Heat Exchangers: Fundamentals and Design Analysis

Prof. Prasanta Kumar Das
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 50
Micro Channel

So, welcome to the course Heat Exchanger Fundamentals and Design Analysis. If you recall, we have started learning and the micro heat exchangers. And for micro heat exchangers it is important to know that how heat transfer takes place, convective heat transfer takes place through micro passages or micro channels. So, we have spend some time we have taken some example, and I have told that the fluid flow particularly gas flow through narrow size passages to micro passages that is unique.

And that has got some difference with similar kind of flow situation when that takes place through a conventional sized conventionally sized channel. So, let us proceed with that.

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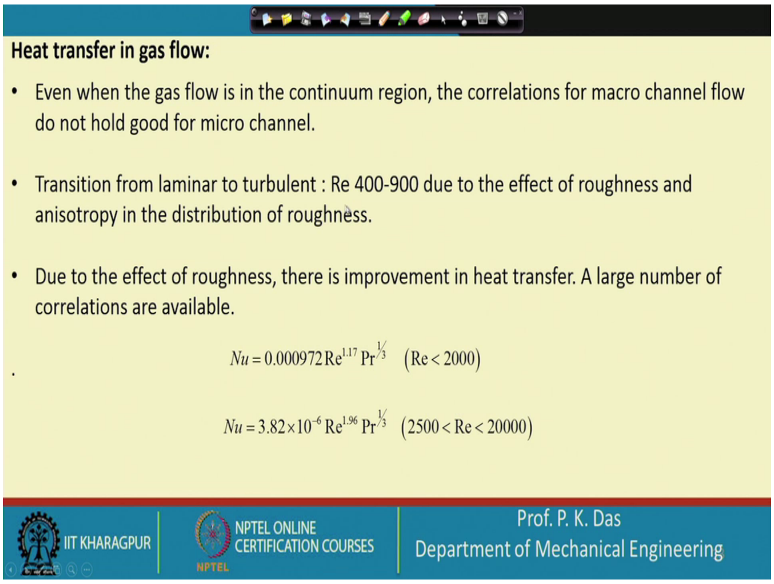

Heat transfer in gas flow and in micro channel we are considering. So, if you recall, that we have told that there could be depending on Knudsen number we can have conventional flow or continuum flow. We can have continuum flow with sleep condition at the wall, there could be transitional flow and there could be free molecular flow.

So, let us say the Knudsen number is such or the channel dimension is such that based on Knudsen number, we are getting the conventional flow. Only that within the channel, there will be there will not be much difference in the flow phenomena compared to a large size channel, but in case of micro channel there are some speciality; when the channel is of small size, there is some speciality, speciality there is some unique features. What are those? That even when the gas flow is in continuum region, the correlation for micro channel flow do not hold good, macro channel flow do not hold good for micro channel, why?

One of the observation is that, transition from laminar to turbulent that occurs in a range and that range is 400 to 900. So, this range is very small, in case of large size channel, this transition occurs around Re is equal to Reynold's number is equal 2000. But here it is occurring within a narrow range 400 to 900. Reason is, due to the manufacturing of this micro channel, these channels are rough. The roughness that is a relative quantity here, the channel dimensions are small, but whatever manufacturing method we adopt; particularly this special manufacturing method which we adopt for making this small channels. They cannot make they can make the channel size small, we can get small channel size, but the roughness sizes are not scale down equally.

So, then what will happen? That the roughness are or roughness elements are large. So, that large roughness; that is, one feature which is special to micro channel. Then due to the manufacturing technique, the roughnesss are non-uniformly distributed. When we are fabricating a larger size channels, then what happens? That roughness is uniformly distributed over the surface area. But here in case of micro channel the roughness could be very non-isotropically distributed over the surface area. So, due to these 2 effects what we will find, that there could be a early transition of laminar to turbulent flow.

There could be an early transition from laminar to turbulent flow. And due to this early transition what will have that, turbulent flow gives good mixing and good heat transfer. So, there could be a tendency of high rate or rather improvement of heat transfer in case of micro channel micro channels flow. And obviously, in such cases the correlations which we used to have for macro channel will not hold good. So, what I have written here? Due to the effect of roughness there is improvement in heat transfer a large number of correlations are available.

