# Chemical Process Intensification
Doctor Subrata K. Majumder
Chemical Engineering Department
Indian Institute of Technology Guwahati
Lecture 12.1 (lec35)
## Hydrodynamics and Transport in Micro Channel-Based Micro-Reactor

Welcome to massive open online course on chemical process intensification. So in this module micro process technology in process intensification, we were discussing something about that introduction and also what are the different applications of microprocessor technology. So in this lecture will try to go through about some hydrodynamics and transport in micro channel-based micro-reactors.

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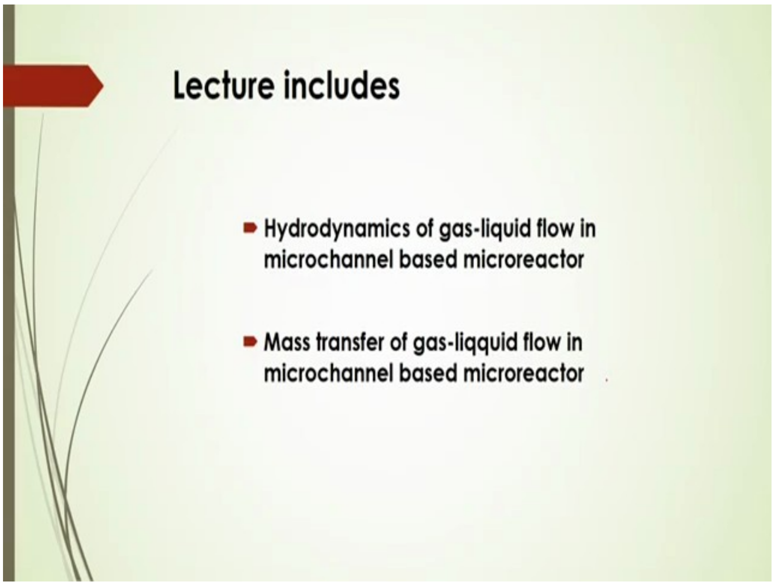

Lecture includes

- Hydrodynamics of gas-liquid flow in microchannel based microreactor
- Mass transfer of gas-liqquid flow in microchannel based microreactor

So we discussed hydrodynamics of gas liquid flow in micro channel-based micro-reactor. And also what is the mass transfer of gas liquid flow in micro channel based micro-reactor.

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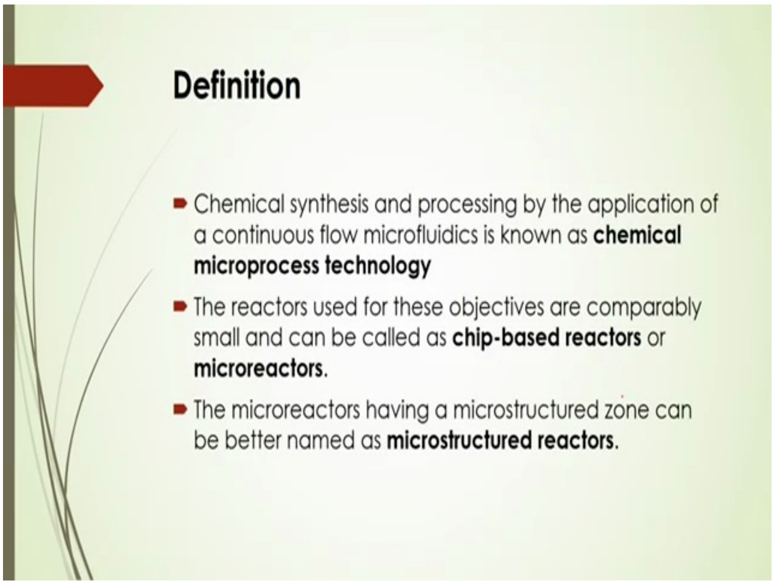

## Definition

- Chemical synthesis and processing by the application of a continuous flow microfluidics is known as **chemical microprocess technology**
- The reactors used for these objectives are comparably small and can be called as **chip-based reactors** or **microreactors.**
- The microreactors having a microstructured zone can be better named as **microstructured reactors.**

Now as we already discuss about that what is the definition of micro process technology and also what are the different types of micro-reactors and how they are designed and also how to actually fabricate all those microstructure reactors that we have already discussed in brief in earlier lectures.

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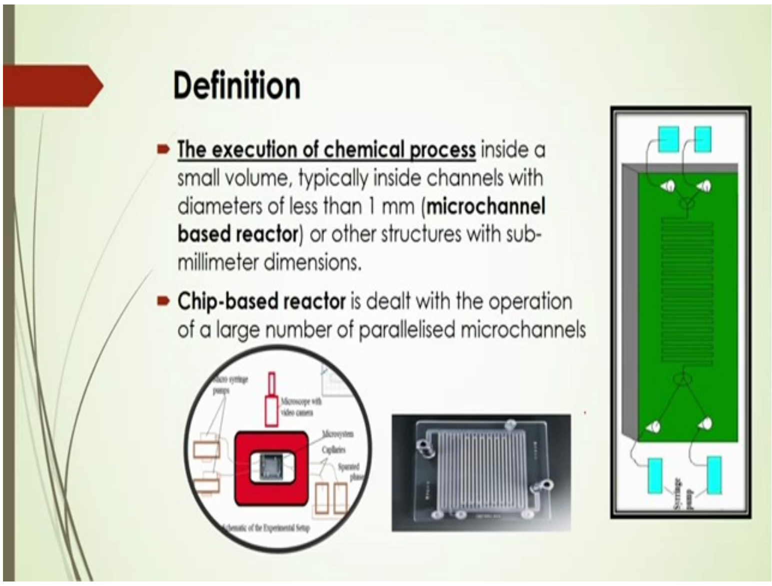

## Definition

- **The execution of chemical process** inside a small volume, typically inside channels with diameters of less than 1 mm (**microchannel based reactor**) or other structures with sub-millimeter dimensions.
- **Chip-based reactor** is dealt with the operation of a large number of parallelised microchannels

Also told that the execution of chemical process in the micro channel based reactor will be in a small volume, typically inside a channel with diameter less than 1 mm and chip based reactor is dealt with the operation of a large number of parallelized micro channel in a compact volume.

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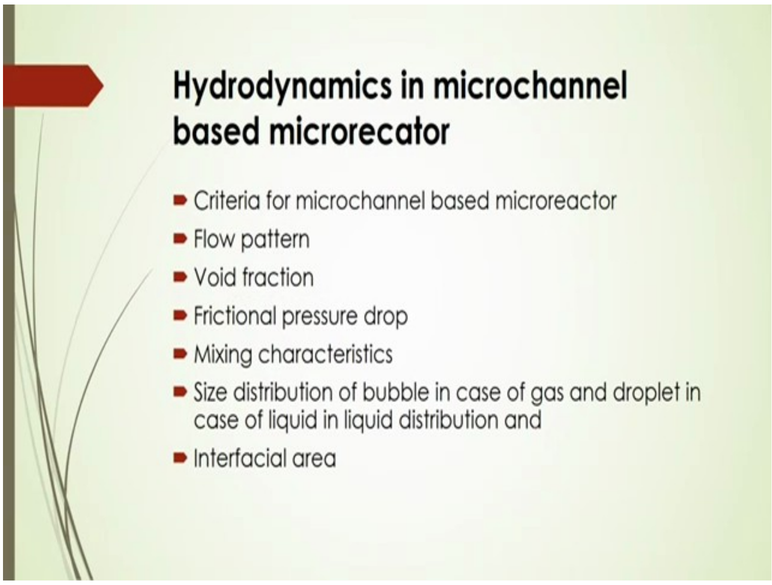

## Hydrodynamics in microchannel based microrecator

- Criteria for microchannel based microreactor
- Flow pattern
- Void fraction
- Frictional pressure drop
- Mixing characteristics
- Size distribution of bubble in case of gas and droplet in case of liquid in liquid distribution and
- Interfacial area

And then we have discussed about that, what are the different applications of that micro channel based reactor? Even other different types of reactors that we have discussed in a previous lecture.

So in this lecture we will try to go through some hydrodynamics aspects like what is that criteria to actually develop micro channel-based micro-reactor what should be the channel diameter and also what will be the flow pattern, and void fraction what should be that in micro channel-based –reactor? And what will be the frictional pressure drop? How to analyze it, when what are the different mixing characteristics that is main intensification criteria in this micro channel based reactor.

And also size distribution of bubble in case of gas and droplet in case of liquid in liquid distribution, interfacial area. So these are the different hydrodynamics characteristics in micro-reactor channels.

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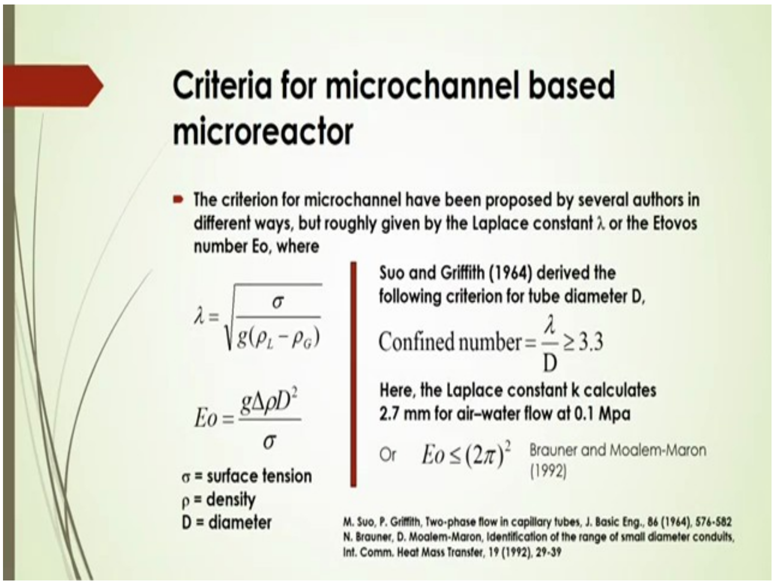

## Criteria for microchannel based microreactor

- The criterion for microchannel have been proposed by several authors in different ways, but roughly given by the Laplace constant λ or the Etovos number Eo, where

$$\lambda = \sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}}$$

$$Eo = \frac{g\Delta\rho D^2}{\sigma}$$

σ = surface tension
ρ = density
D = diameter

Suo and Griffith (1964) derived the following criterion for tube diameter D,

$$\text{Confined number} = \frac{\lambda}{\text{D}} \geq 3.3$$

Here, the Laplace constant k calculates 2.7 mm for air–water flow at 0.1 Mpa

Or $Eo \leq (2\pi)^2$ Brauner and Moalem-Maron (1992)

M. Suo, P. Griffith, Two-phase flow in capillary tubes, J. Basic Eng., 86 (1964), 576-582
N. Brauner, D. Moalem-Maron, Identification of the range of small diameter conduits, Int. Comm. Heat Mass Transfer, 19 (1992), 29-39

Let us try to understand that what should be the criteria for that micro channel-based micro-reactor. That the criterion for micro channel have been proposed by several authors in different way, but roughly given by the Laplace constant lambda or the Etovos number by that Suo et al. in 1964 still it is being used for that design of that micro-reactor channel based on this criteria where you will see that this lambda is called that Laplace constant and $E_O$ is called as Etovos number.

This lambda is defined by this equation here shown in slides.

$$\lambda = \sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}}$$

See $\lambda$ is equal to root of Sigma by $g(\rho_L - \rho_G)$. whereas this Etovos number this is

$$Eo = \frac{g\Delta\rho D^2}{\sigma}$$

Where σ is called surface tension of the liquid and ρ is the density. And $\Delta\rho$ is the density difference of these two immiscible fluids like here if it is gas and liquid should be then $(\rho_L - \rho_G)$.

And D is called diameter of the channel if it is cross-sectional if it is that rectangular channel then there should be a hydraulic diameter to be considered. And also if it is of a circular channel then of course it is a diameter will be the circular channel diameter, hydraulic diameter will be same.

And so as per this Suo and Griffith in 1964 they derived this following criterion for the tube diameter D, for that micro-channel-based reactor development. Here in that case confined diameter should be that lambda by D that should be greater than equal to 3.3.

$$\text{Confined number} = \frac{\lambda}{\text{D}} \quad 3.3$$

So whenever you are going to consider that micro channel it should be of course that in a criteria that lambda by D always should be greater than 3.3.

If you are considering Laplace constant here it should be corrected like this k. It is not that k. It is generally it is lambda. So please correct it here, instead of k it will be lambda. So here this is lambda. So this is lambda is called as Laplace constant and in case of that if you have this D is equal to that… if supposed lambda by D is greater than equal to 3.3 then you have to considered that lambda should be 2.7 for air water flow at 0.1 that a mega Pascal. So in that case what should be D around 831 micro-meters.

So in this way if you considering exactly equal to 3.3 for this Laplace constant of 2.7 then you can say that is micro channel diameter should be of course less than 831 micro-meter. Other way also this you can define that micro channel where $Eo \leq (2\pi)^2$ . So that is given by Brauner and Moalem-Maron in 1992. So in this two criteria can be used for that having a micro channel or defined that micro channel-based micro-reactor.

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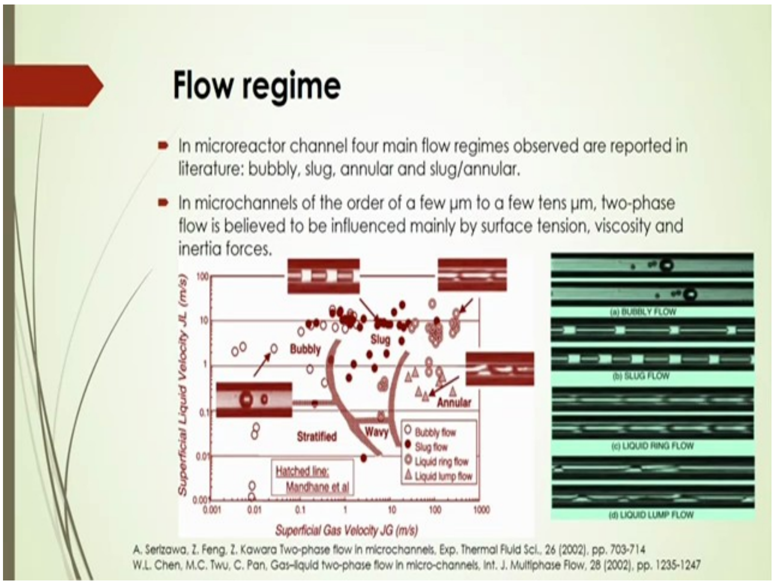

## Flow regime

- In microreactor channel four main flow regimes observed are reported in literature: bubbly, slug, annular and slug/annular.
- In microchannels of the order of a few μm to a few tens μm, two-phase flow is believed to be influenced mainly by surface tension, viscosity and inertia forces.

A. Serizawa, Z. Feng, Z. Kawara Two-phase flow in microchannels, Exp. Thermal Fluid Sci., 26 (2002), pp. 703-714
W.L. Chen, M.C. Twu, C. Pan, Gas-liquid two-phase flow in micro-channels, Int. J. Multiphase Flow, 28 (2002), pp. 1235-1247

Now what are the Flow regimes in micro-reactor channel, you will see as per the reported in literature that four main regimes are generally observed: bubbly, slug, annular and slug annular flow and in micro channels of the order of a few micro-meter to a few tens micro-meter. Two phase flow is believed to be influenced mainly by surface tension, viscosity and inertia forces.

So based on which these due to that interfacial area or surface of this gas liquid or liquid - liquid phases just that making different shape as per those different types of flow patterns are obtained in micro channel. Like here it is shown that different criteria of different operating conditions of having this four types of flow pattern like bubbly flow. You can have this bubbly flow regime in this region in this map here. This map is actually formed by superficial liquid velocity versus superficial gas velocity.

In this case you will see that if you increase the superficial gas velocity and also accordingly superficial liquid velocity as per this scale then at this region you can get bubbly flow. Whereas you can get that stratified flow in this region, here stratified flow means one fluid will be-flowing over the other fluid. Mainly that viscous fluid that is lighter density fluid will be flowing over the density of higher density liquid.

So in that case you can get that very low liquid velocity and low gas velocity you can expect that there will be that stratified flow where that both the phases will be separately flowing having one above the other. So in that case you can maintain this stratified flow only just by controlling this gas flow over the liquid flow. Also you can get that Slug flow where that you will see that liquid if it is single phase, you will see that the liquid will be breaking up and there will be a discreet way of flowing that liquid as a slug.

And if it is on gas liquid flow you will see there also there will be successive breaking of that gas slug and liquid slug and it will be flowing through the channel. Another is annular flow where you can say that heavier liquid that flowing adjacent to the wall of that channel whereas at the flow region there will be a flow of lighter liquid. So this is called as annular flow.

So again this other flow also you can have that heavy flow sometimes stratified flow. If that gas flow rate is higher, then you can expect that there will be a wave formation of the interface of that gas and liquid, so that is called wavy flow. Now you will see that sometimes that liquid will also be flowing as a ring through to the channel. So it is also sometimes called liquid ring flow.

Even some lump amount of liquid will be flowing through the channel and after a certain length it will be breakage and also it will start again for continuous liquid slugs. So it will be called as liquid lump flow. So there are those liquid lump flows or that liquid ring flow it will be coming under that in the annular flow regime. And also at that higher flow rate of liquid flow and also higher gas flow rate.

So in this region you can get that ring flow of that liquid here and also here at this region you can get annular flow where that liquid lump flow will be there. And liquid lump flow and liquid ring flow will actually be consisting that annular flow there. So this type of different types of flow pattern you can get in the channel that is micro channel-based micro-reactor.

So it may be sometimes useful because at different flow pattern you can have that different efficiency of mass transfer even extraction and even other chemical engineering process, even at reactions also even you can get that different reaction performance at different flow pattern. So you have to know that different types of flow pattern in the channel.

