Micro and Nanoscale Energy Transport.
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Lecture – 40
Nano Fluid Heat transfer Part 2

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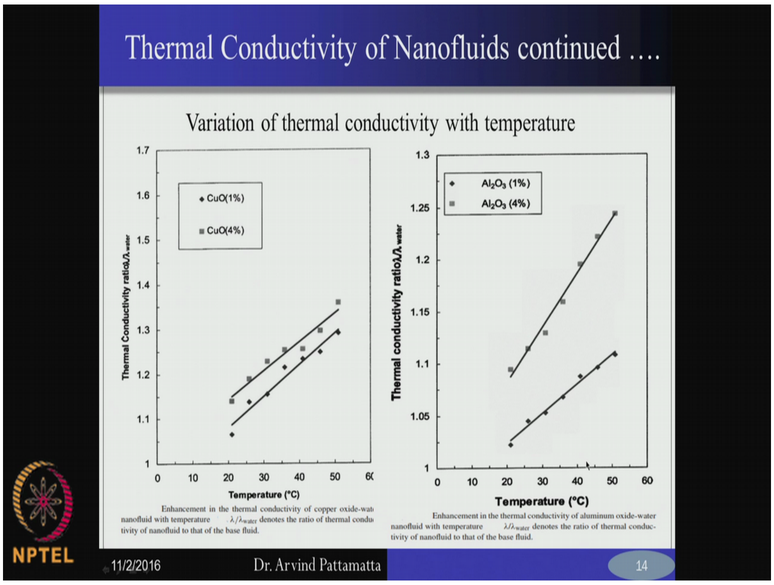

Good morning, we will look at the different models that can be used to predict thermal conductivity, effective thermal conductivity of Nano fluid as a function of the Nano particle volume fraction and most importantly also the dependence on temperature.

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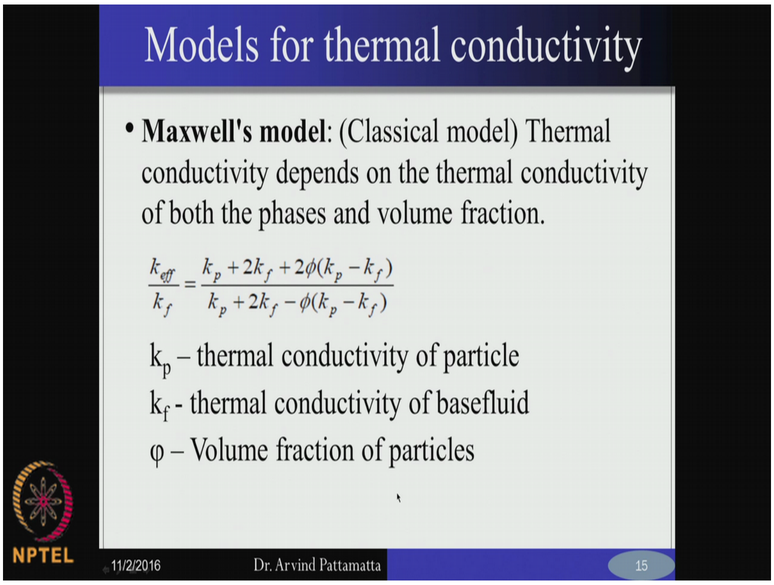

The dependence on the volume fraction can be accounted by models such as the Maxwell's model. Depending on the value of phi whether, it is 0 or 1, takes the case of for example, phi equal to 0 it takes the case of 0 base fluid, phi equal to 1 the Nano particle and some kind of weighted value of K in between K P and K F.

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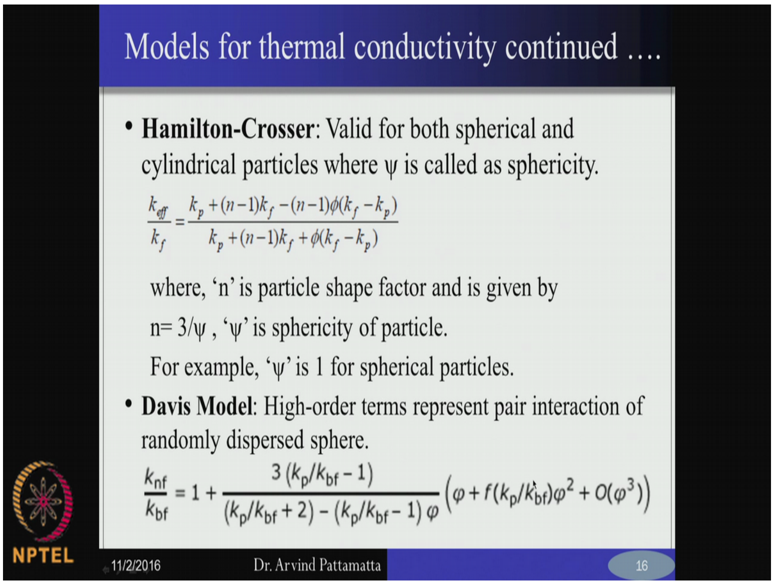

There are also models which account for the shape of the particle because the Maxwell model is actually for spherical particle. Modification to that is called the Hamilton crosser model.

This is quite popular when you want to apply this to non-spherical particle. We have parameter called the shape factor. This parameter is denoted by the notion N and this is equal to 3 by psi. Where psi is nothing, but is call the spheriity of the particle. It denotes how spherical the particle shape is. If sphericity is equal to 1, this is the perfectly spherical particle. If you substitute therefore, N equal to 3 into this expression, you will get the same expression as the Maxwell's model.

Therefore, for the limiting case of spherical particle, the Hamilton crosser model collapses into the Maxwell's model and for values of psi which is dot equal to 1, you can look at particle of different shapes, but nevertheless and there is also something called as Davis model which also includes some of the higher order terms, may be important if you want to look at the interaction between the Nano particles and if you do not include the second order and third order terms, then it becomes again equal to the Maxwell's model.

You see that these are the fundamental models used widely to predict the effective thermal conductivity of the Nano fluid as the function of the volume fraction, but very important behavior is the variation with temperature, which none of these models can account for. The variation in temperature is very clear you can see that although the base fluid shows reduction in thermal conductivity temperature; however, the Nano fluid on the other hand shows the continuous increase. This can be predicted or this can be modeled only if you account for the Brownian motion. The Brownian motion is the most important mechanism which can say why the thermal conductivity should increase to temperature. None of these models are actually accounting any temperature dependents into them.

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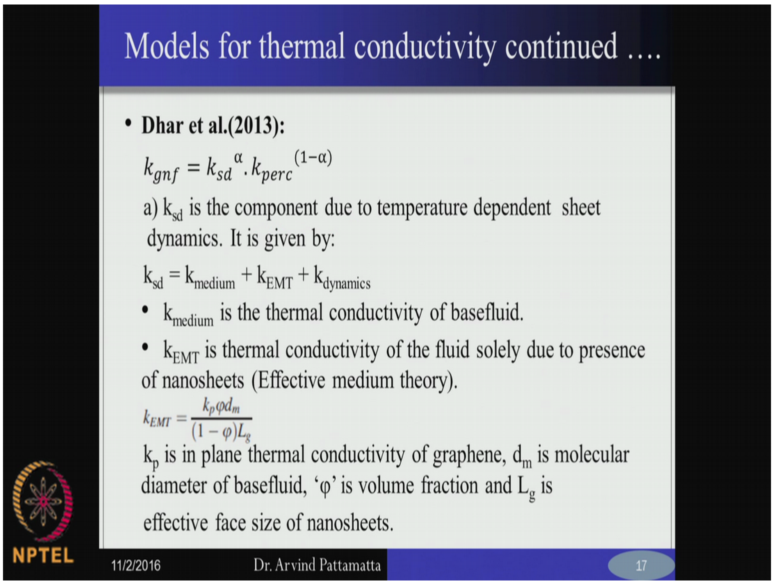

Therefore, 1 of the more recent models is our own work in our lab here. This is published in 2013 with the Ph.D. student in our lab.

This model is more comprehensive model, which we have built that accounts for 2 components. 1 is the random motion due to the Brownian effects. That is called the sheet dynamics. The sheet dynamic part consists of 3 components. 1 is the thermal conductivity of the base, the overall conductivity of Nano fluid. Now, if you break this into 2 components, 1 is sheet dynamic component, the other is the percolation component the sheet dynamic component includes the thermal conductivity of the base fluid, to which we add the Nano particle. Therefore, we also account for the thermal conductivity only due to Nano particles.

That expression is given separately. This is coming from what we call as effective medium theory, if you put here 5 equal to 0, this part will be 0 and 5 tending to 1. 5 can never be directly to 1, but 5 tending to 1 the D M, the ratio of you know D M by L G will be approaching 1 for that case because D M is nothing, but the molecular diameter of the base fluid which is of the order of the close to angstrom, where as if you are talking about L G, L G is the face size of the Nano sheets.

