Particle Characterization

Prof. Dr. R. Nagarajan
Department of Chemical Engineering
Indian Institute of Technology, Madras

Module No. # 12
Lecture No. # 33
Practical Relevance of Particle Characterization: Nano-Fluids

Welcome to the thirty-third lecture in our Particle Characterization course. In the last few lectures, we have been discussing nano-particles. We have discussed methods of synthesizing nano-particles using bottom-up and top-down approaches. We have also talked about properties of nano-particles, dispersion of nano-particles, and finally, methods used for characterization of nano-particles.

So, in today's lecture, we are going to look at another aspect of nano technology that involves nano-particles, and that is essentially heat transfer enhancement in fluids through nano-particle additives. These are known as nano-fluids and they are being increasingly used in heat exchange applications to enhance the heat transfer properties of the fluid by orders of magnitude.

So, before we look at the effect of nano-particles on the conductivity of fluids, we need to talk about thermal conductivity of suspensions of larger particles. Now, we all know that, particles or any solid material typically has some much higher thermal conductivity compared to a fluid, a gas or a liquid. And so, when you take a slurry, which has particles that are suspended in a fluid, you will certainly expect an increased thermal conductivity. So, that is not really surprising, what is surprising about nano-particles and nano-fluids is that, the rate of increase as a function of the volume fraction of the particles is much greater than what you would have expected or predicted. it is a highly non-linear phenomenon.

So, what we really need to try and do is understand the mechanisms involved; why is it that nano-particles behave differently from micron and super micron size particles, in terms of enhancing the thermal conductivity of fluids.

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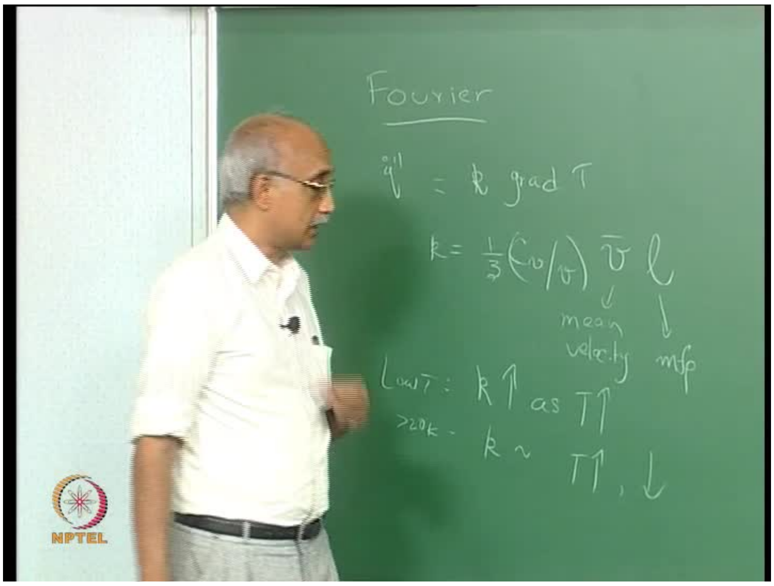

Now, you all know the definition of thermal conductivity. The Fourier law of heat conduction says that; if you look at something like heat flux, you can write this as some thermal conductivity times a gradient in temperature. So, this is the basic law of heat conduction that is attributed to Fourier. Here, thermal conductivity k, can either be obtained experimentally, all you have to do is look at heat flux as a function of temperature gradient, and you can extract thermal conductivity using that technique, or you can also estimate it based on molecular level data. In fact, the definition of k from a molecular view point is 1 by 3 times C v over v times v bar times l; where C v is the heat capacity at constant volume, and so C v by v is essentially the heat capacity per constant volume per unit volume, v bar is the mean velocity of the molecules or the particles and l is the mean free path. So, if you know the molecular properties of the fluid, you can actually estimate the associated thermal conductivity.

The temperature dependence of thermal conductivity then, is a function of the temperature dependence of each of these terms. So, if you look at them, at lower temperatures the dependence of thermal conductivity on temperature is different compared to the dependence of thermal conductivity on temperature at higher temperatures. And the reason for that is that; at low temperatures as you increase thermal conductivity, the mean free path does not change significantly. However the mean velocity will increase, as you essentially provide more thermal energy to the particles or molecules, and the heat capacity at constant volume also shows a slight increase with temperature. So, k will increase as T increases. But at higher temperatures, that is actually greater than about 20 Kelvin or so, you do not see this effect, k remains virtually constant as temperature increases and actually sometimes can even decrease. And the reason for that is that, there is a significant decrease in the mean free path again because of the energization, because particles are now moving around much faster, as you increase the temperature, the mean distance of separation between any two molecules or particles will be significantly reduced. So, there is a substantial reduction in the mean free path, which more than offsets the increase in the velocity of the particles. And the heat capacity at constant volume is virtually independent of temperature, as you go to higher temperature. So, the net effect is that thermal conductivity, if anything shows a slight decrease, as you increase the temperature.

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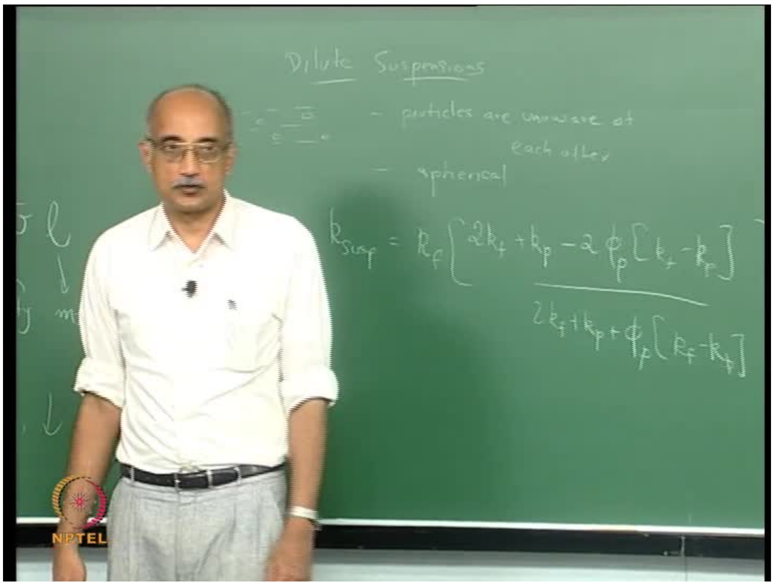

Now, what happens when you make suspensions of particles? We can talk about dilute suspensions where you have a fluid, in which you have particles of fairly large size, let us say, 1 micron and larger, that are suspended in a fluid. And let us say that, it is dilute enough that one particle does not know about the existence of the next particle.

