

**Micro and Nanoscale Energy Transport**  
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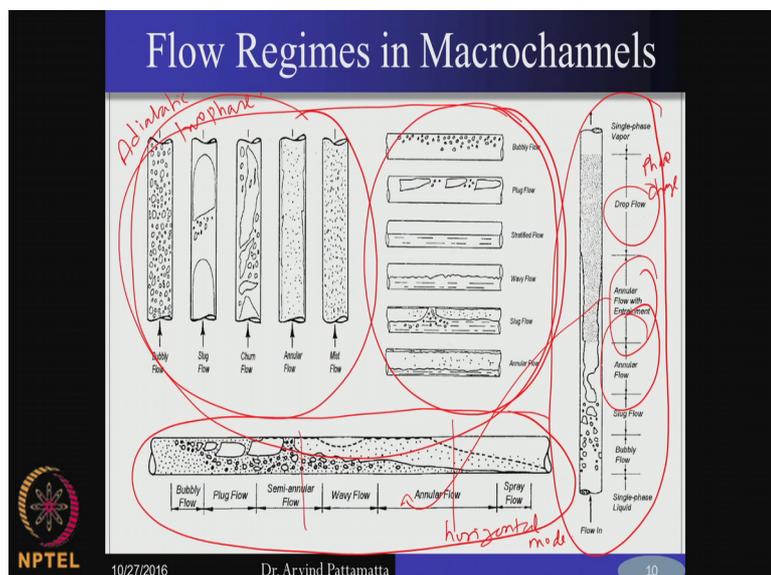
**Lecture – 38**  
**Two Phase Heat transfer in Micro Channels Part 2**

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Good morning, we will continue our discussion related to the face change heat transfer and micro channels.

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Yesterday we saw some of the important flow regimes encountered in case of macro channels. So, one very important difference between the micro and macro channel regimes is the influence of gravity on macro channels. Therefore, depending on the orientation of these tubes whether they are horizontal or vertical you may encounter different flow regimes whereas in the micro channels more or less once the diameter falls of the order few 100 of microns and below. So, you do not have a strong influence of gravity anymore because of the value of bond number being less than say 2 or 2.5. So, in this case you will encounter as I said mostly elongated bubbles.

So, you have a single bubble which is nucleating and it can grow, but unlike in the macro tubes. So, these bubbles will quickly reach the size of the diameter of the tube and then they cannot grow further in the cross sectional area. So, they will only expand along the length of this tube. So, mostly you will be dealing with the elongated bubbly flow are called it is also called the slug flow. So, people also refer to this as the Taylor bubble flow because you have a bubble classical not like a classical spherical bubble, but elongated bubble and you have from the top and bottom although this looks like, it is touching the tube you have very thin film of liquid which is protecting the bubble directly from the impact of heat transfer from the tube. So, therefore, the predominant regimes will be based on the slug flow. So, you have a slug flow and as your volume fraction of vapor increases you convert slowly from a slug flow regime to slug annular.

So, most of the vapor will be completely filling the core of the tube and the liquid will be covering the core as an annulus. So, this will be the slug annular regime right and so, you can also have a wavy annular pattern and finally. If your volume fraction increases then you will still see the kind of missed flow pattern where, you have bulk of the tube is cross sectional area is covered with vapor with the small liquid articles and draft and as the vapor volume fraction further increases you have only pure vapor the end of the tube.

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## Flow Regimes in Microchannels

- It is affected by parameters such as channel dimension, heat flux, mass flux and flow rate.
- **Bubbly flow:**  

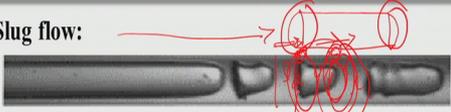
  - Isolated round and elongated bubbles that are smaller than the cross section of the microchannels move in the flow direction.
  - Bubbles generally nucleate at the microchannel walls and detach from the walls after growing.
  - The shape and size of the bubbles vary with flow rate and heat flux.

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So, therefore, I think these are all descriptive, but I think you can probably understand that you know bubbly flow regime in micro channels are quite different because, in the macro channel case you have a cluster of these bubbles at a given cross sectional area.

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## Flow Regimes in Microchannels continued ...

- **Slug flow:** 
  - As the heat flux increases, the bubble generation rate at the walls increases and bubbles become larger as a result of bubble coalescence.
  - At higher heat fluxes or in smaller microchannels, bubbles occupy the entire cross section of the channels, resulting in slug flow
- **Churn flow:**  

  - Small bubbles exist in the liquid slugs between the elongated bubbles.
  - This flow regime consists of vapour chunks transported downstream and large bubbles nucleating at a high rate at the channel walls
  - At high heat fluxes, the nucleation at the walls may be suppressed.

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Whereas in the micro tubes you usually have not more than one at a time and this one will stretch and elongate into the slug or the Taylor bubble flow. So, this is how for example, the slug flow can look the different regimes you know even in the slug flows. So, you do not have all the time a well define elongated bubble like this. So, sometimes

you also have a kind of hysteresis in the advancing and the receding meniscus of this Taylor bubbles.

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Flow Regimes in Microchannels continued ...

- **Wispy-annular flow:**



- A vapour core is separated from the channel walls with a relatively thick and unstable liquid film.
- Large irregular-shaped droplets are entrained into the vapour core.
- Very few nucleation sites remain in the liquid film and result in small vapour bubbles in the liquid layer.

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So; that means, the shape of the meniscus might look different for the advancing side which is moving probably in the direction opposite to the direction of motion of the liquid to the receding one, therefore, if you take, if you take this bubble.

For example, if you take this bubble. So, the classical way of drawing the Taylor bubble is something like this with hemispherical and caps right so; however, in this case you see that the suppose this is your direction of flow. So, we call this as advancing or receding with respect to the movement of the liquid. So, in this case the liquid is this and this vapor. So, the liquid is actually moving should move in this direction for this to be advanced. So, therefore, this is your advancing meniscus and this is your s e d you understand. So, this is your liquid and this is your vapor the direction in which the liquid moves if you see this liquid moves in this direction as the flow. So, this is your advancing meniscus. So, if you look at this meniscus. So, this is your vapor. So, the vapor moves in this direction. So, that is your receding meniscus.