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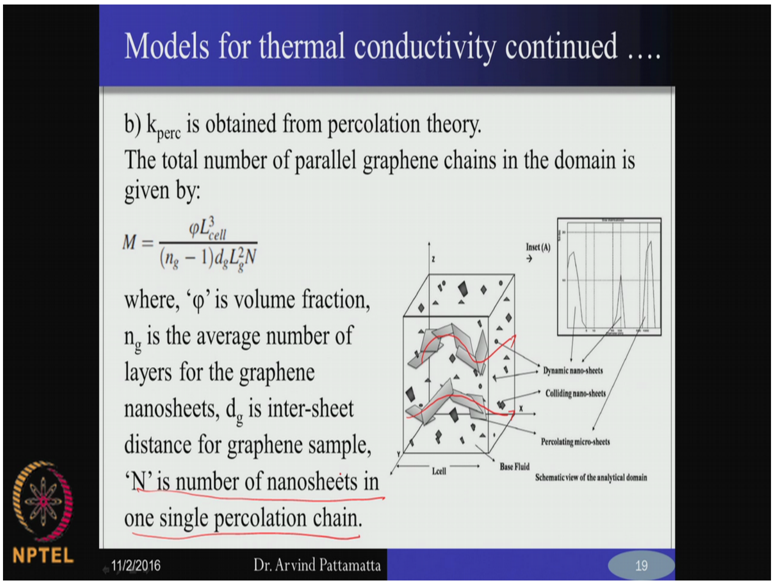

That means if you look at these the construction of a unit cell. We are looking at 1 unit cube of the entire Nano fluid in which we have these Nano particle dispersed.

The Nano particle can be generic, they can be of any shape you know any cross section. If you look at the generic case, they can be like sheets which are linked to each other. These are forming a certain links, if you have pure particle then you may not find this linkage structure to be dominant. It will be just disperse, but if you look at Nano sheet for example, carbon Nano tube, These more likely form chains. These chains consist of the lot of these micro sheets which are held together as linkages and there are several parallel layers like this. If you therefore, take the length of any particular micro sheet, that length is basically the face size of these sheets.

Once you put this, therefore, the value of L G will be of the order of few 100 Nanometers whereas; the value of D M will be few angstroms. Therefore, if you phi is going towards 1, something like 0.99. This 1 minus phi will be a very small term. Therefore, that multiplied by L G will go to the value of D M. That the denominator and numerator the D M by 1 minus phi L G will be approaching unity and therefore, the value of K E M T will approach the value of K P, for limiting case phi approaching 1. You have therefore, contribution from the base fluid, you have contribution from the Nano particles plus you have contribution from the Brownian motion. These are the 3 components which are included in the sheet dynamic part. The contribution from the Brownian dynamics is simply given by an expression which is a function of the Brownian velocity U B. It is also a function of other things like volumetric capacity Nano particle volume fraction phi and D by temperature and so on.

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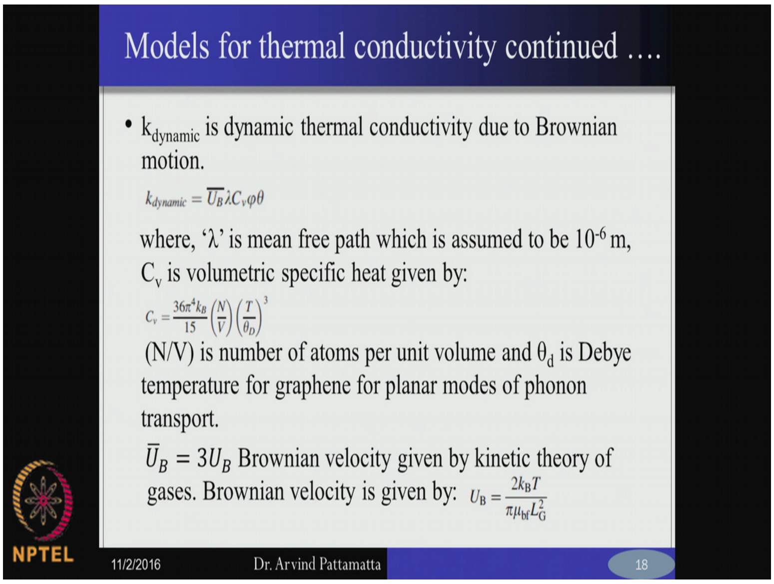

And also the mean free path, but most important is strong function of the Brownian velocity. The Brownian velocity is given by the Einstein expression. This is also call the Einstein scope expression. This also tells you that the Brownian velocity is directly proportional to the temperature and inversely proportional to the size of the particle; the smaller the size, you larger your random velocity and so, is dependents with temperature therefore, if you are applying this particular expression. This now accounts for dependents of thermal conductivity both on volume fraction as well as temperature through the Brownian motion. Therefore, if you are able to use this model, you can accurately predict the variation of the thermal conductivity temperature. We have checked this model with different kinds of Nano fluid including particle type Nano fluids, including sheet type of Nano fluids and they seem to work very well and good prediction.

Now the other component which is very important for the sheet type of Nano fluids like carbon Nano tubes. This is called the percolation part. As I said, if you have carbon Nano tubes, they will form linkages with several of these Nano sheets which are linked together in a chain and several of these chains in parallel. Therefore, we have to also look at the conduction through these chains. There is the conduction of heat from for example, left to right. There will be a conduction of heat through these chains because they form a conduction network similarly through them.

Not only it is a random motion, but also they form a chain which will promote network for transport of heat. This is called the percolation component and to understand to this percolation component we have to first estimate how many number of such parallel chains can be formed. There is 1 empirical expression we have used to calculate this capital M which denotes the number of parallel chain and within each chain, you have several Nano sheets. You can say capital N here represents the number of Nano sheets in 1 chain. That is basically given by this N here. Once you know the number of Nano sheets in 1 chain, you can use this empirical correlation to find out how many number of chains that can be actually formed.

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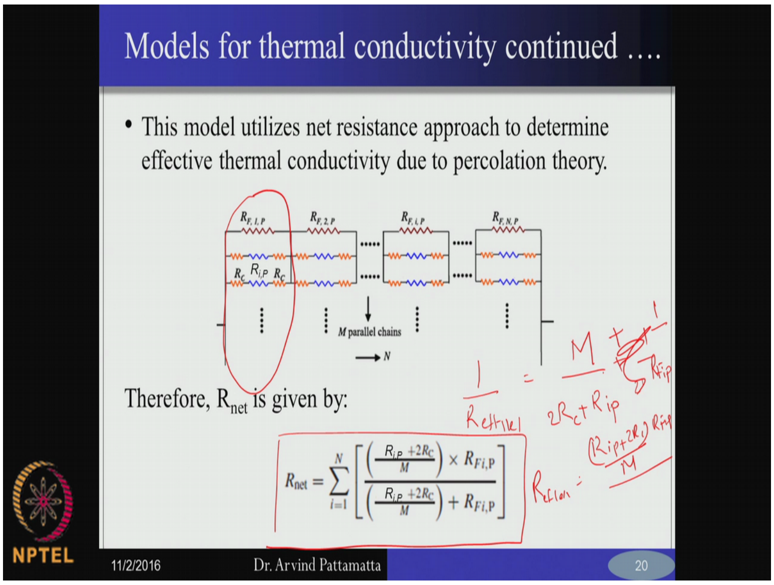

Now you can draw resistance network analogy for the thermal resistance; that means, what are all the resistance is acting? You have if you are talking about heat conduction through this is all in series. Through 1 chain this is in series. Through the Nano sheet you have conduction and between the Nano 2 Nano sheets you have interfacial thermal resistance. Actually these 2 Nano sheets are not exactly touching each other. There is a small gap, I mean you have actually the fluid separating these 2. There is actually contact resistance between the fluid and the solid.

Therefore, in effect if you take 1 Nano sheet you have conduction resistance plus twice the contact resistance on either ends. That is the serial series component of the resistance; you also have a parallel component of resistance which is heat conduction through the base fluid itself and therefore, these M links are all in parallel. Therefore, if you draw the resistance network analogy, essentially you have in series the contact resistance on either ends and you have the conduction resistance to the Nano particle. These are all in series and you know you can have this for N number of chains. This is for 1 Nano film or Nano particle.

Since you have capital N number of Nano particles in 1 chain, they can all be in series and in parallel you have for M number of chains Nano particle chains. You can have all these in parallel. You have M parallel chains and N serial Nano particles forming particular chain not only that, you also have the fluid resistance which is acting in parallel. For each unit cell if you assume this is 1 unit that is 1 Nano particle. You also have the base fluid which is conducting the heat parallel. Therefore, for 1 Nano sheet you have the base fluid in parallel and you will have such M parallel linkages acting. Then you have to repeat this for capital N number of Nano sheets acting in 1 link.

You have simultaneous resistances in series and parallel. Therefore, the net effective resistance, you can actually very quickly we can you can derive this, because first consider only the series the parallel resistances here may be you can all try this out now. You consider only this resistance of 1 Nano sheet all in parallel. Find out what is effect resistance of this. That is 1 by R effective parallel is equal to 1 by. You have in series R C, 2 times R C plus R I P and there are M such linkage M M such linkages in parallel. Therefore, this should be plus 1 by 2 times R C plus R P. M number of time; therefore, you can replace this by M by this. Now plus you have the base fluid which is acting in parallel for a particular Nano particle.

