Refrigeration and Air Conditioning
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Lecture No. # 12
Vapour Compression Refrigeration Systems
(Contd.)

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Welcome back in the last two lectures we discussed single stage vapour compression refrigeration systems. In this lecture I shall introduce multi stage vapour compression refrigeration systems. So the specific objectives of this particular lesson are to introduce discuss limitations of single stage cycles, introduce the concepts of flash gas removal and intercooling, discuss various multi stage multi compression systems with flash gas removal and intercoolers and present steady state analysis of a typical multi stage system.

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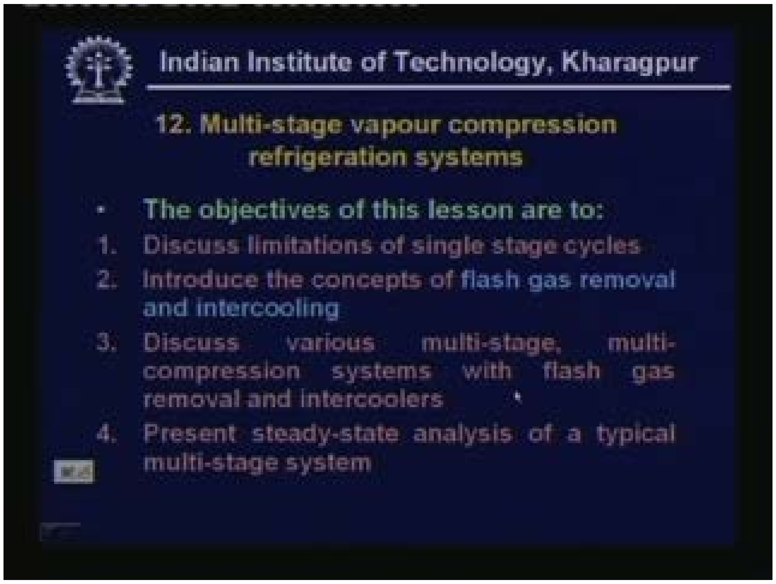

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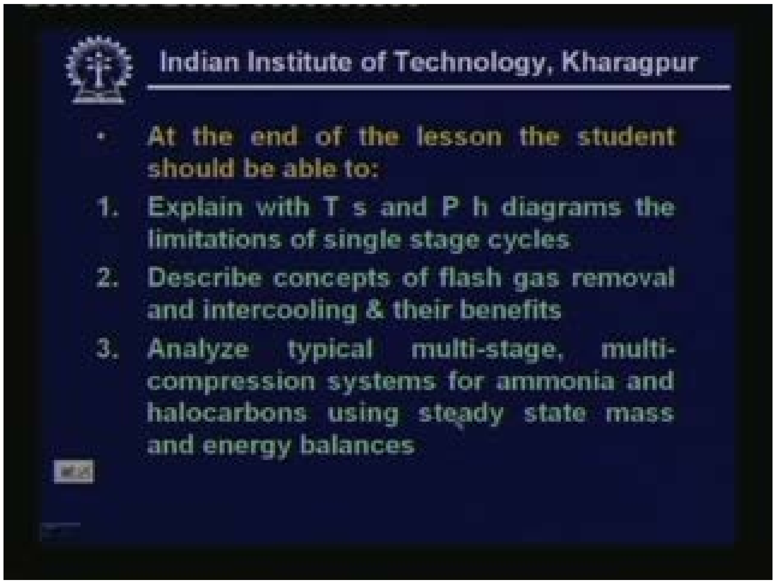

And at the end of this lesson you should be able to explain with T s and P h diagrams, the limitations of single stage cycles, describe concepts of flash gas removal and intercooling and their benefits and analyze typical multi stage multi compression systems for ammonia and halocarbons using steady state mass and energy balances.

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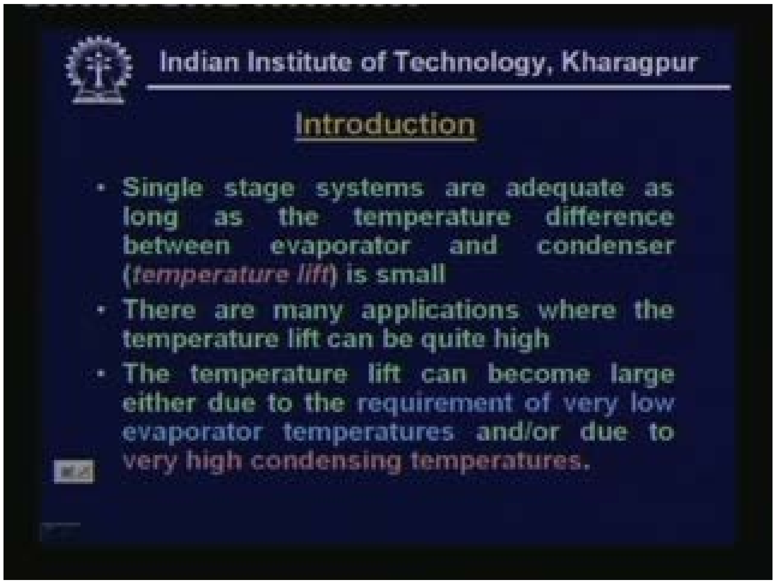