So, the advancing and receding generally is defined with direction to how the liquid moves the direction of the motion of the liquid if the liquid moves from left to right. So, that is your advancing meniscus. If the vapor moves from left to right that your receding meniscus, therefore, the advancing and receding meniscus have different shapes of the

end caps. So, these are some kind of phenomena that can happen because, the temperature at this point of the wall is not the same as this point. So, usually since you are applying a uniform heat flux the temperature of the wall will continue increasing along the length of the tube. So, the temperature at this position will be usually higher than this. So, that will have a higher sometimes can have a higher evaporation rate compare to the portion here.

Therefore, all this will cause hysteresis in the shape of meniscus in the advancing and receding section. So, the slug flow does not always have to look a classical slug flow here that is shown in this particular figure elongated bubbly flow. So, there are also other ways of classifying, but I am not very keen in explaining all this to you because in micro channels.

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Flow Regimes in Microchannels continued ...

- **Annular flow:**



The image shows a micrograph of a microchannel with a central vapor core and a surrounding liquid annulus. Red lines and arrows are drawn over the image to highlight the liquid film and the vapor core.

- The liquid layer is thinner than in wispy-annular flow
- The liquid film thickness decreases as the heat flux increases. Small, round droplets are entrained into the vapour core, while no vapour bubbles are seen in the liquid annulus.
- At very high heat fluxes, when critical heat flux is reached, the walls can completely dry out under certain conditions and a vapour blanket forms at the walls around a liquid core flowing through the centre of the channels.

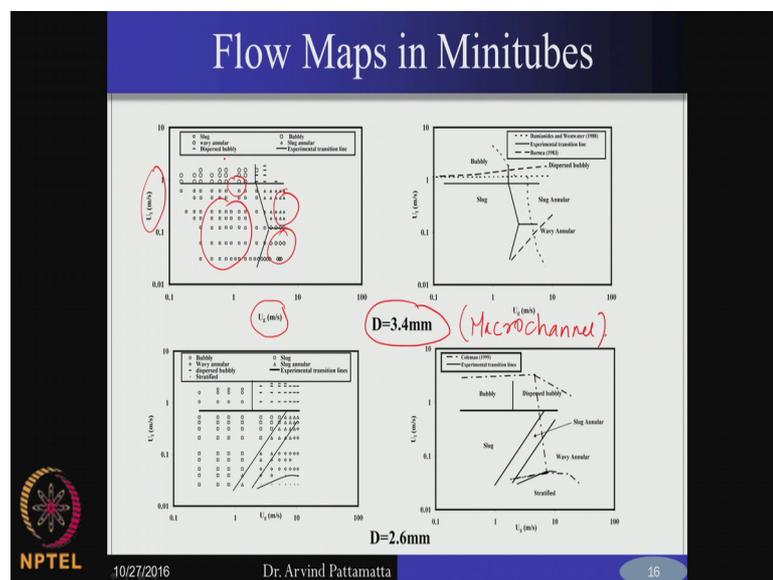
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We have rarely encounter things like wispy annular flow, but annular flow is quite common. So, here you can see that you have a vapor core. So, this is your vapor core here and surrounded by the liquid film is confined to the annular portion outside and the vapor core is now fully surrounded. So, earlier you had bubbles like this vapor bubbles separated by liquids portions. So, you have liquid slugs vapor flux. So, now, has the mass fraction of the vapor increases. So, these flux increasingly become longer and longer is vapor flux and then they quails and then they continuously form a straight core as the volume fraction of the vapor increases the entire core is filled with vapor and the liquid

is confined to the periphery. So, this is this is called the annular flow. So, this happens at a heat flux which is progressively higher than the slug flow regime.

So, if you are going for example, in this direction. So, you first encounter the bubbly flow then the slug flow then you have the annular flow. So, usually in micro channels the most common regime if you are really operating in the micro channel is this slug flow and very high heat fluxes you can also encounter the annular flow regime and we do not want to really dry out right.

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So, dry out is very bad in terms of heat transfer. So, you do not want actually these 2 regimes 1 is pure liquid pure vapor that defeats the purpose of 2 face flow. So, you want to hold as much as possible to the bubbly regime that is why most of the flow regime in micro channels are confined towards the slug flow.

Annular flow can be encountered if you have very high heat fluxes, but beyond that you do not want to result in a dry out and therefore, loss of heat transfer coefficient. So, these give you what are called as flow maps. So, as you can see the as the name suggest. So, these are like mapping the different flow regimes in a two dimensional diagram which plots the mass flow rate of the liquid versus mass flow rate of the vapor. So, on the x axis we plot generally the mass flow rate of vapor. So, mass flow rate are sometimes it is just the velocity on the y axis you plot the velocity of liquid.

So, this is one way of plotting the flow map because at any section if you have more vapor than liquid. So, there will be a slip between the liquid and the vapor. So, both of them will not have the same velocity. Therefore, you have you tend to have either higher liquid velocity compare to gas or if you have more gas you tend to have higher gas velocity than liquid the same is true. If you have adiabatic two phase flows. So, when you mix two different phases air or water.

So, you tend to mix certain flow rate of air or certain flow rate tube water in the tube and this will produce the different flow regimes in either case, you will be measuring what is the velocity of one component with respect to the other and depending on the relative magnitude of one of the one over the other all this flow regimes can be drawn on a two dimensional diagram and marked as flow maps.

