Micro and Nanoscale Energy Transport

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Lecture - 37
Two Phase Heat transfer in Micro Channels Part 1

Very good morning, so yesterday we started another topic related to mini and micro channels this is liquid flow, but two phase or phase change you know phase change is particularly concerned with single components and two phases whereas, general two phase flows can be adiabatic and can be multi component. So, one can be an air and the other can be water. So, we have seen that general adiabatic two phase flows exist in. So, many different applications right any practical application that you take whether it is an atmosphere sciences or biological applications or heat transfer you find two phase flows, but in heat transfer we are emphasizing more on the phase change. But, where you have a single component and you have multiple two phases.

So, typically this kind of phenomena can be applied towards electronic cooling. So, that is where primarily the micro channels and mini channels are being used and therefore, if you want to increase the rate of heat transfer we have seen that compare to the single phase heat transfer co efficient your two phase heat transfer co efficient this three to four orders of magnitude higher. So, these from the basic boiling curve itself, if you look at the basic boiling curve which is called the Nukiyama boiling curve. So, you basically control the heat flux and you would measure the wall temperature.

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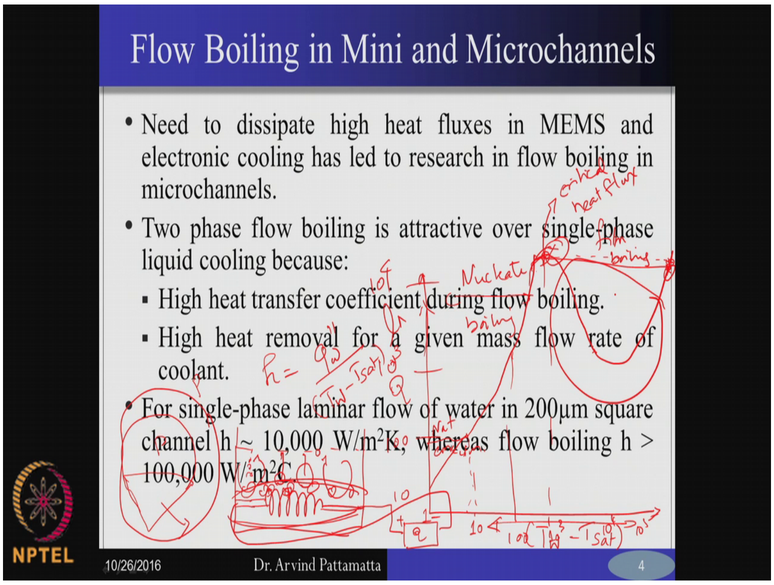

Flow Boiling in Mini and Microchannels

- Need to dissipate high heat fluxes in MEMS and electronic cooling has led to research in flow boiling in microchannels.
- Two phase flow boiling is attractive over single phase liquid cooling because:
  - High heat transfer coefficient during flow boiling.
  - High heat removal for a given mass flow rate of coolant.
- For single-phase laminar flow of water in 200μm square channel h ~ 10,000 W/m²K, whereas flow boiling h > 100,000 W/m²C

critical heat flux

film boiling

Nucleate boiling

$h = \frac{q_w}{T_w - T_{sat}}$

$\log q$

$\log(T_w - T_{sat})$

10/26/2016 Dr. Arvind Pattamatta 4

So, this is a basic experiment which was originally done about nearly 100 years back now by professor Nukiyama.

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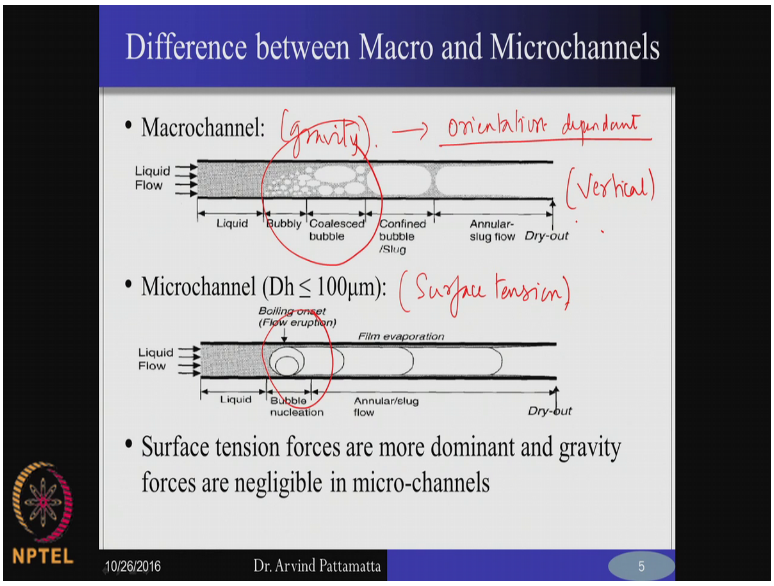

Difference between Macro and Microchannels

- Macrochannel: (gravity) → orientation dependant

(Vertical)

- Microchannel (Dh ≤ 100μm): (Surface tension)

- Surface tension forces are more dominant and gravity forces are negligible in micro-channels

10/26/2016 Dr. Arvind Pattamatta 5

So, what he did was he emerged heater coil in water which was static and. So, he connected this to power supply d c power supply and so, he controlled the power input and therefore, he controlled the heat flux apply to this particular heater coil and as he varies the heat flux you know he also has thermo couples on the surface of the heater coil.

