Refrigeration and Air Conditioning
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Lecture No. # 30
Refrigeration System Components: Expansion Devices

Welcome back in this lecture I shall discuss expansion devices used in refrigeration systems.

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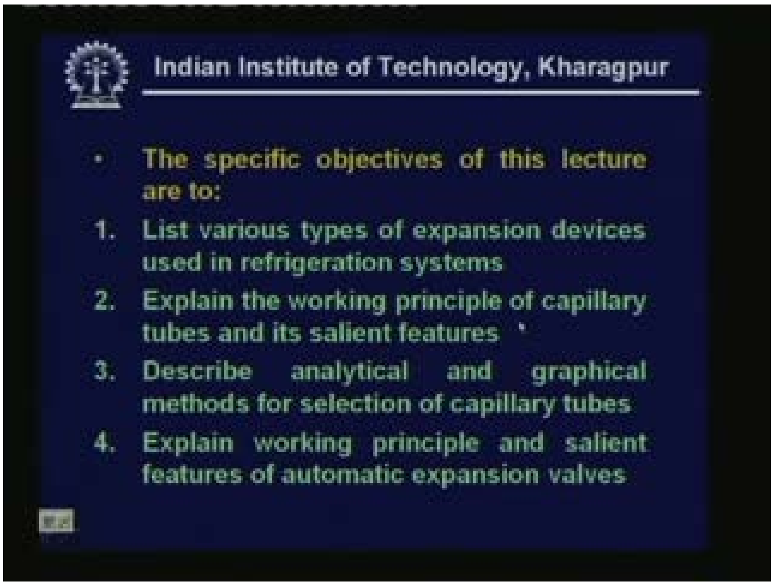

So the specific objectives of this particular lecture are to list various types of expansion devices used in refrigeration systems, explain the working principle of capillary tubes and its salient features, describe analytical and graphical methods for selection of capillary tubes, finally explain working principle and salient features of automatic expansion valves.

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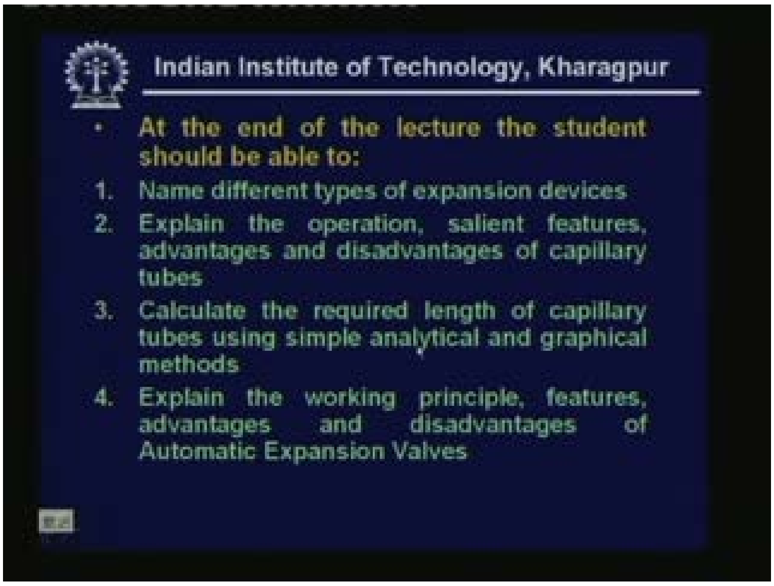

At the end of the lesson you should be able to name different types of expansion devices, explain the operation salient features advantages and disadvantages of capillary tubes, calculate the required length of capillary tubes using simple analytical and graphical methods, explain the working principle features advantages and disadvantages of automatic expansion valves.

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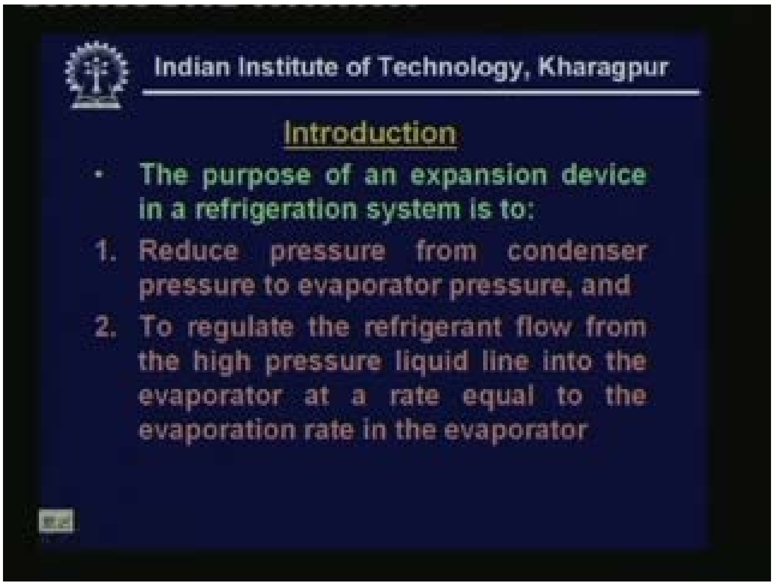

Let me give a brief introduction first of all why do we need a, an expansion device in a refrigeration system. What are its purposes? The purpose of an expansion device in a refrigeration system is to first of all reduce the pressure from condenser pressure to evaporator pressure and to regulate the refrigerator flow from the high pressure liquid line into the evaporator at a rate equal to the evaporation rate in the evaporator. Now the evaporation rate in evaporator is proportional to the load on the system. So when the refrigerant load on the system increases the flow rate should be increased. And when the load reduces the flow rate should be reduced okay. So the one of the main purposes of the expansion device is to of course reduce the pressure from the condenser pressure to evaporator pressure which can be achieved easily. But the second task that is to regulate the flow according to the needs is more difficult but this is also a function of the, a capillary tube I mean, I am sorry a function of the expansion device okay.

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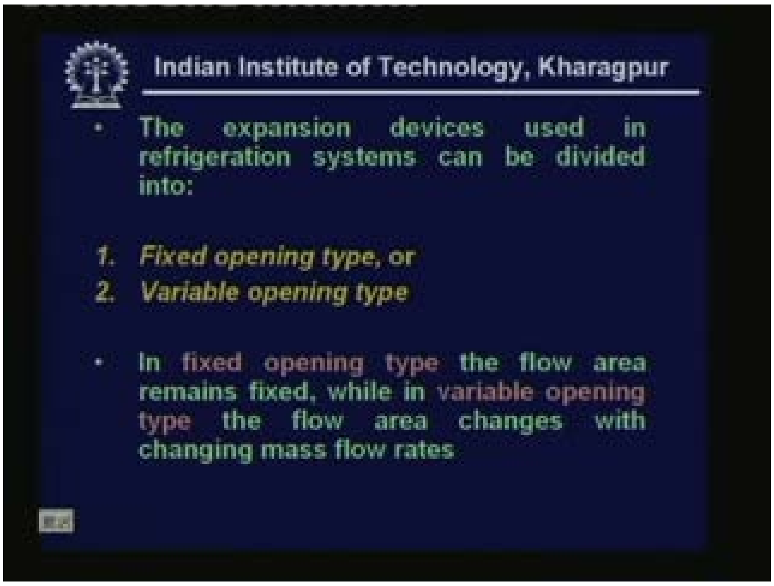

Now the expansion devices is used in refrigeration system can be divided into fixed opening type or variable opening type. In fixed opening type as a name implies the flow area remains fixed while in variable opening type the flow area changes with changing mass flow rates. So there is a different between fixed opening type and variable opening type.

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There are basically seven types of refrigerant expansion devices these are the first one is hand operated valves. Second one is capillary tubes third one is orifice fourth one is an automatic expansion valve fifth one is thermostatic expansion valve sixth one is the float valve and under float valve. We have low side float valve and also high side float valve and finally you also have electronic expansion valve. Out of these seven types I am not going to discuss hand operated valves and orifice because these are used only in special some applications. So I will be describing the remaining five types I will begin this with first one that is a capillary tube.

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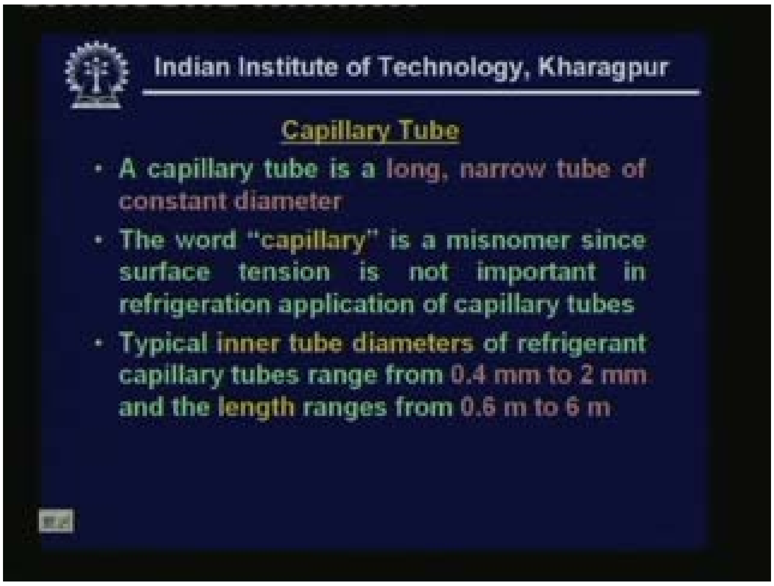

A capillary tube is nothing but a long narrow tube of constant diameter and here the word capillary is actually misnomer. Because the surface tension effect is not really important in refrigeration applications of capillary tube. So it has nothing to do with a capillary effect. It is just the name and as I said it is a longer narrower tube. So what do we mean by narrow? It is inter, inner tube diameters of typical capillary tubes range from point four mm to two mm and the length ranges from point six six meter to six six meters?

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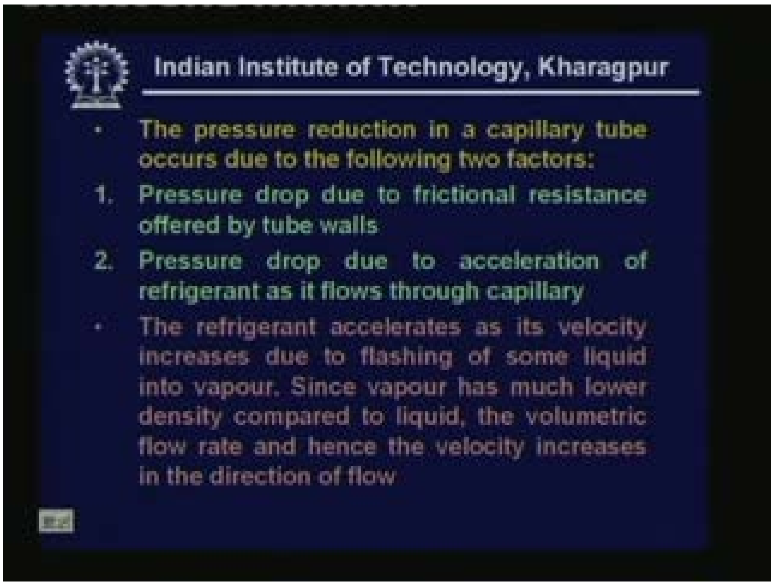

Now the pressure reduction in a capillary tube occurs due to the following two factors capillary tube is an expansion device so obviously pressure reduction should take place across the capillary tube okay. So how the pressure reduction takes place in a capillary tube that is why I am going to explain that there are two factors which causes pressure reduction. The first one is the pressure drop due to frictional resistance offered by tube walls the second factor is pressure drop due to acceleration of refrigerant as it flows through capillary. So why the refrigerant accelerates as it flows from capillary because you know that when the refrigerant flows through the expansion device a flashing of liquid into vapour takes place. So as flashing takes place some vapour is generated and since vapour has much lower density compared to liquid the volumetric flow rate. And hence the velocity increases in the direction of flow.

Since the velocity continuously increases in the direction of flow refrigerant gets accelerated in the direction of flow this requires certain pressure drop. So the pressure ultimately the pressure drop across the capillary tube is because of the frictional effects and because of the acceleration effects okay.

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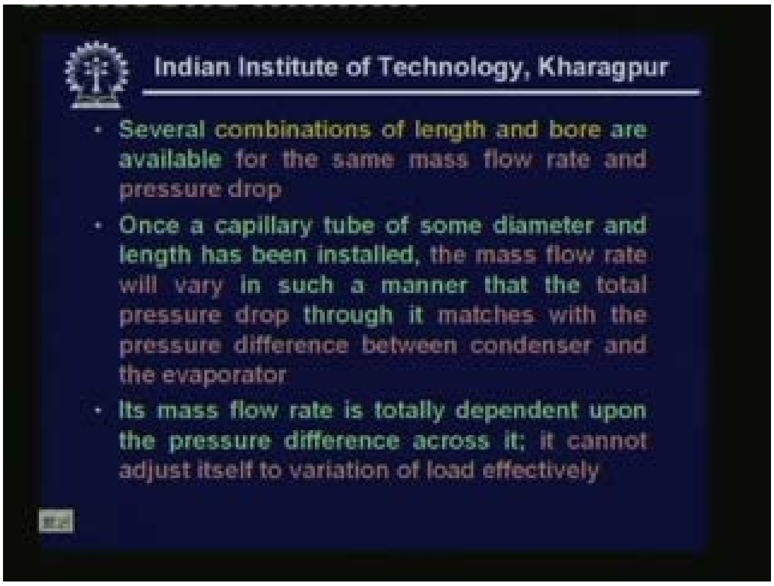

Now there are several combinations of length and bore of for the same mass flow rate and pressure drop. That means if you want a particular pressure drop let us say ten bar pressure drop and a particular mass flow rate. You can choose any diameter and length combination. That means if you are selecting let us say one mm diameter tube then you get certain length okay. So this will give you the required pressure drop and it will also give you the required flow rate. And you can also choose for example two mm diameter capillary and a longer length of capillary okay, or you can go for a smaller diameter capillary and a shorter length of capillary. Like that there are many combinations of diameter and lengths are possible. All of them will give you if you choose them properly will give the required pressure drop and the mass flow rates okay.

