these are the two counts to be remember for the slow mixing, for the total loss of control.

(Refer Slide Time: 36:54)

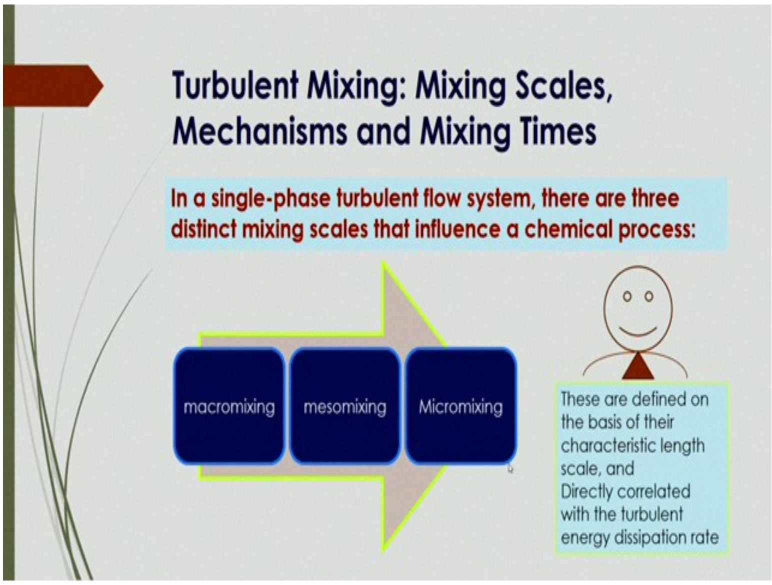


For fast mixing

- When mixing is fast, the AB ratio is uniform and control over the product spectrum can be maintained.
- All the reactor space is used to maximum effect.
- Since the intrinsic kinetics are allowed free rein, the reactor is able to operate at the maximum intensity permitted by the specific chemical system.

For the fast fixing you will see a, when the mixing will be so fast, the AB ratio should be uniform and it should be control over the product spectrum and also the reactors space should be used to maximize this effect and also intrinsic kinetics are to be allowed in a free rein, where the reactor is able to operate at the maximum intensity that will be permitted by the specific chemical systems.

(Refer Slide Time: 37:26)



Turbulent Mixing: Mixing Scales, Mechanisms and Mixing Times

In a single-phase turbulent flow system, there are three distinct mixing scales that influence a chemical process:

These are defined on the basis of their characteristic length scale, and Directly correlated with the turbulent energy dissipation rate

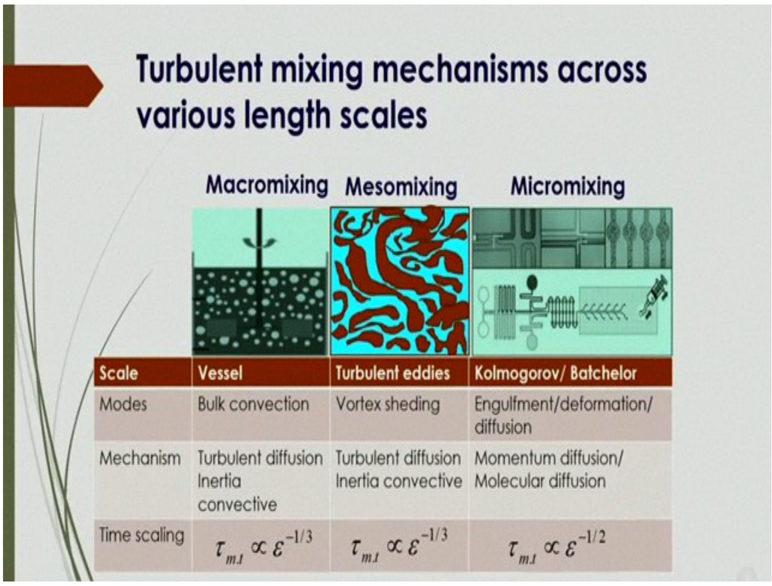
Now, if we go to that the different other mixing mechanism like the turbulent mixing, mixing, scales, mechanism and mixing times in a single-phased turbulent flow system, you will see that there are three distinct mixing scales that influence a chemical process, like macromixing, mesomixing and micromixing. These are the three different mixing scales, generally, are considered for the intensification of the chemical processes. These are defined on the basis of the, you know characteristics length and directly related to the turbulent energy distribution rate.