So, the distance of separation between the particles is sufficiently large that there contribution to heat transfer enhancement is localized, they are not interacting with each other. So, that the two major assumptions, when we talk about the thermal conductivity of a suspension or a slurry; we are assuming that particles are unaware of each other and b most of the established theories of slurry thermal conductivity assume spherical particles. So, under these conditions, if you estimate the thermal conductivity of a suspension, let us call that some k suspension, and you compare it to the thermal conductivity of the fluid, there will be an enhancement. And the enhancement is actually given by, 2 times k f plus k p minus 2 times phi p times k f minus k p divided by 2 k f plus k p plus phi p times k f minus k p; where k f is the thermal conductivity of the fluid, and k p is the thermal conductivity of the particle material, and this phi p factor is the volume fraction of particles in the suspension.

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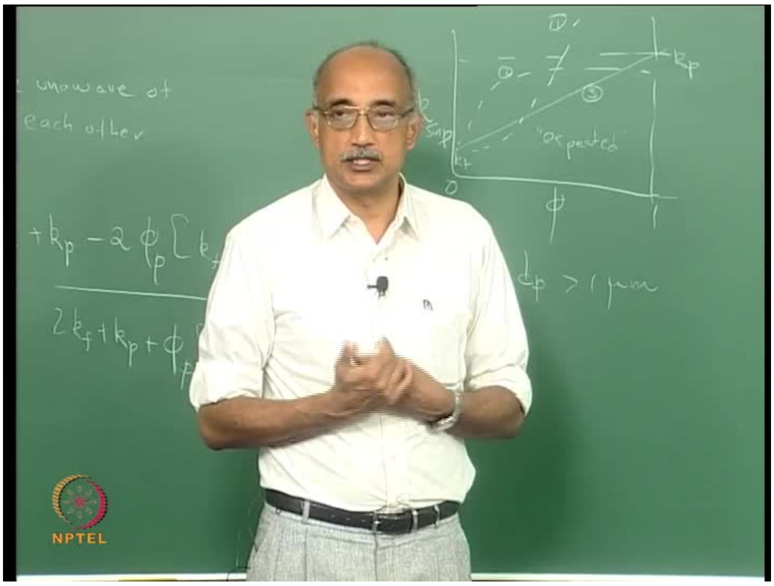

Now, if you take this expression and you plot it, so you actually plot the thermal conductivity of the suspension as a function of the volume fraction of particles in the suspension, you get essentially a straight line. So, this is k f and this is k p, you can expect that as the volume fraction changes from 0 to 1, the thermal conductivity pretty much linearly goes from the value corresponding to a pure fluid to the value corresponding to the pure solid. So, this is what we call the expected behavior. And this typically happens when d p is greater than 1 micron. From a fine particle science view point, a 1 micron particle is a very large particle, and when you have a suspension that is consisting of particles that are a micron and larger, you can expect a linear, quasi linear behavior to happen. So, if you do measurements of the suspension thermal conductivity as a function of volume fraction, this is a kind of behavior you would normally observe.

Now, the interesting thing again is when you do the same experiment with nano sized particles, the behavior is going to be very different. So, again I will poll you on what you expect. Do you think that it will look like this, you think that it will look like this, or do you think it will continue the linear behavior for a nano particle. 1 2 3. So, who thinks that if you if you draw the same plot for nano-particles of thermal conductivity as a function of volume fraction, how many people think it will look like 1? 2? Maybe, we will come back to it later. So, let us complete our discussion of macroscopic particles.

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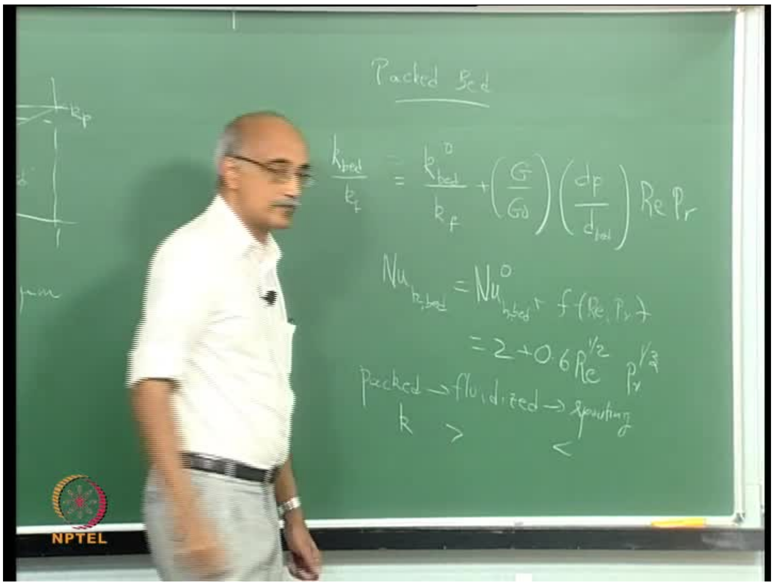

So, we talked about suspensions, now I am sure you all know that the other typical application that involves contact between particles and fluids is packed beds and fluidized beds. Now, in the case of a packed bed, again the thermal conductivity of the bed is going to be different from the thermal conductivity of the particle and the thermal conductivity of the fluid, and it is going to depend on flow parameters. So, in the case of a packed bed, if you take the thermal conductivity of the bed and actually take a ratio of k bed to k fluid, this is going to be k bed 0 over k fluid, where essentially this represents the static conditions whether there is no flow in the bed, plus it is going to involve certain dimensionless parameters, one of them is G by G 0, which is the mass flow rate in the packed bed divided by the superficial mass flow rate under empty tower conditions. Another important dimensionless parameter is d p over a macroscopic dimension like d bed, that is the size of the individual particle divided by the diameter of the bed times, you have Reynolds number and Prandtl number entering the equation as well.

