Multiphase Microfluidics
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Lecture - 15
Taylor Flow: Mass Transfer

In this lecture we are going to talk about mass transfer in Taylor flow. As we have seen that the Taylor flow, or segmented flow or what we call so called slug flow this can occur in gas liquid flow in micro channels or liquid liquid flow in micro channels.

So, we will try to cover both the, mass transfer or mass transfer for gas liquid mass transfer and liquid liquid mass transfer. Additionally or the reactions which are catalytic in nature, catalytic in nature and require a solid catalyst in many instances the channel wall is coated with a layer of the catalyst. So, we have a gas liquid solid or liquid liquid solid mass transfer also happening in such cases.

So, we will cover all such cases here one might try to have an analogy between the gas liquid heat transfer where the heat transfer is happening from wall to the liquid and to the gas phase or from wall to the liquid that is continuous liquid and the dispersed droplet phase. Similarly when we have solid, liquid, gas mass transfer or three phase mass transfer.

Then there is interaction or there are mass transfer resistances in between gas and liquid phase and liquid and solid phase as well as gas solid or phase via the thin film that surrounds these bubbles. So, it is it will be good to have an analogy and try to have a unified model which can be Tailored according to with the mass transfer, heat transfer need.

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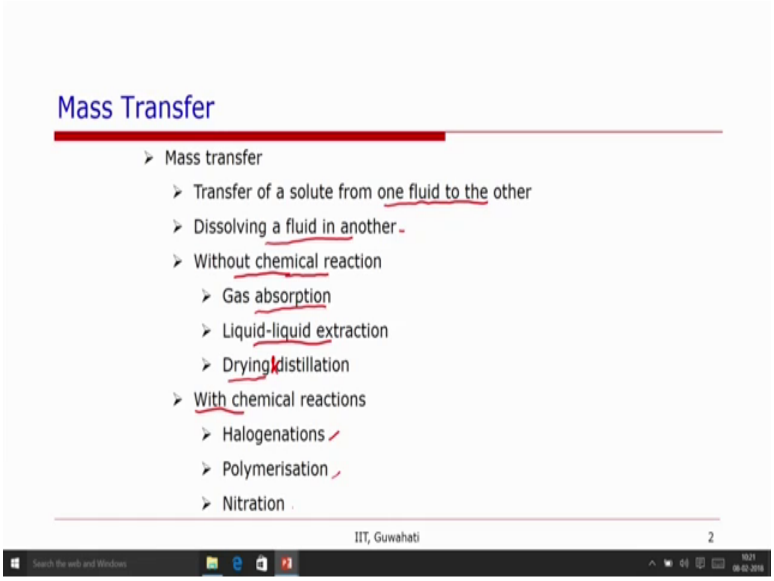

Mass Transfer

- Mass transfer
  - Transfer of a solute from one fluid to the other
  - Dissolving a fluid in another
  - Without chemical reaction
    - Gas absorption
    - Liquid-liquid extraction
    - Drying distillation
  - With chemical reactions
    - Halogenations
    - Polymerisation
    - Nitration

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So, because this course I am not sure how many of you are from the chemical engineering background. And in the chemical engineering background also to understand everything in this course one need to have a background in fluid mechanics heat transfer and mass transfer.

So, we are going to revise some of the basics of mass transfer to start with and then we will look at the a specific details of mass transfer in Taylor flow regime. So, mass transfer is basically transfer of a solute from one phase to another it can be in a single phase also.

But what we are talking about that the how the solute is distributing in the bulk of the liquid so that can be the mass transfer form in a single phase. But what we are talking about mass transfer between gas liquid or liquid liquid phases.

So, mass transfer is generally driven by the concentration gradients or to put it more a specifically in thermodynamic from thermodynamic point of view mass transfer occurs because of the chemical potential or gradient in chemical potential.

So, it can have as we can see here that it can be the transfer of solute from one thread to another or for example, absorption of gas in the liquid phase or dissolving of a fluid in another at which is what I was talking about the absorption of gas in the liquid phase.

And it can accompanied it can be accompanied with chemical reaction or it can be accompanied with chemical reaction or it can happen without chemical reactions. So, without chemical reaction some of the examples are say for example, gas absorbed in a liquid.

So, for example, co 2 absorption in water or CO 2 absorption in amines or sodium hydroxide for that matter and number of liquid liquid extraction examples are there. Then drying and distillation so or drying is also a form of mass transfer it is the evaporation and then or the taking out the moisture from one phase and then distillation.

Then mass transfer with chemical reaction. So, there are number of chemical reactions some of those are say halogenation, polymerization, and nitrogen to name a few.

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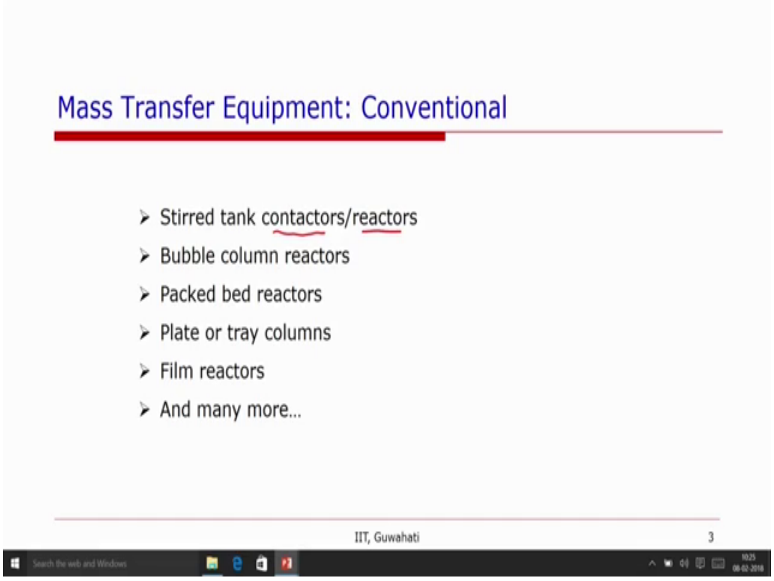

Mass Transfer Equipment: Conventional

- Stirred tank contactors/reactors
- Bubble column reactors
- Packed bed reactors
- Plate or tray columns
- Film reactors
- And many more...

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So, in conventional chemical engineering or in the industrial practice a different a number of contactors or reactors are used. So, there are two terms here where we as we see here contactors and reactors.

Basically they can be used interchangeably the difference in the naming is because when there is only contact between the phases, but there is no reaction. So, there is no point in calling this as a reactor and we term it as contactor and then there is reaction involved then we call this as a reactor.

So, different reactors have been used or are being used in the industry and more and more reactors where the process can be intensified process intensification can happen a number of different reactors are being developed with such a purpose.

So, for example, is stirred tank reactor in the stirred tank reactor by the a stirrer or by the motion of the a stirrer it can be a different kind of a stirrer can be present there. So, they induce a mixing of the two phases one or the dispersed phase is broken down into a smaller droplets or the smaller bubbles and that gives larger interfacial area and the reaction between the two bubble column reactor in the bubble column reactor a number of variations of bubble column reactor are present.

So, in a column of liquid which may be a stationary or which may be also flowing. So, it depending on that it will be a continuous gas liquid reactor or semi batch reactor in which one phase is stationary or in the batch mode and the other phase gas is moving through the column.

So, in the bubble column reactor basically in a column of liquid the gas is introduced it can be introduced at the bottom it can be introduced from the top and that the bubbles when they are introduced a number of bubbles are generated there may be million of bubbles and then they have a plume, bubble plume generated large interfacial area in addition they also cause the mixing in the liquid phase. So, large interfacial area mixing and they are used for number of industrial applications.

Then packed bed reactors in the packed bed reactor as the name denotes that in a column the void is filled with the in solid bed for a catalytic reaction this might be catalytic or it might be a packed bed that may be a static bed it may be a fluidized bed.

So, on the surface of these catalysts the reaction and then voids they cause the reaction between the different pages for example trickle bed reactor. Now next example is plate or tray columns for example, distillation column where there are the plates segment the different sections of the column and mass transfer happens at each stage in between two plates and so on.

Then film reactors so in film reactors basically generally used for gas liquid reaction or gas liquid purposes where a continuous liquid film flows on the wall of the channel and gas flows to it. So, the reaction happen at the gas liquid interface and there are number of other variations of these reactors in conventionally.