So based on the energy dissipation, in case of turbulent condition you can actually optimize that mixing characteristics, so that is why sometimes in a reactor, some provisions are made to, you know that get the intense mixing inside the fluid, based on this turbulent flow, if you are supplying the fluid mixture or you know inlet streams as a highly flow rate and if you are using some provisions like baffles inside the reactor and cross bubbles.

Or sometimes you will see some, you know nowadays, you know that helical coil systems are also important there and inside that helical coils if you use some, you know some nozzles that will stuck your flow up the systems, so at high flow rate whenever it will go through this, you know provisions of the helical systems or some coil systems they are, you know there will be a, you know intense sheer stress inside the reactor.

So based on that sheer stress, higher energy dissipation inside the reactor, this fluid gets more, you know turbulent and because of fluid there will be a higher energy distribution and dissipation and get the more mixing inside the reactors and the path of the fluid mixing, you may also get the change by just giving this provision of this baffles or that some nozzles or some obstructions inside the reactor, so that the mixing times, maybe will be a higher or lower based on that, you know design.

(Refer Slide Time: 39:52)



Turbulent mixing mechanisms across various length scales

	Macromixing	Mesomixing	Micromixing
Scale	Vessel	Turbulent eddies	Kolmogorov/ Batchelor
Modes	Bulk convection	Vortex sheding	Engulfment/deformation/ diffusion
Mechanism	Turbulent diffusion Inertia convective	Turbulent diffusion Inertia convective	Momentum diffusion/ Molecular diffusion
Time scaling	$\tau_{m,t} \propto \varepsilon^{-1/3}$	$\tau_{m,t} \propto \varepsilon^{-1/3}$	$\tau_{m,t} \propto \varepsilon^{-1/2}$

Now, if we see this figure as shown here in the slide that, the turbulent mixing how actually this various length scales this mixing are happened, you know macromixing, mesomixing and micromixing are there, so if we are considering then modes of this mixing, then we can have this macromixing like in the vessel that is bulk convection of the speed will be happened.

Whereas in the mesomixing in that case turbulent eddies will be formed, some chunk of the fluid elements will be, you know that generated inside the reactor or inside the unit and those chunks of the fluid elements will be called as eddies which will be arbitrary or you know that random motions will be there and getting that intense mixing inside the reactor or unit and there will be a formations of that vortex sheding by this eddies and by energy dissipation, so you can get this mesomixing, this type of phenomena is called mesomixing.

And here, this micromixing, in this case you will get producing some channel based, where you know that plug flow phenomenal will be produced and some engulfment of phenomena will be produce of this fluid element or deformation of this fluid element, just making that different provisions here in the reactor inside the reactors or sometimes know that coil type reactors will be produce so that there will be a, you know change of, you know engulfment like maybe that secondary flow will be produced, that will give you the more mixing of this fluid element.

And that deformation also sometimes some provisions will be there, that fluid elements will be deformed, that fluid systems will be deformatted and in that case there will be a mixing and also diffusions will happen, there, that is molecule diffusions will happen, molecule level, the convective diffusions will be less compare to that molecular diffusion there, through the thin fluid layer, so that you can get the more, you know the molecular level diffusion.

Mechanism in the case of macromixing you will see that what this macromixing turbulent diffusion there should be there, so inertia, convective inertia would be there and also turbulent diffusion in case of mesomixing will be observed, inertia convective terms with their that is convective inertia will be produced because of these energy dissipation and in the case of micromixing there would be a momentum diffusion and molecule diffusion, both will be there because there engulfment formation and deformation of that fluid, that is why momentum diffusion and molecular diffusion will be the major effect there.

