Heat Exchangers: Fundamentals and Design Analysis
Prof. Prasanta Kumar Das
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

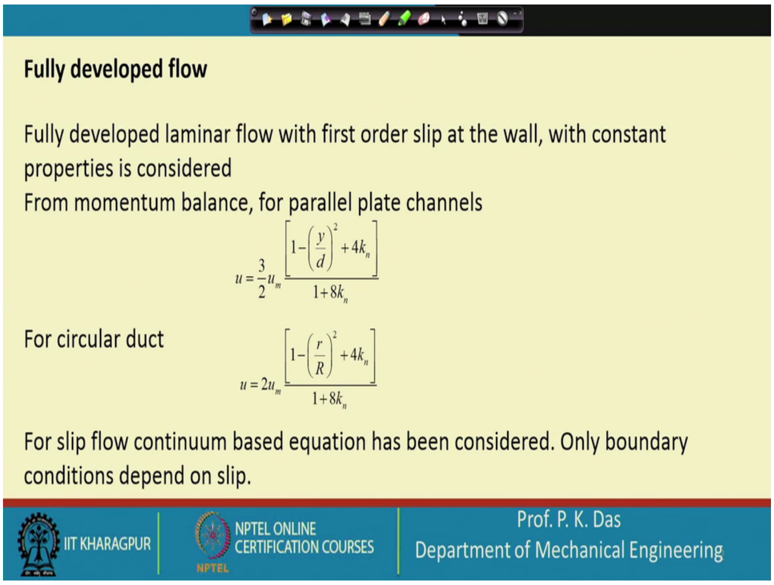
Lecture – 49
Micro Scale Heat Transfer (Contd.)

Welcome, to the course Heat Exchangers Fundamentals and Design Analysis. If you recall we were discussing the special topic on Micro Heat Exchangers. So, micro heat exchangers as you have seen that it is a special class of heat exchangers where the heat exchanger passages are very small. Basically, these channels the channels of micro heat exchangers can be called as micro channels and also the micro heat exchangers they handle less amount of fluid. So, in that way they are slightly different from compact heat exchangers though there are lot of similarities.

And, as the channel channels are of small dimension so, we find that the physics of the flow phenomena and physics of heat transfer that is different and in that respect two different sorry two special effects due to the small size of the channel that has been already discussed; one is slip at the wall that mean the at the wall the velocity of the fluid and the velocity of the solid they are not the same. For most of the cases the wall is stationary, but the velocity is not equal to 0 at the wall. So, this is called slip the phenomenon of slip.

And, in case of conventionally conventional heat exchangers or conventional passages larger passages macro passages we find that the temperature of the wall and the temperature of the fluid adjacent to wall they are the same, but in micro channel there is a temperature jump; that means, temperature of the fluid at the wall and temperature of wall they are different. So, these two phenomena has been has been discussed in our last lecture and the boundary conditions then they are different for micro channel and macro channel. With this let us proceed to the next slides.

(Refer Slide Time: 02:46)



Here we I have given two equation for fully developed flow fully developed laminar flow with first order slip at the wall; slip just now I have explained what is first order slip with constant properties is considered from momentum balance for parallel plate channel. Parallel plate channel we get u is equal to 3 by 2 u m and then 1 minus y by d whole square plus 4 k n divided by 1 plus 8 k n upon 1 plus 8 k n.

So, most of the symbols you can understand, but even for your benefit let me explain it; u is the velocity at any point suppose we consider a channel let me draw it here itself so that it will be clear. Suppose we consider a channel parallel plate channel and the thickness of the channel or width of the channel that is d and in this direction we have got y.