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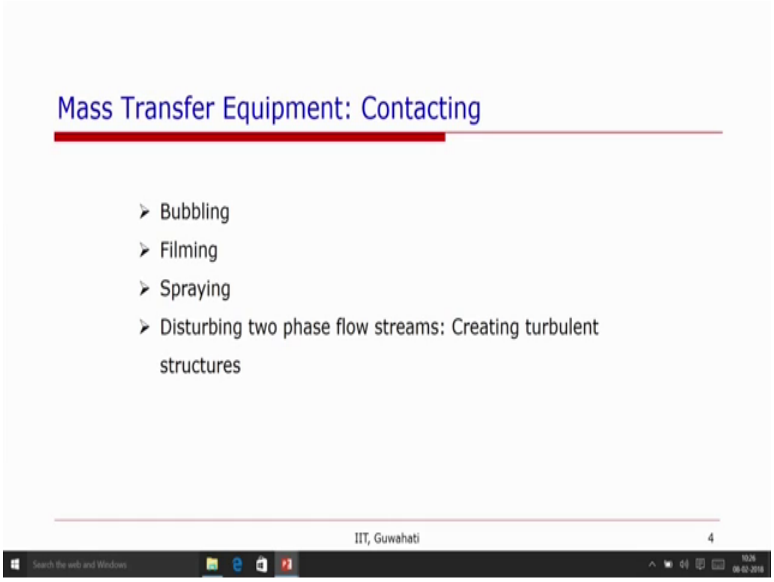

Mass Transfer Equipment: Contacting

- Bubbling
- Filming
- Spraying
- Disturbing two phase flow streams: Creating turbulent structures

So, the contacting pattern in these reactors may be by bubbling as we have seen in bubble column or a film reactor filming or a spring. So, by a spraying the small droplets of the mass transfer can happen of say for example, further when the drying of milk formation from milk to milk powder this kind of electrodes are used and say another application can be the coating of different pharmaceutical granules etcetera.

So, then the distributing two phase flow stream. So, devising the ways by which the two phase flow stream can be mixed or the turbulent structure or the mix mixing structure in the fluids can be created. So, there can be different contacting patterns and that reactors can be classified based on this contacting patterns.

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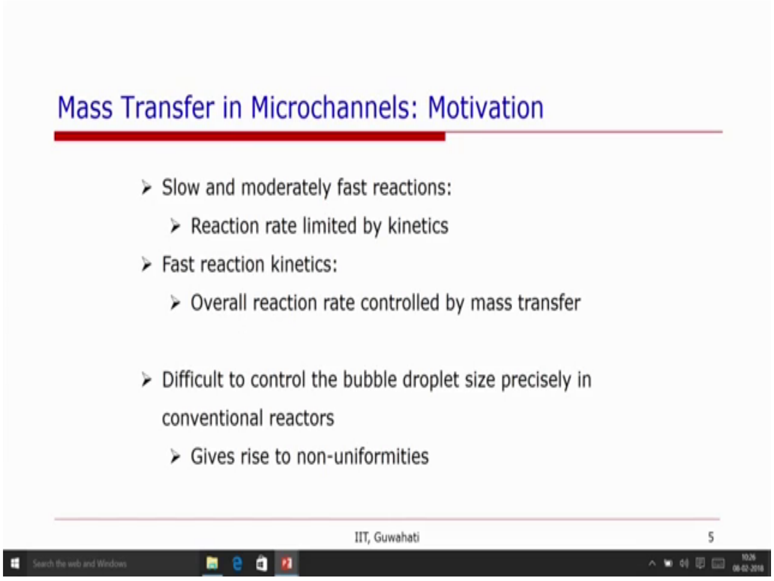

Mass Transfer in Microchannels: Motivation

- Slow and moderately fast reactions:
  - Reaction rate limited by kinetics
- Fast reaction kinetics:
  - Overall reaction rate controlled by mass transfer
- Difficult to control the bubble droplet size precisely in conventional reactors
  - Gives rise to non-uniformities

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So, contacted between the phases is important because the mass transfer between the two phases happens by the interface so it is important to have a large interfacial area ok. So, that is where we have a micro channels coming to picture.

Now when we talk about reactions or for reactions especially reaction in multi phase hen there can be two kind of kinetics or two extremes of kinetics in one case where a the reaction kinetics is flow in another case the reaction kinetics is very fast and last is in between the two limits.

So, because for the reaction to happen the gas and liquid or liquid; liquid or the phases which are to react this will come into contact first, there are two kinds of resistances in this case one is the resistance for the reaction. So, we can say that one over the reaction rate that can be the reacts are the resistance by the kinetics and the resistance by the mass transfer.

Now as we know then when there are reactions in chain then the slowest step or which have the smallest rate will be the rate limiting step. So, if the reactions are slow or moderately slow then mass transfer will not be a problem because the phases will mix and then there will be enough time for the reaction to happen.

However, if the reaction is fast and the reaction is fast as soon as the two phases come into contact reaction will happen and the rate of the reaction will be limited by the mass transfer. So, in such cases where the reaction rate is limited by the mass transfer which will happen where the reaction chemistry or reaction kinetics is very fast the overall rate is controlled by mass transfer.

And as we know that micro reactors have very large interfacial area density. So, per unit volume they have very high interfacial area so that is where micro channels or micro reactors can know why intensification to the process can be used as a tool for intensification for increasing the efficiency or the performance yield selectivity of the reactions with fast kinetics. Additionally in the conventional reactors most of them it is not possible to control the bubble or droplet size precisely.

For example, take a bubble column reactor you have a sparger and the gas is coming from it the bubbles will be generated depending on the local fluid conditions the size of the bubbles at the center and at the corner near the wall will vary.

Now these bubbles will interact with each other and they will coalesce or break up and there will be a size distribution of bubbles which can vary an order or more. So, it is very difficult to get an accurate idea of the interfacial area density in such cases and there will be non uniformities so it is very difficult to have control over the precise control over the happenings that are happening in the reactor.

So, in such cases Shatila flow regime where we have bubbles of a are bubbles of a size or a particular size we can generate or control the size of the bubble, or size of the droplet and the reaction can happen continuously in these size of in these regular sized bubbles or the uniform bubble sizes.

So, we can have a very precise control over the happenings over the activities that can happen in the in a micro reactor so that is advantage of micro reactors.

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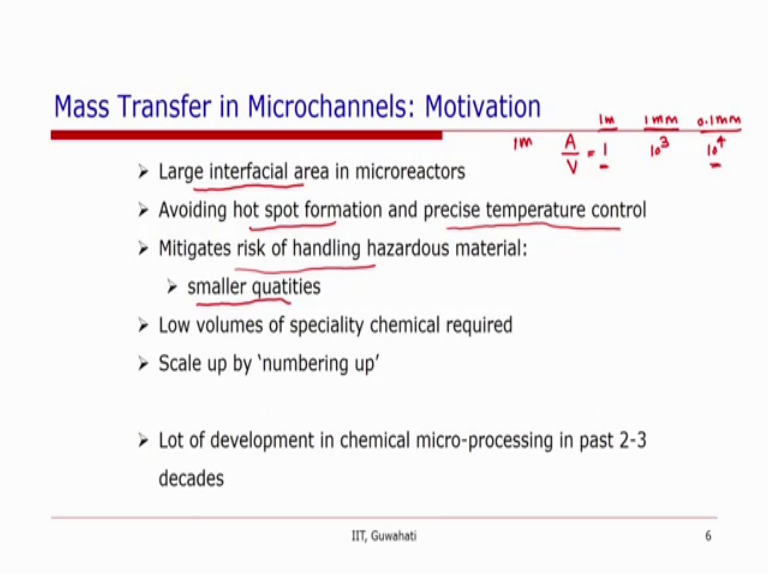

Mass Transfer in Microchannels: Motivation

1m 1mm 0.1mm

1m $\frac{A}{V} = 1$ 10^3 10^4

- Large interfacial area in microreactors
- Avoiding hot spot formation and precise temperature control
- Mitigates risk of handling hazardous material:
  - smaller quatities
- Low volumes of speciality chemical required
- Scale up by 'numbering up'
- Lot of development in chemical micro-processing in past 2-3 decades

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So, we are here we have listed down the different advantage or issues that are relevant to micro reactors. So, in micro reactors we have interfaced area to be large just to remind ourselves if the channel size is one meter area over volume is one of the order of one.

