Heat Exchangers: Fundamentals and Design Analysis
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Lecture – 36
Phase change heat exchangers

Welcome back. Today we are going to start a new topic and we will be dealing with this topic for quite a few lectures. This is a very important topic as far as heat exchangers are concerned. And basically we are going to look into some typical heat exchanger. Again there are many variations, but we have classified them into or we have we have assembled them for the sake of understanding in one group and which I am calling as which I am calling as heat exchangers involving phase change. So, in some heat exchanger, we will see that there is a change of phase. So, those kind of heat exchangers we are calling heat exchanger involving phase change or Phase change heat exchanger.

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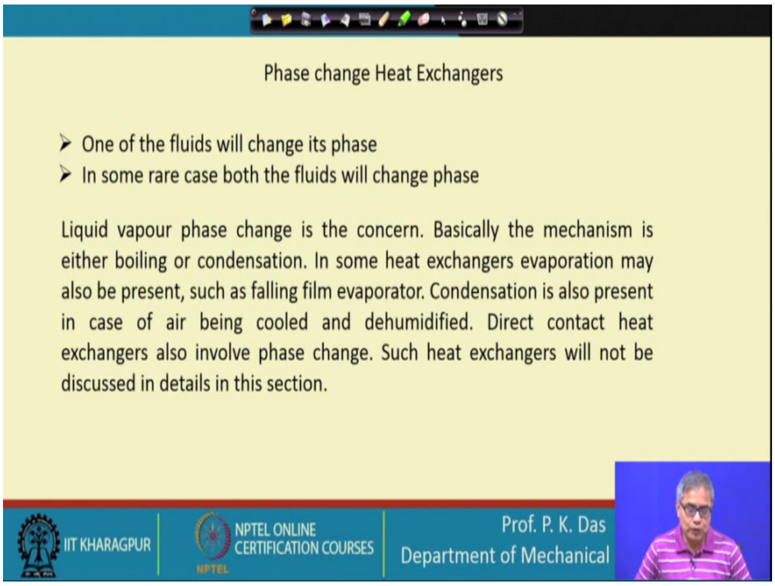

So, now let us go to the next slide. So, phase change heat exchangers. One of the fluids will change its phase at least one of the fluid that has to change its phase in some rare case both the fluids will change its will change phase.

So, basically u can understand that we are considering two fluid heat exchanger. Of course, there is no harm having multi fluid heat exchanger, sometimes again in a very special case one can have multi fluid or multi stream heat exchanger. And then the requirement of its qualification as a phase change heat exchanger is there at least one of the fluid will change its phase. And change of phase could be many like from solid to liquid to solid liquid to vapour to liquid, but liquid vapour phase change or vapour liquid phase change is the concept.

So, either ; that means, the change between liquid to vapour or wise versa is the concern. Basically the mechanism is either boiling or condensation. In some heat exchanger evaporation may also be present like there are falling film evaporator etcetera. So, evaporator may also be present in some cases. But mainly we will see that phase change is taking place either by condensation or by boiling. Condensation is also present in case of air being cooled and dehumidified. Very common experience that during summer particularly in a country like India, whenever air conditioner is there and lot of water drips from the air conditioner because the hot and humid air comes in the contact of the cooling coil. It gets dehumidified and the air gets dehumidified and the water vapour present in the air condenses.

So, then this dehumidifier coil or the cooling and dehumidifier coil of the air conditioner is also taking part in condensation. But those kind of heat exchanger we will not discuss here. There are many direct contact heat exchanger where heat exchange takes place. So, not very elaborated description of those heat exchanger will be possible with the minimum amount of time we are having by this time probably you have appreciated that heat exchanger is a vast topic.

So, we will try to give some general idea of phase change heat exchanger and some of the important phase change heat exchangers, we will try to deal in a bit details. So, with this let us go to the next slide.

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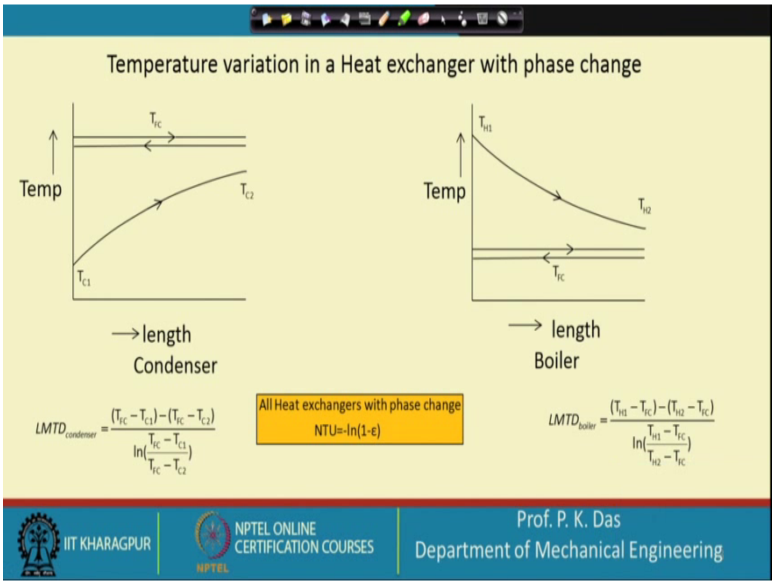

Now here, I am showing how the temperature changes in a purely phase change heat exchanger. What is purely phase change heat exchanger? One fluid in the heat exchanger will be changing its phase from the inlet of the heat exchanger till the exit of the heat changer. Always if we call this mode of heat transfer or this condition as a two phase condition, so one of the flowing fluid will always be in two phase condition from the beginning of the heat exchanger till the end of the heat exchanger. So, this is a purely phase change heat exchanger or let us define it to be a purely phase change heat exchanger.