Therefore, your R effective parallel will be nothing, but R I P plus 2 2 times R I C times R F I P by this is M divided by plus. If you if you take the reciprocal of this, this is basically product in the denominator summation in the numerator if you take reciprocal product moves to the numerator, reciprocal the summation moves to the denominator. And then finally, what do you have? This is 1 set of effective resistance. Now you have series of them so capital N number of them. Therefore, the effective resistance should be summation of this over N number of these Nano particles. Therefore, finally, from that you get this expression. All of you can quickly check if you are able to get this.

Basically we start with 1 Nano sheet, everything in parallel and then for extending in this for N number of Nano sheets in all over all the linkages. Basically this R I P is nothing, but the conduction resistance through each Nano particle and R C is the contact resistance between successive Nano particles.

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We are con considering together as 1 fluid resistance.

Student: upper resistance as well as lower resistance is the single.

Correct. What we say is the total fluid resistance is included as 1 resistance in parallel and each of these links, we are considering the resistance is separately in parallel. This is the approach we follow therefore, from once you estimate the net resistance. We can calculate thermal conductivity component due to percolation.

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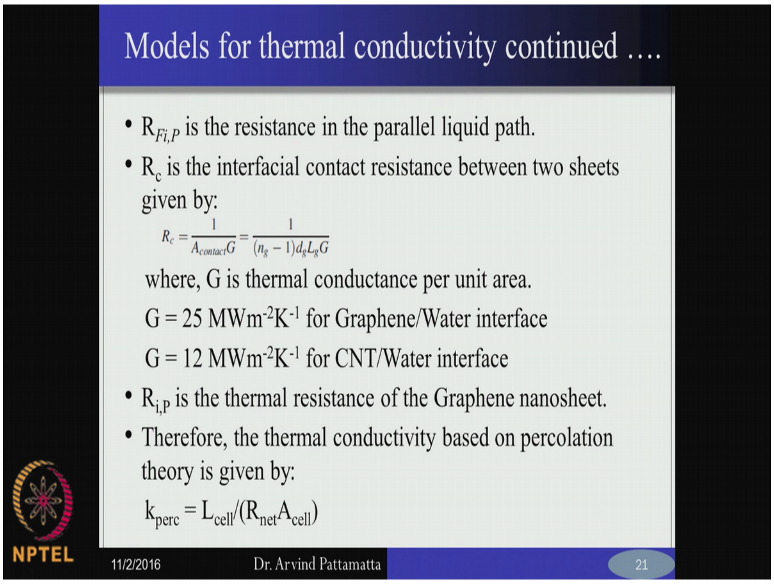

How do you calculate by using this expression finally, L by R net A cell. You remember you furrier's equation where we express your resistance conduction resistance as L by K A. From which we can calculate K S L by R A. Same way now we our L is nothing, but the length of the cell; that means, this cell is a unit cell with the particular length L and this as total net resistance R net and the corresponding cross sectional area of the cell K cell. Understand? From this we get the K percolation component and we can also estimate the conduction resistance from another empirical correlation which depends on the thermal conductance per unit area and depending on the type of Nano fluid, you have to use the value of G appropriate.

From the components of K percolation and sheet dynamics, we use a power law rule to calculate the total thermal conductivity of the Nano fluid. We use a factor alpha and 1 minus alpha to take the individual contribution. Suppose if there was it was purely spherical particles then what will happen to the percolation component? Percolation component should not be there. If your value of alpha equal to 1 then K Nano fluid will be only K sheet dynamics so; that means, only Brownian motion is responsible for increase in thermal conductivity, but if you take Nano fluid which is purely carbon Nano tubes, then these carbon Nano tubes form these flakes structures, linkages and your Brownian component will be almost 0 because they cannot move as fast like the spherical particles. In that case your alpha will be 0. Your total effective conductivity will be only coming from the percolation conductivity. For Nano fluid like grapheme, this has somewhat intermediate it is neither to be big form huge linkages not too small to just simply move around. It will have contribution from both components Brownian components as well as the conduction component. In that case we use a value of alpha may be 0.7 or 0.8 and it will take into both these components.

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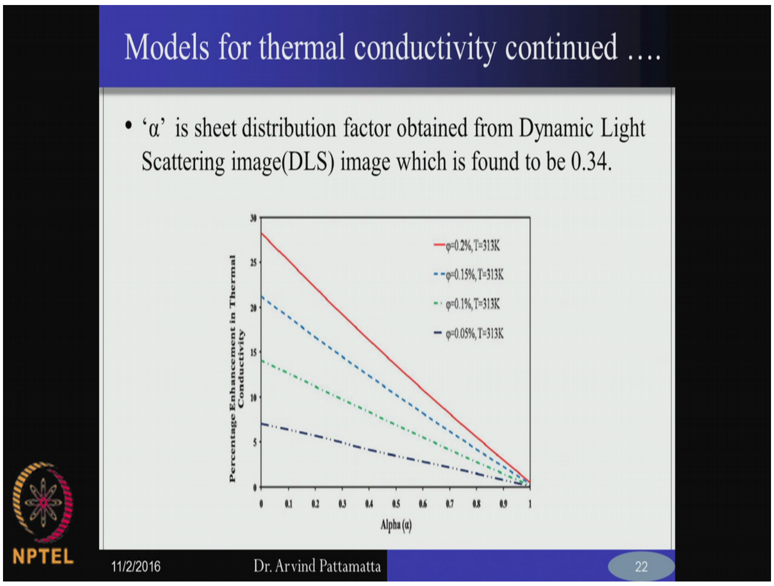

Therefore, the alpha is called the sheet distribution factor. It tells you how much weightage you have to use for the percolation component verses Dianam the Brownian motion. See for example, grapheme, we use the value 0.34. We give more weightage to percolation, for the grapheme compared to sheet dynamics. For purely spherical Nano particle like alumina, copper, metallic, Nano particles then we put alpha equal to 1, pure sheet dynamics component. This is a very very comprehensive model, which accounts for explanation on Y and how the thermal conductivity increases with temperature with volume fraction not only for 1 type of Nano particle, but different shapes of Nano particles.

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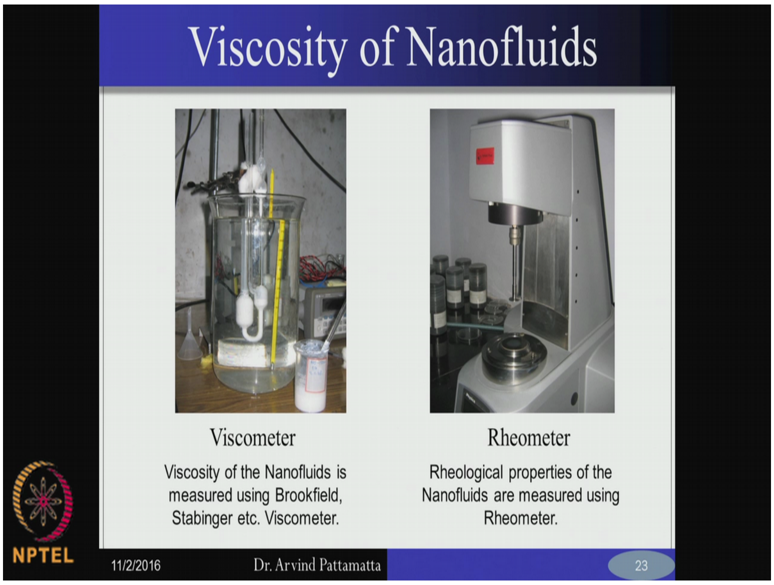

This is probably 1 of the best model that are available, for in literature which can be used for a wide different kinds of Nano fluids and you can get satisfactory agreement. This is 1 component, the other is to estimate the viscosity of this Nano fluids. Now, when you add the Nano particles to base fluid, your viscosity also will increase and therefore, you do not know 2 things. 1 what is the effective viscosity, you cannot take a simple volume average for effective viscosity here you have to determine them or we have to have a good model which can predict and you do not even know whether you will always get Newtonian fluid. That is the second question.

Therefore, if you want to simply estimate only the viscosity, you can use a viscometer, which gives you directly what is the dynamic viscosity of this fluid, but if you want to really know if this is a Newtonian fluid or not we cannot use a viscometer, but we to have to use a Rheometer. Rheometer, it gives you, what is the, for a given shear stress? It gives you what is the corresponding strain rate. So, you plots stress verses strain verses stress and you will yourself know whether this is linear curve or it is changing somewhere so that we can approximate this as a Newtonian fluid or non-Newtonian fluid. Therefore, the Rheometer in that sense is even better to assess the fundamental Newtonian behavior of these Nano fluids, but most of the basic Nano fluids like alumina, copper, what are even carbons Nano tubes graphite or very small volume fractions. Mostly they behave like a Newtonian fluid. We can use this like the way you measure thermal conductive with hot wire technique, we can measure viscosity of any fluid need not be Nano fluid say whether using a viscometer or Rheometer.

