Adiabatic Two-Phase Flow and Flow Boiling in Microchannel

Prof. Gargi Das
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

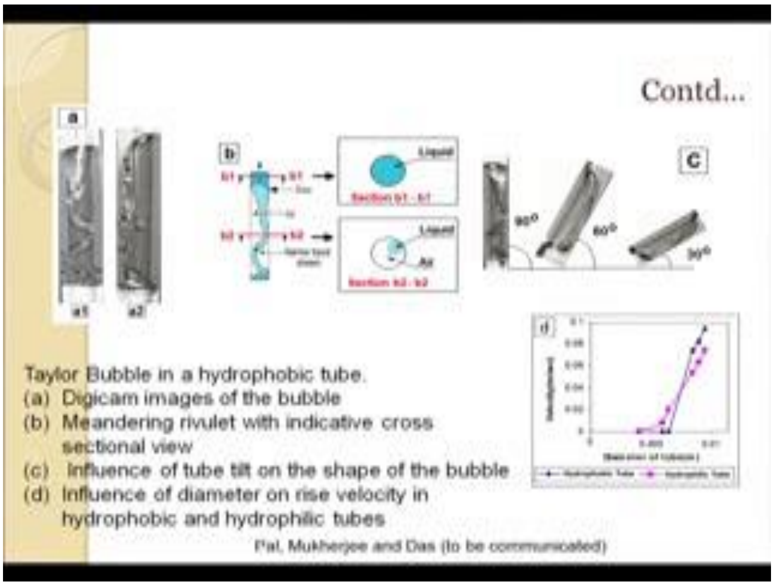
Lecture – 16

Void Fraction Characteristic Mini and Micro Channel

Well, welcome to the last week or this particular lectures series and this particular week we are we will specific specifically dealing with the different analytical modules which are available rather which are widely used in to this flow and in macro systems.

But and how they can be applied to micro systems, but before that there is a small portion which I could not complete last week, but I am very tempted to share it with you. We will be discussing that particular portion regarding the effect of involve wet ability on to phase hydrodynamics and then we will be shifting to the other hydrodynamic parameters.

(Refer Slide Time: 01:08)



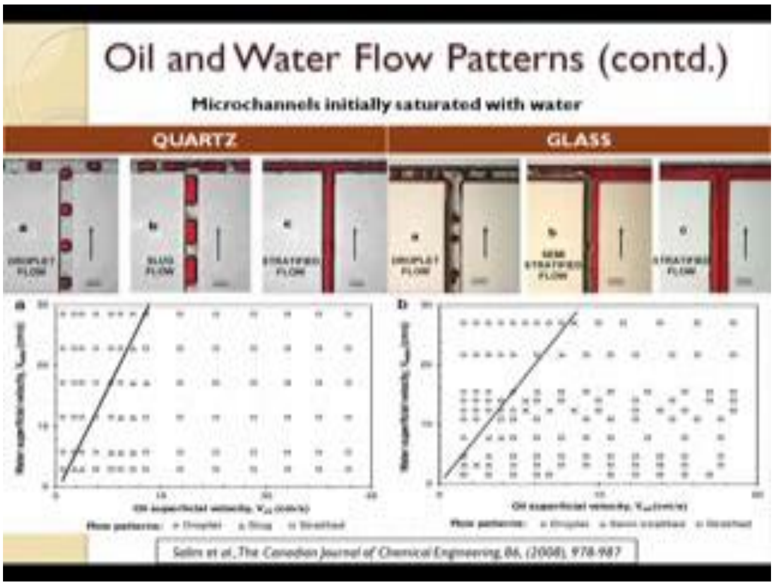
Contd...

Taylor Bubble in a hydrophobic tube.

(a) Digicam images of the bubble
(b) Meandering rivulet with indicative cross sectional view
(c) Influence of tube tilt on the shape of the bubble
(d) Influence of diameter on rise velocity in hydrophobic and hydrophilic tubes

Pal, Mukherjee and Das (to be communicated)

(Refer Slide Time: 01:09).