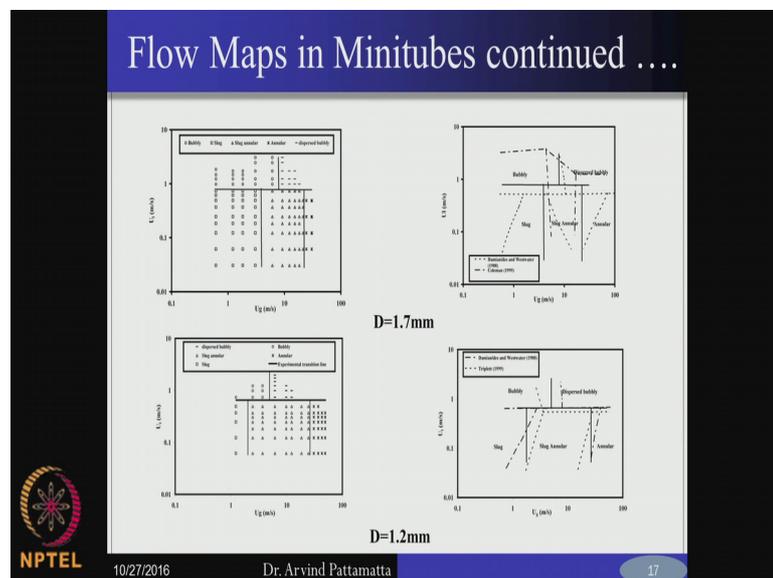
So, for example, if you have value of velocity of vapor which is very low and also the value of liquid velocity also very low. So, so that you have same order of magnitude, you are somewhere here right. So, you are somewhere in this particular regime. So, this March one transition from one flow regime to the other so; that means, if you have very less liquid flow rate and moderate gas flow rate. So, the kind of pattern that you will get, will be what slug and if you increase the gas flow rate further then, you end up for the same similar liquid flow rate. If you continue increasing your gas flow rate you end up getting in to the annular regime.

So, therefore, you have therefore, the slug annular here or you have the wavy annular again depending on the order of magnitude of the liquid velocity. So, so this is for a typical diameter of 3.4 mm. So, you can call this almost like a macro channel. So, as you have very high values of liquid velocity compare to gas velocity you are still in the bubbly flow regime. So, all these are very interesting to plot it on a two dimensional figure because from this you know the transition from one regime to the other. So, these give you the transition lines or change of regime lines. So, you know exactly if you want to get a particular flow regime what kind of velocities of liquid and gas that you have to operate right. So, once you do an experiment and obtain a map like this. So, anybody who wants to replicate it will go to the map they will know for identifying this particular regime I have to operate with these values of liquid and gas velocities.

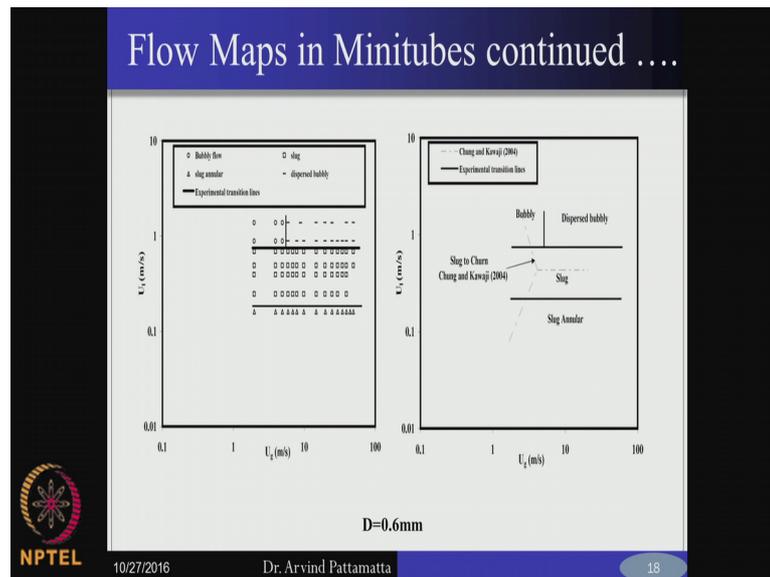
This is definitely for a particular working fluid again for different working fluid it will be different and again for different heat flux this will be different. So, usually when you plot the flow pattern map if, you plot it in a dimensional form you have to specify which working fluid is this and which heat flux which diameter of the tube if this is an adiabatic case then you do not worry about the heat flux. So, you just only specify which diameter and which working combination air water or some other liquid here.

Now, what is clear is that as you go. So, on the left we have the data points and also the transition lines on the right figure we have only the transition lines. So, there you have all the patterns mark and these are coming from different experiments. So, there is no perfect agreement between two sets of experimental data right. So, that is very important to note. So, sometimes depending on the order of accuracy of the way they measure the velocities and identify, because this is purely visual identification. So, the transition from one flow pattern to the other sometimes may not be. So, easy to identify visual therefore, that is why the transition lines tend to slightly deviate between different experimental groups. So, as you reduce the size of the tube now what do you find.

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So, for example, now let us go to the next case these are the real small tubes. Now we have 1.7, 1.2. Now 0.6 we have 600 micron tube now what do you see from 1.7 1.2 and this case.

Yeah and you see the slug regime is getting increasingly center and more dominant for a wide range of gas velocities. So, here for a limited range of gas velocities you have the slug pattern whereas, if you go to micro channel for a wide range of gas velocities you still have the slug pattern and finally, your pattern is mostly predominantly slug or slug annular right. So, these are your major area under the flow patterns maps. So, it becomes very straight forward you know we operate, with whatever gas velocities. Now, it only depends on the liquid velocity if, your liquid velocity is somewhat moderately high then you are in the slug regime if the liquid velocity drops then you are in the annular regime. So, only these 2 regimes, you have a more or more or less like a binary map binary flow regime.

So, you either you are in the slug or slug annular. So, or if it is very, very high value then you are in the bubbly pattern. So, this is how it tends to shift. So, you have predominance. So, in the other case you might have depending on the value of gas velocity slug annular. But as you go towards micro channel irrespective of whatever gas velocity, if you controlled your liquid velocity you always can maintain a slug flow. So, that; that means, your slug flow is a most predominant flow pattern in a micro channel.

So, that is why usually most of the face change phenomena and micro channels always deal with slug flow slug flow Taylor bubbles.

so I think with this you have kind of an understanding about how to look at the flow regimes and map it to a two phase flow map and therefore, identify the different regimes.