So, in a packed bed with flow, there is an enhancement over the packed bed without flow that depends on the mass flow conditions, the particle size as well as the prevailing Reynolds number and Prandtl number. So, if we take a Nusselt number for the packed bed, this is again going to be the Nusselt number under no flow conditions plus a function of Reynolds number and Prandtl number.

If we take the reference value as the Nusselt number for heat transfer corresponding to a spherical particle in quiescent conditions, then this is going to be approximately equal to 2, and this function is normally written as 0.6 times Reynolds number to the power half times Prandtl number to the power one-third.

So, the point is that any time you have particles that are suspended in a liquid or any fluid or contacted by a fluid, you will expect an enhancement in the thermal conductivity of the system over the thermal conductivity of the fluid itself. Now, what happens under fluidization conditions. Suppose you keep increasing the velocity of flow and the bed starts to fluidize, now normally initially you would expect that there will be an increase in the thermal conductivity as the velocity keeps increasing, because of this relationship; however, once you reach greater than a certain velocity, the reverse trend will start to happen. Essentially if the fluidization level is too high, then the inter particle contact will be reduce significantly, and therefore, you will actually start seeing a reduction in thermal conductivity, that is called the spouting behavior.

So, you can go from a packed bed to a fluidized bed, to a spouting fluidized bed, where essentially the motion of particles becomes very localized and very non-uniform. So, the thermal conductivity will increase going from here to here, but it will decrease as you keep increasing the fluidization velocity. Also when you talk about particles that are suspended, particularly in gases, and you are supplying a source of energy, for example, radiative energy, the rate of energy pickup will be very different between particles and gas molecules. So, the particles will essentially heat up much faster form the radiation compared to the non-particulate fluid molecules that are present. That is why, for example, in combustion gases the suit particles are actually glowing, because they reach a much higher temperature compared to the gaseous specious that are around them. And similarly, in coal combustion, the ash particles that result from the combustion process, will be at a much higher temperature compared to the gas molecules surrounding them. This increase will happen until the particle themselves reach an equilibration temperature, at which stage their temperatures will stabilize. But there will be a significant delta in the temperature of the solid media that are entrained in gases compared to the gaseous molecules themselves. So, clearly it is not a new technology to involve particles in fluids to enhance their conductivity, whether its thermal conductivity or it could be even electrical conductivity.

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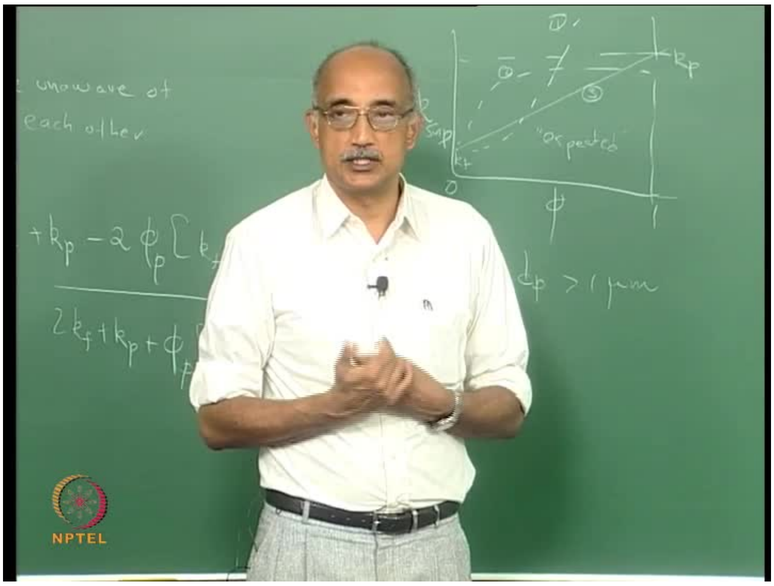

It has been well known over the years that the adhesion of a solid phase to a liquid phase or to a gas phase will significantly enhance its conductivity, but all of our previous experience had been on this linear terms, that you could essentially expect what type of enhancement you will get, simply by looking at the volume fraction and linearly scaling between the fluid value and the particle value. When we got into nano-particles that changed dramatically, so some experiments were done to take a metal particles, metal oxide nano-particles as well as nano tubes, and mix them in with a liquid, and monitor the thermal conductivity of the liquid as a function of volume fraction.

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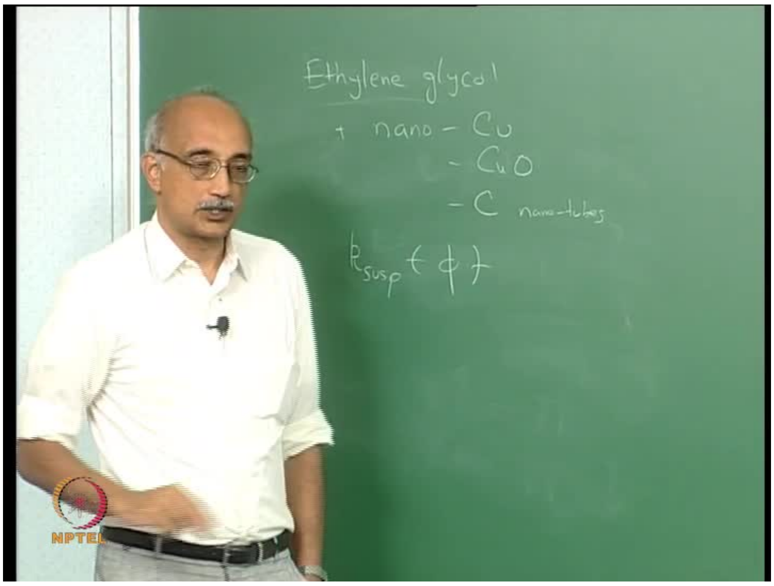

So, this experiment was done with ethylene glycol; in which we mixed in nano copper, nano copper oxide and a carbon nano tubes. And the experiment was essentially to look at the thermal conductivity of the suspension as a function of the volume fraction of these materials.