And for one meter and if this becomes 1 millimeter then the same number becomes 10 raised to the power 3, it should becomes 0.1 mm the same number will become 10 raised to the power 4. So, as compared to one we can get interfacial area of 10 raised to the power 4 in micro reactors.

So, of course, a lot of advantage in terms of interfacial area then avoiding heat hotspot formation so when the reaction is exothermic and large amount of heat is being generated during the reaction then where the reaction happening in these zones the the high temperature may occur and the hot spot may form.

So, in micro reactors as we have discussed in the previous lectures the heat transfer one can precisely control the temperature in the reactors. So, one can avoid the hot spot formation and it is also easier to or to carry out these exothermic reactions safely in micro reactors.

Then one can handle specially the hazardous materials or a specialty chemicals fine chemicals which cost a lot. So, these coming especially in the pharmaceutical industry or consumer goods industry or so in these cases one can work with because the micro channels size is small.

So, one can work with the small quantities and mitigate the risk of handling hazardous materials in their speciality chemicals one can work with smaller nano litre or the pico litter size of the droplets and carry out the reactions and find out the I mean do the analytical chemistry or whatever formulations or the reactions are to be done especially in pharmaceutical applications one can do.

So, micro reactors are useful there then the always question will come that all this is fine, but micro reactor is for the same region that it handles very small amount of volume. So, how do we scale this up so scaling up micro reactors I will again give the example of say printed circuit heat exchangers that we talked about in the heat transfer case.

So, the same concept where a sheet of metal it can have channels edged straight channels or meandering or tortuous channels etched on this plate if the number of channels may be 1000 and then stack those plates together. So, one has 1000 micro reactors or 100s of micro reactors and then 100's of these plats plates stacked up together.

So, if one can distribute the gas and liquid phases or liquid liquid phases or whatever the liquids one is working with uniformly in these micro channels then the scaling up can be achieved without really changing the size of the channel.

So, the by scaling of achieved the scalene up in micro reactors is achieved by numbering of the channels by numbering of the units that we are working with rather than scaling up the reactor from lab scale to pilot scale to the industrial scale.

So, in with the with these promises of chemical micro processing or micro reactors a number of applications or number of researchers has focused on understanding the mass transfer, chemical reaction, reaction engineering in these micro reactor channels in past two decades not only from the academic word from the industry.

And some of those has started to come up in the industrial production also. So, so for example, in the pharmaceutical industry the impotence has been to use micro channels for the continuous production. Because in the most of the reactors that are used in the pharmaceutical industry they are batch reactors.

So, and batch reactors they have its own disadvantages. So, it will be advantageous to convert these processes into continuous processes, but the volume that is handled in these reactors may not be high or in these industries may not be high or they need to use the same system for different processes. So, this can be easily achieved using micro reactors and this has been or this has been increasingly explored by the pharmaceutical industry.

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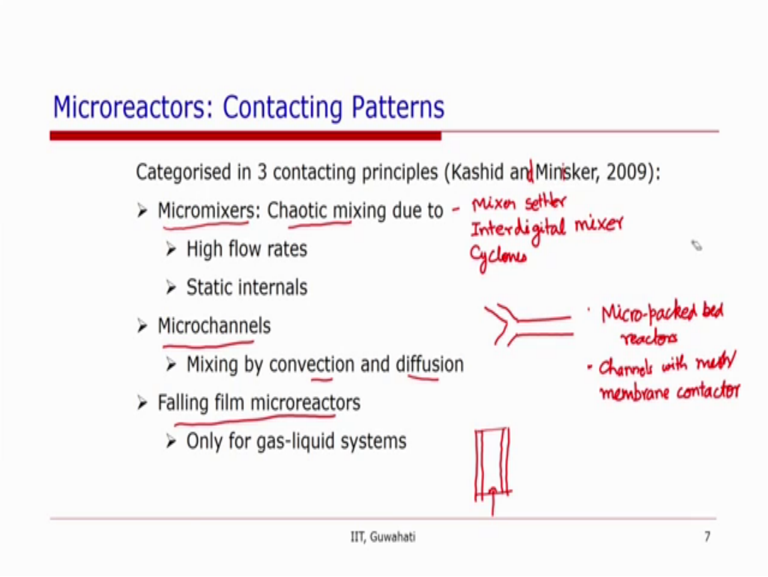

Microreactors: Contacting Patterns

Categorised in 3 contacting principles (Kashid and Minisker, 2009):

- Micromixers: Chaotic mixing due to - Mixer settler
  Interdigital mixer
  Cyclones
  - High flow rates
  - Static internals
- Microchannels
  - Mixing by convection and diffusion
- Falling film microreactors
  - Only for gas-liquid systems

- Micro-packed bed reactors
- Channels with mesh/ membrane contactor

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So, coming back to micro reactors specially for gas liquid or liquid liquid flow Kashid and Minisker I think I have a spelling mistake here. So, Kashid and Minisker they divided the micro mixers into or micro channels or micro reactors into three different categories based on the contacted principles micro mixers, micro channels, and falling fault film reactors.

So, in the micro mixers some of the examples are mixer settler, or inter digital mixer, or cyclones. So, if they can also have a static internals. So, which gives rise to chaotic mixing or in micro channels where the mixing is basically either by diffusion or convection. So, one can have say different kind of y shape channels or t shaped channels or micro packed bed reactors.

Channels with mesh or membrane contactor the other option is falling fuel micro reactor. So, in this case a liquid film falls on the walls of the channel and the gas is flowing either from the bottom or from the top. So these are three different categorizations for micro reactors.

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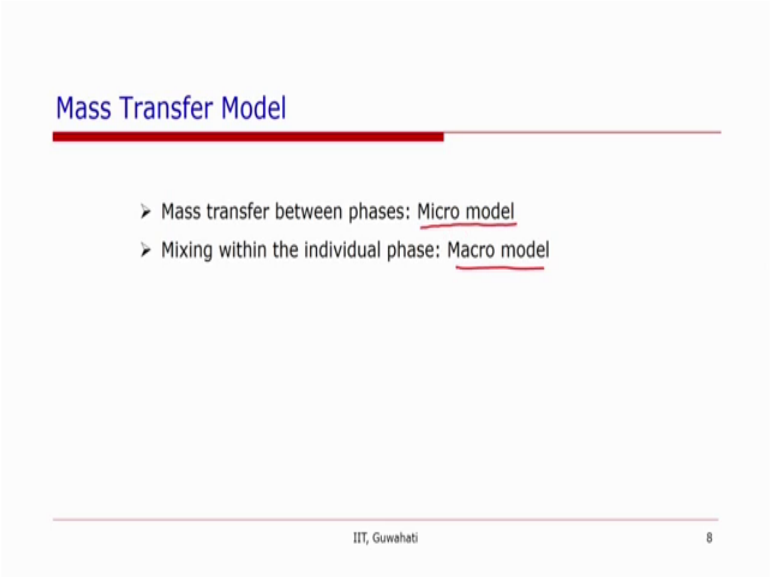

Mass Transfer Model

- Mass transfer between phases: Micro model
- Mixing within the individual phase: Macro model

And now we will look at some generic features of the mass transfer models. Now there can be or there are two different kind of models because one need to look at the mixing within the phase itself once the transfer through the interface has happened then the solute or the liquid or the gas phase will mix in the liquid phase so that comes under macro model so, that is mixing within a phase.

And then before that when the mixing happens at the interface one need to liquid mass transfer between the phases. So, different micro models what are called what are this called mass transfer between phases at the interface the models developed or called micro models.