But of course there are certain practical limitations are practical constraints in final selection of capillary tube okay. Once a capillary tube of tube of some diameter and length has been installed. The mass flow rate will vary in such a manner that the total pressure drop through it matches with the pressure difference between condenser and the evaporator. You cannot change the, it is a fixed area type. So you cannot change the cross sectional area. So once you select the capillary tube then the mass flow rate will always will match. So that the pressure difference across it will be the same as the pressure difference between the condenser and the evaporator. And its mass flow rate is totally dependent upon the pressure difference across it cannot adjust itself to variation of load effectively. So this is one of the limitations of capillary tubes.

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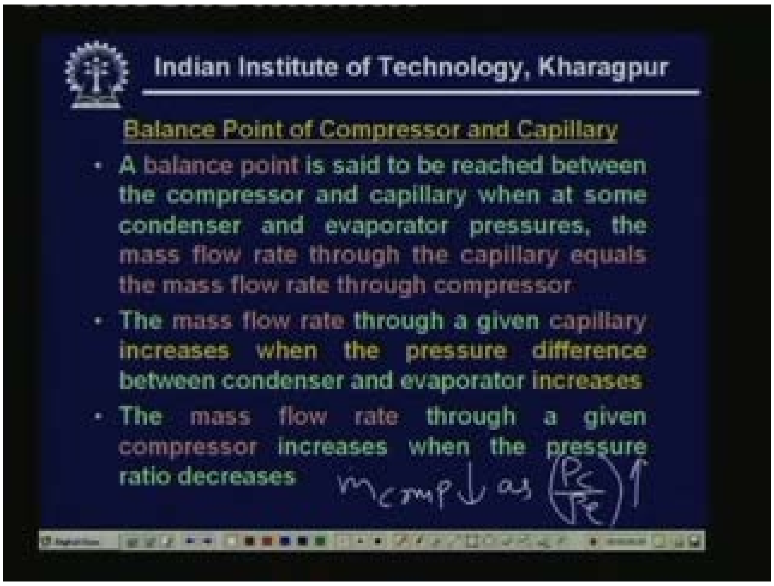

Now let us discuss an important concept that is called as balance point of compressor and capillary. A balanced point is said to be reached between the compressor and capillary when at some condenser and evaporator pressures. The mass flow rate through the capillary equals a mass flow rate through compressor. In fact when you say that the overall system is balanced. What you actually mean is that the flow rate through all the components are same okay. For example the flow rate through evaporator is equal to the flow rate through the compressor which in turn is equal to the flow rate through the condenser which is finally equal to the flow rate through the capillary okay. So under this condition you say that the system is balanced. So basically for selection of capillary a matching between capillary and compressor is important okay. So when you say that compressor and capillary are balanced. That means the flow rate through the capillary is equal to the flow rate through the compressor okay.

Now the mass flow rate through a given capillary increases when the pressure difference between condenser and evaporator increases. That means if m dot Cp, this is the mass flow rate of the capillary. This is always proportional to P condenser minus P evaporator okay. So as the, this difference increases mass flow rate through the capillary increases on the other hand the mass flow rate through a given compressor increases when the pressure ratio decreases. This is what we have seen in fact while discussing compressors. That means mass flow rate though the compressor decreases as Pc by Pe increases okay. So the pressure difference has opposing effects on compressor and capillary.

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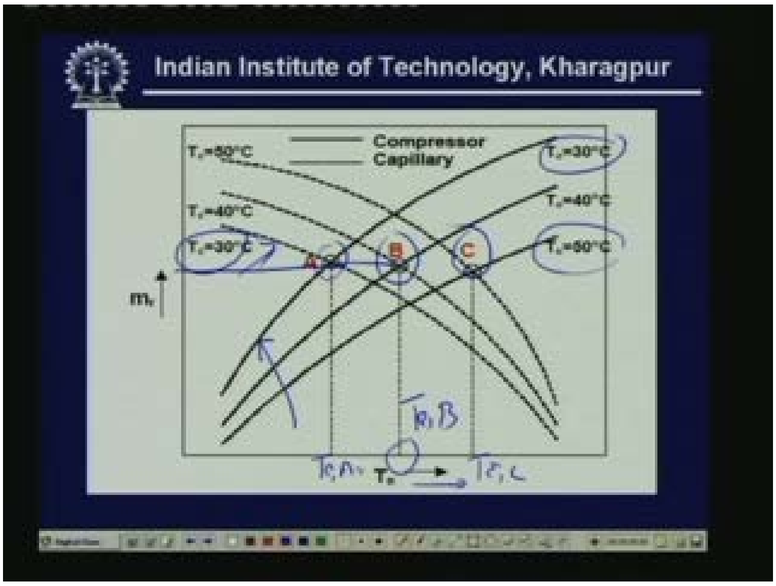

Now this picture shows the balance points between capillary and compressor. You can see that here the x-axis x axis is the evaporated temperature and on the y-axis we have the mass flow rate of the refrigerant and these solid lines are for the compressor. So you can see that for a given condenser temperature. Let us say thirty degree centigrade as the evaporator temperature increases evaporator pressure increases. So pressure ratio reduces. So the volumetric efficiency of the compressor increases as a result the mass flow rate through the compressor increases okay, that what you can see here.

Similarly at a given evaporated temperature as the condenser temperature increases the pressure ratio across the compressor increases volumetric efficiency reduces. So mass flow rate reduces that is why you get this kind of three curves for the compressor and as I said for the capillary the characteristics are entirely different. For example for a capillary at a given condenser temperature. Let say thirty degree centigrade as the evaporated temperature increases evaporator pressure increases. That means Pc minus Pe reduces okay. So as Pc minus Pe reduces as I have already explained mass flow rate through a capillary reduces. So that is what is shown here for a fixed condenser temperature. Its evaporator temperature is increasing and mass flow rate through the capillary is reducing.

Similarly at a given evaporator temperature as the condensing temperature is increasing condenser pressure increases pressure difference across the capillary increases. So mass flow rate increases okay. Now I was talking about the balance points you can see that the points A and A B C are the balance points why do you call them as balance points. For example at thirty degrees condenser temperature. This is the capillary tube line and this is the mass flow rate through the compressor. And the point where theses two line intersect that is this point at this point the mass flow rate through the capillary is equal to mass flow rate through the compressor. So this is the balance point for this particular condenser temperature of thirty degree centigrade and the corresponding evaporator temperature. Let us say TeA okay.

Similarly at forty degrees condenser temperature point B is the balance point. Because at point b the mass flow rate through the capillary is equal to the mass flow rate through the compressor right.

And the corresponding evaporated temperature is TeB similarly point C is the balance point for fifty degrees centigrade condenser temperature and TeC is the corresponding evaporated temperature okay. One thing you can notice here is that as the condenser temperature is increasing the evaporated temperature at which the balance is taking place is also increasing okay. So for example Tec is greater than Teb and TeB is greater than TeA.

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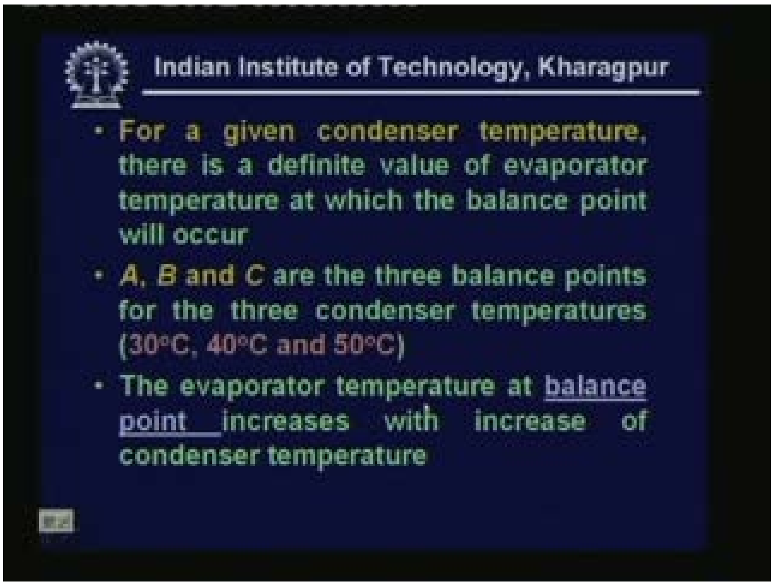

So that is what is summarise here for a given condenser temperature. There is a definite value of evaporator temperature at which the balance point will occur A B C are the three balance points for the three condenser temperatures thirty degrees forty degrees and fifty degrees centigrade. And the evaporator temperature at balance point increases with increase of condenser temperature I have already explained this.

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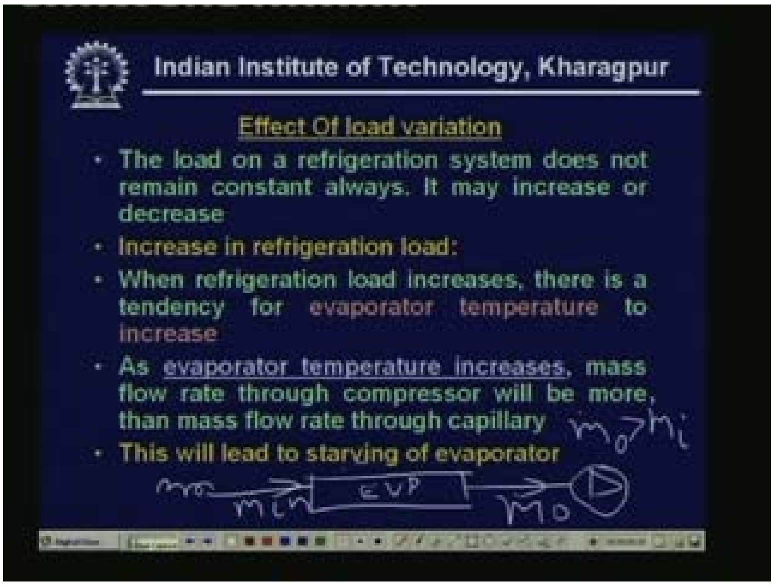

Now let us look at the effects of load variation the load and the refrigerant system does not remain constant always this we have discussed before the load may increase or decrease. So what happens when the load increases or decreases first. Let us look at what happens when the refrigeration load increases when the refrigeration load increases there is a tendency for evaporator temperature to increase why the evaporator temperature increases. Because once the load increases more liquid boils. And so the evaporator pressure increases as a result evaporator temperature also increases. As evaporator temperature increases mass flow rate through the compressor will be more than the mass flow rate through the capillary. Because as the evaporator temperature increases the pressure difference across the capillary. That is the condenser pressure minus evaporator pressure reduces once it reduces flow rate through the capillary reduces.

At the same time the pressure ratio across the compressor increases as the evaporator pressure increases as a result compressor will pump more refrigerant okay. So the, that means there is a imbalance as a result of this, the evaporator will start starving okay. So what do you mean by this that means you have the let us say that this is the evaporator okay. So refrigerant is coming from the capillary you have the capillary on this side and the compressor on this side okay. Let us say this is the mass flow rate mass flow rate inlet mass flow rate and this is the outlet mass flow rate okay. So when the evaporator temperature increases m dot o will be greater than m dot i okay. That means you are taking out more refrigerant from the evaporator than you are supplying to the evaporator as a result the evaporator will starve okay.

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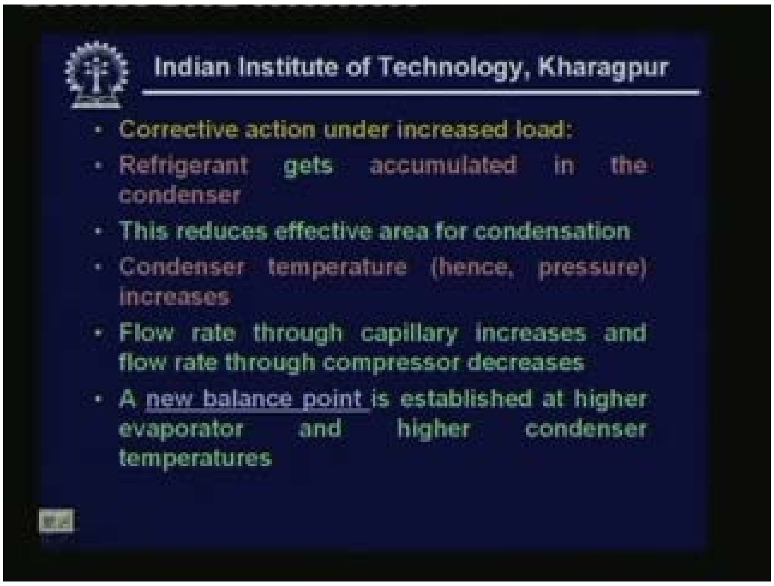

Now this cannot continue indefinitely there must be some corrective actions. So what is the corrective action? The corrective action under increased load is like this refrigerant gets accumulated in the condenser. Because the evaporator starves the refrigerant goes and gets accumulated in the condenser. Once refrigerant gets accumulated in the condenser effective area for condensation reduces as a result condenser temperature and pressure increases once the condenser temperature and pressure increases flow rate through capillary increases and flow rate through compressor decrease okay. So this is the corrective action and a new balance point is established at higher evaporator and high condenser temperatures. Let me show this.

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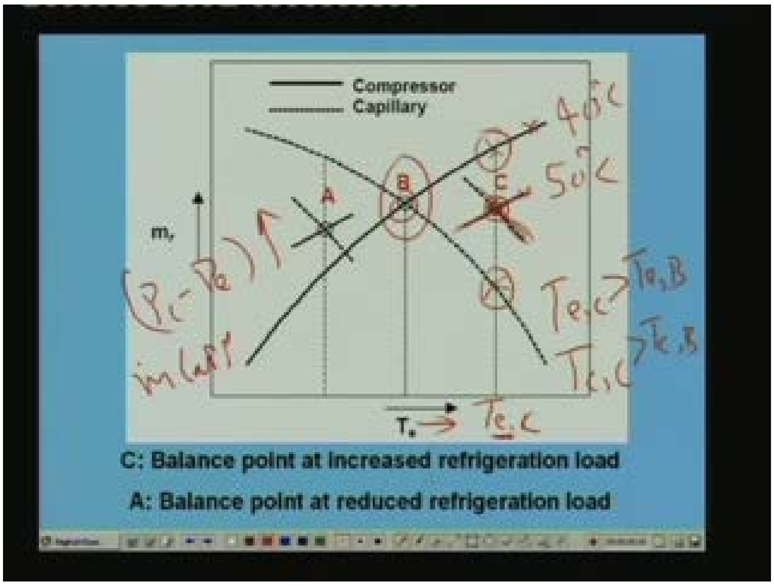

As I said this is the let us say that this is the initial balance point and there is suddenly, there is increase in load. Once the load increases evaporator temperature as i said increases. Let us say that this is the new evaporator temperature under increased load okay, Tec. So at this point initially you can see that the mass flow rate through the capillary is much less than the mass flow rate through the compressor okay. So as a result as I said the evaporator will starve and liquid gets accumulated in the condenser once liquid gets accumulated in the condenser temperature increases okay. So the condenser temperature comes down from this point to increases from this point to this point okay.