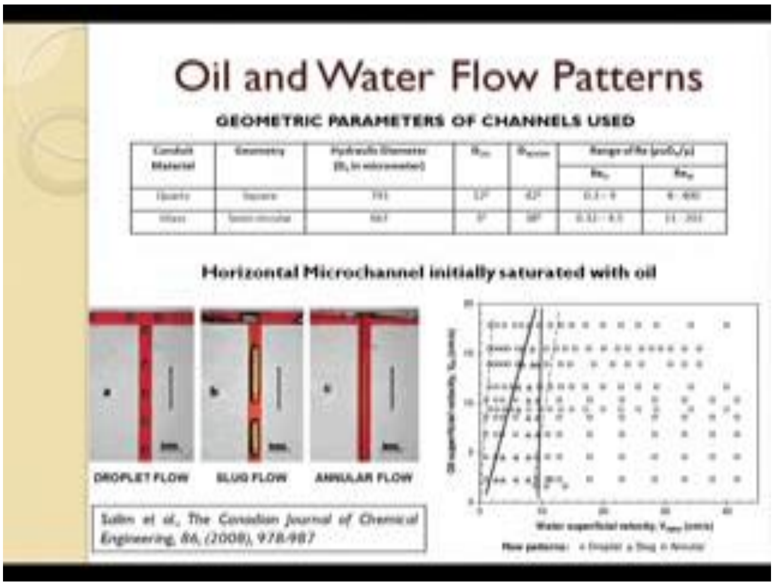


Oil and Water Flow Patterns (contd.)

Microchannels initially saturated with water

Salim et al., The Canadian Journal of Chemical Engineering, 86, (2008), 978-987

(Refer Slide Time: 01:11)



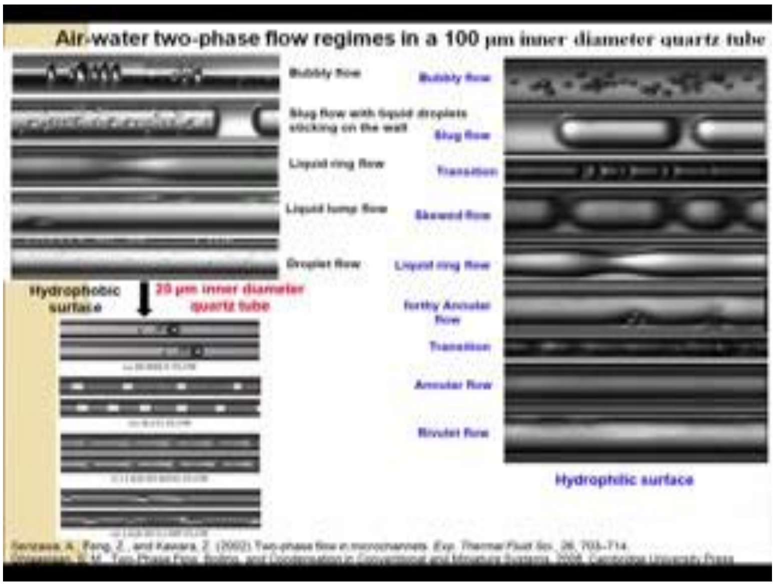
Oil and Water Flow Patterns

GEOMETRIC PARAMETERS OF CHANNELS USED

Horizontal Microchannel initially saturated with oil

Salim et al., The Canadian Journal of Chemical Engineering, 86, (2008), 978-987

(Refer Slide Time: 01:12)


Air-water two-phase flow regimes in a 100 μm inner diameter quartz tube

Serizawa, A., Feng, Z., and Kawara, Z. (2002) Two-phase flow in microchannels. Exp. Thermal Fluid Sci., 26, 703–714.

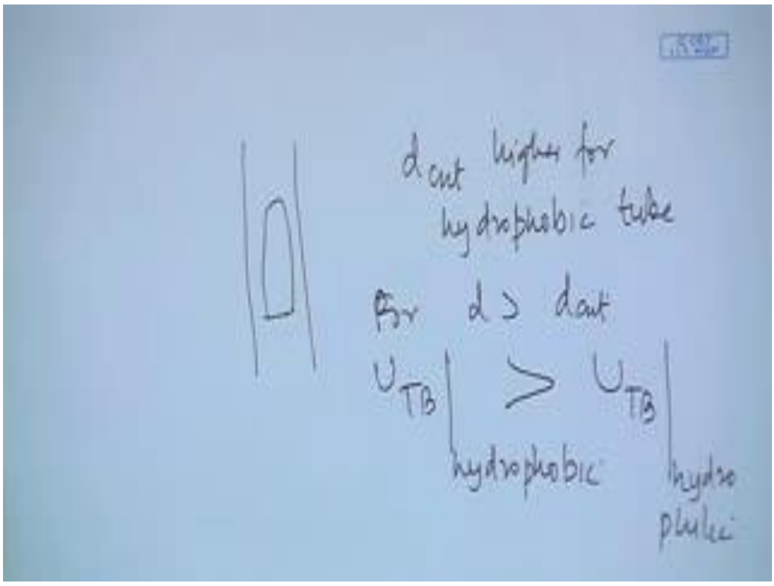
.

