Adiabatic Two-Phase Flow and Flow Boiling in Microchannel

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Lecture – 23
Flow Boiling in Microchannels

Well hello everybody. Now in this particular case I would like to tell you during the entire course of my lecture series I had touched boiling on several occasions initially if you remember when, I was dealing with macro channel flow patterns, I had shown you air water flow patterns, then I had shown you steam water flow patterns when liquid sub could liquid or liquid at a saturation temperature was been introduced in a heated channel.

After, that when you are discussing micro channels, I was trying to giving the criteria for defining micro channels, then there was a one criteria based on hydraulic diameter there was one criteria based on suitable values of some important dimensional numbers namely the bond number, and the confinement number, and then there was 1 other criteria based on bubble departure diameter which again was a criteria pertaining to flow boiling in micro channels.

After that of course divide during the discussion of the flow patterns and the effects of operating parameters on flow pattern, it was predominantly confined to adiabatic gas liquid flows and also for liquid flows then if I came to the analysis part, I had I had first discussed the general analysis and then I had given expressions and formula which are applicable to boiling 2 phase flow as well as to adiabatic 2 phase flow.

Now before I end this lecture series I would like to just discuss some salient or some unique features of boiling 2 phase flow in micro channels compare to macro channels and also boiling 2 phase flow in micro channels, compare to adiabatic 2 phase flow in micro channels. So, we will present a brief discussion on this and then you would be ended this particular lecture series.

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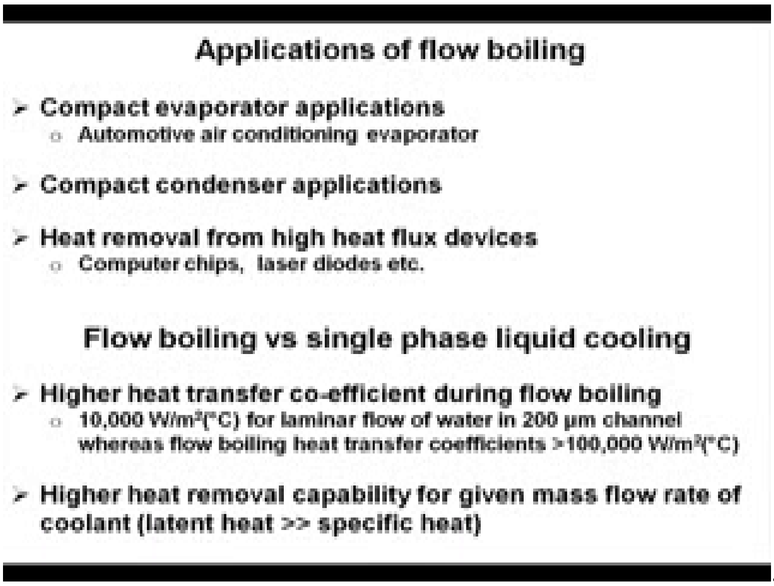

Now, well before we proceed it is very important to know the applications of flow boiling and here I would you already know that I had already discussed certain things that they are applicable in compact evaporator applications and particularly in automotive air conditioning evaporator then, for compact condenser applications and then there is a there was a huge application for due to heat removal from high heat flux devices.

Now, this is the most important application due to fetch flow boiling in micro channels as been receiving lot of attention in their recent years. Now why does flow boiling it is more attractive as compare to single phase liquid cooling; there are 2 reason for it the first reason is definitely even for single phase flow through micro channels, we find that the heat transfer coefficient is quite high; it is around say ten thousand watt per meter square for laminar flow of water in 200 micro meter channel.

But we find that for flow boiling the heat transfer coefficients are many times higher as is evidence from the data I have provided here. The other thing is if you observed the then will know that the heat removal capability for a given mass flow rate of the coolant is much higher if the heat removal occurs by Latented as compared to sensible heat.

So, therefore, these are the reasons why flow boiling as received much more attentions recent years.