So, you can measure the temperature and average them that will be the wall temperature and then he starts with some low value of heat flux and gradually increases this. So, initially you see a curve which is going like this and when you observe the flow part flow regime or flow patterns there will be no bubbles. So, this is the point where you can say your wall temperature is just above the saturation temperature. So, saturation temperature for water if you take at 1 atmosphere it is close to 100 degrees right. So, he is maintaining suppose wall temperature 100 and 100.5. So, he starts slightly above the saturation temperature. So, just at the con liquid which is contact in contact with the heater you find the temperature is close to the saturation whereas, the bulk of the liquid will be more or less at room temperature.

So, therefore, the kind of heat transfer will be purely by natural convection. So, there will be natural convection currents which will be driving the heat transfer from the heater fluid at the heater towards the surface right. So, these are the basic natural convection currents. So, in that case the slope of this particular diagram will give you what heat transfer co efficient. So, you can actually measure q versus t wall mi minus t sat correspondingly. So, your h will be simply q wall this is your heat flux divided by t wall minus t sat. So, till some heat flux this is going to happen. Now, if you increase the heat flux beyond this you see that the wall temperature exceeds.

This you can all this you can start with say one here. So, this could be of the order of 10 and once suppose say the wall temperature exceeds the saturation temperature by 10 degrees. So, you will say that the liquid is reasonably well above the saturation temperature at the heater surface near the heater surface. Now, this is the state which will induce boiling. So, therefore, if liquid is above the saturation it has to evaporate right it is not very stable phase the stable phase will be to slowly start evaporating and transition to a vapor state.

But in the process how the evaporation happens. So, there are two things one is evaporation is a loosely understood what evaporation is usually surface phenomena and in a normal context even at room temperature you can have evaporation and evaporation is driven by mass transfer right. For example, if you take a water body big reservoir. So, and you compare the fraction mass fraction of water vapor in the ambient. So, this is measured by the relative humidity if the relative humidity is 10 percent; that means, you have very little water vapor saturated in air. So, the partial pressure of water vapor in air is very little compare to the overall pressure.

So, therefore, this partial pressure the pressure difference between what is at the interface minus what is in the ambient or the concentration difference is going to drive the evaporation. So, a few molecules will be excited at the interface has enough kinetic energy and they can break free from the liquid state they will become vapor because there is a very high potential gradient outside. So, that the liquid molecules can transition from a liquid to a vapor state and exist and this keeps on happening continuously till there is a relative humility increase.

So, if it reaches 100 percent then there is fully saturated then there is no room in the surrounding atmosphere to hold anymore vapor and the evaporation will stop. So, evaporation is purely a mass transfer phenomena and driven by concentration gradient and it can happen at any temperature, it need not be above the saturation temperature whereas, boiling is a bulk phenomena and it is not specifically surface process it is happening throughout the entire bulk of the liquid and it is driven by temperature gradients. So, this is one of the most important facts.

So; that means, you can consider an environment which is completely evacuated there is no air; that means, only vapor. So, it is already saturated it is already saturated. So, in this case there is no classical evaporation happening. So, your air is fully saturated now according to your classical evaporation. Now, there can cannot be anymore phase change, but according to the temperature gradients. So, your bulk of the fluid is at a temperature higher than the saturation temperature and this temperature gradient is going to drive the boiling process. So, phase change will happen because, simply because of the diagram t s diagram or p v diagram where if your temperature is above the saturation this has to move from the saturated liquid to saturated vapor state.

So, this phenomena and boiling is purely temperature gradient induced phenomena. So, therefore, you have to understand, we sometimes use evaporation also to mean boiling, but evaporation classically means it is mass transfer driven evaporation. Whereas, boiling is temperature difference a temperature gradient induced phenomena. So, this pa particular nu Nukiyama curve is purely a boiling curve. So, we are not considering diffusion of ah you know species and mass transfer induced change of phase. Now, at this particular point therefore, when it is starts to change the phase how it happens is very difficult process to imagine. So, typical explanation is that the heater itself should have roughness some elements which are rough enough to induce artificial cavitations sides for the bubble growth.

So, you can zoom in and you can see that at the Nanoscale a few nanometers or may be one micron size you can see this is the cavity this are cavities formed by the roughness elements on the heater, which will hold basically the vapor broccoli right the phase change is happening right at the heater surface. So, this vapor has to sufficiently grow. So, that it can it is pressure can be higher than the surrounding liquid pressure locally. So, it can form bubble nice clerical bubble and then this bubble should be able to rise up all the way because of buoyancy and at the same time the pressure different should be high enough for the bubble to sustain till the top of the surface.