Now, as I discussed in the last class if you remember I have discussed lot about in valve wet ability characteristics and we found that when the pipe was hydrophobic naturally the liquid did not want to wet the pipe valence and large number of other flow patterns they emerged.

And they evaluate flow pattern came up now just to demonstrate that in a better way we performed our favorite Taylor bubble experiments in a hydrophobic tube where the contact angle was about 110 to 115 degrees. And we found that very interesting metamorphoses of the Taylor bubble took place in this particular case if you observe the Taylor bubbles we find that the Taylor bubbles they are excess symmetric bullet shaped in the circular type and the same type with the same dimension.

When it was a glass pipe infatuate perform this experiments and the same type when it was coated with silent to the contact angle of around 115 degrees we found that the shape of the Taylor bubble underwent quiet an interesting change firstly, if you remember in the previous case we had a hemispherical known in the we have shown it a number of times.

(Refer Slide Time: 02:34)



d_{cut} higher for hydrophobic tube

For $d > d_{cut}$

$U_{TB}\Big|_{hydrophobic} > U_{TB}\Big|_{hydrophilic}$

It was something of this sort it had a hemispherical nose and a flat tail in this particular case we find that at the top it under goes a transformation and develops in to a corner sort of a thing unlike, the nice rotationally symmetric shape in a hydrophobic pipe. And at the same time we find that the tip it shifts from the liquid center of the liquid axis to 1 end and immediately it begins to expand to occupy the maximum area between the bubble and the volume.

Therefore, what happens the first thing is there is a change in the nose of the shape and it automatically tells us that definitely then the rise velocity should also be changing in the particular case we do not have a nice rotationally symmetric case symmetric bubble in this case we find that it has it developed in to a corner and it has shifted from the tube axis to 1 particular wall where it immediately touches the wall and then immediately tries to spread out.

And at the same thing what happens continues annual liquid fill which was there we find that the liquid fill now it is no longer continuous it gets distracted and the liquid is compelled to flow down and for rivulet along the bubble surface.

The rivulet which I was talking about it also assumes this particular shape we observe the reb rivulet it emerges from the tip of the corner it changes its coats randomly and it produces a curious meandering pattern which is somewhat free to somewhat similar to the free end of a garden host.

Is not it if you observe it you will find we do not find annular fill you find that the liquid fill as the bubble it comes in contact with the tube wall the liquid fill it falls down as a meandering pattern somewhat like when you when you water the garden the water the way it comes out from a garden hose it usually takes up that particularly shape and generates a moving 3 phase contact line which makes an angle with respect to the overall duration of propagation of the bubble.

While, the bubble is flowing up we find that the 3 phase contact line it is not in the direction of that motion, but it makes an angle with respect to the overall deduction of motion and it continuously changes it is orientation as the bubble moves vertically up.

And we find that this particularly meandering tendency it is maximum for the vertical case as we tell it that you we notice that the liquid it just has one predominantly one particular space to flow down so therefore, as the tilt increases we find that the meandering tendency that also decreases with time.

Interestingly, if we try to find out the rise velocity of bubble what we find we find that in a hydrophobic tube the initially when the tube diameter is very small as we all know I have already discussed that for any particular tube, there is a critical diameter below which the bubble does not rise.

Now this diameter is the function of (Refer Time: 06:43) this diameter is different for kerosene bubble, it is different for a air bubble, it is different from some other liquid bubble. It is dependent upon the properties of the confining fleet and the rising fleet.

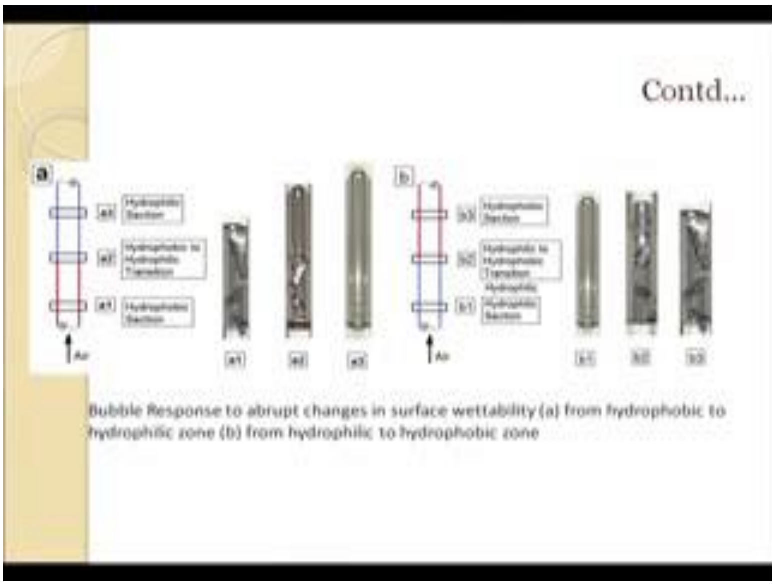
Naturally we know that there is some particular critical bubble sorry tube diameter bellow which the bubble remains stationery does not rise. And this particular critical diameter it is different for a air bubble and it is different for a kerosene bubble and this is the function of adverse number several researches have suggested different critical adverse number at which bubble rises.

