Micro and Nanoscale Energy Transport
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Lecture – 02
Overview to Micro/Nanoscale Energy Transport Part 2

Good morning all of you and welcome back to the 2nd lecture. We should be focused on the introduction part to this particular course yesterday I gave you a brief outline about the contents I think one person was not able to come, but you can probably attest get it from your friends we discussed about the different topics that we will be covering here. So, which will start from the sub continuum level energy carriers and me know the transport phenomena associated with them and then will gradually move towards the micro scale single phase convection to phase change convection some nano fluids and application all that. I have also given the text books and the references that will be useful for this particular course and also the grading pattern.

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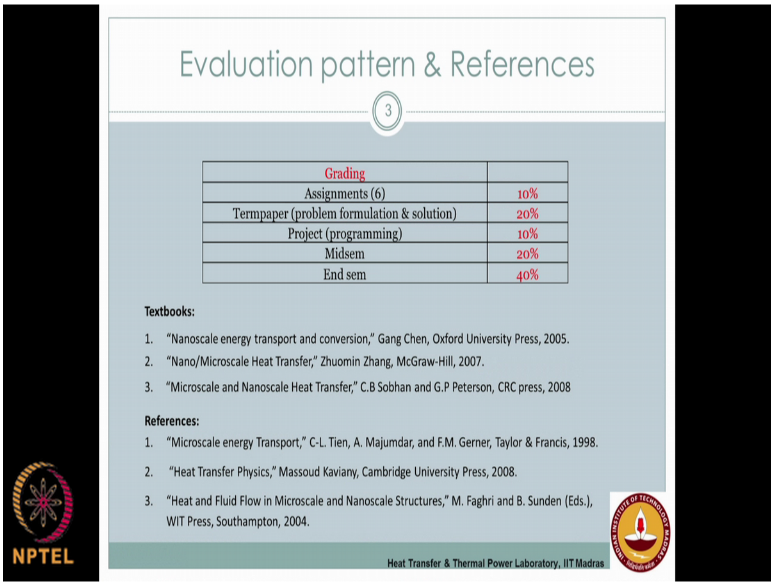

Evaluation pattern & References

Grading	
Assignments (6)	10%
Termpaper (problem formulation & solution)	20%
Project (programming)	10%
Midsem	20%
End sem	40%

Textbooks:

1. “Nanoscale energy transport and conversion,” Gang Chen, Oxford University Press, 2005.
2. “Nano/Microscale Heat Transfer,” Zhuomin Zhang, McGraw-Hill, 2007.
3. “Microscale and Nanoscale Heat Transfer,” C.B Sobhan and G.P Peterson, CRC press, 2008

References:

1. “Microscale energy Transport,” C-L. Tien, A. Majumdar, and F.M. Gerner, Taylor & Francis, 1998.
2. “Heat Transfer Physics,” Massoud Kaviany, Cambridge University Press, 2008.
3. “Heat and Fluid Flow in Microscale and Nanoscale Structures,” M. Faghri and B. Sunden (Eds.), WIT Press, Southampton, 2004.

So, I think these are pretty pretty must clear I hope. So, today we will go into the introduction part to mean if you take any generic course on a micro scale or nano scale.

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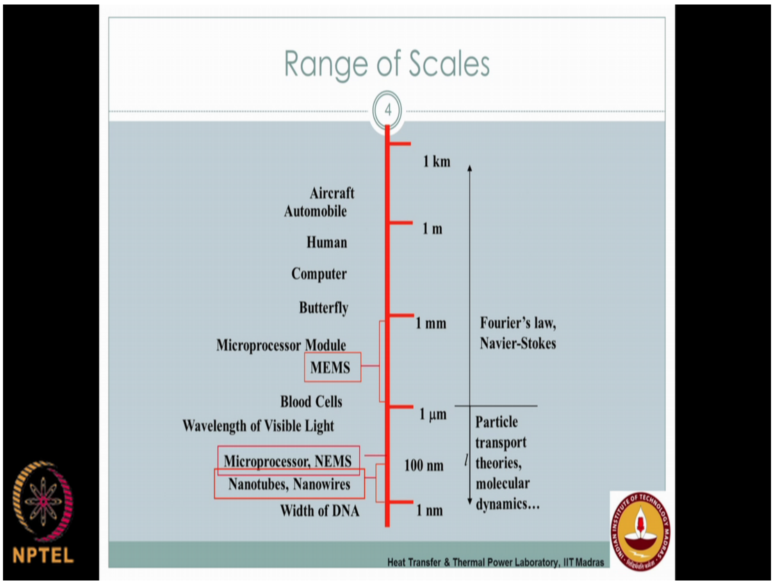

Range of Scales

1 km

1 m

1 mm

1 μm

100 nm

1 nm

Aircraft

Automobile

Human

Computer

Butterfly

Microprocessor Module

MEMS

Blood Cells

Wavelength of Visible Light

Microprocessor, NEMS

Nanotubes, Nanowires

Width of DNA

Fourier's law, Navier-Stokes

Particle transport theories, molecular dynamics...

The first thing that you have to understand this time and lengths scales that we will be dealing with. So, this particular illustration shows you what are the typical lengths scale you can also convert this into an equivalent float of time scales. Because a many thing that is associated with the scales of nano meter will also have time scales associated which are of you know the order of may be Pico seconds or Pemto seconds you know which will make it again something like local thermal non equilibrium or local non equilibrium energy transport. So, wherever you considered very small length scales and also the time scales. So, this is where, what we call as nano scale phenomena start appearing.

So, and when you look at memes for example. So, which is typically in the micron scale it can span anywhere between 1 micron all the way up to a millimeter. So, you have devices which are built bay based on the memes principles which can have all these dimensions ranging between a micrometer and millimeter right. So, when you are talking about blood cells you know. So, you are talking about of the order of memes because these memes devices are also devices which are typically used in medical applications know D N A protein separation you know. So, say such kind of application. So, you are dealing with separation of blood cells for example, from plasma. So, their also of the order of micron size and.

Now, you can also talk about devices which are now being used may not be within the medical application itself, but you are looking at says semi conducted devices which are used in microelectronic components. So, you can talk about micro process there. So, which consist of devices made of nano tubes nano wires or any silicone on insulated devices? So, eyes as they call. So, which make up a fundamental semi conducted device will be of the order of one nanometer up to hundred nanometers. So, as the speed of your processors is going up tremendously right. So, we have this moors law and we have to scale up you know. So, the we have to pack more processors within a given square meter or square millimeter cross section of micro processor chip and in order to do that you have to rapidly increase the number of transistor or transistor density and to do that you have to look at sub nanometer kind of semi conducted devices which can be accommodated and associated with that will be the problem of heat dissipation.