So, for example, if you are talking about very low super heats, there will be a bubble formation near the heater surface, but it may not have enough strength to rise all the way up to the top. So, it will just disappear. This will not induce enough pressure for inside the bubble to overcome this surrounding liquid pressure and it will somewhere collapse, but as you keep increasing the super heat that; that means, you keep increasing the heat flux you rise the super heats to say thirty degrees forty degrees fifty degree then you will find that these cavities will now hold a lot of vapor with sufficient vapor pressure.

Correspondingly this bubble can actually have la much large diameter near the surface and they can rise continuously till the surface and you will find that at the surface they will collapse right. So, this is what you observe when you heat water in a pan. So, initially you do have only natural convection you can actually see the motion of the fluid due to natural convection and then, you will slowly start seeing bubbles forming from the surface, but collapsing as you continuously heat. You will see that these bubbles grow in size because of higher vapor pressure because your vapor pressure is nothing, but pressure corresponding to a corresponding temperature.

So, the more you heat the vapor. So, the higher the temperature higher the pressure inside higher the vapor pressure because these are compressible substances. So, they you can use the ideal gas law for example, higher the temperature of heating of the vapor higher the pressure. Therefore, once you have higher pressure of vapor near the surface. So, they can rise up to longer to larger heights and they finally, at the interface they have to collapse.

So, this will continuously happening, as you keep rising the heat flux you will suddenly see that this slope will now increase, this is all the initial portion which is the natural convection where you get very moderate values of heat transfer coefficient and then once the nucleation and bubble growth starts. So, this regime is called the nucleate boiling regime. So, in this nucleate boiling regime you see all these bubbles growing and you see the bubble size corresponds to the amount of super heat the larger the super heat the larger will be the bubble size and the number of bubbles also will be increasing.

So, you will find that every where you find large bubbles and from which you know this rise and then you finally, keep and this continuously happens stream of bubbles are generated which rise up to surface and collapse right. So, this continuous till some point of heat flux, as you keep increasing the heat flux you keep going up and you see that the slope of this is much higher than this and remember this is all in lock scale and denominator as well as here in the numerate. So, you can say that initially you are starting with 10. So, this could be hundred this could be 10 power 3 then this could be 10 power 4 and so on. So, it similarly you have a 10. So, you could have 100 and you can have 1010 power 3 then you have 10 power four 10 power 5.

Now, add some particular point what happens the amount of super heat is. So, that completely vap the surfaces quoted with only vapor. So much of superheat and instant evaporation of everything near the heater surface, the vapor film actually quotes the complete heater surface and now this causes a decrease in the heat transfer coefficient because the vapor has lower thermal conductivity compare to water. So, therefore, this will add as a resistance to transfer of heat from the surface into the bulk therefore, the heat transfer coefficient will start dropping. So, the slope becomes smaller and. So, reduce then it will actually start dropping. So, what happens is in the practical case when you control the heat flux you do not actually go down. So, the actual curve looks something like this, but you do not go down you actually go from this point directly to state here because by the time you increase the heat flux a little bit. So, I should actually draw this is slightly higher than this.

So, this point should be slightly higher than this point by the time is straightly increase the heat flux a little bit it is already in the, you know case where vapor is completely coating. So, this is a film boiling regime and this increases the temperature of the heater surface the heater surface rises, but the heat transfer rate is not enough for the heat to dissipate directly from the heater surface to the bulk. Therefore, even if you increase q, this is not efficiently getting dissipated. So, your surface temperature will now tremendously increase. So, it increases an order of magnitude suppose you are somewhere close to four hundred five hundred. So, from there it goes to few thousands and what happens that is the melting point of the metal and immediately this entire metal fails this will break the heater itself will break.

So, therefore, you directly go from this point directly to the point where it melts and breaks fails. So, this maximum value is called the critical heat flux. So, this is actually like a you know cautionary value you know tells you do not operate beyond critical heat flux always be much lower than the critical heat flux. So, for every fluid and particular surface combination you have a particular heat flux when, you do this experiment. So, it depends, if you use water with the particular surface polished aluminum you get a particular curve. If you replace this with rough surface aluminum surface you get a slightly difference critical heat flux if you use some other copper surface you get.

So, therefore, it depends on the liquid and material combination depending on which you get different two phase curves and you have different values of critical heat fluxes. So, you have to first understand, what is the critical heat flux for a given working fluid and surface combination? You should always operate well below the critical heat flux to avoid this damage to the surface. So, therefore, you should always be in the nuclear boiling regime. So, this is the very favorable regime as for as heat transfer co efficient is concerned.

And as per as damage to the surface is concerned this is the say first pa you know regime if you goes close to the critical heat flux and marginally slightly above. So, you directly go and damage the complete heater. So, if you are controlling your heat flux you cannot actually get this particular part of the boiling curve. So, for doing this you have to control the surface temperature rather than heat flux. So, therefore, you have to put a heat exchanger and maintain the heater with isothermal condition and you slowly increase this temperature of the heater. So, then you will be able to go from this temperature to this temperature. So, all these are increasing temperatures.