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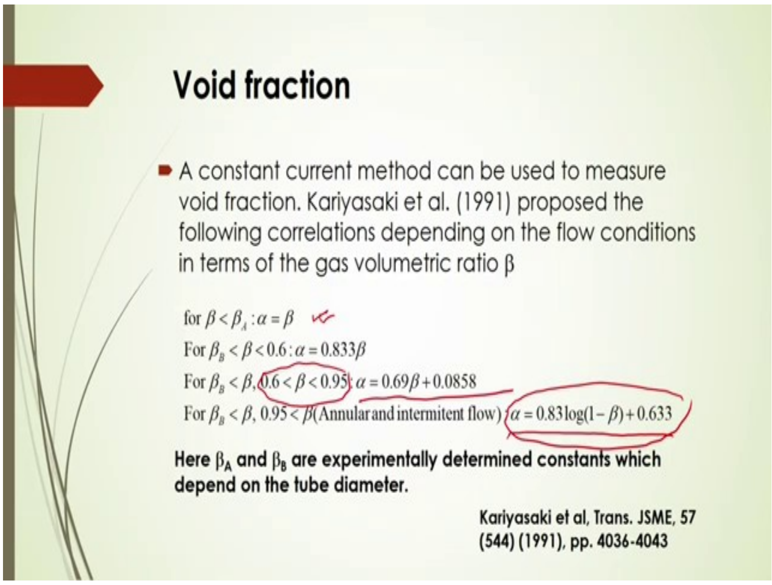

## Void fraction

- A constant current method can be used to measure void fraction. Kariyasaki et al. (1991) proposed the following correlations depending on the flow conditions in terms of the gas volumetric ratio β

for $\beta < \beta_A : \alpha = \beta$

For $\beta_B < \beta < 0.6 : \alpha = 0.833\beta$

For $\beta_B < \beta, 0.6 < \beta < 0.95 : \alpha = 0.69\beta + 0.0858$

For $\beta_B < \beta, 0.95 < \beta$(Annular and intermitent flow) $: \alpha = 0.83\log(1-\beta) + 0.633$

**Here $\beta_A$ and $\beta_B$ are experimentally determined constants which depend on the tube diameter.**

**Kariyasaki et al, Trans. JSME, 57 (544) (1991), pp. 4036-4043**

Void fraction is also one of the important parameter in that accessing that mass transfer efficiency or mass transfer performance there. Because it depends on that void fraction, if it is suppose gas liquid operations suppose gas is absorbed in a liquid medium. Then you can have more interfacial area if your void fraction is increased there. So there are several methods actually are available to find out that void fraction mainly in micro channel-based reactor, a constant current method can be used to measure that void fraction.

It is actually proposed by Kariyasaki here in 1991 and also as per their experimental results they have suggested some correlations to actually predict that gas hold up in the channel. So according to their observations that if suppose that certain constants there beta is less then beta A then Alpha should be equal to beta. What is that beta? Beta is nothing but gas volumetric ratio beta.

So gas volumetric ratio beta means here what is volumetric flow rate of the gas upon what will be the total flow rate of the gas and liquid? So it is denoted by that beta. So in that case volume fraction should be equal to alpha is equal to beta that means volume fraction will be equal to gas volumetric ratio. If that volumetric ratio is very low.

Whereas if this volumetric ratio is less than 0.6 then you can aspect that this void fraction will be is equal to 83% of gas volumetric ratio. Again if this volumetric ratio if it is greater than 0.6 and less than 0.95. Here you can expect that void fraction of the gas will be equal to 0.69 into beta plus 0.0858. So by this correlation you can calculate what should be the void fraction.

Even if your volumetric ratio that is beta is more than 0.95 in that case you can predict that void fraction by this correlation as given by this Kariyasaki et al in 1991. So this correlation is very useful to calculate the void fraction if you know that gas and liquid flow rate in your operation.

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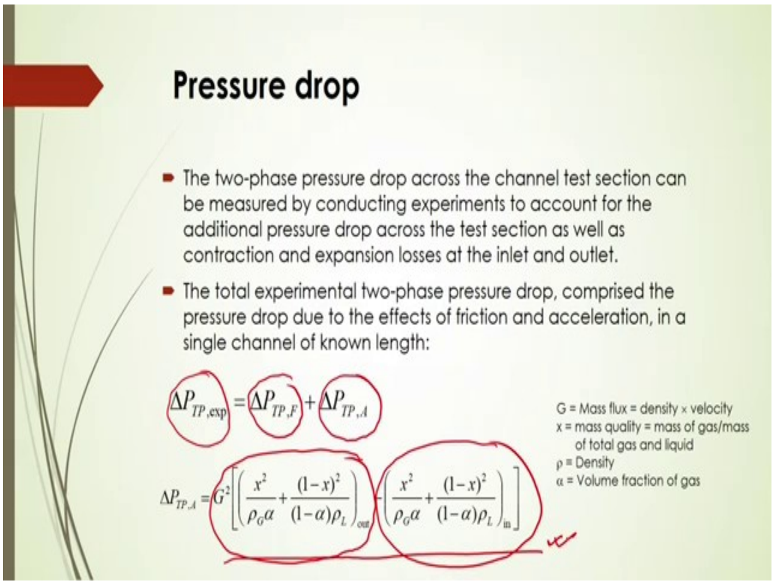

## Pressure drop

- The two-phase pressure drop across the channel test section can be measured by conducting experiments to account for the additional pressure drop across the test section as well as contraction and expansion losses at the inlet and outlet.
- The total experimental two-phase pressure drop, comprised the pressure drop due to the effects of friction and acceleration, in a single channel of known length:

$$\Delta P_{TP,\exp} = \Delta P_{TP,F} + \Delta P_{TP,A}$$

$$\Delta P_{TP,A} = G^2\left[\left(\frac{x^2}{\rho_G \alpha} + \frac{(1-x)^2}{(1-\alpha)\rho_L}\right)_{out} - \left(\frac{x^2}{\rho_G \alpha} + \frac{(1-x)^2}{(1-\alpha)\rho_L}\right)_{in}\right]$$

G = Mass flux = density × velocity
x = mass quality = mass of gas/mass of total gas and liquid
ρ = Density
α = Volume fraction of gas

And also pressure drop is also one of the important aspect of that design of that micro channel-based reactor because based on this pressure drop there will be energy dissipation and based on that energy dissipation how that mixing is happened inside the micro channel. This is one of the important aspects there. So that is why you have to know that what should be the frictional pressure drop inside the micro channel and how to analyze and how to predict that frictional pressure drop.

Now the two phase pressure drop across the Channel test section that can be measured by conducting experiments to accounts for the additional pressure drop across the test section as well as contraction and expansion losses at the inlet and outlet. So whenever you are going to measure this pressure drop in micro channel you will see that. You have to be very careful about that whenever liquid is flowing through that micro channel and before entering that micro channel of course this two fluids are coming from that two pipe entry.

So in that case the pipe entry whenever it will be coming to and joint to one point and from there the channel will start. So you will see that there will be a change of cross-sectional area from that two inlet way one channel inlet there. So in that case of course there will be some contraction or expansion factor that should be also considered there, so due to that contraction and expansion losses in inlet and outlet also... there will be additional pressure drop across the test section, so that should be also considered in your calculation.

So in that case the total experimental two phase pressure drop, it will comprised for the pressure drop, due to the effects of friction and acceleration in a single channel of known length. So it can be calculated like this, this is your experimental total two-phase pressure drop that will be that summing of frictional pressure drop of that two phase and also additional pressure drop that is due to that expansion even or contraction of losses. So according to this additional pressure drop that can be calculated by this equation here this is simply by that momentum balance you can have here where this can be calculated by this G square where in terms of mass flux even mass quality of the gas even density even volumetric void ratio this things.

So at the inlet and outlet what should be this component of this equation and what should be the in the outlet component of which here? In this case $x$ is called that mass fraction of the mass quality or you can say mass fraction of that gas of gas liquid mixture and $\rho$ is the density is the mass flux that is density × velocity you have to calculate. So by this equation you can calculate what should be the additional pressure drop due to that contraction and expansion losses.

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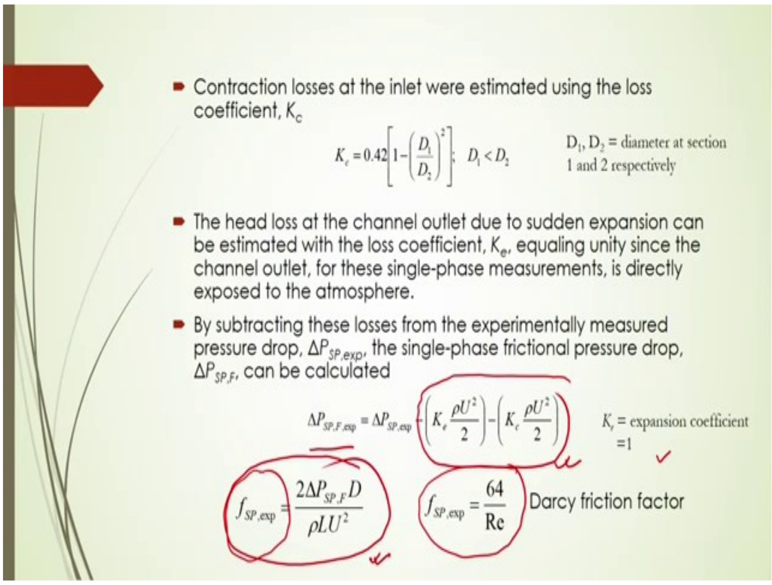


- Contraction losses at the inlet were estimated using the loss coefficient, $K_c$

$$K_c = 0.42\left[1-\left(\frac{D_1}{D_2}\right)^2\right];\quad D_1 < D_2$$

$D_1, D_2$ = diameter at section 1 and 2 respectively

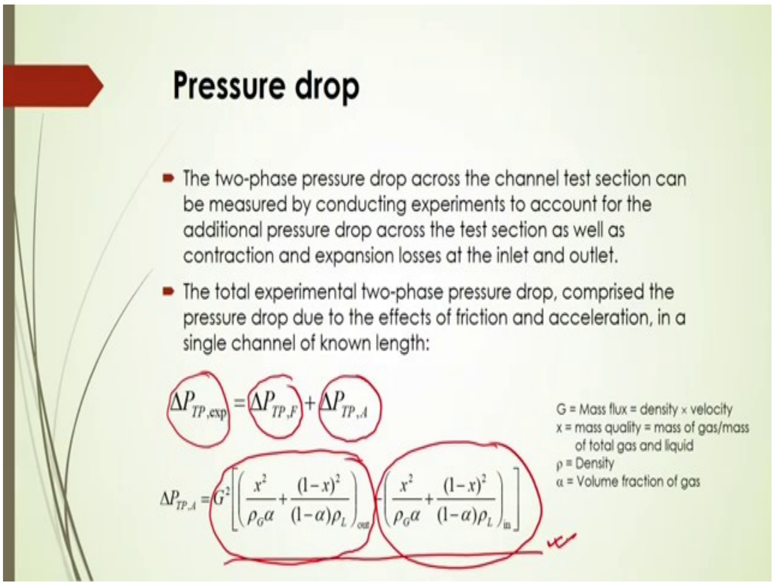
- The head loss at the channel outlet due to sudden expansion can be estimated with the loss coefficient, $K_e$, equaling unity since the channel outlet, for these single-phase measurements, is directly exposed to the atmosphere.
- By subtracting these losses from the experimentally measured pressure drop, $\Delta P_{SP,exp}$, the single-phase frictional pressure drop, $\Delta P_{SP,F}$, can be calculated

$$\Delta P_{SP,F,exp} = \Delta P_{SP,exp} - \left(K_e\frac{\rho U^2}{2}\right) - \left(K_c\frac{\rho U^2}{2}\right)$$

$K_e$ = expansion coefficient =1 ✓

$$f_{SP,exp} = \frac{2\Delta P_{SP,F} D}{\rho L U^2} \qquad f_{SP,exp} = \frac{64}{Re}$$

Darcy friction factor



## Pressure drop

- The two-phase pressure drop across the channel test section can be measured by conducting experiments to account for the additional pressure drop across the test section as well as contraction and expansion losses at the inlet and outlet.
- The total experimental two-phase pressure drop, comprised the pressure drop due to the effects of friction and acceleration, in a single channel of known length:

$$\Delta P_{TP,exp} = \Delta P_{TP,F} + \Delta P_{TP,A}$$

$$\Delta P_{TP,A} = G^2\left[\left(\frac{x^2}{\rho_G\alpha} + \frac{(1-x)^2}{(1-\alpha)\rho_L}\right)_{out} - \left(\frac{x^2}{\rho_G\alpha} + \frac{(1-x)^2}{(1-\alpha)\rho_L}\right)_{in}\right]$$

G = Mass flux = density × velocity
x = mass quality = mass of gas/mass of total gas and liquid
ρ = Density
α = Volume fraction of gas

Now contraction losses at the inlet actually is estimated using the loss coefficient that is $K_C$. That $K_C$ will be equal to 0.42 into 1 minus $D_1$ by $D_2$ the whole square.

$$K_c = 0.42\left[1-\left(\frac{D_1}{D_2}\right)^2\right];\quad D_1 < D_2$$

Where $D_1$ should be less than the $D_2$. In this case $D_1$ and $D_2$ are the diameters at the section 1 and 2 respectively. So this head loss or you can say that contraction losses at the inlet can be calculated by this equation because it is required in that case because of that friction actually that depends on this expansion and contraction and loss coefficient and lost there.

And the head loss at the channel outlet due to certain expansion can be estimated with the loss coefficient *Ke* that equaling unity since the channel outlet for these single phase measurements is directly exposed to the atmosphere.

By subtracting these losses from the experimentally measured pressure drop that is $\Delta P_{SP,F,\exp}$ that we have given in the earlier equation there, this experimental single phase frictional pressure drop can be calculated by this equation here.

$$\Delta P_{SP,F,\exp} = \Delta P_{SP,\exp} - \left( K_e \frac{\rho U^2}{2} \right) - \left( K_c \frac{\rho U^2}{2} \right)$$

Here in this case $K_e$ should be the expansion coefficient that expansion coefficient will be equal to 1 because in this case channel outlet for the single phase measurement is directly exposed to the atmosphere that is why this $K_e$ expansion loss should be equal to 1. Whereas in this case you will see that this single phase frictional pressure drop, that is $f$ is for frictional here single phase friction of pressure drop it will be actually, what should be the measured frictional pressure drop?

That minus that expansion or contraction losses there. So in this way you can calculate what should be your total frictional pressure drop as per experimental data.

After that what should be that friction factor for this single phase flow? You can calculate by this equation, as per Fanning equation you get here.

$$f_{SP,\exp} = \frac{2\Delta P_{SP,F} D}{\rho L U^2}$$

$$f_{SP,\exp} = \frac{64}{\mathrm{Re}}$$

Or you can say it will be that $\frac{2\Delta P_{SP,F} D}{\rho L U^2}$. So these friction factor is actually that Darcy friction factor. And this Darcy friction factor will be actually depending on that Reynolds number. And that it will be 64 by Reynolds number if you're flow is laminar in condition.

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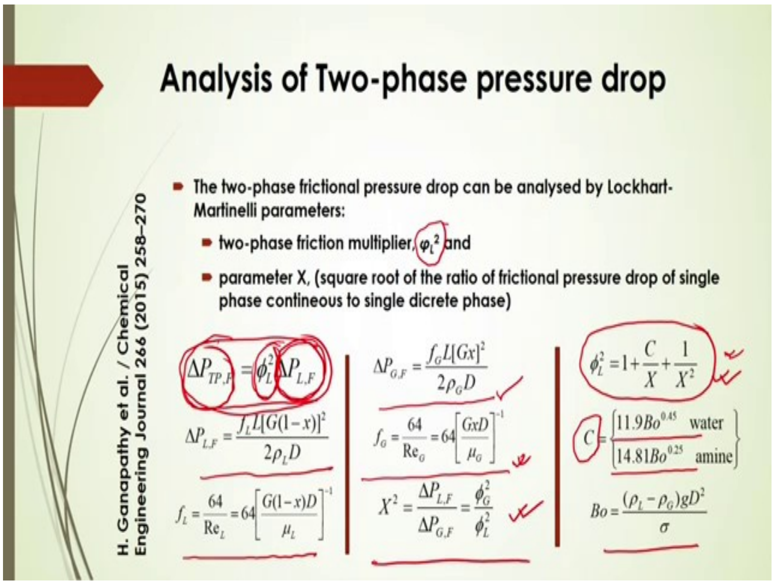

## Analysis of Two-phase pressure drop

- The two-phase frictional pressure drop can be analysed by Lockhart-Martinelli parameters:
  - two-phase friction multiplier, $\varphi_L^2$ and
  - parameter X, (square root of the ratio of frictional pressure drop of single phase contineous to single dicrete phase)

$$\Delta P_{TP,F} = \phi_L^2 \Delta P_{L,F}$$

$$\Delta P_{L,F} = \frac{f_L L[G(1-x)]^2}{2\rho_L D}$$

$$f_L = \frac{64}{\mathrm{Re}_L} = 64\left[\frac{G(1-x)D}{\mu_L}\right]^{-1}$$

$$\Delta P_{G,F} = \frac{f_G L[Gx]^2}{2\rho_G D}$$

$$f_G = \frac{64}{\mathrm{Re}_G} = 64\left[\frac{GxD}{\mu_G}\right]^{-1}$$

$$X^2 = \frac{\Delta P_{L,F}}{\Delta P_{G,F}} = \frac{\phi_G^2}{\phi_L^2}$$

$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2}$$

$$C = \begin{Bmatrix} 11.9Bo^{0.45} & \text{water} \\ 14.81Bo^{0.25} & \text{amine} \end{Bmatrix}$$

$$Bo = \frac{(\rho_L - \rho_G)gD^2}{\sigma}$$

H. Ganapathy et al. / Chemical Engineering Journal 266 (2015) 258–270

And how to analyses of two-phase frictional pressure drop. That Lockhart Martinelli in 1949 they have given that the concept for analyzing that two-phase frictional pressure drop based on single phase frictional of pressure drop. They have actually expressed that what should be the multiplication factor of these two-phase frictional pressure drop based on that single phase pressure drop. And that two-phase frictional multiplication factor is called two-phase fiction multiplier which is actually denoted by $\phi_L^2$.

And also another parameter as per their model that which is actually the ratio of the frictional pressure drop of single phase pressure drop continues to single discrete phase. So in that case this parameter is denoted by X. So it is actually defined as the square root of that ratio of frictional pressure drop of single phase continues to single phase and discrete phase.

So according to that two parameter $\phi_L$ and X you can asses that two-phase fictional pressure drop. Now according to Lockhart Martinelli models this concept is like this. This your two-phase frictional pressure drop. This will be the some multiplication of single phase frictional pressure drop. It may be that $\Delta P_{TP,F} = \phi_G^2 \Delta P_{G,F}$ also. So in that case that it will be that frictional multiplier for gas and frictional multiplier for liquid here as $\phi_L^2$.

So this is the main concept that if you are considering single phase liquid pressure there then it will be denoted by $\Delta P_{L,F}$ frictional pressure drop of single phase liquid. And if you multiply by that factor $\phi_L^2$ with this $\Delta P_{L,F}$ then you can have this two phase frictional pressure drop.

Now what should be that single phase liquid frictional pressure drop that can be calculated by this equation and where $f_L$ is called that Darcy friction factor that can be calculated by this equation? And also if you are considering that gas phase then single gas phase frictional pressure drop can be calculated by this equation, whereas this $f_G$ is called that friction factor of the single phase gas. This is Darcy friction factor of that single phase gas which will be calculated by this equation.

$$f_L = \frac{64}{\mathrm{Re}_L} = 64\left[\frac{G(1-x)D}{\mu_L}\right]^{-1}$$

$$f_G = \frac{64}{\mathrm{Re}_G} = 64\left[\frac{GxD}{\mu_G}\right]^{-1}$$

And also $X^2$ square that is Lockhart Martinelli para meters X is defined as that $X^2 = \frac{\Delta P_{L,F}}{\Delta P_{G,F}}$ so it will be actually after simplification will be becoming $\phi_G^2/\phi_L^2$. Whereas Chisholm, he has given that $\phi_L$ should be actually related with that Lockhart Martinelli parameter X and it is actually expressed by this relationship that is

$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2}$$

where C is called as Chisholm constant.