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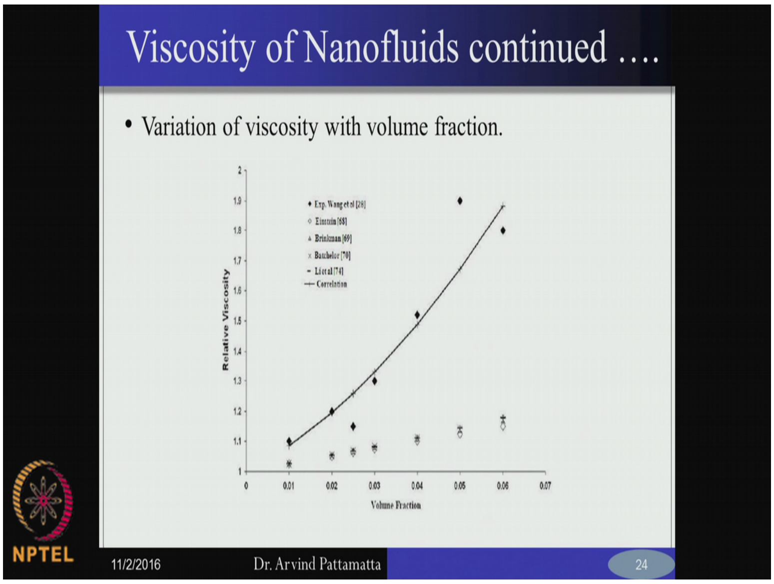

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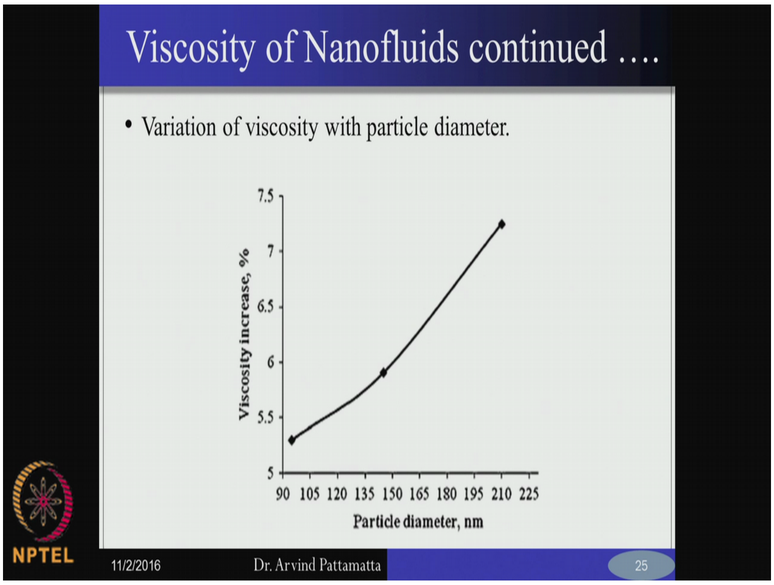

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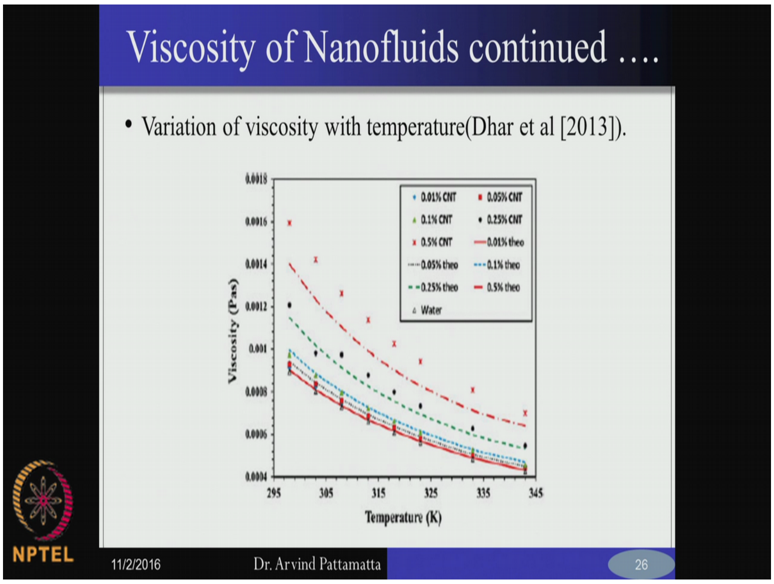

And we can get the effective viscosity and we can see that this is a very strong function of once again the volume fraction. The volume fraction increases considerably and also with the temperature, the volume fraction drops. For the fluids again with increasing temperature the viscosity actually drops. Overall the Nano fluid also shows this behavior;

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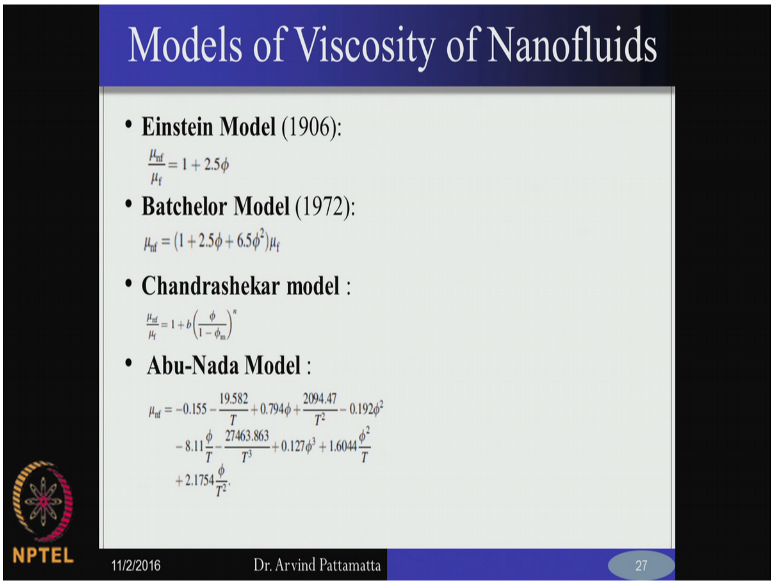

However, you have to have again accurate models which can show, predict the behavior of a variation of the Nano fluid viscosity with respect to both Nano particle volume fraction and temperature, the model such as the Einstein model, bachelor model and Chandrasekhar model. They are used for suspension, they have been used for a long time, but there are all only functions of phi and there not comprehensively built in temperature relationships. The temperature relationship affectively comes from only the base fluid viscosity as a function of temperature, the model by Abu Nada for example, as explicitly dependence on temperature for the Nano fluid also. These are some of the common models which can be used, some of them mostly have been a obtained from experiments and some from simple theory.

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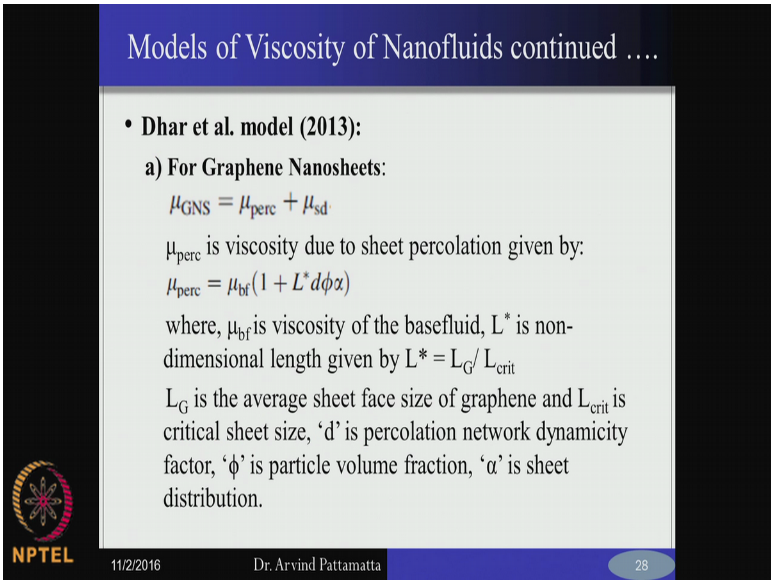

We have also proposed a symbol or model, using our peculation a component and sheet dynamics component. It is not that the percolation and sheet dynamic affects only the thermal conductivity, but also they play a very important role in the viscosity as well. Your sheet dynamics component and percolation components for viscosity are separately calculated using these expressions. For example, here L star is nothing, but the non-dimensional length which is the size of the Nano sheet divided by some critical length and D is the D is called the percolation network dynamicity factor; phi is the volume fraction alpha is the sheet distribution. If suppose, you take the case of pure spherical particles, percolation components should be 0, in that case you just only have the sheet dynamic components.