So, as I have told that boiling and condensation are the two mechanisms of phase change which we will consider in our discussion. So, either we are dealing with a condenser or we are dealing with a boiler. So, let us say that we are dealing with a condenser. So, the condenser temperature change is shown here as it is although the heat exchanger in the two phase condition. So, it is maintaining that phase change temperature T FC it is maintaining throughout the length. And then as it is it has to be cooled or heat has to be extracted from here, there is a cooling stream in case of power plant condenser.

Let us say the steam is condensing it is maintaining a constant temperature and water is cooling it. So, water is getting heated up. So, this is the cooling stream which is getting heated up. What is important to see that let us say the first arrangement the top curve here T FC that is T F exchange and this is the cooling curve.

So, typically this is a parallel flow heat exchanger. Now if we change the direction of the condensing fluid. So, then, it becomes some sort of a counter current flow heat exchanger, but the performance will not change; the performance of the heat exchanger will not change. If we keep the heat exchanger designed constant, then the inlet and outlet temperatures of the fluid that will not change. So, it is independent of orientation. This is one thing we have keep it in mind that in phase change heat transfer when there is purely phase change for a particular fluid, there is it is independent of orientation. So, same thing for a boiler it has been shown that here the fluid is evaporating throughout the length of the heat exchanger and probably it is getting its thermal energy needed for let it heat of vaporization from the from the from a hot fluid. So, the hot fluid is getting cold cooled. So, here also the it will not matter whether we are going for a parallel flow or a counter flow.

So, LMTD is given by these expressions and this LMTD is independent of orientation. And if we go for effectiveness NTU, all the heat exchanger with phase change will have this relationship; very easy to remember. So, this is the relationship between NTU and effectiveness this is effectiveness. And this is N T U number of transfer unit and this is the relationship.

So, for a simple phase change heat exchanger this kind of relationship we will get and I have shown two arrangement parallel and counter flow. It does not matter which way you are arranging it.

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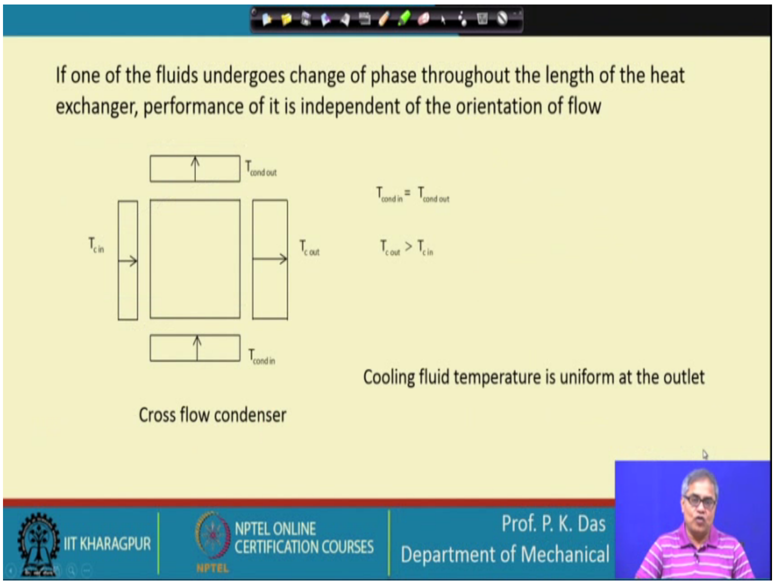

Now, this is a cross flow heat exchanger. Let us say our phase change heat exchanger is a cross flow heat exchanger. If you remember in fin tube heat exchanger, we have taken some example where the end and we have basically going to solve the problem of finned tube condenser. So, that is that was a cross flow condenser.

So, here also this is a cross flow heat exchanger. So, for cross flow heat exchanger; let us say this is the condensing fluid and this is the condensing fluid. It is inside, this will be the temperature distribution and this will be the temperature distribution at the condensing fluid exit. And as it is in the phase change condition, there will not be any change in the temperature from inlet to outlet. And there will not be any variation of temperature also along the inlet plain or along the exit plain.

This is the coolant which is gaining heat. So, when at the inlet it will have uniform temperature low temperature. At the outlet there will not be any variation of temperature variation of temperature at the outlet is characteristic of cross flow heat exchanger, but here we will not get it. So, here we will have this kind of temperature distribution and.

So; obviously, you see that there could be other reasons for selecting the arrangement whether we will go for parallel flow, counter flow or cross flow for a phase change heat exchanger, but thermally all of them are equivalent. There could be other mechanical reason, there could be that we have to accommodate more amount of tubes etcetera. So, other reasons planned related reason could be there, but thermally they are identical.

Cooling fluid temperature is uniform at the outlets. So, this is one very important observation.