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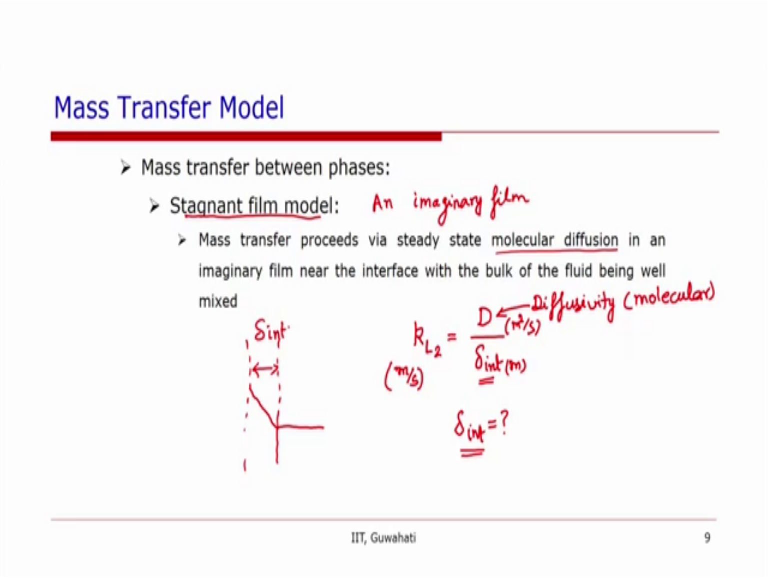

Mass Transfer Model

- Mass transfer between phases:
  - Stagnant film model: An imaginary film
    - Mass transfer proceeds via steady state molecular diffusion in an imaginary film near the interface with the bulk of the fluid being well mixed

δ_{int}

$$k_{L_2} = \frac{D \; (m^2/s)}{\delta_{int} \; (m)} \quad (m/s)$$

D ← Diffusivity (molecular)

$\delta_{int} = ?$

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So, looking at the micro models which are the specific to two phase flows there are different models that are being used. So, the first one is stagnant film model so it assumes that there is a, at the interface there is a stagnant film which is imaginary.

So, this film do not really anxious by the assumption is that this film and in this stagnant film the mass transfer proceeds via molecular diffusion just next to the interface and the remaining fluid remains well mixed. So, one has the concentration gradient here and then it is well mixed that is what the assumption in the stagnant film is.

So, the mass transfer coefficient in the stagnant film kl in the second phase is given as D where D is the diffusivity or molecular diffusivity or molecular diffusivity divided by delta interface.

So, the thickness of this interface one can also look at the units the unit of D is meter square per second and the unit of delta is meter. So, the mass transfer unit in this case is meter per second so it because this is in imaginary layer surrounding the liquid. So, the question in such models generally come what is the thickness of this film.

So, the stagnant film model requires to determine or it is required to determine the thickness of this film.

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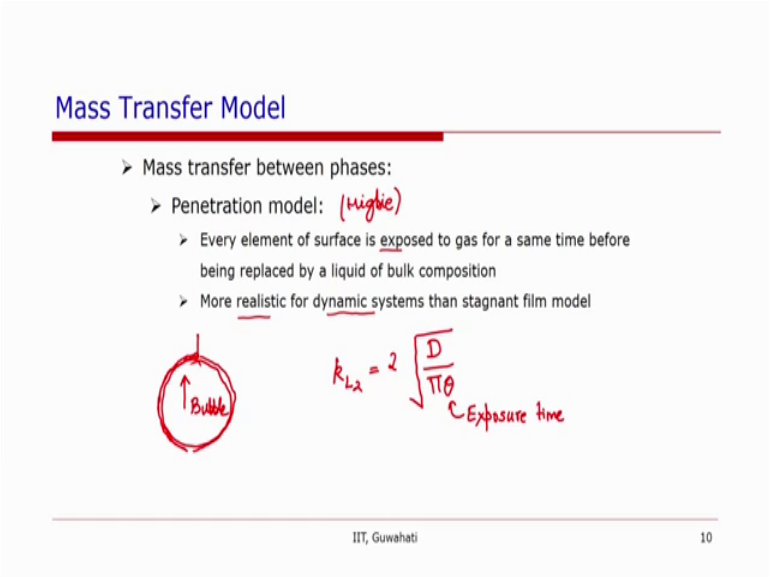

Mass Transfer Model

- Mass transfer between phases:
  - Penetration model: (Higbie)
    - Every element of surface is exposed to gas for a same time before being replaced by a liquid of bulk composition
    - More realistic for dynamic systems than stagnant film model

$k_{L2} = 2\sqrt{\frac{D}{\pi\theta}}$

Exposure time

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Another approach that is used is called penetration model and this is due to Migbie and so in this basically what it suggested that each liquid elements take the same time in contact with the fluid or each element of surface.

So, surface means the interface. So, consider a bubble that is rising in the liquid. So, a liquid element will come in contact with this bubble at this point and then it will move on the interface of the bubble and then eventually we will leave the.

So, what the assumption of penetration model is that liquid at the interface is continually being renewed. So, at one point there was one molecule of liquid, but the next time it moves here and another liquid come here. So, one molecule of liquid or one liquid particle or fluid particle will remain in contact with the interface for a certain time and then it will be it will leave the liquid.

So, this liquid is being continuously replaced by a new liquid. So, what they have suggested that the mass transfer coefficient is proportional to the square root of diffusivity divided by pi theta where theta is the exposure time or contact time of the liquid to get the gas phase.

Now this approach seems to be more realistic for dynamic system where the the bubble or the dispersed phase or that the relative velocity between the two phases.

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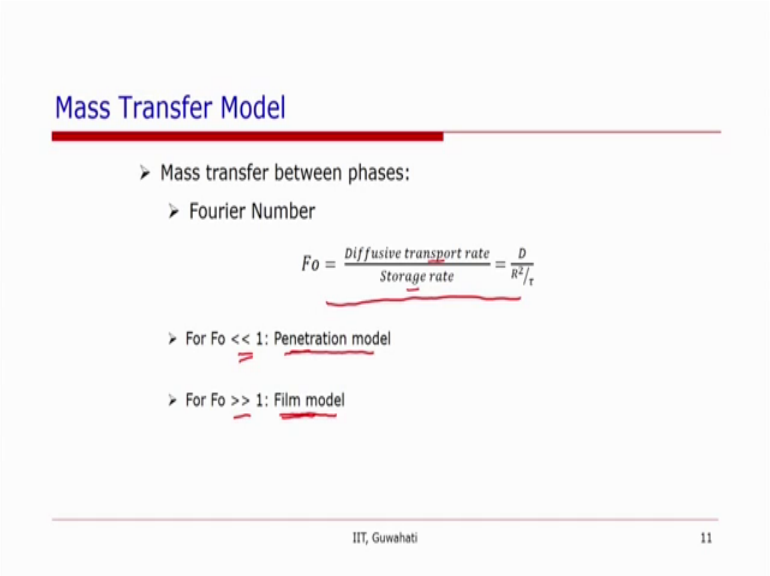

Mass Transfer Model

- Mass transfer between phases:
  - Fourier Number

$$Fo = \frac{Diffusive\ transport\ rate}{Storage\ rate} = \frac{D}{R^2/\tau}$$

  - For Fo << 1: Penetration model
  - For Fo >> 1: Film model

It has been suggested that the choice of the penetration model and film model can be determined by a non dimensional number or Fourier number which is defined as the ratio of diffusive or molecular diffusion divided by the storage depth.

So, molecular diffusion is given by the diffusivity or molecular diffusivity and the storage rate is the length scale. So, for a channel it will be the channel radius or diameter and r square over tau so, tau is a typical time scale.

So, the ratio of this is known as Fourier number and if the Fourier number is less than 1 that means the diffusion rate which is smaller than the storage rate then it is suggested to use the penetration model. If it is other way round that if the diffusion rate is high then one can assume the film to be a stagnant and use a stagnant film model.

So, there are versions in which one uses a combination of film and penetration theory so there are number of other theories that can be based around this or further modification to these theories.