So if it is let us say give a, to a give an example if this is forty degree centigrade. And let us say it becomes fifty degree centigrade. Because the accumulation of the liquid. So this is the fifty degree centigrade line okay. So this is the new compressor mass flow rate line. And similarly this is the new capillary mass flow rate line because as the condenser temperature increases Pc minus Pe increases okay. So mass flow rate through capillary increases okay. So you find that the new line is capillary line in this and the compressor line is this. So and again the point of intersection is here where the mass flow rate through capillary will be equal to the mass flow rate through the compressor okay. So again a new balance point is restored. So one thing you can notice here is that before the load increased this was the balance point. So the new balance point under increased load is here and this. At this point you can see that the evaporator temperature is higher than the original point. That means TeC is greater than TeB. Similarly the condenser temperature at the new balance point that is condenser temperature at C is greater than condenser temperature at B. So a new balance is point is restored but at much higher temperatures.

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Now let us look at what happens when there is a decrease in refrigeration load when there is a decrease in refrigeration load. There is a tendency for the evaporator temperature to decrease. Because less refrigerant will boil so pressure will reduce so temperature also reduces. So capillary tube feeds more refrigerant to the evaporator than the compressor can remove this. Again I have explained to you again you have the evaporator here okay. So capillary tube is here and you have the compressor on this side okay. So the capillary tube feeds means more refrigerant enters and less refrigerant leaves okay. That means now m dot o is less than m dot i okay.

That means the refrigerant gets accumulated in the evaporator this effect is exactly opposite to what happens when the load increases okay. So this leads to accumulation of liquid refrigerant in the evaporator causing flooding of the evaporator this may lead to slugging of the compressor. And as you know that slugging of the compressor is dangerous and it should be avoided otherwise the compressor may get damaged. So to avoid slugging capillary tube based systems are critically charged okay. So what do we mean by critically charged system.

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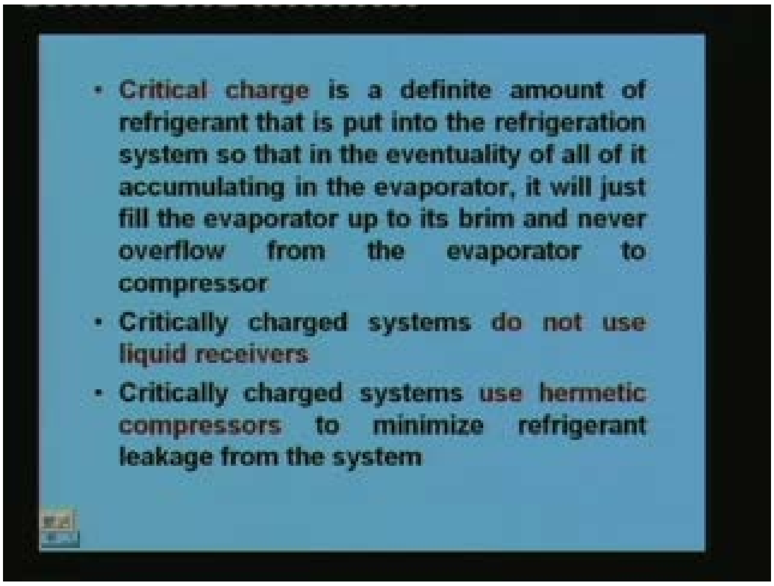

Critical charge is a definite amount of refrigerant that is put into the refrigeration system. So that in the eventuality of all of it accumulating in the evaporator it will just fill the evaporator up to its brim and never overflow from the evaporator to compressor. That means when you say that the system is critically charged what it means is the refrigerant. That is inside the system and the evaporator volume are such, when you transfer all the refrigerant into the evaporator all the refrigerant means all the refrigerant from the condenser and other components and all into the evaporator still the refrigerant amount will not be sufficient to overflow from the evaporator okay. It may fill the evaporator completely okay but liquid will not overflow from the evaporator.

So what is the advantage of this since the liquid cannot overflow from the evaporator there is no possibility of liquid entering into the compressor okay. Because once the liquid enters into the compressor the compressor may get damaged okay. So this kind of a system is called as critically charged system okay. Critically charged systems do not do not use liquid receivers and critically charged systems use hermetic compressors to minimize refrigerant leakage from the system. Now when you charge the system critically that means you put the right amount of the refrigerant into the system okay. So if there is any leakage from the system. Let us say then after sometime you find that the amount of refrigerant inside the system is much less than what is required okay. That means system will be running under less refrigerant okay this will affect the performance in an adverse manner okay. So whenever you have critically charged systems you must minimise leakage okay. If you want to minimise the leakage you cannot use open type compressors. Because in open type compressors refrigerant leakage is higher okay. So normally not, normally you have to go for hermetic or seal type of compressor so that refrigerant leakage from the compressor and from the system is minimised. So all the critical charged systems used sealed compressors okay.

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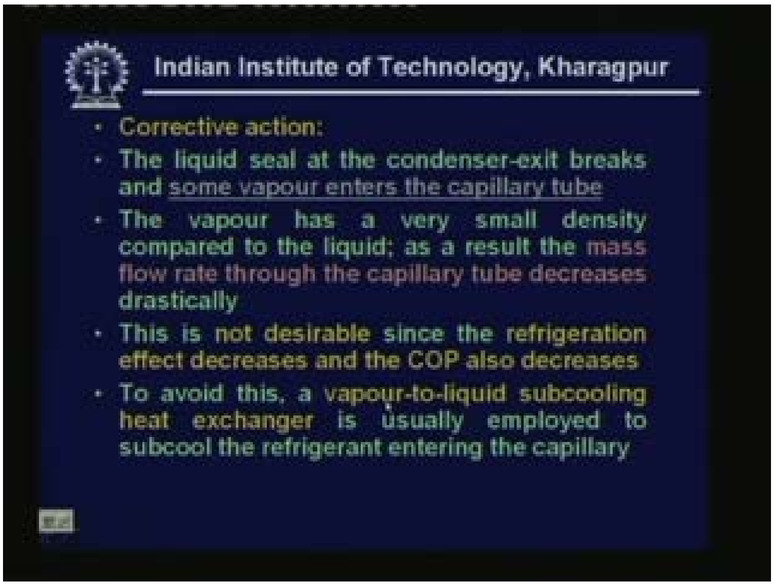

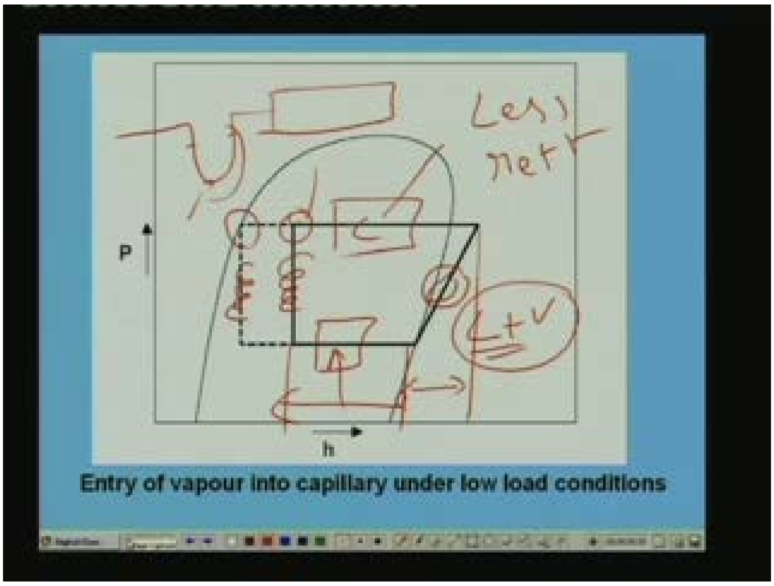

Entry of vapour into capillary under low load conditions

Now what is the corrective action under reduced load corrective action under reduced load is like this the liquid seal at the condenser exit breaks and some vapour enters the capillary tube okay. This happens because okay so originally under design condition this was the entry point of the capillary because you have the capillary here okay. Evaporator here compressor here and condenser here right. The, but now under the reduced load more refrigerant gets accumulated here. So there will be a less refrigerant in the condenser okay. This is the condenser so there is less refrigerant in the condenser.

So once there is less refrigerant in the condenser typically a condenser will have a liquid seal. That means just to give a simple idea you may have a seal like this which will be filled with liquid okay. This is required. So that no vapour enters into the capillary tube but when the load is less this liquid seal will be broken okay. Because there is less refrigerant in the condenser and it is not possible to maintain the seal. Once the liquid seal breaks the vapour possibility of vapour entering into the capillary occurs okay. That means the new condition under or less refrigerator load will be this okay. This is in he two phase region that means to the, into the capillary some liquid plus vapour enter okay.

So you can see that under these conditions the refrigeration low effect is reduced very much where as the compressor power input remains same okay. This is inefficient right the vapour has a very small density compared to the liquid. As a result the mass flow rate through the capillary tube decreases drastically this is not desirable since the refrigeration effect decreases and the COP also decreases as I have already explained. So to avoid this is a vapour-to-liquid sub cooling heat exchanger is usually employed to sub cool the refrigerant entering the capillary okay.

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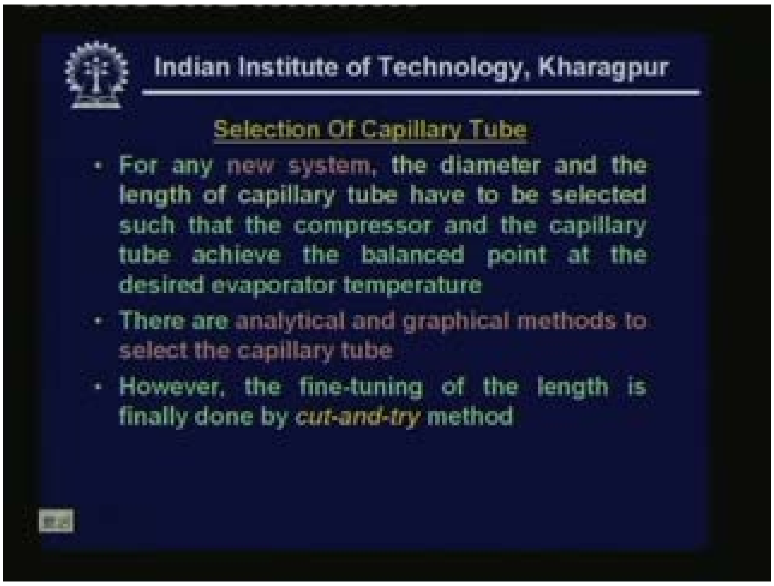

So this is how the capillary tries to get adjusted to varying loads and you have seen that it is not very effective when the load is varying okay. So the capillary tube is very effective when the load is constant. But once a load varies then the balance point shifts to new points okay. And the especially it is dangerous when the load reduces because there is the possibility of flooding and the performance also gets reduced okay. Now let us look at the selection of a capillary tube what do you mean by selection of a capillary tube selection of a capillary tube. Means given all other parameters like given the refrigeration capacity operating temperatures compressor size etcetera. And the mass flow rate through the system all these things are known to us. We have to find the required diameter and the length of the capillary tube this is what is known as the selection of the capillary tube. In such a way that, it at the design point the mass flow rate through the capillary will be same as the mass flow rate through the compressor.

That means at design point the system will be under steady state okay. So that is what is explained here for any new system the diameter and the length of capillary tube have to be selected such that the compressor and the capillary tube achieve the balance point at the desired evaporator temperature. And there are analytical and graphical methods to select the capillary tube but both these methods involve sudden assumption. So finally you for the fine tuning of the capillary tube the it is always done by using what is known as the cut-and-try method okay.

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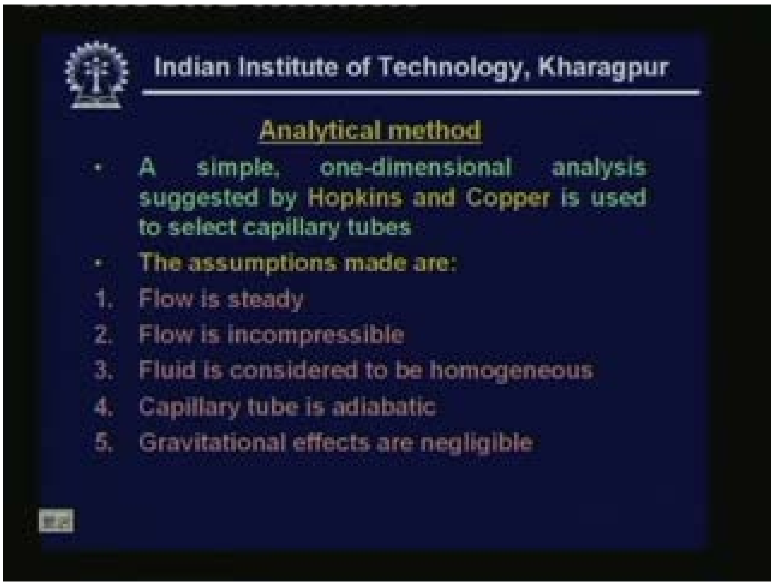

Now let us look at an analytical method. This is a simple analytical method and it is suggested be Hopkins and Copper long time ago okay. It is a one dimensional analysis and the analysis is carried out under the following assumptions. It is assume that the flow is steady flow is incompressible fluid is considered to be homogeneous capillary tube is assumed to be adiabatic gravitational effects are negligible.