And if you are considering the timescale, what would be the time that will be required for the macromixing, for that macromixing, will see that what will be the energy will be dissipated, that will be directly related in that case, you know, degree of mixing will be directly related to that energy dissipation, whereas mixing time will be inversely related to that energy dissipation, if you are considering the efsilon (ε) as energy dissipation, so for the macromixing, the time of mixing will be proportional to the epsilon to the power minus 1 by 3.

$$\tau_{m.t} \propto \varepsilon^{-1/3}$$

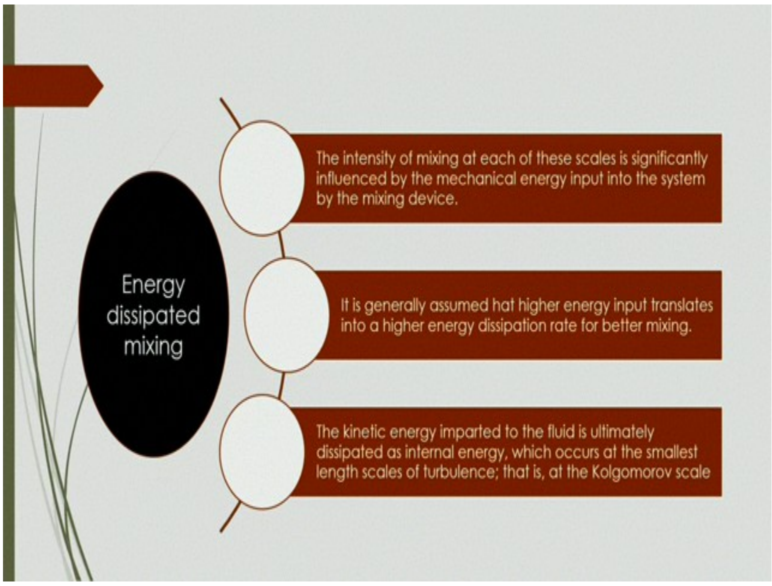
Whereas for turbulent eddies it will be also the same, that should be proportional to the inverse of this 1 cubic root of that energy dissipation,

$$\tau_{m.t} \propto \varepsilon^{-1/3}$$

that is the TMIT here, similarly, for micromixing this time of mixing or missing time it is inversely proportionate to the square root of that energy dissipation,

$$\tau_{m.t} \propto \varepsilon^{-1/2}$$

so based on this timescale that macromixing, mesomixing and micromixing how this timescale is actually depending on that energy dissipation that you can get it from this idea. (Refer Slide Time: 43:47)



Energy dissipated mixing

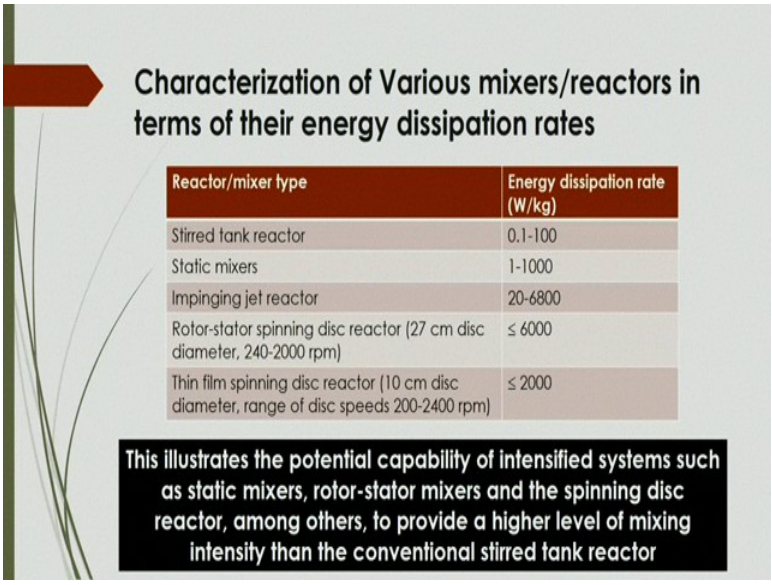
The intensity of mixing at each of these scales is significantly influenced by the mechanical energy input into the system by the mixing device.

It is generally assumed hat higher energy input translates into a higher energy dissipation rate for better mixing.

The kinetic energy imparted to the fluid is ultimately dissipated as internal energy, which occurs at the smallest length scales of turbulence; that is, at the Kolgomorov scale

Now energy dissipated mixing, the intensity of the mixing at each of these scales that is macro, meso or micro is significantly influenced by the, you know that mechanical energy input into the system by mixing device and it is generally assumed that higher energy input translates into a higher energy dissipation rate for better mixing, the kinetic energy imparted to the fluid is ultimately dissipated as internal energy, which occurs at the smallest length scales of turbulence and that will give you that the timescale, this will be represented by that Kolmogorov, you know that timescale there.