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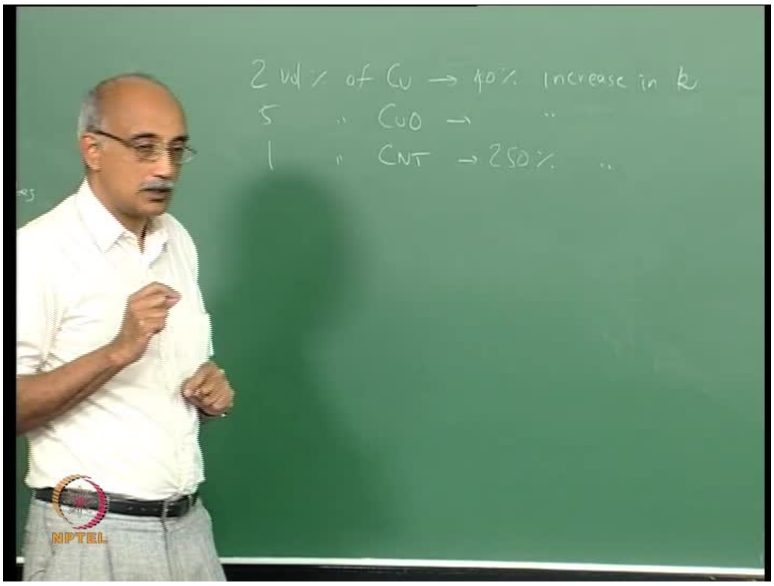

And the interesting observation was that, 2 volume percent of copper was enough to give a 40 percent increase in k. And roughly, 5 volume percent of copper oxide was also able to give a 40 percent increase in the thermal conductivity. A 1 percent addition of carbon nano tube was enough to give 250 percent increase in thermal conductivity.

Now, these data are fascinating because it violates this principle, because I mean in some of the basic assumptions in this are; a that the enhancement effect is not shape dependent, this basically says it does not matter what the particle looks like as long as you tell me the volume fraction, I will tell you what the expected enhancement is, and clearly this violates that.

The second assumption of course, is regarding again the linearity itself, it basically says that the thermal conductivity enhancement should happen in a linear and progressive fashion, and not in such a dramatic manner. So, again the simple theory of linear additivity of a conductivity does not work. And also the material, because the same increase in thermal conductivity is achieved at two different volume fractions of two materials, so clearly the material dependence is also built into it. However, that is not a sensitive effect as, for example, the shape of the particle.

So, clearly something is going on here which cannot be explained on the basis of a liner augmentation of thermal conductivity alone. So, to explain what is going on, you really have to speculate on the mechanisms involved. So, based on what we have studied about particles in this course, we can actually offer some hypothesis.

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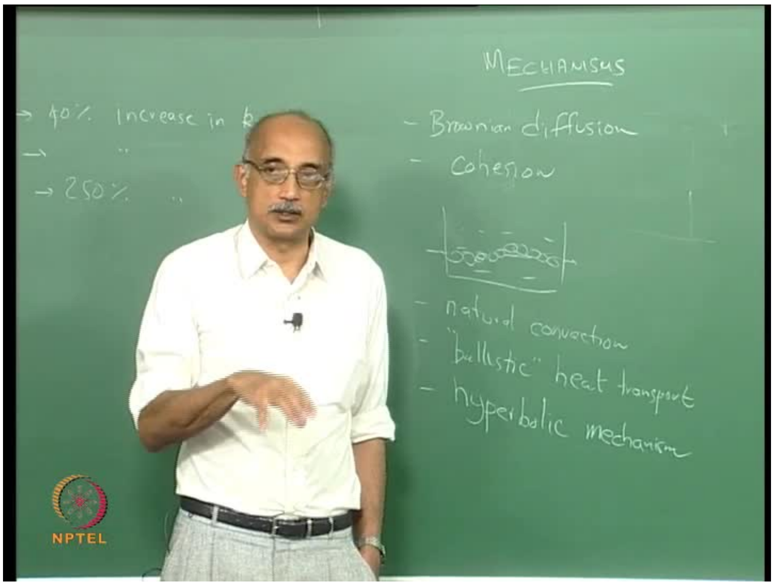

For example, one of the hypotheses for the mechanism was that; unlike larger sized particles, nano-particles are not static in solution. We have been repeatedly saying that, as particle dimensions gets smaller and smaller, it is becomes increasingly difficult to hold them in place, they have a natural tendency to move around. And in particular, Brownian diffusion is a major effect. The argument goes like this, essentially you have these very fine particles that are in solution, and they are constantly moving around at very high rates. And because they have higher thermal conductivity compared to the fluid molecules around them, they have a tendency to increase the thermal conductivity everywhere in the fluid, because of their increased motion in the medium.

Of course, the next obvious thing to speculate on is cohesion. When particles are completely separate, as assumed in the basic model, there is no way for them to communicate with each other. But, if you have a suspension and the particles start to agglomerate, then what happens? In the extreme case, you can actually think about the particles forming like a conductive bridge across the solution, so that if you measure conductivity across the liquid, what you will really measure is a conductivity that is happening through the solid bridge that has formed due to agglomeration and cohesion of the nano-particles.

So, the cohesive behavior and the tendency to form structures, so the big difference now is that, you have formed a nano particulate structure, which is very different from the molecular structure of the fluid itself. For example, something from a fluid mechanics view point, a Newtonian fluid with the addition of nano particles, will start behaving like a non-Newtonian fluid. And similarly from a thermal conductivity view point, a fluid that has a certain conductivity based on its molecular model, will now have a completely different characteristics that is based upon particle to particle contact.