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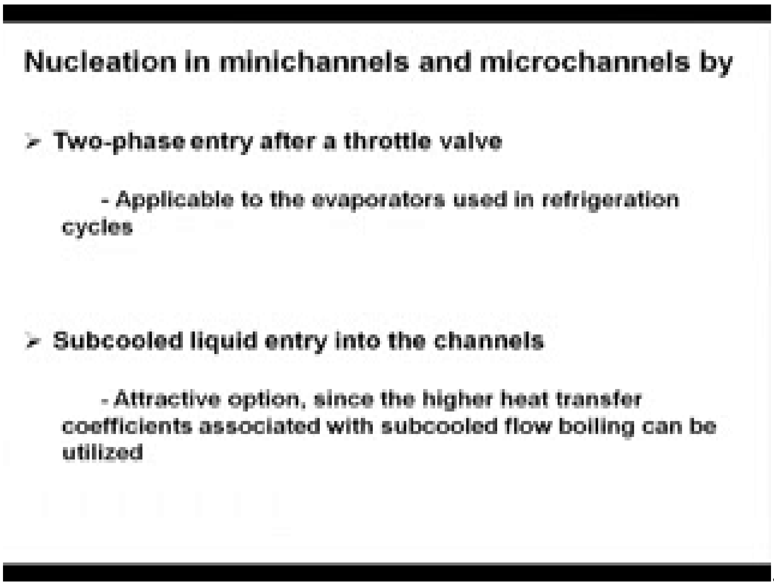

And we find that for flow boiling in many channels and micro channels, the predominant mechanism is by nucleation and if we observed we find that their 2 ways in fetch flow boiling can be expected to be implemented in mini and micro channels. One is 2 phase entry after throttle valve sorry 2 phase entry after throttle valve now very frequently this is particularly applicable to evaporators in refrigeration cycles n now the throttle valve prior to the evaporator it can be designed to provide sub cooled liquid entry. But more commonly it provides a 2 phase entry with the quality bearing between 0 and 0.1, this of course as got it is problems.

The first problem is the distribution of the 2 phase mixture at inlet headers. So, therefore, this poses to be a major obstacle in achieving stable operation, but any how this is practiced more or less. The other thing is subcooled liquid entry into the channels and then gradually it is starts boiling due to the heat features being applied to the channel this is off course an attractive option, because in this case the higher heat transfer coefficients associated with subcooled flow boiling can be utilized in these cases.

But for both the both the mechanisms of initiating flow boiling in small diameter channels for both of them the babble nucleation are an important consideration. It is also true for 2 phase entry because in this particular case also we find that slat flow prevails and nucleation occurs in the liquid slugs and this is an important parameter fact regulating the flow boiling in these particular cases.

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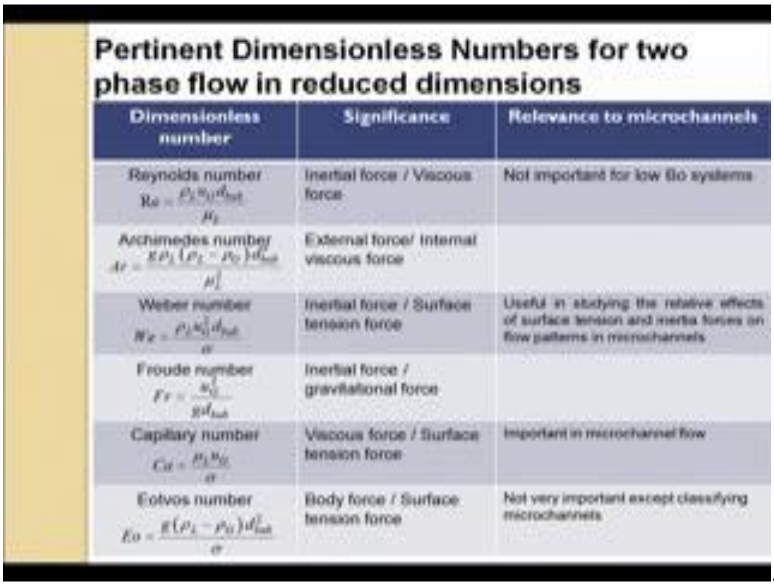