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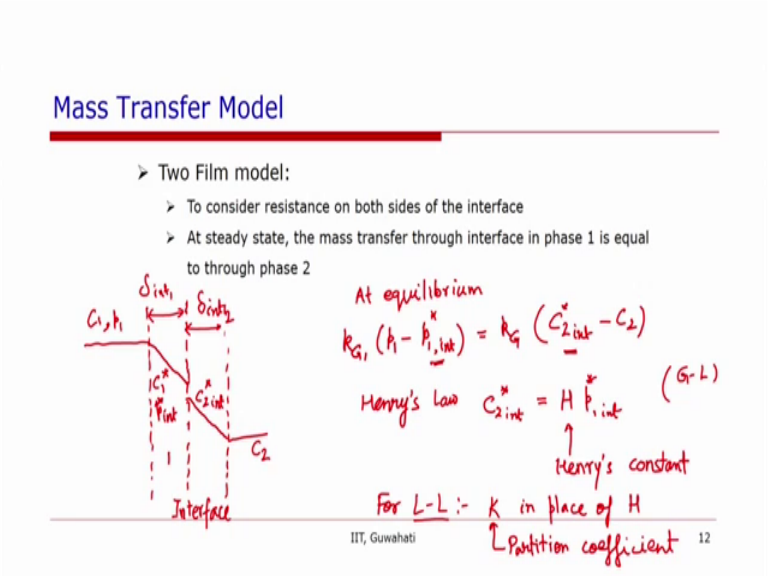

Mass Transfer Model

- Two Film model:
  - To consider resistance on both sides of the interface
  - At steady state, the mass transfer through interface in phase 1 is equal to through phase 2

At equilibrium

$$k_{G_1}(p_1 - \underline{p^*_{1,int}}) = k_G(\underline{C^*_{2int}} - C_2)$$

Henry's Law $C^*_{2int} = H\, p^*_{1,int}$ (G-L)

$\uparrow$ Henry's constant

For $\underline{L-L}$:- K in place of H

$\llcorner$ Partition coefficient

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Now, consider the mass transfer at an interface. So, if this is the interface between two phases and if we consider that there is considerable resistance on both sides of the interface so we plot the films surrounding this and this is delta int 1 we can call in phase 1 and this is delta int 2.

The phase 2 the concentration in phase 1 is C 1 and partial pressure in this phase is p 1 and that is decreases to the a concentration let us call this as C 1 star p 1 star.

And then in the second phase the concentration is C 2 and the interface the concentration is C 2 and the interface. So, at equilibrium and steady state the mass transfer trough interface from the the rate of mass transfer from phase 1 to phase 2 will be equal for the rate of mass transfer will be equal.

So, what is given as is as k G 1 p 1 minus p 1 interface star is equal to k G 2 C 2 at the interface minus C 2. Now we need to relate this and the p 1 into star and C 2 into star and so this is given by Henry's law.

It suggests that C 2 is equal to H p 1 star interface. So, a H is called Henry's constant for this is for gas liquid systems for liquid liquid H i s replaced by K and K is called partition coefficient.

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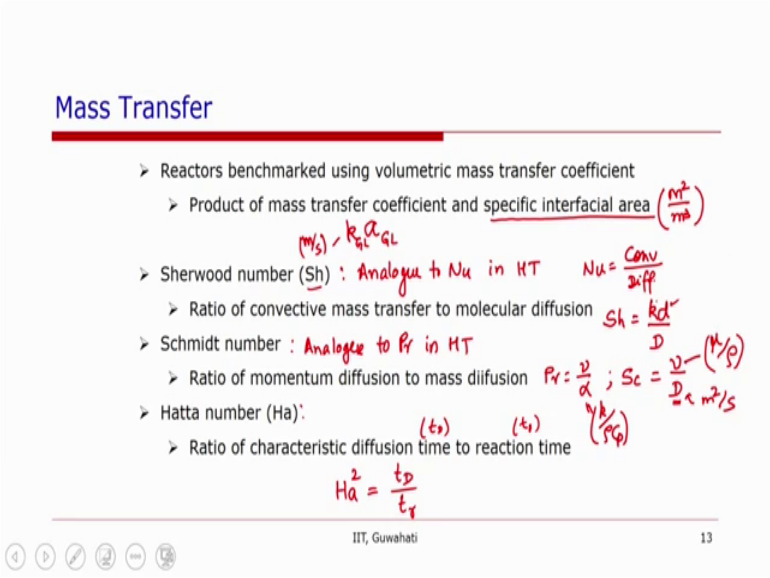

Mass Transfer

- Reactors benchmarked using volumetric mass transfer coefficient
  - Product of mass transfer coefficient and specific interfacial area $\left(\frac{m^2}{m^3}\right)$

    $(m/s) - k_{GL} a_{GL}$
- Sherwood number (Sh) : Analogue to Nu in HT $\quad Nu = \frac{Conv}{Diff}$
  - Ratio of convective mass transfer to molecular diffusion $\quad Sh = \frac{kd}{D}$
- Schmidt number : Analogue to Pr in HT
  - Ratio of momentum diffusion to mass diifusion $\quad Pr = \frac{\nu}{\alpha}\ ;\ Sc = \frac{\nu}{D} - (\mu/\rho)$, $\alpha \left(\frac{k}{\rho C_p}\right)$, $D \sim m^2/s$
- Hatta number (Ha):
  - Ratio of characteristic diffusion time (t_D) to reaction time (t_r)

$$Ha^2 = \frac{t_D}{t_r}$$

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So, some more basics about the mass transfer the reactor because the mass transfer is a function of mass transfer coefficient as well as the interfacial area so, the reactor performance is generally given as k multiplied by interfacial area density. So, it may be a so a k gas to liquid interfacial area gas to liquid. So, a specific interfacial area that is interfacial area per unit volume meter square per meter cube k has unit of meter per second.

So, the total unit will be meter per second divided by meter now some non dimensional numbers. So, Sherwood number is an analogue to Nusselt number in heat transfer.

So, the Nusselt number of heat transfer if you remember H T it is convection over diffusion or conduction H T over k similarly Sherwood number is k d over capital D or so where D is a length scale and k is the mass transfer coefficient and the H diffusivity Schmidt number agent analogue to Prandtl number in heat transfer.

So, Prandtl number is alpha cp mu over k. So, that is nu over alpha Schmidt number is defined as nu over D where nu as you will know that mu over rho so and the n D is the molecular diffusivity both of them have unit meter square per second. So, alpha is thermal diffusivity which is defined as k over rho cp D is molecular diffusivity or mass diffusivity and nu is momentum diffusivity.

Another important non dimensional number which is relevant during the reactions, which gives a ratio of or Hatta number square is a ratio of diffusion time to the reaction time. So, t D is diffusion time, and t r is the reaction time. So, this is important than we have react mass transfer coupled with the reactions.

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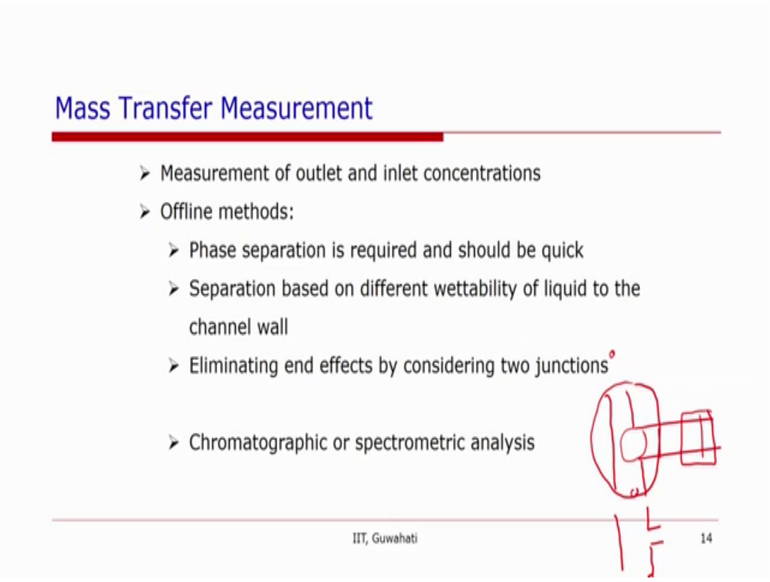

Mass Transfer Measurement

- Measurement of outlet and inlet concentrations
- Offline methods:
  - Phase separation is required and should be quick
  - Separation based on different wettability of liquid to the channel wall
  - Eliminating end effects by considering two junctions
  - Chromatographic or spectrometric analysis

Now, when the experiments are conducted different methods are used to measure the mass transfer. So, mass transfer will be basically measured by measuring the concentrations either locally or at the inlet and outlet. So, every time we want to do the there are two different methods one is offline method. So, for the offline method one take a sample or one has the known concentration at the inlet and then the concentration at the outlet has to be determined.

So, because it is multi phase flow so we have to or we might need to determine the concentration in the two phases and we need to separate the two phases. So, one need to look at a phase separation method and this phase separation has to be quick because the reaction times or the contact time in micro reactors is short so if the separation time is longer than the accurate results will not be obtained.