So, you can you can try find a fabrication technology to do that, but how would you deal with the tremendous amounts of heat fluxes that are coming out I will show me know you few slides down the line that the kind of heat fluxes we are dealing with in micro processor chips now are of the order of the heat fluxes from the sun. So, we have to also maintain these at a fixed temperature preferably around seventy eighty degree Celsius. So, we have to do a lot of work on the cooling part of removing the heat or heat dissipation from semi conducted devices. So, we have these devices which are in the sub micron range. So, these are typically used in micro processors or micro electronics and these are standing from one nanometer to hundred nanometer.

So, now you are width of the D N A is also the order of a nanometer. So, now, if you want to invent any device it should be a nano device name, which is dealing with operations with using D N A and so on. So, it should be of the order of nanometer or sub nanometer. So, these are the typical length scales right now that people have been dealing with we have not really grown into sub nanometer length scales till now at least not we do not have any applications on that, but we have I mean may be take 50 years back or even 30 40 years back we did not have applications ranging sub micron we used to deal with if you are dealing with millimeter range know a device that was considered really a you know small device you know and still that that was operating in the continuum range. So, on the right hand side here you can see that the corresponding the description of transport process how they are associated with the length scales. So, if you are talking about micron size and above.

So, you can still use your classical continuum a mechanics which basically use nervier stokes equation what describing the fluid flow transport and for example, constitute of relationship which links your for example, heat flux with your temperature gradient should took which is. So, so this is required to close the nervier stokes equation also similar as your Newton Newtonian the assumption of a Newtonian fluid on the nektons law of viscosity. So, you need that to close your equations nervier stokes equation, so that you can solve them. So, rather than leaving them in terms of stresses you need to express them in terms of velocities and similarly the energy equation in terms of temperatures. So, you use these constitute laws to fill this particular gap. So, also all these are valid only if you have the assumption of continuum. So, far you look at devices 30 years before.

So, they where all dealing with this kind of devices which are of the order of millimeter and above and everything was working with the continuum assumption. And suddenly when people in the microprocessor industry where just scaling down their devices at such a rapid phase and you had you know devices which are going to the order of nanometers and suddenly people wanted to study the heat dissipation mechanisms and they failed using the Fouriers law.

And this is where the sub continuum use of continuum theories started emerging although they were present even before the nanometer devices where discovered definitely you know in physics we have practical base theories you know we have Boltzmann transport equation and all of these existed almost 100 years before, but nevertheless the application of these series to sub micron level as emerge only in the last 30 years or so, and particularly when you are dealing with nanometer size devices only in the last 5 to 10 years have these kind of applications picked up. So, this is to just give a broad idea about the overall scales that we are able to deal with know ranging a nanometer to kilometer.

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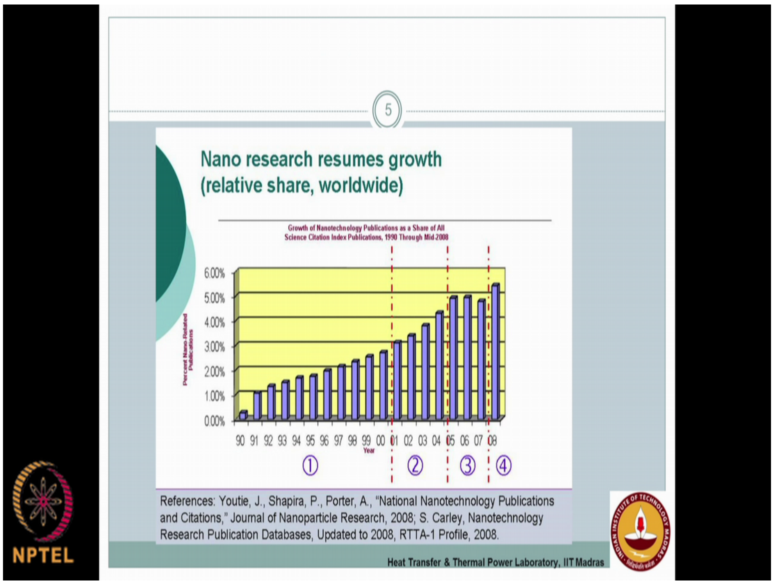

Nano research resumes growth (relative share, worldwide)

References: Youtie, J., Shapira, P., Porter, A., "National Nanotechnology Publications and Citations," Journal of Nanoparticle Research, 2008; S. Carley, Nanotechnology Research Publication Databases, Updated to 2008, RTTA-1 Profile, 2008.

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So, also to give an idea about the amount of research that has been done you know this gives you also the trend of you know volume of research that has been growing over the period of time from 1990 till about you know 2010 I would say you know I have not compile the data in the last 5 6 years, but you can see that it has been increasing very steadily and you can see 1990 for example, less than you know it is. So, very small fraction you know, it is almost negligible percentage of the total research that has been related to nano scale it could be nano scale heat transfer it could be nano scale you know any phenomena and physics chemistry or material science, you know my making nano structured material synthesis it could be anything, but that was only a negligible fraction of the total body of research that was existing at the time and suddenly you see in 1 year 90 to 91.

So, there was big jump you know. So, of all the research 1 percent was occupied out of the entire volume of research the publications related to nano is now steadily increasing that clearly shows the importance of this towards the applications that we are dealing with.

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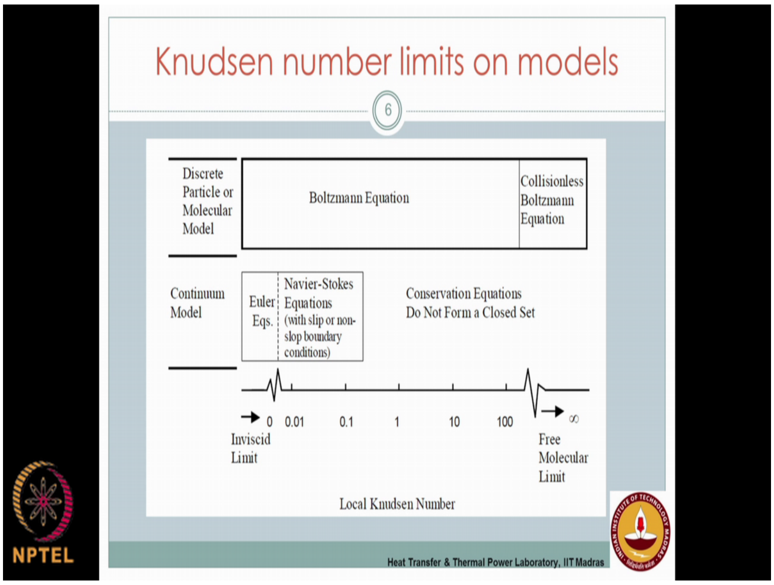

Knudsen number limits on models

Discrete Particle or Molecular Model

Boltzmann Equation

Collisionless Boltzmann Equation

Continuum Model

Euler Eqs.