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Pressure Drop during flow boiling in Microchannels and Minichannels

- The pressure drop in a microchannel or a minichannel heat exchanger is the sum of the following components:

$$\Delta p = \Delta p_c + \Delta p_{f,l-ph} + \Delta p_{f,tp} + \Delta p_a + \cancel{\Delta p_g} + \Delta p_e$$

Where,

- c – contraction at the entrance
- f,l-ph – single phase pressure loss due to friction, including entrance region effects
- f,tp – two-phase frictional pressure drop
- a – acceleration associated with evaporation
- g – gravitational
- e – expansion at the outlet

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So, I will now quickly go little bit in to the estimation of pressure drop. So, this is very important parameter in micro channels. So, in micro channels you have a large pressure penalty right because the diameter of the tube is very small for the same value of friction factor you have to apply a large pressure drop to drive the flow for the same Reynolds number. So, pressure drop estimation becomes very important.

Now, the more added complexities you have two phases. So, therefore, how do you theoretically build correlations to understand pressure drop the next portion will be your heat transfer coefficient. So, in general again for a micro channel or mini channel you have different contributions to the pressure drop over all pressure drop similar to that, we have seen in pure single phase liquid flow you have contraction process you have expansion losses. So, the first term here represents the contraction pressure loss.

so your over all pressure drop has contraction pressure loss your expansion pressure loss there could be some influence of gravitational head, but this can be neglected most of the times sometimes locally evaporation leads to more production of vapor which can

actually accelerate. So, there could be component which can also be important sometimes at very high heat fluxes or on the regions where you have non uniform temperatures. So, locally suddenly the temperature wall temperature going up. So, suddenly they the amount of the volume of vapor can increase on this can accelerate.

Apart from the two important contributions one is the single phase pressure loss due to friction the other is the two phase pressure drop. So, the single phase pressure loss is straight forward; that means, if you fill your entire tube with say liquid what would be the pressure drop this is coming from your Darsi Chart, but what you actually have is actually a two phase flow. So, therefore, you have to somehow account also for the two phase pressure drop. So, how do we account for that, each component?

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Pressure Drop during flow boiling in Microchannels and Minichannels continued ....

- Pressure loss due to sudden contraction:

$$\Delta p_c = \frac{G^2}{2\rho_L} \left[ \left( \frac{1}{C_o} - 1 \right)^2 + 1 - \frac{1}{\sigma_c^2} \right] \psi_h$$

Where,

G – mass flux  
 $\sigma_c$  – Contraction area ratio (header to channel > 1)  
 $C_o$  – Contraction coefficient

$$C_o = \frac{1}{0.639(1 - 1/\sigma_c)^{0.5} + 1}$$

$\psi_h$  – two-phase homogeneous flow multiplier  
 $\psi_h = [1 + x(\rho_L/\rho_V - 1)]$   
 where, x- quality



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So, your delta p c that is pressure loss due to sudden contraction, these are some standard correlations depending on the contraction ratio and so on. So, you can substitute the corresponding parameters. So, this also has what we called as a two phase flow multiply. So, if you remember our Martinelli parameter.

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**Non-dimensional Numbers [Based on Empirical Considerations]**

**1) Martinelli parameter, (X):**  $X^2 = \left( \frac{dp}{dz} \right)_{F/L} / \left( \frac{dp}{dz} \right)_{F/V}$

- Ratio of frictional pressure drops with liquid and gas flow.
- Used in two-phase pressure drop model two-phase pressure drop models.

**2) Convection number, (Co):**  $Co = [(1-x)/x]^{0.8} [\rho_V/\rho_L]^{0.5}$

- Used in correlating heat transfer flow boiling heat transfer data.

**3) Boiling number, (Bo):**  $Bo = \frac{q''}{G h_{LV}}$   $x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l}$

- Heat flux is non-dimensionalized by mass flux and latent heat
- Used in empirical treatment of flow boiling



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So, this is your Martinelli parameter which gives you the ratio of pressure drop if the tube was filled with entirely liquid to the pressure drop with the tube is filled with entirely vapor. So, that is generally used in pressure gradient correlation. So, you have a correlation in which now psi is a function of x x is the quality. So, this becomes a kind of two phase flow multiply; that means, depending on the quality even the contraction loss is can be different. So, if it is pure liquid you have a different contraction loss if it is pure vapor you have a different contraction loss the for a two phase mixture. So, therefore, even the contraction loss becomes a function of the quality of mixture.

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**Pressure Drop during flow boiling in Microchannels and Minichannels continued ....**

- The exit pressure loss:  $\Delta p_e = G^2 \sigma_e (1 - \sigma_e) \psi_s$   
Where,  $\sigma_e$  – area expansion ratio (channel to header >1)  
 $\psi_s$  – separated flow multiplier  $\psi_s = 1 + \left( \frac{\rho_L}{\rho_V} - 1 \right) [0.25x(1-x) + x^2]$
- The local friction pressure gradient at any section is calculated by:  
$$\left( \frac{dp_F}{dz} \right) = \left( \frac{dp_F}{dz} \right)_L \phi_L^2$$
- Where,  $\phi_L^2$  – two phase multiplier (Chisholm 1983)  
$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2}$$



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So, similarly you have another correlation for calculating the exit pressure loss. So, this is also a function of the mass fraction. So, through  $\psi$  this is a function of  $x$ . So, the local friction pressure gradient so; that means, for a two phase flow. So, we want to calculate the pressure loss. So, that is this particular component two phase pressure drop. So, the two phase pressure drop usually is calculated as the pressure drop, if you had fully filled it with liquid because this is the largest value that you will get multiplied by what is called as two phase multiplier.

So, what is the maximum value of pressure drop you will get is if you fill it completely with pure liquid. So, that is basically the value multiplied by a correction factor for two phase flow. So, this called two phase multiplier and this, two phase multiplier is written as function of capital  $x$  what is capital  $x$  Martinelli parameter. So, you independently look at the pressure drop if it is completely filled with liquid completely filled with gas take the ratio. Now, you therefore, now what is your two phase multiplier and this will give you what is the two phase pressure drop.