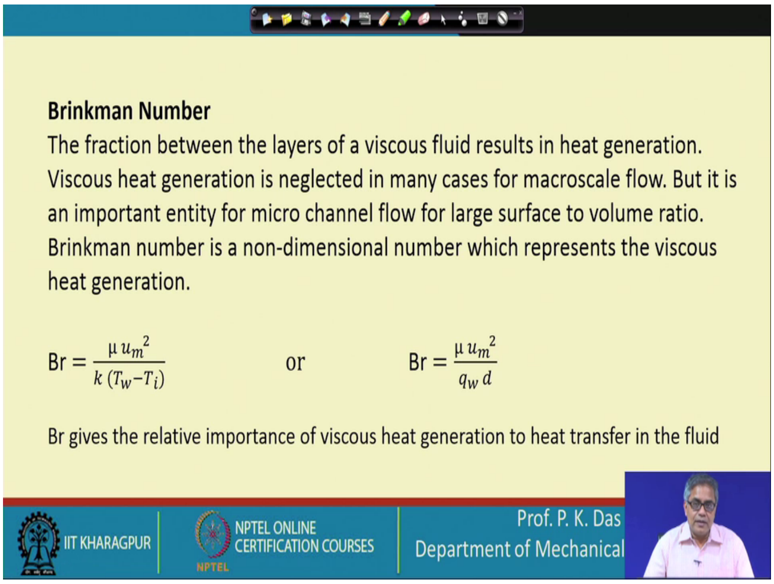
So, at any y the velocity u is given by this particular formula and then u m is the average velocity, y is the distance from the bottom wall let us say d is the width of the channel and k n is the Knudsen number already we have defined what is Knudsen number. So, then we will get this formula I mean get this expression.

Now, you see in this expression if Knudsen number is equal to 0, then the flow is your flow through conventional channel and it becomes the or it gives the expression which we have derived for plane Poiseuille flow or flow through parallel plates earlier from momentum equation. Similarly, for circular duct we will get the next equation. Here for the circular duct again if we draw the figure, so, let us say this is your capital R and any dimension that is your small r and then at any radius r the velocity is given by this formula and obviously, it depends on Knudsen number if it is macro if it is a flow through macro sized pipeline or tube then what will happen, then we will have your k n is equal to 0 and then our equation is u is equal to twice u m 1 minus small r by capital R whole square upon 1, that means, k n is equal to 0 in this case.

So, this will be the equation conventionally we get for Hagen-Poiseuille equation or for fully developed flow through a circular pipe or tube. So, for slip flow continuum based equation has been for slip flow. Continuum based equation has been considered only boundary condition depends on slip. So, this is just an example how in case of macro channel flow the analysis is slightly different; f course, if we go to transitional region or free molecular region there will be a larger amount of difference.

So, with this let us move to another important aspect of micro channel flow. If we go to the next slide if we go to the next slide, let me go to the next slide hm.

(Refer Slide Time: 07:27)



So, we define another num or other another aspect becomes important in case of micro channel flow. As I have already mentioned that in micro channel flow as the surface area is large compared to the volume at the wall there is viscous resistance due to viscosity at the wall there will be lot of resistance and that is why ultimately what we will get we will get a viscous dissipation which cannot be neglected.

Viscous dissipation is there always when a fluid flows through some sort of a channel whether it is a macro channel or micro channel there will be viscous dissipation. That means, due to viscosity there will be some loss and that loss that loss of energy will be converted into thermal energy, this is called viscous dissipation. Ultimately that will get converted into thermal energy.

Now, this viscous dissipation is neglected in many of the case when we do the analysis for conventional channels or channels of larger size. The friction between the layers of viscous fluid results in heat generation viscous generation is neglected in many cases for macro scale flow, but it is an important entity for micro channel flow for large as the surface to volume ratio is large. So, we introduce a number called Brinkman number which is also a non dimensional number which represents the viscous heat generation.

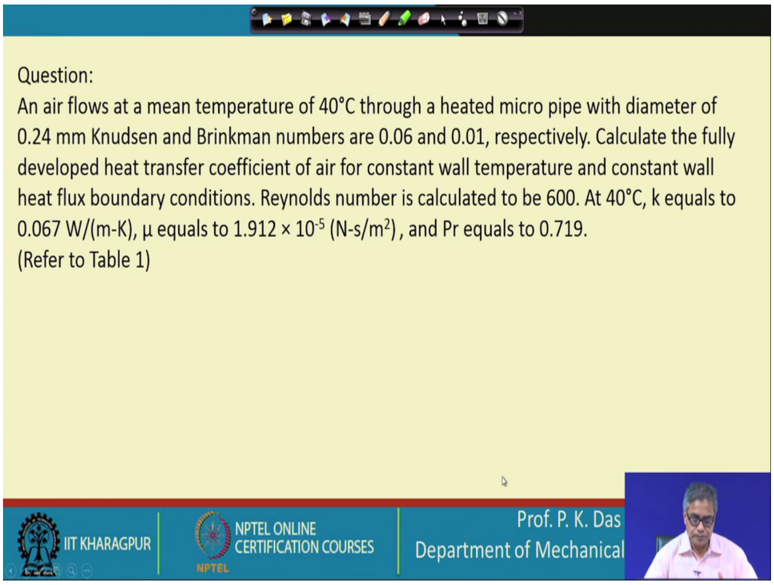
Now, the definition of Brinkman number that depends on it is a heat transfer problem so, it depends on the boundary condition. So, the here you see Brinkman number that is given by Br and two expressions have been given. Br is equal to mu into u m square; mu is the viscosity dynamic viscosity u m is the mean velocity u m square divided by k into T w minus T i. So, wall temperature and the temperature of the fluid. So, by this we can get Brinkman number when the wall temperature is given.