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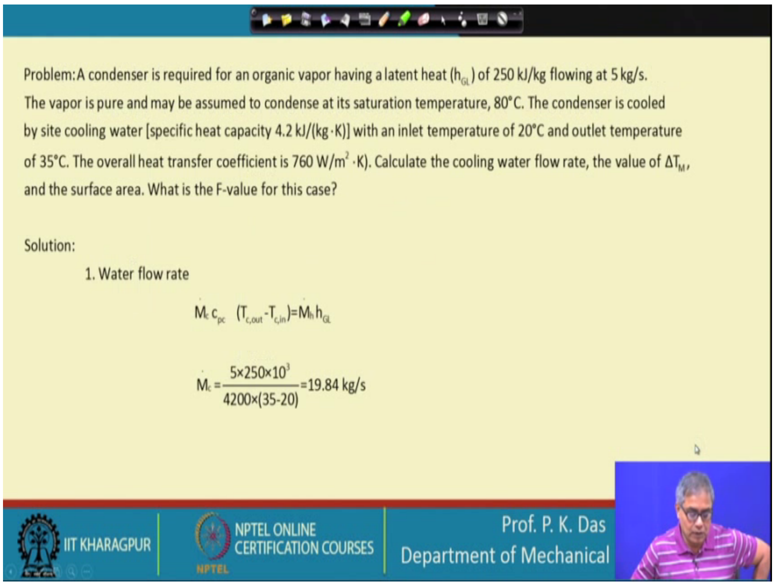

Now, let us take up a problem. A condenser is required for an organic vapour having a latent heat of 250 kilo joule per kg flowing at 5 kg per second. The vapour is pure and may be assumed condensate at its saturation temperature of 80 degree Celsius.

The condenser is cooled by site cooling water specific heat has been given with an inlet temperature of 20 degree Celsius and outlet temperature of 35 degree Celsius. The overall heat transfer coefficient that has been given calculate the cooling water flow rate the value of delta T and the surface area. What is the f value for this case. So, water flow rate we have got. So, from that M dot c p e cool and we can find out and this is equal to this is the total heat gained by heat exchange sorry gained through heat transfer by the cooling water stream.

So, this is the heat which is rejected by steam also. So, heat rejected by steam that will be equal to the steam flow rate and the latent heat because it is in the two phase condition. So, right hand side everything is known and from the left hand side, it has been told that the water inlet temperature of the water is 20 degree Celsius and outlet temperature is 35 degree Celsius. So, from there, we will get the mass flow of water that is 19.84 kg per second. So, mass flow of water is known at this point.

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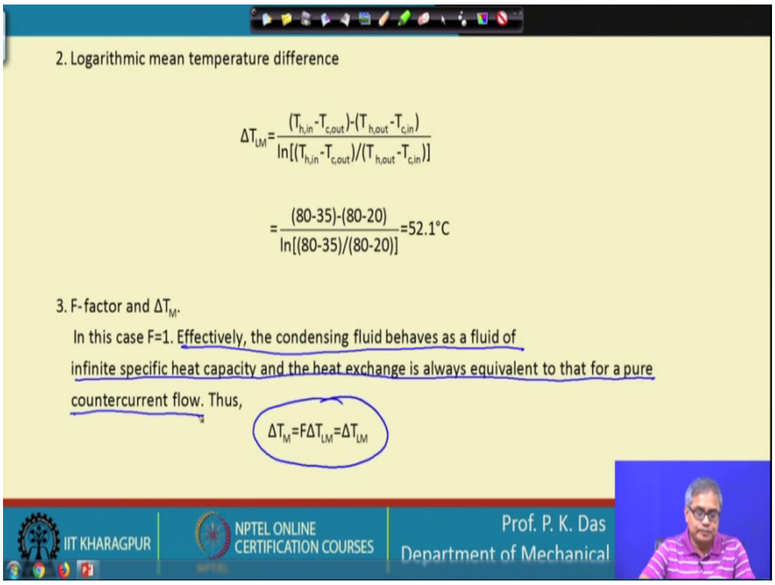

Next what we can do? We can calculate the log mean temperature. So, log mean temperature we have calculated. One fluid will be at a constant temperature that is your 80 and other fluid, there will be inlet temperature of 20 and outlet temperature of 35. So, other fluid also we can get the temperature. And from there, we can calculate the log mean temperature which is 52.1 degree Celsius. Now in this case, as I have already told that whether we are having cross flow, counter flow parallel flow everywhere, one fluid is at a constant temperature. So, the flow distribution really does not affect the thermal performance. So, we will get F is equal to 1 for any arrangement.

So, that is what has been written in this case F is equal to 1. Effectively the condensing fluid behave as a fluid at infinite specific heat capacity and the heat exchange is always equivalent to that of a pure countercurrent flow. Thus we have got this kind of relationship. This is very important and you can note this. So, this is one important point and this is also important to note for a purely phase change heat exchanger. Already I have explained what is purely phase change heat exchanger. So, this is very important to note ok.

So, please try to correlate the problem which we have done at the end of our discussion on fin tube heat exchanger. That was much more elaborate because the fin side heat transfer coefficient pressure drop etcetera, we wanted to take care off. But that was also a cross flow heat exchanger, there also we have calculated LMTD. So, please look into that problem go back to your to my earlier lecture and please look into that problem. But whatever I have underlined these points are very important and this is how we will get the delta T.