So, now this has some constants. So, all these are empirical these are not very exact ways of finding  $\Delta p$  exact ways to only do an experiment and find it. So, if you want to do it the theoretically.

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Pressure Drop during flow boiling in Microchannels and Minichannels continued ....

- The value of 'C' depends on phase and whether it is laminar or turbulent:  
 Both phases turbulent C = 21  
 Laminar liquid and Turbulent Vapour C=12  
 Turbulent liquid and Laminar vapour C=10  
 Both phases laminar C=5
- Martinelli parameter is given by the following equation:  

$$X^2 = \left( \frac{dp_f}{dz} \right)_L / \left( \frac{dp_f}{dz} \right)_V$$
- Mishima and Hibiki(1996) gave the equation for 'C' as:  

$$C = 21(1 - e^{-319D_h})$$


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So, these are coming from experimental data. So, so if the constants are all empirical values. In the case of the two phase multiplier, this has a constant  $c$ . So, this constant  $c$  is

attributed to Chisholm sometimes called the Chisholm parameter. So, you have different values of  $c$  depending on either you have a Laminar or Turbulent regime.

So, if your both the liquid and vapor phases are turbulent it can be very high twenty one if both phases are laminar then this is a lowest value and your  $x$  square is your Martinelli parameter you should remember. So,  $x$  will be square root of the Martinelli parameter. So, there are also some correlations for getting out  $c$  for non circular use. So, for circular tubes you just put in both phases are laminar you substitute  $c$  equal to five, but for non circular tubes you calculate the hydraulic diameter  $d_h$  and then use this correlation given by Mishima and Hibiki to calculate  $c$  and that you substitute to calculate the two phase multiplier and therefore, the two phase pressure drop.

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Pressure Drop during flow boiling in Microchannels and Minichannels continued ....

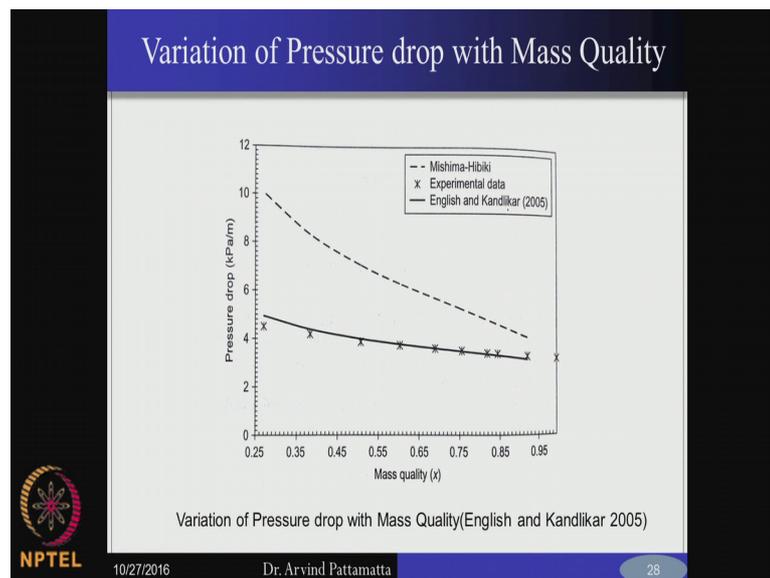
- The acceleration pressure drop:  $\Delta p_a = G^2 v_{LV} x_e$   
Where,  $x_e$  – exit quality  
 $v_{LV} = v_V - v_L$  difference between the specific volume of vapor and liquid phases.
- The gravitational pressure drop:  
$$\Delta p_g = \frac{g(\sin \beta)L}{v_{LV} x_e} \ln \left( 1 + x_e \frac{v_{LV}}{v_L} \right)$$

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So, apart from these you have also contribution from what we called as a acceleration pressure drop. So, the acceleration pressure drop is depending on the difference between the densities of vapor and liquid and locally this can accelerate. If you have large amounts of vapor suddenly produced. So, this is given by this particular equation. So,  $G$  is the volume flow rate and you have the difference between the specific volume of vapor and liquid phases that is  $v_V - v_L$  and you have the quality of vapor at the exit. So, all these are some empirical correlation and since similarly another correlation for the contribution of gravitational pressure drop.

So, usually in as this diameter of the channel gets smaller and smaller this gravitational pressure drop will become negligible. So, the contribution of usually the two phase pressure drop due to friction this will be the biggest contribution and you can also have significant entry and exist loss because in micro channels as I said entry and exit losses are significant because of very high contraction and expansion ratios. So, they also have to be accounted for.

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Therefore, if you look at the comparison of if you calculate your overall pressure drop from these correlations and you compare it with experimental data you see some deviations can be possible.

For example, if you use the value of  $c$  from Mishima and Hibiki you see there is a substantial deviation from the experimental data whereas, the other model for  $c$  proposed by English and Kandlikar. So, that shows a closure agreement. So, overall this is the thumb rule way of calculating pressure drop. So, take into account the contraction expansion acceleration gravitational two phase pressure drop the two phase pressure drop is the one which depends on the Martinelli parameter. So, you define what is calling the two phase multiplier which is the function of the Martinelli parameter. So, you estimate the Chisholm parameter or factor  $c$  depending on whether the flow is turbulent or laminar and you have, to check for either flow the vapor could be turbulent, while the

liquid could be laminar more often in the case the vapor velocity is higher than the liquid.