Now, we have observed that the critical diameter is a higher for a hydrophobic pipe right because, it is quite natural because when will the liquid sorry when will the bubble rise it will rise by the down word displacement of liquid and naturally the liquid if it wets the wall the displacement becomes easier.

Therefore, when it does not wet the wall naturally it is very difficult for the bubble to pierce the liquid and rise and force the liquid to fall as a fill. As this is evident from this particular graph if you observe we find that for a hydrophobic pipe the critical diameter is lower as compare sorry for a hydrophobic pipe we find that the critical diameter it is higher as compared to hydrophilic pipe or in other words the bubble rises due to at higher diameter or begins to rise with buoyancy at a higher diameter in a hydrophobic as compared to a hydrophilic pipe. But once, it begins it to rise the rise velocity in hydrophobic pipe is higher is compared to rise velocity in a hydrophilic pipe.

Therefore, there are 2 things which need to the kept in mind in this particular case one is D cratic crate higher for hydrophobic pipe. Therefore, a bubble will raise hydrophobic tube and other words the bubble will rise or begin to rise at a higher diameter when the tube is hydrophobic. But for D greater then D crate UTB in a hydrophobic tube is greater than UTB in a hydrophilic tube.

(Refer Slide Time: 09:47)



Contd...

Bubble Response to abrupt changes in surface wettability (a) from hydrophobic to hydrophilic zone (b) from hydrophilic to hydrophobic zone

Along, with that for we wanted to do was we also wanted to see height of bubble response to abrupt changes in type fit ability for this what we did we took a pipe and we had the portion of the pipe was salienced as a result of which the first half of that tube was hydrophilic the second half was hydrophobic and vice-versa.

We performed experiments with the hydrophobic section presiding, a hydrophilic section and a hydrophilic section presiding a hydrophobic section and very interestingly what did we observe we found that when it was rising through the hydrophilic section the bubble assumed the nice rotationally symmetric shape.

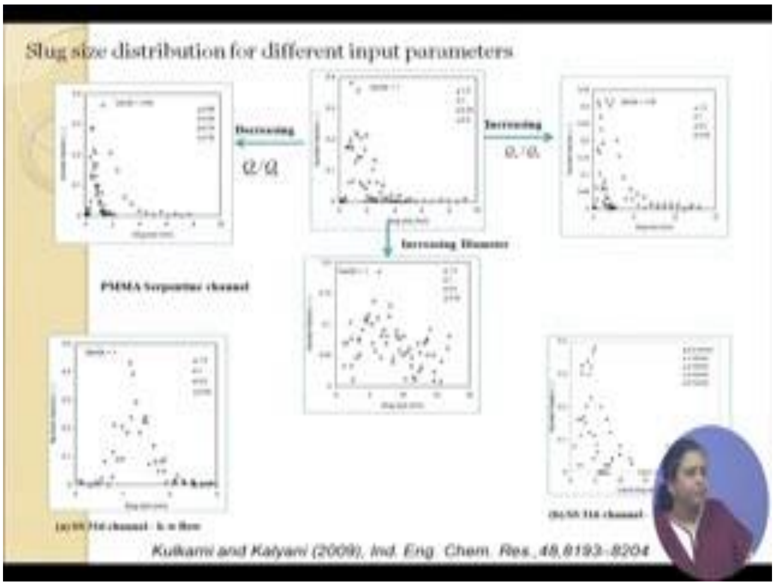
Then, moment it enter the hydrophobic section the first change occurred in the nose because the nose first came in contact with the hydrophobic volt immediately movement it entered the nose initially it was trying to maintain it is spherical shape the it initially did not warn to rapture this spherical shape. But the liquid it was unable to maintain the continuous fill.

The liquid meandering it is started and gradually the nose with this liquid meandering as it gradually travel towards the top the nose was pushed to 1 side and it form the open co typical open corner shape that we have observed previously.