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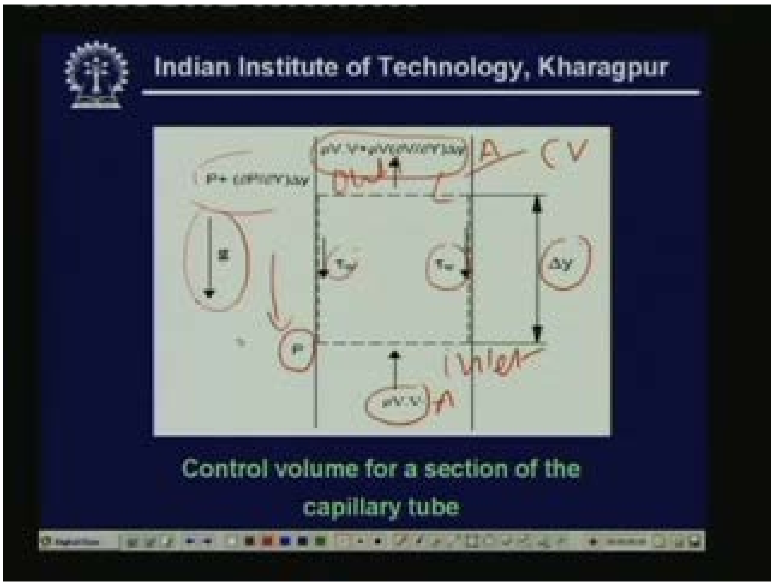

Okay, so under these assumptions the analysis carried out and this picture shows the control volume for selection of a capillary tube okay. These are nothing but this, here, I have shown the, a section of the capillary tube which is vertical okay. So this is the direction of the gravity is like this. So this a vertical portion of a capillary tube and this is a control volume which is the small section of the capillary tube okay. It has a, let us say that elemental height of delta y and this is the inlet right so this is the inlet to the control volume and this is the outlet to the control volume. At the inlet the pressure is P at the outlet the pressure is P plus dhow P by dhow Y into delta by this is obtained by applying Taylor series expansion. Similarly at the inlet the rho V into V multiplied by the area is the momentum at the inlet and this term multiplied by the area is the momentum at the outlet okay. And a tau W is the shear stress acting near the walls.

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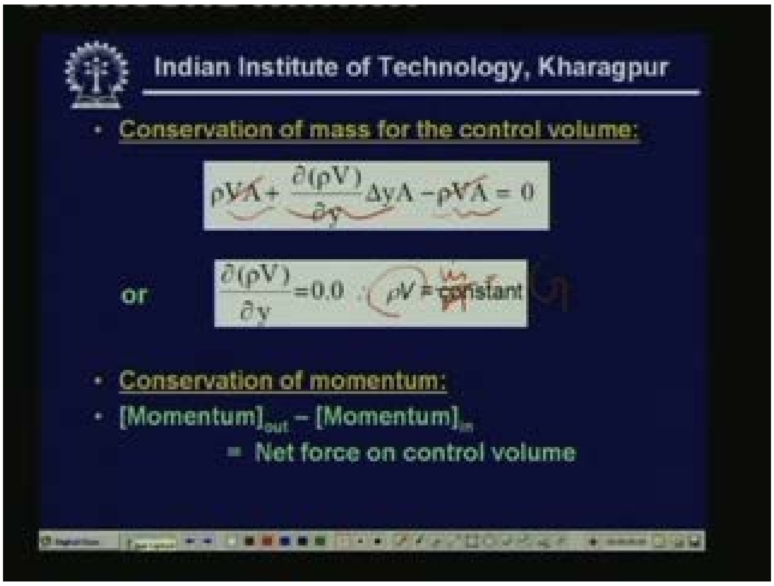

Now we apply the conservation of mass for the control volume. So the conservation of mass has, we have seen earlier is nothing but mass balance. And since we assume the float V is steady we don't have the time terms here. So simply this term this entire term is nothing but the mass flow rate at the exit of the control volume and this is the mass flow rate at the inlet to the control volume okay. So in steady sate what are mass is entering into the control volume must leave the control volume that is the statement of conservation of mass for steady state okay.

So this term gets cancelled and finally you find that dhow rho V by dhow Y is equal to zero and that means rho V is constant and rho v is nothing but mass flow rate divided by area. And this is equal to what is known as mass velocity G okay. So finally the conservation of mass states the mass velocity G through the capillary tube remains constant okay. Now the next we have to apply conservation of momentum and what is a conservation of momentum. Conservation of momentum simply states that momentum out minus momentum in that means momentum at the outlet of the control volume minus momentum of the fluid at the inlet of the control volume is equal to the net force acting on the control volume this is the statement of conservation of momentum linear momentum okay.

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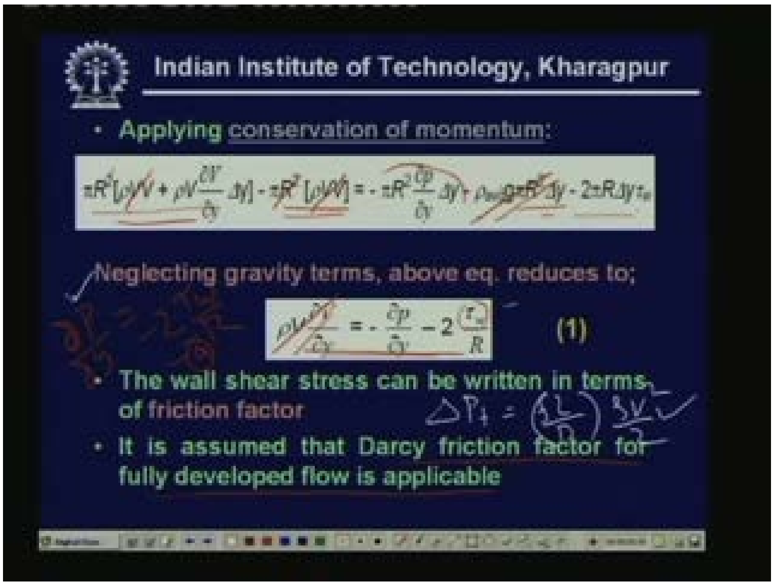

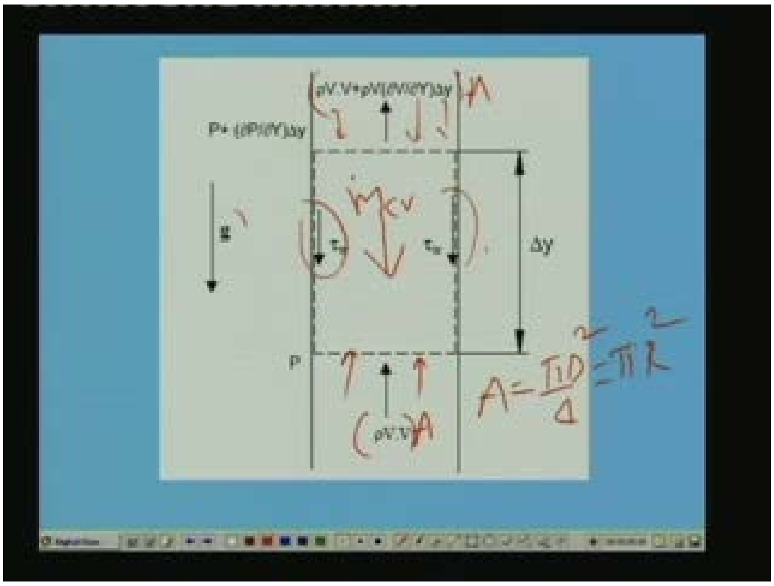

If we apply the conservation of momentum. Now, so if you apply the conservation of momentum you get this equation and let me just show this control volume once again okay. As I said the this term multiplied by the area is the momentum at the inlet to the control volume and this term multiplied by the area is the momentum at the outlet of the control volume and what are the different forces acting here one force acting is due a because the mass of the control volume okay. That means because the acceleration due to gravity. So that force will be acting in the downward direction okay. Let us say that this is mass of right due to the mass of the fluid in the control volume. This is one force and you also have force due to shear stress at the wall of the capillary tube. This also acts in the opposite direction it tries to retard the flow of refrigerant okay.

So this also acts in the downward direction and the pressure acts at the inlet of the control volume in this direction and at the outlet the pressure acts in this direction okay. So these are the different forces acting and the momentum in and out and the area density is cylindrical. The area is simply equal to phi d square by four or phi R square where R is the inner radius of the capillary and D is the inner diameter of the capillary. So if you apply this you find that the conservation of momentum equation boils down to this is the momentum at the outlet of the control volume momentum at the inlet to the control volume. This is the net pressure force acting and this is the force due to the gravity and this is the frictional force due to the shear stresses okay.

Now if you neglect the gravity term. That means if you neglecting this term because this term is normally very small compared to the other terms. So you can neglect this term okay. And when you manipulate this equation you find that this phi r square term phi r square term gets cancelled and this term gets cancelled here with this term. So finally you get this equation okay. This is the equation for the conservation of momentum for the control volume here as I said tau w is the wall shear stress now the wall shear stress can be written in terms of friction factor okay. And for simplicity sake we assume that Darcy friction factor for fully developed flow is applicable okay.

What do we mean by Darcy friction factor for fully developed flow? Once if develop flow is fully developed this term will not be there okay. This term vanishes for fully developed flow once this term vanishes you find that dhow P by dhow Y okay, is equal to from this equation. Because this is zero is equal to minus two tau w by R okay. So this is let us say that equation A. Then you also have another equation using the definition of the friction factor from the definition of the friction factor delta Pf that is a frictional pressure is equal to fl by D into rho v square by two okay. So what we do is we replace this shear stress term by using this equation and using this okay.

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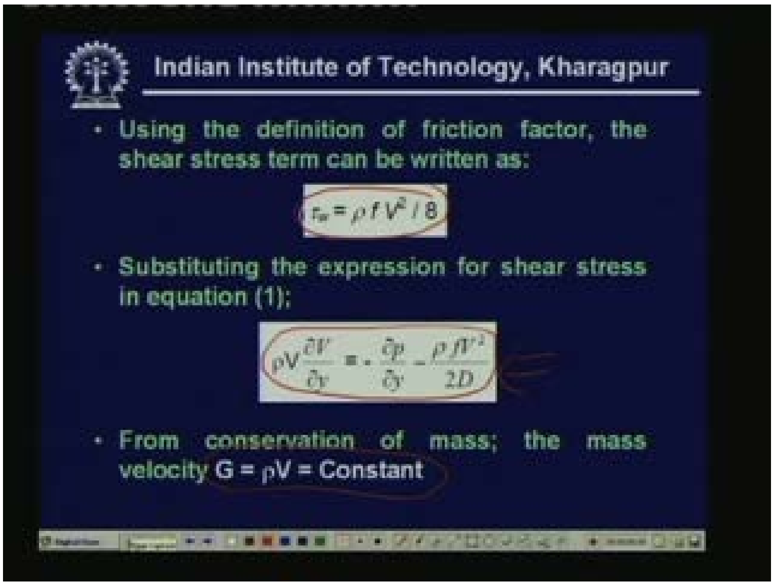

So using the definition of friction factor the shear stress term can be written finally written in this form like this okay, tau w is rho f v square by eight where rho is the density f is the friction factor and V is the velocity of the fluid right. And substituting this expression in the expression for shear stress we finally get this expression okay, rho V dhow V by dhow y is equal to minus dhow p by dhow y minus rho f v square by two D. And we have seen that from the conservation of mass G is equal to constant so what we do is we replace V by G. That means we write this equation in terms of mass velocity G because this is constant right.

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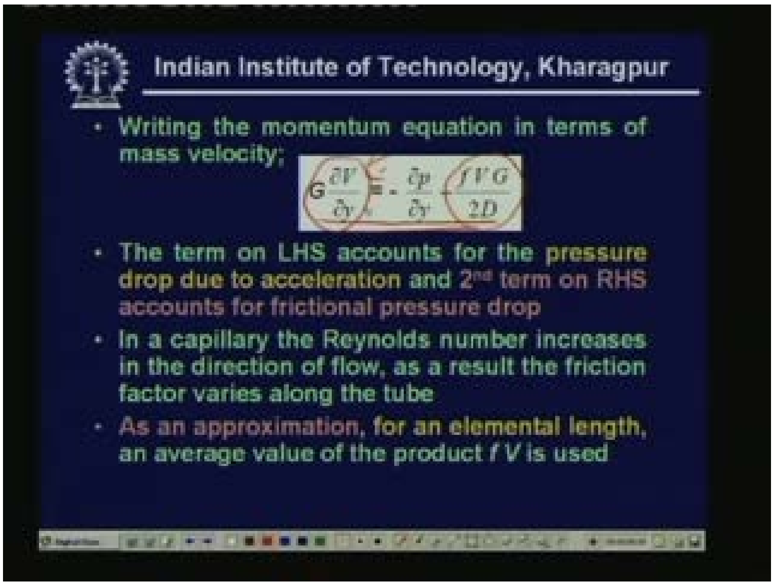

So writing the momentum equation in terms of mass velocity we get this equation okay. And you can see that this term that is the term on the left hand side this accounts for the pressure drop due to acceleration. As I said pressure drop in a capillary tube is because of the acceleration and because of the frictional effects. So this term accounts for the pressure drop due to acceleration. And this term accounts for the pressure drop due to friction okay. f is the friction factor and the total pressure drop dhow p by dhow y pressure radian is the result of frictional pressure drop and acceleration pressure drops okay. And we have to find out what is the friction factor okay.

We have to evaluate the friction factor how do you find the friction factor in a capillary tube. The Reynolds number increases in the direction of flow, why the Reynolds number increases, because the velocity increases in the direction of flow so Reynolds number increases. As the result the friction factor also varies along the tube. But what we do is as an approximation for an, a small elemental length. We select an average value of the product f and V okay. That means we take a small elemental length and we assume that for that elemental length this product is constant or we take a mean of this this thing okay. fV mean we take for the elemental length.