Pertinent Dimensionless Numbers for two phase flow in reduced dimensions

Dimensionless number	Significance	Relevance to microchannels
Reynolds number $Re = \frac{\rho_L u_G d_{hyd}}{\mu_L}$	Inertial force / Viscous force	Not important for low Bo systems
Archimedes number $Ar = \frac{g \rho_L (\rho_L - \rho_G) d_{hyd}^3}{\mu_L^2}$	External force/ Internal viscous force	
Weber number $We = \frac{\rho_L u_G^2 d_{hyd}}{\sigma}$	Inertial force / Surface tension force	Useful in studying the relative effects of surface tension and inertia forces on flow patterns in microchannels
Froude number $Fr = \frac{u_G^2}{g d_{hyd}}$	Inertial force / gravitational force	
Capillary number $Ca = \frac{\mu_L u_G}{\sigma}$	Viscous force / Surface tension force	Important in microchannel flow
Eotvos number $Eo = \frac{g(\rho_L - \rho_G) d_{hyd}^2}{\sigma}$	Body force / Surface tension force	Not very important except classifying microchannels

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Now, just as I discussed for adiabatic cases the pertinent dimensionless numbers I have just written it down for you just for your consideration you will notice that you should be having some other additional numbers also.

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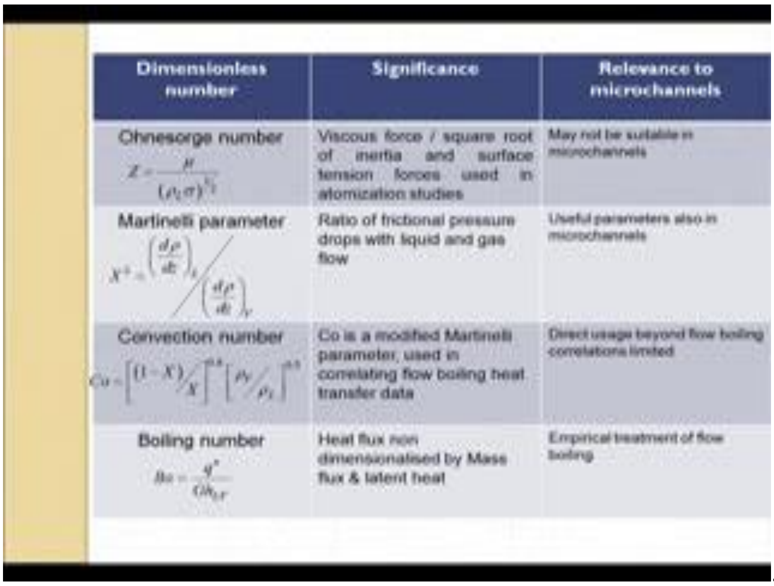

Dimensionless number	Significance	Relevance to microchannels
Ohnesorge number $Z = \frac{\mu}{(\rho_L \sigma)^{1/2}}$	Viscous force / square root of inertia and surface tension forces used in atomization studies	May not be suitable in microchannels
Martinelli parameter $X^2 = \left(\frac{dp}{dz}\right)_L \Big/ \left(\frac{dp}{dz}\right)_V$	Ratio of frictional pressure drops with liquid and gas flow	Useful parameters also in microchannels
Convection number $Co = \left[\frac{(1-X)}{X}\right]^{0.8} \left[\frac{\rho_V}{\rho_L}\right]^{0.5}$	Co is a modified Martinelli parameter, used in correlating flow boiling heat transfer data	Direct usage beyond flow boiling correlations limited
Boiling number $Bo = \frac{q''}{G h_{LV}}$	Heat flux non dimensionalised by Mass flux & latent heat	Empirical treatment of flow boiling

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Now, if you observe the numbers which are important for flow boiling cases, we will find that for flow boiling whatever numbers are there except the boiling number none of them considers the heat flux parameter; but this particular the heat flux this is particularly important if you have to considered the flow boiling cases and because why because due to due to this particular heat flux there is a change of phase from the liquid to the vapor and this is associated with the large momentum change which will be evident from this particular figure.