Just for example, I have given 2 example 2 correlations that for 2 different ranges of Reynolds number, we will have these 2 correlation for Knudsen number for calculation of a heat transfer. Calculation of heat transfer coefficient for estimating heat transfer. You need not think that these are the only correlation, there are many correlations. Similar correlations are there for friction factor also which I have not given, because it will be boring to give go through all these correlation. As and when needed depend getting a good reference book or handbook or technical paper one can pick up this correlations.

What I like to stress upon which is very important, that even in the continuum level, or even in the continuum region if the passage size is small, then we can have a difference in heat transfer between the small size channel and a large size channel. So, obviously, we should need to have different sets of correlation; this is important to know.

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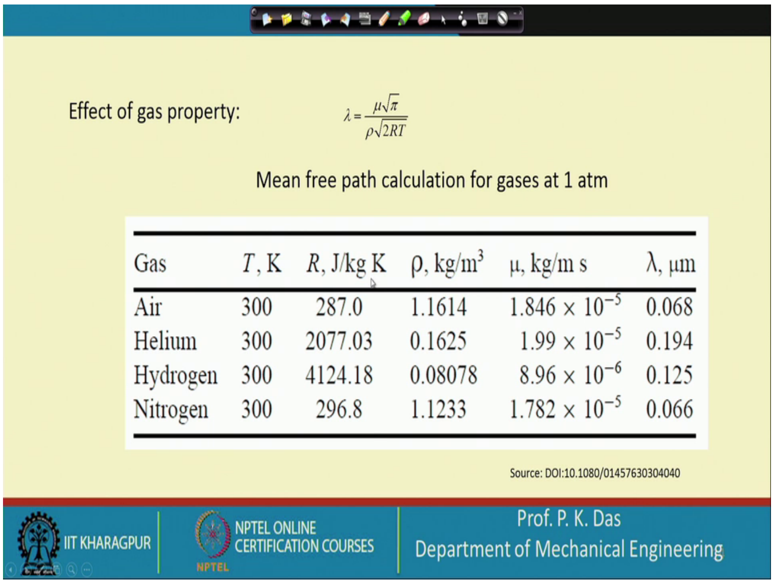

Gas	T, K	R, J/kg K	ρ, kg/m^3	μ, kg/m s	λ, μm
Air	300	287.0	1.1614	1.846×10^{-5}	0.068
Helium	300	2077.03	0.1625	1.99×10^{-5}	0.194
Hydrogen	300	4124.18	0.08078	8.96×10^{-6}	0.125
Nitrogen	300	296.8	1.1233	1.782×10^{-5}	0.066

With this let us proceed. Well, now let us think of we are considering gas flow through narrow passages. So, let us think of what are or let us look into what are the effect of gas property.

So, Knudsen number that can be defined by the gas properties; like, here we have got Knudsen number the basic definition is from the molecular free path and the scale length of the system or problem we are considering. So, mean free path that is one important parameter of Knudsen number. And Knudsen number is important when we are dealing with micro scale heat transfer. So, mean free path calculation which depends on gas property so, lambda is given by this formula. So, lambda is equal to mu into root over pi upon rho under root 2 RT. Mu is the dynamic viscosity, rho is the density, R is the gas constant and T is the temperature.

So, here you see then the mean free path that is different for different gases, it should be and we have tabulated here air, helium, hydrogen and nitrogen. All are at same temperature; R values are different rho are different mu different. So, the molecular free mean free path, that is also different. So, obviously, the gases which are lighter gases, they will have larger molecular mean free path. Before a coalition they should cover larger distance. So, what we can find for helium and hydrogen. Air and nitrogen they are very close so, 0.068 and 0.066.

So, these 2 are close and these 2 are small compared to hydrogen or helium. With this let us go to another aspect.