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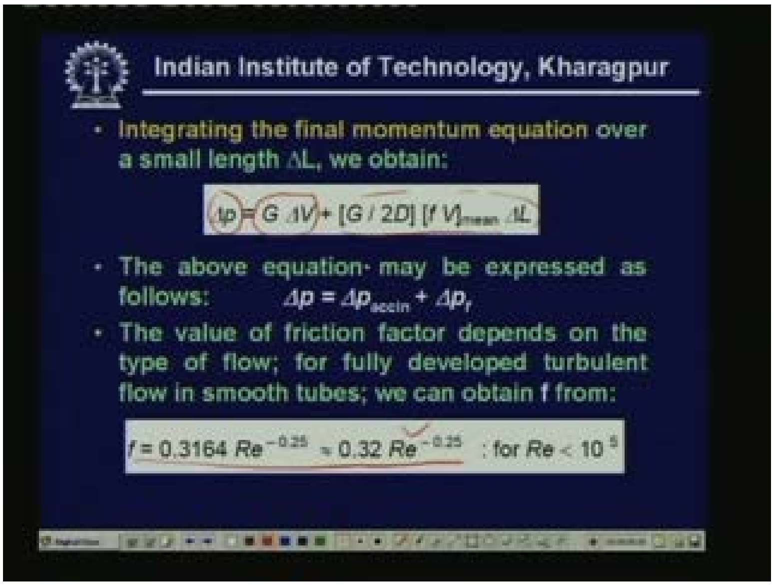

So integrating the final momentum equation over a small length delta L we obtain this equation delta p is equal to G into delta V plus G by two D into fV mean into delta L. Again this term, this term account. So this is the total pressure drop for the small element and this is the pressure drop due to acceleration and this is the pressure drop due to friction okay. So the above equation can be written in terms of like this delta p is equal to delta p acceleration plus delta p friction. And the value of friction factor depends on the type of flow and for fully developed turbulent flow in smooth tubes we can obtain f from this equation f is approximately equal to point three two Reynolds number to the power of minus point two five. So if you know the Reynolds number then you can find out the friction factor. Once you find the friction factor and you know other things then we can find out what is the required length. Now let us look at the solution procedure this is the model suggested originally.

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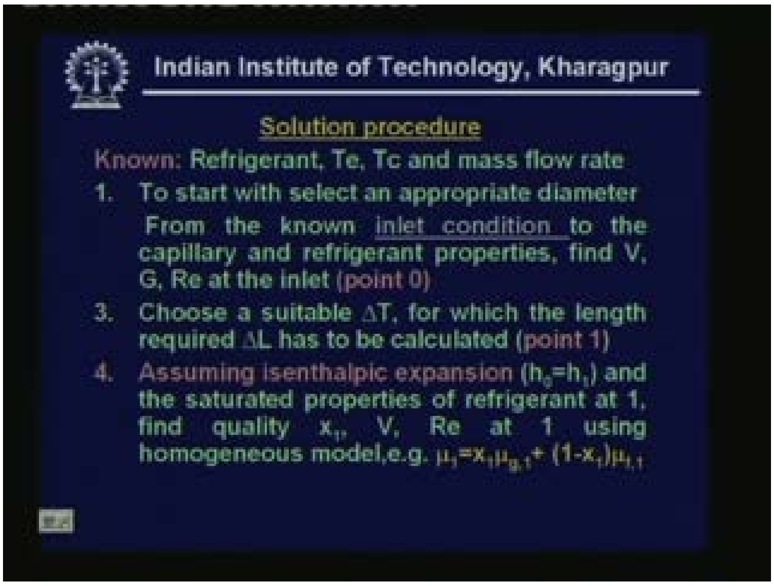

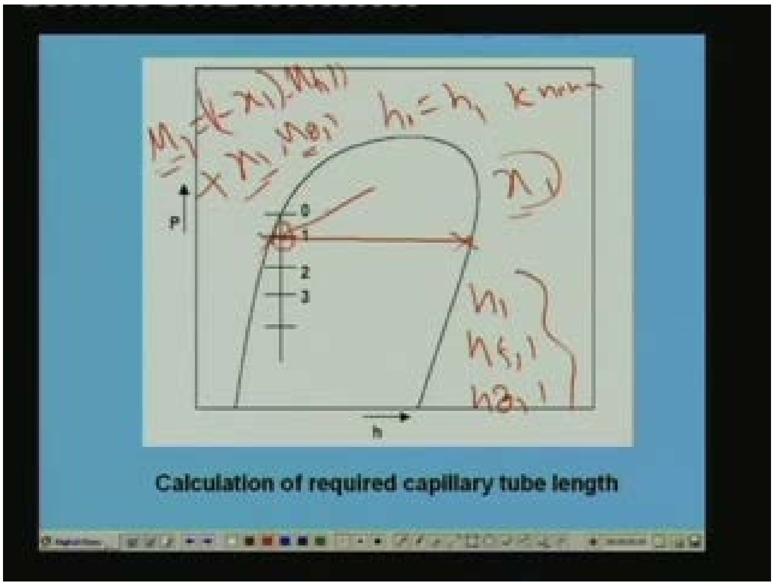

And how do we solve this, the solution procedure is like this. Now as I said we know thewhat is the refrigerant use we also know the evaporator and condenser temperature and we also know the mass flow rates. So with these inputs we have to find the required diameter and length of the capillary tube. So let me quickly explain how this is done. Let us say that this the capillary tube okay. And the total length of the capillary tube is let us say Lc and this is the inlet to the capillary tube and this is the outlet to the capillary tube.

So at the inlet were what are the conditions we have the temperature some Tc and pressure is Pc which is nothing but the condenser pressure. And at the outlet is connected at the evaporator. So we know that the temperature is Te and pressure is Pe okay. So all these things are known to us temperatures are known pressures are known and we also know the mass flow rate okay. So if you look at the temperature across the capillary a temperature drop of Tc minus Te is taking place right. Similarly a pressure drop of Pc minus Pe is taking place across the capillary. We have to find out what is the required what is the length of the capillary.

So that this much amount of temperature drop and this much corresponding pressure drop can take place across the capillary okay. So what we do is we break this capillary tube into several small elements. Let us say that to give an example let us say Tc is fifty degree centigrade and Te is equal to zero degree centigrade okay. That means Tc minus Te is fifty degree centigrade right. So I will take fifty elements of the capillary tube. That means I divide the capillary tube into fifty elements and across each element one degree temperature drop takes place okay. That means if the in the, for this one if this is the element one and here if the temperature is fifty degree centigrade. At this point the temperature is forty-nine degree centigrade and at this point it is forty-eight degree centigrade. So like that the temperature reduces in this direction finally when you come to this last point the temperature is zero degrees centigrade okay.

So what I do is, I first, I take the first element. And for the first element what I do is from the given information I find out what is the length required. So that this one degree temperature drop can take place across the first element okay so that is delta L one okay. Then I move from first element to second element and for the second element. Again I find out what is the length required delta L two required. So that the temperature can drop from forty-nine degrees to forty-eight degrees. And similarly for the third element find out delta L three. So the temperature drops from forty-eight degrees to forty-seven degrees. So I proceed starting with the inlet right up to the outlet and I go on finding the elemental lengths okay. And finally if you add up all these elemental lengths you find out what is the required capillary tube length okay so this is the procedure okay.

So let me summarise whatever I have explained. Of course you have two unknowns that is the diameter and length. So we always have to start with some appropriate diameter and then find out the length okay, from the known inlet condition to the capillary and refrigerant properties find velocity V mass velocity G and Reynolds number at the inlet okay. That means, let us say that our inlet condition is saturated. So I know this point at this point as I said I know the mass flow rate okay. Mass flow rate the refrigerant and i am assuming some diameter of the capillary. So I know cross section area okay. That is phi D square by four is the cross section area of the capillary tube. So again find out the mass velocity G which is nothing but m dot by phi D square by four right. I can also find out velocity at the inlet. That means at this point V naught V naught is nothing but mass velocity divided by density at inlet rho naught. So I can find out V naught. Similarly I can find out other properties like specific volume at this point viscosity at this point right. So all the properties are known because I know the state exactly.

Since the state is known to me we can find out all the points and we can also find out the Reynolds number rho VD by mu. Once you know the Reynolds number you can find out friction factor because friction factor is equal to point three two Reynolds number to the power of minus point two five okay. So this is the friction factor at the inlet. So likewise I find out all the required quantities at this point okay. Then what I do is, I assume suitable temperature drop. As I have already explained to you as once you assume the suitable temperature drop that means you come to the point one okay. So you come to the point one and if you assume that the process is isenthalpic. That means ho is h one which is known okay.

And this temperature is known. Because you are assuming a suitable temperature drop. So this temperature is known, so you can fix this state once you can fix this state you can find out the saturated liquid and vapour properties. And you know that saturated liquid and properties and you also know the enthalpy of the mixture that means hone is known to us okay, and hf one is known hg one is known right. Since all these three parameters are known we can find out what is the dryness fraction or quality. At this point once you know the dryness fraction you can find out all other properties using the homogeneous model. Homogeneous model means you treat the two phase flow as a pseudo single phase fluid and for example any property can be found as a weighted average of the saturated liquid and vapour properties.

For example the viscosity at point one is obtained as viscosity of the liquid saturated liquid and its mass fraction. That means one minus x one into mu f one plus x one into mu G one okay. So this is the viscosity of the mixture which is equal to the mass fraction of the saturated liquid into saturated liquid the viscosity mass fraction of the saturated vapour into saturated vapour viscosity likewise you can find out all other properties okay. Now choose a suitable delta T for which the length required delta L has to be calculated point one assuming isenthalpic expansion. And the saturated properties of the refrigerant at one find quality x one V Re at one using homogenous model this is t i have already explained to you.

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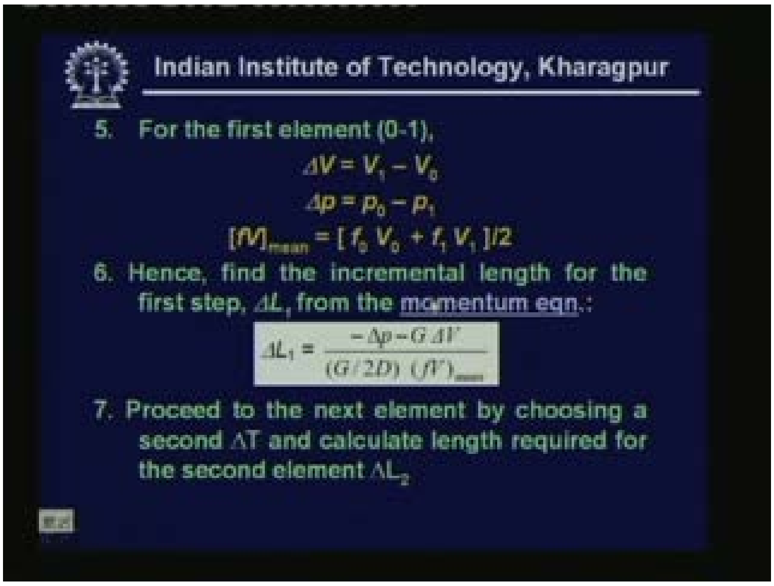

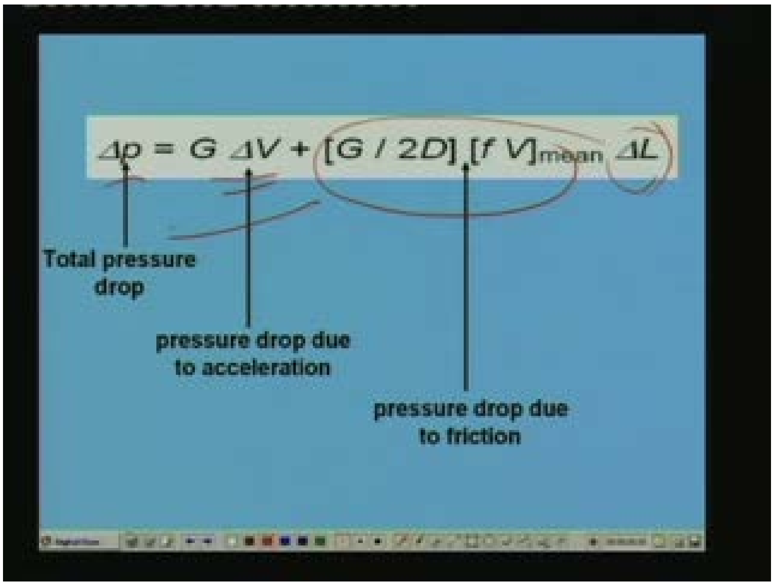

For the first element delta V is equal to V one minus V naught you know V one and you also know V naught. So we can find out V one minus V naught and delta P is equal P naught minus P one which are known to us and fV mean is nothing but f naught into V naught plus f one into V one by two where f naught and f one are the friction factors at point zero and one V naught and v one are the velocity set point zero and one okay. Hence we can find out the incremental length for the first step delta L L one from the momentum equations. The momentum equation is rewritten in this fashion okay. So where rewrite the momentum equation this is the momentum equation okay. So you take this term to this side and write everything in terms of for delta L okay. So take these terms also onto this side then you get this expression. So we know the length of the first element then you proceed to the next element by choosing a second delta T and calculate length required for the second element delta two L two.

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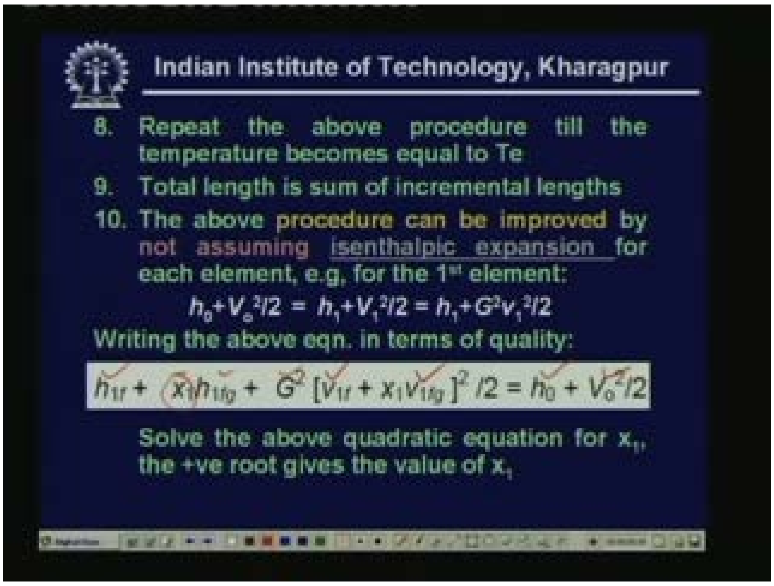

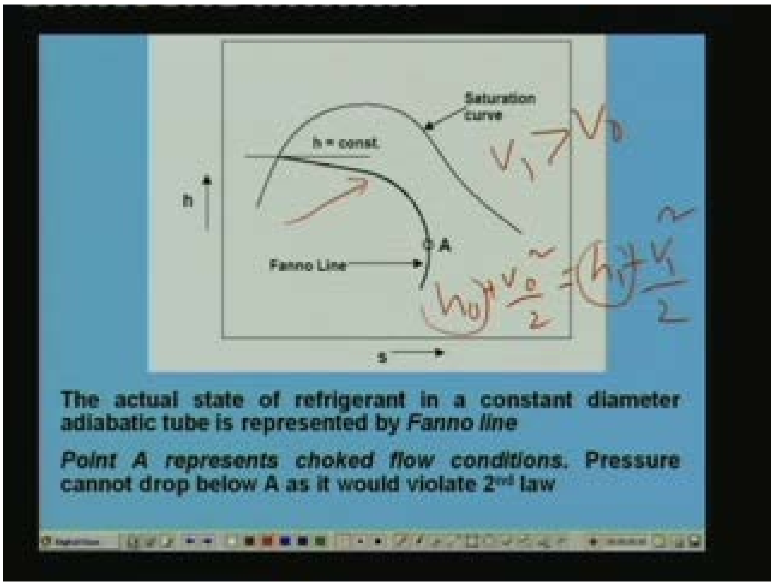

Repeat the above procedure till the temperature becomes equal to Te okay. As I have already explained you and total length is the sum of incremental lengths the above procedure can be improved by not assuming isenthalpic expansion for each element you find that in actual case the flow through capillary is not isenthalpic. But the enthalpy reduces inside the capillary tube why the enthalpy reduces the enthalpy reduces. Because from the energy balance equation at any point h one plus V naught square by two equal to h one plus v one square by two. And we know that in the direction of flow the velocity increases. That means v one is greater than v naught okay.