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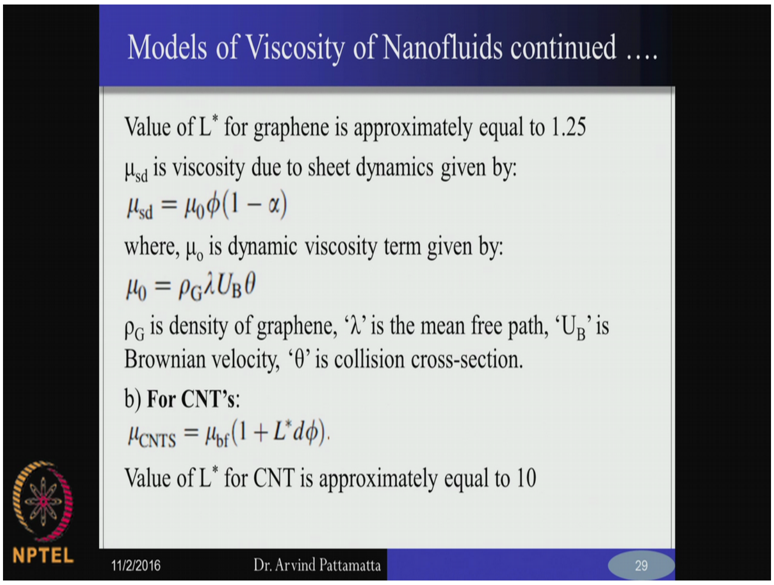

If you substitute, for example, alpha equal to 0, you have only the sheet dynamic component and the percolation component will disappear. You have new percolation will be only mu base fluid. Mu base fluid plus the sheet dynamics component will be there. Mu not here from the dynamic sheet dynamics point of view, it is again a function of Brownian velocity. What it says the Brownian velocity also affects the viscosity, not only thermal conductivity, but also it describes the viscosity increase. Higher the Brownian motion, more is the increase in the viscosity and, this is and now again the dependence on temperature is also brought in through the Brownian velocity. We have used this model, for example, if you take the case of carbon Nanotube, the value of this non dimensional length L star is approximately equal to above 10.

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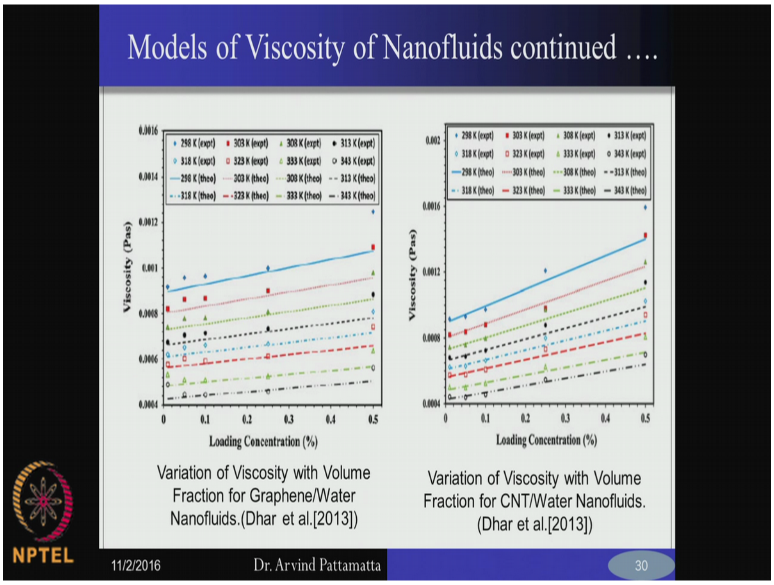

And if you use this, we have found that this model can also very accurately predict the effective viscosity of the grapheme water Nano fluids, carbon Nano tube water Nano fluids. 1 on the left is grapheme water; the other on the right is carbon Nano tube water. All functions of different volume fractions and at different temperature also, not only the volume fraction dependence, but the temperature dependence is also properly predicted by these models.

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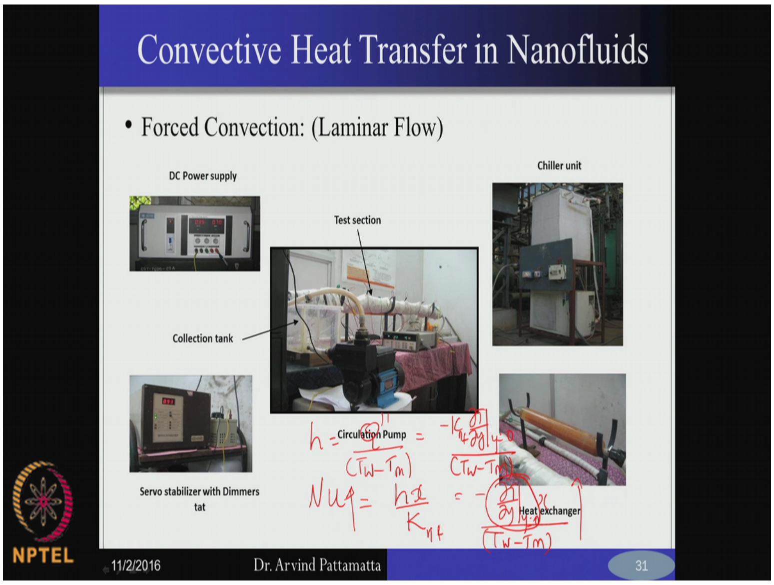

We will finally, move now in to the heat transfer characteristics. We have whatever we have talked about till now, it is a only the case were it is static, static fluid were we measure the thermo physical properties now when you start motion, bulk motion what happens if you have Nano fluids replacing the bulk fluids? For that several experiments had been conducted on the forced convection, single phase forced convection, natural convection, then phase change. Quickly I will run over all of these. The first convection experiment also we had in our lab before students who were doing this.

This is a kind of a setup where we heat the tube using a D C power supply and we pass fluid. First the base fluid and look at the Nusselt number, calculate the Nusselt number of the base fluid by measuring the heat flux and also the temperature distribution along the wall of the tube, then we replace this with the Nano fluid and again they do the same thing and then we plot the ratio of the Nusselt number Nano fluid by Nusselt number of the base fluid, and we check what kind of enhancement we get using Nano fluid; that means, it is not just enhancement coming from thermal conductivity itself, but that coming from the convection component because if you define Nusselt number, the say if you say H. H is nothing, but heat flux divided by T wall minus T M. This is a bulk temperature or bulk mean temperature.

Your Nusselt number now becomes H X by K and this Q and the wall is nothing, but minus K D T by D Y say at Y equal to 0. Now, for the Nano fluid, this becomes K Nano fluid. If you use Nano fluid in the definition of Nusselt number, what happens if you substitute this? This will become minus D T by D Y. Y equal to 0 X by T wall minus T M. The thermal conductivity gets cancelled out so; that means, any increase in the Nusselt number, if you replace the base fluid with Nano fluid, should be purely because of increase in the temperature gradient and not because of increase in the thermal conductivity, whereas if we look at H and if you and you look at values of H, H can be higher, but Nusselt number, if you divide it by thermal conductive heat of the Nano fluid, the effect of thermal conductivity increase will be compensated. That gets cancelled out. Essentially you are only relating Nusselt number to the temperature gradient. If a temperature gradient increases; that means, you are saying the Nano fluids have a better heat transfer characteristics.

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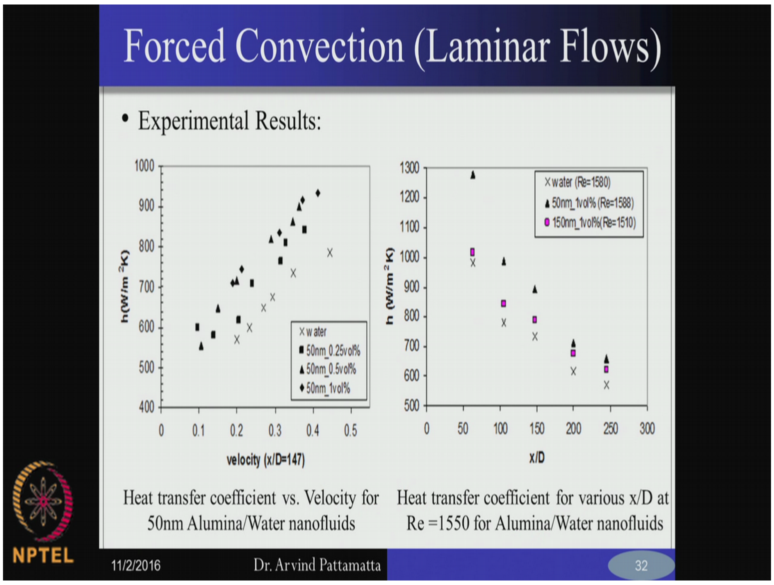

Most of the literature, what they do is they mainly plot heat transfer coefficient, but of course, you know when they are doing this, they sometimes have this problem where for the base fluid you use K of base fluid and for the Nano fluid we use K of Nano fluid. You do not know whether the increase in H is due to the higher value of thermal conductivity or it is actually due to increase in the temperature gradient. This is actually where some of the literature becomes confusing.

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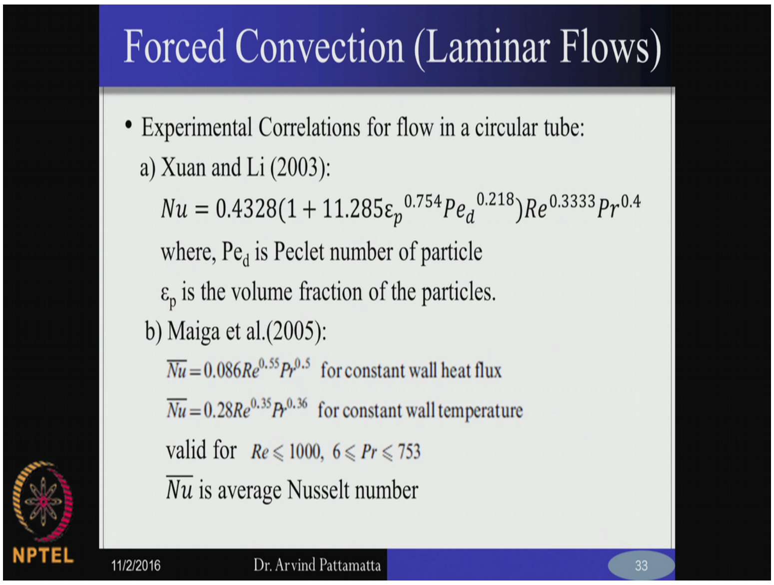

And the correct way of plotting it will be to actually plot the Nusselt numbers. The mussel number does not have the enhancement due to thermal conductivity. There is some standard correlations for laminar flows.