On the other hand when it first was raising through hydrophobic section the typical shape of hydrophobic section was there and the movement it entered the hydrophilic section immediately the nose it took up a the semicircle and hemispherical shape while the fill continued to meandered in the lower portion and then gradually as the bubble progressed completely into hydrophilic section of (Refer Time: 11:50) we find that it resumed its rotationally symmetric shape which it has all other fit which we are familiar with.

Therefore, this was 1 particular thing which I thought I should be sharing with you.

(Refer Slide Time: 12:04)


Slug size distribution for different input parameters

Kulkarni and Kalyani (2009), Ind. Eng. Chem. Res., 48,8193-8204

.

And the other thing also which I would like to discuss in very brief is as we all know that in micro channels flat flow is predominant. I thought we should be also be knowing that in slug flow occurs in a particular micro channel how the slug parameters get influenced with wall wet ability sorry candid diameter and you are differently ratios of the water and the kerosene phase this particular the as well as with water and the air phase is.

Therefore, in this particular case we find that more or less experiment have been done with oil water and air water and the slug parameters they were measured and it was observed that the slug parameters the distribution of thus of the slug parameters they were a then plotted and the different slug characteristics they were then observed in this particular case. Very briefly I will try to just show the situation suppose we take the situation for equal flow ration of the 2.

What we do find for equal flow ratio we find that more or less this the majority of the slugs they had the same size and there were very few slugs which are larger than the average size right. But when we increase the diameter we find that this particular peaked character in this appears and the slug size varies over larger size ranges which suggest that with increase in diameter tuning of the different slug parameters becomes difficult in this particular case.

Again, we find that for QW by QK if W is water and K is kerosene we find that when we come to lower QW by QK we find there is a more remarkable influence of water velocity. In this paragraphs what we have done we have plotted then for different flow ratios and for each flow ratios the legions show different water velocities we have plotted then for QW by QK is equal to 1 and less than 1 and greater than 1 in a polyethylene mitaxilate serpentine channel.

And we have also rather not we I am very sorry this particular research they have also performed experiments in a stainless steel channel they are performed experiments in a PMMA in a serpentine channel for 2 different diameters. And apart from doing experiments on water kerosene they have also done experiments on air water flow from these experiments what we find is that when, QW by QK the flow ratio of water and kerosene is not equal to one the influence of flow rate is much more drastic as you can observe from these 2 graphs

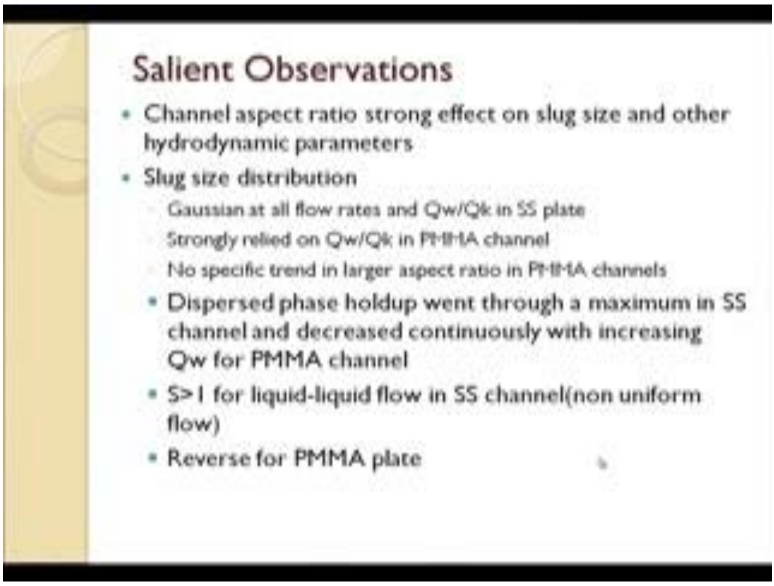
We find that for each of these we find that the influence of flow rate is much more drastic as the curves we if you follow the curves from different flow rate whereas, in for QW by QK is equal to 1 it is more or less the flow rate the influence of flow rate is not so drastic and so we increase the pipe diameter we find that the slug sizes can vary over the wide range.

Therefore, more of this viscosity is not maintained in this particular case very interestingly if we instead of PMMA serpentine channel we come to a stainless steel channel we find that the distributions becomes more or less Gaussian in nature. And in this particular flow the influence of your flow parameters rather the flow rate it is not as pronounced as this particular case.