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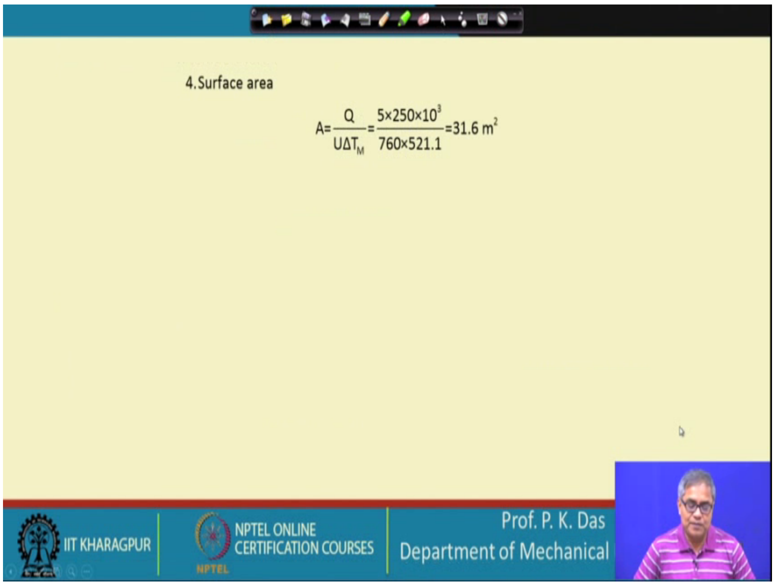

Now let us go to the next page. So, surface area we can calculate from here. So, this is our end of the problem very simple problem, but it gives us an idea how to calculate the basic calculation of a phase change heat exchanger.

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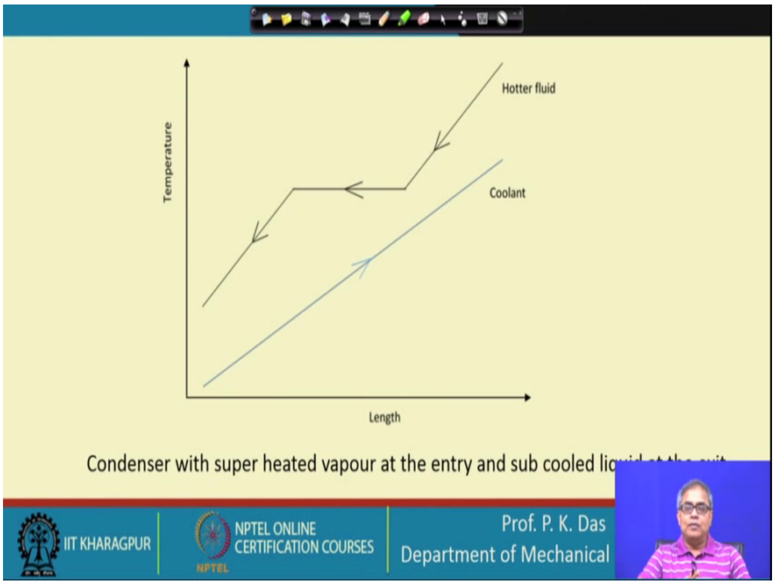

Now, you see I have coined some sort of a word or terminology a purely phase change heat exchanger. Now most of the practical heat exchangers where phase change of a fluid stream takes place is not like this. So, in phase change heat exchanger, we will have change of phase, but before that and after that there could be single phase heating or cooling.

So, let us say here we can see condenser with a super heated vapour at the entry. So, let us say this is the condensing fluid which we have to condense, but the fluid is not exactly at the saturated condition when it is entering the heat exchanger. It is it is the hotter fluid is entering at super heated state. So, if it is entering at a super heated state over here, so then it has to be brought to this saturation condition and this is single phase cooling for the fluid, then there will be phase change heat transfer and then again there could be sub cooling and this is again single phase cooling. And this is how the coolant temperature coolant is a single phase fluid. So, coolant temperature will continuously increase. I have shown linear, but this curve this curve can be non-linear, this can be non-linear and this can be non-linear in general. I have shown them linear drawn them linear, but this curves could be non-linear.

So, in most of the practical cases, we will get a heat exchanger like this. Let us consider the let us consider the condenser of a refrigeration unit. So, in a refrigeration unit after the compressor, hot vapour comes out and that will be in super heated state. And then in the condenser, it condenses either it will be partially condensed also, but; obviously, it will enter with a super heated state in the condenser. So, you see that the curve will be something like this and this either it can go to this range or it can come out of the condenser like this. So, sub cooling could be there, sub cooling may not be there, but; obviously, there will be super heated vapour which is to be cooled first and then it has to be condensed.

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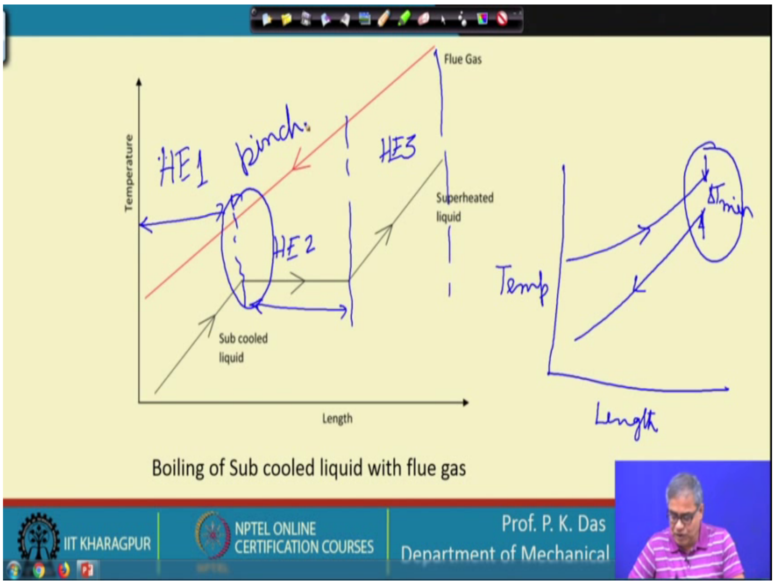