1 is proposed by Xuan and Li, which states that even in these are average mussel numbers; that means, you are not looking at either developing region or fully developed region, but overall for the entire tube which has both these components, developing and developed you are calculating the average Nusselt number and this average Nussult number is expressed as a function of Reynolds number prenatal number. Now also as a function of the Nano particle volume fraction and for example, Xuan and Li have used Peclet number, Peclet number is nothing, but product of Reynolds and prenatal number and, but how are this is defined for the Nano particle so; that means, we use the diameter of the Nano particle in defining the Peclet number these are correlations built from lot of experiments.

So, experiments like this for heat transfer coefficient Nusselt number have been done for different Reynolds numbers, prenatal numbers different volume fractions and they have built a very detailed correlation and similarly there is 1 by Maiga At all in 2005. Depending on the boundary condition whether it is a constant wall temperature or constant wall heat flux and they have given 2 different expressions as a function of Reynolds and prenatal number. Overall what it says that if you replace your base fluid with Nano fluid here? For example, if you put A epsilon P epsilon P is the volume fraction if you put this to 0 you get the base fluid average mussel number and if you add Nano particle to this the Nusselt number is increasing. Therefore, most of the experiment say that the addition of Nano particles lead to an improvement in the convective heat transfer rate.

This is a Nusselt number; you can say that this is not due to thermal conductivity increase alone, but also convective heat transfer enhancement. The thermal conductivity enhancement will already contribute to conduction heat transfer, but we are only looking at temperature gradient which is the measure of convective heat transfer increase. Clearly most of the experimental studies agree that there is an increase in the Nusselt number with the addition of Nano particles, but only the percentage increase is not very consistent. Some people claim it can be 10 percent, some people claim it can be 15 percent or some 20-25 percent. It is, there is not a very consistent number.

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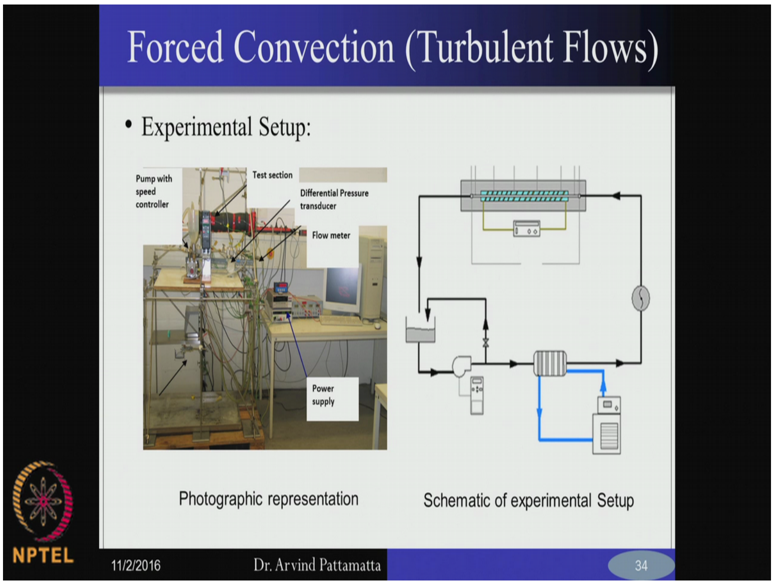

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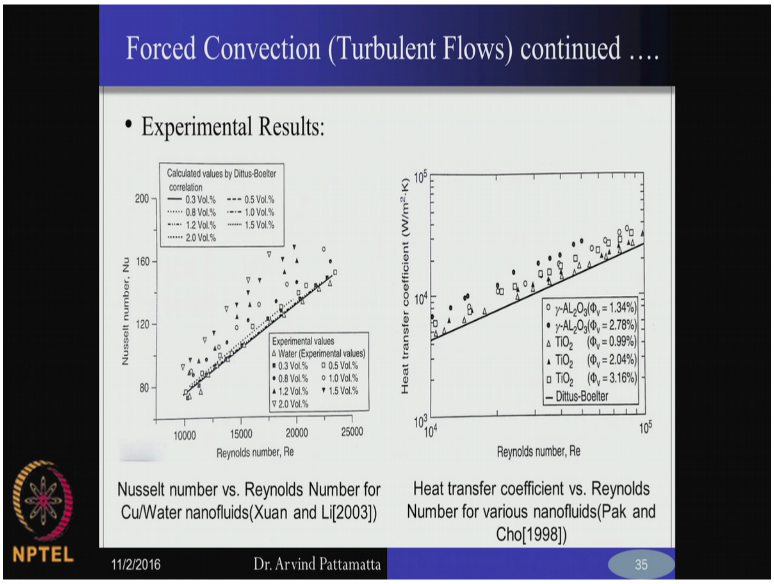

Similarly in turbulent flows, also they have seen that there is possible enhancement with addition of Nano particles. Same Xuan and Li themselves have conducted experiments in the turbulent regime.

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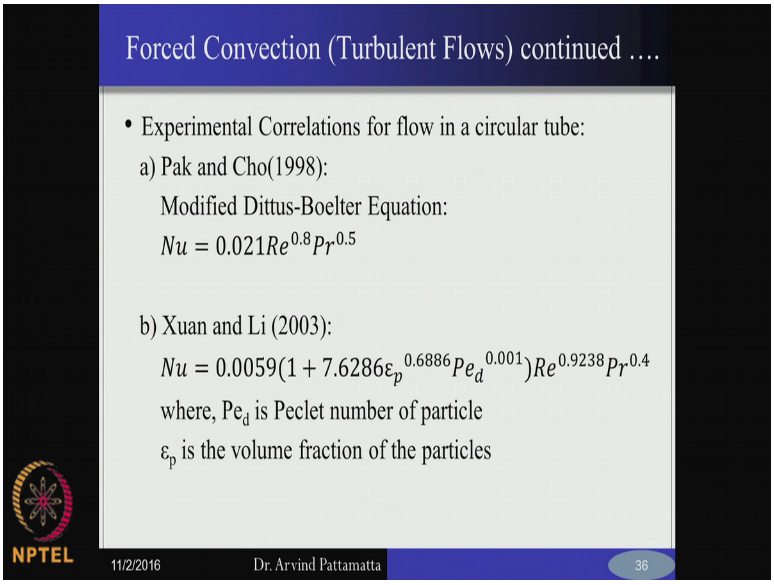

And they have again given a similar expression, similar to the laminar flow regimes. The turbulent flows also have a function of the Nano particle volume fraction and Peclet number. Only the constants are little different, some people have also used the Dittus Boelter equation which says that, there is a dependency on Reynolds number to the power 0.8 and prenatal number to the power either 0.3, 0.4. They have modified that little bit for the Nano fluids by changing the constants for the prenatal number and also the constant in front that is 0.021 and this was given by Pak and Cho. This is a very simple expression does not have present account for the volume fraction whereas, the expression by Xuan and Li explicitly states that for different volume fractions you have different values of Nusselt number.

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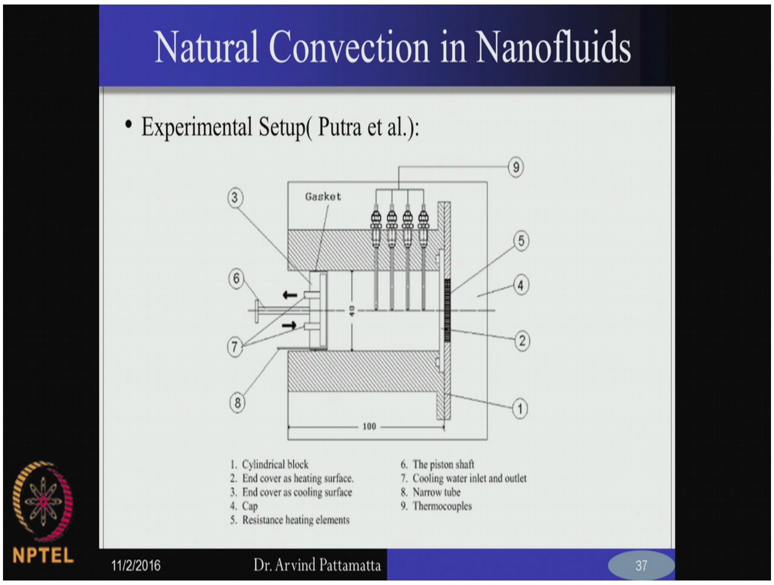

These are average Nusselt numbers.