The other mechanism that we can speculate about is natural convection. So, you have these particles moving around due to Brownian diffusion, but they are at a higher temperature compared to the fluid around them, in general. So, what is that going to do? As the particles move around, you are actually going to setup a temperature gradient within the fluid. And because of that you are going to develop a density gradient, and the density gradient is going to induce natural convection flow. So, this is a particularly prevalent mechanism in gases, where the change in density due to temperature change can be quite high. So, this mechanism of natural convection that sets in when nano-particles begin to move around, again can account for this larger than expected increase in the thermal conductivity value.

So, instead of being a quiescent fluid, in which conduction diffusion is a primary mechanism of heat transfer, now you have added natural convection as an additional mode of heat transfer. And convective transport rates are always higher compared to conductive transport rates. So, that is another mechanism that we could speculate on.

Researchers have also wondered about, what they call the ballistic nature of heat transport in the presence of nano-particles. So, this is another extension of the thought process to say that, when particles move around violently they induce something like turbulence, so that instead of being simple quiescent heat transfer, now you enter the realm of turbulent heat transfer. And again we know that, under turbulent conditions transports rates are significantly enhanced over their laminar and static counter parts. It is called a ballistic mechanism because these particles are almost behaving like ballistic missiles, not the rate that they are moving around compared to the fluid molecules that are surrounding them, it begins to look like you are transferring heat not by a conductive mechanism but actually by physically taking masses of materials and relocating them from one place to another, which is exactly like a turbulent eddy. That is, what happens in turbulent eddies, you are not transporting heat mass and momentum through layer by layer conduction, but rather you are taking entire layers of the fluid and flinging them around. So, something similar starts to happen in this case as well.

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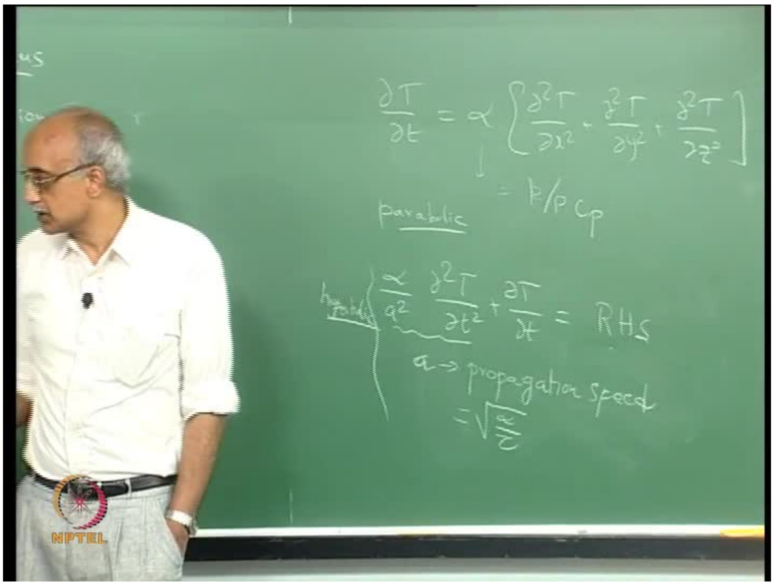

Another hypothesis is that, the whole transport mechanism changes from a parabolic nature to a hyperbolic nature. So, if you write the energy conservation equation under quiescent conditions, again the Fourier formulation for heat conduction would say that, delta T by delta t equals alpha times del square T by del x squared plus del squared T by del y squared plus del squared T by del z squared; where because delta t by T is temperature, small t is time, so this represents the rate of change of temperature with time and on the right hand side you have the diffusive term, that is represented by the thermal diffusivity alpha which is equal to k by rho c p. So, this is the conventional heat transfer by unsteady heat transfer by conduction model, that we are all familiar with from our heat transfer courses.

The solution to this can be obtained by method of separation of variables. This is called the parabolic equation and there are well known techniques for solving this equation and obtaining the temperature profile and so on. So, this is the parabolic formulation of the heat conduction equation.

The hypothesis here is that, in the case of hyperbolic heat transfer, what we mean is an additional term is added on the left hand side, which is alpha over a squared delta squared T over delta t squared plus delta T over delta t equals again all the terms on the right hand side. So this term, that has been added is called the hyperbolic term. And what that represents is the wave nature of heat transfer. When this term a is called the thermal propagation speed, when this tends to infinity, you recover the parabolic form of the equation. So what that means is that, essentially heat is transferred through the fluid without any impediment so that, the propagation speed is essentially infinity. What we mean when we add this term is that, there is actually an obstruction in the fluid which results in a slowing down of this wave of heat transfer, and that is associated with the properties of the suspension itself.

So, this a parameter, the propagation speed is simply given by square root of alpha over tau; where tau is a characteristic time constant, and the ratio of alpha over tau that we are referring to as a propagation speed, essentially means that the thermal diffusivity of the fluid is now playing a role in terms of affecting its temperature evolution as a function of time. Now, the fact that you have a del square T over del t square term, here what is the main implication of that? Normally in order to solve a problem like this, how many initial conditions do you need. Just need one initial condition and two boundary conditions. Here, essentially you need two conditions reflecting time. So, time at time equal to 0 and time at another some characteristic time. You need to know the conditions of the system at these two different times, in order to solve the equations completely. Which again means that these fluids essentially have a memory effect, it matters at what time you start doing the simulation, so the past has an effect on the present, but the past and the present also have an effect on the future.

So, the time dependent behavior of thermal conductivity of such fluids is also very different from the thermal time dependence behavior of parabolic fluids. So, again this is known as a hyperbolic heat transfer mechanism. And the heat transfer rates, in this type of hyperbolic fluid, tend to be much larger compared to heat transfer rates in the case of a parabolic fluid.