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**Heat Transfer Correlation**

- Kandlikar and Steinke (2003), Kandlikar and Balasubramanian (2004) introduced the laminar flow equations as follows:

For  $Re_{LO} > 100$

$$h_{TP} = \text{larger of } \begin{cases} h_{TP,NBD} \\ h_{TP,CBD} \end{cases}$$

$$h_{TP,NBD} = 0.6683Co^{-0.2}(1-x)^{0.8}h_{LO} + 1058.0Bo^{0.7}(1-x)^{0.8}F_{FI}h_{LO}$$

$$h_{TP,CBD} = 1.136Co^{-0.9}(1-x)^{0.8}h_{LO} + 667.2Bo^{0.7}(1-x)^{0.8}F_{FI}h_{LO}$$

where,

$$Co = [(1-x)/x]^{0.8}(\rho_V/\rho_L)^{0.5} \text{ and } Bo = q''/Gh_{LV}$$

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So, now if you go into the heat transfer, what are the correlations available how you calculate heat transfer rate for two phase flows. So, lot of experiments have been done there are there are no analytical methods to calculate h like the way for single phase we do not have a fully developed correlation like in the single phase. So, we generally have 2 regimes, 1 either for a laminar flow or for a turbulent flow.

So, now the most important correlation which is been proposed by Kandlikar and Steinke 2003 and Kandlikar and Balasubramanian 2004. So, for the laminar flow regime they have produced a very comprehensive correlation. So, that is you have to check if your Reynolds numbers a greater than 100. So, in this case how do you get the value of two phase heat transfer h TP is two phase heat transfer? So, this has contributions from two components, two empirical correlations. So, one is the NBD the other is CBD. So, depending on whichever is larger you calculate you put the corresponding value of convection number Co is nothing but convection number and h LO is nothing, but the single phase heat transfer coefficients; that means, you fill the entire tube with liquid. So, that is why it is h subscript l.

Fully with liquid and calculate the single phase heat transfer coefficient and you substitute into this. So, your Bo is nothing, but boiling number. So, some small confusion

they have used Bo for both boiling and bond number. So, here it refers to boiling number  
 $Co$  is the convection number. So,  $h_{LO}$  is a single phase heat transfer coefficient if it is  
 fully filled with liquid and  $x$  is your quality of vapor or mass fraction there is a parameter  
 called  $F_{F1}$ .

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Heat Transfer Correlation continued ....

Fluid	$F_{F1}$
Water	1.00
R-11	1.30
R-12	1.50
R-13B1	1.31
R-22	2.20
R-113	1.30
R-114	1.24
R-134a	1.63
R-152a	1.10
R-32/R-132	3.30
R-141b	1.80
R-124	1.00
Kerosene	0.488

Recommended  $F_{F1}$  (fluid surface parameter)  
 values in flow boiling correlation by Kandlikar



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So, this is again another empirical parameter and depending on different working fluids  
 this parameter will be different.

All these have been recommended by Kandlikar. So, this is what is generally used if your  
 Reynolds number. So, how do you calculate your Reynolds number Reynolds number  
 should be calculated based on only the liquid properties? So, that is why we have  $r$   
 subscript  $l$ . So,  $l_o$  means he says liquid only. So, if you replace the two phase mixture  
 with fully liquid that is a value of  $r_{el}$  and  $h_l$ .

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**Heat Transfer Correlation continued ....**

- The single-phase all-liquid flow heat transfer coefficient  $h_{LO}$  is given by:
  - for  $10^4 \leq Re_{LO} \leq 5 \times 10^6$   $h_{LO} = \frac{Re_{LO} Pr_L (f/2)(k_L/D)}{1 + 12.7(Pr_L^{2/3} - 1)(f/2)^{0.5}}$
  - for  $3000 \leq Re_{LO} \leq 10^4$   $h_{LO} = \frac{(Re_{LO} - 1000) Pr_L (f/2)(k_L/D)}{1 + 12.7(Pr_L^{2/3} - 1)(f/2)^{0.5}}$
  - for  $100 \leq Re_{LO} \leq 1600$   $h_{LO} = \frac{Nu_{LO} k}{D_h}$
- For Reynolds number below 100, the nucleate boiling mechanism governs and the correlations becomes:
 
$$h_{TP} = h_{TP,NBD} = 0.6683Co^{-0.2}(1-x)^{0.8}h_{LO} + 1058.0Bo^{0.7}(1-x)^{0.8}F_{fl}h_{LO}$$

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So, what happens to other values of Reynolds number? So, if you are Reynolds number is yeah. So, for the single phase you know the correlations right. So, for calculating  $h_{LO}$  again you can refer to correlations which could be by Gnielinski or Petukhov these are the standard correlations the Gnielinski and Petukhov are also valid for turbulent regimes for laminar regime that is for Reynolds number up to say 16100 you use your Laminar Nusselt number whether it is a constant heat flux or constant temperature constant temperature is 3.6 constant heat flux is 4.36.

Now, once the flow regime goes to turbulent then you can use either the Gnielinski or Petukhov. So, it depending on whether it is very highly turbulent or moderately turbulent. So, from this correlation you get the single phase heat transfer coefficient then you go and plug it into this expression find the greater of the 2. So, that gives you the two phase heat transfer coefficient. So, this is again for Reynolds number based on the liquid property greater than 100.

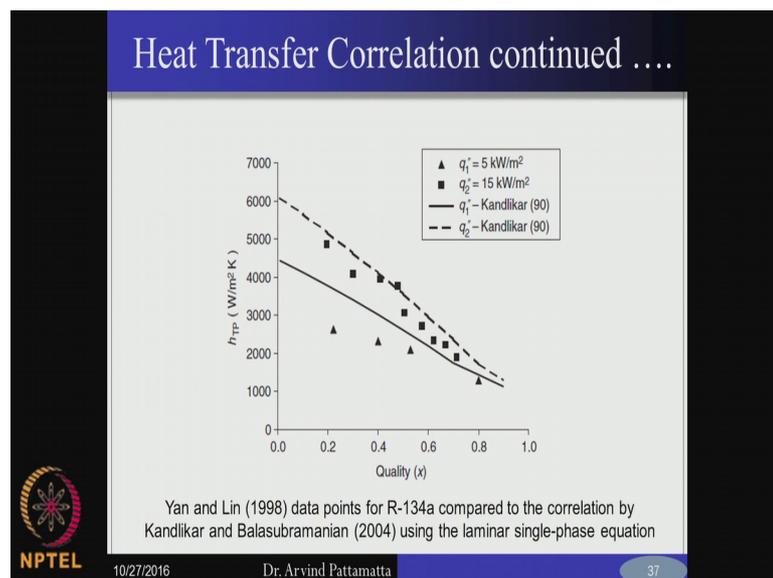
So, what happens for very small Reynolds numbers? So, there is another correlation. So, that is purely based on only  $h_{TP,NBD}$ . So, that is the same as this. So, that you do not have to calculate  $h_{TP,CBD}$  and find the larger of the 2. So, you directly estimate your two phase heat transfer coefficient has equal to  $h_{TP,NBD}$ . So, this is the function of again convection number boiling number and single phase heat transfer coefficient.