And this Chisholm constant actually depends on the physical properties of the fluid as well as the geometry of the channel. Now if we are considering that water or amine flowing through the channel with air, then you can say C can be calculated from this correlation here this for water and this for amine. It is suggested by H. Ganapathy et al. 2015 and they have published in the chemical engineering Journal.

So according to their calculation, according to the correlation you can easily calculate what should be the C. And if you substitute C for a particular operating condition in this equation then you can calculate what should be the phi L square that is two phase multiplier, fiction multiplier. Once you know that two phase friction multiplier and then if you multiply it by this that single phase liquid friction factor then you can have that total frictional pressure drop in the channel.

So based on this equation you can easily predict what should be the frictional of two phase pressure drop there in the channel at a particular operating condition.

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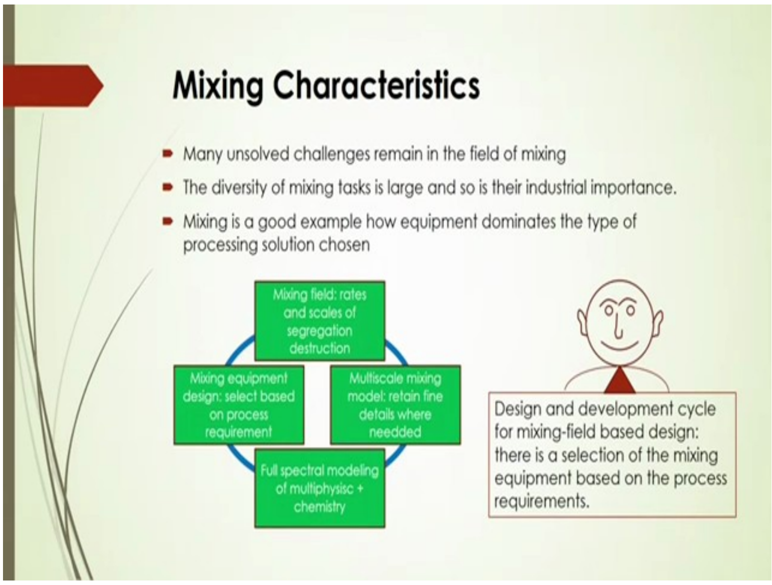

## Mixing Characteristics

- Many unsolved challenges remain in the field of mixing
- The diversity of mixing tasks is large and so is their industrial importance.
- Mixing is a good example how equipment dominates the type of processing solution chosen

Mixing field: rates and scales of segregation destruction

Mixing equipment design: select based on process requirement

Multiscale mixing model: retain fine details where needded

Full spectral modeling of multiphysisc + chemistry

Design and development cycle for mixing-field based design: there is a selection of the mixing equipment based on the process requirements.

Now later of course very interesting and also they have actually correlated that frictional pressure drop with the mixing characteristic. Now what is that mixing characteristics? That many unsolved challenges remain in the field of mixing in micro channel. In that case the diversity of mixing task is large and so industrial importance and mixing is a good example how that equipment dominates the type of processing solution chosen here. So in this case you have to remember that design and development cycle for mixing field-based design, there is a selection of the mixing equipment based on the process requirements. So it is very important to actually remember here.

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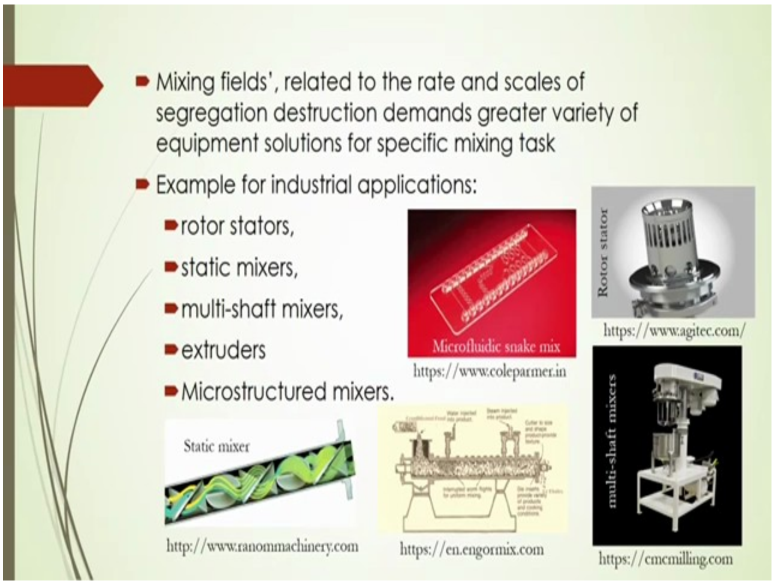

- Mixing fields', related to the rate and scales of segregation destruction demands greater variety of equipment solutions for specific mixing task
- Example for industrial applications:
  - rotor stators,
  - static mixers,
  - multi-shaft mixers,
  - extruders
  - Microstructured mixers.

Microfluidic snake mix

https://www.coleparmer.in

Rotor stator

https://www.agitec.com/

Static mixer

http://www.ranommachinery.com

https://en.engormix.com

multi-shaft mixers

https://cmcmilling.com

Now one important term it is called mixing fields that is related to the rate and scales of the segregation destruction demands that greater variety of equipment solutions for specific mixing task. Example for industrial applications like rotor stators type mixing equipment, static mixers, multi-shaft mixers, extruders, micro-structured mixers. So these are the different to know that device based mixing equipment for the micro-mixing in a particular devices.

And this is actually denoted by that mixing fields and it is related to the rate and how that mixing will happen, and what will be the effectiveness of the mixing and what should be the scales of segregation there and how that scales of segregation destruction actually changing that mixing pattern and mixing task in that particular micro channel based reactor?

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## Drivers for Mixing in Micro Spaces

- Many passive microstructured mixers follow design principles used at the macro-scale for static mixers with internal packings. It has some advantages such as:
  - compactness and low capital cost
  - low energy consumption and other operating expenses
  - negligible wear and no moving parts, which minimizes maintenance
  - lack of penetrating shafts and seals, which provides closed-system operation
  - short mixing time and well-defined mixing behavior
  - narrow residence-time distribution
  - performance independent of pressure and temperature.

Now what should be the drivers for that mixing in micro spaces? We are talking about the micro channel based reactor, suppose in that very small volume or micro spaces you can say that many passive micro-structured mixers that follow design principles used at the macro scale for static mixers with internal packings. It has some advantages, some compactness and low capital cost, low energy consumption and other operating expenses, lack of penetrating shafts and seals there.

You will see narrow residence time distribution. You can expect performance independent of pressure and temperature. Sometimes narrow residence distinction time also you can expect. Low energy consumption and other operating expenses will be there. So these are the drivers for mixing that having in the micro channel based reactor or micro scale based devices to get intensified mixing there for the process intensification.

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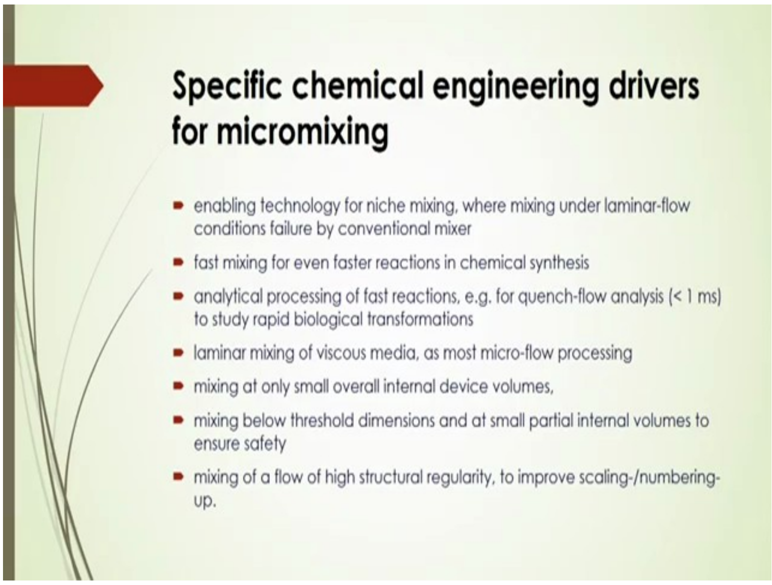

## Specific chemical engineering drivers for micromixing

- enabling technology for niche mixing, where mixing under laminar-flow conditions failure by conventional mixer
- fast mixing for even faster reactions in chemical synthesis
- analytical processing of fast reactions, e.g. for quench-flow analysis (< 1 ms) to study rapid biological transformations
- laminar mixing of viscous media, as most micro-flow processing
- mixing at only small overall internal device volumes,
- mixing below threshold dimensions and at small partial internal volumes to ensure safety
- mixing of a flow of high structural regularity, to improve scaling-/numbering-up.

Now specific chemical engineering drivers for micro-mixing like it enables that mixing, where mixing will be under laminar flow conditions and that is failure by conventional mixer. And also in this case chemical engineering drivers for micro-mixing it will give you fast mixing for even faster reactions in chemical synthesis. Mixing at only small overall internal device volume. Mixing of a flow of high structural regularity, where that you can improve scaling and numbering up also.

And in this case you will see that laminar mixing of viscous media, as most micro-flow processing there because all those things are actually in favor of that micro processing and also process intensification in specific chemical engineering application.

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## Mixing Principles

- Rely only on two principles which are diffusion and convection.
- Diffusion between short distances, establishing high concentration gradients
- Diffusion has some limits (robustness (fouling) and costs (complex microfabrication)
- to overcome the limits by diffusion mixing, the induction of secondary-flow (convective) patterns which are superposed on the main flow, recirculation patterns, chaotic advection and swirling flows, etc are developed

Now what are the mixing principles that in a channel whenever fluid will be flowing that two phase flow will be there? What should be that principle of mixing by different mechanism?

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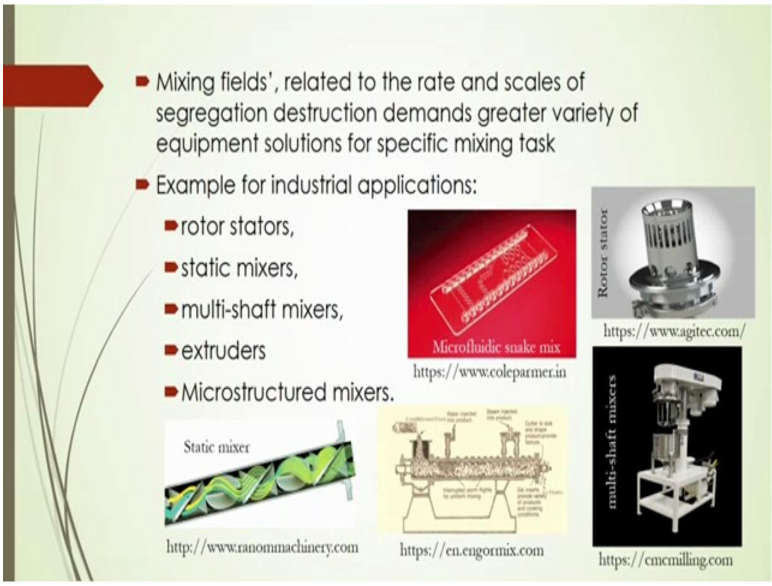

- Mixing fields', related to the rate and scales of segregation destruction demands greater variety of equipment solutions for specific mixing task
- Example for industrial applications:
  - rotor stators,
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  - multi-shaft mixers,
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  - Microstructured mixers.

Microfluidic snake mix

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Rotor stator

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Static mixer

http://www.ranommachinery.com

https://en.engormix.com

multi-shaft mixers

https://cmcmilling.com

That we have discussed in the field like rotor stators, static mixers, multi-shaft mixers, extruders, micro-structured mixers so in this industrial application of different type of micro-mixers based on different principles how it will be working that we have to know.

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## Mixing Principles

- Rely only on two principles which are diffusion and convection.
- Diffusion between short distances, establishing high concentration gradients
- Diffusion has some limits (robustness (fouling) and costs (complex microfabrication)
- to overcome the limits by diffusion mixing, the induction of secondary-flow (convective) patterns which are superposed on the main flow, recirculation patterns, chaotic advection and swirling flows, etc are developed

Because if you are considering different types of micro-mixers that whether this diffusion process will be enhanced or not. Whether that limits of the diffusion mixing will be improved or not. Whether there will be other types of flow produced or not. Whether it will be that secondary flow or convective flow patterns are imposed on that channels or not, what will be the superposed capacity of the flow on the other flow of this other liquid-liquid, is there any recirculation patterns or not?

Chaotic advection or swirling flows are there or not? So based on that you can access that mixing in that particular devices. And because of which you can get that process intensification of the mixing in the micro channel devices. So that mixing principle rely only on two principles which are diffusion and convection.

So diffusion between short distances, establishing high concentration gradients and also the diffusion has some limits robustness that will be fouling and also cost complex micro fabrication is one important factor there. Now to overcome these limits by diffusion mixing, the induction of the secondary flow like convective pattern which are superposed on the main flow.

Sometimes recirculation patterns, chaotic advection, swirling flows and even that deal flows also are developed to have this.

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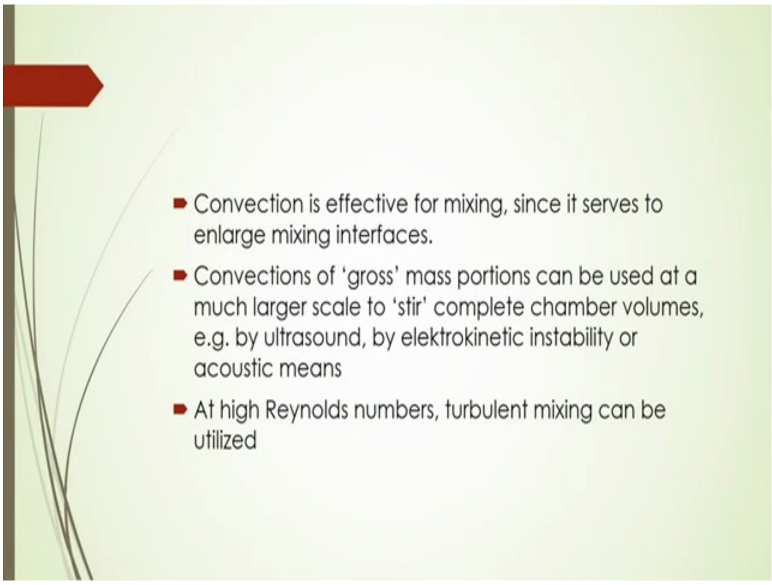

- Convection is effective for mixing, since it serves to enlarge mixing interfaces.
- Convections of 'gross' mass portions can be used at a much larger scale to 'stir' complete chamber volumes, e.g. by ultrasound, by elektrokinetic instability or acoustic means
- At high Reynolds numbers, turbulent mixing can be utilized

Now convection is effective for mixing since it serves to enlarge mixing interfaces, convections of gross mass portions can be used at a much larger scale to stir even complete chamber volumes, some other means also you can get that micro-mixing there in the devices like ultrasound, some other electric field also can be applied to get that micro-mixing also. At high Reynolds number you can have turbulent mixing that can be also utilize just by making the mechanical provision to the channel so that you can get high turbulent and high Reynolds number and also intermixing will be more there.

Now what will be the means for that mixing of micro spaces? There may be some devices that may actively give that mixing process sometimes passively.

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## Means for Mixing of Micro Spaces

The means of mixing can be classified as either ***active*** or ***passive***

***Passive micro mixers:***

- use part of the flow energy for feeding and thereby generate special flow schemes with ultra-thin flow compartments such as
- lamellae for diffusion mixing or
- Utilize chaotic advection by secondary flows to enlarge the interfaces.

So there are two means of mixing that can be classified as either active or passive. Now passive micro-mixers means use part of the flow energy for the feeding and thereby generate special flow schemes with ultra-thin flow compartments such as Lamellae for diffusion mixing or utilize chaotic advection by secondary flows to enlarge the interfaces.

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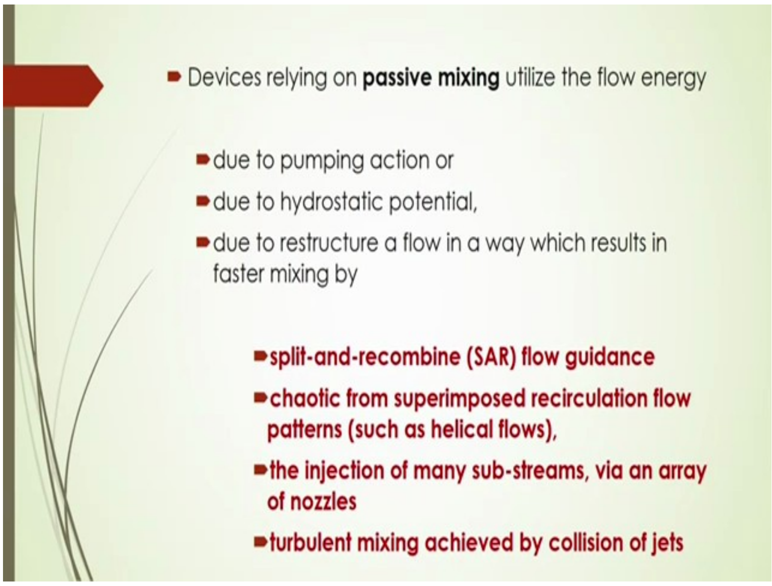

- Devices relying on **passive mixing** utilize the flow energy
  - due to pumping action or
  - due to hydrostatic potential,
  - due to restructure a flow in a way which results in faster mixing by
    - **split-and-recombine (SAR) flow guidance**
    - **chaotic from superimposed recirculation flow patterns (such as helical flows),**
    - **the injection of many sub-streams, via an array of nozzles**
    - **turbulent mixing achieved by collision of jets**

Now devices that rely on passive mixing utilize the flow energy may be due to the pumping action, due to hydro static potential, due to restructure a flow in a way which results in faster mixing by some different means like you can get passive mixing by split and recombine of the flow and also you can have that by chaotic from the superimposed recirculation flow pattern. You can have that mixing by the injection of many sub streams, via an array of nozzles. You can get that passive mixing by turbulent mixing achieved by collision of jets there.

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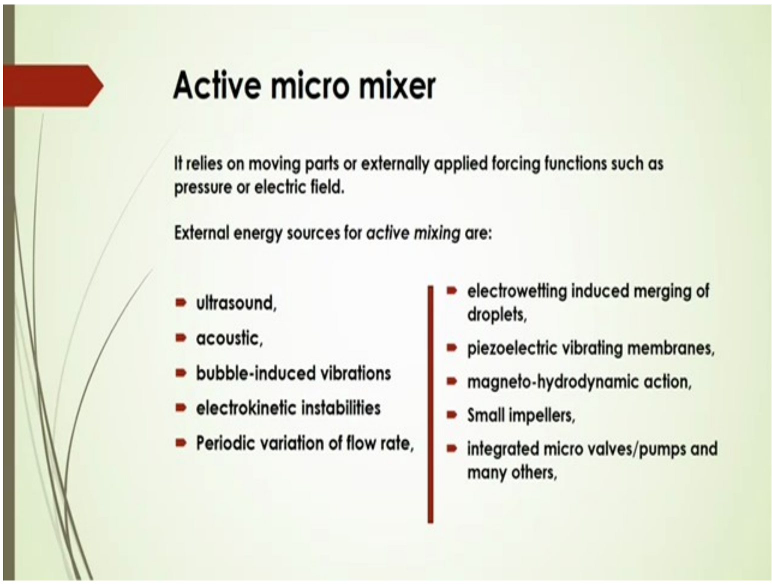

## Active micro mixer

It relies on moving parts or externally applied forcing functions such as pressure or electric field.