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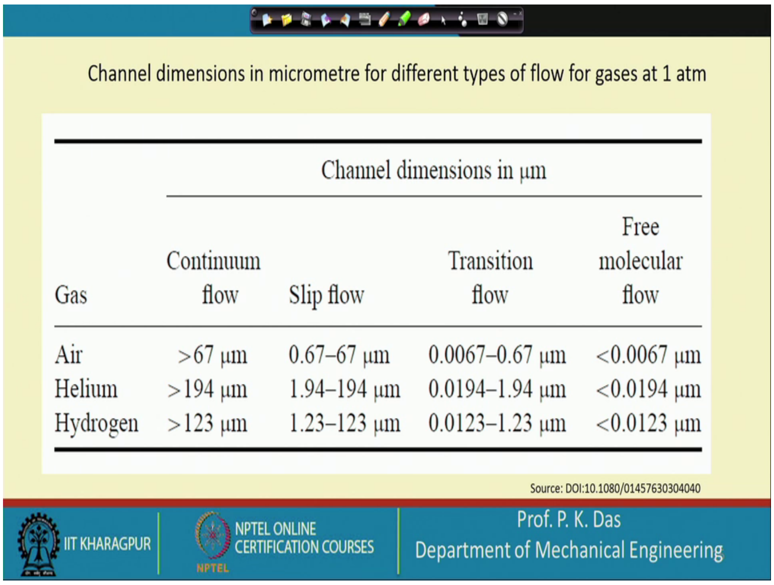
Channel dimensions in micrometre for different types of flow for gases at 1 atm

	Channel dimensions in μm			
Gas	Continuum flow	Slip flow	Transition flow	Free molecular flow
Air	>67 μm	0.67–67 μm	0.0067–0.67 μm	<0.0067 μm
Helium	>194 μm	1.94–194 μm	0.0194–1.94 μm	<0.0194 μm
Hydrogen	>123 μm	1.23–123 μm	0.0123–1.23 μm	<0.0123 μm

Channel dimension in micrometre for different types of flow for gases at one atmosphere. 2 4 type 4 different kind of flow I have defined towards the beginning of this course, towards the beginning of this topic that is continuum flow. Continuum flow with sleep boundary, then transitional flow and free molecular flow; so, for different gases we have given the channel dimension in millimetre.

One example let us take. For air if the channel dimension in micrometre, it is greater than 67 micrometre, then it is continuum flow. If it is within 0.67 to 2 67 micrometre, then it is slip flow 0.0067 to 0.67 micrometre, then it is transition flow and less than 0.0067 micrometer then it is free molecular flow. I like to remind you once again that for this 4 different kind of flow regimes, we will have different kind of physical laws. For the first case, we are familiar with the laws that let us say we are solving a momentum balance problem. So, Navier Stokes equation will be used for continuum flow.

But again we have to consider just sometimes back. I have discussed that, sorry, they the wall roughness that plays a very important role. So, the many of the conventional correlations we cannot use or we have to use with caution. Then we have got the slip flow region; where Navier Stokes equation will be useful, but the boundary conditions are different. Then we have got transitional flow, here we have to have some sort of statistical loss like Boltzmann technique or we can have the Monte Carlo method, then we have got free molecular flow.

Each and every molecule motion of each and every molecule becomes important here. So, these I have explained earlier, and here also I once again I like to tell you. And here we can see that how with channel dimension we can have different kind of flow, for different kind of gases ok. So, the channel dimension for sleep flow will be different for air and hydrogen. So, this we have to keep it in mind.

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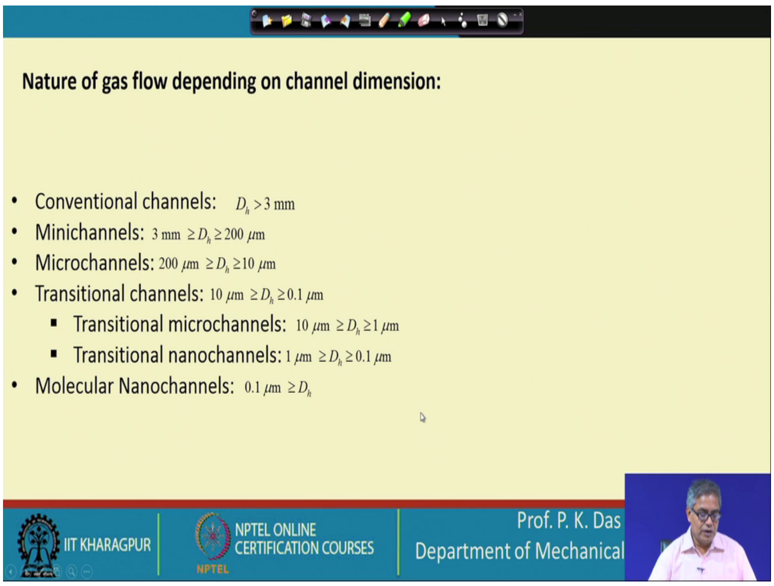

Let us go to the next information. Here all the different kind of flow phenomena has been described. And hydraulic diameter has been given in millimetre or micrometre.