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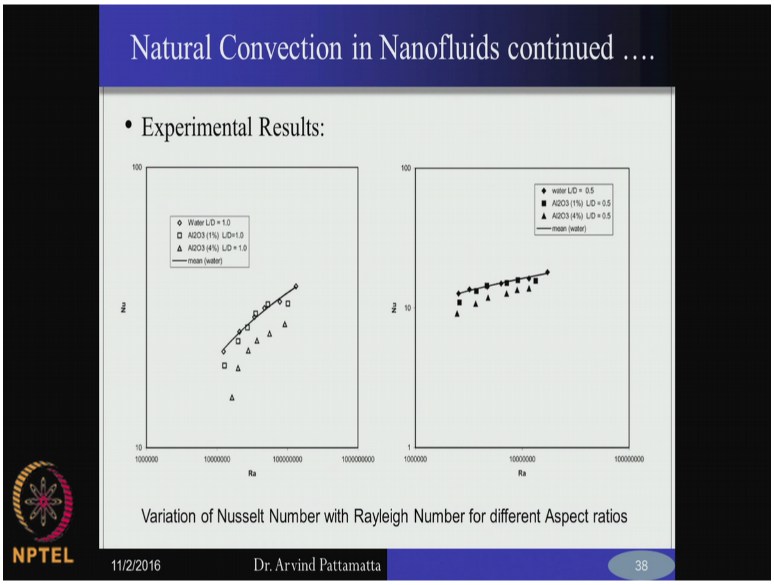

Now coming to natural convection on the other hand, the experiments done by Utra at all, natural convection in a cavity shows that; however, unlike the force convection experiments, there is deterioration in Nusselt number in the natural convection case because the problem here is if you add particles with the density higher than the base fluid. Your effective density is increasing and therefore, what happens to the buoyancy force? It reduces. The higher the effective density, the smaller is the buoyancy force and therefore, the natural convection which is strong function of density. Lighter fluid will be able to experience natural convection better than heavier fluid. Therefore, there is deterioration with the addition of Nano fluids in terms of natural convection.

Nano fluids are always not giving in a better heat transfer everywhere. Depends on whether you are in the first convection or natural convection.

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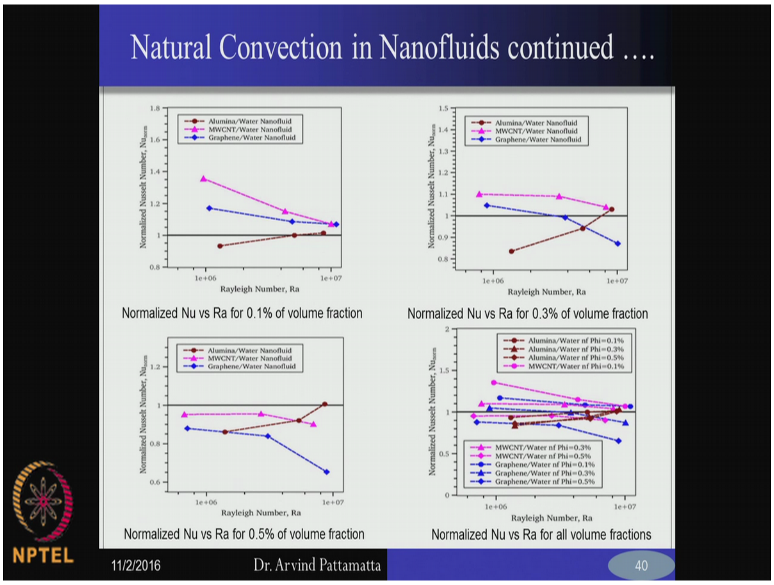

But; however, when we did these experiments in our group, we found that yes, there is a deterioration we find as long as we use the regular spherical Nano particles like alumina, but if you move towards carbon Nano tube, flake type of Nano particles on the other hand we see enhancement. In this particular a figure first figure we have 0.1 percent volume fraction of all Nano fluids. We have plotted the Nusselt number of the Nano fluid by Nusselt number of the base fluid therefore, this value equal to 1 means it is equal to the base fluid value. If you look at carbon alumina, alumina shows that for all Rayleigh numbers, it is always less than the base fluid or at the best it is only equivalent to the base fluid. Whereas, when we add carbon Nano tube on grapheme they show enhancement of up to 35 percent or 30 percent at Rayleigh number of 10 power 6, If any Nano particle addition, which contributes to overall increase in the density, should result in deterioration of buoyancy. Why does carbon Nano tube and grapheme contribute to and enhancement? This was again something which we cannot explain very simplistic ways. Then we found out that there are slip mechanism which play very important role you know we did a scaling analysis in which we found out that several forces like drag force also play very important role apart from Brownian force so on. What we have obtained from the scaling analysis is the drag is a very important; drag force is a very important contribution especially if you look at flake type of Nano particles like Nano carbon Nano tube and grapheme compared to spherical Nano particles.

That is causing an enhancement even though the overall density is increasing. The heat transfer or the natural convection is augmented by means of this drag force. That is the only way that we can explain why certain Nano particles like carbon Nano tube and grapheme can result in an enhancement while general theory is any heavier Nano particle should contribute to deterioration.

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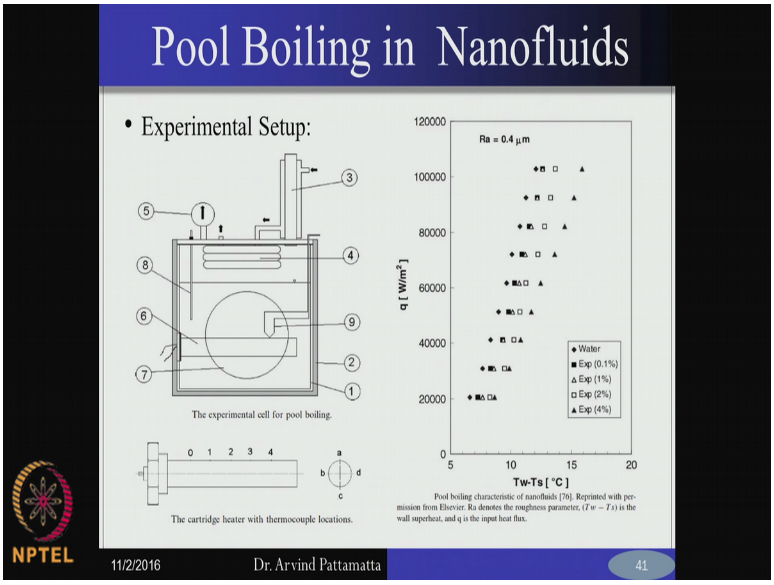

These are some recent results which we are in the process of publishing. These are with respect to the single face convection when we go to phase change for example, pool boiling that is we just have a cavity filled with Nano fluid and we look at the boiling characteristics. We are finding that generally with increasing volume fraction the heat transfer coefficient decreases with the Nano fluid.

If you therefore, plot Q verses T wall minus T S you take the ratio of at any at any value of T wall minus T S, you calculate Q, the value of Q will be smaller if you add Nano particles; that means, the pool boiling heat transfer coefficient actually comes down with the addition of Nano fluids.

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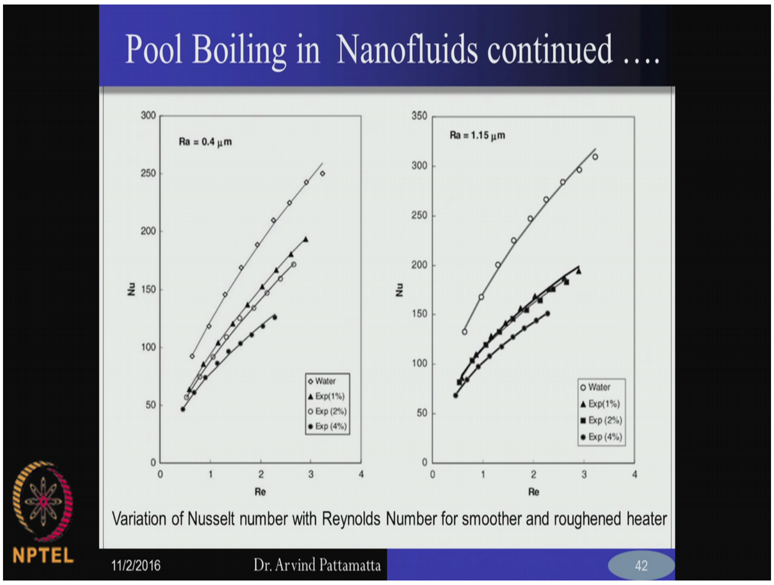

Therefore, if you plot this as Nusselt number, you can see that the Nusselt number actually deteriorates in the pool boiling case.