(Refer Slide Time: 44:32)



Characterization of Various mixers/reactors in terms of their energy dissipation rates

Reactor/mixer type	Energy dissipation rate (W/kg)
Stirred tank reactor	0.1-100
Static mixers	1-1000
Impinging jet reactor	20-6800
Rotor-stator spinning disc reactor (27 cm disc diameter, 240-2000 rpm)	≤ 6000
Thin film spinning disc reactor (10 cm disc diameter, range of disc speeds 200-2400 rpm)	≤ 2000

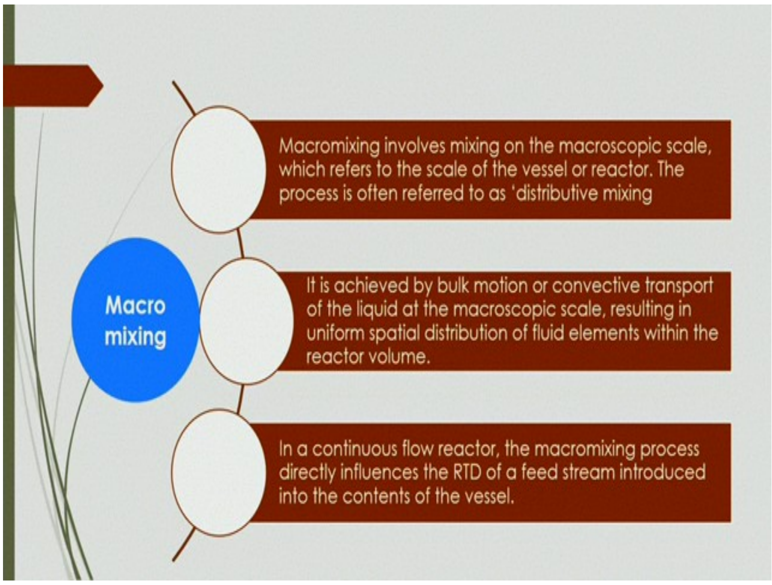
This illustrates the potential capability of intensified systems such as static mixers, rotor-stator mixers and the spinning disc reactor, among others, to provide a higher level of mixing intensity than the conventional stirred tank reactor

Now characterization of the various mixers and reactors in terms of their energy dissipation rates, here some examples, some intensification of the unit are there, like stirred tank reactor, in that case energy dissipation rate per unit or you know mass of that fluid system that will be 0.1 to 100 watt and for the static mixture for this mixing their energy dissipation is 1 to 1000 watt per KG.

Impinging jet reactors are important reactors where that fluid is actually coming into the pool of the liquid and impinge on the pool of the liquid to make the or entrain the other fluid element, so that is called impinging jet reactors, their intense mixing by the jet energy, so in that energy dissipation rate should be 20 to, you know 6800 watt per KG.

Like rotor-stator spinning disk reactor, thin film spinning disk reactor, their energy dissipation rate should be or, you know that less than 6000 watt per KG, so this illustrates the potential capability of the intensified systems such as static mixers, rotor-stator mixers and the spinning disk reactor, among others to provide the higher level of mixing intensity than the other conventional mixing devices.

(Refer Slide Time: 45:57)



Macro mixing

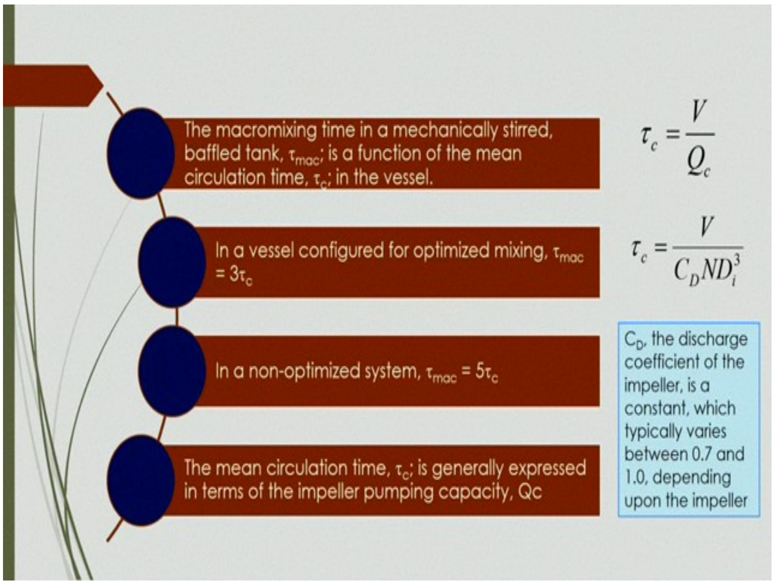
Macromixing involves mixing on the macroscopic scale, which refers to the scale of the vessel or reactor. The process is often referred to as 'distributive mixing