Conventional channel generally hydraulic diameter this is greater than 3 millimetre. Mini channels 3 millimetre to 200 micro millimetre, 200 micrometre micro channel so, 200 micrometre to 10 micrometre. Transitional channel 10 micrometer to 0.1 micrometer, transitional micro channels, we will have 10 micrometre to 1 micrometre. Transitional nano channels 1 micrometre to 0.1 micrometer and molecular nano-channels that will be 0.1 micrometre and less. So, you see that people for convenience they have name the channels. This is not very sacrosanct, there could be some difference and this is for gas flow. Some people say that we should follow the same kind of classification for liquid flow or flow for 2 phase fluid, but some people say, no for liquid flow or for flow of multiphase mixture 2 phase mixture, we should have different classification.

But it just gives an idea that, what we can consider as conventional channel micro channel transitional channel etcetera. Let us go to another information.

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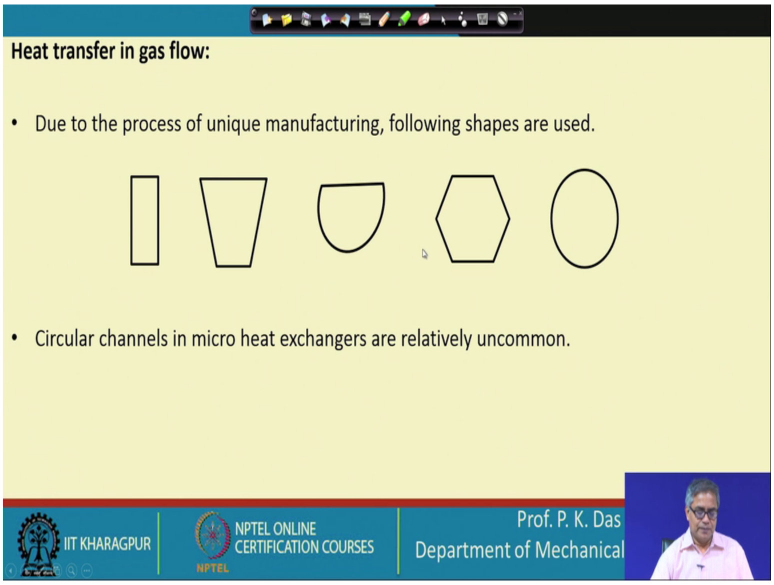

So, we have got some idea regarding micro channel. Now micro channel are modal size channel, what could be their dimension? So, that also we have some idea. What is the shape of the micro channel? The shape of the micro channels are shown here. So, you see first we can see a rectangular micro channel, then this is a kind of a trapezoidal. This is part of a circle the perception is part of a circle.

This is an hexagon and this is a circular passage. So, let me tell you these different kind of passages are passages are seen in micro channel design or in micro heat exchanger, in micro heat sink. Because most of the cases this micro channels are manufactured by some special techniques. The conventional techniques are not suitable for making micro channel; we will come to this aspect very soon. And out of all this shapes though there are circular shapes, circular passages of circular cross section present in micro heat exchangers micro heat sinks, but that is not very common.

At the beginning I have started with an example of a cell and tube heat exchanger where micro tubes are used, but that is not very common. When there are number of passages in a heat exchanger, generally they are of non circular cross section. So, this is also one speciality of micro channel heat sinks or micro channel heat exchangers that the passages are in most of the cases non circular. So, it should not be thought that circular passages are not possible, but they are rare. Let us go to the next slide.