Navier-Stokes Equations (with slip or non-slop boundary conditions)

Conservation Equations Do Not Form a Closed Set

Local Knudsen Number

And again this is another float which shows you the instead of the length scale now we used a different parameter which we are now introducing this is called the Knudsen number. So, Knudsen number is a non dimensional parameter. So, which is defined the as the ratio of your mean free paths to the characteristic length scales that you are using.

So, therefore, when you are talking about Knudsen number which is very high. So, you are talking about either very large mean free path between the energy carriers we will define all these in detail, but I think we should understand that the rough idea of looking at mean free paths the approximate distance that energy carriers have to travel before they collide with each other. So, for example, if you take molecules, if you talking about rarefied gases for example, we do not encounter rarefied gases. So, commonly known in earth conditions, but when you are traveling to the outer space. So, as and when you are leaving the atmosphere you are encountering the rarefied phenomena.

So, in those cases you can actually come to a stage where you are Knudsen number is exceeding hundred then slowly approaching infinity. So, rarefied gases are 1 good example where you know with respect to molecules as the energy carriers you can have a very high Knudsen number. The other example is you can deal with earth phenomena, but you can talk about phenomena happening at very small characteristic length scale.

So, since we define Knudsen number as the ratio of mean free path to the characteristic length scale, it can be either you can also have very small length scale the mean free path could be absolutely normal it could be of the order of you know nanometers or whatever it is at know the normal atmospheric condition; however, they device dimension is 2 small that the energy carriers cannot actually have multiple collisions with themselves, but they collide with the boundaries of the system and therefore, this could also lead to a sub continuum kind of transport.

So, therefore, very high Knudsen number here indicates that we are deviating completely away from the equilibrium continuum theories. So, everything is non equilibrium. So, there is also a local non equilibrium existing and a very high Knudsen number approaching infinity means is a completely free molecular limit. So, the molecules hardly even see each other. So, they only see the boundaries of the domain if you have a close domain and on the other hand if you are talking about Knudsen number which is extremely small. So, then you are talking about the conventional you know continuum based approximation. So, where you have lot of molecules statistically large enough to describe you know properties such as you know pressure temperature and so on. So, this is how you define a continuum and associate a particular property inside the continuum and this is valid at the small Knudsen number limit. So, you have the device dimensions which are substantially larger compare to your mean free path.

So, that you have enough collisions of energy carriers happening, that you can statistically use some theory to describe an average property or anything within this particular system. So, therefore, if you are looking at classification of the theories whether they are either continuum or sub continuum, usually they are classified on based of Knudsen number, it is hard to say whether you can use continuum model if your length scale is of the order of microns, it is also possible that your length scale could be of the order of microns, but your mean free path could also be extremely large. So, in that case still your continuum theories may fail. So, the right way to classify whether you can use a continuum approach or a sub continuum approach is to look at the non dimensional Knudsen number.

So, typically all your continuum models will be valid if you are approaching a Knudsen number close to 0 that is your theoretical hypothetical know assumption that your mean free path or your length scales are much larger than your mean free path and you k. Now, therefore, you have very small Knudsen number of the order of 0.0001 or something like that and there you can definitely use your continuum model. And as and when you know you are increasing your Knudsen number that is either by increasing your mean free path or decreasing your length scales slowly you start deviating from the continuum assumption. So, when you do an experiment you find a certain phenomena emerge for example, if you have flow of gas. So, gases have actually a larger mean free path compare to the liquids. So, more likely you will start observing these phenomena in gases compare to liquids.

So, the 1st thing that you will observe is what we call as a slip that is happening between the fluid and the boundary. So, your classical continuum theory always says that your fluid cannot slip the wall you know there is always a no slip boundary condition and the fluid as to posses the same velocity as the solid. Now as your Knudsen number keeps increasing you see that this particular phenomena emerges where there is a slip coming up and how do we now account for this. So, there are theories which say that if your Knudsen number is in a reasonable range something like point up to point 1 let us say you can still use your continuum theory like nervier stokes equation, but we can correct for the condition at the wall by introducing some slips.

So, instead of using a no slip we give a partial slip or a slip, but that we do not know how much of slip as to be given, so that from the experimental data we have to find out and you have to give the corresponding the quantity or parameter of slip that is required. So, that is one theory and if your Knudsen number exceeds this value of point 1 even the continuum approximation outside will breakdown and therefore, you cannot use any form of continuum approximation.

So, therefore, what is used as a referred to yesterday is the Boltzmann transport equation. The Boltzmann transport equation is actually a sub continuum model which can also be used in continuum level and we will also see that we can derive this continuum equation from the Boltzmann equation this is a most fundamental equation and this Boltzmann equation as 2 parts we will I will come to that, but I am just explaining orally. So, you have a particular term which is an advection term. So, similar to your advection term that you have in your nervier stokes equation, the other term is basically a collision term. So, you can think that you know this advection is equivalent to the advection in of a you know nervier stokes equation, but it is exactly not that because if you do what we call as a taking a moment higher order moments and recover your nervier stokes also some advection comes out of collision term here, because the collision term also plays the role of you know advocating the fluid as well as defusing. So, we have 2 terms. So, 1 is an advection the other is a collision term in the Boltzmann equation.

So, this collision can still be significant at small Knudsen numbers and as you keep increasing their Knudsen number to very large value finally, you can reach state where there is no collision possible between the energy carriers and that term goes to 0 and you have a purely hyperbolic equation which as only the advection term. So, that equation is called the collision less Boltzmann equation. So, that is used when you are approaching the free molecular limit on one hand. So, you know if you are using the Boltzmann equation you can use it for all kinds of Knudsen number ranges; however, the computational effort that will be required to solve the Boltzmann equation is tremendously large compared to the nervier stokes and especially when you are approaching the continuum limit small Knudsen number you will find that it becomes very inefficient to solve the Boltzmann equation.

Therefore, we just come back to the nervier stokes and directly solve it whereas, for larger Knudsen numbers we typically have to definitely go away from the continuum nervier stokes equations and use something like the Boltzmann transport equation people also talk about doing molecular dynamics.

So, there is a cash in using the Boltzmann transport equation it requires that you know what the mean free path of the energy carries and. So, on sometimes you may not even know this and also sometimes you may need to even in order to solve the energy equation through the Boltzmann transport you need to know things like heat capacity and. So, on which you may not also have a prior knowledge. So, to understand to get the physical properties, you need to even go to the molecular level just look at ha you know fundamental molecular interactions describe them with some kind of potentials and solve them for all the molecules within the system. So, this is called molecular dynamics. It is a simplest you just apply the Newtonian principle, but the interaction potentials between the molecules will bring out all the difference and that is again something which is not easy to know most of the common potentials that are used or the inert gas potential and they are also used for even atoms and. So, on which is big approximation.