It is achieved by bulk motion or convective transport of the liquid at the macroscopic scale, resulting in uniform spatial distribution of fluid elements within the reactor volume.

In a continuous flow reactor, the macromixing process directly influences the RTD of a feed stream introduced into the contents of the vessel.

In the case of macromixing that involves the mixing on the macroscopic scale, which refers to the scale of the vessel reactors, the process is often referred to as you know the distributive a mixing and it is achieved by bulk motion of the fluid element and that is transported by, you know that liquid at the macroscopic scale and resulting in uniform spatial distribution of fluid elements across the reactor volume and in a continuous flow reactor, you will see that the macromixing process directly influences the resistance time distribution of the feed stream that is introduced into the reactor.

(Refer Slide Time: 46:40)



The macromixing time in a mechanically stirred, baffled tank, τ_{mac}; is a function of the mean circulation time, τ_c; in the vessel.

In a vessel configured for optimized mixing, $\tau_{mac} = 3\tau_c$

In a non-optimized system, $\tau_{mac} = 5\tau_c$

The mean circulation time, τ_c; is generally expressed in terms of the impeller pumping capacity, Qc

$$\tau_c = \frac{V}{Q_c}$$

$$\tau_c = \frac{V}{C_D N D_i^3}$$

C_D, the discharge coefficient of the impeller, is a constant, which typically varies between 0.7 and 1.0, depending upon the impeller

And the macro mixing time in a mechanically stirred baffled tank, that is taw mac you can represent it, that will be the function of a mean circulation time, that is means a how much circulations time will be there inside the reactor of the fluid element that will effect this macromixing time, so that circulation time is actually defined as volume of the reactor divided by what is the flow rate of the circulation

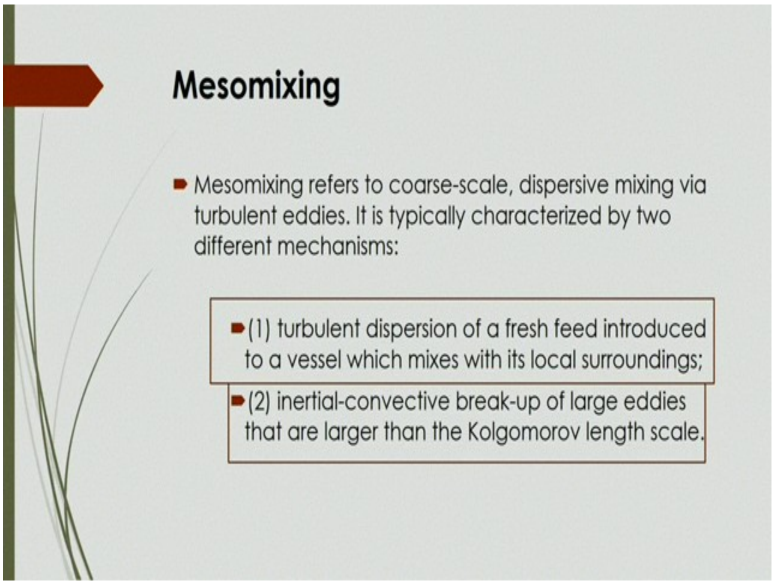
$$\tau_c = \frac{V}{Q_c}$$

or you can circulation rate and in a vessel that is configured for the optimised mixing that taw mac should be 3 times of that circulation time. In case of stirred tank reactor, the circulation time is defined by this equation here, the V by CD into NDQ,

$$\tau_c = \frac{V}{C_D N D_i^3}$$

CD is that the discharge coefficient of the impeller, if it is being used for the stirred tank reactor and it is a constant, which typically varies between 0.7 and 1.0, that depending on the impeller design. In a non-optimized system, this macromixing time should be 5 times of that circulation time and the means accretion time is generally expressed in terms of the impeller pumping capacity also that is denoted by QC here.