And, when the wall temperature is not known it is not a constant wall temperature case, but there is a heat flux that is specified at the wall then we will have mu into u m square divided by q w into d; d is the characteristic length of the channel. So, Br gives the relative importance of viscous heat generation to heat transfer in the fluid.

So, this is our Brinkman number and Brinkman number is often associated when we will do the convection analysis of micro channel flow or flow through micro channel because viscous dissipation we cannot neglect in case of micro channel at least we should try to see how much is the contribution is due to viscous dissipation we cannot be ignorant of viscous dissipation in case of micro channel flow.

So, with this let us go to the next slide.

(Refer Slide Time: 10:59)



Next slide what I have done after we have seen what is our temperature jump what is our velocity slip and what is Brinkman number I have taken just an example very simple example just to give some idea and this is the problem or example in an air flow at a mean temperature of 40 degree Celsius through a heated micro pipe with diameter of 0.224 millimeter Knudsen and Brinkman numbers are 0.06 and 0.01. So, we have got Brinkman number and Knudsen number that has been given.

Calculate the fully developed heat transfer coefficient for air of air for constant wall temperature and constant wall heat flux boundary conditions. For these two conditions we have to calculate the heat transfer coefficient. Reynolds number is calculated to be 600 at 40 degree Celsius for these conditions, k is 0.067 watt per metre Kelvin, k is the conductivity of the fluid, mu equals to 1.912 into 10 to the power minus 5 Newton second per metre square, mu is the dynamic viscosity and Pr equals to 0.719. Additionally this values have been given additionally one table has been given also the table is there in the next slide.

Now, we have to calculate the heat transfer coefficient. So, how we can calculate heat transfer coefficient? Consider a conventional flow situation. So, for a conventional flow situation in such cases either one has to do an analysis and come out with some sort of a expression for Nusselt number and from there one can calculate the heat transfer coefficient or for such type of problem one has to look for a suitable correlation and the correlation will be in terms of let us say Nusselt number Reynolds number Prandtl number and in that equation putting the Prandtl number and Reynolds number one can get the Nusselt number and then in the next step one can get the heat transfer coefficient.

Here we will do it slightly differently though there are many possibilities here if we go to the next slide it will be clear that how we are going to do it.

(Refer Slide Time: 13:55)