So, the phase separation has to be quick one of the natural way to do it separation of different variability of the liquid to the channel wall. So, that will require lot of understanding of the interface or the variability behaviour of liquid different liquids with the channel wall ok.

So, some of the efforts has gone in this direction the other challenges that because what we know is the concentration at the inlet.

So, to because as a channels for example, if one uses a t junction channel then the changes in the concentration just before they mix and when this happens so the mass transfer will be very high in this region. So, we will not be able to get the mass transfer in the fully developed region or where the hydrodynamics has well developed and a structured pattern has been obtained.

So, one of the options people have looked at that they have devised two channels in one case the study the mass transfer in the entire length of channel and in the another case the mass transfer studied just in the inlet section so that one can know how much mass transfer or what mass transfer has taken place.

In this inlet section and then subtract it from the total mass transfer and of course, once the sample has been obtained at the outlet it has to be analyzed or using different analytical techniques chromatographic or spectrometric balances.

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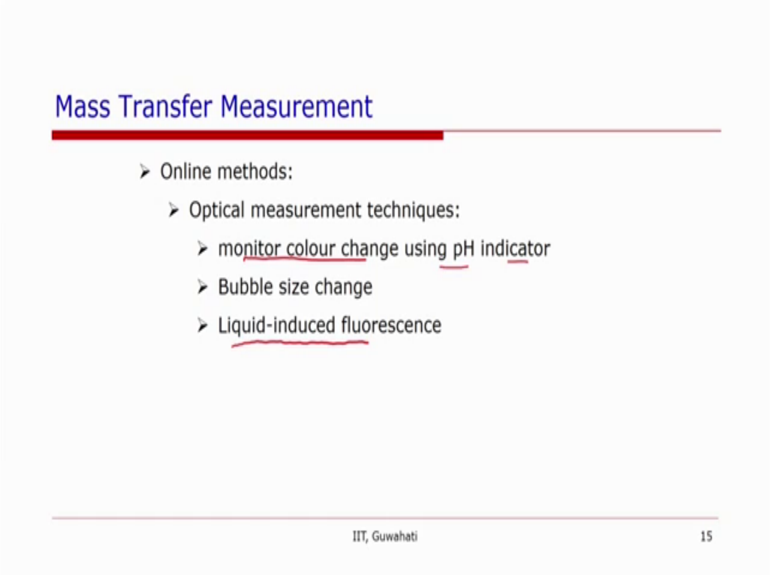

Mass Transfer Measurement

- Online methods:
  - Optical measurement techniques:
    - monitor colour change using pH indicator
    - Bubble size change
    - Liquid-induced fluorescence

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In the online measurement most of these online measurement techniques which means that the concentration is being measured as the fluids move in the channel so, these online measurement techniques most of them are based on the optical measurements.

So, for example, one can take the pictures if for example, gas liquid flow is happening and C O 2 is being absorbed in any wedge then the concentration of or the the size of the bubbles will change because the C O 2 is being dissolved in the fluid.

So, as one move from the inlet to the outlet the size of bubble will keep reducing so, if one can take the image of the channels at different lengths then one will have by estimating the size of the bubbles one can have an idea about the mass transfer that had happened from gas phase to the liquid phase.

So, the other option is to use different indicators say for example ph indicators which can monitor the colour change so by monitoring the change of the colour at different lengths so one can make an estimate of the change in concentration a relatively recent , but very promising technique is alaia for liquid induced fluorescence where dyes fluorescent dyes are available which are sensitive to the concentration.

So, these concentration sensitive dies are introduced and by the laser light the reflected light is the intensity of the reflected light or the is read by the images and then an estimate of the concentration field can be made.

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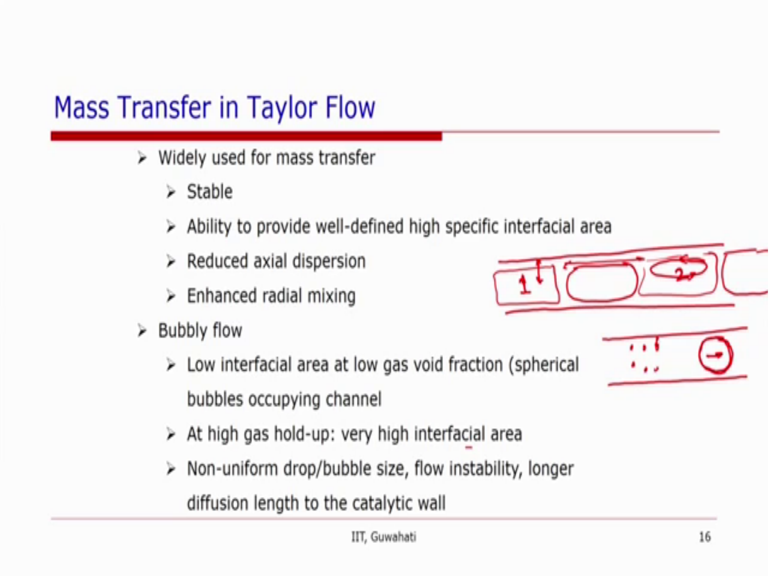

Mass Transfer in Taylor Flow

- Widely used for mass transfer
  - Stable
  - Ability to provide well-defined high specific interfacial area
  - Reduced axial dispersion
  - Enhanced radial mixing
- Bubbly flow
  - Low interfacial area at low gas void fraction (spherical bubbles occupying channel
  - At high gas hold-up: very high interfacial area
  - Non-uniform drop/bubble size, flow instability, longer diffusion length to the catalytic wall

So, now coming to mass transfer in the Taylor flow regime it is extensively used in most of the mass transfer applications in micro channels for gas liquid or liquid liquid flow. Taylor flow regime or the segmented flow is one of the most popular flow regime in which work with because it provide interfacial area which is large as well as which is well defined interfacial areas.

Another advantage of this is that the axial dispersion is reduced for example, if we have a bubble and two slugs surrounding the bubble and there is very little interaction you almost no interaction between slug 1 and slug 2. So, there is no dispersion we can treat these two streams separate with each other and there is no interaction between two a stream.

So, there is no axial dispersion for these two streams and this has intense mixing. So, if number of number of bubbles are in you can think of these number of slug reactors in series which will eventually be a slug flow reactors.

And then of course, the diffusion lengths are small and there is internal re circulations. So, the radial mixing is also enhanced.

Another question which might come in general in all of us we can have this question that the bubbly flow regime the size of bubbles is very small. So, why not use bubbly flow regime where one can use or when one can get very high interfacial area.

And bubbly flow regime has been classified in different literature from small bubbles they are also called bubbly flow regime or spherical bubbles or almost a spherical bubble which occupy the entire channel they are also called bubbly floe regime.

So, this will be the case when the volume fraction is small and there is very small. So, in this case the interfacial area will be smaller. If we have high gas holdup one may have smaller bubbles interfacial area might be high. But again no control on the bubble or droplet size flow might be unstable and then there is the it is catalytic reaction then the diffusion lengths will be larger.

So, one the most attractive flow regimes in micro channels H Taylor flow regime the annular flow regime because again if it is liquid liquid flow. Then can have parallel flow and can have the interaction between the phases , but for the gas liquid flow the annular flow is generally unstable there are instabilities present on the interface so that can be a problem for a number of cases.

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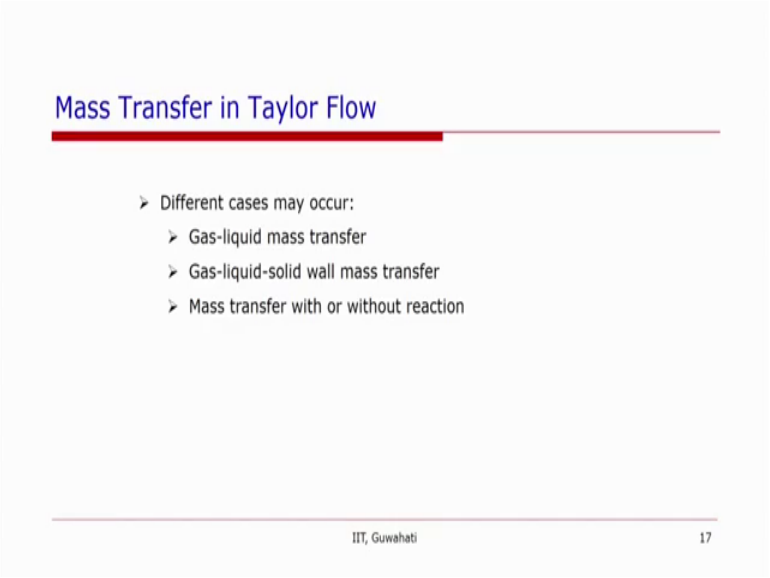

Mass Transfer in Taylor Flow

- Different cases may occur:
  - Gas-liquid mass transfer
  - Gas-liquid-solid wall mass transfer
  - Mass transfer with or without reaction

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So, mass transfer in Taylor flow there can be number different type of problems that one may want to study or different applications can be there. So, one is that there is mass transfer between the gas and liquid phases. Another one is mass transfer between gas liquid and solid catalytic wall and this mass transfer can be with or without reactions.