This, the most commonly used heat transfer correlation, I think there is a nice review paper by Sathish Kandlikar appearing in general of heat transfer in two thousand four. So, in that he has given a summary of these correlations. So, the important thing is first you check the Reynolds number based on pure liquid property and if, it is less than hundred you directly calculate your two phase heat transfer coefficient has equal to  $h_{TP}$  NBD based on this if it is greater than hundred you check the larger value of  $h_{TP}$  NBD or  $h_{TP}$  CBD.

Now, what is NBD and CBD? What I have not told you? So, one is the nucleate boiling the other is convective boiling. So, your nucleate boiling is similar to the boiling phenomenon that happens in pool boiling when, you have bubbly flow bubbly flow regime. So, that is driven purely by the heat flux whereas, the convective boiling is driven by the mass flux. So, you have higher flow rates higher values of Reynolds number. So, in that the mixing which is the very important component is brought by the mass flux which also will impact the heat transfer and evaporation process.

So, therefore, for high Reynolds number there is a contribution from both the nucleate boiling as well as the convective boiling whereas, for low Reynolds numbers you can ignore the convective boiling contribution. So, just to show you how these correlations works.

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So, depending on the vapor volume fraction you can. So, you see these correlations are all functions of vapor volume fraction or mass fraction  $x$  is mass fraction.

So, depending on the mass fraction you get different values of  $h_{TP}$  right. So, therefore, if you heat the tube continuously and put it in say vertical mode and you want to calculate the heat transfer coefficient right from the bubbly regime all the way to the annular regime. So, you can use the same correlations and plot this as a function of  $x$ . So, as your  $x$  increases; that means, you are transitioning from one flow regime to the other. This is what the plot says, you are going virtually from 0 to 1. So, one you will never be able to achieve completely and you do not want, but the data points are plotted between 0 and one; that means, you have heated the tube and locally you want to see how the heat transfer coefficient varies.

So, what this shows is the maximum value of two phase heat transfer coefficient somewhere at around 0.2. So, this is where the slug flow regime is. So, as you increasingly go towards higher mass fractions towards the annular flow and then finally, dry out the heat transfer coefficient drops. So, and you see that there is a comparison of experiments versus the  $h_{TP}$  evaluated from these correlations. So, both seem to be very close. So, they are compared for one smaller value of heat flux the other which is quite high and although some deviations are absorbed for the smaller value of heat flux overall. The correlations developed empirically seem to be having a good agreement.

So, therefore, the most important part of the two phase flow is to understand how to calculate pressure drop and heat transfer coefficient and depending on the flow regime we should be able to identify what is your mass fraction, you should be able to understand for a given Reynolds number, how to extract your heat transfer coefficient from these correlations.

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## Heat Transfer Mechanisms

- Two mechanisms:
  - Convective boiling [High mass flux and high vapour quality]
  - Nucleate boiling [High heat flux and low vapour quality]

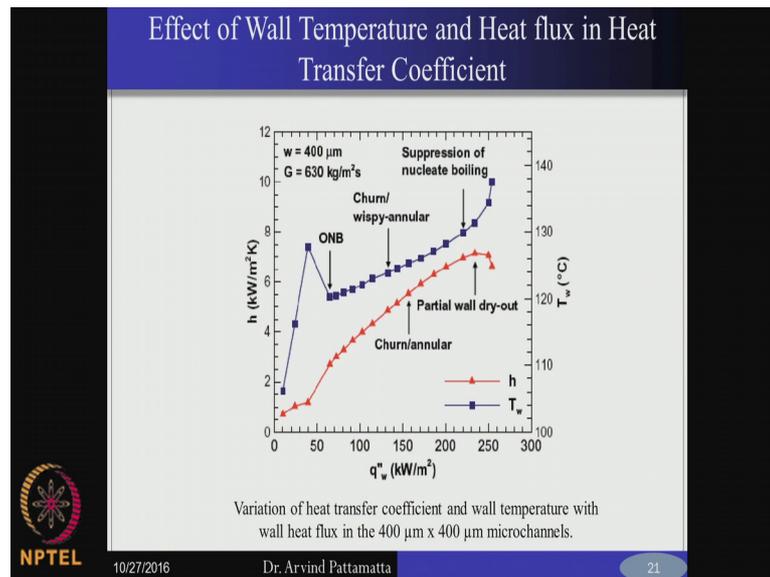
Liquid Motion (convective Boiling)      Rapid Evaporation (Nucleate Boiling)

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I think I was packing about therefore, these two regimes. Now, that you understand that in the heat transfer coefficient correlation you have contribution from the nucleate boiling and also the convective boiling. So, what is the difference? So, this initial nucleation and evaporation is happening due to the presence of gravitational, sights and this depends on the temperature gradient. So, if you are local temperature exceeds the saturation temperature then you have the bubble coming and this starts to grow and the bulk of the liquid also starts to boiling, this is a nucleate boiling phenomenon the convective boiling is and top of these if, you induce some bulk motion it is like stirring. So, you are going to augment the evaporation rates.