And again the hypothesis here is that, a fluid that behaves like a parabolic fluid in the absence of nano particle additives, will start behaving in an hyperbolic manner when you start adding nano-particles to it. So, what is again the underline thinking behind that, that the particles that are suspended in the fluid actually act in a way that they interfere with a wave propagation of energy through the fluid, and they have the ability to actually increase the heat transfer rate. And another way to think about it is, suppose you had no particles in the fluid, and energy is being transported as a wave, then that is not sufficient time for this wave to transfer the energy to the fluid molecules. So, the heat source essentially will enter and leave the fluid without heating the fluids significantly.

On the other hand, if you have these particles that are suspended in the fluid, they can actually slow down the propagation of the heat wave through the fluid and give more time for the fluid molecules to draw heat and energy from the wave that is passing through. So, it increases the contact time between the incident energy wave or heat wave and the molecules that are present in the fluid.

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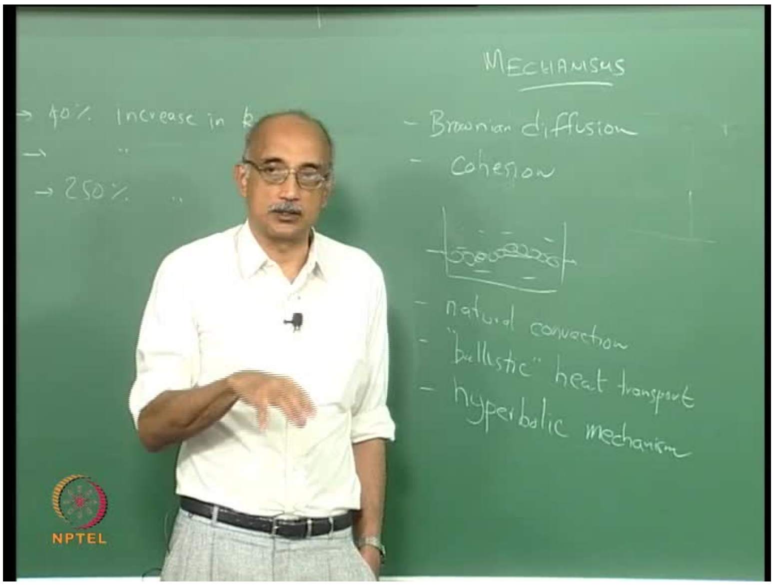

So, the nano-particles are acting somewhat in indirect fashion, in this case, and enhancing thermal conductivity of the entire fluid. So, this view point is very different from, for example, the solid bridging view point, which essentially says the particles are not really doing anything to affect heat transfer to the fluid molecules, instead they are providing an alternating path for heat to be conducted through the fluid. So, that is a very different view point because this would say that, except in this localized area, in the remainder of the fluid it continues to behave as it was without the addition of the nano-particles, and that the only increased comes because of the nano-particles tending to a cohesive behavior in some regions of the fluid. Whereas, the hyperbolic mechanism essentially proposes that, the particles not only have a direct affect in this manner, they also have an indirect effect of essentially slowing down the process by which energy is transferred through the fluid, and allowing more time for the fluid molecules to absorb energy from whatever is being passed through the fluid medium.

So, all these mechanisms have been proposed, and it is interesting that there is still no consensus among researches on which is the predominant mechanism. All of these are still speculations at this point, there is no conclusive proof that, one or all the other mechanism dominates over the others in a particular application. We can certainly investigate these mechanisms and try to validate or invalidate them.

For example, if you want to prove the Brownian diffusion is the main characteristic, then you would essentially freeze everything else and just do experiments with, let us say two particles, one of which has a very different Brownian diffusion compared to the other. But, how do you differentiate in Brownian diffusion? It is essentially by changing size, but then, the problem is once you change size, it affects not only the Brownian diffusion characteristics, but it also affects all the other mechanisms, and that is what make it is complicated. It is very difficult to test each one of these independently of the others, because they are all coupled mechanisms. Brownian diffusion leads to cohesion, Brownian diffusion plus cohesion leads to natural convection, all of these processes together result in the ballistic behavior. And finally, the hyperbolic mechanism is one that is somewhat disconnected with the rest of them, but again the only way to prove whether this mechanism is prevailing or not is to prevent all of these from happening, somehow freeze the fluid so that we know for a fact, that these mechanisms are not happening, and then try to see if there is still a significant increase in the thermal conductivity. Not easy to do.

So, nano-fluids are actually a great place still to do research. There is lot that is not known, there is a lot of empirical data. Everybody knows that nano-fluids are extremely good enhancing heat transfer efficiency, but the principle mechanisms have not been identified. And also there are down sides, when you try to use nano-particles as a heat transfer enhancer in a heat transfer application, heat exchange application, what are the biggest problems is what do you do with these nano-particles. They will form a sediment, they will starts settling and forming a deposit on the heat exchanger surfaces. So, the fact that nano-particles have high transport rates, which helps you with the heat transfer part, it kind of hurts you from a mass transfer part.

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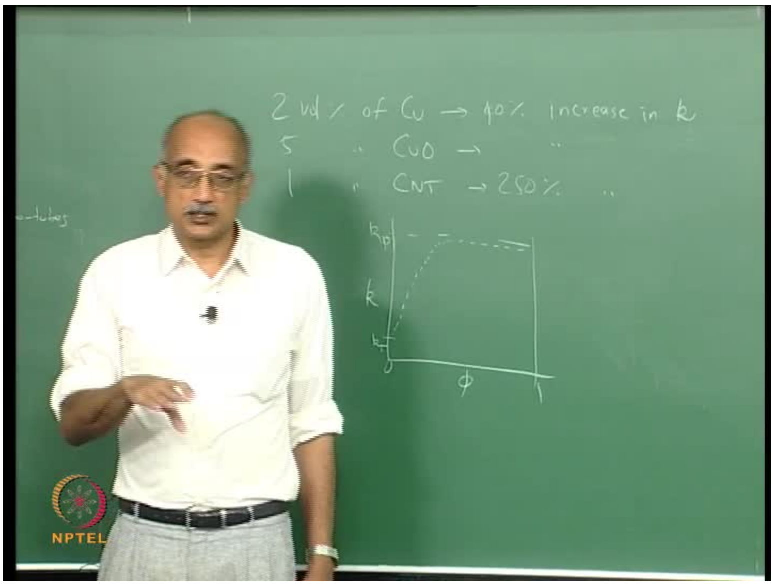

So, if you have a heat exchanger tube and you want to increase the conductivity, so you mix in some nano-particles with the heat transfer fluid. Yes, initially you will see an enhancement, but pretty soon you will start finding fouling of the heat exchanger surface is happening. So, periodically you have to take it down, clean it. And we know from our previous discussions that, nano-particles have extremely high adhesion forces to surfaces. So, very difficult to remove as well. So, that is another challenge that you need to overcome.