So, people working in molecular dynamics as steadily developing neuron better potentials, but apart from that it is just solving f equal to m a for the entire system of atoms or molecules within the system. So, it is limited only to a small system you cannot do this for a very large system you know you cannot rely on molecular dynamics too in expensive computationally, but to understand the thermo physical properties this can be done and that can be plugged into Boltzmann transport equation and the non equilibrium phenomena can be studied from that. So, there are different ways of doing this, but nevertheless this slide clearly tells you that you know depending on the kind of Knudsen numbers you know you have to know that where the continuum approximation ends and where you have to go to sub continuum models.

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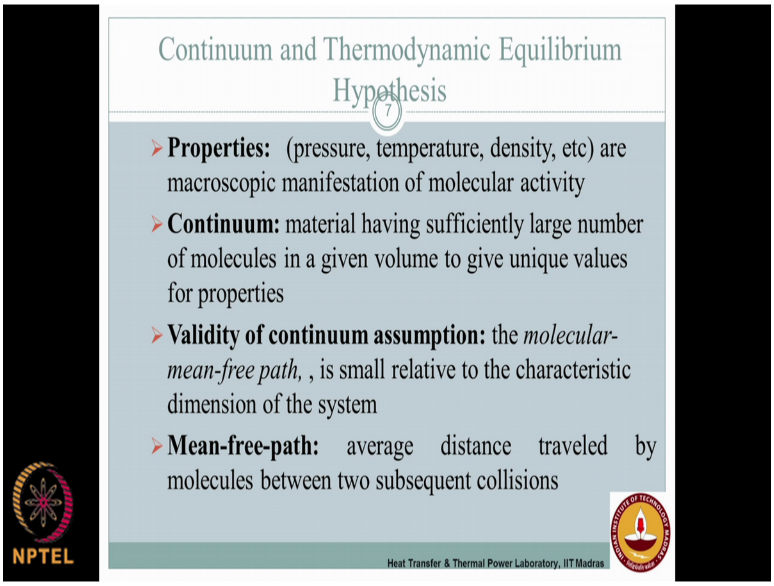

Continuum and Thermodynamic Equilibrium Hypothesis

- **Properties:** (pressure, temperature, density, etc) are macroscopic manifestation of molecular activity
- **Continuum:** material having sufficiently large number of molecules in a given volume to give unique values for properties
- **Validity of continuum assumption:** the *molecular-mean-free path*, , is small relative to the characteristic dimension of the system
- **Mean-free-path:** average distance traveled by molecules between two subsequent collisions

So, when we therefore, talk about continuum I think which most of you are already aware. So, we are assigning certain properties to certain small finite volumes or control volumes where which in which within which we are make an assumptions that continuum approximation is valid. So, therefore, within this particular control volume we assign certain properties, which is a statistical average of all the molecules presents within this continuum we say that you this particular continuum as is defined pressure temperature density and. So, on the classical float to describe the continuum which I do not have it here, but I will show it in the coming lectures this your way you float your density that is delta m by delta v as a function of your delta v right.

So, as you have a very small control volumes size this quantity which is nothing, but the density will not be consistent. So, if your control volume size is too small we will not have enough molecules within the system to define a stable statistical ensemble property called density. So, that will show lot of fluctuations right and then as you increase your control volume size to accommodate more and more molecules then you will reach a point, where you have a stable value and the property called density emerges and that becomes constant and there is a therefore, a critical volume of this size of this control volume, which is required to define this concept of continuum. So, less than this you do not have enough molecules to describe a property like density above this it becomes stable and therefore, you can use this continuum assumption.

So, this is a very important concept that you learn, when you 1st start your fluid mechanics or heat transfer or thermo dynamics this is the assumption of continuum and what is continuum. So, and you never know what is on the left side of this critical volume what happens you are always dealing with the right side. So, what happens to this left side? So, that is where you have to go into the sub continuum models right. So, I think all these pretty much known to you. So, I am not gone a sp end more time on defining continuum validity of continuum assumption we have already seen that.

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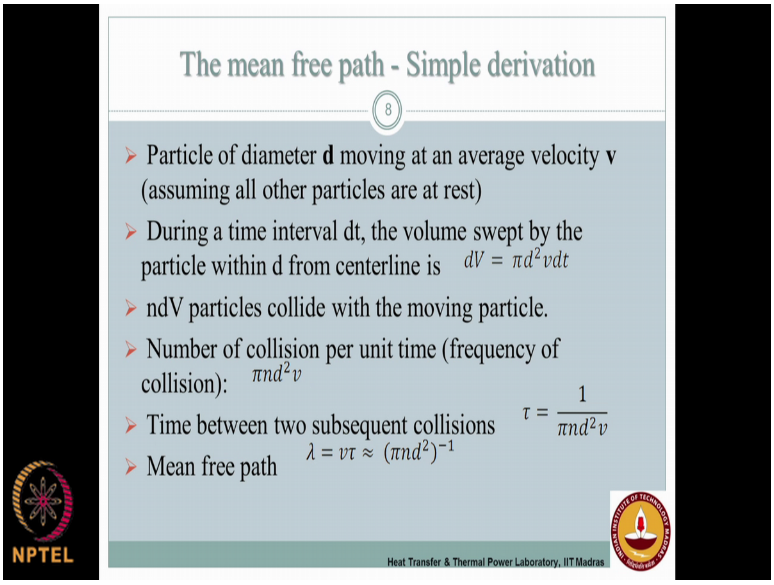

The mean free path - Simple derivation

- Particle of diameter **d** moving at an average velocity **v** (assuming all other particles are at rest)
- During a time interval dt, the volume swept by the particle within d from centerline is $dV = \pi d^2 v dt$
- ndV particles collide with the moving particle.
- Number of collision per unit time (frequency of collision): $\pi n d^2 v$
- Time between two subsequent collisions $\tau = \dfrac{1}{\pi n d^2 v}$
- Mean free path $\lambda = v\tau \approx (\pi n d^2)^{-1}$

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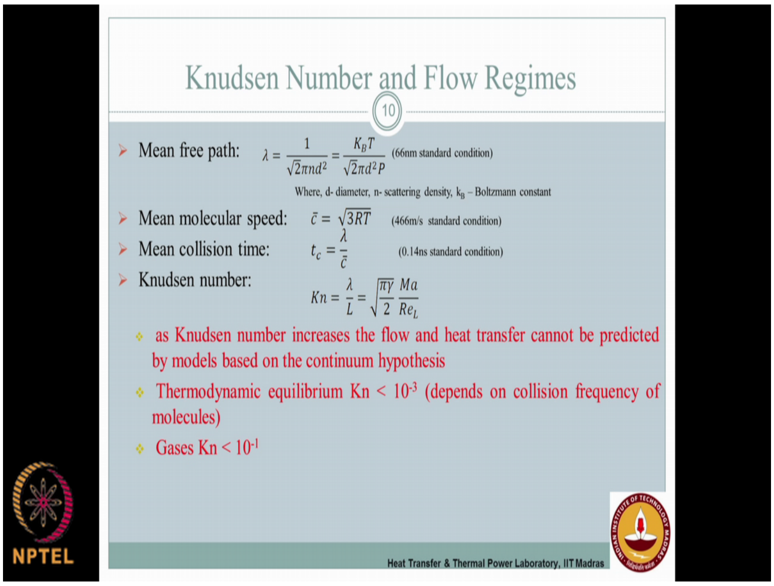