And again we find that if we come to air water flow for and this is one more thing if we are working with stainless steel conduits we find that the general slug size is smaller as compared to the PMNA conduit. This is something very interesting I should note that this these stainless steel channels they are competitively more hydrophilic as compare to PMMA channels and we find that the slug sizes in this case is smaller because the wetting characteristics this strongly inflows this slug size and therefore, this shows that the effective interfacial area available for mass transport increases for the stainless steel as compare to the PMMA channel.

This is 1 particular interesting thing, but just by manipulating the wet ability we can actually change the interfacial area available for different mass transport process the other thing is as we increases diameter we find that the size various over the white range and also along with that we are observed that lower internal circulations occurs for the higher type diameter which explains by the mass transfer decreases as we increase the type diameter.

(Refer Slide Time: 18:06)



Salient Observations

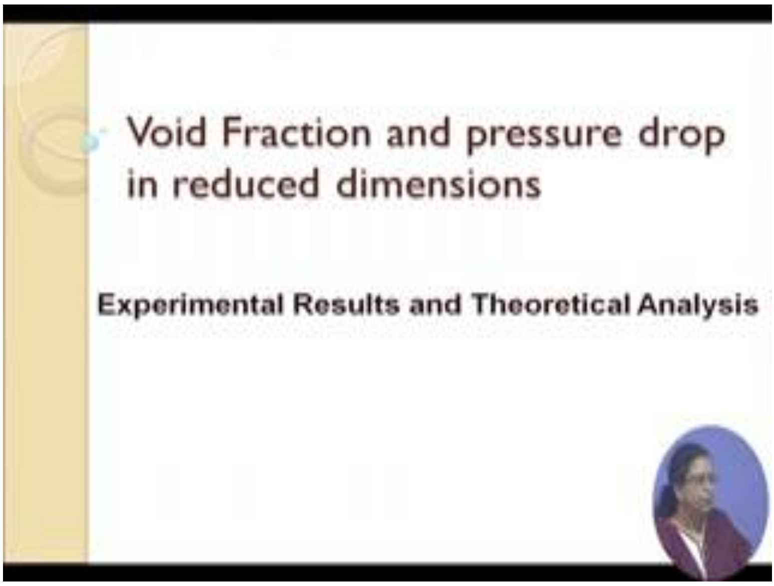
- Channel aspect ratio strong effect on slug size and other hydrodynamic parameters
- Slug size distribution
  - Gaussian at all flow rates and Qw/Qk in SS plate
  - Strongly relied on Qw/Qk in PMMA channel
  - No specific trend in larger aspect ratio in PMMA channels
  - Dispersed phase holdup went through a maximum in SS channel and decreased continuously with increasing Qw for PMMA channel
  - S>1 for liquid-liquid flow in SS channel(non uniform flow)
  - Reverse for PMMA plate

.

And in conclusion if we need to discuss the results the conclusions will be firstly, that the channel aspect ratio it has strong effect on slug size and other hydrodynamic properties. We find that the slug size distribution its more or less Gaussian at all flow rates and that all QW by QK ratio in a hydrophilic stainless steel pipe while in a PMMA channel it is strongly relied on the ratio of QW by QK and we also found that there was no specific trend in the large aspect ratio PMMA channel.

Further we found that there the dispersed phase holdup if holdup is computed from these particular distributions we found that the dispersed phase holdup it went through a maximum in the stainless steel channel but decreased continuously with increasing QW for a PMMA channel and the slip ratio for liquid flow that is greater than one for stainless steel channel and the reverse happen for PMMA channels.

(Refer Slide Time: 19:24)



Void Fraction and pressure drop in reduced dimensions

Experimental Results and Theoretical Analysis

.

Now this portion of the information I wanted to share with you because this would give up sufficient insight into have to engineer the void surface and obtain the not only the flow pattern of our interest, but also to modify the slug parameters in order to increase the interfacial area even if an that same flow pattern is existing right.