(Refer Slide Time: 47:58)

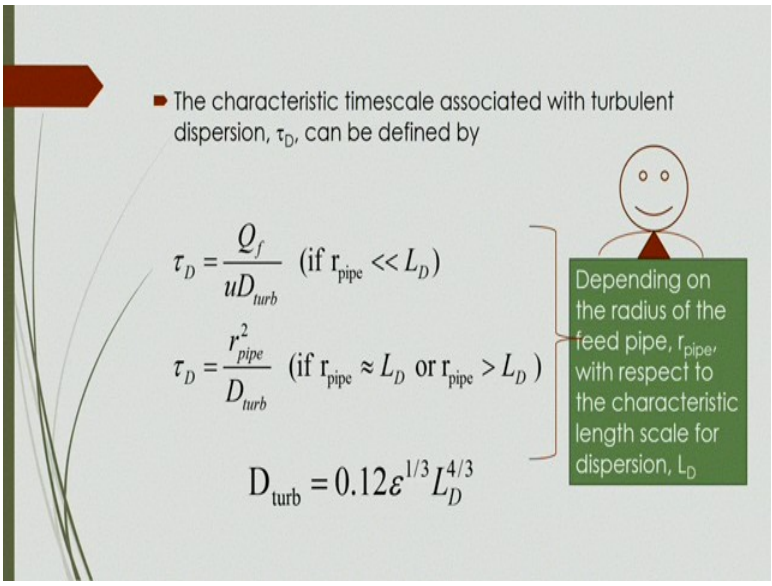


Mesomixing

- Mesomixing refers to coarse-scale, dispersive mixing via turbulent eddies. It is typically characterized by two different mechanisms:
  - (1) turbulent dispersion of a fresh feed introduced to a vessel which mixes with its local surroundings;
  - (2) inertial-convective break-up of large eddies that are larger than the Kolgomorov length scale.

For mesomixing, you know that will refer to, you know coarse-scale and dispersive mixing via turbulent eddies, that eddies will literally, randomly moved inside the reactor and it will be characterized by two different mechanisms, like one is turbulent dispersion of the fresh feed that will be introduce to a vessel, which mixes with its total surroundings and other is inertia convective breakup of the, you know large eddies, sometimes you are using that different provisions that eddies should be broken-up into a smaller eddies and then you can get the, you know very small scale of this interaction of this two eddies there and then you can enhance that mesomixing time there.

(Refer Slide Time: 48:48)



- The characteristic timescale associated with turbulent dispersion, τ_D, can be defined by

$$\tau_D = \frac{Q_f}{uD_{turb}} \quad (\text{if } r_{pipe} << L_D)$$

$$\tau_D = \frac{r_{pipe}^2}{D_{turb}} \quad (\text{if } r_{pipe} \approx L_D \text{ or } r_{pipe} > L_D)$$

$$D_{turb} = 0.12\varepsilon^{1/3} L_D^{4/3}$$

Depending on the radius of the feed pipe, r_{pipe}, with respect to the characteristic length scale for dispersion, L_D

The characteristic timescale associated to the turbulent dispersion, you know by turbulent there will be dispersion, the turbulent dispersion, it is denoted by that, you know timescale of that, you know the mesomixing dispersion, so that will be represented by taw D and it can be defined by that QF by UD turbulent, here if R pipe is less than less than equal to LD, LD is the, you know that dispersion length characteristics, length scale of the dispersion and also R is the pipe diameter, you know that the turbulence the dispersion coefficient of that turbulent medium and the turbulent scheme of this, you know dispersion.