Knudsen Number and Flow Regimes

- Mean free path: $\lambda = \dfrac{1}{\sqrt{2}\pi n d^2} = \dfrac{K_B T}{\sqrt{2}\pi d^2 P}$ (66nm standard condition)

  Where, d- diameter, n- scattering density, k_B – Boltzmann constant
- Mean molecular speed: $\bar{c} = \sqrt{3RT}$ (466m/s standard condition)
- Mean collision time: $t_c = \dfrac{\lambda}{\bar{c}}$ (0.14ns standard condition)
- Knudsen number: $Kn = \dfrac{\lambda}{L} = \sqrt{\dfrac{\pi\gamma}{2}}\dfrac{Ma}{Re_L}$
  - as Knudsen number increases the flow and heat transfer cannot be predicted by models based on the continuum hypothesis
  - Thermodynamic equilibrium Kn < 10^{-3} (depends on collision frequency of molecules)
  - Gases Kn < 10^{-1}

So and mean free path I will just come back to this derivation I will just put it here. So, what is required is this particular definition of Knudsen number here. So, if are right now you are just assume that you know how to calculate the mean free path of energy carriers in different medium it could be liquids it could be gases it could be solids.

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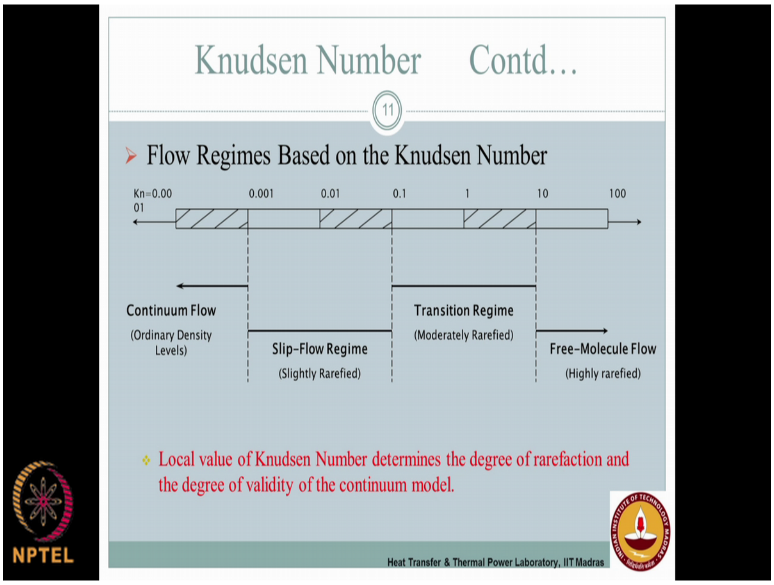

Knudsen Number Contd…

- Flow Regimes Based on the Knudsen Number

Kn=0.0001 0.001 0.01 0.1 1 10 100

Continuum Flow (Ordinary Density Levels)

Slip-Flow Regime (Slightly Rarefied)

Transition Regime (Moderately Rarefied)

Free-Molecule Flow (Highly rarefied)

- Local value of Knudsen Number determines the degree of rarefaction and the degree of validity of the continuum model.

So, once you know this particular quantity called the mean free path you define the Knudsen number and then we classified the different regimes based on the Knudsen number.

So, once again you know I am bringing the same kind of you know explanation in different ways. So, this is again another float which shows Knudsen number variation from very small value to a very large value from left to right and therefore, again talking about where the continuum approximation is valid and where we can use continuum model, but may be a correction at the boundary conditions for the slip. So, that is likely rarefied regime and then you have a moderately rarefied people classify this as transition and all that, but still there is a lot of doubt whether you can use the continuum model there and once you go to large Knudsen numbers definitely, so the degree of rarefaction. So, the rarefaction here is a term which is applied with gases generally when you are talking about electrons rather energy carriers you do not use this word rarefaction, but commonly with gases we talk about rarefaction so, but; however, for all the energy carriers we still use the Knudsen number to classify the flow regime and then we also say that for Knudsen numbers greater than ten or for large Knudsen numbers the validity of a continuum model reduces.

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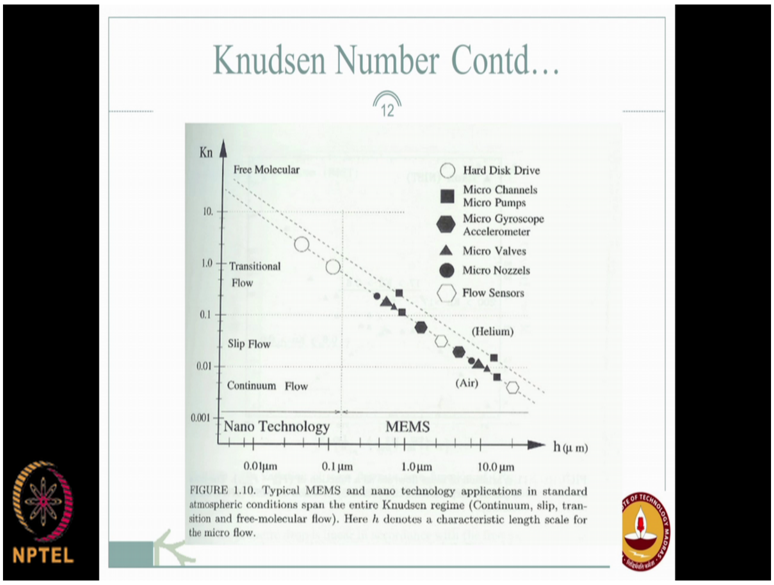

Knudsen Number Contd…

FIGURE 1.10. Typical MEMS and nano technology applications in standard atmospheric conditions span the entire Knudsen regime (Continuum, slip, transition and free-molecular flow). Here *h* denotes a characteristic length scale for the micro flow.

So, here mid gives the typical values of you know Knudsen numbers that you are dealing with in different systems. This is the float Ii have taken from crania dories book that is also a book related to micro scale flows, but also some emphasis on the modeling on the modeling part that is why I not included that in your references so.

So, this particular float here shows what are the typical values of length scale that you are dealing with in different systems, and also the corresponding kind of theory validity of the continuum model and so on. So, for example so here, on the y axis you are floating the Knudsen number and on the x axis corresponding x axis you have the length scale right. So, if you take typically your devices like for example, micro valves or micro nozzles. So, these are of the order of micron size and as you can see the maximum length scale that we are dealing here is of the order of 10 microns.