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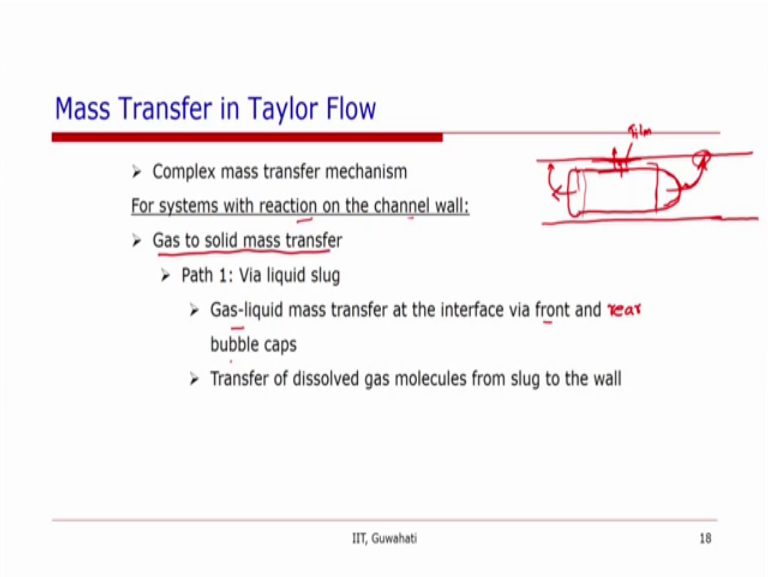

Mass Transfer in Taylor Flow

- Complex mass transfer mechanism

For systems with reaction on the channel wall:

- Gas to solid mass transfer
  - Path 1: Via liquid slug
    - Gas-liquid mass transfer at the interface via front and rear bubble caps
    - Transfer of dissolved gas molecules from slug to the wall

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So, the mass transfer mechanism in such cases will be a can be complicated. So, let us look at the mass transfer we have the systems have reaction on the channel wall. So, if we have a solid wall and the Taylor bubble into it so there are two paths for mass transfer from gas to for the gas to go to the solid one is via a liquid slug.

So, the gas interacts from these gaps with the liquid slug and then slug moves to the from the slug the gas comes in contact with the solid phase. So, the first contact is gas liquid mass transfer at the interface via the front and rear bubble caps.

And then transfer of dissolved gas molecules. So, the gas that has dissolved it transfer from here to the wall the other path is via the wall. So, it goes via the film so the gas dissolves in this liquid film and then from film it moves towards the wall. Generally this film is almost a stagnant. So, it is one can use the stagnant film model there.

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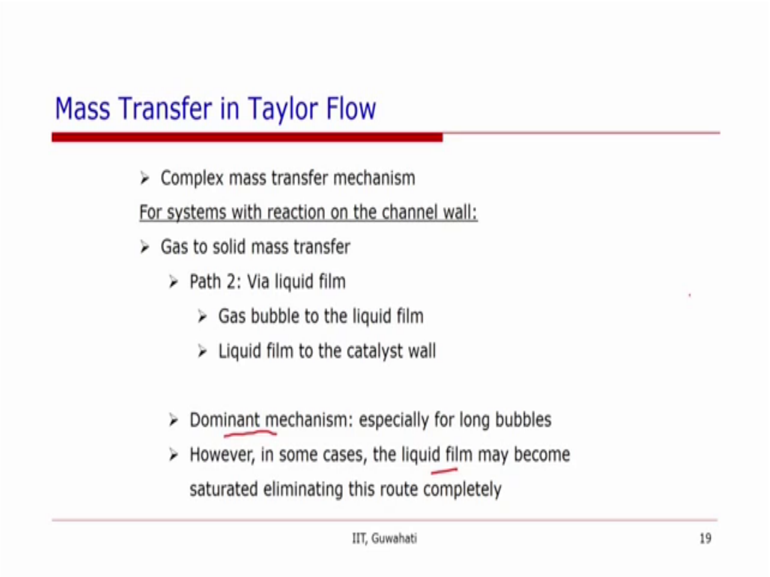

Mass Transfer in Taylor Flow

- Complex mass transfer mechanism

For systems with reaction on the channel wall:

- Gas to solid mass transfer
  - Path 2: Via liquid film
    - Gas bubble to the liquid film
    - Liquid film to the catalyst wall
  - Dominant mechanism: especially for long bubbles
  - However, in some cases, the liquid film may become saturated eliminating this route completely

This is thought to be a dominant mechanism especially when the bubble is longer than the interfacial area of the film region will be large compared with the interfacial area and those caps.

However, in some cases if this liquid film becomes saturated then there will be no mass transfer via the liquid film.

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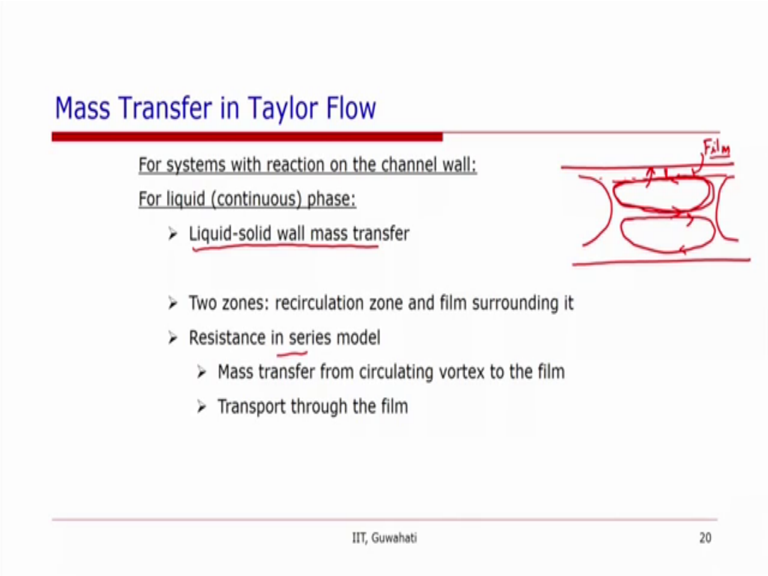

Mass Transfer in Taylor Flow

For systems with reaction on the channel wall:

For liquid (continuous) phase:

- Liquid-solid wall mass transfer
- Two zones: recirculation zone and film surrounding it
- Resistance in series model
  - Mass transfer from circulating vortex to the film
  - Transport through the film

So, one need to look into all these cases now for systems with reaction on the channel wall so what we have looked at is gas to solid mass transfer. Now another important mass transfer that one need to look at from liquid to solid.

So, that will basically be in the slug phase the liquid interacts with the solid. So, again though there is only one liquid but as we know from the hydrodynamics that this have liquid slugs on it and surrounding the slug there is a thin film of liquid.

So, one can take two resistances in series the first resistance to mass transfer when it is circulating in this bulk and then transport through the film.