External energy sources for *active mixing* are:

- ultrasound,
- acoustic,
- bubble-induced vibrations
- electrokinetic instabilities
- Periodic variation of flow rate,
- electrowetting induced merging of droplets,
- piezoelectric vibrating membranes,
- magneto-hydrodynamic action,
- Small impellers,
- integrated micro valves/pumps and many others,

So other also principles of having that micro-mixing like it is called as active micro-mixing process. And it relies on moving parts externally applied force that will give fluctuations in that fluid elements based on which there will be intensified mixing in the fluid device. So that is why external energy gives you that micro-mixing and that is why it is called as active micro-mixing process.

That external energy, what should be that external energy? That may come from ultrasound source that may be acoustic, make that may be bubble induced vibrations. That may be electro kinetic instabilities. That may be periodic variation of flow rate. That may be that small impellers or micro impellers you can say and that may be magneto hydrodynamic action.

That may be piezoelectric vibrating membranes. That may be electroplating induced merging of droplets. So these are the different way of producing external energy by which you can have that micro-mixing in a micro channel based reactor or other micro-reactors.

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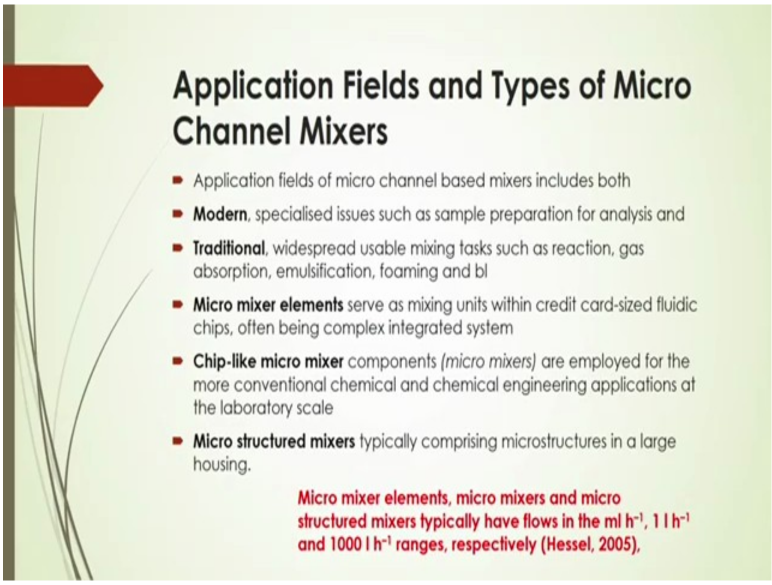

## Application Fields and Types of Micro Channel Mixers

- Application fields of micro channel based mixers includes both
- **Modern**, specialised issues such as sample preparation for analysis and
- **Traditional**, widespread usable mixing tasks such as reaction, gas absorption, emulsification, foaming and bl
- **Micro mixer elements** serve as mixing units within credit card-sized fluidic chips, often being complex integrated system
- **Chip-like micro mixer** components *(micro mixers)* are employed for the more conventional chemical and chemical engineering applications at the laboratory scale
- **Micro structured mixers** typically comprising microstructures in a large housing.

**Micro mixer elements, micro mixers and micro structured mixers typically have flows in the ml h$^{-1}$, 1 l h$^{-1}$ and 1000 l h$^{-1}$ ranges, respectively (Hessel, 2005),**

Now what are the application fields and types of micro channel based mixers there. So application field of micro channel based mixer includes both modern and traditional you can say and also you can have that micro-mixer element chip like micro-mixer, micro-structured mixers there. And chip like micro-mixer components that micro-mixers are employed for the more conventional chemical and chemical engineering applications at the laboratory scale.

Whereas micro-structured mixers typically comprising microstructures in a large housing and micro-mixer elements, micro-mixer, micro-structured mixers typically have flows in the range of millimeter per hour, 1 liter per hour to and 1000 L per hour ranges respectively. So in that case we can have different applications within certain range micro-mixing efficiency based on that channel structure.

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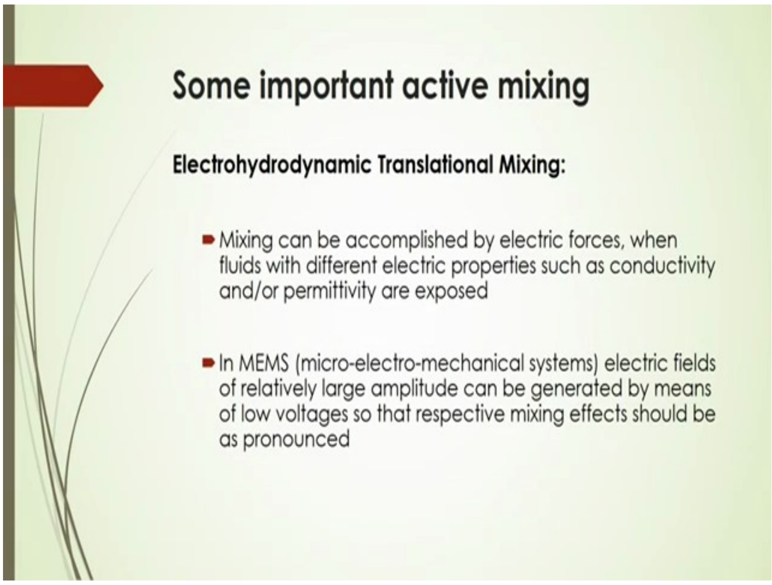

## Some important active mixing

**Electrohydrodynamic Translational Mixing:**

- Mixing can be accomplished by electric forces, when fluids with different electric properties such as conductivity and/or permittivity are exposed
- In MEMS (micro-electro-mechanical systems) electric fields of relatively large amplitude can be generated by means of low voltages so that respective mixing effects should be as pronounced

Some important active mixing like electro hydrodynamic translational mixing can be accomplished by electric forces here. When fluids with different electric properties such as conductivity and permittivity are exposed there. In micro-electromechanical systems the electric fields of relatively large amplitude can be generated by means of low voltage so that respective mixing effects can be improved or you can have that more influence to get that mixing phenomena.

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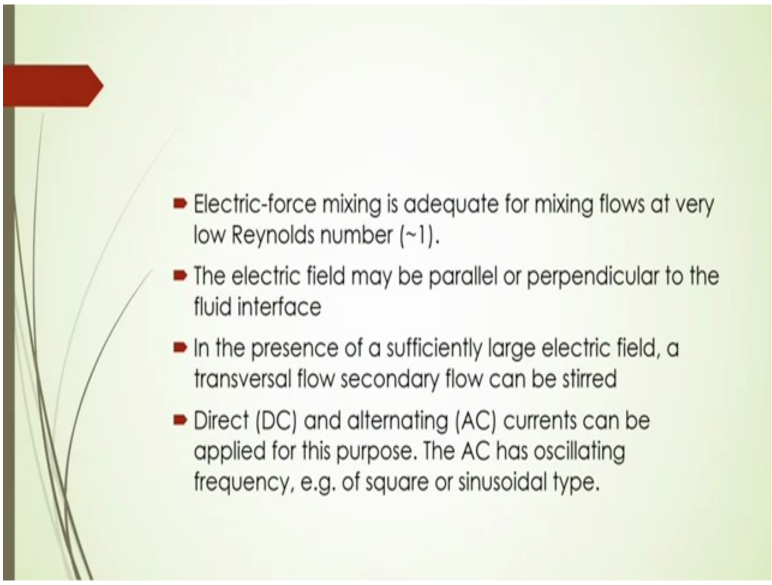

- Electric-force mixing is adequate for mixing flows at very low Reynolds number (~1).
- The electric field may be parallel or perpendicular to the fluid interface
- In the presence of a sufficiently large electric field, a transversal flow secondary flow can be stirred
- Direct (DC) and alternating (AC) currents can be applied for this purpose. The AC has oscillating frequency, e.g. of square or sinusoidal type.

Electric force mixing is adequate for mixing flows at very low Reynolds number. As this may be parallel or perpendicular to the fluid interfaces this field. And in the presence of a sufficiently large electric field, a transversal flow secondary flow can be stirred. Direct DC and alternating currents can be applied for this purpose. This AC has oscillating frequency and example of like square or sinusoidal type. So this oscillating frequency will generate that micro-mixing or will governed that or will enhance that mixing processes there.

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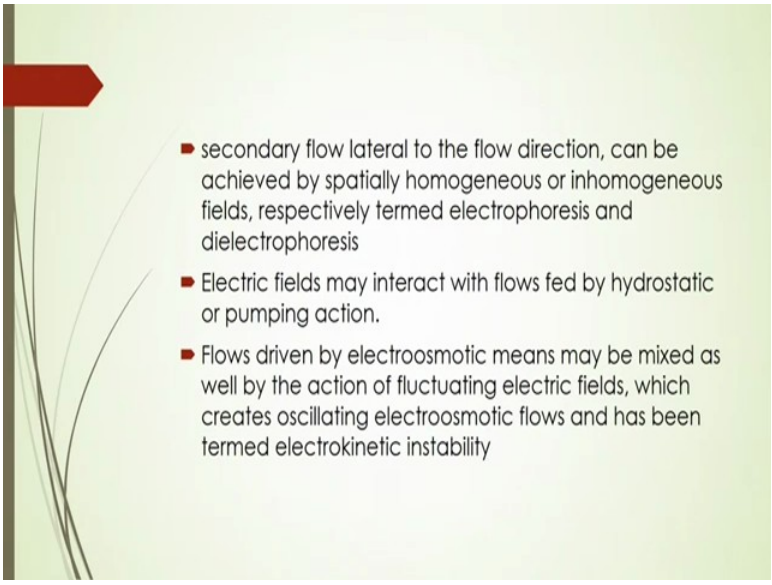

- secondary flow lateral to the flow direction, can be achieved by spatially homogeneous or inhomogeneous fields, respectively termed electrophoresis and dielectrophoresis
- Electric fields may interact with flows fed by hydrostatic or pumping action.
- Flows driven by electroosmotic means may be mixed as well by the action of fluctuating electric fields, which creates oscillating electroosmotic flows and has been termed electrokinetic instability

Secondary flow lateral to the flow direction can be achieved by in this case especially homogenius or inhomogeneous feelings, respectively termed as electrophoresis and di-electrophoresis. And electric fields may interact with flows fed by hydro static or pumping action. Flows driven by electro osmotic means may be mixed as well by the action of fluctuating electric fields, which creates oscillating electro osmotic flows and has been termed electro kinetic instability.

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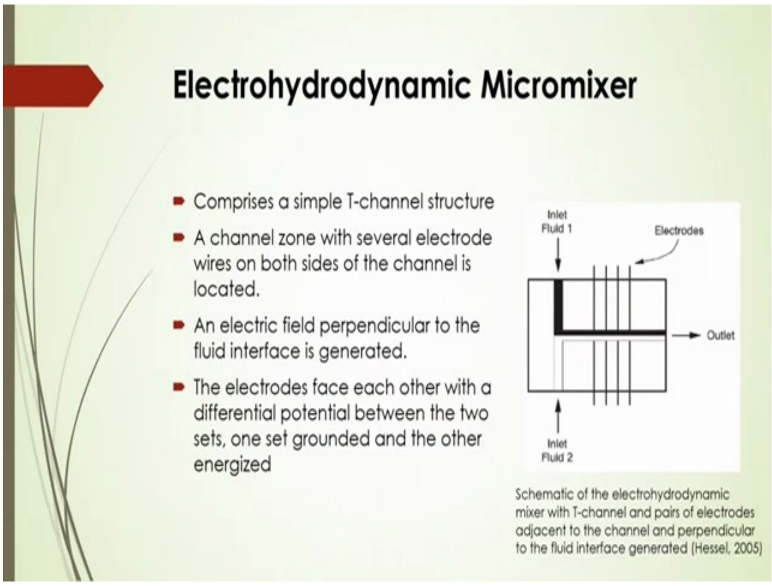

## Electrohydrodynamic Micromixer

- Comprises a simple T-channel structure
- A channel zone with several electrode wires on both sides of the channel is located.
- An electric field perpendicular to the fluid interface is generated.
- The electrodes face each other with a differential potential between the two sets, one set grounded and the other energized

Schematic of the electrohydrodynamic mixer with T-channel and pairs of electrodes adjacent to the channel and perpendicular to the fluid interface generated (Hessel, 2005)

So electro hydrodynamic micro-mixer is also one of the important development of that micro-mixer for that intensification of this mixing process. In this case it generally comprises of a simple T-channel structure. In this case electric field perpendicular to the fluid interface is generated. And the electrodes face each other with the differential potential between the two sets, one set grounded and the other set will be energized. So based on this principle mixing is happened.

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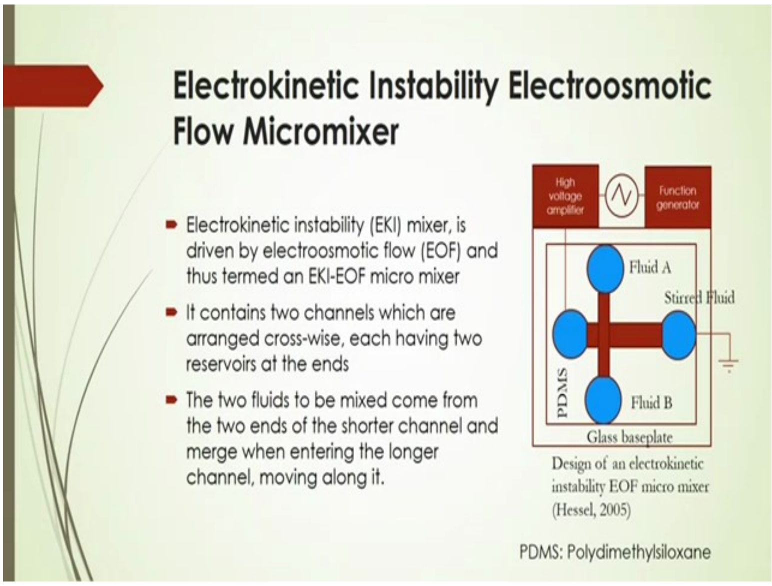

## Electrokinetic Instability Electroosmotic Flow Micromixer

- Electrokinetic instability (EKI) mixer, is driven by electroosmotic flow (EOF) and thus termed an EKI-EOF micro mixer
- It contains two channels which are arranged cross-wise, each having two reservoirs at the ends
- The two fluids to be mixed come from the two ends of the shorter channel and merge when entering the longer channel, moving along it.

Design of an electrokinetic instability EOF micro mixer (Hessel, 2005)

PDMS: Polydimethylsiloxane

And this electro kinetic instability, electro osmotic flow micro-mixer is also there. In this case Electro kinetic instability mixer is driven by electro osmotic flow and thus termed an EKI-EOF micro-mixer. So in this slide it is given that you can design an electro kinetic instability of micro-mixer there as per Hessel 2005. In this case two fluids to be mixed come from the two ends of the shorter channel and merge when entering the longer channel and moving along it. And you will see that based on that interaction of the fluids there will be intermixing or micro-mixing.

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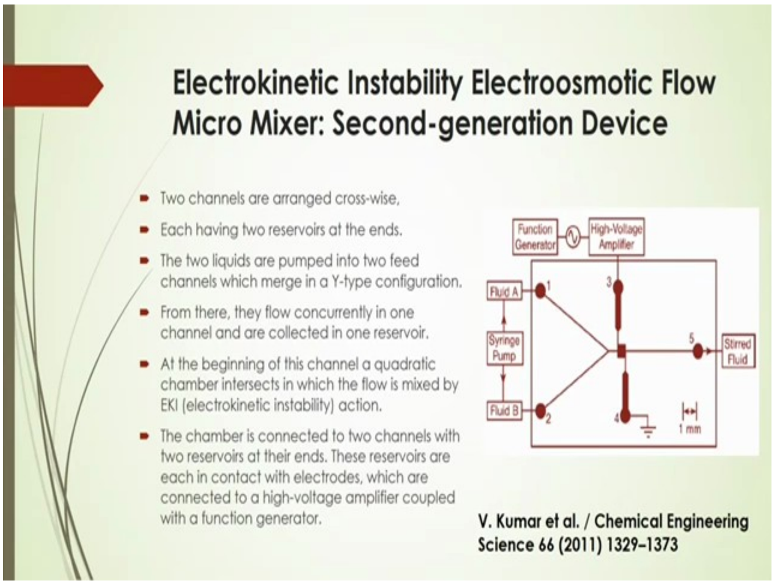

## Electrokinetic Instability Electroosmotic Flow Micro Mixer: Second-generation Device

- Two channels are arranged cross-wise.
- Each having two reservoirs at the ends.
- The two liquids are pumped into two feed channels which merge in a Y-type configuration.
- From there, they flow concurrently in one channel and are collected in one reservoir.
- At the beginning of this channel a quadratic chamber intersects in which the flow is mixed by EKI (electrokinetic instability) action.
- The chamber is connected to two channels with two reservoirs at their ends. These reservoirs are each in contact with electrodes, which are connected to a high-voltage amplifier coupled with a function generator.

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And electro kinetic instability electro osmotic flow micro-mixer this can be also enhance there. In this case channels are arranged crosswise there and while see that each having two reservoirs at the ends as shown in the figure here according to that Kumar et al. 2011 and in this case two liquids are pumped into two feed channels which merged in a Y-type configuration. And from there they flow co-currently in one channel and are collected in one reservoir.

At the beginning of this channel you will see that a quadratic chamber intersects in which the flow is mixed by this electro kinetic instability action. And also the chamber is connected to 2 channels with two reservoirs at their ends. And these reservoirs are each in contact with the electrodes, which are connected to high-voltage amplifier coupled with a function generator. So in this way this is the steps by which you can have this micro-mixing, by this electro kinetics instabilities action.