Also, when we actually plot volume fraction verse thermal conductivity enhancement, for a nano-fluid, if you plot volume fraction versus k, and let us say that this is your k fluid value, and let us say that this is your k particle value and you go from 0 to 1, the behavior is essentially like this, it quickly reaches a value that is near the value for the pure particle and then asymptotes out. It can never really get to the value of the particle itself, because that is theoretically at least not possible. But the offset between the k p value and the k suspension value, can be reduced significantly by optimizing the nature of the particles. One of the interesting things we saw with the carbon nano tube experiment is that, see carbon actually has much lower thermal conductivity compared to metals, but you are able to get such a huge heat transfer enhancement at a much lower concentration for the carbon nano tube compared to metal nano-particles. So, clearly the shape plays a big role.

So, what is the primary difference between carbon nano tubes and, let us say copper nano-particles? The copper nano-particles are not going to be spherical, they are crystalline. So, is there a big shape difference between, say a copper nano particle and a carbon nano tube? I mean, the main difference is that, if you look at a CNT essentially has a cylindrical shape.

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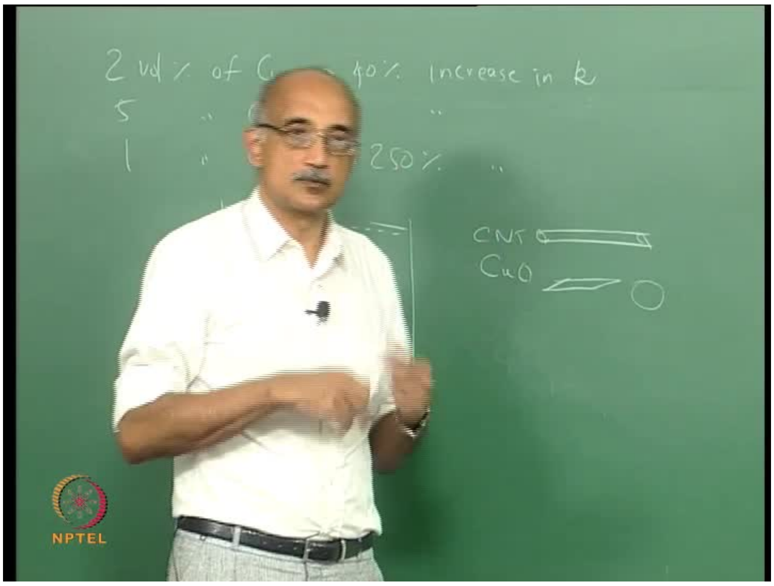

In one dimension you have nano scale, but in the other dimension you have a much longer length scale. Whereas, if you look at something like copper or copper oxide, you are likely to see a structure that is much more crystalline, although it depends on the method of synthesis, you can actually make nearly spherical nano metal particles as well as highly elongated metal nano-particles. But they are all going to have some either crystallinity associated with them or sphericity associated with them. Why is it that, a crystalline shaped nano particle, nano metal particle is not able to give as great heat transfer enhancement as a carbon nano tube, even though in terms of l by d they are very similar, in a highly crystalline structure as well the length scale will be much greater than the width scale. So, it seems to matter not only what a simple l by d ratio is, but it also matters whether it is something that is precisely control. When the difference between a CNT and a copper oxide nano particle is; in a carbon nano tube, you actually prepared a particular shape essentially with molecular level controls, whereas in the case of a copper oxide nano particle, even if you are doing bottom-up type of synthesis, you do not have that level of control over the structure of the particle. And is that the reason why we see a huge difference between the two? Or is it that, again you go back to cohesion.

When you have carbon nano tubes, because of the uniformity in their shape and size, they can easily accommodate each other and form clusters that are grouped together in this fashion. You can imagine that it will be very easy to form such a structure, if you are using the cylindrical tubes, it is just like lying rods next to each other and getting them to attach. Whereas, if you have highly spherical particles or crystalline particles, to get them to align in a certain way is not as easy. And so, this actually would lend credentials to this type of hypothesis, where you require the formation of a essentially a solid bridge, in order to achieve the enhancement in thermal conductivity.

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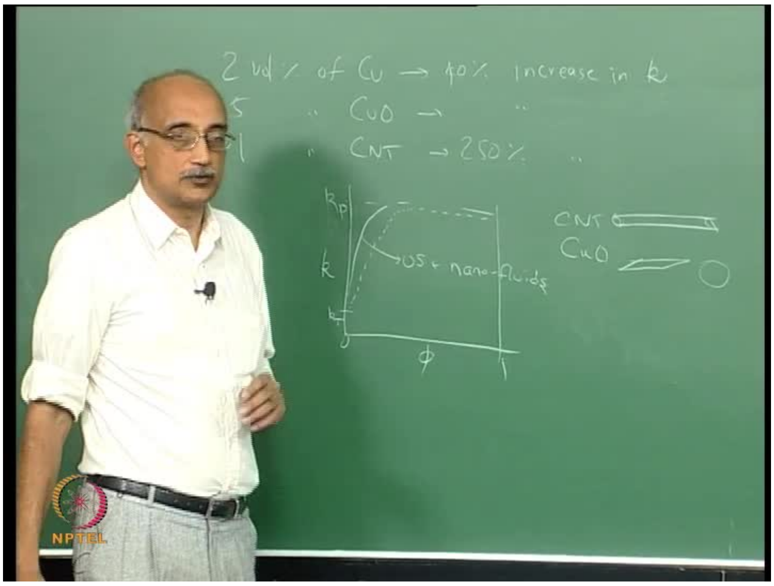

Another approach that is been taken to increase the conductivity of nano suspensions is actually, to expose them to additional heat transfer mechanism, such as ultrasound. As we have seen earlier, acoustic fields can promote many things including size reduction, surface cleaning and so on. Another application of acoustic field is to promote heat transfer in fluids. Here again, the mechanism that happens is, you know nano-particles are already in an agitated state. Suppose, you combine an energy field like an acoustic field to a nano fluid, what is going to happen? It is going to enhance the turbulence even further, it is going to make the particles move around even faster.