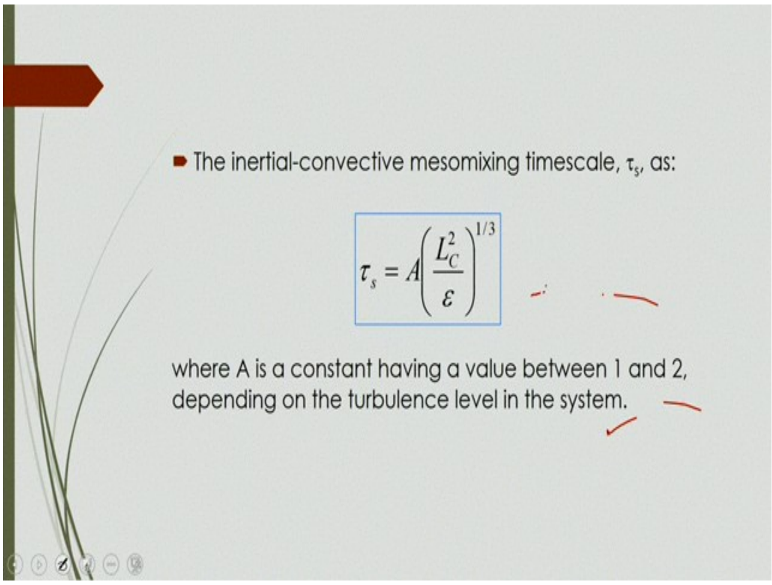
$$\tau_D = \frac{Q_f}{uD_{turb}} \quad (\text{if } \mathrm{r}_{\mathrm{pipe}} << L_D)$$

$$\tau_D = \frac{r_{pipe}^2}{D_{turb}} \quad (\text{if } \mathrm{r}_{\mathrm{pipe}} \approx L_D \text{ or } \mathrm{r}_{\mathrm{pipe}} > L_D)$$

$$\mathrm{D}_{\mathrm{turb}} = 0.12\varepsilon^{1/3} L_D^{4/3}$$

So taw D that will be R square pipe by D turbulent, if I pipe of the reactor or you know that radius of the pipe if it is almost equals to the characteristics length or if it is greater than, you know, characteristics length you can define by this equation here and also you can say that dispersion coefficient at this turbulent motion it will be 0.12 epsilon to the power 1 by 3 into LD to the power 4 by 3, this epsilon is called energy dissipation per unit mass and L is the characteristics length in that turbulent dispersion.

(Refer Slide Time: 50:11)



- The inertial-convective mesomixing timescale, τ_s, as:

$$\tau_s = A\left(\frac{L_C^2}{\varepsilon}\right)^{1/3}$$

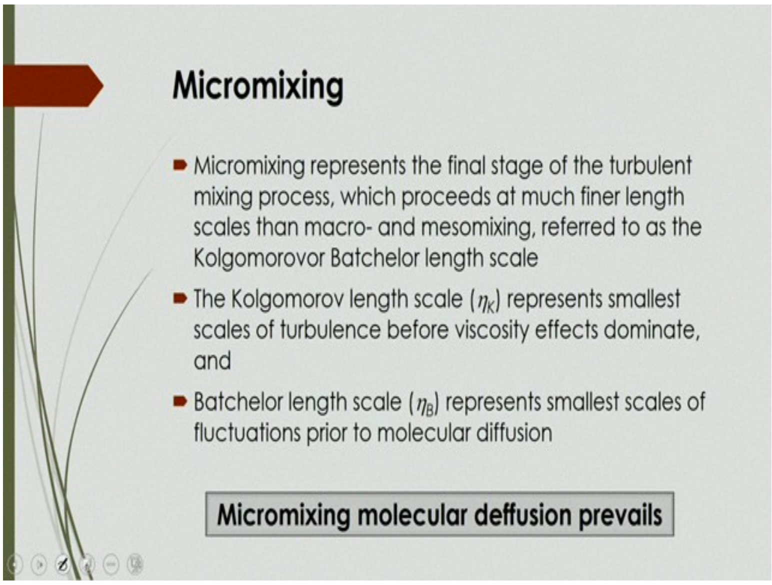
where A is a constant having a value between 1 and 2, depending on the turbulence level in the system.

And the inertial-convective mesomixing timescale that will be represented by taw S that will be defined by this equation here as shown in this here in the slides,

$$\tau_s = A\left(\frac{L_C^2}{\varepsilon}\right)^{1/3}$$

where A is a constant that will have a value between 1 and 2, that depends on the turbulence level in the system.