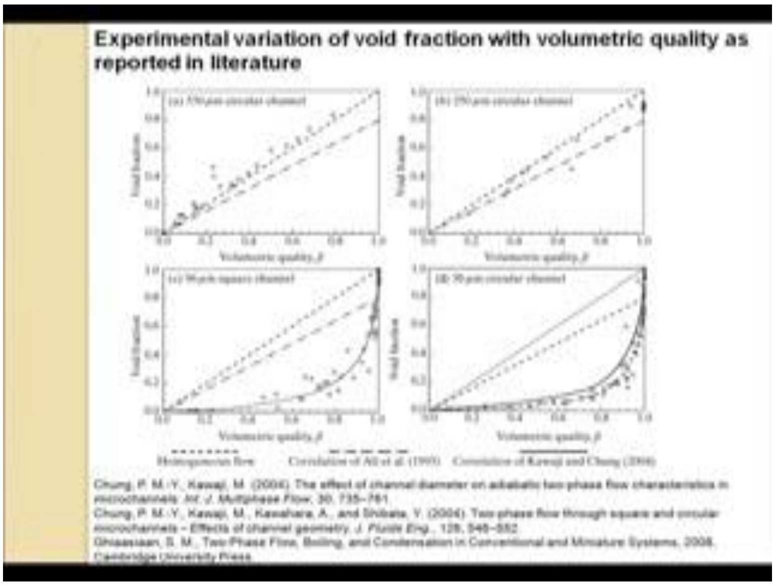
Because, we found that inter facially ideate increased at when we used stainless steel channel and then therefore, by playing with all these things we can attempt to rather to increase the transport properties just by changing the conduit matter material in an intelligent manner. Well, this completes our discussion on the effect of operating parameters on the flow morphology it was quite long at almost a week long discussion I hope you have not been much bored with it.

Now we come about to discuss the effect of operating parameter on void fraction and pressure drop. Now in this regard I would like to remind you that what fraction depends upon the flow morphology or the flow patterns.

Therefore, we find that the influence of input parameter on void fraction is more intimately related to the change of flow patterns then to anything else for example, what fraction it has one particular sought of a relationship with say increase in gas and liquid velocity at we find that the relationship changes with flow pattern more than the superficial velocity as expected what fraction will increase with gas superficial velocity it will decrease with liquid superficial velocity if we are dealing with air water systems.

But the nature of the curves I expected to be different for different flow patterns and the influence of operating parameters one void fraction it primarily depends upon how they influence the flow morphology between the phases.

(Refer Slide Time: 22:11)



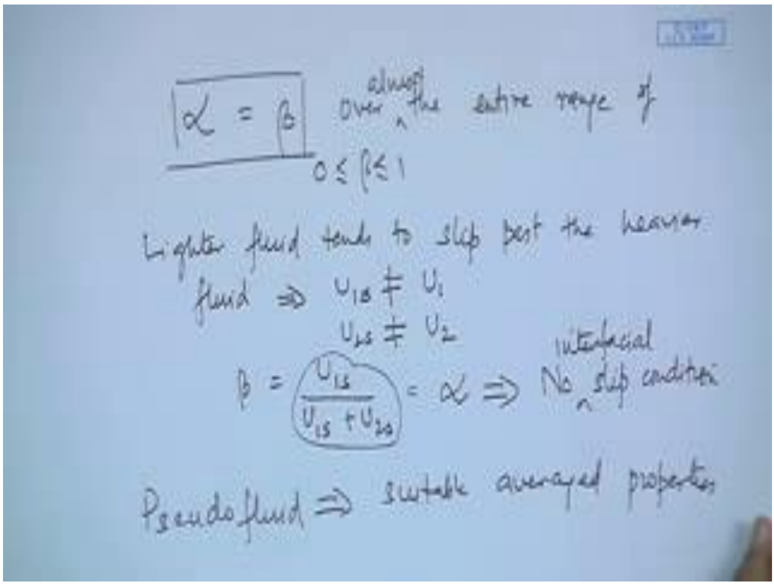
Experimental variation of void fraction with volumetric quality as reported in literature

Chung, P. M.-Y., Kawaji, M. (2004). The effect of channel diameter on adiabatic two-phase flow characteristics in microchannels. *Int. J. Multiphase Flow*, 30, 735–761.
Chung, P. M.-Y., Kawaji, M., Kawahara, A., and Shibata, Y. (2004). Two-phase flow through square and circular microchannels – Effects of channel geometry. *J. Fluids Eng.*, 126, 546–552.
Ghiaasiaan, S. M., Two-Phase Flow, Boiling, and Condensation in Conventional and Miniature Systems, 2008, Cambridge University Press.

Now let us see more or less quite a good number of work has been performed and the general characteristics which have been observed number of researches are done there are some contradictory results, but the generally trends I would like to discuss this trend it gives you an idea regarding the how void fraction it behaves with the inlet volumetric fraction or in other words as I already mentioned in the nomenclature how alpha varies with beta and how this variation again depends upon the channel dimension in the micro domain.

Now if you observe in this particular part we find that for the larger channel we find that more or less the date all experimental data they are lying on the 45 degrees line which shows that for completely larger channels alpha equals to beta over the almost be I should write over almost the entire range of beta ranging from zero to one this is quite evident.