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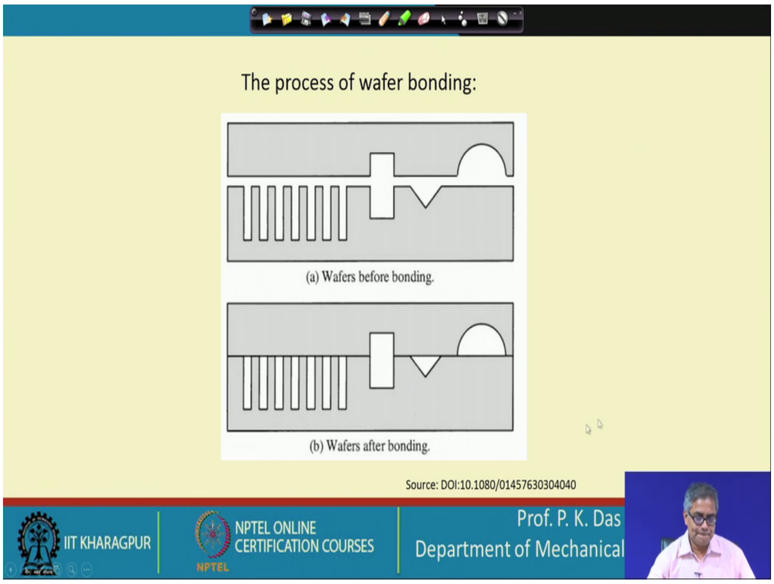

So, one method only I have shown. Micro channels or micro channel heat sinks micro channel heat exchanger. They are made of many different kind of material. One could be silicon wafer. So, from the silicon wafer how we are making these channels. So, this is one way one can see that let us say we have taken 2 wafer on one wafer we have made this kind of impression. And in another wafer we have made this kind of impression. And then these 2 wafers are bond together. So, if these 2 wafers are bond together. So, we can get rectangular passages like this, we can get a rectangular passage like a triangular passage like this a semi-circular passage.

So, you can see that this is how the micro channels are formed, and even with this method we can create some sort of a micro channel heat sinks or heat sink or micro channel heat exchanger. And probably this particular slide explains why we get different kind of channel geometry, because the manufacturing method is completely different. Of course, this is not the only manufacturing method, that is why we get different kind of micro channels, micro channels of different shapes. The shapes which are not very common in case of conventional heat transfer equipment. So, with this let us go to the next slide.

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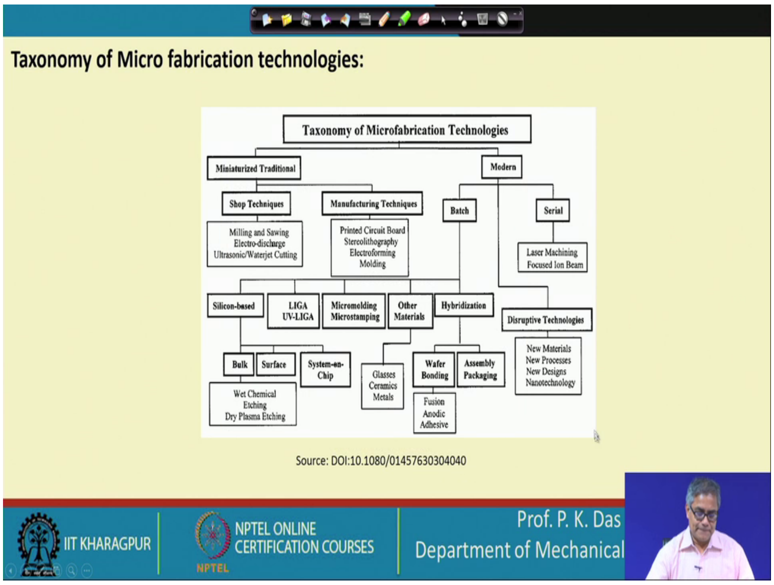

Here we are giving a taxonomy of micro fabrication technologies. Micro fabrication when I am telling or when I am mentioning micro fabrication, this is meant for making micro channels, and ultimately they can be used for micro heat exchangers. So, this is for your micro channels. Now what are the techniques? So, one side we have got traditional manufacturing, traditional method of manufacturing miniaturized channels, and the other side we have got modern method of manufacturing.

Let me tell you I have mentioned somewhere and again I like to stress upon the point; that as the micro channel heat exchangers are becoming more important, there are more areas of application day by day, we are finding more application. So, the manufacturing or fabrication of micro channel, that is also an active field of research and different new techniques are being evolved. So, conventional technique or traditional technique if we see that, let us go to the conventional machining technique; which has been mentioned as shop techniques; milling and sawing, electro discharge ultrasonic water jet cutting. So, these are some of the methods, these are some of the methods which are used for making micro channel.