So, even the micron size is enough to use the continuum model here, we do not have to talk about large scale mechanical devices here. So, we are talking about even micro valves and micro nozzles which of the order of microns few microns and you know if you take the example of you know air for example, and define the Knudsen number. So, the Knudsen number comes to the order of 0.01 you know and bellow. So, therefore, very clearly for these cases you can use the continuum based models right now if you are going to certain other areas you know they could be a micro channels or micro pumps with gas flow.

So, micro channels with liquids still would be in the continuum range because their mean free paths of liquids are smaller whereas, if you if you operate micro channels with gases its quite likely the Knudsen number can exceed 0.1 as you can see in this particular this square symbol here right. So, it can cross 0.1 and you can actually be in a slip or a transitional regime. So, in that case you still probably can use your continuum model nervier stokes equation, but you have token for this slip conditions happening at the boundary through corrections and so on and now when you are going to the size of your hard disk drive. So, in your hard disk drive you know so it is rotating at such high speeds and there is a lazar which is always you know point at the lazar had. So, close to the actual drive that is rotating to retrieve this malformation. So, that the separation distant is less than 0.1 micron. So, this is like what 100 nanometers that you are talking about.

So, you are already now approaching the nanometer regime and the air which is in that gap. So, will be experiencing a Knudsen number which is of the order of 1 and above, in such a case clearly you are gone away from your continuum approximation. So, in that case you have to when you are solving equations to describe the transport of air which is between the head and between the particular drive. So, you are talking about know high Knudsen numbers and therefore, you have to look at sub continuum models to solve this particular equation. So, this is kind of float which gives you an idea even between scales ranging from microns to the order of nanometers you can see a rapid demarcation in the flow regimes it start from continuum up to the order of say 1 microns, but suddenly bellow 1 micron something happens and then again your continuum laws breakdown and you start looking at sub continuum models.

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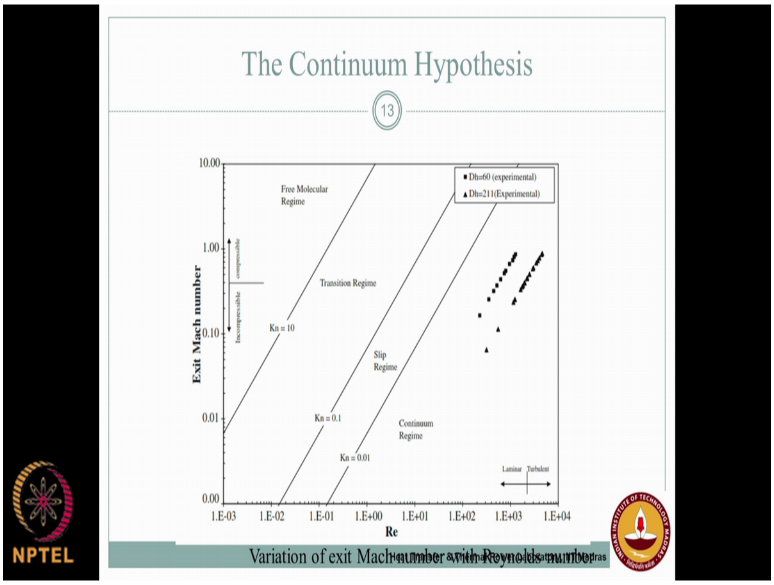

The Continuum Hypothesis

Variation of exit Mach number with Reynolds number

So, this is again another float for example, if you take a micro channel this gas flows. So, you have say 2 different micro channels and then you float the corresponding variation of mach number. See, the mach number here is floated to also classify the flow regime as either compressible or incompressible and you also have and you also have a Renaults number variation on the x axis to classify the flow as either laminar or turbulent. Now on top of that you can also float these patterns, the pattern map here for different channel diameters and this can be classified based on their corresponding Knudsen numbers. So, if you are talking about these are all in the order of microns.

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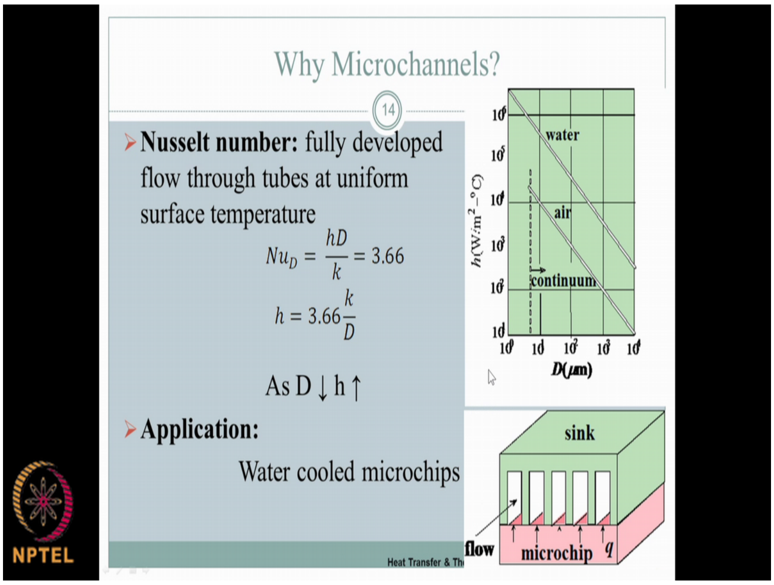

Why Microchannels?

- **Nusselt number:** fully developed flow through tubes at uniform surface temperature

$$Nu_D = \frac{hD}{k} = 3.66$$

$$h = 3.66\frac{k}{D}$$

As D ↓ h ↑

- **Application:**

Water cooled microchips

So, if you are talking about 200 microns. So, if you are talking about the channel diameter of the order of 200 microns they are still in the continuum regime. So, 60 microns will be moving towards the left and so on and so forth. And as you start reducing the size of these dimensions to the order of one micron you might start experiencing the slip regime here and once again within the slip regime you can actually vary the Reynolds number drastically all the way you know from this end to this end and also you can also transition from an incompressible to a compressible regime. So, all these flow conditions are possible. So, this is a typical flow pattern map.

So, you can classify whether it is a laminar or turbulent flow depending on the Renaults number or compressible or incompressible flow and you can also have very high Knudsen number flows depending on the lengths scales. So, all this is all these variation is possible, if you are reducing the channel size you know and then now a days people are looking at using micro channels for a lot of application and especially. So, for cooling, I mean we are now looking at also convection. So, we have. So, far focused on the application of continuum or sub continuum models depending on Knudsen number, now we are also looking at convection aspects where it is of the order of micron size and above 1 typical example is the micro channel. So, micro channels are gaining lot of importance it is not just a fundamental device where you see some phenomena happening at micro scale, but the more important application is in cooling electronic circuits.