So, therefore, if you rather than using of ISO flux condition, if use an isothermal condition, you should be able to go through this route before you hit this particular point. So, therefore, this is to give a basic understanding and this is with pool boiling; that means, you have static fluid in a container and you change the heat flux or boil temperature and you observe the flow regime the same thing happens; when you have flow through a channel or a duct with the constant wall flux or a wall temperature. So, in that case you also see that these bubbles which form from the nucleate boiling will also move along with the bulk fluid and depending on the diameter of this bubble and depending on the vapor volume fraction. So, as you keep going from left to right what happens the vapor volume fraction is increasing right. So, on depending on the vapor volume fraction you have a two phase mixture with different regimes.

So, therefore, in the flow boiling case it becomes even more complicated because it is not only the temperature gradient which is driving the boiling process, but also the mass flux or the amount the what is the Reynolds number at the inlet correct. So, here is also an advection process which is driving the boiling apart from your temperature gradient. So, there is also combined effect of mass flux and heat flux in the case of flow boiling which makes it little bit more complicated, but in general. So, why do we prefer two phase regime? So, as you can see from this curve your heat transfer coefficients are at least three orders of magnitude higher, if you are operating in the nucleate boiling regime.

So, therefore, whether it is a macro channel or micro channel we always prefer a two phase regime and in micro channel although we already have a high value of h for single phase flows because of the small diameters we still prefer two phase flows because this stills much higher compare to the single phase h. So, most of the applications in electronic cooling are actually in the two phase regimes in micro channels, yesterday we saw the major difference between the a flow regimes in a macro channel versus micro channel. So, in the macro channel case one of the most important differences the effect of gravity. Therefore, you can you can actually say that you know in this case this is completely driven by gravity and this is driven by surface tension.

So, this is one perspective the other this with respect to the relative size of the bubble the diameter of the channel is much larger in the macro channel case. So, very unlikely you find that one single bubble will occupy the entire channel cross section whereas, in the micro channel case many times you will find only one bubble occupying the entire channel gross section and it cannot grow further. So, it will be elongated along the length of the channel. So, usually you will find a bubbly regime where you have multiple bubbles and multiple bubbles simultaneously growing callusing and so on. Callusense is just merger of these bubbles when they come to close whereas, here you find one single bubble which is nucleating which is growing which quickly filling the channel diameter and then it is continues elongated.

So, the bubbly regime is quite different. So, you have. So, many bubbles in the macro channel whereas, this is only 1 or 2 bubbles and also the elongation is very rapid in the micro channel case. So, 2 things; one is the effect of gravity. So, therefore, what happens with the macro channel the other disadvantage is it is dependent on orientation so; that means, if you keep this horizontal you observe a different flow pattern you can also have a stratified flow, where the liquid can collect to the bottom and vapor at the top whereas, if you have a vertical mode of operation you will probably see something like this. So, the flow pattern map here it is actually for vertical mode in horizontal mode you will also find a stratification. Whereas, micro channel is independent of orientation, you whatever angles are direction you keep more or less the flow transition will happen in the similar way.

So, it is very advantages to use micro channel where you know you put it on an object or a surface which is always you know reorienting itself towards gravity. So, for example, if you take space craft cooling all the time it is attitude changes. So, if you have a ma macro channel you will find that suddenly, if you gravity becomes important in one particular orientation. So, you may find the flow pattern changing which is not good. So, therefore, you can use micro channels in such a case where it is independent of this kind of gravity effects. So, let us look at some important non dimensional numbers when it comes to phase change.

So, I will start with what is called as a bond number. So, this bond number is nothing, but ratio of buoyancy force to the surface tension force.

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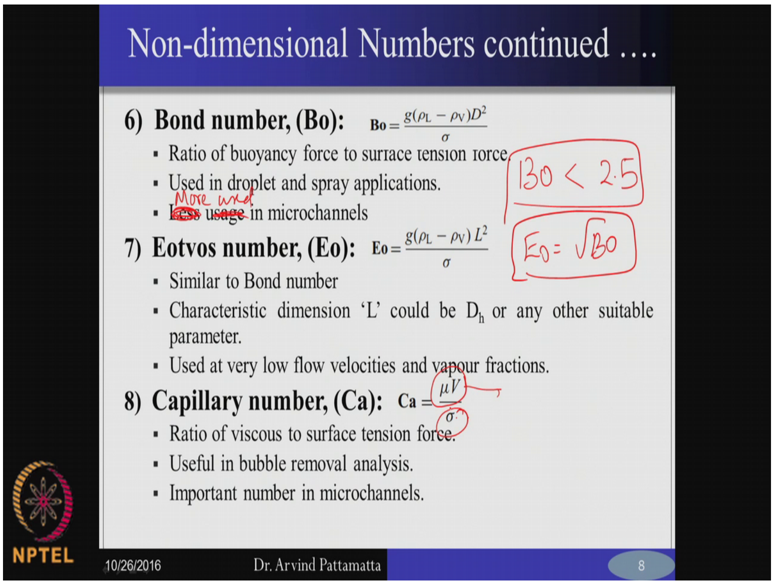

Non-dimensional Numbers continued ….