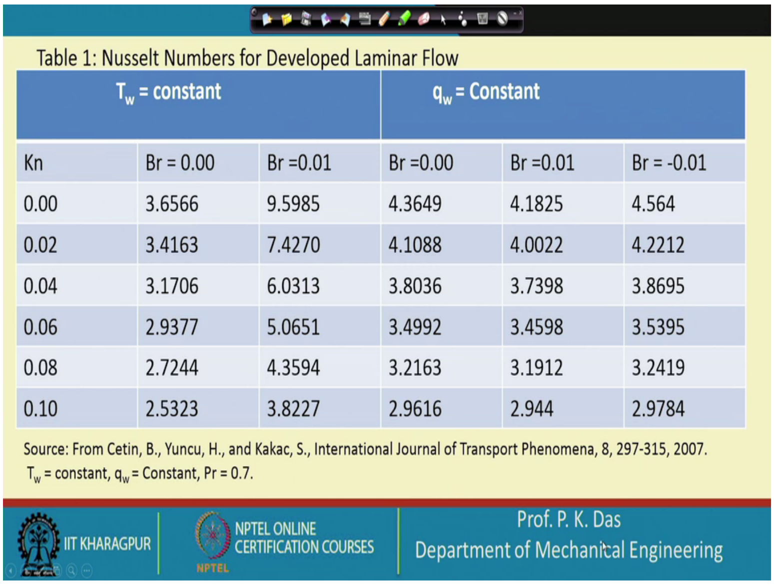


Table 1: Nusselt Numbers for Developed Laminar Flow

	T_w = constant		q_w = Constant		
Kn	Br = 0.00	Br =0.01	Br =0.00	Br =0.01	Br = -0.01
0.00	3.6566	9.5985	4.3649	4.1825	4.564
0.02	3.4163	7.4270	4.1088	4.0022	4.2212
0.04	3.1706	6.0313	3.8036	3.7398	3.8695
0.06	2.9377	5.0651	3.4992	3.4598	3.5395
0.08	2.7244	4.3594	3.2163	3.1912	3.2419
0.10	2.5323	3.8227	2.9616	2.944	2.9784

Source: From Cetin, B., Yuncu, H., and Kakac, S., International Journal of Transport Phenomena, 8, 297-315, 2007. T_w = constant, q_w = Constant, Pr = 0.7.

So, first let us see the property table. So, property table the Nusselt number actually it is not a property table it is table of the non dimensional numbers the Nusselt number for developed laminar flow is tabulated. So, it can be taken like this that the way we get Nusselt number in case of flow through large size passages. So, there it is a function of Reynolds number and Prandtl number. Many of the cases functional relationship is known, but in this case at least there is effect of Reynolds number Prandtl number and also Brinkman number is important and Nusselt number is also important.

So, you see depending on the Nusselt number and Brinkman number we will have some correlations which again will be dependent on Reynolds number and Prandtl number let me repeat it again. So, basically for getting the heat transfer coefficient one has to know the Nusselt number. For large size passage the Nusselt number for large size passage the Nusselt number is given by a function of Reynolds number and Prandtl number. It is a small size passage. So, the transport phenomena will depend on Knudsen number plus there will be viscous dissipation. So, there will be effect of Brinkman number depending on Knudsen number and Brinkman number the Nusselt number will have a functional relationship with Reynolds number and Prandtl number. So, it is a complex kind of a correlation interrelationship.

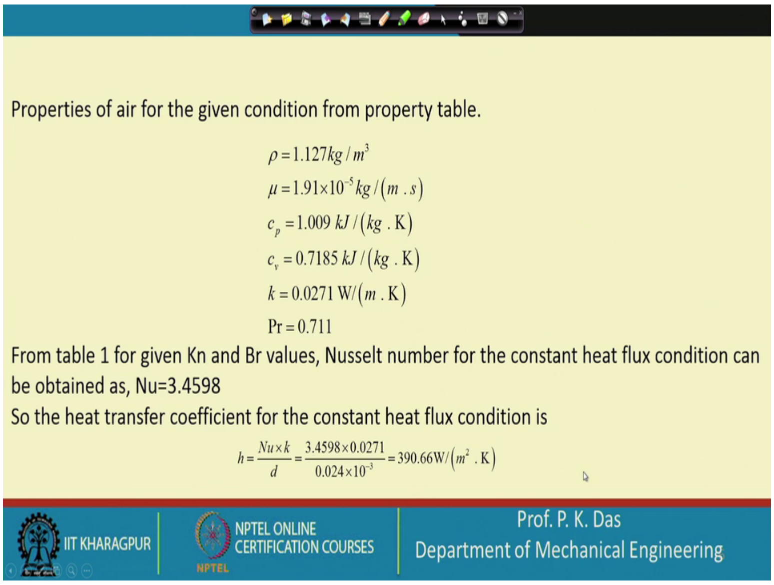
So, for that what is done that a table has been given. So, we have got Nusselt number, Brinkman number depending on Nusselt number and Brinkman number it is like this that we have got a Nusselt number, we have got different values of Brinkman number 4 1 2 3 4 5 Brinkman number have been considered and based on these Nusselt number and this Brinkman number we have got the, let me explain it once again, sorry. So, we have got Knudsen number tabulated on the particular on particular column. So, we have got Knudsen number starting from 0 to 0.1 and then we have got Brinkman number two different values of Brinkman number we have considered 0 and 0.01.