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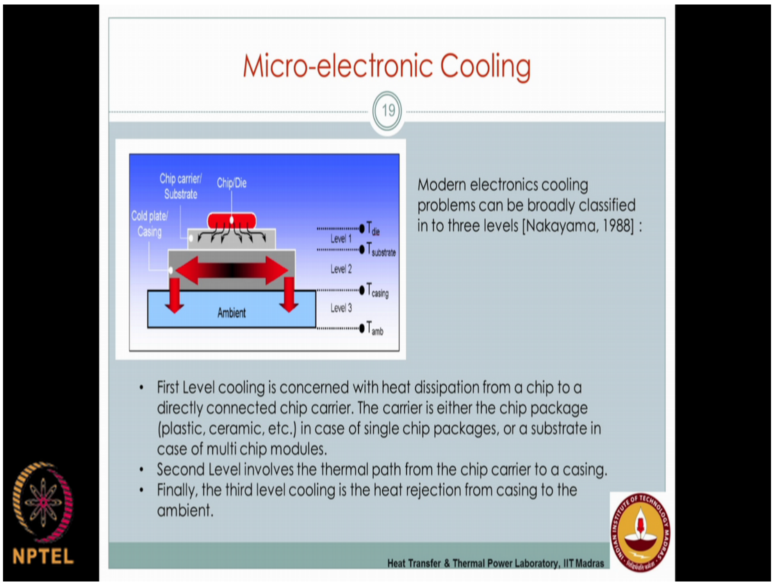

Micro-electronic Cooling

Modern electronics cooling problems can be broadly classified in to three levels [Nakayama, 1988] :

- First Level cooling is concerned with heat dissipation from a chip to a directly connected chip carrier. The carrier is either the chip package (plastic, ceramic, etc.) in case of single chip packages, or a substrate in case of multi chip modules.
- Second Level involves the thermal path from the chip carrier to a casing.
- Finally, the third level cooling is the heat rejection from casing to the ambient.

So, here this particular figure shows that you have a microchip micro processor now there are different levels of cooling in a chip which I think I will try to bring when the slide here, I think probably I should describe this before I go there. So, in microelectronic cooling you have different levels of cooling.

So, the 1st level of cooling is happening from the heat generation which is happening within the semi conductors of the order of nanometers inside your chip your chip consist of billions of semi conducted devices and that is where the heat generation is happening and that as to be removed from the chip to the chip carrier or the substrate. So, you have basically what we called as a packaging the chip is actually is not just a standalone thing it is actually package to a substrate and now this chip packaging could be of the order of one millimeter or few millimeters, now from that you have a larger level a plate or a casing which is of the order of centimeters. So, now, from this you have to remove it to the ambient.

So, this is how the multiple length scales play role in removing the heat dissipation. So, heat generation happens at nanometers and then 1st level is happening as heat dissipation to the chip carrier or substrate now this is mostly happening due to the contact resistance. So, this is bonded to the substrate and this as to be therefore, overcoming the contact resistance and so on. So, that is purely material phenomena and from the substrate you have to remove it to the casing now this substrate is of the order of millimeter square. So, this there is a possibility that we can actually put a micro channel inside this we can etch micro channels parallel micro channel system into the substrate and therefore, we can make this transfer of heat from the substrate to for example, the cold plate outside much easier from the cold plate the convectional techniques are all standard you can have either heat pipes to remove the heat to the ambient or you can have fan or infringement cooling.

So, these are working at the macro scale. So, these are the normal techniques that have that have been used and they have been very well understood, but what is not understood is how do we dissipate the heat from the level 1 and level 2 So, level 3 heat dissipation is fairly you know as been worked out for the last 10 20 years and is been clear, but many times you will find that the processor fails because of the problems with level 1 or level 2 now. So, this classification was done by Nakayama in 1988 and it is broadly used you know by people working in the electronic cooling industry to understand the heat removal. So, coming to this, you can now understand that this micro channel cooling system can fit into the level 2 of cooling the level 1 of cooling is purely material science more efficient materials which can with high thermal conductivity and less inter facial thermal resistance. So, that is basically a material science problem usually and not what we can do us you know as mechanic or thermal engineers what we can probably do is predicted predict the heat dissipation, but beyond that it is a material science problem.

Whereas level 2 it is a place where we can use this micro memes devices like micro channels and this is where the concept of attaching the micro channel as a heat sink directly to the substrate. So, and that dissipates the heat to the third level and from there it goes to the ambient which is the ultimate sink right. So, this is a conceptual picture like how you can basically attach a parallel micro channel system to the microchip or the carrier or the substrate now why do we use micro channels. So, typically if you see that a Nusselt number what we have know defined in heat transfer it is for the laminar flow for fully develop laminar flow it is a constant value right. For example, for the case of uniform surface temperature it is exactly three points 6 for constant wall flux it is 4 point 3.

So, similarly if you are talking about developing flow you have function of your Renaults number and your pantone number and if you are again looking at turbulent flow it is again a function of Renaults number pantone number given by detours barratry equation whatever may be finally, the Nusselt number is either fixed value or for a given specified Renaults and pantone number its again a constant. So, irrespective of what kind of dimensions you are dealing with. So, therefore, according to this principle if you apply this scaling it tells you that as your diameter of the channel scales down goes down your corresponding heat transfer coefficient will also go up; that means, if you are reducing your channel dimension from a millimeter to micrometer. So, 3 orders of magnitude down your h value goes 3 orders of magnitude up which results in very high values of heat transfer rate because according to the Newton law of cooling q is equal to h a dell 30.

So, as your heat transfer coefficient goes up 3 orders of magnitude your heat transfer rate goes up and this is the very simple way of explaining why a micro channel system is more efficient and using macro channel system. So, all you are doing is scaring down bringing down the diameter and therefore, increasing the overall heat transfer rate. So, one way of looking at it is you are increasing the surface area to the volume ratio. So, there therefore, more surface area is available for effective heat dissipation and most of the micro channels now that are being proposed to be used with micro electronics they all work with liquids you do not come out with gases because gases have low thermal conductivity and therefore, there you know heat transfer performance which will be lower than using liquids.

So, most of them employ liquids and also not generally water could be even possibility there could also be using refrigerants you know liquids with lower boiling points depending on the kind of temperature that you want to achieve right. Say if you are talking about temperatures of the order of 70 80 degrees water will be perfectly fine, but if you are talking about maintaining temperatures may be of the order of 50 degrees 40 degrees then you have to go for liquids with lower boiling points and high volatility right. So, this is generally what is used and use look at the order of heat transfer coefficient that is floated as a function of diameter here.

So, if you take water for example, if you are talking about the know millimeters sized you know channels the convectional channel. So, your heat transfer coefficient is very small whereas, if you are reducing the channel diameter to the order of you know few microns you are tremendously increasing. So, it is a linear float you can see that. So, propositional to the reduction and h d is you are increasing the h whether you use water or air you can see that naturally your water is having higher heat transfer coefficient than air and that is why it is usually used as the working floor.