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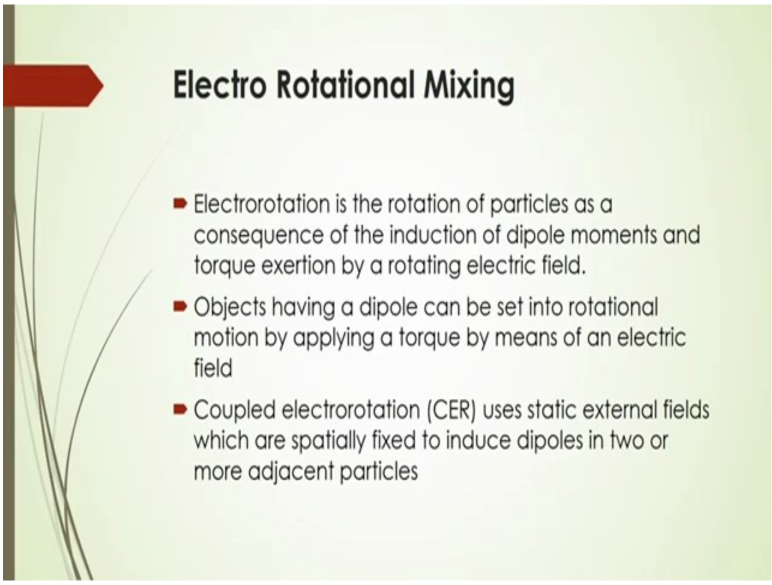

## Electro Rotational Mixing

- Electrorotation is the rotation of particles as a consequence of the induction of dipole moments and torque exertion by a rotating electric field.
- Objects having a dipole can be set into rotational motion by applying a torque by means of an electric field
- Coupled electrorotation (CER) uses static external fields which are spatially fixed to induce dipoles in two or more adjacent particles

Also electro rotational mixing is one of the important other mixing principles thereby which you can have that micro-mixing inside the micro-reactor. In this case electro rotation is done as a consequence of the induction of dipole moments and torque exertion by rotating electric field. And in this case the coupled electro rotation uses static external feeds which are spatially fixed to induce dipoles in two or more adjacent particles there.

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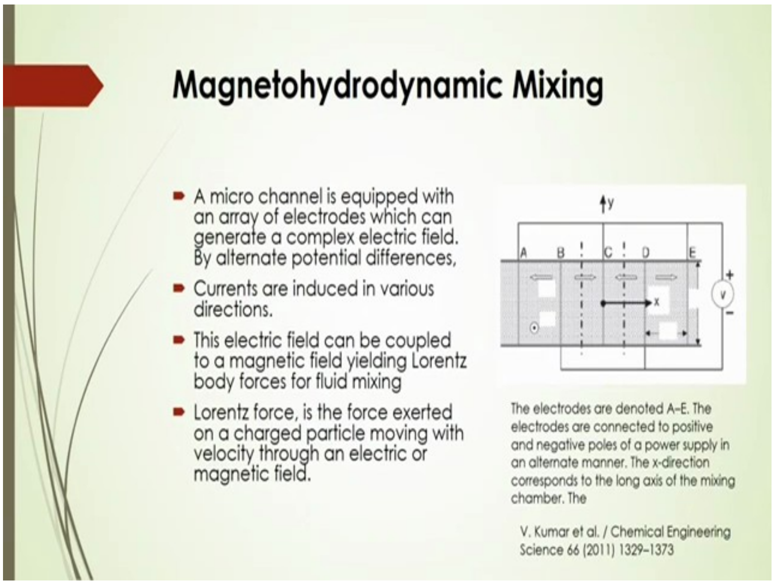

## Magnetohydrodynamic Mixing

- A micro channel is equipped with an array of electrodes which can generate a complex electric field. By alternate potential differences,
- Currents are induced in various directions.
- This electric field can be coupled to a magnetic field yielding Lorentz body forces for fluid mixing
- Lorentz force, is the force exerted on a charged particle moving with velocity through an electric or magnetic field.

The electrodes are denoted A–E. The electrodes are connected to positive and negative poles of a power supply in an alternate manner. The x-direction corresponds to the long axis of the mixing chamber. The

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Also magneto hydrodynamic mixing also another important mechanism by which you can have that micro-mixing. In this case a micro channel is equipped with an array of electrodes which can generate a complex electric field, by alternate potential differences. In this case the currents are induced in various directions. And the electric field that can be coupled to a magnetic field that will yield you that some Lorentz body forces for the liquid mixing.

And Lorentz force is actually the force that is exerted on a charged particle moving with the velocity through an electric or magnetic fields. So by this mechanism also you can have that micro-mixing phenomena.

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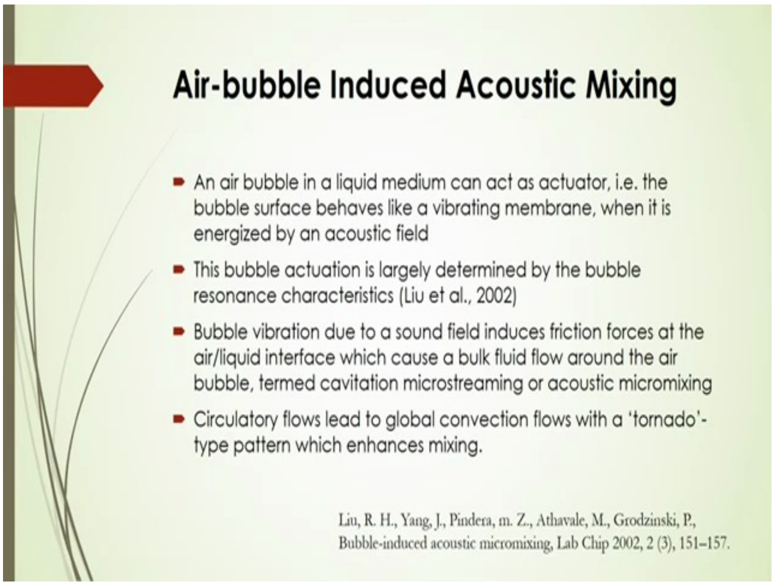

## Air-bubble Induced Acoustic Mixing

- An air bubble in a liquid medium can act as actuator, i.e. the bubble surface behaves like a vibrating membrane, when it is energized by an acoustic field
- This bubble actuation is largely determined by the bubble resonance characteristics (Liu et al., 2002)
- Bubble vibration due to a sound field induces friction forces at the air/liquid interface which cause a bulk fluid flow around the air bubble, termed cavitation microstreaming or acoustic micromixing
- Circulatory flows lead to global convection flows with a 'tornado'-type pattern which enhances mixing.

Liu, R. H., Yang, J., Pindera, m. Z., Athavale, M., Grodzinski, P., Bubble-induced acoustic micromixing, Lab Chip 2002, 2 (3), 151–157.

Now another important micro-mixing phenomena is called Air bubble induced acoustic mixing. An air bubble here in a liquid medium can act as actuator. In this case the bubble surface that behaves like a vibrating membrane, when it is energized by an acoustic field and in this case the bubble actuation is largely determined by the bubble resonance characteristics. And the bubble vibration is due to that sound field that is induced and that induction actually based on the friction forces at the air liquid interface and that cause a bulk fluid flow around the air bubble.

And because of which you will see there will be an interface fluctuation and based on which you can say that there will be an acoustic micro-mixing and this type of phenomena is called cavitation micro-streaming or you can say that acoustic micro-mixing. And circulatory flows around that bubble that lead to a global convection flows with a Tornado type patterns which enhances the mixing there.

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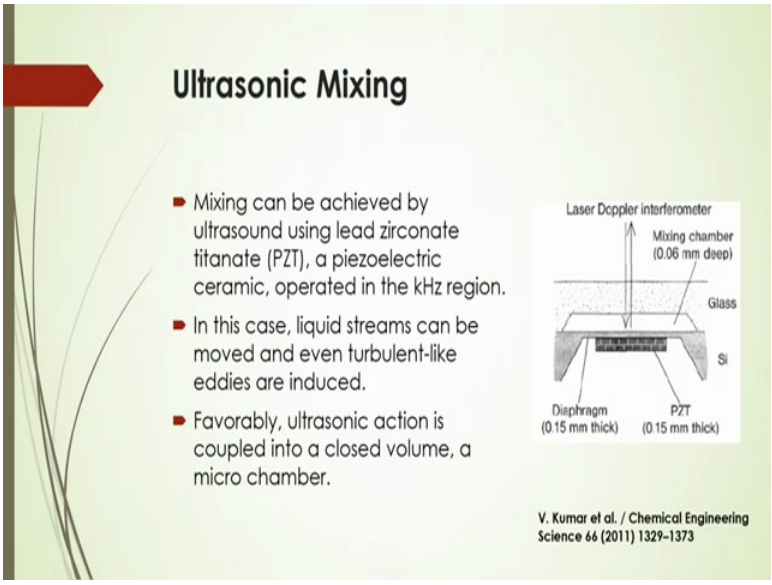

Ultrasonic Mixing

- Mixing can be achieved by ultrasound using lead zirconate titanate (PZT), a piezoelectric ceramic, operated in the kHz region.
- In this case, liquid streams can be moved and even turbulent-like eddies are induced.
- Favorably, ultrasonic action is coupled into a closed volume, a micro chamber.

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Ultrasonic mixing is also one of the important of that micro-mixing that can be achieved by ultrasound using lead Zirconate, Titanate or a piezoelectric ceramic operated in the kilo hertz region as given or reported by Kumar et al. in 2011. In this case, the liquid streams can be moved and even turbulent like eddies are induced. Favorably you can say that ultrasonic action is coupled into a close volume, a micro-chamber.

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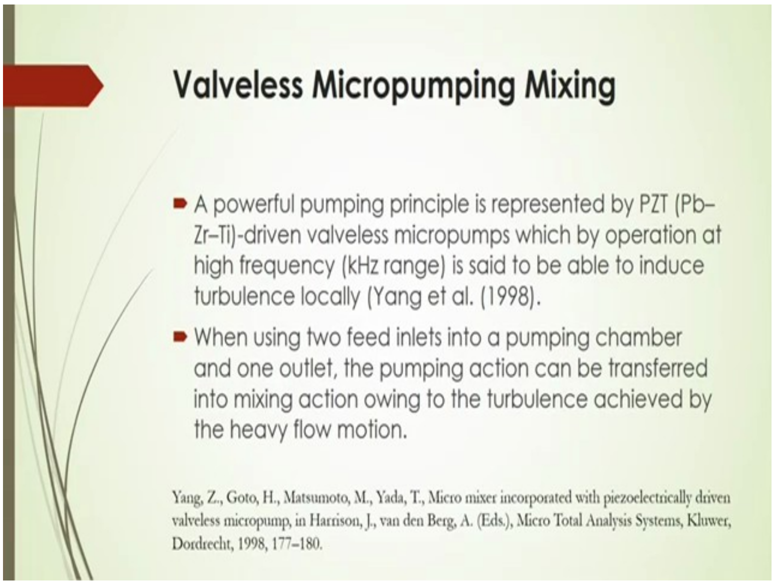

## Valveless Micropumping Mixing

- A powerful pumping principle is represented by PZT (Pb–Zr–Ti)-driven valveless micropumps which by operation at high frequency (kHz range) is said to be able to induce turbulence locally (Yang et al. (1998).
- When using two feed inlets into a pumping chamber and one outlet, the pumping action can be transferred into mixing action owing to the turbulence achieved by the heavy flow motion.

Yang, Z., Goto, H., Matsumoto, M., Yada, T., Micro mixer incorporated with piezoelectrically driven valveless micropump, in Harrison, J., van den Berg, A. (Eds.), Micro Total Analysis Systems, Kluwer, Dordrecht, 1998, 177–180.

Other different types of micro-mixing like Valveless micro-pumping.

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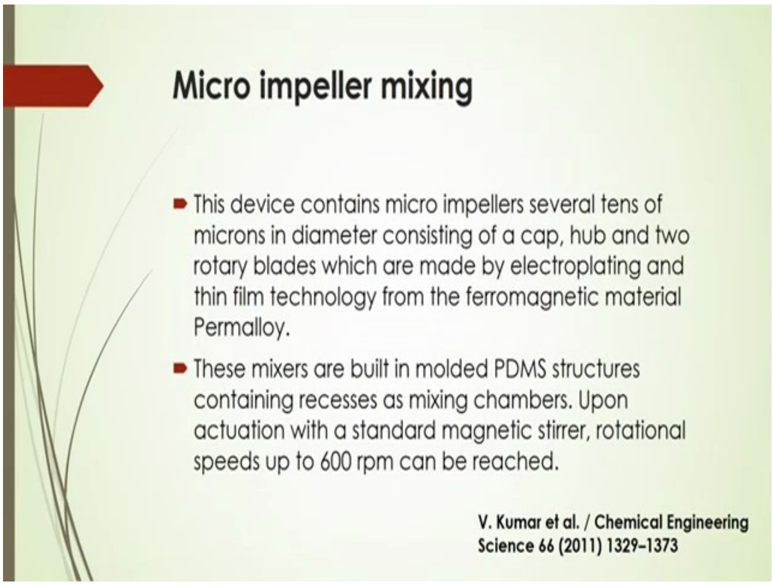

## Micro impeller mixing

- This device contains micro impellers several tens of microns in diameter consisting of a cap, hub and two rotary blades which are made by electroplating and thin film technology from the ferromagnetic material Permalloy.
- These mixers are built in molded PDMS structures containing recesses as mixing chambers. Upon actuation with a standard magnetic stirrer, rotational speeds up to 600 rpm can be reached.

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Micro-impeller mixing there.

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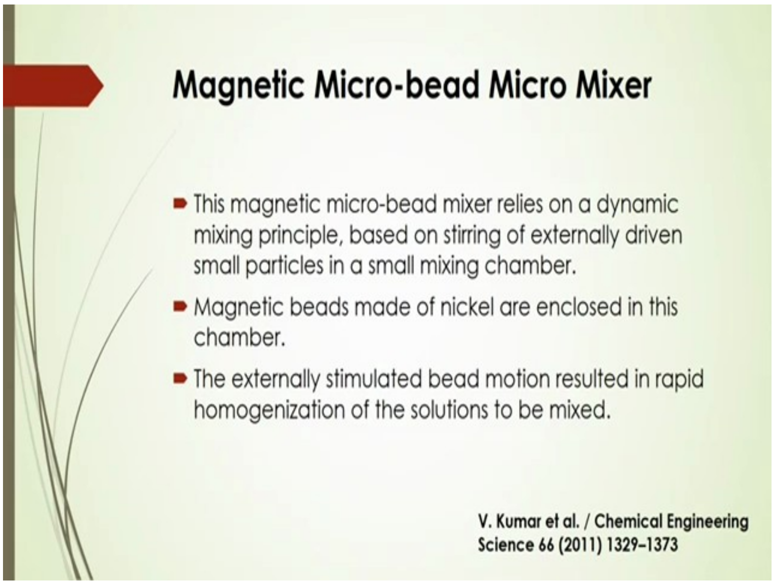

## Magnetic Micro-bead Micro Mixer

- This magnetic micro-bead mixer relies on a dynamic mixing principle, based on stirring of externally driven small particles in a small mixing chamber.
- Magnetic beads made of nickel are enclosed in this chamber.
- The externally stimulated bead motion resulted in rapid homogenization of the solutions to be mixed.

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Even magnetic micro-bead micro-mixer.

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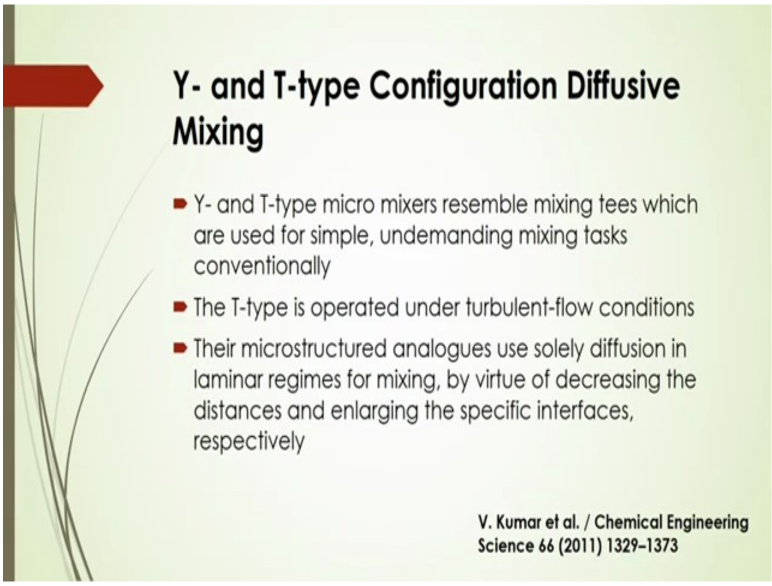

## Y- and T-type Configuration Diffusive Mixing

- Y- and T-type micro mixers resemble mixing tees which are used for simple, undemanding mixing tasks conventionally
- The T-type is operated under turbulent-flow conditions
- Their microstructured analogues use solely diffusion in laminar regimes for mixing, by virtue of decreasing the distances and enlarging the specific interfaces, respectively

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Y- and T type configuration diffusive mixing.

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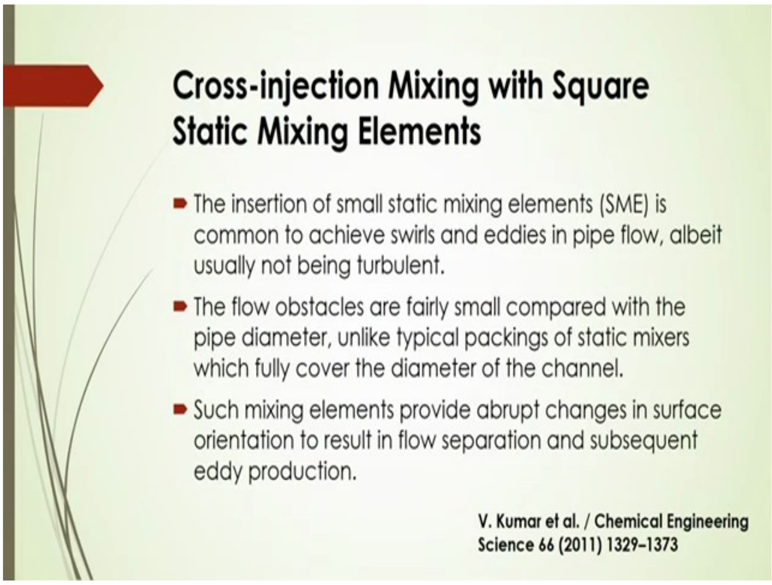

## Cross-injection Mixing with Square Static Mixing Elements

- The insertion of small static mixing elements (SME) is common to achieve swirls and eddies in pipe flow, albeit usually not being turbulent.
- The flow obstacles are fairly small compared with the pipe diameter, unlike typical packings of static mixers which fully cover the diameter of the channel.
- Such mixing elements provide abrupt changes in surface orientation to result in flow separation and subsequent eddy production.

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And also cross injection mixing with square static mixing elements.

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## Jet Collision Turbulent or Swirling-flow Mixing

- Impinging jets are one way to generate large interfaces by 'converting' fluids from large reservoirs into multiple small-diameter micro plumes.
- The various impinging jet techniques exploit freshly generated interfaces.
- Impinging jets can be contacted in a mixing chamber or in free space.
- They may be guided into air or gas media or introduced into a liquid (which is filled from prior jets).
- The jets may be directed without offset, i.e. collide, or with off-set, to penetrate deeply into a liquid and by flowing aside the next jet to create eddies which further enlarge the interface.
- By collision of jets, in particular at high fluid velocity, mixing can be accomplished.

Jet collision turbulent or swirling flow mixing.