6) **Bond number, (Bo):** $Bo = \frac{g(\rho_L - \rho_V)D^2}{\sigma}$

- Ratio of buoyancy force to surface tension force
- Used in droplet and spray applications.
- ~~Less usage~~ More used in microchannels

$Bo < 2.5$

7) **Eotvos number, (Eo):** $Eo = \frac{g(\rho_L - \rho_V) L^2}{\sigma}$

- Similar to Bond number
- Characteristic dimension 'L' could be D_h or any other suitable parameter.
- Used at very low flow velocities and vapour fractions.

$Eo = \sqrt{Bo}$

8) **Capillary number, (Ca):** $Ca = \frac{\mu V}{\sigma}$

- Ratio of viscous to surface tension force.
- Useful in bubble removal analysis.
- Important number in microchannels.

10/26/2016 Dr. Arvind Pattamatta 8

So, this is one of the most fundamental numbers, when you look at micro in. In fact, I would to an extent. Where I would strike of this because in some text book this is mentioned that this is less used, but I would say this is more used because you classify your micro channel based on the bond number. So, your bond number should be less than 2.5 for example, in order to clearly say that this is the micro channel where your surface tension is more dominant than gravity.

So, therefore, these definitions tell you the relative order of magnitude of gravitational force with respect to the surface tension force and we use this to classify. In fact, what is a micro channel? So, you cannot simply use only the absolute numbers for example, 100 micron for a particular liquid with the very low value of surface tension could be a micro channel whereas, 500 micron with a liquid with very high surface tension could be a micro channel. So, we generally check the bond number see whether it is less than 2.5 and accordingly we classify this as a micro channel.

Sometimes the bond number is also referred to as Eotvos number. So, people in Europe use the definition of Eotvos number and people in USA, they use the bond number, but they are very similar. In fact, there are some slight differences sometimes the Eotvos number can be defined as square route of bond number, but never the less it still containing the same information saying that it is the ratio of buoyancy to the surface tension force. So, you can also define another important number call the capillary number. So, the capillary number gives you the ratio of viscous force to the surface tension force. So, this is a very important number whenever you have flow through micro channels for example, where you classify the order of surface tension force to the inertia or viscous forces.

So, if you have very low velocities for example. So, this v is the velocity mu is the dynamic viscosity if you have very low velocities. So, then you typically have low capillary number where surface tension forces may be more dominant and if you have very large velocities then your surface tension forces may not be that important. So, your capillary number tells you on cases where you can neglect surface tension force due to very high flow velocity for example. So, this gives your relative order of magnitude of viscous force to surface tension force or you can also say inertia force because of presents of velocity there. So, the other number is called Ohnesorge number this Ohnesorge number is actually similar if you look at the way it is defined to the capillary number except that it does not have velocity in the numerator, but it is also ratio of viscous force to surface tension force.

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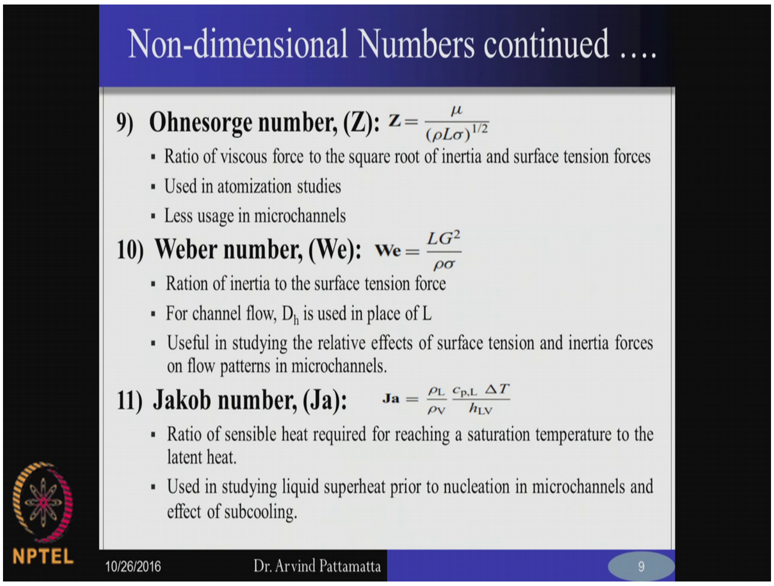

Non-dimensional Numbers continued ….

9) Ohnesorge number, (Z): $Z = \frac{\mu}{(\rho L \sigma)^{1/2}}$

- Ratio of viscous force to the square root of inertia and surface tension forces
- Used in atomization studies
- Less usage in microchannels

10) Weber number, (We): $We = \frac{LG^2}{\rho\sigma}$

- Ration of inertia to the surface tension force
- For channel flow, D_h is used in place of L
- Useful in studying the relative effects of surface tension and inertia forces on flow patterns in microchannels.