Next, if you see what is happening in case of a boiler? Let us say it is a steam power boiler steam power plan boiler. So, here sub cooled water goes to the boiler and then there will be vaporization and then there is super heated liquid. And let us say this is the flue gas. Only thing is that in a power plant boiler this may not be a single heat exchanger the super cool sub cool liquid and the vaporizer and the super heated liquid or super heated vapour should be super heated vapour. So, they are not in the same heat exchanger. So, initially there could be some sort of economizer then there could be boiler drum and the raiser tubes in which vaporization will take place. And then there could be a super heater.

So, but one can think of some sort of an evaporator where there could be sub cool liquid to super heated vapour coming from the evaporator and all the three parts will be present. Why I am presenting this kind of pictures you know, because you have to appreciate one thing that real phase change heat exchanger are complex in nature. The problem which I have done at the beginning of this class may give a misconception things are easy because one side the fluid temperature is not changing. One may think that one side the fluid temperature is not changing, so, things are little bit easy.

But things are not easy because rather the things are more complex because we have got this kind of abrupt change in the temperature curve. If there is abrupt change in the temperature curve, then what happens ? Basically we are having three heat exchangers.

So, we can think that this is one heat exchanger, this is a purely phase change heat exchanger and this is another heat exchanger. So, let me write heat exchanger 1 heat exchanger 2 and we are having heat exchanger 3. So, 3 heat exchanger. So, when I have to do the analysis I have to do the analysis for 3 heat exchanger. Then there is another thing let me tell you, probably I will take up this point later on also.

Suppose I am a normal two fluid heat exchanger and both the fluids are. So, let us say this is a counter current 2 fluid heat exchanger and both the fluids are in single phase. So, this side it is temperature and this side it is length. So, here you see the counter current heat exchanger and how I will decide the length of the heat exchanger. One consideration is that the minimum temperature difference which can be allowed for heat transfer to take place delta T minimum. One can call it terminal temperature difference. So, what is the minimum terminal temperature difference we can allow? That is how I have to this is one kind of a decision the design engineer has to take and this takes place at one end of the heat exchanger; that means, this terminal temperature difference is taking place at one end of the heat exchanger.

In case of this phase change heat exchanger where there are sub cooling and super heating, the minimum temperature takes place here which is called pinch. So, this gives one restriction to the heat exchanger design and this is happening inside the heat exchanger. So, this is very important and we have to maintain a pinch temperature probably I will elaborate this as we proceed on and that is how another complexity is added to your phase change heat exchanger. We will elaborate this thing as we will proceed.

So, for phase change heat exchanger we have seen one unique feature that the minimum temperature difference between the two fluids that can take place somewhere in between the heat exchanger. Particularly, when sub cooling or super heating or both are involved in a phase change heat exchanger. So, once again I like to draw your attention to this particular figure. So, I have taken a typical case of a boiler where the flue gas is heating the liquid. So, that from the sub cool state the liquid goes to the saturated condition, then vaporization takes place and then we are having super heated vapour.

So, super heated liquid it has been written, but it is in the super heated condition. So, it is super heated vapour. So, probably in a boiler, we will find this kind of an phenomena or in a condenser also, we can find out the sub cool region then the phase change region and then super heated region in the reverse order. That means, in case of a condenser it will start from super heated vapour, it will go to the phase change zone and then it will be in the sub cool condition depending on the process requirement. Now the point which I liked to make is that that initially let us say we are considering a condenser. So, initially the fluid is at vapour state, its density is low and then it is in the 2 phase region the quantity of vapour reduces and the quantity of liquid increases and then it comes out totally in the sub cool region.

So, you can imagine that from the beginning of the from the start of the heat exchanger to its end, there is a large change in the density of the fluid or fluid mixture. So, volume flow rate is changing. So, it is a challenge to the designer that how we can accommodate it in a single heat exchanger.

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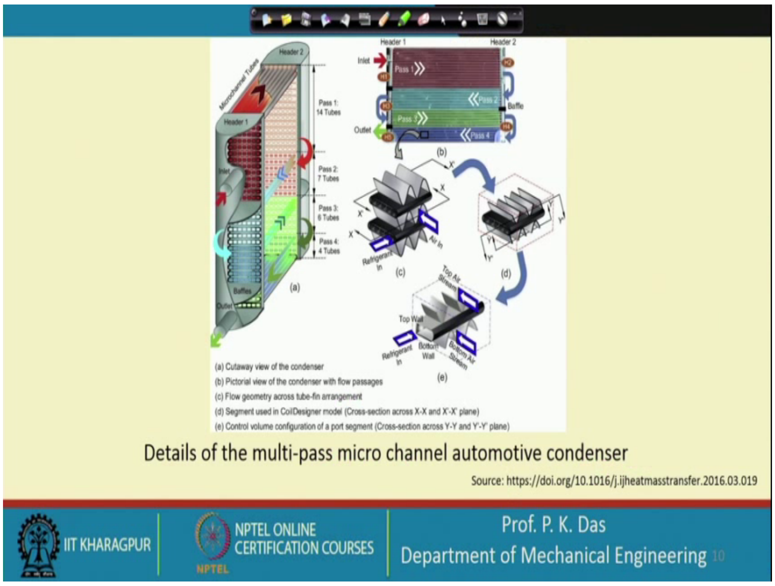