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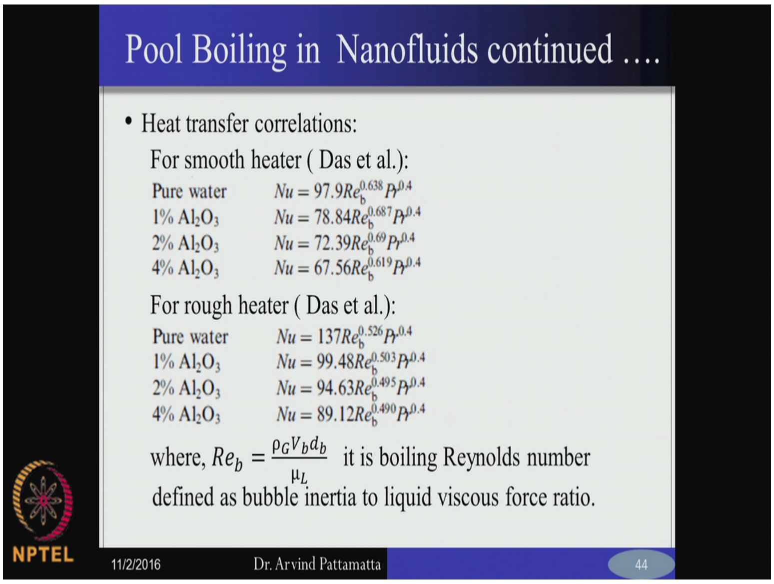

We have also some correlations developed you know from our lab itself professor Das and their group they have done this for this concentrations and for this heater configuration. Depending on weather you have a smooth heater or rough heater, a rough heater will have a higher value of Nusselt number compared to a smooth heater.

You can see all this constants are multiplying constants are larger in the case of rough heater because of the overall higher heat transfer coefficient because the roughness will promote addition nucleation sides, which will improve the nuclide boiling capability. These are some simple correlations in which there are functions of Reynolds number, here Reynolds number we have to be careful. It is not the flow Reynolds number it is based on the velocity of the nucleating bubbles and the bubble diameter. These bubbles which are just rising from the surface, from the surface of the heater all the way to the top, they have a certain bubble velocity and bubble diameter some average values which you can put in and using that you can predict the Nusselt numbers.

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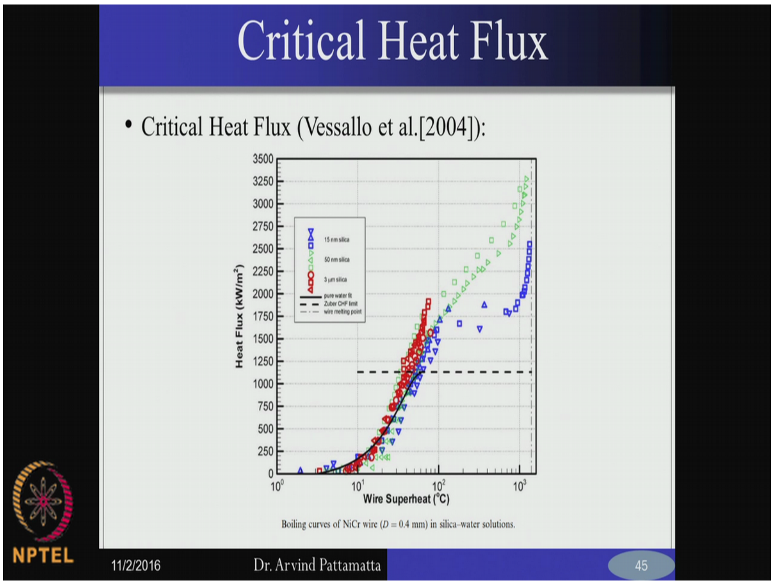

These are or for the pool boiling case and a very important aspect of Nano fluids is not only the deterioration of heat transfer coefficient, but the critical heat fluxes enhanced by the addition of Nano particles. This is very very important for example, for nuclear safety. If you are talking about boiling water reactors, these boiling water reactors they their boiling at say certain values of critical heat flux. Now if you increase the value of critical heat flux the chance of transition from a nuclear boiling to film boiling is reduced because you are augmenting that cap. If this was lower very quickly you can transition from the nuclear to the film boiling. So, this is very good this is prevent from the dry out you know that can lead to no vapor pressure increase and explosion chances and all that. From cooling point of view this is a very important aspect of Nano fluids.

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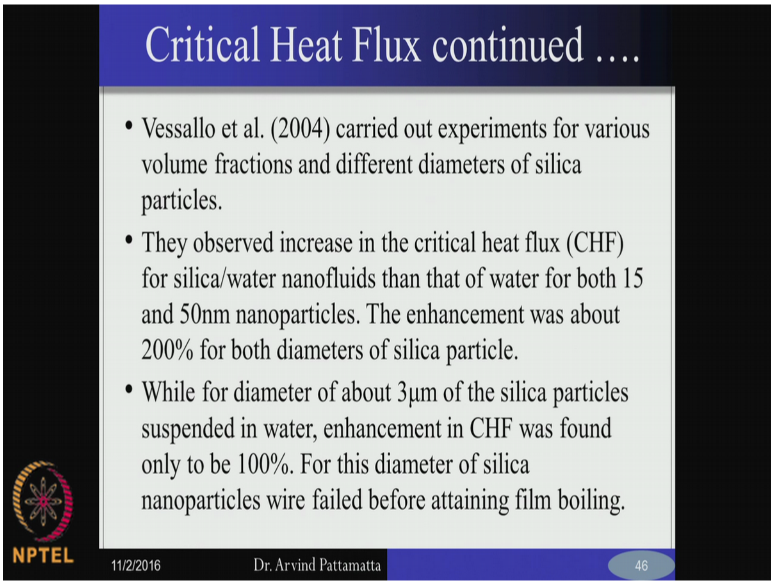

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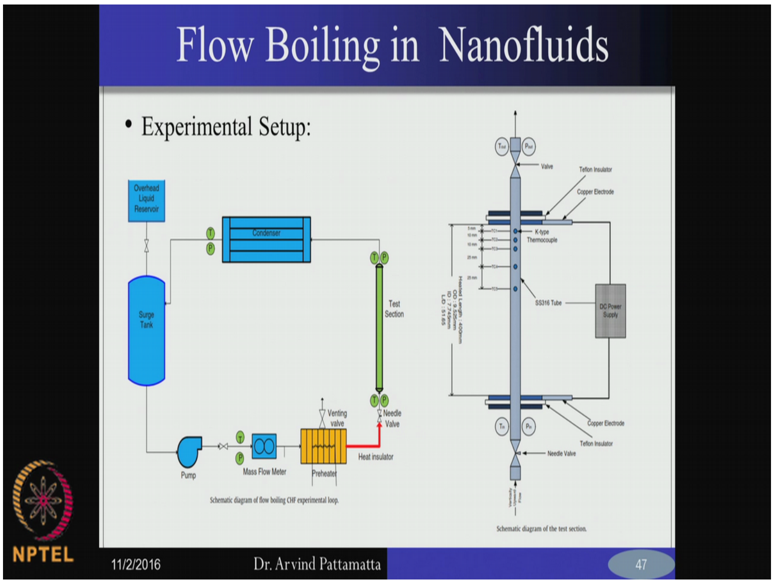

In the case of pool boiling, you see that the critical heat flux is augmented and very large values, you know sometimes it is of the order of the 200 percent sometimes it is of the order of 100 percent. Finally, coming to flow boiling there have not been many studies, Flow boiling of Nano fluids.

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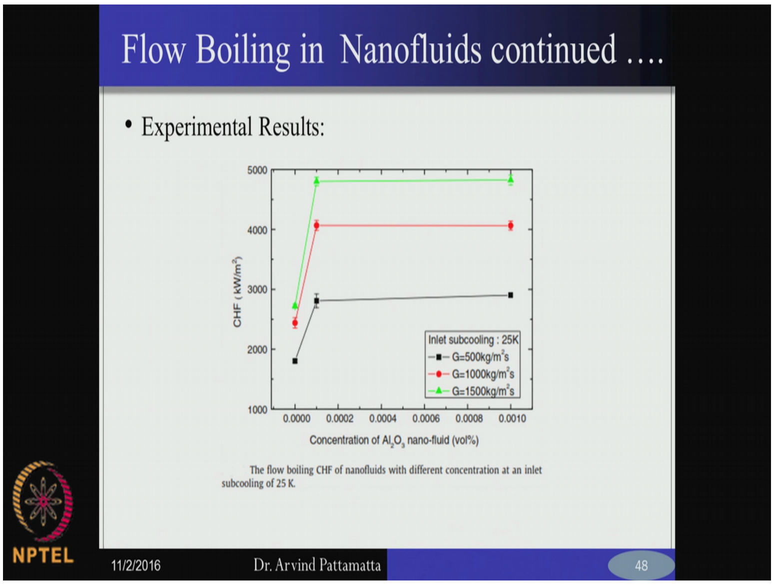

There also in the flow boiling also they have shown that the critical heat flux can be augmented by the use of you know Nano fluids. This is for different Reynolds numbers. As you change the Reynolds numbers, the critical heat flux its flow boiling increases and also with the addition of Nano particles, there is an augmentation in the value of critical heat flux

I will kind of stop here with this kind of gives you an overall summary about the heat transfer convective heat transfer characteristics because there are still lot of topics which are for in ongoing research is been conducted. This is not a closed ended subject. I am only giving you some important correlations which you can use, but the other things a still being you know developed. With this we will stop our discussion on Nano fluid and from tomorrow, the next couple of classes we will look at our last topic which is measurement techniques, measurement techniques in Nano on micro scale. I will see a how much I can basically cover in these 2 classes; I will try to brush through them.

Thank you.