11) Jakob number, (Ja): $Ja = \frac{\rho_L}{\rho_V} \frac{c_{p,L}\,\Delta T}{h_{LV}}$

- Ratio of sensible heat required for reaching a saturation temperature to the latent heat.
- Used in studying liquid superheat prior to nucleation in microchannels and effect of subcooling.

It also has density coming into the pictures. So, therefore, it is also kind of clubbing some part of inertia force also in the denominator. So, therefore, you can say that it is a ratio of viscous force to the square router of inertia and surface tension forces club together. So, usually we do not use this much in micro channels, but mostly in atomization of liquid jets when the jet breaks up.

So, we look at a criteria when the jet can break up very easily if you have a very high inertia for example, and very low surface tension. So, you can talk about break up process depending on the values of Ohnesorge number see the other number that we use is call the weber number. So, weber number is the ratio of inertia to the surface tension force. So, here g is the flow rate volumetric flow rate. So, this is again very informative in terms of channel flows we do not use this as much as the capillary number because the capillary number and weber number are interchangeably used and capillary number is more often used in micro channels than weber number.

Weber number also is use for impingement of droplets you know mo motion of droplets where you are looking at the relative order of magnitude of the inertia force emotion of the droplet to the surface tension. So, it tells you what will be the shape of this drop for example. So, if the drop has very high surface tension it is more likely that it is well rounded and less subject to deformation. So, if the values of surface tension is very small then it can actually spread more easily and it is more deformer, but in terms of micro channel notation we use capillary number more often because a capillary number itself has part of the motion that is velocity built in to it. So, we do not have to again define a weber number, further sometimes people use also weber number.

So, all these are just hydrodynamic quantities right whether you take bond number capillary number Ohnesorge number or weber number. So, what about heat transfer? So, when you are supplying some heat flux to the wall and you measure the amount of super heat super heat to the wall that is the difference between the wall temperature and saturation temperature. So, how do you characterize the heat transfer? So, in that case we use what is called Jakob number. So, Jakob number gives you the ratio of what is the sensible heat divided by what is the latent heat, ratio of these two the sensible to the latent heat. So, this is a number which is usually used to see how well the nucleation can happen depending on whether you slightly superheated or you superheated to a large extent or sometimes even you sub cool it. So, because the first part the numerator part is simply nothing, but the sensible heat part. So, it does not tell you that there should be phase changes whereas, the denominator tells you that in case of phase change what is the amount of heat that you supply due to phase change that is the enthalpy of evaporation.

So, it is a relative effect of sensible enthalpy to enthalpy of evaporation if there is lot of sub cooling of the liquid at the inlet of the channel. So, the sensible heat part will be higher compared to the latent heat part then you know that you are mostly in the single phase regime when you are talking about values which are close to saturation or above saturation then the latent heat part will be much higher when you supply heat the heat goes in to the evaporation more than changing the temperature. So, then the values of Jakob number will be much smaller right. So, large values of Jakob number indicate more, more mostly it is in the single phase regime and small values of Jakob number indicate that you are mostly in the phase change regime.

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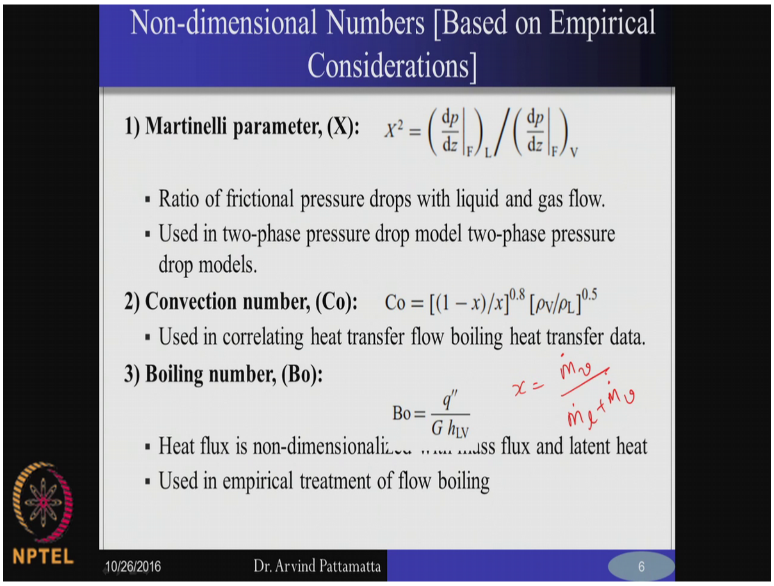

Non-dimensional Numbers [Based on Empirical Considerations]

1) Martinelli parameter, (X): $X^2 = \left(\frac{dp}{dz}\Big|_F\right)_L \Big/ \left(\frac{dp}{dz}\Big|_F\right)_V$

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

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

3) Boiling number, (Bo):

$$\mathrm{Bo} = \frac{q''}{G\,h_{LV}}$$

$$x = \frac{\dot m_v}{\dot m_l + \dot m_v}$$

- Heat flux is non-dimensionali[illegible] [illegible] [illegible]ss flux and latent heat
- Used in empirical treatment of flow boiling

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10/26/2016 Dr. Arvind Pattamatta 6

So, apart from this we also have a few more definition. So, one is call the Martinelli parameter.