So, we have considered two cases; one is constant wall temperature and another is constant wall heat flux. So, let us say we are trying to consider one situation that Knudsen number is 0.02 and Brinkman number is 0.001 and wall temperature is constant. So, we will have this is we will have this value of Nusselt number. So, Nusselt number value will be 0.74270 and in between for in between values we have two interpolate.

So, this is not very difficult to understand how this table can be used. It has been taken from a source that this is the internal journal of transport sorry international journal of transport phenomena one paper and all this important informations have been given and Prandtl number has been assumed as 0.7 as the as the fluid is here. So, Prandtl number has been taken as 0.7.

So, now if we have understood then of course, the solving the problem does not take much time because from the table we can pick up a value and that will be the answer. So, if we go to the next slide.

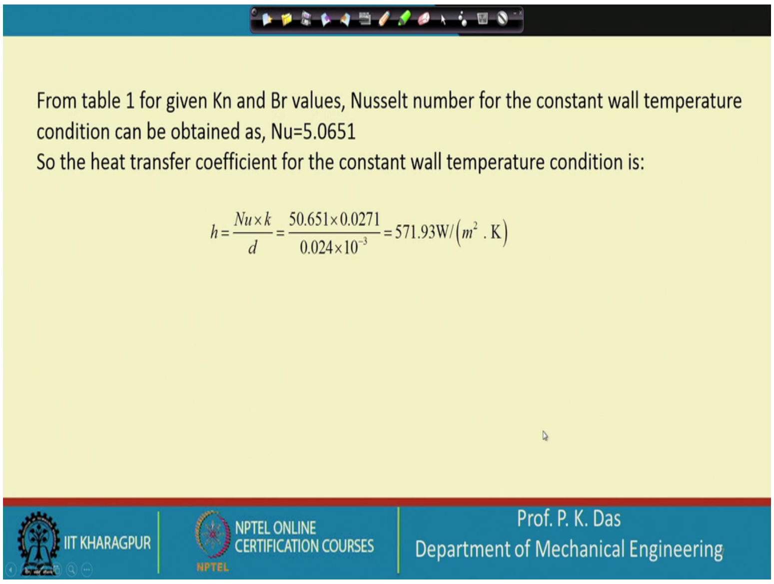
(Refer Slide Time: 18:19)



Then, you can find that from the table one for given Knudsen number and Brinkman number, Nusselt number for constant heat flux condition can be obtained. Nusselt number is equal to 3.4598. So, heat transfer coefficient we can calculate and that is 390.66 watt per metre square Kelvin, that is your heat transfer coefficient.

And let us complete the problem complete the solution.

(Refer Slide Time: 18:52)

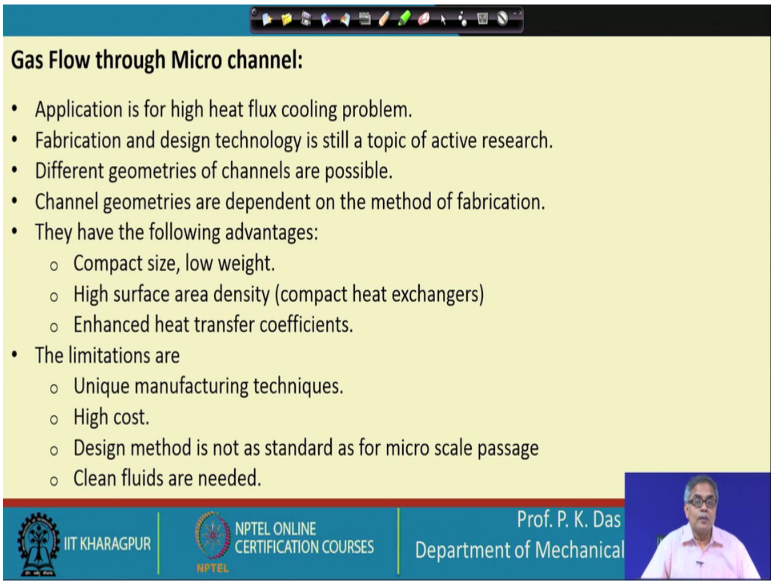


So, for the other case that is the constant wall temperature case Nusselt number is equal to 0.50651 from the table given table and the coefficient for heat transfer just like before we can calculate and it is 571.93 watt per metre square Kelvin.