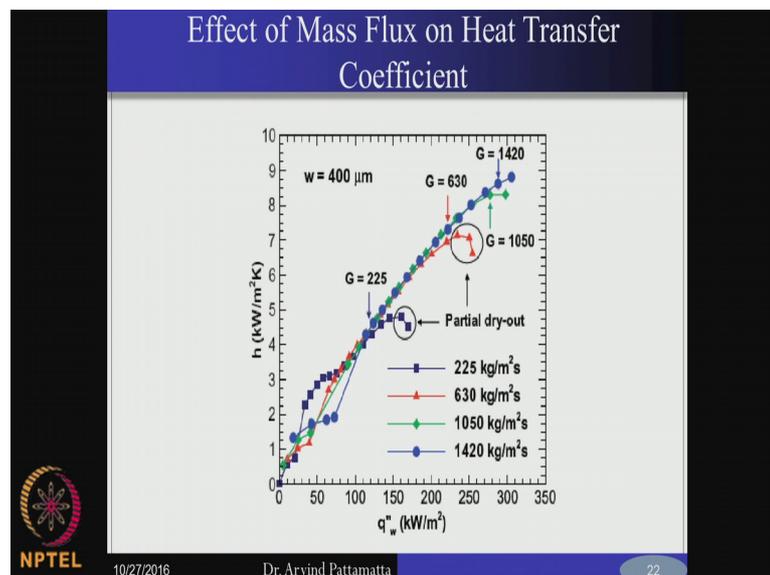
So, therefore, overall effect of flow boiling will therefore, be and effect of stirring and addition to the localized evaporation due to temperature gradient. So, that is why the heat transfer coefficient is higher in the flow boiling regime due to the contribution of convective boiling to towards the nucleate boiling.

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So, these are some kind of data people have generated as you change the heat flux. So, what happens to the heat transfer coefficient and. So, on I think this you can go through I will upload the ppt. So, so one is probably looking at the critical heat flux and departure from nucleate boiling.

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So, I think these are mostly coming from the experiments there is there is no rigorous theory or analytical models for these, but I will upload this you should if you need to refer to any other topic you can go to the text book and also take the reference from

there. So, with this we will kind of conclude the phase change heat transfer in Microchannels, if you have any questions or anything we can probably discuss for 4 5 minutes.

So, how many of you are actually doing some related to microchannels or. So, what are you are also. So, two of you; what kind of are you doing experiment?

Student: For both.

Micro nozzles and this is the heat transfer.

Student: yeah right in order to have that heat transfer single micro nozzles all right you have heat transfer finally, micro crystals in an adder, and heat generated in 1 of the nozzles was enough to in hide the module in our next nozzle.

This is having an application micro.

Student: Yeah, micro satellites.

So, with whom are you working?

Yeah ok. So, you are working on what related to microchannel heat transfer.

Student: We should continue on the pressure drop for multiple purpose on.

OK.

Student: So.

The heat transfer or this adiabatic.

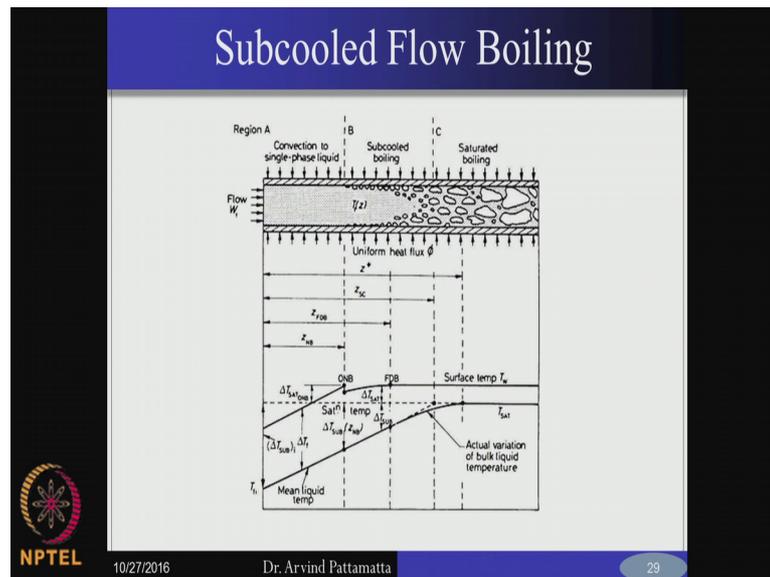
Student: Transfer.

So, you are doing experiments.

Student: Or trying to develop a model or it is all ready a model, trying to.

Yeah; I mean because in terms of experiments also the general problem is getting an agreement between different experiments. So, many times they are not repeatable because of the local condition of the surface place a very important role here.

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So, they are what you see here is see suppose you have sub cooled flow coming at the inlet you know it take some time for this to heat up reach saturation and then the nucleation starts. So, you see that these nucleation happens at the surface and this is a completely surface texture related phenomena, and you do not have control you can have a control if you give precision nucleation sites. If you take a general surface and you are studying. So, person who is doing experiment here and another room will not get the same values because a nucleation sites will completely changed the flow regimes. So, if the surface is been very smooth the same heat flux you applying you will not get nucleation the surface is very less, where a lower heat flux already you will have a lot of bubbles.

One very difficult part of experimentation is repeatability, but in spite of that I think I mean as this figure shows I think they have put lot of effort especially the group from Sathish Kandlikar in building useful practical correlations I mean they, have not been for example, tested for all different kinds of working fluids all different kinds of surfaces, but in general. So, this is for r 1 34 a. So, they must have used at least 2 or 3 working fluids it is building his data. So, if you use it for completely different working fluid which is highly volatile it may not yield good results.

So, it is not a closed problem. So, you should understand that these have been built in the only in the last eight or nine years work somehow correlations are also coming out for

different fluids, but increasingly difficult to find make it very generic for all class of working fluids. So, this the biggest challenge with two phase flows all right.

So, we stop here, I will upload this later on I hope you saw the assignment five that is uploaded please work on it the last date is on 8th of November these are that is the last class. So we have four more classes after this. So, I will be covering something related to nanofluids because, that is also very popular these days. So, nano fluid and related heat transfer and finally, something on the experimental methods what micro nanoscale because that is also very important. If you want to do experiment you should understand that you cannot just simply use standard thermocouple to measure the temperature of these things.

Then what is the right kind of thermocouple that you use what should be the sensitivity of this. So, all this need to be also understood it is not only the just theory part, but very important is the recent advancements in the experimentation to measure things at micro nanoscale.