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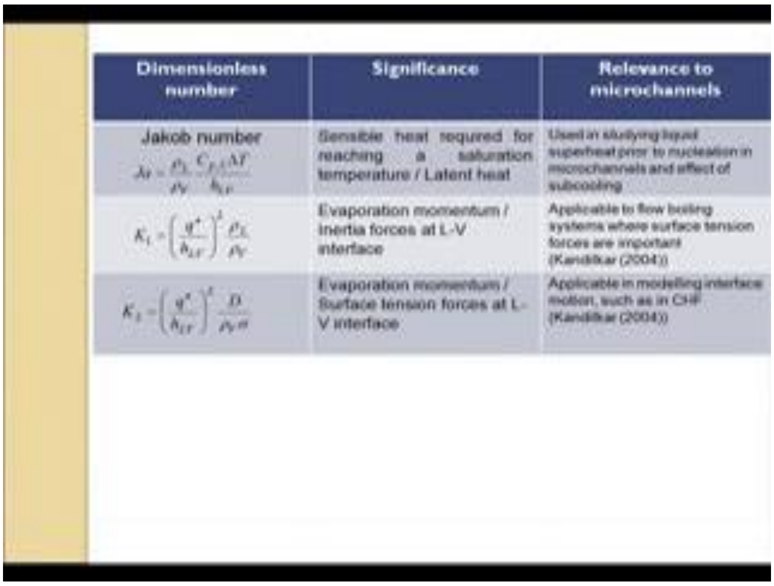

Dimensionless number	Significance	Relevance to microchannels
Jakob number $Ja = \frac{\rho_L}{\rho_V}\frac{C_{p,L}\Delta T}{h_{LV}}$	Sensible heat required for reaching a saturation temperature / Latent heat	Used in studying liquid superheat prior to nucleation in microchannels and effect of subcooling
$K_1 = \left(\frac{q''}{h_{LV}}\right)^2 \frac{\rho_L}{\rho_V}$	Evaporation momentum / Inertia forces at L-V interface	Applicable to flow boiling systems where surface tension forces are important (Kandlikar (2004))
$K_2 = \left(\frac{q''}{h_{LV}}\right)^2 \frac{D}{\rho_V \sigma}$	Evaporation momentum / Surface tension forces at L-V interface	Applicable in modelling interface motion, such as in CHF (Kandlikar (2004))

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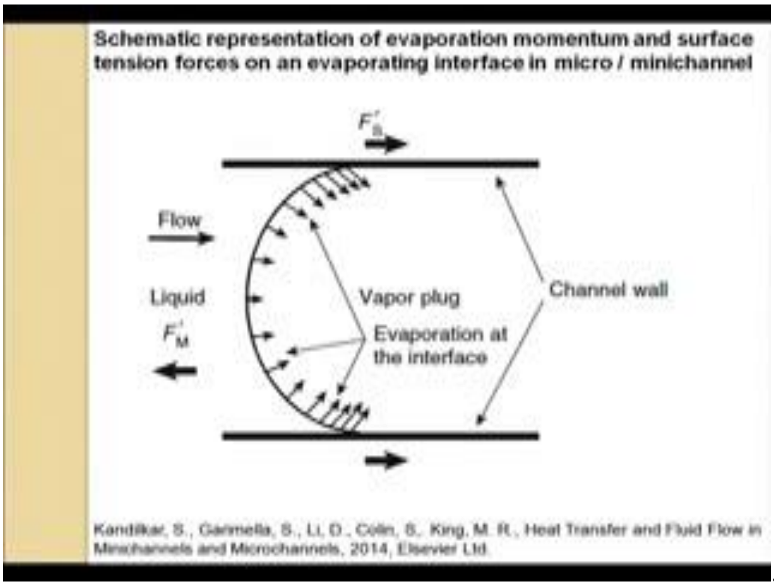

Now this figure shows an evaporating interface which occupies the entire channel. And we observe from here that due to the change of phase from liquid to vapor, it is associated with the large amount of momentum change. Why because the specific volume of the vapor, is much higher as compare to the specific volume of the liquid.

And due to this large momentum change there is a result in force which needs to be considered for proper representation of the 2 phase flow characteristics and also to understand the inter facial shape and to it is motion during flow boiling in mini and micro channels.