That means h one should be less than h one h naught okay. So the actual line will be something like this is this is known as the Fanno line okay. So the actual enthalpy

reduces as the flow takes place through the capillary okay. And point A is known as choked flow condition and I will explain this later. So you can improve as i said the above procedure by considering non isenthalpic expansion. That means if we write the energy equation also in addition to the mass and momentum equations like this h naught v ones h naught plus v one square by two is equal to h one plus v one square by two and replace v one by mass velocity G and specific volume v one okay. And that equation is written in terms of the dryness fraction x one right.
So you ultimately get this equation in this equation we know all these things all these things are known to us okay. This is known to us this is known to us known to us so only unknown is x one. So you can see that this is a quadratic equation. So when you solve this quadratic equation it will give you two roots and you have to select the root that is positive okay. So the positive root of this quadratic equation gives you the correct value of dryness fraction okay.
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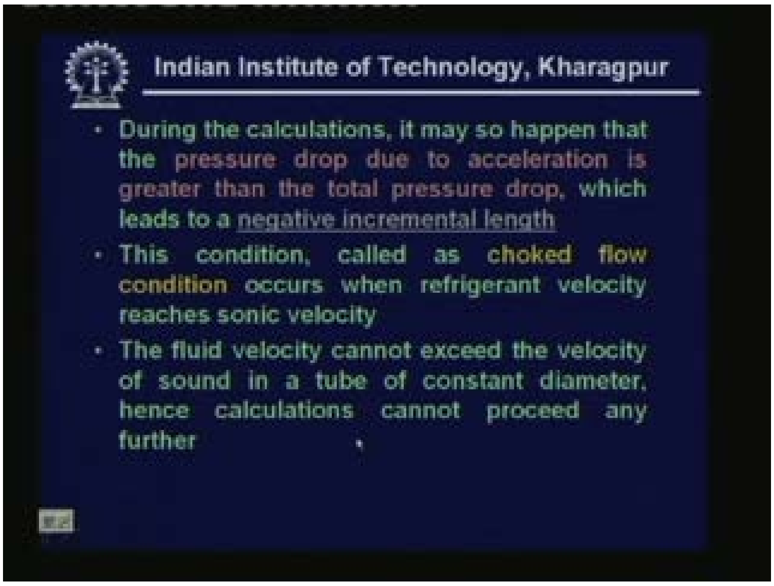

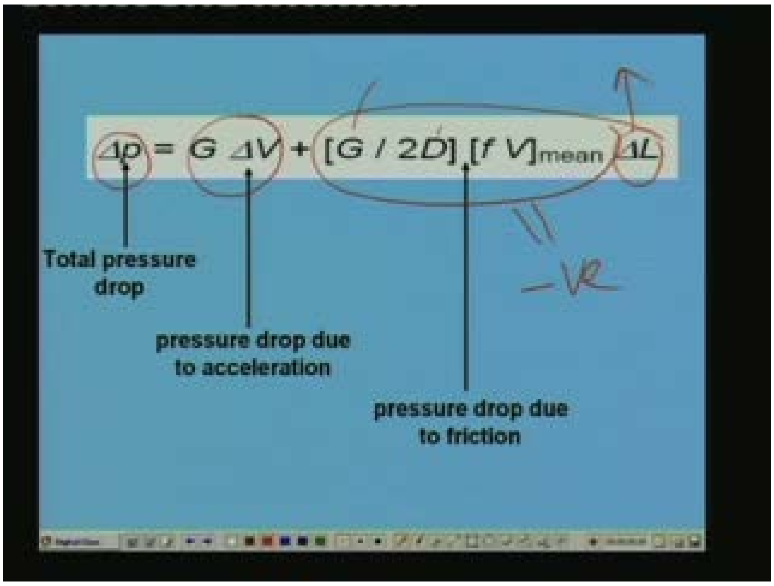

Now during the calculations it may, so happen that the pressure drop due to acceleration is greater than the total pressure drop okay. So there are some circumstances under which this will happen this leads to total this leads to a negative incremental length okay. That means under certain circumstances this quantity will be greater than this okay. But this equation must be satisfied always and this quantity is greater than this means this has to be negative okay. So this must be negative G cannot be negative D cannot be negative f and V cannot be negative.

So the only possibility is delta L has got to be negative. That means the incremental length becomes negative okay. This actually has no meaning okay. So this kind of a condition is called a choked flow condition and this condition occurs when refrigerant velocity reaches sonic velocity okay. That means the velocity of the sound at that point and the fluid velocity cannot exceed the velocity of sound in a tube of constant diameter hence calculations cannot proceed any further okay. There is a problem of choked flow.

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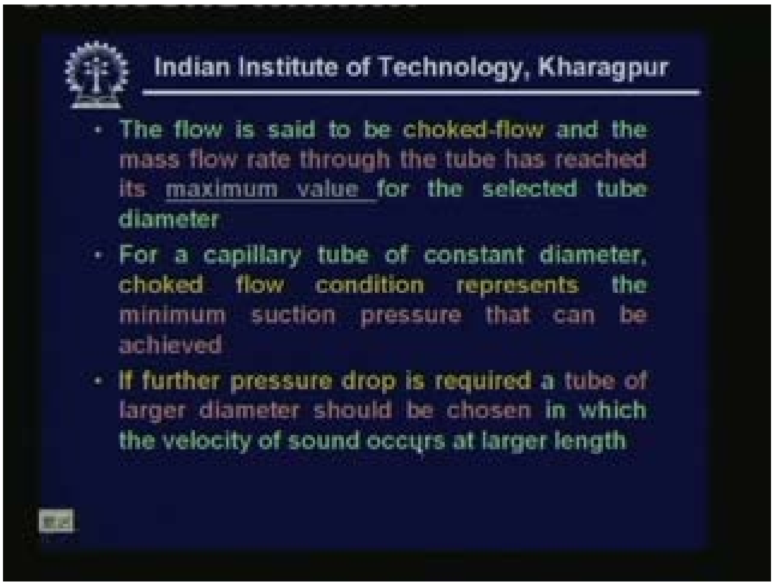

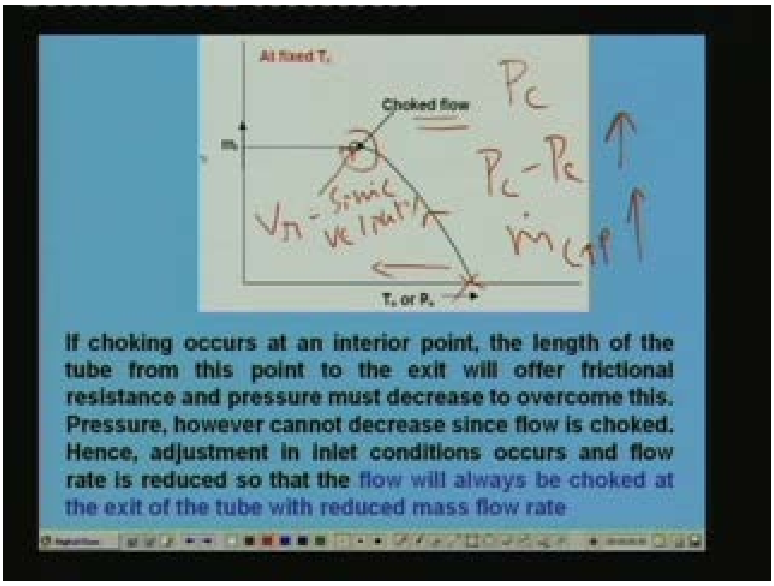

And the flow is said to be chocked flow and the mass flow rate through the tube has reached its maximum value for the selected tube diameter okay. That means to plot the you can see that if you are plotting let us say that you are fixing condenser pressure and condenser temperature. And if you are reducing the evaporator temperature or evaporator pressure and proceeding in this manner. Let us say that this is the initial mass flow rate as you are reducing the evaporator pressure Pc minus Pe increases because Pc is fixed and Pe is getting reduced. So mass flow rate through the capillary as i have already explained to you increases okay. So this this process goes on like this mass flow rate increases continuously but a point will come at at which further reduction in evaporator temperature will not give any further rise in the mass flow rate okay.

That means beyond this point mass flow rate remains constant. So this condition is what is known as choked flow condition this happens because at this point the velocity of the refrigerant okay reaches that of the sonic velocity okay. Once it reaches the sonic velocity the velocity cannot increase further. So mass flow rate cannot increase further so the mass flow rate remains constant this is a typical problem encountered in compressible flow for example in nozzles etcetera. And this is known as choking as I said and if choking occurs at interior point the length of the tube from this point to the exit will offer friction resistance and pressure must decrease to overcome this.

However pressure cannot decrease because flow is choked hence adjustment in inlet conditions occurs and flow rate is reduced. So that the flow will always be choked at the exit of the tube with reduce mass flow rate okay. So for a capillary tube of constant diameter chocked flow condition represents the minimum suction pressure that can be achieved and if further pressure drop is required a tube of larger diameter tube should be chosen in which the velocity of sound occurs at larger length. So let me once again repeat this to start the selection procedure what we have done is we have assume some diameter okay, and we started calculating the required length.

And while you have, let us say that you have selected some diameter and such a way that your encountering choked flow situation okay. And so if your encountering choked flow situation increasing the length will not help right. So what you have to do is you have to go back and you have to increase the diameter. So that the length can be increased and the velocity of the refrigerant can be reduced. So that sonic velocity does not take place inside the capillary okay. So this process is some kind of a trial and error kind of a procedure okay.

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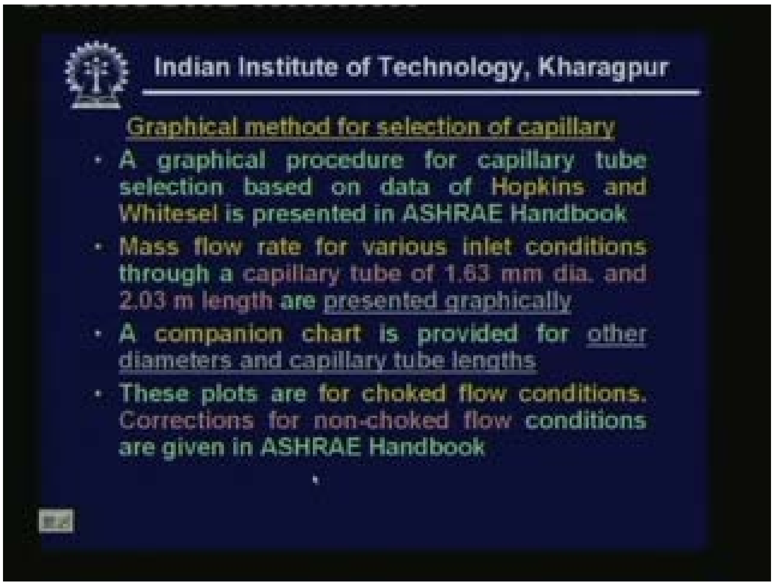
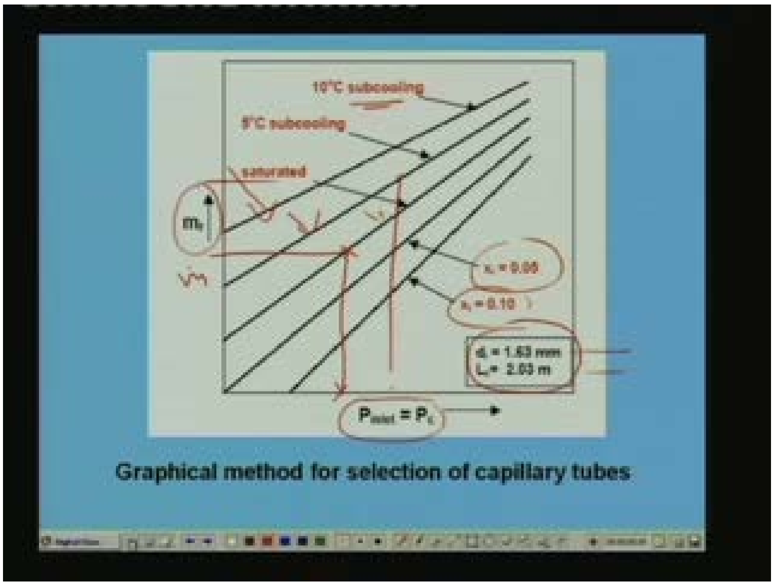
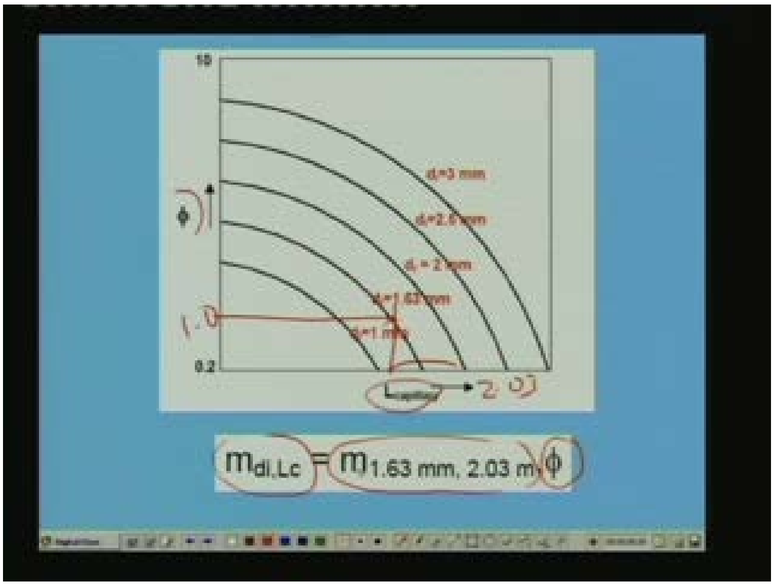