So, things to be noted in this exercise is that that Nusselt number depends on a large number of parameter. It depends on Reynolds number, Prandtl number in case of large or conventional channels, but in case of small channels or micro channel, it also depends on Knudsen number and Brinkman number just to impress up on this fact that we have taken this example, ok. So, you can understand that there will be different correlations or tables like this and we have to pick up the Nusselt number or we have to estimate the Nusselt number accordingly and from the Nusselt number we can get the heat transfer coefficient.

So, let us move.

(Refer Slide Time: 20:15)



The micro channel let us first consider gas flow through the micro channel. Now, why gas flow, because the effect of micro channel or other the difference between the flow through micro channel and macro channel or large size channel will be prominent in case of gas flow. We have you have noticed that we have discussed mach number compressibility of the fluid those are more relevant in case of gas flow.

So, let us see what are the attributes or what are the specialities of gas flow through micro channel; application is for high heat flux cooling problem. So, micro channel; obviously, they are adopted for high heat flux cooling problem, conventional heat exchangers are used where the dissipation of heat is not that challenging not that high the fabrication and design technology is still a topic of active research. So, how we will fabricate this kind of heat exchanger?

So, newer techniques are being adopted and so, that is one way fabrication, but analysis also you see the way we have got very well established correlations for macro channel flow, for micro channel flow we do not have those established correlations. Theory is also difficult because you see there are so many interlinked phenomena from our earlier example you can understand that newer dimensions are coming because Knudsen number and Brinkman number are being important.

Different geometries of channels are possible. So, actually let me tell you we will elaborate it in our in the in next slide or in not in the next slide, but coming in coming some slide. In some coming slide we will explain this that you see different type of techniques are adopted different type of techniques for fabrication of micro channels are adopted.

Depending on the methods of fabrication we have got different geometries of the channel and obviously, the way we get very standard channels in case of conventional heat exchanger. In conventional heat exchanger we get circular passages in many cases, so, those kind of passages are not very common there could be circular passages. But, there could be passages of other geometry which are very specific to micro heat exchangers.

Channel geometries are dependent on the method of fabrication. They have the following advantages the micro heat exchangers or micro channel will have the following advantage compact size, low weight, high surface area density. So, most of them are compact heat exchangers though compact heat exchangers and micro heat exchangers are not the same this statement I use time and again to impress upon you that these two heat exchangers are not just the same.

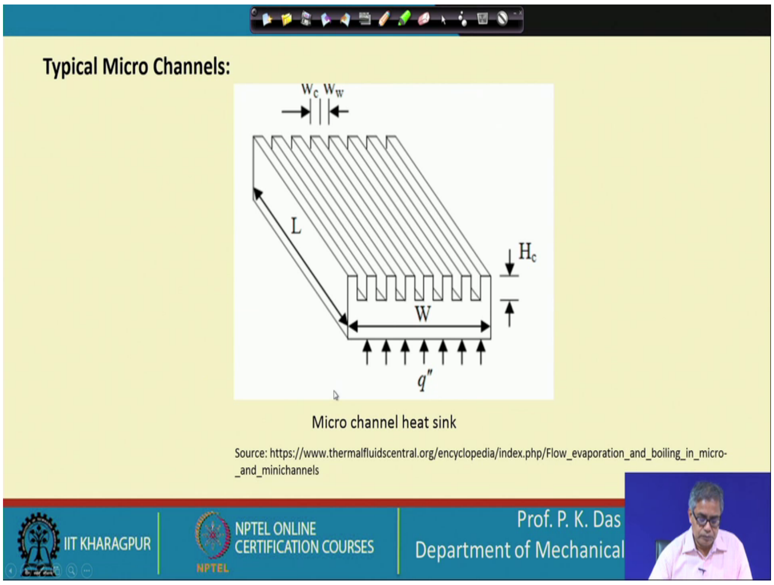
Enhanced heat transfer coefficient due to this passage geometry etcetera, we will have in most of the cases a high heat transfer coefficient. It is not mandatory to have always high heat transfer coefficient for handling low volume of fluid, low volume flow rate of fluid we may have unique design of heat exchanger that need not have a very it is not always possible to have a very high heat transfer coefficient, but most of the cases the heat transfer coefficient is also high.