Let be elaborate this let us go to the next slide. In the next slide I have shown the schematic diagram and cutaway view of an automotive condenser. You know in cars or automobile, there will be for comfort condition to ensure comfort condition. There will be a refrigeration system and in there will be a condenser. Vapour compression refrigeration system; so, there will be a compressor up after the compressor the compressed vapour that means, which is at superheated state and high pressure that will enter the condenser. So, in vapour state it will enter, then it will become liquid and in many cases it will come out of the condenser as sub cool liquid.

So, you see from super heated vapour to sub cool liquid, there is lot of change in density lot of change in flow rate. How do we take care of it? So, we take care of it very interestingly. We take care of it in this particular heat exchanger by providing different pass. So, you see there are different passes, this is the inlet this is the first pass and then this is the second pass 2 and then this is pass 3 and then this pass 4. Well the passes are not very uncommon in heat exchanger.

In heat exchanger, there could be number of passes and here also we are having, but what is to be noted in the first pass where the super heated vapour is flowing, there are 14 tubes. All the tubes are of same dimension. So, 14 tubes means large cross sectional area as the density is low for vapour we have to provide large cross sectional area. Then in the second pass the vapour is now being cooled and it will go to the two phase region in the second pass there are 7 tubes. So, drastic reduction in the number of tubes and in the third pass there are 6 tubes and fourth pass the fluid will be in the sub cooled liquid condition, then there will be only 4 tubes; pass 4, there will be 4 tubes.

So, you see this is one opportunity to see a cutaway view of the heat exchanger. This is a cross flow kind of heat exchanger which is very common in refrigeration application, refrigeration condenser. So, tube side refrigerant flows and the tubes are also very unique. You can see the tubes this are flatten tubes and in one tube, there are seven passages. So, basically what we are saying a cross flow two face heat exchanger using micro tubes because this passages are of small dimension. This is also a compact heat exchanger because the area density area of heat transfer area density per unit volume is very large. And so, this is cross flow refrigerant is flowing in this direction or in this direction depending on the which pass it is and then, it is air cooled or rather the heat transfer is to air.

So, air passage is provided by this fins. So, these are the different types of fins sorry these are the fins they are attach to the flatten tube. So, on through the fin side through the fin side air passes. So, this is very unique heat exchanger it has got. So, many speciality. Let me point out all of them one by one. First thing it is a phase change heat exchanger, second thing in this phase change heat exchanger both three I mean, all the three regions are there; super heated vapour region, then two phase region, then the sub cooled region. Third it is a cross flow heat exchanger. It is a compact type heat exchanger flatten tube are used and in this tubes there are 7 passages in each tube and the air side is made by fins. And then there are 4 passes and the number of tube per pass is not uniform to take care of the change in volume, alright.

So, one thing I like to mention that we have started our discussion on phase change heat exchanger. Most of the cases I will deal with condenser; that means, liquid is condensing. The reverse is the evaporation or boiling of liquid; though we call evaporation, but the exactly reverse of it will be boiling of liquid and boiling of liquid is needed in many places but where we are boiling the liquid with the direct application of heat like firing cool or nuclear power or some sort of coil or in some cases electric heating in small sized unit. So, we call it a boiler.

So, where particularly where there is firing, we call it a boiler, but we can have boiling in other places also like in a refrigeration system the refrigerant will boil, but that we call as evaporator. So, what I will do as mostly I have discussed condenser. Evaporators are not very different from them. So, I think one can pickup, but boiler I have not discussed. So, I like to briefly discuss boiler before I end this lecture. So, let us go to the next slide.

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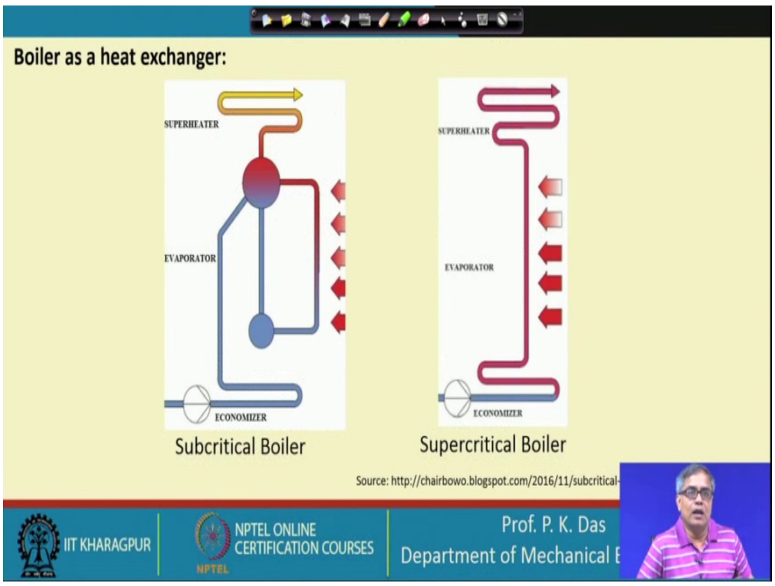

So, this shows the schematic diagram of a boiler. So, first I have shown super critical boiler sorry sub critical boiler where the pressure of the working fluid is below the critical point and then I show the super critical boiler. Here the pressure of the working fluid that is low at the beginning, but this pressure raises and ultimately this pressure goes above the critical point.