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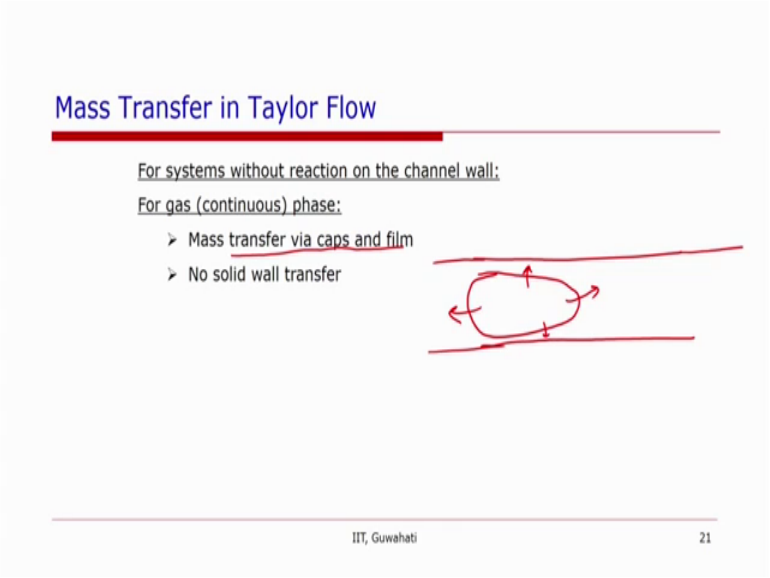

Mass Transfer in Taylor Flow

For systems without reaction on the channel wall:

For gas (continuous) phase:

- Mass transfer via caps and film
- No solid wall transfer

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So, what we have looked at is mass transfer in case where there is a gas solid liquid system and reaction is happening when there is no reaction on the channel wall then one just need to look at the mass transfer.

So, the steps at the wall are no longer important, but we still have the mass transfer via caps and the film in this case so if we have say C O 2 absorption in NaOH or CO 2 absorption in water then the bubbles will be in contact with the so, the gas liquid mass transfer from the cap regions and the gas liquid mass transfer from the film region.

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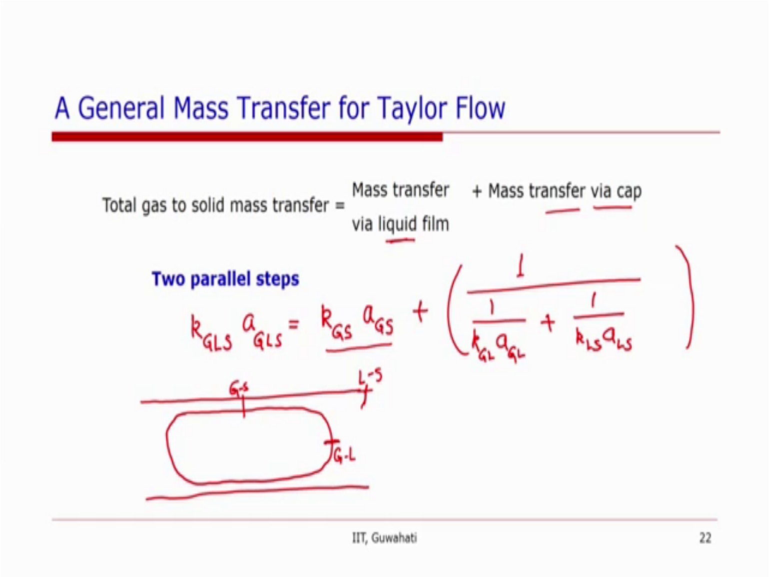

A General Mass Transfer for Taylor Flow

Total gas to solid mass transfer = Mass transfer via liquid film + Mass transfer via cap

Two parallel steps

$$k_{GLS}\, a_{GLS} = k_{GS}\, a_{GS} + \left(\frac{1}{\frac{1}{k_{GL} a_{GL}} + \frac{1}{k_{LS} a_{LS}}} \right)$$

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So, one can write that the total gas to solid mass transfer or k let us say G L S into a G L S will be equal to there are two parallel steps that the mass transfer happens via the liquid film and mass transfer via cap.

So, for this we can write k G S a G S plus there are two steps in series. So, for which we can write this the steps in series that mass transfer via a k G L a G L plus 1 over k L S a L S.

So, we can draw a schematic of it so things become clearer we have a bubble here and what is called G S which gas liquid via film and this is gas liquid and this is liquid solid.

So, the total mass transfer gas to solid mass transfer is the combination of it can happen via the liquid film and via caps. So, via liquid film we can have k G S a G S directly plus it can have two steps in series at it has to a steps in series mass transfer via the caps and mass transfer from the slug to the wall.

So, these two comes in series one can remember the expressions that we developed for heat transfer and you can see the analogy between the two here.

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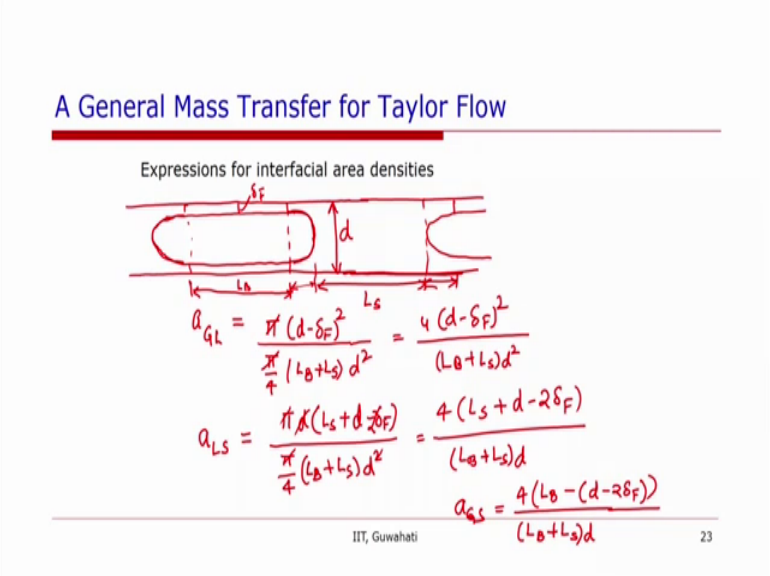

A General Mass Transfer for Taylor Flow

Expressions for interfacial area densities

$$a_{GL} = \frac{\cancel{\pi}(d-\delta_F)^2}{\frac{\cancel{\pi}}{4}(L_B+L_S)d^2} = \frac{4(d-\delta_F)^2}{(L_B+L_S)d^2}$$

$$a_{LS} = \frac{\cancel{\pi}\cancel{d}(L_S+d\cancel{-2}\delta_F)}{\frac{\cancel{\pi}}{4}(L_B+L_S)d^{\cancel{2}}} = \frac{4(L_S+d-2\delta_F)}{(L_B+L_S)d}$$

$$a_{GS} = \frac{4(L_B-(d-2\delta_F))}{(L_B+L_S)d}$$

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Now, these because the bubbles can be approximated so one can easily get an idea of the geometries or the interfacial area densities in these cases. For example, for the a G L case where G L is the interfacial area density of the caps.

So, if we say that this film thickness is delta F and length of the slug is L S and length of the bubble is L B. So, one can write G L a G L is the interfacial area of the caps and assuming that they are spherical cap so, hemispherical caps.

So, one can have pi d cap squared. So, let us say this channel diameter is d and the cap diameter will be d minus delta F square per unit cell volume. So, unit cell volume will be pi by 4 L B plus L S d square. So, pi will cancel out and we will have 4 d minus delta F squared divided by L B plus L S d squared.

In the same manner one can also calculate the area for the liquid solid. So, the volume of the unit cell will remain same pi. So, L B plus L S d square now this length is the area is 2 pi d into L of this slug length.

So, L S plus if we consider the entire length in this is the we have the mass transfer is happening via liquid slug then we will have L S plus d minus delta F and it will be 2 delta F because there are films on the top and bottom so that will this will be pi dl.

So, it will not be there pi will cancel out and we will have 4 L S plus d minus 2 delta F over L B plus L F into d. Similarly one can find out the area for this film region which is called that a G S which will be equal to liquid zone fluid get rid of this 4 L B plus L S d L B minus d minus 2 delta F.

ah So, these are the difference interfacial areas that we can now we can huge approximations for example, if the film is very thin then we can neglect the film with respect with respect to d and so on and so forth.

In summary what we have looked at is obtained the we reviewed some of the basics of mass transfer look at the some of the non dimensional numbers Sherwood number, and Schmidt number.

The definition of the mass transfer at the interface the film the micro models we for example strain and fluid model and penetration theory and then we have looked at the mechanism qualitatively the mechanism at the interface.

Now in the next lecture we will try to look at different models that have been developed by researchers based on their experiments or from the fundamentals to develop the to give these mass transfer for the film region, mass transfer from cap at the bubble caps from gas to liquid slug and then mass transfer from slug to the wall ok.

Thank you.