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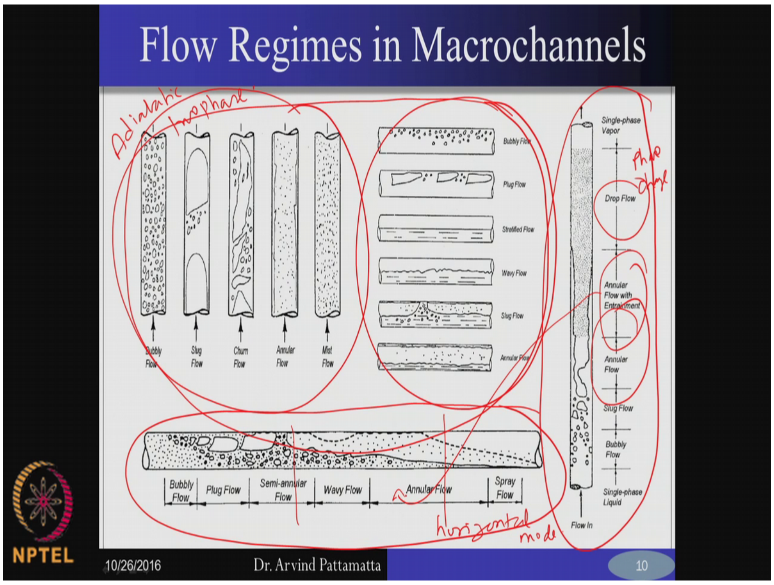

Flow Regimes in Macrochannels

10/26/2016 Dr. Arvind Pattamatta 10

So, what is interesting here if you probably observe this flue two phase patterns is that you have a mixture of both liquid and vapor simultaneously therefore, how do we explain a model for pressure drop. So, pressure drop now is because of both the components liquid and vapor components. So, therefore, to in order to explain the pressure drop we define a relative ratio of pressure drop due to liquid to the pressure drop due to vapor alone suppose if this entire duct was filled purely with liquid. So, what is the pressure drop due to the liquid alone? So, that is the dp by d z due to liquid and similarly if you replace this by pure vapor what will be the pressure drop. So, this ratio is used and usually the liquid pressure drop will be higher than the vapor pressure drop.

So, therefore, this ratio will be usually greater than one and this is use to develop correlations for describing pressure drop of actual two phase mixtures. So, they are all functions of this Martinelli parameter why because, it is easier to find the Martinelli parameters because you know the friction factor depending on the standard moody diagram. So, you can find out for pure single phase liquid or pure single phase vapor what is the pressure drop. So, you can find this ratio and therefore, the Martinelli parameter and depending on that you can build correlations for the actual two phase case as function of two single phase pressure drops.

So, usually this Martinelli parameter is used in two phase pressure drop models. So, this is built in to that. So, you know the Marginally parameter upfront depending on what is the flow rate of liquid. What is a flow rate of gas? You estimate your dp by dx from the single phase friction factor correlations and then substitute in to the empirical correlation to determine the two phase pressure drop correlations. So, that is one important parameter the other important parameter is called the convection number. So, this is kind of xs here, the quality of vapor or the mass fraction of vapor that is basically your you can define x as mass of vapor divided by mass of liquid plus mass of wave or if, you are talking about flow phenomena you replace this by the flow rates.

So, this gives you the vapor mass quality the higher the vapor content higher will be the value of x and therefore, the value of convection number will be larger or smaller will be smaller. So, depending on the volume vapor the quality vapor quality being very low you have larger convection number vapor quality being very high you have smaller convection number. So, depending on this convection number you can build correlations for heat transfer heat transfer rate heat transfer coefficient and so on as a function of this convection number because this contents the information with respect to the regime.

So, this convection number tells you in which regime you are in whether you are in a regime where you are you are pure liquid or pure vapor or somewhere in between and depending on that you can built correlations for heat transfer coefficient and similarly the other important number similar Jakob number. So, Jakob number tells you the relative magnitude of the sensible to the latent heats whereas, we define another number called boiling number it tells you of the total heat flux that you give that is the numerator. So, what fraction of that is going as latent heat of evaporation?

Also you can use this when you talk about the relative influence of mass flux to the heat flux driven boiling. So, in the flow boiling case you also have mass transfer I mean because of the convection. So, you have to therefore, bring in number to denote the order of magnitude of the heat flux driven evaporation to the mass flux driven evaporation. So, the boiling number relatively tells that importance of the heat flux driven evaporation to mass flux driven evaporation and usually this is used only in flow boiling. So, in pool boiling you do not use boiling number.