So, I have given a name to this slide boiler as a heat exchanger. So, these two heat exchanger; these are basically heat exchanger, they are slightly different. Because in the sub cool condition particularly if we are away from the critical point, there is a large difference between the density of liquid and vapour even at a particular saturation pressure or particular saturation condition. So, the same problem occurs here which I have discussed that I have to handle sub cool liquid in the economizer, then I have to handle a two phase mixture in the vaporizer portion of the boiler and then I have to handle super heated vapour in the super heater of the boiler.

So, this is true for a subcritical boiler and generally what happens boiler is a very big unit. So, there these three though there is a connection, these three are three different kind of heat exchangers. Grossly if I call them heat exchangers, then these three are 3 different types of heat exchangers. So, this is your economizer and in economizer, we will find the type of heat exchanger we have studied it is not much different from that then evaporator which is not this section, but this loop kind of a section. Here of course, we are having a completely different kind of arrangement which I will explain little bit.

This is the main part of the boiler. We do not have much scope to discuss this in this particular course because boilers are considered as fired heat exchanger and in our course fired heat exchanger; we have excluded only a glimpse of it I will discuss. And then after that we will have the saturated vapour which will be taken to the super heated condition at the corresponding pressure in the super heater.

Whereas, in the super critical boiler, it is sometimes also called it is called once through boiler because the fluid passes continuously may be through different sections of the tube and it enters as in the sub cool liquid in the economizer and comes out as super heated vapour at the end of the super heater. Whereas, if I see the subcritical boiler what we will find there is a loop kind of a thing, here we will have liquid circulation or liquid and vapour circulation which is I mean to some extent different from in concept from the other kind of heat exchangers. So, you will look it look at it in to little bit details. Let us go to the next slide.

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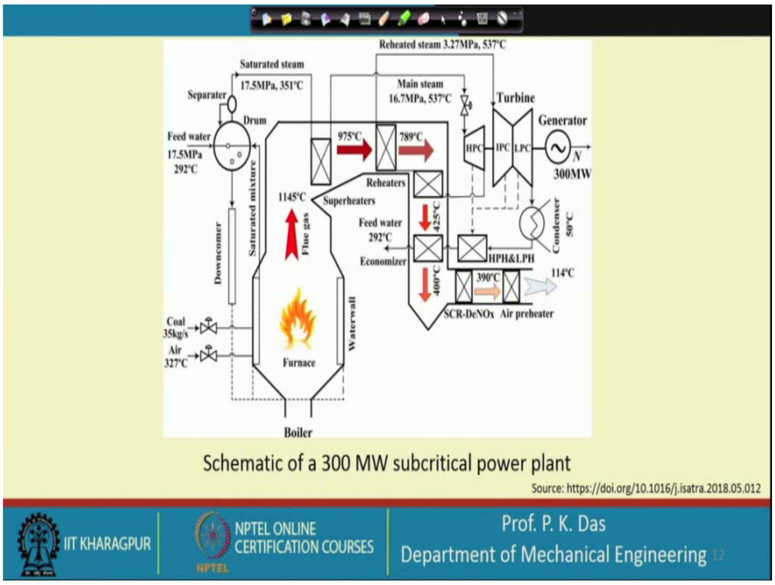

So, in this slide, schematically 300 megawatts subcritical power plant is show of course, not the entire power plant may mostly we have concentrated on the boiler side. So, this is the furnace. So, furnace is part and partial of the boiler. So, you see boiler income process um many kind of operations like one is furnace where heat generation will be there and at the same time the heat exchanger part of it where the from the hot gas or from the hot source of combustion, the heat will be transferred to the fluid. So, the furnace here the coal or oil or some suitable fuel will be fired, it will be generated. So; obviously, the furnace is some sort of a enclosed body and at the wall of the furnace, we can have the tubes these are vertical tubes and through this vertical tubes liquid will pass. And when it is passing through vertical tube, some amount of vapour will be generated.

So, if we go to the previous slide once, what we can find that this is the furnace wall; here heat is given to the flowing water. So, it will get evaporated, but it will not get completely evaporated, partly it will get evaporated and it will come this come to this circular section which is called steam drum where the vapour and liquid will get separated. The vapour will go to the super heater and the liquid this is called down comer through the down comer it will come, there is a small drum at the bottom. And from this drum, again it will go up which is called raiser. So, in a boiler, you see there are two very important component; one is a raiser and one is a boil one is a down comer and liquid circulation is continuously through this raiser to the steam drum and to the down comer. Here there could be a pump, it could be assisted by pump or the circulation could be assisted by buoyancy. So, this is completely a different kind of heat exchanger though it is heat exchanger, but it is a completely different kind of heat exchanger what we find in case of boiler. Let us go back to the next slide.