So, this slope can actually be further enhanced by the use of ultrasound plus nano-fluids. So, the additional incorporation of an acoustic field to improve the thermal conductivity characteristics of a nano-fluid, is again a field of investigation that is receiving quite a bit of attention.

Now, one of the advantages here is that, the volume fraction can be reduced even further to achieve the same effect. Now we talk about 1 percent CNT giving 250 percent enhancement, is that good enough? Hard to tell. I mean nano-particles are still very expensive so even 1 percent, particularly in a high volume application, may be a lot of material. So, if we can get the same heat transfer enhancement by using, let us say 0.5 percent, that would represent a huge cost savings to the manufacturer or the person running the process. And that you have the ability to do that because, you know, essentially you can achieve the same thermal conductivity with a lower volume fraction in the presence of an acoustic field. So in particular, the behavior of heat exchangers that are running with nano-fluids with and without ultrasonic enhancement, is a field that is being studied in several labs.

The other advantage of coupling an ultrasound is that it prevents this fouling from happening. Because when you take a nano-fluid, as I said the biggest problem is deposition of these nano-particles to on surfaces over time. But if you are coupling it to an acoustic field, the field will essentially keep the particles agitated on the surfaces so that, they do not really ever settle down and adhered to the surface.

So, the particles will continuously be suspended and entrained and removed by the flow of the fluid. So, the advantage of coupling ultrasound to a nano-fluids is twofold, it increases the thermal conductivity even further, and it also prevents deposition from happening on the heat exchanger surfaces. Because the third advantage, which we have looked at earlier, is that the ultrasound can continuously break down agglomerates.

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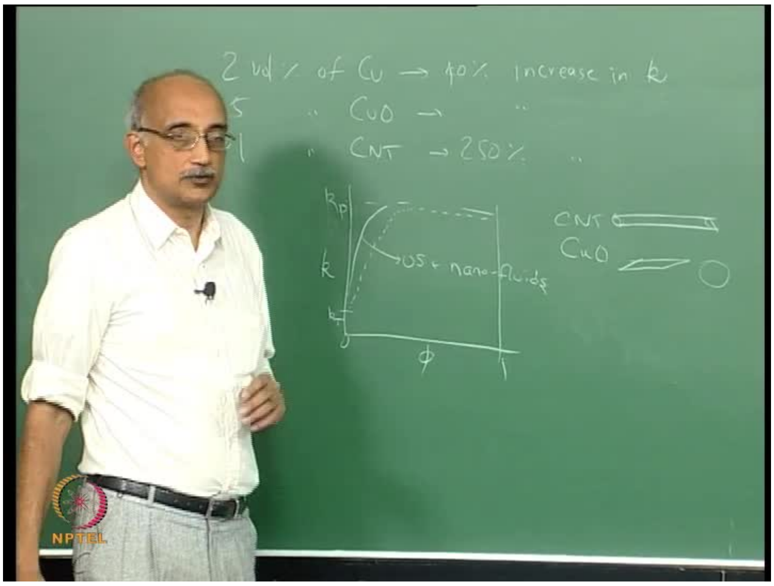

Now, breaking down of agglomerates may or may not be a good thing, in terms of heat transfer. In general, it is good because you know you do not want nano-particles to be cohesive, but in case of promoting heat transfer, you know, may be the cohesion helps. So, ultrasound has somewhat of a mixed effect, in that sense. It will take individual particles in and reduce size, we know that is good, because as particles size reduces you know the enhancement effect will increase. But if ultrasound also starts breaking down clusters, for example, if this bridge forms and you use ultrasound, it is going break it. So, you have to be careful, in that sense, that you have to be monitored the effect of these external fields and make sure that they are actually enhancing the heat transfer rather than reducing it.

There are also other fields that have been tried in nano-fluids. We can actually, if you have, for example, magnetic particles that are suspended in the fluid, you can use a magnetic field to get them to align in a certain way, and thereby increase the conductivity of the fluid. Or if you have charged particles in a fluid, you can use an electric field to get them to align. So, the formation of this bridge is considered very crucial, to achieving this enhancement in thermal conductivity. In a simple nano-fluids , you essentially wait for this bridge to form because of the natural diffusion and cohesion tendencies of the particles. But the more advanced technologies involved forcing the particles to forms such bridges by imposing an external field, on whether they are acoustic fields or magnetic fields or electrical fields or whatever you want to use. But anyway, nano technology, I mean nano-fluids in particular, offer some interesting opportunities because of the close link between the characteristics of the nano-particles and their end effect. There is a very close tie between the two.

And here again is an example of an application, that you cannot fully control and optimize, unless you do the work up front to characterize the nano-particles and their behavior in such fluids.

So, we will stop the discussion of nano-fluids at this point. In the next few lectures, we will examine the behavior properties and characteristics of nano-particles, of particles, in essentially a high technology manufacturing environments. There are some very interesting ways in which particles characteristics affect the yield of processes, the reliability of devices, even the quality of products that are made in such manufacturing processes. So, we will take a closer look at that.

Any questions on what we have talked about today?

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Where here

Yeah

No, it is just that the rises very quick. I mean as soon as you have even a small fraction of particles being added, you get a substantial increase, but then you have to start as asymptoting out, because you cannot go above certain values. So, it just represents a very rapid initial rise, there is no time constant, I mean there is no reason for it will look like this, because as soon as you put it in even a small volume fraction of the particles, the increase starts to happen.

See you at the next lecture.