Milling and sawing, actually milling is a good method for making micro channel. So, it will create open micro channel, and then if there is a top cover we can get the close channel. And with milling particularly micro milling and milling kind of a thing, what we will get to? We will get channels of probably we will we will be conveniently I mean one can conveniently make rectangular channel, but the channel did not be always very straight channel, we can have zigzag or serpentine channel.

We can have bends etcetera in the channel. So, that is possible with micro milling particularly n milling type of operation machining operation. Then with sawing also, one can have straight channel, at least straight channels one can have with sawing, circular saw one can have straight channel. With diamond cutter one can have one can create channels. So, these are the methods by which one can do. And viridian is again another method one can make channels of unique shapes. And also the whole design if there are bends etcetera, by proper manufacturing process. Conventional manufacturing process, but by proper planning of manufacturing process, those types of channels can be made.

So, this is one way. Particularly for manufacturing metallic micro channels micro passages this is important. Then there is another method manufacturing technique which generally is not used for manufacturing of metallic component, but for other component these processes are used. That is printed circuit board, the way we fabricate printed circuit board. Using the same procedure we can make micro channels, small channels with some sort of bends etcetera; with serpentine features we can make it.

Then stereolithography is one method by which we can make it. Then electroforming moulding these are the method by which we can make it. So, though I like to give a word of caution that though very large number of methods have been given in this particular slide. So, it is not kind of all-inclusive, there could be some other methods like some other forming methods that can be also used for making micro channel.

So, here one can see that by some moulding method it can be done. So, with this we come to an end of traditional technique. The left side of the traditional technique is for generally adopted for metallic parts and right side we are adopting it for other technology other manufacturing process, but they can be taken for making micro channel also. The modern technique so, modern technique again we have got several classification.

One is batch technique. So, batch technique if we consider, so, one is silicon based. Many of the micro channel heat sinks and sometimes even a small heat exchanger can be made out of silicon. And it is made out of silicon, because we have to have electronic component cooling is a very important feature for having reliable circuitry, for higher scale of integration. And for that we have to have micro channel in electron sorry silicon wafer. So, so the technique which are silicon based are can be classified as bulk, surface and surface on sorry system on chip. Then bulk that can be done by wet chemical etching and dry plasma etching.

So, silicon wafer on silicon wafer if we have to have these passages. So, generally some sort of etching process can be done, chemical etching process is there or dry plasma etching process is there. For some metallic component also one can adopt some sort of chemical or electrochemical process, some sort of etching process with proper masking that can be adopted. Then we can have liga or UV liga, ultraviolet liga; liga actually is a German word for lithography. So, some technique of lithography.

This is a course of heat exchanger, we cannot go into details, but for micro heat exchanger what are the methods let us see very quickly. Then we can have micro moulding and micro stamping process etcetera. Then our, for other materials what kind of other materials we can have? We can have glass ceramic metal already I have we have told, but some of the metal processing can be done by this modern techniques also. Then hybrid processes are there, then wafer bonding already I have told that on the wafer you create channel and you bond to wafer to give some sort of a specific cell.

Fusion, anodic, adhesive; so, that is also one way of getting a unique channels. And then assembly packaging and there are other methods by laser you can have many different kind of passages done. And then there are some other technique which is which has been mentioned here as disruptive technique. New materials new processes, new design nanotechnology. So, these are some sort of disruptive processes by which things can be done. So, basically due with the help of non-conventional processes we can have it. Laser processes I cannot discuss due to paucity of time in details.

But by laser processing a very large number of passages or very large number of geometries small features that can be made, and that can be used for micro scale heat transfer and micro scale heat exchanger fabrication. So, what happens? We make micro passages, after that they have to be stacked and joined. So, diffusion bonding is one method by which it can be done. Laser welding or laser based joining process, electron beam based joining process, these are also processes which are used. So, just to give a give a brief idea how this heat exchangers are made.

Because these techniques some of these techniques are cutting etch techniques, new techniques which are under development; but there very important if the micro scale heat exchangers are to be made. So, with this I come to an end of today’s lecture. What we will do? We will we have some idea regarding the micro scale heat transfer and micro passages micro channels how they are fabricated. We will take it forward, and then ultimately very quickly with we will end with some idea regarding micro heat exchanger.

Thank you.