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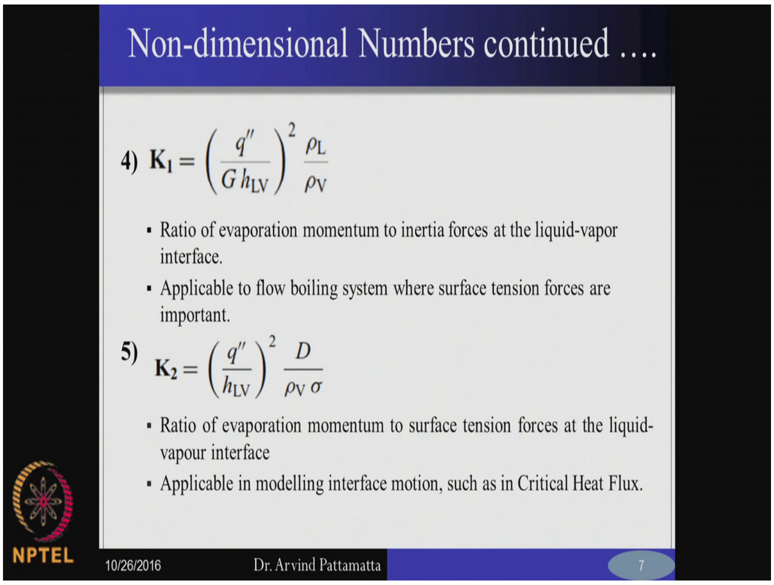

Non-dimensional Numbers continued ….

4) $K_1 = \left(\frac{q''}{G\,h_{LV}}\right)^2 \frac{\rho_L}{\rho_V}$

- Ratio of evaporation momentum to inertia forces at the liquid-vapor interface.
- Applicable to flow boiling system where surface tension forces are important.

5) $K_2 = \left(\frac{q''}{h_{LV}}\right)^2 \frac{D}{\rho_V\,\sigma}$

- Ratio of evaporation momentum to surface tension forces at the liquid-vapour interface
- Applicable in modelling interface motion, such as in Critical Heat Flux.

10/26/2016 Dr. Arvind Pattamatta

So, these are some of the numbers there are also other parameters which can be defined not. So, important, but the most important parameters are the bond number capillary number Jakob number boiling number Martinelli parameter and convection numbers. So, based on this you can actually build lot of correlations for different regimes.

So, just before we stop today I will show you some of the flow regimes that are therefore, for macro channels and. So, you can you can see very clearly there are two distinct regime. So, one towards the left, this particular regime is classical two phase regime where you can have 2 different components the adiabatic conditions you can mix them and you can produce this. So, one is obtained when you have vertical mode of operation the other is when you have horizontal mode.

So, this is your adiabatic two phase flow. So, the other is your phase change. So, when you heat this tube what happens now this is the phase change two phase flow and this is in vertical mode of operation the other is the same phase change in horizontal mode. So, therefore, you can have different kinds of two phase flow pattern maps flow, pattern regimes and maps. So, one where you do not heat it you just mix air and water in different proportions in different mass fractions and you generate whether you are in a vertical mode or horizontal mode different patterns.

So, that is the adiabatic case the other is you heat the tube you pass liquid at one end purely and you start heating and you observe how the two phase changes regime changes from one end to the other. So, there also you can have a horizontal and vertical mode because as I said the macro channels are sensitive to the orientation. So, therefore, typically when you start with single phase liquid and you start heating you see the bubbles multiple, bubbles forming and these bubbles elongate they become what are called as slugs and these slugs continue elongating. So, the core is filled with vapor, but it is surrounded by thin liquid film at the annulus which is sticking to the wall.

Now this core keeps increasing in size and finally, you will reach a point where this is called a mist flow; that means, the entire tube is diameter cross section is filled with vapor and the liquid is strapped as find mist within this vapor. So, it is just like your fag you have full of a vapor and inside that you have trap liquid. So, the same way finally, as the mass fraction keeps increasing you have very little of liquid. So, this liquid gets entrapped within a complete vapor and becomes a drop flow or a mist flow and finally, even that evaporates and you have pure vapor.

So, progressively from the inlet where your mass fraction can be equal to 0 you can reach a mass fraction of one. If you continuously heat this and this tube is sufficiently long enough you can see all these regimes happening and same way, if you orient it in a horizontal direction you will get similar patterns except that some pattern here is influenced by gravity and you have stratification of the liquid down and vapor upwards.

So, you will not have a clear annular flow that you find with the vertical alignment in the horizontal case. So, there you have a perfect vapor core surrounded by liquid in the horizontal alignment the liquid will kind of settled down and the vapor tend to settle up and you have stratification. But after that as your mass fraction keeps increasing here also it will slowly go towards a mist flow or a drop flow and finally, it becomes pure vapor.

So, tomorrow we will look at the flow regimes in the mini channels and I will quickly go over these regimes and we will look at the correlations for pressure drop and heat transfer co efficient.