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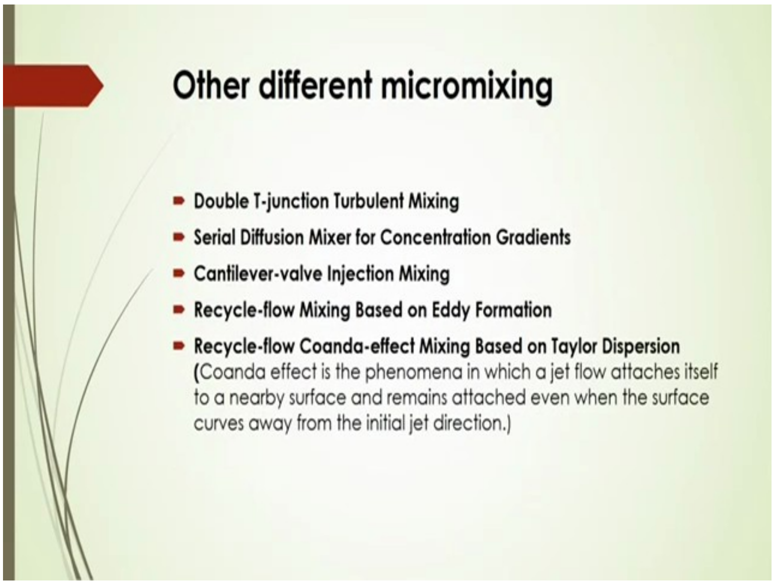

## Other different micromixing

- Double T-junction Turbulent Mixing
- Serial Diffusion Mixer for Concentration Gradients
- Cantilever-valve Injection Mixing
- Recycle-flow Mixing Based on Eddy Formation
- Recycle-flow Coanda-effect Mixing Based on Taylor Dispersion (Coanda effect is the phenomena in which a jet flow attaches itself to a nearby surface and remains attached even when the surface curves away from the initial jet direction.)

Other different micro-mixing here, double T-junction turbulent mixing, serial diffusion mixer for concentration gradients, Cantilever-valve injection mixing, Recycle flow mixing based on Eddy formation, Recycle flow Canada effect mixing based on Taylor dispersion. There are several other different types of micro-mixing are there.

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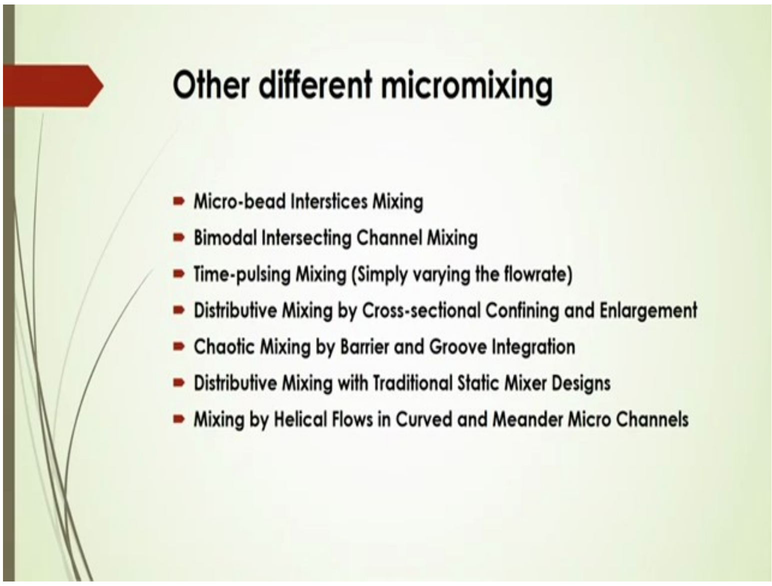

## Other different micromixing

- Micro-bead Interstices Mixing
- Bimodal Intersecting Channel Mixing
- Time-pulsing Mixing (Simply varying the flowrate)
- Distributive Mixing by Cross-sectional Confining and Enlargement
- Chaotic Mixing by Barrier and Groove Integration
- Distributive Mixing with Traditional Static Mixer Designs
- Mixing by Helical Flows in Curved and Meander Micro Channels

Micro-bead interstices mixing, bimodal intersecting channel mixing, mixing by helicon flows curved and Meander Micro channels. So these are other different types of micro-mixing mechanism there.

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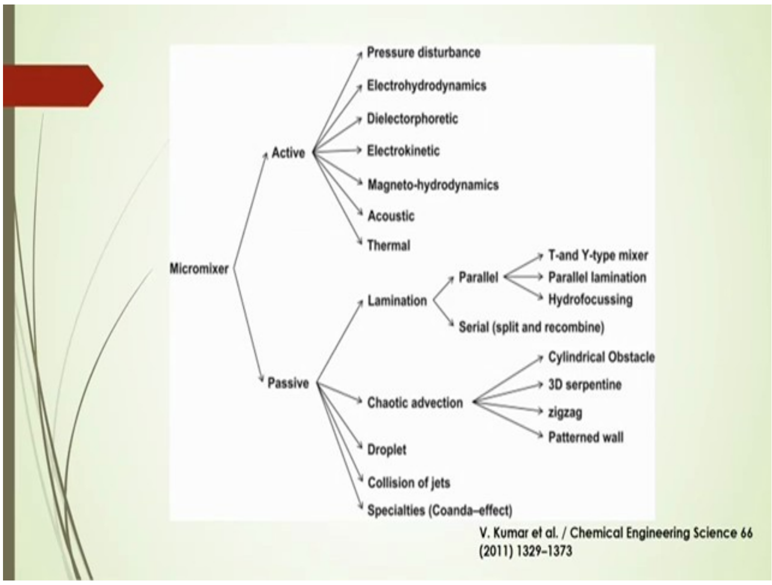

- Micromixer
  - Active
    - Pressure disturbance
    - Electrohydrodynamics
    - Dielectorphoretic
    - Electrokinetic
    - Magneto-hydrodynamics
    - Acoustic
    - Thermal
  - Passive
    - Lamination
      - Parallel
        - T-and Y-type mixer
        - Parallel lamination
        - Hydrofocussing
      - Serial (split and recombine)
    - Chaotic advection
      - Cylindrical Obstacle
      - 3D serpentine
      - zigzag
      - Patterned wall
    - Droplet
    - Collision of jets
    - Specialties (Coanda–effect)

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So here in tabular format we have given here that different types of micro-mixer that may be active passive and how it will be differentiate there in this table. So please go through this and Kumar et al has described in details of the process here. Please go through that paper if you know. Otherwise through the slides you can have the idea of what will be the micro-mixing mechanism.

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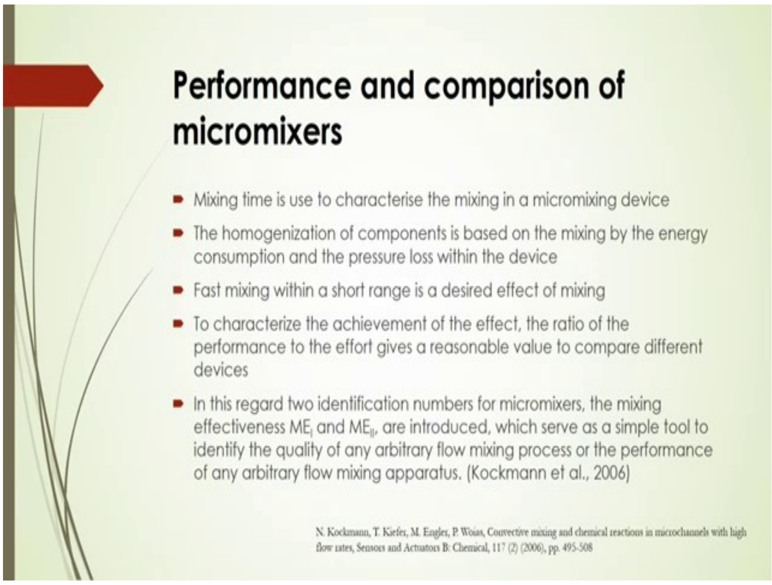

## Performance and comparison of micromixers

- Mixing time is use to characterise the mixing in a micromixing device
- The homogenization of components is based on the mixing by the energy consumption and the pressure loss within the device
- Fast mixing within a short range is a desired effect of mixing
- To characterize the achievement of the effect, the ratio of the performance to the effort gives a reasonable value to compare different devices
- In this regard two identification numbers for micromixers, the mixing effectiveness $ME_I$ and $ME_{II}$, are introduced, which serve as a simple tool to identify the quality of any arbitrary flow mixing process or the performance of any arbitrary flow mixing apparatus. (Kockmann et al., 2006)

N. Kockmann, T. Kiefer, M. Engler, P. Woias, Convective mixing and chemical reactions in microchannels with high flow rates, Sensors and Actuators B: Chemical, 117 (2) (2006), pp. 495-508

Now performance and comparison of micro-mixer of course there are several types of micro-mixers there. Now you have to analyze that performance or comparison of the micro-mixer and how to analyze that. So in this case mixing time is used to characterize the mixing in a micro-mixing device and the homogenization of the components that will be based on the mixing by the energy consumption and the pressure loss within the device.

And fast mixing within a short-range is a desired effect of mixing. To characterize the achievement of the effect, the ratio of the performance to the effort that gives a reasonable value to compare different devices. In this regard two identification numbers for micro-mixers, the mixing effectiveness ME1 and MEII are introduced there by Kockmann et al 2006 based on which you can analyze the performance of the micro-mixer.

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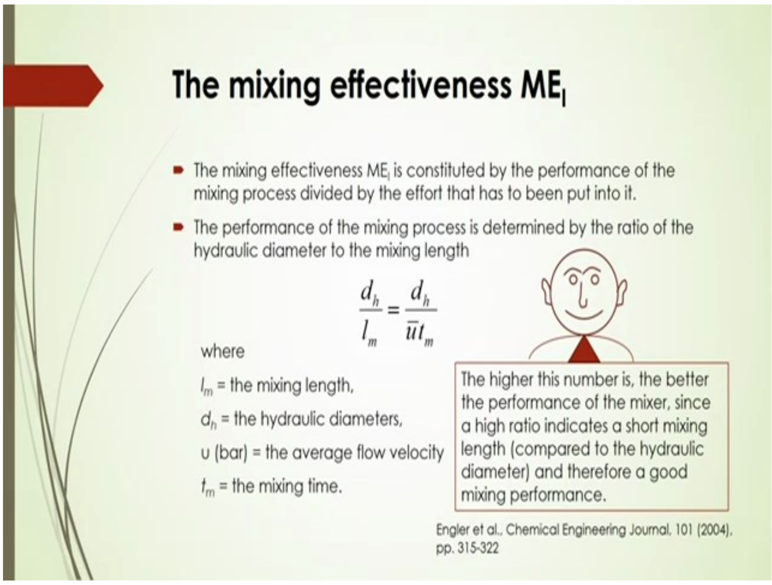

## The mixing effectiveness ME$_I$

- The mixing effectiveness ME$_I$ is constituted by the performance of the mixing process divided by the effort that has to been put into it.
- The performance of the mixing process is determined by the ratio of the hydraulic diameter to the mixing length

$$\frac{d_h}{l_m} = \frac{d_h}{\bar{u} t_m}$$

where

$l_m$ = the mixing length,

$d_h$ = the hydraulic diameters,

u (bar) = the average flow velocity

$t_m$ = the mixing time.

The higher this number is, the better the performance of the mixer, since a high ratio indicates a short mixing length (compared to the hydraulic diameter) and therefore a good mixing performance.

Engler et al., Chemical Engineering Journal, 101 (2004), pp. 315-322

So according to the Engler et al. 2004, the mixing effectiveness is constituted by the performance of the mixing process that is divided by the effort that has been actually put into it. The performance of the mixing process is determined by the ratio of the hydraulic diameter to the mixing length as shown in the slide by this equation you can have this what should be the hydraulic diameter and mixing. And what should be the ratio of hydraulic diameter to the mixing length.

$$\frac{d_h}{l_m} = \frac{d_h}{\bar{u} t_m}$$

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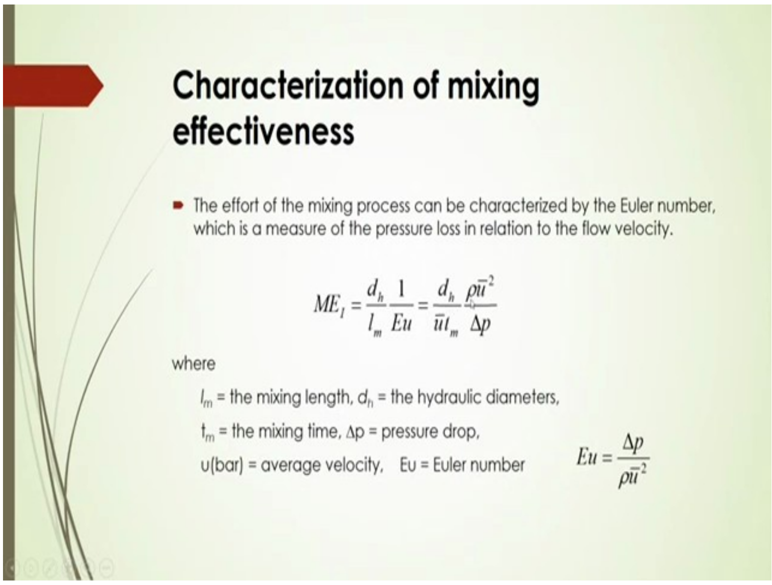

### Characterization of mixing effectiveness

- The effort of the mixing process can be characterized by the Euler number, which is a measure of the pressure loss in relation to the flow velocity.

$$ME_I = \frac{d_h}{l_m}\frac{1}{Eu} = \frac{d_h}{\bar{u}t_m}\frac{\rho\bar{u}^2}{\Delta p}$$

where

$l_m$ = the mixing length, $d_h$ = the hydraulic diameters,

$t_m$ = the mixing time, $\Delta p$ = pressure drop,

u(bar) = average velocity, Eu = Euler number $Eu = \frac{\Delta p}{\rho\bar{u}^2}$

And then if that hydraulic diameter and the mixing length, effort of the mixing process can be characterized by the Euler number and with this ratio of this hydraulic diameter to the mixing length. This is a measure of the pressure loss in relation to the flow velocity. So this mixing effectiveness can be calculated by this equation if you know that pressure drop and velocity and also this hydraulic diameter and mixing time there.

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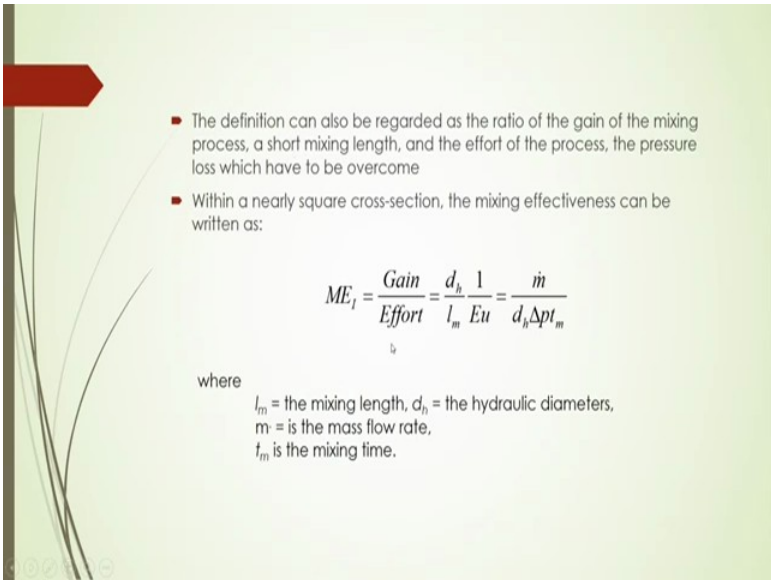

- The definition can also be regarded as the ratio of the gain of the mixing process, a short mixing length, and the effort of the process, the pressure loss which have to be overcome
- Within a nearly square cross-section, the mixing effectiveness can be written as:

$$ME_I = \frac{Gain}{Effort} = \frac{d_h}{l_m}\frac{1}{Eu} = \frac{\dot{m}}{d_h \Delta p t_m}$$

where

$l_m$ = the mixing length, $d_h$ = the hydraulic diameters,

m· = is the mass flow rate,

$t_m$ is the mixing time.

Again if you know that mass flow rate based on that mass flow rate also you can calculate with that frictional pressure drop there. So based on which you can also calculate this mixness of this effect of this micro channel mixer. And if you are having less mixing time there of course the mixness will be effectiveness of the mixing will be increased. If you have more pressure frictional pressure drop also you can say that mixing effectiveness will be less there.

So according to this you can easily access in which cases that or which mixer should give the relatively higher effectiveness of the mixing there.

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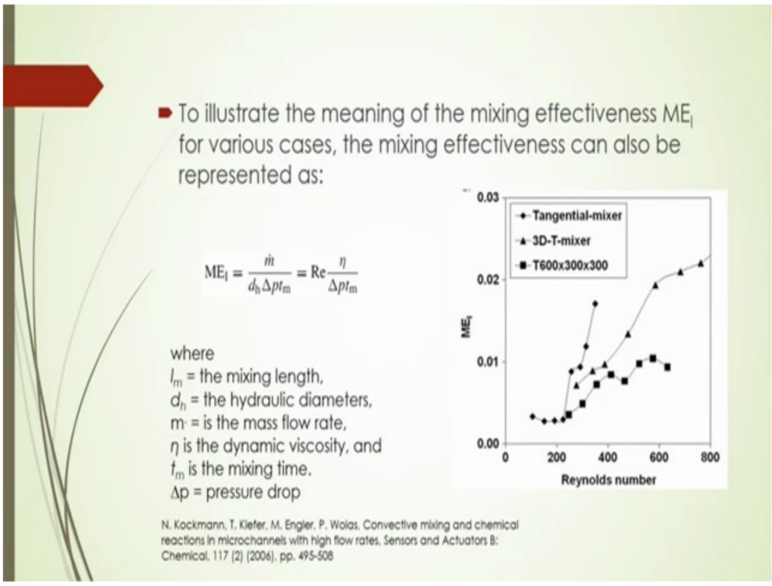

- To illustrate the meaning of the mixing effectiveness $ME_l$ for various cases, the mixing effectiveness can also be represented as:

$$ME_l = \frac{\dot{m}}{d_h \Delta p t_m} = Re \frac{\eta}{\Delta p t_m}$$

where
$l_m$ = the mixing length,
$d_h$ = the hydraulic diameters,
$\dot{m}$ = is the mass flow rate,
$\eta$ is the dynamic viscosity, and
$t_m$ is the mixing time.
$\Delta p$ = pressure drop

N. Kockmann, T. Kiefer, M. Engler, P. Woias, Convective mixing and chemical reactions in microchannels with high flow rates, Sensors and Actuators B: Chemical, 117 (2) (2006), pp. 495-508

You will see there Kockmann et al. 2006, they have compared this different mixers based on the Reynolds number and this effectiveness of the mixing actually if it is increased at Reynolds number. If it is increased of course that higher flow rate will give you that more mixing there. But you will see that as per figure shown that 3-D-T-mixer will give you that relatively less mixing compared to that tangential mixer if your Reynolds number is considered to keep with constant there.