So, here what we can see. So, this is the furnace wall. So, this wall are to be kept cool. So, what we do then we provide the water tube through this? So, that is why these are called water wall. So, it absorbs the heat some amount of steam is generated is goes to the drum and then through the down comer it comes. Now what is to be noted that in a boiler, there are number of heat exchanger and many of them are phase change heat exchanger. So, here of course, some of them are not phase change heat exchanger, but some of them or many of them are phase change heat exchanger. The way I have shown it this is to make this things simple, because it will be easy to understand, but actual boiler there will be lot of complexities and pipe layouts are quite complex. So, I will show another slide to give you some sort of an idea.

So, what kind of heat exchanger what we can see here? Here we can see super heated super heater. So, this super heater will be a single phase change heat exchanger this boiler evaporators section that will be a two phase heat exchanger. Here we can have feed water heater which is a single phase heat exchanger. But here what we can have feed water heater. So, these are again two phase change heat exchanger.

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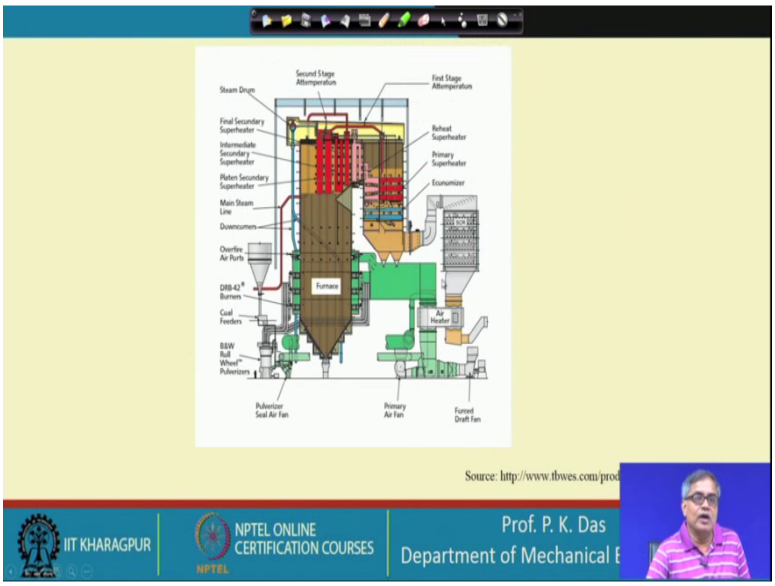

So, let us go back to some sort of a boiler. This is how it looks; you can see the vertical lines. These are all tubes and furnace wall is surrounded by this tubes. So, that the heat absorption is there by this by the water flowing through this tube and tube wall is also kept cooled ok. And here we can see through this nozzle the fuel is injected either in the form of pulverized coal or in the form of oil and combustion takes place.

So, other heat exchangers if you closely look into this figure you will find other heat exchanger re heater super heater etcetera you will find. So, there is some air pre-heater also which is a gas to gas heat exchanger.

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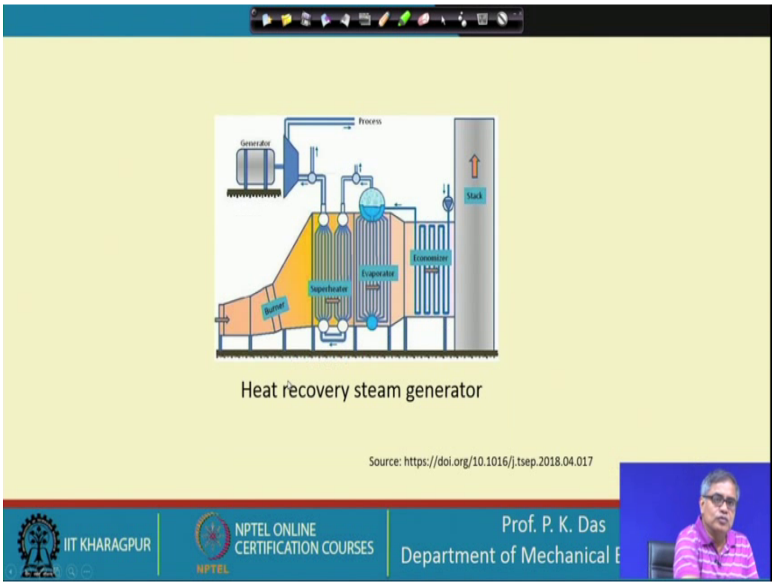

Quickly, let us go to the next slide which is the last slide of my this one of this lecture. So, here we can see one heat recovery steam generator. So, basically no combustion is there in this case or may be some auxiliary combustion is there with the help of burner. So, prior to this there could be some sort of a gas turbine plant and the exhaust gas of the gas turbine which is at high temperature it is coming. So, what I want to show that in boiler, there are three operation the sub cooled water is to be brought to the saturated condition.

The saturated liquid is to be evaporated and then the saturated vapour is to be superheated. And though in small kind of heat exchanger we can do it in same heat exchanger in a boiler, there are three elaborate section. This is the economizer where the liquid temperature is increased and it comes to the saturated condition. Then this is the boiler where through circulation, we generate steam evaporator or vaporizer. And after this steam generated we have got the super heater where the saturated steam temperature is increased. So, this is how we are having a boiler plant.

So, this gives in a nut cell some introduction to phase change heat exchanger. We will see more of it, we will solve problem in our next classes; next lectures.

Thank you for your attention.