There are certain limitations, what are the limitations? Unique manufacturing techniques are needed we will we are going to spend some time on manufacturing techniques. So, we will find that the techniques of manufacturing that is not as common as in case of conventional heat channels or conventional heat exchanger. So, as to have some unique technique for fabrication of this heat exchanger, the cost is also high material of these heat exchangers are unique. So, that is why the cost is also high. Design method is not as standard as for it should be microscale passage.

So, micro scale heat exchanger sorry macro scale passage. So, for large passages we have got design methods very standard, but in this case it is not so. Please note down the typo in the line which I have just read it just read that conventional size of the passages or conventional heat exchangers the passages are large. So, we have got some very standard design practice, but the design practice yet to be standardized in case of micro heat exchangers or micro scale passages.

Then clean fluids are needed. So, as the passage dimensions are small so, it is prone to clogging and it cannot with stand it cannot with stand fouling. So, we have to consider only clean fluid through it could be gas flow clean gas flow free from particulates etcetera or it could be some fluid with which does not have dust or dirt and which does not react with the with the passage material. So, that the fouling is less and there is no clogging, no blocking of the channels.

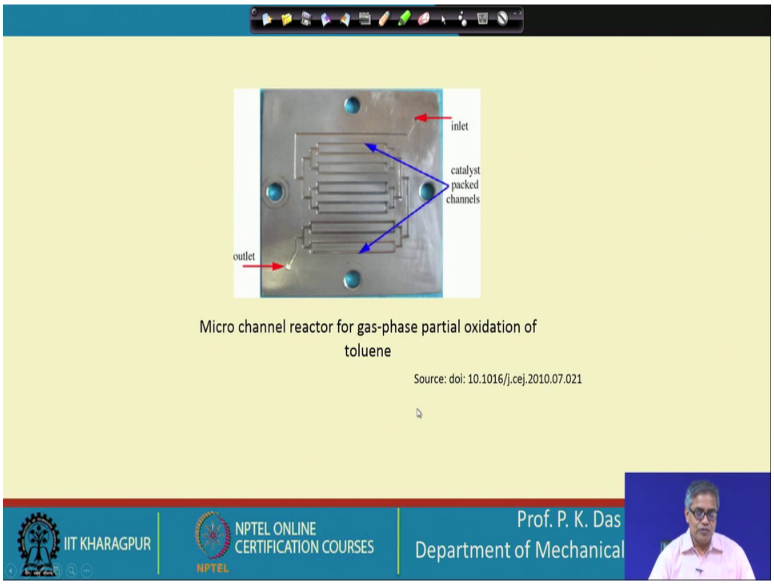
(Refer Slide Time: 26:43)



So, I have shown two examples; one example this is a typical micro channel very simple example. So, let us say this is for electronic component cooling. So, for electronic component cooling let us say that thee there is heat generation and that heat is to be dissipated. So, from that hot surface or heated surface over the hot surface or heated surface we can put this kind of a module. In this module we can see that there are channels and these channels are of small size. So, through this channel, so, how the channels are defined or they let us say how their dimensions are it is length is equal to one particular channel length is L; L could be large comparable to the conventional lengths.

But, there is restriction of this H; if H c is the channel height and here you see there is some sort of a W w the this is the channel width. So, there will be restriction to W w and H c values of W w and H c. So, basically it provides some sort of a rectangular channel ok. So, if there is a top cover then it becomes some sort of a rectangular channel and this rectangular channel is of narrow cross section height is H c which is small and width is W w which is also small. This could be one design.

(Refer Slide Time: 28:21)



Another design here we can see another design. So, this is on a metallic surface and you can see that maybe with a special manufacturing technique these channels have been made and one can see the fluid inlet and fluid outlet. So, this is a micro channel reactor for gas phase partial oxidation of toluene a typical example and we have given some sort of a source it is from a paper.

So, the source that has also been given, this is your micro channel and obviously, in case of a heat exchanger there will be number of channels like this. Probably there will be stacking let us stay on one plate this kind of channel is coming, so, at the top of this there will be another plate. So, there will be stacking and ultimately we will have the heat transfer.

So, with this let us stop our discussion. We will proceed with this that we have started gas flow through micro channel, some of the special attributes of gas flow through micro channel we have discussed and some example of micro channel I have shown. In the next lecture we will proceed from this point.

Thank you.