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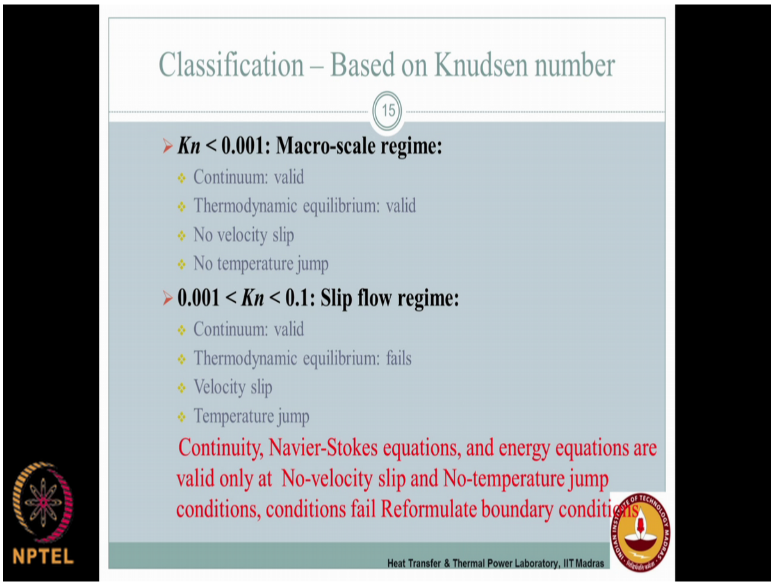

Classification – Based on Knudsen number

- **$Kn < 0.001$: Macro-scale regime:**
  - Continuum: valid
  - Thermodynamic equilibrium: valid
  - No velocity slip
  - No temperature jump
- **$0.001 < Kn < 0.1$: Slip flow regime:**
  - Continuum: valid
  - Thermodynamic equilibrium: fails
  - Velocity slip
  - Temperature jump

Continuity, Navier-Stokes equations, and energy equations are valid only at No-velocity slip and No-temperature jump conditions, conditions fail Reformulate boundary conditions

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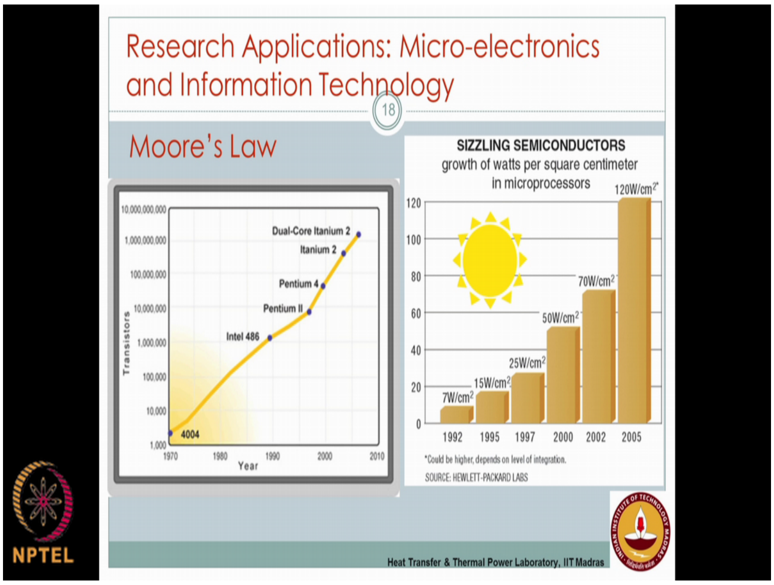

Research Applications: Micro-electronics and Information Technology

18

Moore's Law

SIZZLING SEMICONDUCTORS
growth of watts per square centimeter in microprocessors

*Could be higher, depends on level of integration.

SOURCE: HEWLETT-PACKARD LABS

Heat Transfer & Thermal Power Laboratory, IIT Madras

So I think just I want to also show you 1 more slide because now we are talking about electronic cooling. So, 1 last slide before we stop here and. So, which when we talk about micro electronics people generally refer to moors law which says that every 2nd year your transited density will keep doubling. So, that is the amount of transistors that you basically package within a given cross sectional area. So, that is supposed double every 2nd year in order to account for the tremendous increase in the computing power processing speed, but unfortunately there is a bottle neck to that and that bottle neck is what the heat dissipation the moors law never moore never knew that you know just the if you just keep scaling up you know just packing more and more transistors.

So, you little bit he thought that the computing power will increase off course, but he did not realize that also the associated heat transfer becomes a big bottle neck and the heat dissipation how to remove this heat generated at the source efficiently is what hidden predict and that is why we do not now scale exactly with mores law it is slowing down, if you look at the kind of you know processor speeds. Now we have reached a limit I do not think which we can increase tremendously we have reach may be more than 3 gigahertz for example, if you look at the clock speed of your computers.

Now, I am if you looked at your clock speeds 10 years back that time anything above 1 gigahertz was something really terrific speed and if you looked at something 3 years back we had already where closed to three gigahertz. And now in the last 3 years we have really not achieved you know 4 or 5 or 6 gigahertz we are still at around 3 gigahertz and we are almost saturated there. The thing is the higher the clock speed; that means, the more should be the device the transited density. So, that the communication can be faster, but the heat transfer is big bottle neck. So, most of the electronic device is fail because of cooling problems not because of any other you know fundamental hardware difficulties, but it is because of inefficient cooling the same laptop which you operate in an air condition environment works perfectly fine and you put it outside in a normal non air condition room within a few days it made give you a trouble.

So, therefore, if you look at the corresponding heat fluxes that are generated from microelectronic devices, now you are talking about already it as crossed you know for the kind of clock speeds that we are discussed it is cross the fluxes at the surface of a sun. So, that is more than hundred watts per centimeter square the heat fluxes are tremendous, but at the same time we need to maintain the temperature of the semi conducted device not more than 80 90 or 100 degrees beyond which it will fail. So, therefore, the emphasis will be on very efficient heat dissipation here. So, it is very important that we integrate efficient heat prediction systems heat prediction methodology first you have to predict how much of heat is actually dissipated.

So, if you are law talking about nanometers we cannot use the 4 years law to do this prediction, if you do not predict it right you are definitely go into design your cooling system inefficiently. So, once the prediction is done properly then you can build the appropriate support system. So, advances in materials will be one good thing at level 1 and then incorporating technologies such as micro channels and other micro heat pipes will be very efficient at level 2 and also very efficient phase change heat transfer for example, infringement cooling with phase change could be a very efficient mechanism of heat removal at level three. So, with these kinds of things you can probably deal with some of these issues.

So, will stop here today and tomorrow we will also look at some other applications or some other examples of particularly with respect to heat transfer.

Thank you.