So that is why that different mixness factors will give you that an assessment of the mixing efficiency of the channel based on this.

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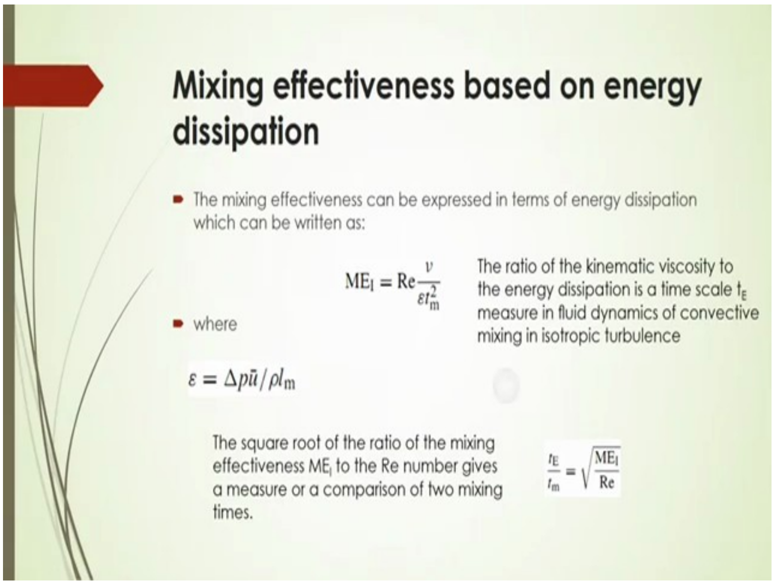

## Mixing effectiveness based on energy dissipation

- The mixing effectiveness can be expressed in terms of energy dissipation which can be written as:

$$\mathrm{ME_I} = \mathrm{Re}\frac{\nu}{\varepsilon t_\mathrm{m}^2}$$

The ratio of the kinematic viscosity to the energy dissipation is a time scale $t_E$ measure in fluid dynamics of convective mixing in isotropic turbulence

- where

$$\varepsilon = \Delta p\bar{u}/\rho l_\mathrm{m}$$

The square root of the ratio of the mixing effectiveness $\mathrm{ME_I}$ to the Re number gives a measure or a comparison of two mixing times.

$$\frac{t_\mathrm{E}}{t_\mathrm{m}} = \sqrt{\frac{\mathrm{ME_I}}{\mathrm{Re}}}$$

And mixing effectiveness can also be expressed in terms of energy dissipation like here by this equation you can express this mixing effectiveness. If you know that energy dissipation, that energy dissipation depends on that pressure drop, this pressure drop will give you that what will be the energy dissipation through the channel. And once you know that energy dissipation you can easily calculate this. Where this kinematic viscosity is new kinematic viscosity epsilon is called energy dissipation and this tm is the mixing time and Re is the Reynolds number.

The ratio of the kinematic viscosity to the energy dissipation is a timescale that will measure in a fluid dynamics of convective mixing in isotropic turbulence and the square root of the ratio of the mixing effectiveness to the Reynolds number gives a measure or a comparison of two mixing times there.

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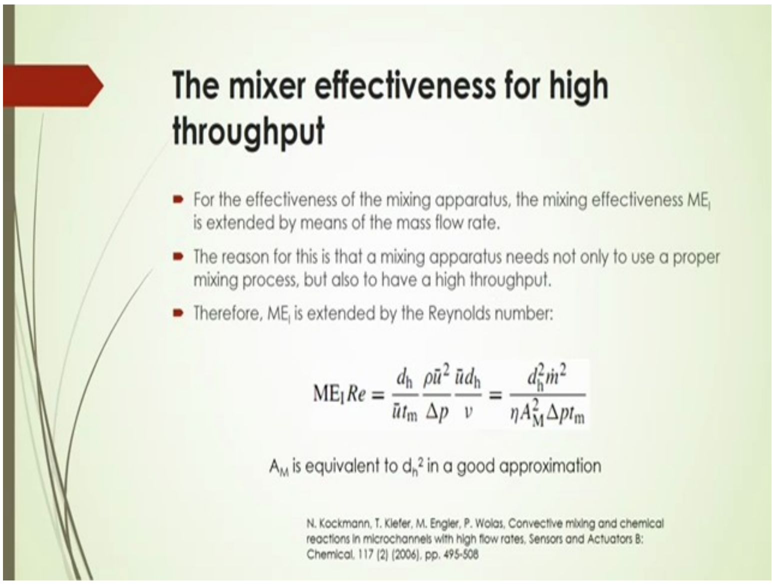

## The mixer effectiveness for high throughput

- For the effectiveness of the mixing apparatus, the mixing effectiveness $ME_I$ is extended by means of the mass flow rate.
- The reason for this is that a mixing apparatus needs not only to use a proper mixing process, but also to have a high throughput.
- Therefore, $ME_I$ is extended by the Reynolds number:

$$\mathrm{ME_I}\,Re = \frac{d_\mathrm{h}}{\bar{u}t_\mathrm{m}}\,\frac{\rho\bar{u}^2}{\Delta p}\,\frac{\bar{u}d_\mathrm{h}}{\nu} = \frac{d_\mathrm{h}^2\dot{m}^2}{\eta A_\mathrm{M}^2\Delta p t_\mathrm{m}}$$

$A_M$ is equivalent to $d_h^2$ in a good approximation

N. Kockmann, T. Kiefer, M. Engler, P. Woias, Convective mixing and chemical reactions in microchannels with high flow rates, Sensors and Actuators B: Chemical, 117 (2) (2006), pp. 495-508

Also for high throughput devices that how to calculate that mixer effectiveness there. In this case that mixing effectiveness for that particular mixer can be extended by the Reynolds number here, as per this $ME_1$ into Re that will be divided as $ME_2$. So it will be calculated by this equation as shown here in the slides there.

$$\mathrm{ME_I}\,Re = \frac{d_\mathrm{h}}{\bar{u}t_\mathrm{m}}\,\frac{\rho\bar{u}^2}{\Delta p}\,\frac{\bar{u}d_\mathrm{h}}{\nu} = \frac{d_\mathrm{h}^2\dot{m}^2}{\eta A_\mathrm{M}^2\Delta p t_\mathrm{m}}$$

So by this equation you can calculate what will be the mixing effectiveness for the high throughput devices.

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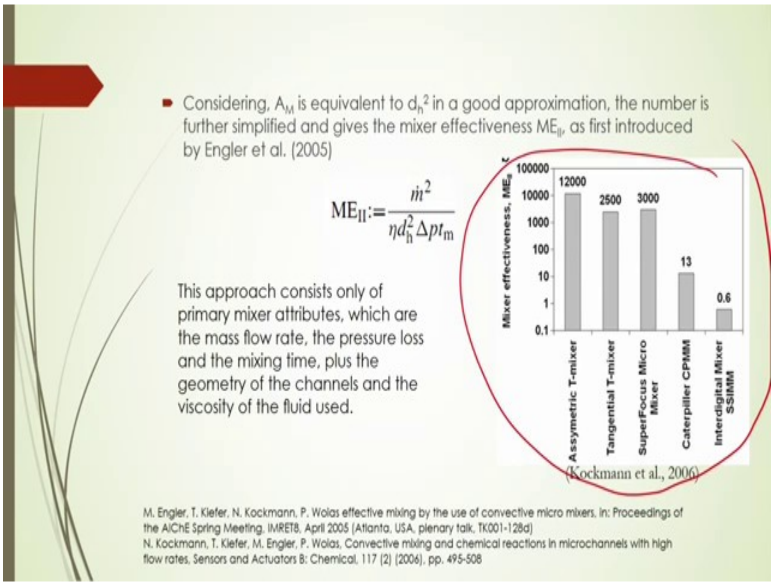

- Considering, $A_M$ is equivalent to $d_h^2$ in a good approximation, the number is further simplified and gives the mixer effectiveness $ME_{II}$, as first introduced by Engler et al. (2005)

$$\mathrm{ME_{II}} := \frac{\dot{m}^2}{\eta d_\mathrm{h}^2\Delta p t_\mathrm{m}}$$

This approach consists only of primary mixer attributes, which are the mass flow rate, the pressure loss and the mixing time, plus the geometry of the channels and the viscosity of the fluid used.

(Kockmann et al., 2006)

M. Engler, T. Kiefer, N. Kockmann, P. Woias effective mixing by the use of convective micro mixers, in: Proceedings of the AIChE Spring Meeting, IMRET8, April 2005 (Atlanta, USA, plenary talk, TK001-128d)
N. Kockmann, T. Kiefer, M. Engler, P. Woias, Convective mixing and chemical reactions in microchannels with high flow rates, Sensors and Actuators B: Chemical, 117 (2) (2006), pp. 495-508

And here in this figure there is some comparisons are given for different micro-mixers there. And based on that mixer effectiveness for high throughput equipment there and you will see and for asymmetric T-mixer is giving the maximum mixer effectiveness there.

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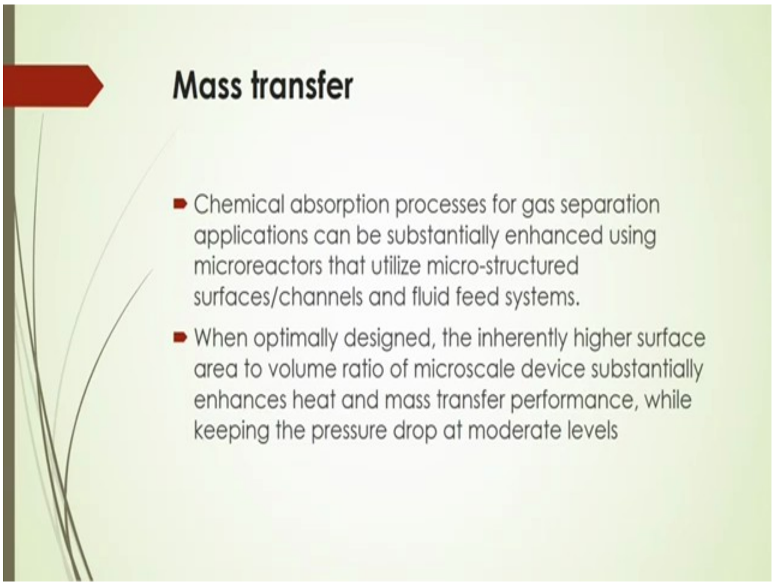

## Mass transfer

- Chemical absorption processes for gas separation applications can be substantially enhanced using microreactors that utilize micro-structured surfaces/channels and fluid feed systems.
- When optimally designed, the inherently higher surface area to volume ratio of microscale device substantially enhances heat and mass transfer performance, while keeping the pressure drop at moderate levels

And then Mass transfer. Mass transfer of course based on this mixing characteristic that you can analyze that mass transfer, higher mixing will be of that more diffusion more that effectiveness of the mass transfer there because in this case there is no back mixing that may sometimes hindered that mass transfer efficiency but in the micro-Channel based reactor there will be no back mixing. So in that case you can increase the mass transfer by this channel.

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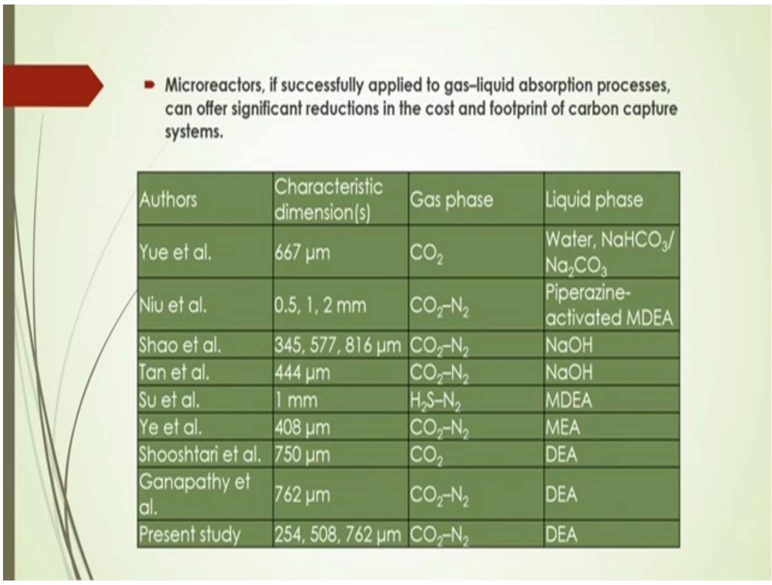

- Microreactors, if successfully applied to gas–liquid absorption processes, can offer significant reductions in the cost and footprint of carbon capture systems.

| Authors | Characteristic dimension(s) | Gas phase | Liquid phase |
|---|---|---|---|
| Yue et al. | 667 µm | $CO_2$ | Water, $NaHCO_3$/ $Na_2CO_3$ |
| Niu et al. | 0.5, 1, 2 mm | $CO_2$–$N_2$ | Piperazine-activated MDEA |
| Shao et al. | 345, 577, 816 µm | $CO_2$–$N_2$ | NaOH |
| Tan et al. | 444 µm | $CO_2$–$N_2$ | NaOH |
| Su et al. | 1 mm | $H_2S$–$N_2$ | MDEA |
| Ye et al. | 408 µm | $CO_2$–$N_2$ | MEA |
| Shooshtari et al. | 750 µm | $CO_2$ | DEA |
| Ganapathy et al. | 762 µm | $CO_2$–$N_2$ | DEA |
| Present study | 254, 508, 762 µm | $CO_2$–$N_2$ | DEA |

Here some characteristics of the channels dimension and the application of mass transfer with that gas phase of carbon dioxide carbon dioxide and nitrogen-carbon dioxide, hydrogen sulphide with that different liquid solvent like water, sodium bicarbonate even sodium hydroxide even Methyl, even diethylamine also. So these are the different studies of that mass transfer in a micro channel for gas liquid system.

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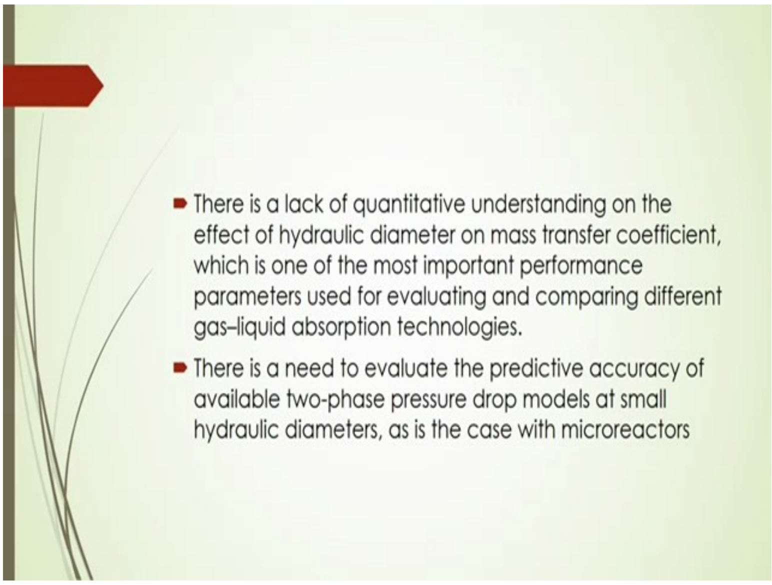

- There is a lack of quantitative understanding on the effect of hydraulic diameter on mass transfer coefficient, which is one of the most important performance parameters used for evaluating and comparing different gas–liquid absorption technologies.
- There is a need to evaluate the predictive accuracy of available two-phase pressure drop models at small hydraulic diameters, as is the case with microreactors

There is a need to evaluate the predictive accuracy of available two phase pressure drop models at small hydraulic diameters, as the case with the micro-reactors because it is actually directly influences mass transfer characteristics in the channel.

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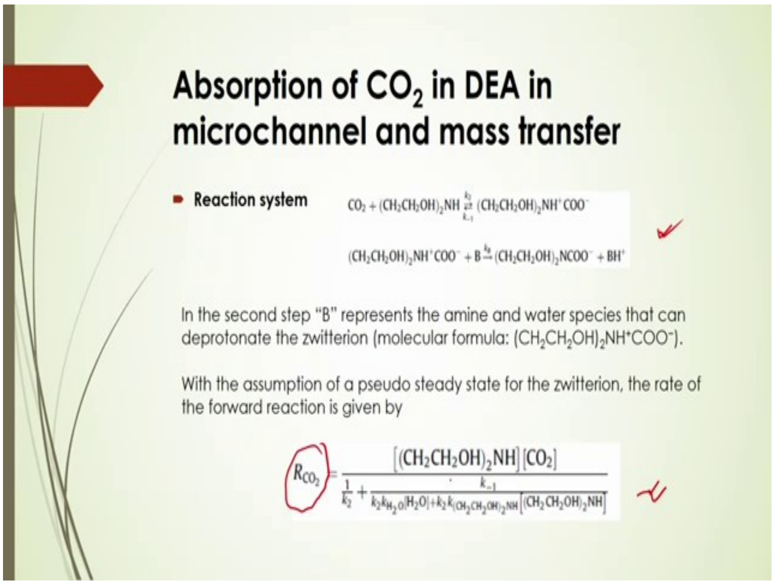

## Absorption of $CO_2$ in DEA in microchannel and mass transfer

- **Reaction system**

$$CO_2 + (CH_2CH_2OH)_2NH \underset{k_{-1}}{\overset{k_2}{\rightleftharpoons}} (CH_2CH_2OH)_2NH^+COO^-$$

$$(CH_2CH_2OH)_2NH^+COO^- + B \xrightarrow{k_B} (CH_2CH_2OH)_2NCOO^- + BH^+$$

In the second step "B" represents the amine and water species that can deprotonate the zwitterion (molecular formula: $(CH_2CH_2OH)_2NH^+COO^-$).