(Refer Slide Time: 50:35)



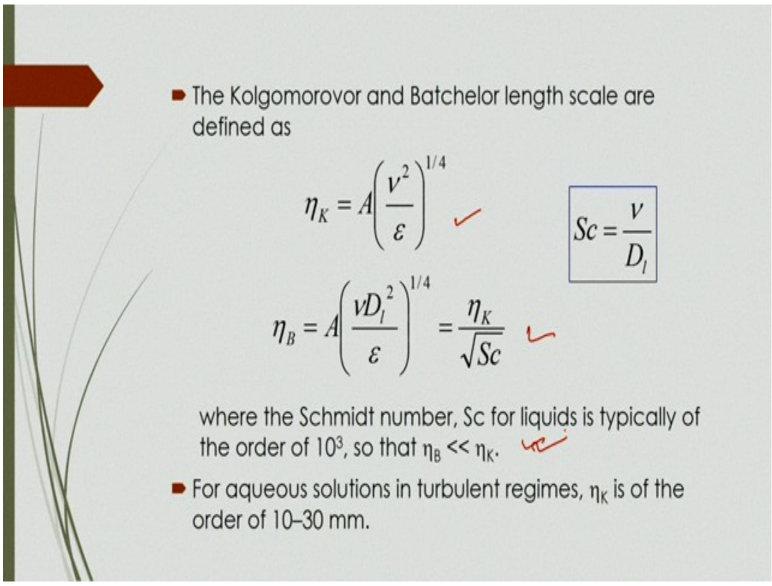
Micromixing

- Micromixing represents the final stage of the turbulent mixing process, which proceeds at much finer length scales than macro- and mesomixing, referred to as the Kolgomorovor Batchelor length scale
- The Kolgomorov length scale (η_K) represents smallest scales of turbulence before viscosity effects dominate, and
- Batchelor length scale (η_B) represents smallest scales of fluctuations prior to molecular diffusion

Micromixing molecular deffusion prevails

And then, you know the micromixing represents the final stage of the turbulent mixing process, which proceeds at mass, you know final length scales that macro or meso mixing that will referred by Kolmogorov or Batchelor length scale, the Kolmogorov, you know the length scale represents the smallest scale of, you know the turbulence before viscosity effects that will dominate and also Batchelor length scale it is denoted by eta B represents the smallest scale of the fluctuations prior to the molecular diffusion, so macromixing molecular diffusion prevails there

(Refer Slide Time: 51:17)



- The Kolgomorovor and Batchelor length scale are defined as

$$\eta_K = A\left(\frac{\nu^2}{\varepsilon}\right)^{1/4}$$

$$\boxed{Sc = \frac{\nu}{D_l}}$$

$$\eta_B = A\left(\frac{\nu D_l^{\,2}}{\varepsilon}\right)^{1/4} = \frac{\eta_K}{\sqrt{Sc}}$$

where the Schmidt number, Sc for liquids is typically of the order of 10^3, so that $\eta_B << \eta_K$.

- For aqueous solutions in turbulent regimes, η_K is of the order of 10–30 mm.

Also this Kolgomorovor or that, you know that Batchelor length scale can be defined by this here equation given here, eta K and eta B,

$$\eta_K = A\left(\frac{\nu^2}{\varepsilon}\right)^{1/4}$$

$$\eta_B = A\left(\frac{\nu D_l^2}{\varepsilon}\right)^{1/4} = \frac{\eta_K}{\sqrt{Sc}}$$

where this Schmidt number SC for liquid is typically for the order of 10 to the power 3,

$$Sc = \frac{\nu}{D_l}$$

so that eta B should be very less than eta K, for aqueous solutions in turbulent regimes this eta K is of the order of 10 to 30 mm, so based on this the criteria of this length scale of this macromixing, that devices are developed for getting more mass transference, heat transference in the system.

I think I have covered some this process intensification phenomena based on this mixing characteristics, so this lecture will be helpful for the process intensification criteria, where you are considering the design of any, you know micro reactors or other reactors based on this timescale and it will be helpful for you for this process intensification system and for further reading I am suggesting the textbook to follow and in the next lecture onward we will also discuss the more about this, you know that this process intensification based on other characteristics, so thank you for this lecture.