So, therefore, this particular effect, it was first recognized by Kandliker and he proposed 2 dimensionless number which are commonly known as K1 and K2, if you observe these 2 numbers you find that this is nothing, but modified boiling number, this has been modified by incorporation of the vapor and liquid densities.

And K2 it relates the evaporation momentum and the surface tension forces at the liquid vapor interface.

So, these 2 numbers their encounter during flow boiling, along with that the boiling number is also important and I would like to mention also that just like I had told you in micro channels, we find that in this case the adverse number or the bond number is not very important because gravity or buoyancy fourth is not important in micro channels.

It is just important to classify micro channels both for adiabatic 2 phase flow as well as for under boiling condition. On the contrary we find that the Weber number and the capillary number these 2 is expected to be much useful parameters, in representing some of the complex features of flow boiling.

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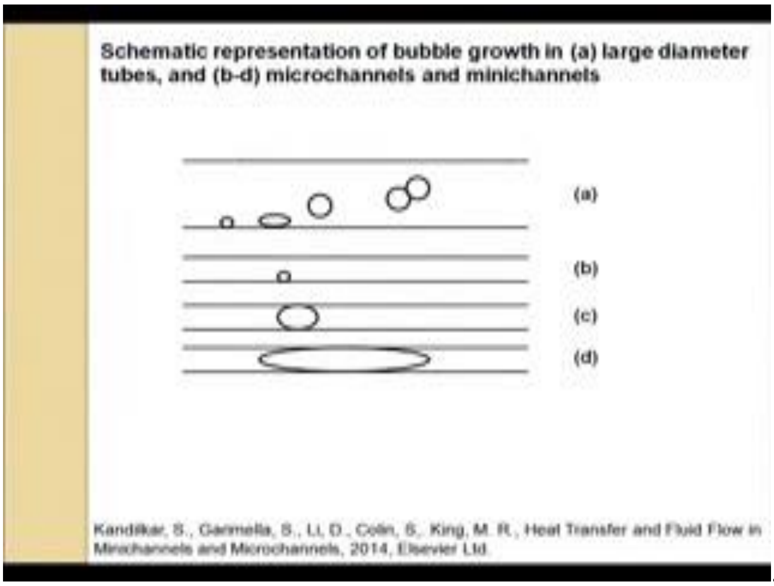

Now, if we considered the flow patterns and the rather how the flow patterns evolve in micro and mini channels. As expected that way I had discussed for adiabatic flows in this case also we know that surface tension forces become important of an surface tension forces become important what happens let us see this is the situation for a larger channel.

In this case there are number of nucleation sides bubble starts forming in the nucleation sides initially the bubbles are spherical then gradually they start growing larger as they start growing larger they detach from the wall and they raise due to gravity.

And then initially they remain as this first bubble as more and more bubbles are formed they gradually collides to form the slug flow and then finally all these, slug or the flux they collides to found the annular flow. This had already discussed when I was discussing the flow patterns in macro systems in a heated tube.

In this case what happens let us see in this particular case definitely just like the previous case the bubble nucleates then as the bubble the with advent of time the bubble this starts growing larger in the same way that at happened in micro channels, but in micro systems contrary to micro macro systems we find as the bubble starts growing instead of getting detach from the wall it cannot do this particular thing because as it is start growing it comes in contact with the upper wall.

And therefore, it gets confined between the 2 walls and it cannot detach it is elf from the nucleation side as a result of which the flow pattern which we encounter here they are slightly differently named in this particular case.