Indian Institute of Technology, Kharagpur
Graphical method for selection of capillary
A graphical procedure for capillary tube selection based on data of Hopkins and Whitesel is presented in ASHRAE Handbook
Mass flow rate for various inlet conditions through a capillary tube of 1.63 mm dia. and 2.03 m length are presented graphically
A companion chart is provided for other diameters and capillary tube lengths
These plots are for choked flow conditions. Corrections for non-choked flow conditions are given in ASHRAE Handbook


10°C subcooling
5°C subcooling
saturated
x = 0.05
x = 0.10
d = 1.63 mm
L = 2.03 m
P inlet = P
Graphical method for selection of capillary tubes


10
0.2
d=3 mm
d=2 mm
d=1 mm
L capillary
m di,Lc = m 1.63 mm, 2.03 m φ

Now let me quickly explain the graphical method for selection of capillary tubes. A graphical procedure for capillary tube selection is based on the data of Hopkins and Whitesel and this is presented in ASHRAE handbooks. Here the mass flow rates of for various inlets conditions through a capillary tube of one point six three mm diameter and two point zero three meter length are presented graphically okay, for example okay. So this is a typical graph where this is the x axis is the inlet pressure which is nothing but the condenser pressure. And y axis is the mass flow rate through the capillary okay. And this data is given for a particular diameter of the capillary and particular length that is one point six three mm inner diameter and two point zero three meter of length.

And the mass flow rate is given for different inlet conditions one is the pressure the other one is the degree of sub cooling okay. For example this curve is for ten degree sub cooling this curve is for five degree sub cooling this is for the saturated condition here is for two phase entry that means the quality is for point zero five here the quality is point one. So for different inlet conditions mass flow rates are reduced mass flow rates are given. For example if you know the inlet conditions, let us say that it is saturated and you also know the pressure here. So you can find out what is the mass flow rate through this capillary that is one point six three mm and two point one zero three meter length capillary right for any other inlet conditions also you can find out what is the mass flow rate.

Now a companion chart is provided for other diameters and capillary tube lengths okay. So this is the companion this thing because it not necessary that your capillary diameter is one point six three millimetre and length is two point zero three meters okay. You can have any other diameter and length. If you have any other diameter and length the actual mass flow rate through that diameter and length is nothing but the mass flow rate through the standard one point six three meter mm diameter capillary multiplied by a flow correction factor phi okay.

This flow correction factor phi is given as the function of the length of capillary and different diameters okay. For example if the length of the capillary is two point zero three let us say this is two point zero three meter okay. And the diameter is one point six three mm then the flow correction factor will be one because this is the standard capillary and here the mass flow rate is same as the mass flow rates of the standard capillary okay. These plots are for choked flow conditions and ASHRAE has also given corrections for non chocked flow conditions.

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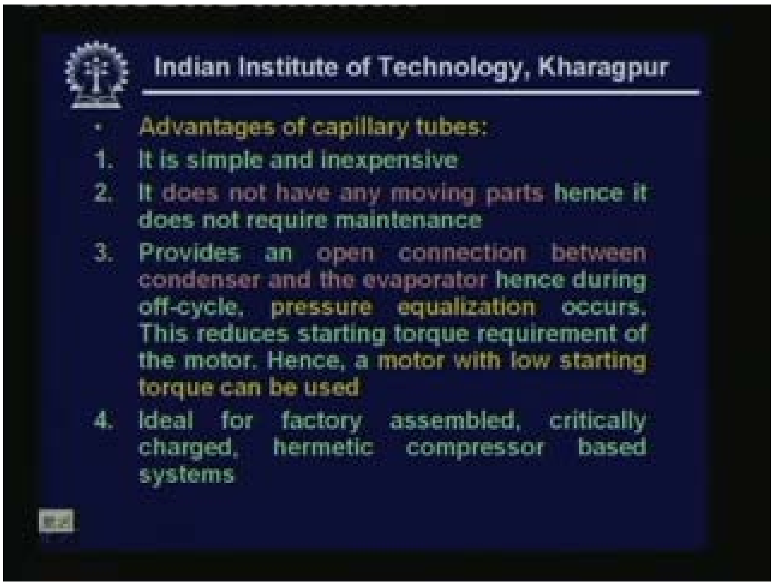

Now let me quickly summarise the advantages of capillary tubes. It is simple and inexpensive. It does not have any moving parts hence it does not require maintenance it provides an open connection between condenser and the evaporator. Hence during off cycle pressure equalization occurs this reduces starting torque requirement of the motor hence a motor with low starting torque can be used. This is one biggest advantage of capillary tubes when the system is off that means when the compressor is not running condenser pressure is much higher than the evaporator pressure.

So the pressure equalisation takes place through the capillary tubes because capillary tube is nothing but an open tube right. So finally you find that during the off condition if sufficient time is allowed the entire system pressure will be fame okay. When the compressor starts at the after the off condition it has to start again as the same head back pressure okay. That means it does not require a lot of starting torque to start okay. That means you can use low starting torque motors. And the this is ideal for factory assembled critically charged hermetic compressor based systems.

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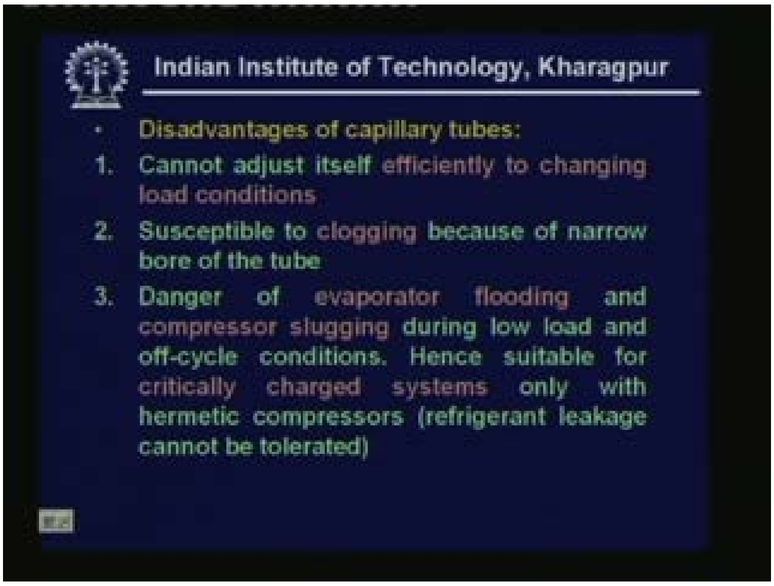

Of course a capillary tubes also has some disadvantages. What are the disadvantage s of the capillary tube? It cannot adjust itself efficiently to changing load conditions this is what we have seen and it is susceptible to clogging because of narrow bore of the tube okay. Since your inner diameter is very small if there is any impurity or some solidity impurity or some moisture which may freeze inside the capillary. It will block the capillary and flow cannot take place okay. So cleanliness is very important when you are using capillary tubes and there is danger of evaporator flooding and compressor slugging during low load and off cycle conditions. Hence suitable for critically charged system only with hermetic compressors okay. This I have already explained to you.

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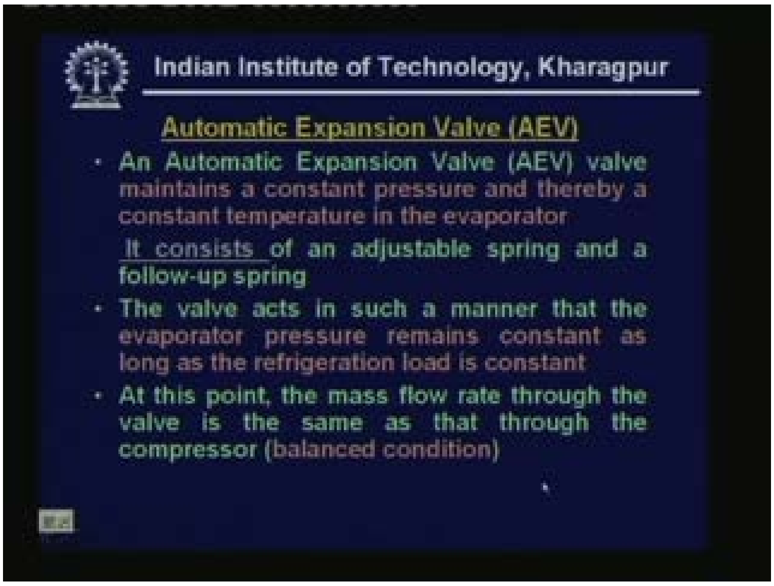

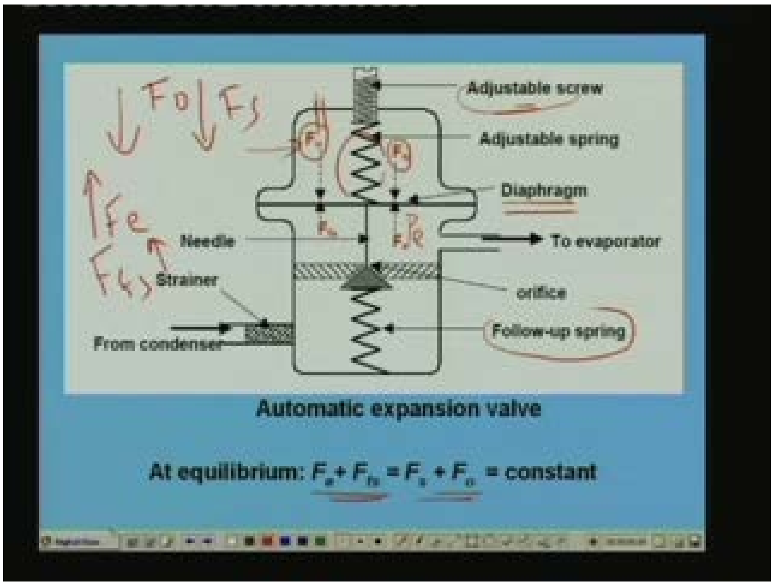

Now let us look at the other kind of expansion devices that is known as automatic expansion valve an automatic expansion valve maintains a constant pressure. And thereby a constant temperature in the evaporator it consist of an adjustable spring and a follow up spring. Let me show the picture of this. This is the schematic of an automatic expansion valve this is also known as the constant pressure expansion valve okay. So this is the inlet to the valve. So refrigerant comes from the high pressure condenser and it flows through the strainer. So that no dust particle are other impurities enter into the valve so strainer is used here and refrigerant at high pressure enters here and there is an orifice here okay. Through the orifice the refrigerant flows and finally it comes out from the valve and it goes out to the evaporator. And here you have the evaporator pressure and here you have the condenser pressure. So all the pressure drop takes place across the orifice okay.

This is very important to remember. So this orifice provides a very narrow opening right and the mass flow rate through the orifice. That means the mass flow rate through the orifice is proportional to the pressure difference Pc minus Pe and its also proportional to the area of the opening okay. So if the area of the opening is high for the given pressure difference there will be higher flow rate if the area opening is small there will be less flow rate okay. Now if you look at the schematic of the automatic expansion valve it consist of a diaphragm okay, or bellows you can also use bellows and an, the adjustable spring here and an adjustable screw. So using the adjustable screw you can adjust the spring compression right the spring constant can be the force exerted by the spring can be adjusted by with the help of the adjustable screw. And this is normally opened to atmosphere so atmospheric pressure also will also be acting here. So now if you look at the force acting on the diaphragm.

What are the forces acting on the diaphragm you have one force due to atmospheric pressure acting here that is f naught and force due to spring that is Fs okay. So the upward force is F naught and Fs and what is the downward force the downward force is first one is due to the evaporator pressure. Because as I said here the evaporator pressure acts because it is connected with the evaporator. So you have the upward force that is evaporator due to evaporator pressure and there is also an upward force because of the follow up spring okay. That is Ffs right and when the valve is balanced these forces must be balanced. So at equilibrium the downward force that is Fs plus Fo is balanced with the upward force that is Fe plus Ffs okay. Now the valve acts in such a manner that the evaporator pressure remains constant. As long as the refrigeration load is constant at the at this point the mass flow rate through the valve is same as that through the compressor. So you have the balanced condition.