(Refer Slide Time: 23:10)



$\boxed{\alpha = \beta}$ over always the entire range of $0 \le \beta \le 1$

Lighter fluid tends to slip past the heavier fluid $\Rightarrow U_{1s} \neq U_1$

$U_{2s} \neq U_2$

$\beta = \frac{U_{1s}}{U_{1s} + U_{2s}} = \alpha \Rightarrow$ No interfacial slip condition

Pseudofluid $\Rightarrow$ suitable averaged properties

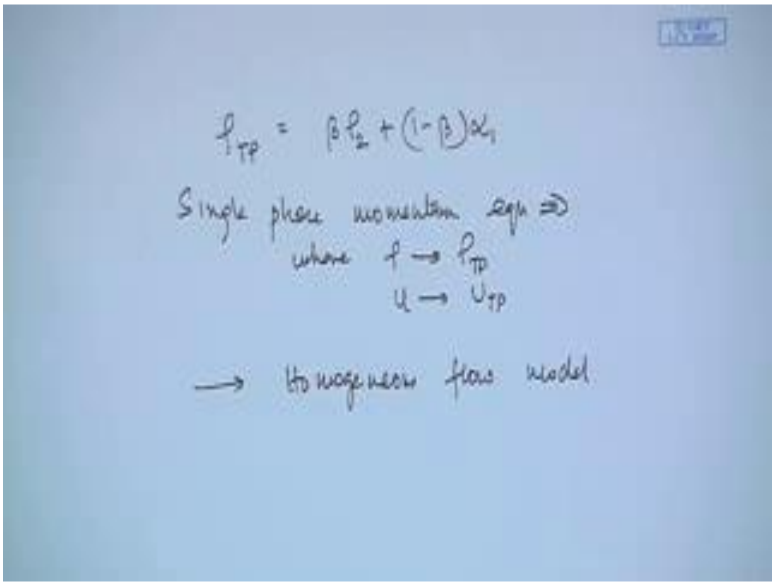
.

Now, when we see that alpha equals to beta what does it automatically imply it implies that the incisive and inlet compositions are the same now if you again go back to my initial lecture what did I say that when the lighter fluid tends to slip past the heavier fluid if you remember I have mentioned it is in the slide of my introductory lecture and when the lighter fluid tends to slip past the heavier fluid naturally what happens the inlet velocity of any particular fluid which is defined as the superficial velocity will not be equal to the incisive velocity for either phase 2 or phase 1 right.

And we have defined beta as U1S by U1S plus U2S. Now from this particular graph if you find that alpha is almost equal to beta then what does it imply, it implies but more or less alpha can also be predicted from the inlet condition and this hints at a no slip condition or rather a better way to this slide is no interfacial slip condition.

Therefore, if such a condition exists it means that the 2 fluids are flowing as a single unit or the 2 fluids are flowing as a pseudo fluid with suitable average properties. Therefore, if they have to develop a model for this particular fluid what we can do we can assume that 2 fluids to be flowing at the same particular velocity.

(Refer Slide Time: 25:57)



$\rho_{TP} = \beta\rho_2 + (1-\beta)\alpha_1$

Single phase momentum eqn ⇒

where $\rho \rightarrow \rho_{TP}$

$u \rightarrow u_{TP}$

→ Homogeneous flow model

.

And we can just say that the density of the fluid rho TP this can be determined from the inlet void fraction in this particular form and therefore, if you remember the single phase momentum equation that I have written down, that same particular single phase momentum equation should be applicable in this particular case where rho is replaced by rho TPU is replaced by UTP and therefore, this particular model is known as the homogeneous flow model.

Where we assume that true fluids to be completely mixed and flowing at the same axial velocity and then in this case the single phase momentum equation is applicable with suitable average properties.

We find that for the 2 larger pipe dimension more or less this particular equate this particular homogeneous model is suitable, but the deviation from the homogeneous flow model gradually increases as the pipe dimension decreases here alpha is almost equal to beta for most of the cases here also it is equal to beta, but the deviations particularly at low beta begins to increase.

But if you further reduce the channel dimension we find that the variation changes completely in this particular case we find that alpha is in no way equal to beta and the curve suggests a very strong influence of slip which needs for the discussion we will be continuing our discussion on the void fraction characteristics as well as on the pressure drop characteristics in our subsequent lectures and will be in very brief we will discussing the homogeneous flow model will be incorporating the slip in the homogeneous flow model in order to make it little more robust and will discuss what are the different models or rather how this particular models can be applied to micro channel flow in our subsequence lectures.

Thank you very much.