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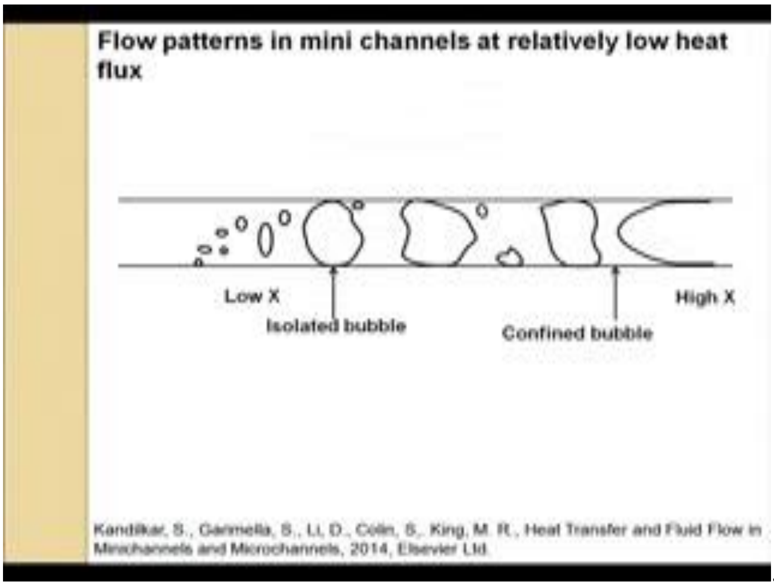

And as we will observed this is for a low heat flux condition initially we have bubbly flow then gradually the bubble this start growing bigger and they flow as discrete irregular shaped bubbles this particular pattern is known as isolated bubble flow after sometime the bubble after sometime the bubbles this start growing much more larger and they assume the this shape that I had shown this is known as confined bubble flow they are basically bubbles which are confined by the 2 walls and that cannot nucleate and so that driven off by the liquid also which is flowing and finally, this confined bubbles collides with one another at high quality and they gradually form the annular flow pattern.

But there is 1 thing which I would like to mention in this particular case that here there is I will just show you this and then I will mention once more.

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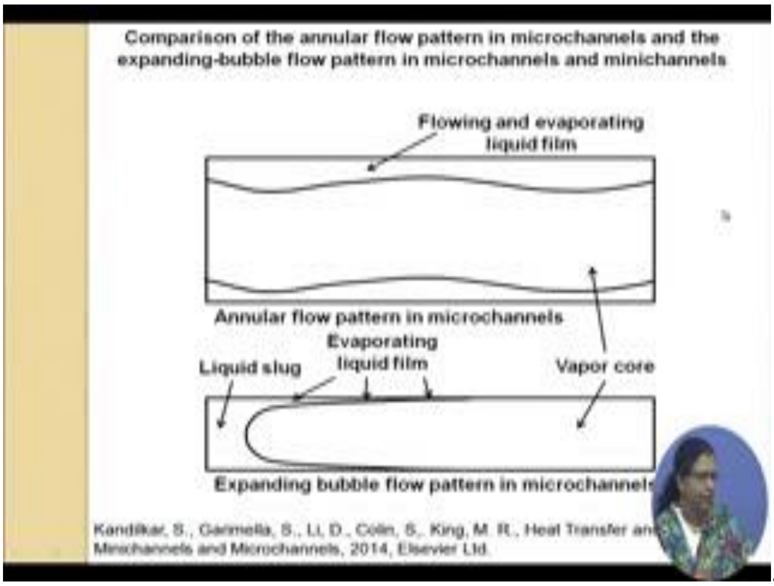

So, this was the case for low heat flux condition now at high heat flux condition a very interesting thing occurs in this case what happens as the bubble it is starts growing if you observe this as the bubble it is starts growing the liquid is, flowing in this particular portion.

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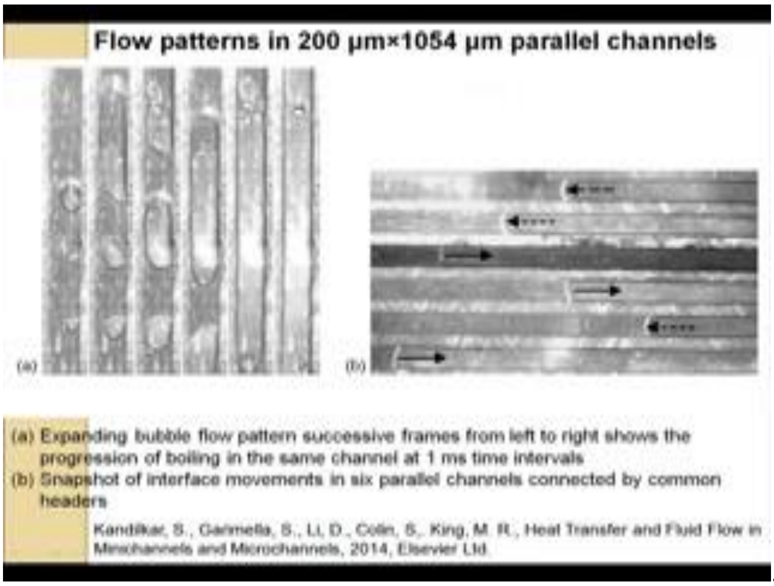