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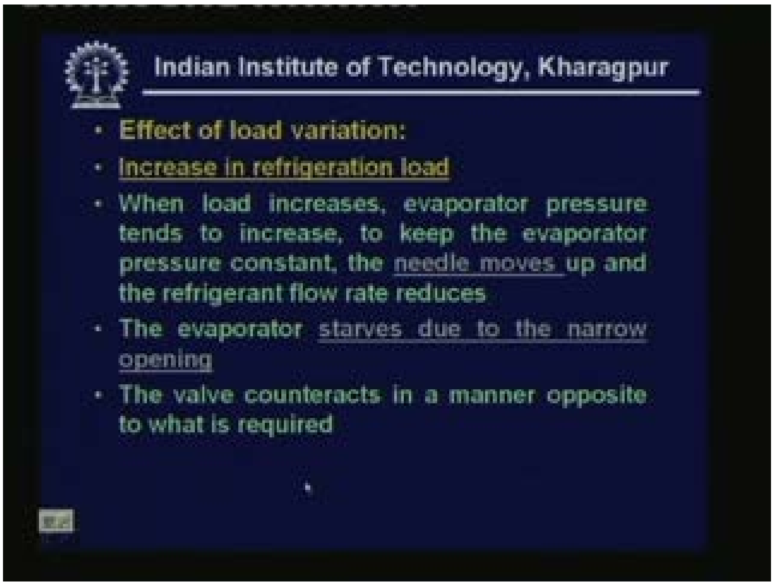

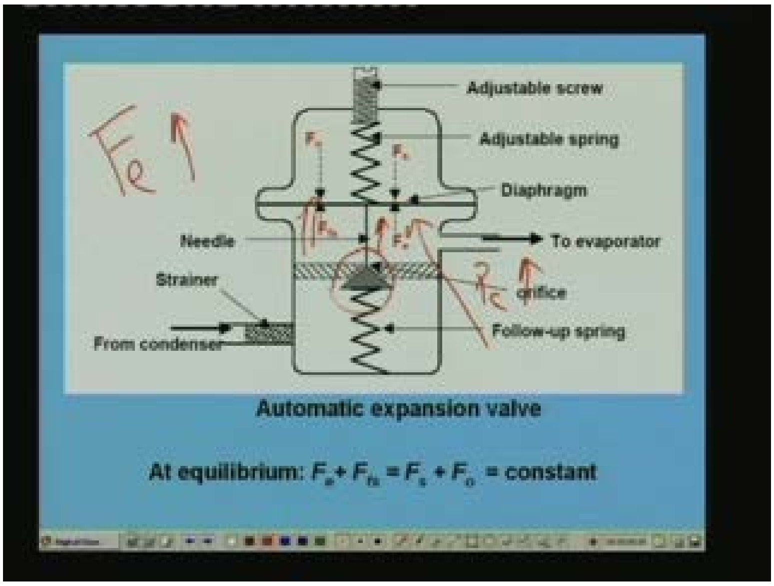

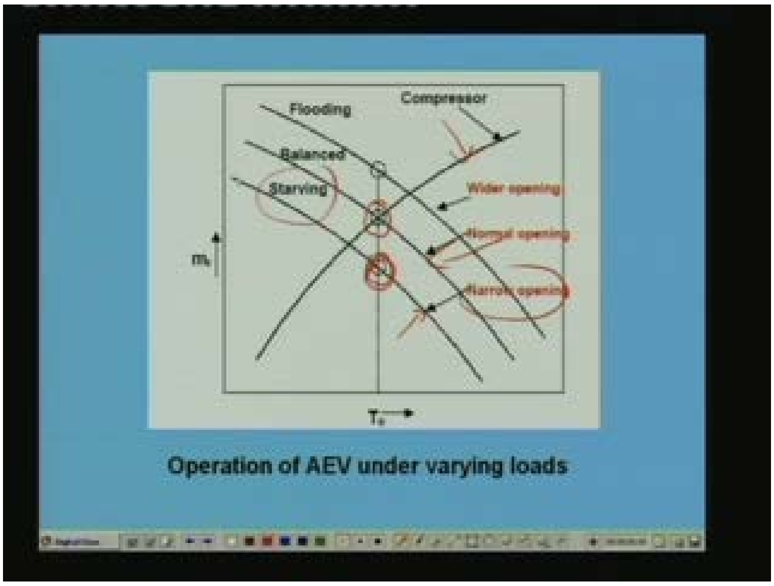

Now effect of load variation what happens when the load increases. Let us say when the load increases when load increases evaporator pressure tends to increase. So to keep the evaporator pressure constant the needle moves up and the refrigerant flow rate reduces okay. That means let us say that because of increase in the load this pressure increases okay, Pe increases once Pe increases Fe increases right. That means the downward force increases okay the downward force increases. Once the downward force increases a balance will be restored at a higher position of the needle. That means the needle moves up okay. The spring gets compressed and a new balance is achieved at a narrower opening of the orifice okay. That means when the load increases the orifice opening becomes narrower once the orifice openings becomes narrower the mass flow rate through the valve reduces okay. So the once the mass flow rate through the valve reduces the evaporator starves due to the narrow opening okay.

So this is the mass flow rate curve for the narrow opening. So mass flow rate reduces this is the balance condition at which mass flow rate through the compressor is equal to the mass flow rate through the capillary. But because the increase in load the needle moves up and opening become narrow mass flow rate through the valve reduces. So the new point is this, so you are supplying less and you are taking out more from the evaporator. So evaporator starves. So you have the starving condition actually this is opposite to what we required because when the load increase we want the refrigerant flow rate to increase. But unfortunately in this valve opposite thing happens mass flow rate reduces so that evaporator pressure is maintained.

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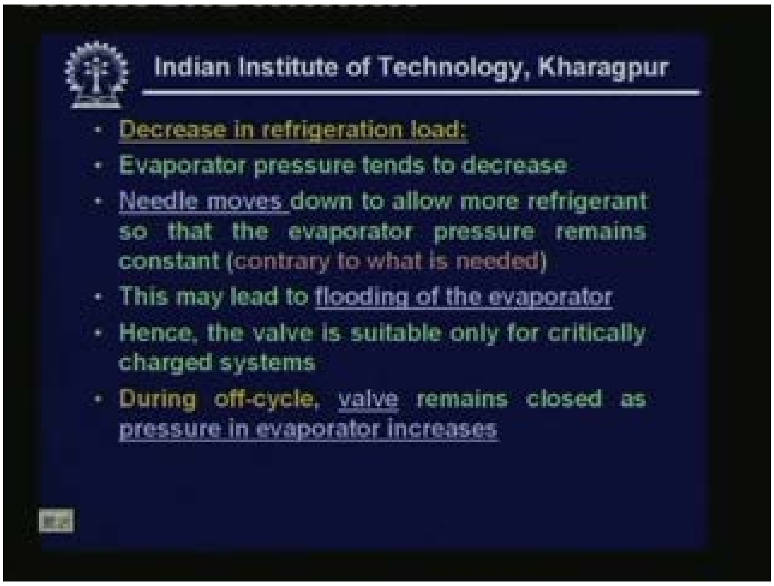

Now what happens when the refrigeration load decreases when the refrigeration load decreases evaporator pressure tends to decrease needle moves down. Because the upward force is higher now to allow more refrigerant. So that the evaporator pressure remains constant okay. That means when the load reduces more there will be more mass flow rate okay. So that the pressure is maintained this is again contrary to what we expect and this may also lead to flooding of the evaporator okay. And hence the valve is suitable only for critically charged systems okay, just like capillary tubes and during off cycle valve remains closed as pressure in evaporator increases okay, that means during off cycle.

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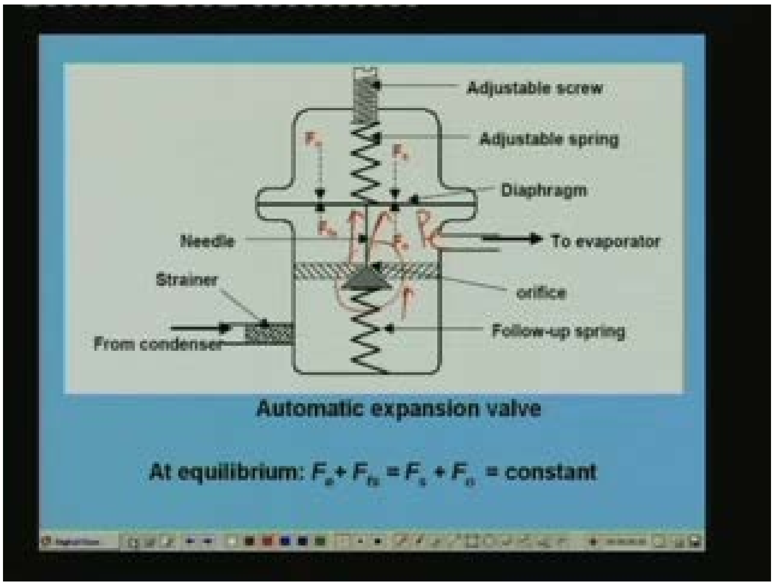

This pressure will be higher okay. So during off cycle Pe will be higher because Te will be higher. So the higher force is higher in the downward direction. So the needle will be moved up this orifice will be closed. So there will not be any mass flow rate okay during the off condition.

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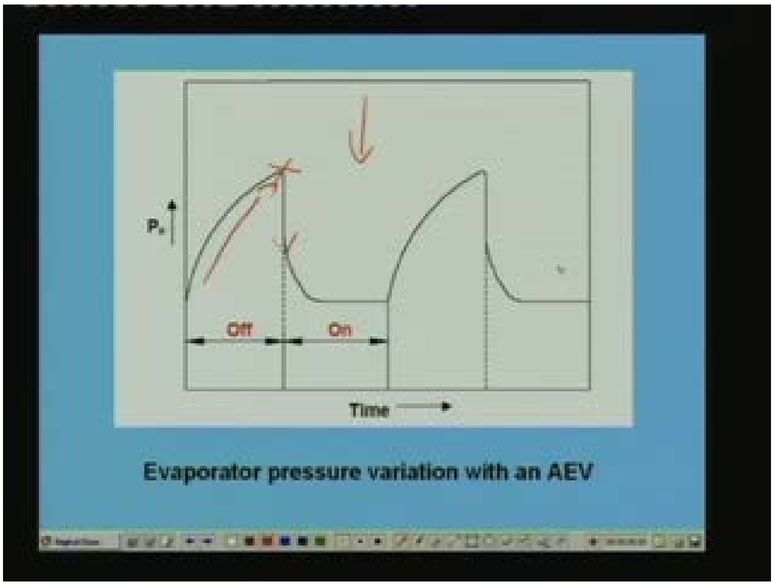

And this is how the pressure varies during off and on okay, during the off pressure increases like this right. In this manner and at this point the compressor is switched on once a compressors switched on evaporator pressure drops. Once the evaporator pressure drops the upward force increases. Now the valve opens the refrigerant is supplied so again the pressure drops like this okay. So this is how the pressure varies when you are using an automatic expansion valve.

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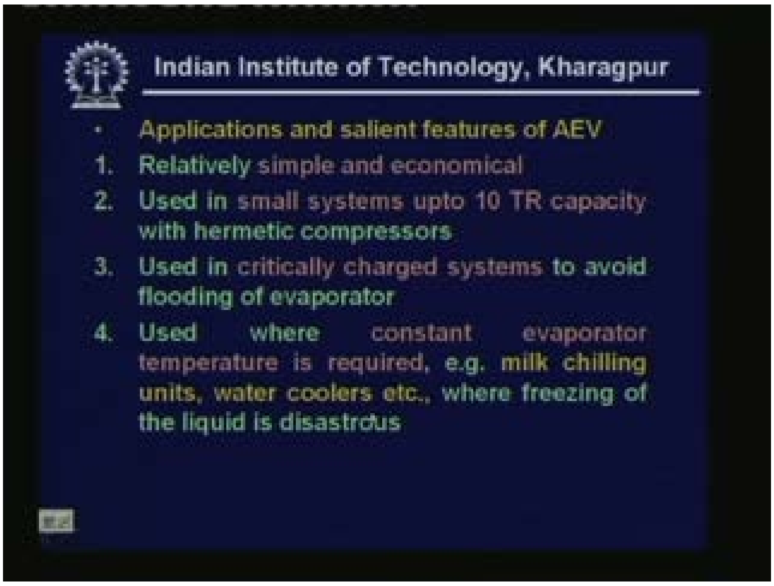

Now applications and salient feature of automatic expansion valves. These valves are relatively simple and economical compared to other types of valves. And they are used in small systems up to ten TR capacity with hermetic compression. They are used in critically charged systems to avoid flooding of evaporator. They are used where constant evaporator temperature is required okay. This is very important use of this particular type of valve because this always maintains the evaporator pressure constant. That means the evaporator temperature constant.

So it finds application in milk chilling plants and in water coolers etcetera. In milk chilling plants and water coolers etcetera. The most important requirement is that the temperature should not fall below the freezing point of the liquid okay. Once the temperature falls below the freezing point of the liquid for example in the water cooler the water may freeze in the pipes okay. Once the water freezes then the pipes will burst okay. So this should be avoided at any cost okay. That means you must make sure that the evaporator temperature is not going below certain point under any circumstances okay. Whatever may be the load the evaporator temperature not going down. The only valve which can ensure the, this is the automatic expansion valve. So the automatic expansion valve is normally used in water coolers and milk chilling plants etcetera. Of course as you know the, it has its own disadvantages like it can lead to flooding. And all it does not supply the refrigerant as per the requirement because when the load increases it supplies less and when the load reduces it supplies more.

So this is the disadvantage of this particular type of valve. But still in some circumstances where the load remains relatively constant and where we require constant evaporator temperature we use this kind of a valve okay. Now to conclude in this lecture.

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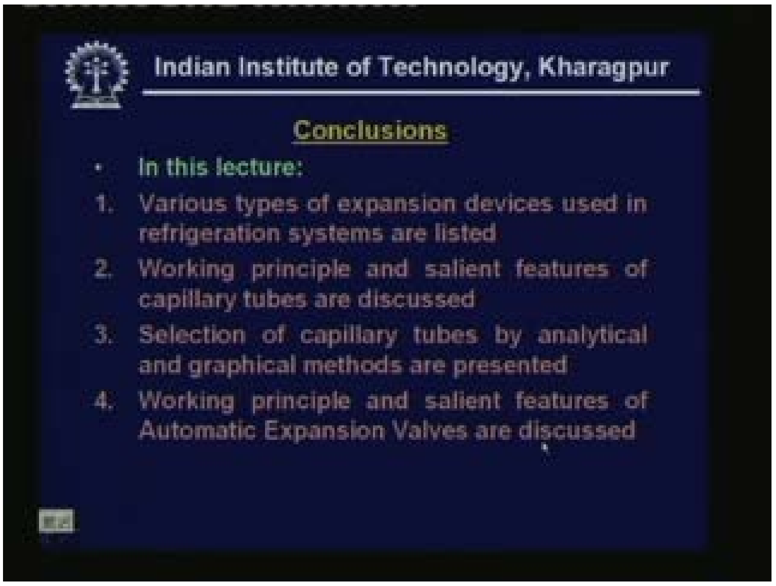

Various types of expansion devices used in refrigeration system are listed working principles. And the salient features of capillary tubes are discussed selection of capillary tubes by analytical and graphical methods are presented. And finally working principle and salient features of automatic expansion valves are discussed. So I shall discuss the other types of expansion devices in the next lecture.

Thank you.