With the assumption of a pseudo steady state for the zwitterion, the rate of the forward reaction is given by

$$R_{CO_2} = \frac{\left[(CH_2CH_2OH)_2NH\right][CO_2]}{\frac{1}{k_2} + \frac{k_{-1}}{k_2 k_{H_2O}[H_2O] + k_2 k_{(CH_2CH_2OH)_2NH}\left[(CH_2CH_2OH)_2NH\right]}}$$

So here some reaction systems of the absorption of carbon dioxide in a diethylamine in micro channel and its mass transfer here as per reactions how that reactive mass transfer will happen with that carbon dioxide to that diethylamine and in this case, based on this you can say what will be that absorption rate there that can be calculated by this equation.

$$R_{CO_2} = \frac{\left[(CH_2CH_2OH)_2NH\right][CO_2]}{\frac{1}{k_2} + \frac{k_{-1}}{k_2 k_{H_2O}[H_2O] + k_2 k_{(CH_2CH_2OH)_2NH}\left[(CH_2CH_2OH)_2NH\right]}}$$

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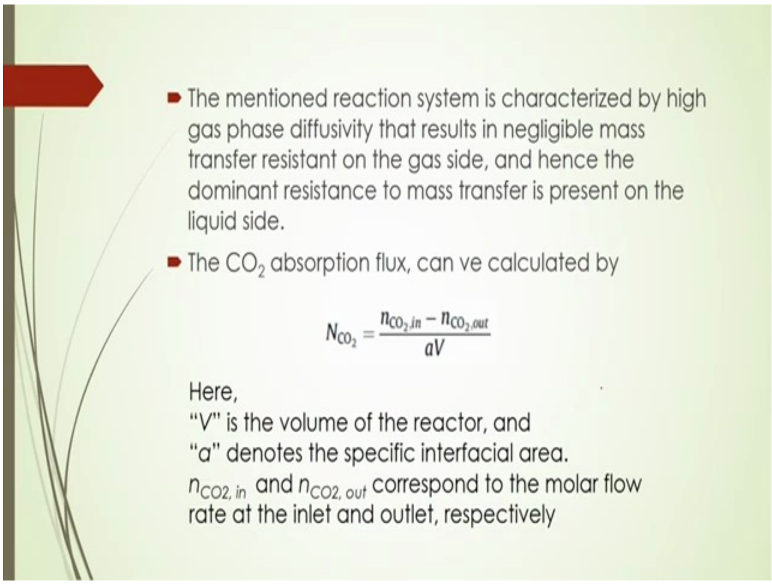

- The mentioned reaction system is characterized by high gas phase diffusivity that results in negligible mass transfer resistant on the gas side, and hence the dominant resistance to mass transfer is present on the liquid side.
- The $CO_2$ absorption flux, can ve calculated by

$$N_{CO_2} = \frac{n_{CO_2,in} - n_{CO_2,out}}{aV}$$

Here,
"V" is the volume of the reactor, and
"a" denotes the specific interfacial area.
$n_{CO2,\,in}$ and $n_{CO2,\,out}$ correspond to the molar flow rate at the inlet and outlet, respectively

And then absorption flux will be calculated by the equation

$$N_{CO_2} = \frac{n_{CO_2,in} - n_{CO_2,out}}{aV}$$

once that Molar flow rate at the inlet and outlet in the channel.

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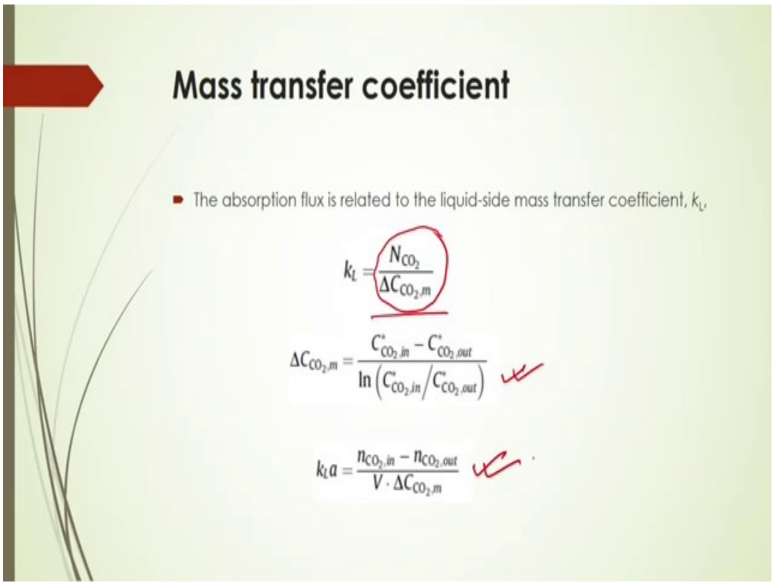

## Mass transfer coefficient

- The absorption flux is related to the liquid-side mass transfer coefficient, $k_L$,

$$k_L = \frac{N_{CO_2}}{\Delta C_{CO_2,m}}$$

$$\Delta C_{CO_2,m} = \frac{C^*_{CO_2,in} - C^*_{CO_2,out}}{\ln\left(C^*_{CO_2,in} / C^*_{CO_2,out}\right)}$$

$$k_L a = \frac{n_{CO_2,in} - n_{CO_2,out}}{V \cdot \Delta C_{CO_2,m}}$$

And mass transfer coefficient can be calculated from that absorption flux that is $N_{CO2}$ and if that concentration gradients there as per the mass transfer principles so that you can calculate from this equation that concentration gradient can accordingly mass transfer coefficient you can calculate.

$$k_L = \frac{N_{CO_2}}{\Delta C_{CO_2,m}}$$

$$\Delta C_{CO_2,m} = \frac{C^*_{CO_2,in} - C^*_{CO_2,out}}{\ln\left(C^*_{CO_2,in} / C^*_{CO_2,out}\right)}$$

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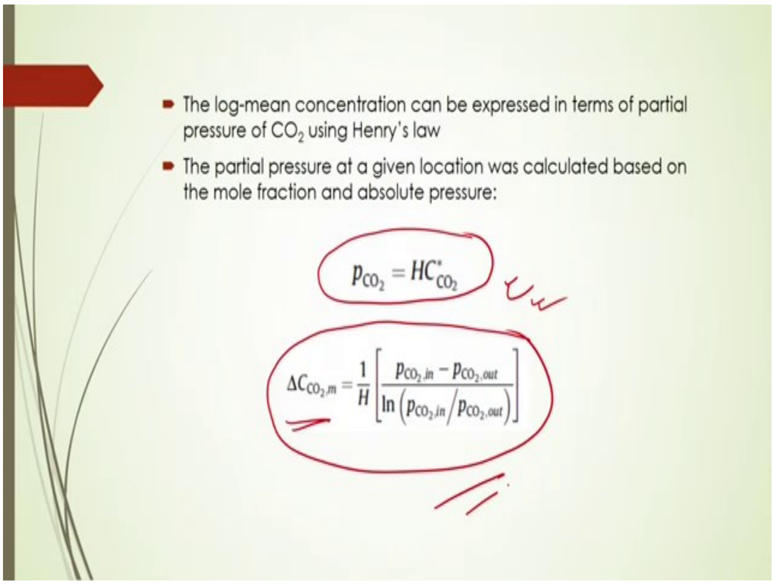

- The log-mean concentration can be expressed in terms of partial pressure of $CO_2$ using Henry's law
- The partial pressure at a given location was calculated based on the mole fraction and absolute pressure:

$$p_{CO_2} = HC^*_{CO_2}$$

$$\Delta C_{CO_2,m} = \frac{1}{H}\left[\frac{p_{CO_2,in} - p_{CO_2,out}}{\ln\left(p_{CO_2,in} / p_{CO_2,out}\right)}\right]$$

And this mass transfer coefficient you can calculate in terms of that pressure also that concentration because this concentration you can calculate in terms of pressure because that at the partial pressure at a given location it can be calculated based on the mole fraction and absolute pressure, so according to the Henry's law that you can calculate what will be the partial pressure if you know that equilibrium concentration of the gas.

So here based on this here Henry's law you can easily calculate what will be the partial pressure? Now this concentration driving pressure differences you can easily express in terms of partial pressure according to that Henry's law.

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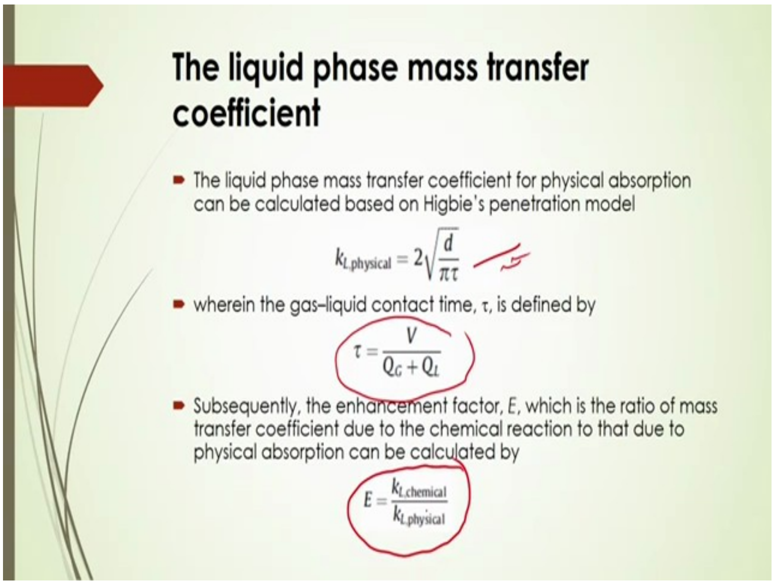

## The liquid phase mass transfer coefficient

- The liquid phase mass transfer coefficient for physical absorption can be calculated based on Higbie's penetration model

$$k_{L,\text{physical}} = 2\sqrt{\frac{d}{\pi\tau}}$$

- wherein the gas–liquid contact time, $\tau$, is defined by

$$\tau = \frac{V}{Q_G + Q_L}$$

- Subsequently, the enhancement factor, $E$, which is the ratio of mass transfer coefficient due to the chemical reaction to that due to physical absorption can be calculated by

$$E = \frac{k_{L,\text{chemical}}}{k_{L,\text{physical}}}$$

Now liquid mass transfer also you can access by the penetration model. This is your penetration model as per physical liquid phase mass transfer coefficient, individual mass transfer coefficient that is

$$k_{L,\text{physical}} = 2\sqrt{\frac{d}{\pi\tau}} \quad .$$

Where in this case d is that size of the bubble diameter of the bubble and $\pi$ and $\tau$ is the residence time there. And also where in the gas liquid contact time or residence time you can say that is defined by this equation here.

$$\tau = \frac{V}{Q_G + Q_L}$$

That can be calculated where V is the volume of the reactor that is gas liquid mixer volume and $Q_G$ is the volumetric flow rate of the gas and $Q_L$ is the volumetric flow rate of the liquid. If you know these things then you can easily calculate the gas liquid contact time. Once you know that gas liquid contact time and also size of that bubble or slug inside the channel and equivalent diameter of the bubbles or liquid slug's then you can easily calculate what will be the $K_L$ there.

Once you know that $K_L$ in chemical process and also $K_L$ in physical process than what should be the enhancement factor that can be calculated based on this equation there.

$$E = \frac{k_{L,\text{chemical}}}{k_{L,\text{physical}}}$$

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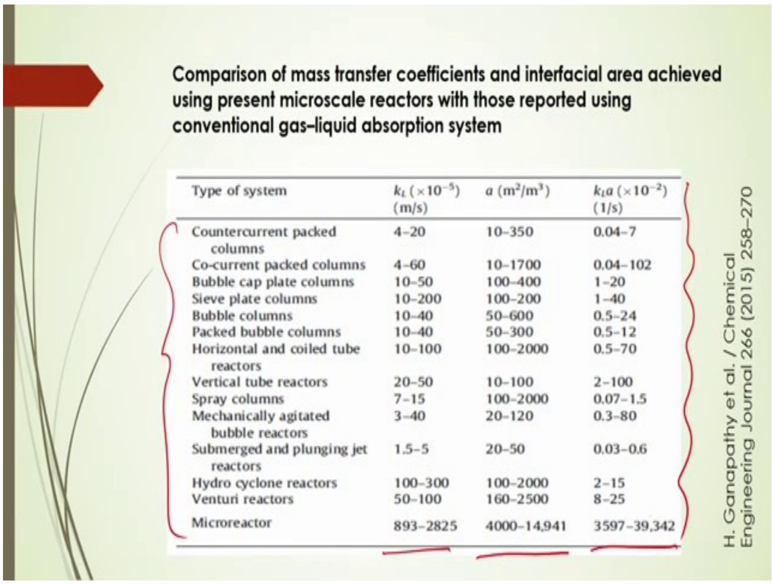

Comparison of mass transfer coefficients and interfacial area achieved using present microscale reactors with those reported using conventional gas–liquid absorption system

| Type of system | $k_L$ ($\times 10^{-5}$) (m/s) | $a$ ($m^2/m^3$) | $k_La$ ($\times 10^{-2}$) (1/s) |
|---|---|---|---|
| Countercurrent packed columns | 4–20 | 10–350 | 0.04–7 |
| Co-current packed columns | 4–60 | 10–1700 | 0.04–102 |
| Bubble cap plate columns | 10–50 | 100–400 | 1–20 |
| Sieve plate columns | 10–200 | 100–200 | 1–40 |
| Bubble columns | 10–40 | 50–600 | 0.5–24 |
| Packed bubble columns | 10–40 | 50–300 | 0.5–12 |
| Horizontal and coiled tube reactors | 10–100 | 100–2000 | 0.5–70 |
| Vertical tube reactors | 20–50 | 10–100 | 2–100 |
| Spray columns | 7–15 | 100–2000 | 0.07–1.5 |
| Mechanically agitated bubble reactors | 3–40 | 20–120 | 0.3–80 |
| Submerged and plunging jet reactors | 1.5–5 | 20–50 | 0.03–0.6 |
| Hydro cyclone reactors | 100–300 | 100–2000 | 2–15 |
| Venturi reactors | 50–100 | 160–2500 | 8–25 |
| Microreactor | 893–2825 | 4000–14,941 | 3597–39,342 |

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So there are some individual mass transfer coefficient and interfacial area and overall mass transfer coefficient for different mixing devices here as given by Ganapathy et al. 2015. As per that and based on this table you will have that this micro-reactor will give you very high mass transfer coefficient even high interfacial area when individual mass transfer coefficient there compared to the others. So that is why this micro channel based micro-reactor, why it is important for the process intensification there?

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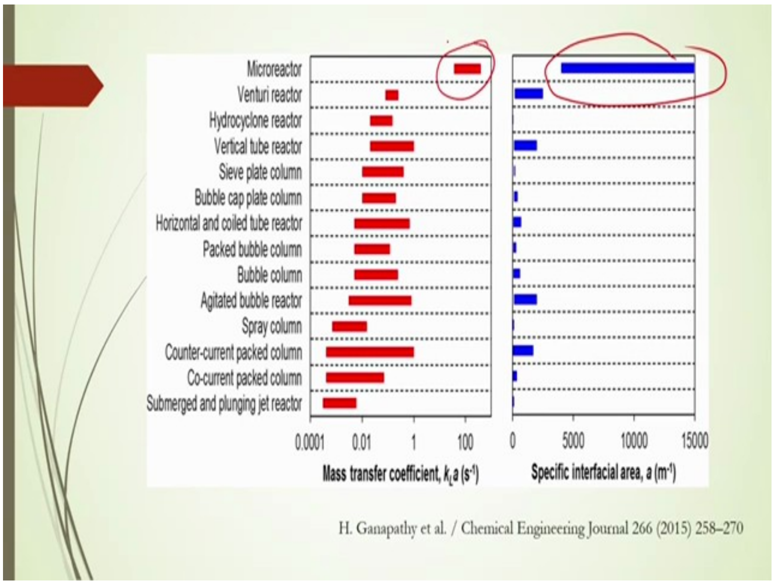

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And these are some other comparison of that micro-reactor with the different mixing devices. This case you will see that very high specific interfacial area you can get for the micro-reactor and also mass transfer coefficient there.

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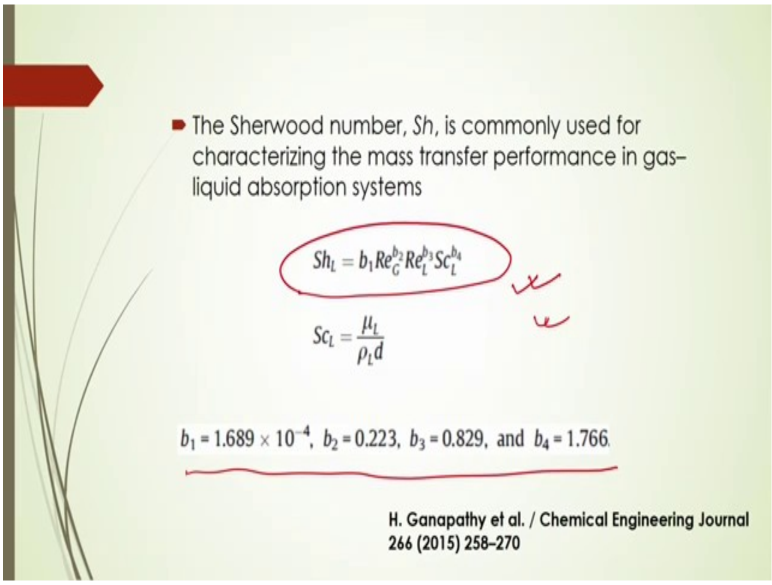

- The Sherwood number, *Sh*, is commonly used for characterizing the mass transfer performance in gas–liquid absorption systems

$$Sh_L = b_1 Re_G^{b_2} Re_L^{b_3} Sc_L^{b_4}$$

$$Sc_L = \frac{\mu_L}{\rho_L d}$$

$b_1 = 1.689 \times 10^{-4}$, $b_2 = 0.223$, $b_3 = 0.829$, and $b_4 = 1.766$

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And based on the different operating para meters operating variables then you can also have a correlation to calculate or predict that mass transfer coefficient. Based on this correlation as suggested by Ganapathy et al. there in 2015 that you can predict that mass transfer coefficient in the channel by this correlation

$$Sh_L = b_1 Re_G^{b_2} Re_L^{b_3} Sc_L^{b_4}$$

$$Sc_L = \frac{\mu_L}{\rho_L d}$$

where here $b_1$, $b_2$, $b_3$, $b_4$ are the coefficients and this coefficients are given here in the slides. so based on this equation you can easily calculate what should be the mass transfer coefficients for a particular operating conditions.

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## Further reading......

- David Reay, Colin Ramshaw, and Adam Harvey, Process Intensification: Engineering for efficiency, sustainability and flexibility, IchemE, 2nd edition, 2013, Elsevier.
- Kamelia Boodhoo and Adam Harvey. Process Intensification for Green Chemistry Engineering Solutions for Sustainable Chemical Processing, Edited by Kamelia Boodhoo and Adam Harvey , School of Chemical Engineering & Advanced Materials Newcastle University, UK. Willey, 2013
- Juan Gabriel Segovia-Hernández, Adrián Bonilla-Petriciolet Editors, Process Intensication in Chemical Engineering Design Optimization and Control, Springer, 2016.
- https://www.sciencedirect.com/science/article/pii/S1385894714016386
- https://www.sciencedirect.com/science/article/pii/S1385894706005092
- https://www.sciencedirect.com/science/article/pii/S030193220200037X
- https://www.sciencedirect.com/science/article/pii/S1385894717315462

So I will suggest to go further about these through this references to get more about that hydrodynamics and mass transfer characteristics of two phase even not only the gas liquid when liquid-liquid system also you can have more information about that. So I think you have here that compact knowledge of that channel, hydrodynamics and also what is that mass transfer characteristics.

So this is very preliminary idea of mass transfer as well as hydrodynamics there in the channel based reactor. So it depends on how you are actually developing your micro channel based reactor. And once you developed a micro channel based reactor you can study. What should be that mass transfer coefficient what would be the effectiveness factor? What should be the fictional pressure drop? How that mixing characteristic can be effective based on pressure drop frictional pressure drop that you can analyze?

So that is why is basic preliminary idea of mass transfer even hydrodynamics characteristics are required for the further development of the micro-mixture micro channel based micro-reactor for the chemical engineering process intensification, so I that will suggest to go further about that for your further more information, better understanding of that. So thank you for your attention.