And the bubble has to expand it expands both upstream as well as downstream if you observe here in this particular photograph we have shown the expanding bubble flow pattern we find that the way the bubbles are expanding and if you observe the bubble expanding we will find that the interface flows both in the upstream and as well as in the downstream direction.

Now, due to this we get or rather we come across the unique phenomena which has been rather specified of which has been termed as flow reversal and this particular flow due to this particular flow reversal and additional instability sets in micro channels apart from the instabilities which are present in large tubes.

In large tubes we come across excursive and parallel channel instability and in micro channel apart from these 2 instabilities they in stay an additional instabilities induce due to flow reversal and that also as to be considered this is something unique for flow boiling in micro channels.

The other things which is important in during flow boiling is particularly in micro channels in the mini systems as I have mentioned we come across the confined bubble flow and the isolated bubble flow and then the annular flow.

In micro channels we come across 2 things 1 is phenomena of flow reversal and the other thing is an expanding bubble flow pattern what happens the bubble gets formed and then it keeps an increasing and it forms almost Taylor bubble finger sort of a thing and then it gradually occupies the entire channel when the entire liquid has vaporized.

Now, here I would just like to mention that this evaporating or rather expanding bubble flow pattern as some differences with the annular flow pattern that we observed under adiabatic condition what is the main difference if you observe the annular flow pattern we find that here there is a flowing liquid film and the flowing vapor or gas core while in this particular case we find that the bubble keeps on expanding through the and pushing the liquid at the film and this liquid film it is basically it is stationary it simply acts as a film under the growing vapor bubble rather than a flowing film.

And therefore, the heat transfer mechanism is similar to nucleate boiling and we find there this is strong dependence of heat transfer coefficient on heat flux in during flow boiling in micro channels which naturally again ends at the suggested dominants of nucleate boiling.

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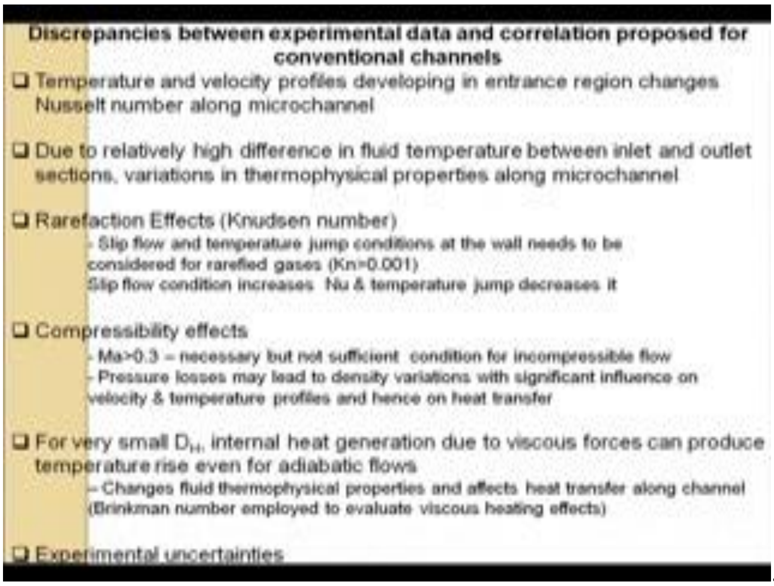

Now, the pressure drop and the white fraction characteristics they are more or less similar. So, there is nothing to discuss and as far as the heat transfer coefficients are concerned what we observed this that there are a large number of discrepancies between the reported results some say conventional channel correlations are find some say they are not at all find some say they are find under certain conditions and not find under certain conditions.

So, at the end I would just like to discuss the cause for the discrepancies between experimental data and the correlations proposed for conventional channels and that will be the end of this particular lecture series.

The first thing which we observe is the temperature and velocity profiles their they keep on developing in the entrance region and as a result the Nusselt number also start changing along the micro channel and therefore, it is very difficult to define a unique Nusselt number for the entire micro channel.

Suddenly, we find that there is a high difference in the fluid temperature between the inlet and outlet section now what happens due to this there is a variation in the thermophysical properties across the micro channel. So, naturally if the thermophysical properties change it is very difficult to predict unique Nusselt number.

The third part is the ready fraction effects now usually the ready fraction effects they are present for the gas phase and this is generally quantified by the Nusselt number. Now in this particular case behind if we find that for verified gases the slip flow and the temperature jump conditions they needs to be considered for verified gases because they influence the Nusselt number slip flow increases Nusselt number while temperature jump decreases Nusselt number.

And particularly for gas vapor liquid flows it is very important to considered these effects before we get proper prediction of Nusselt number again if you considered the compressibility effects generally for do we postulate for compressible flow that way mack number is greater than point 3 we assume that it is incompressible flow equations are applicable.

But we must remember that this particular condition this is a necessary, but not a sufficient condition for incompressible flow because all though the mack number at the inlet can be greater than point three due to pressure losses it may lead to density variations which again can significantly influence the velocity and temperature profiles and therefore, can alter the heat transfer characteristics.

And also another factor which is very important for small diameter or small hydraulic diameters that is the internal heat generation due to viscous forces even in adiabatic flows also we find that this can produce a significant temperature raise which again changes the fluid thermophysical properties effects the heat transfer along the channel.

And in order to evaluate the influence of the heat generation due to viscous forces it is important to employee the brink man number where the brink man number it can it is usually defined as the ratio of the heat rather the ratio of viscous heating which the brink man number which is defined as the ratio of the viscous heating rate and the average heat transfer rate.

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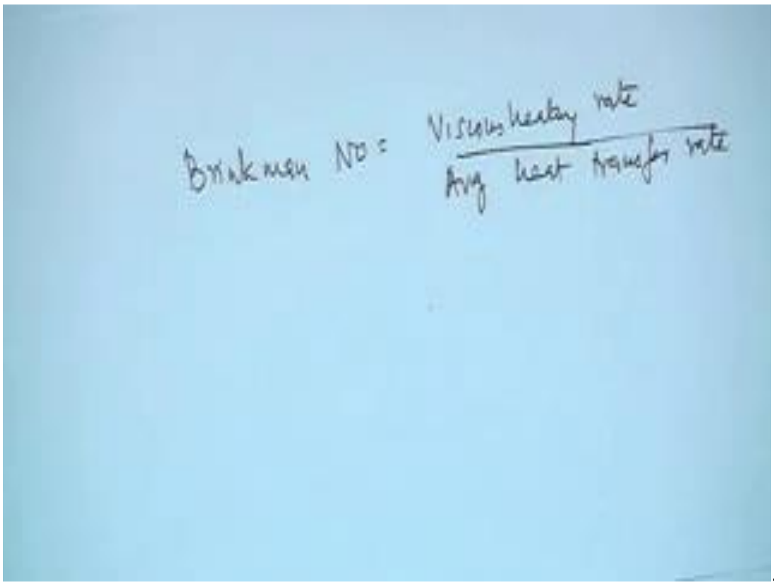

So, therefore, in order to evaluate how important this heat generation due to viscous forces is we need to employ brink man number to evaluate the viscous heating effect and because we know that this also is going to influence the Nusselt number and the heat transfer coefficient.

And over and above everything as I have been mentioning for all the experiments in micro channels for finding out flow pattern pressured of white fraction, I have already mentioned there are large numbers of experimental uncertainties. So, therefore, these also required are required to be considered for finding out or rather during the heat transfer experiments in micro channels.

So, with this I conclude the lecture series on adiabatic two phase flow and flow boiling in micro channels and based on the assignments and the presentation, we will be given an evaluation test and you are free to ask all your doubts and all your questions while you are through this course me and my (Refer Time: 21:25) will be very glad to address them.

Thank you very much.