We have seen that single stage systems are adequate as long as the temperature difference between the evaporator and condenser is small. This difference is normally known as temperature lift. That means the temperature difference between the condenser and evaporator is known as temperature lift and as long as the temperature lift is small single stage systems are adequate. But there are many applications where the temperature lift can be quite high and the temperature lift can be large either due to the requirement of very low evaporator temperatures and or due to very high condensing temperatures. That means there are many applications where for a given condensing temperature you require very low evaporated temperatures this will increase the temperature lift. There are other applications where the evaporator temperature is not so low but the required condensing temperature is very high this also increases the temperature lift. So for these temperature lift applications single stage system we shall see now that they have many limitations okay.

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For example on the low temperature side let me give some examples where we can encounter very low evaporated temperatures. For example in frozen food industries the required temperatures can be as low as minus forty degree centigrade or lower. Typically you have to freeze food products and if you are talking about quick freezing also you require very low temperatures of the order of minus forty or minus fifty. Another very typical application where you require very low temperatures are in the chemical industries where really very low temperatures as low as minus one fifty degree centigrade or even lower are required for liquefaction of gases.

So these are the two typical applications where you encounter very low evaporator temperatures. And on the high side if you are using the refrigeration system as a heat pump for heating applications then the required condensing temperature can be very high. The typical applications of refrigeration system in the form of heat pump could be for example in process heating or in the drying. So these are two typical examples where the temperature lift is very high.

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And in fact in the last class we have seen that as a temperature lift increases single stage systems become inefficient. Let me repeat this with the help of T s and P h diagrams.

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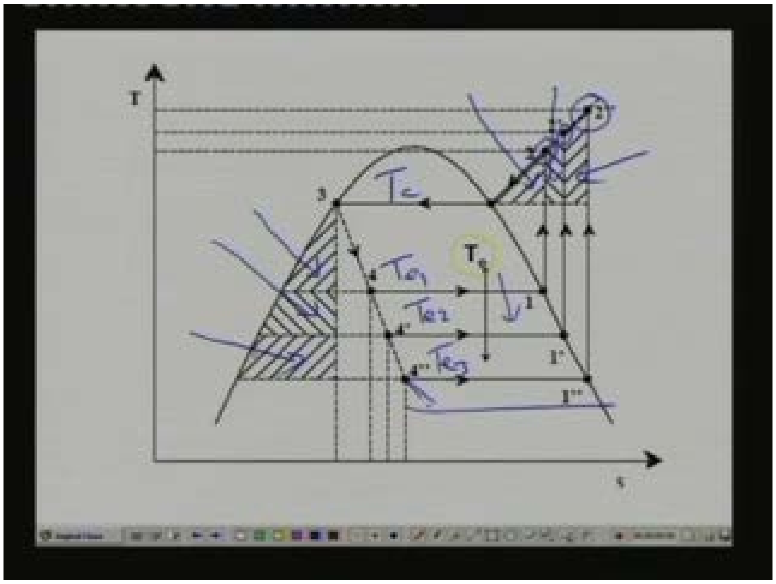

For example here on T s diagram we have shown the effect of evaporator temperature here condenser temperature is fixed. This is the condenser temperature which is fixed I am increasing, I am decreasing the evaporator temperature in this direction for example cycle one two three four is for let us say an evaporator temperature of T e one okay. For this particular evaporator temperature this is the throttling loss and this is your superheat horn or superheat loss and this is your compressor discharge temperature.

Now if this evaporator temperature is reduced to T e two then you can see that throttling losses have increased by this amount and superheat losses have increased by this amount and you can also see that the discharge temperature also increases. If you reduce the temperature further for example to T e three you will see that throttling losses increase some more and again there will be more losses in the superheat side also okay. Again you can see that there is a large increase in the decompressor discharged temperatures. So as you can see that if you reduce it further this isenthalp continues in this manner and continuously the throttling and superheat losses increase.

Let me show this in P h diagram also.

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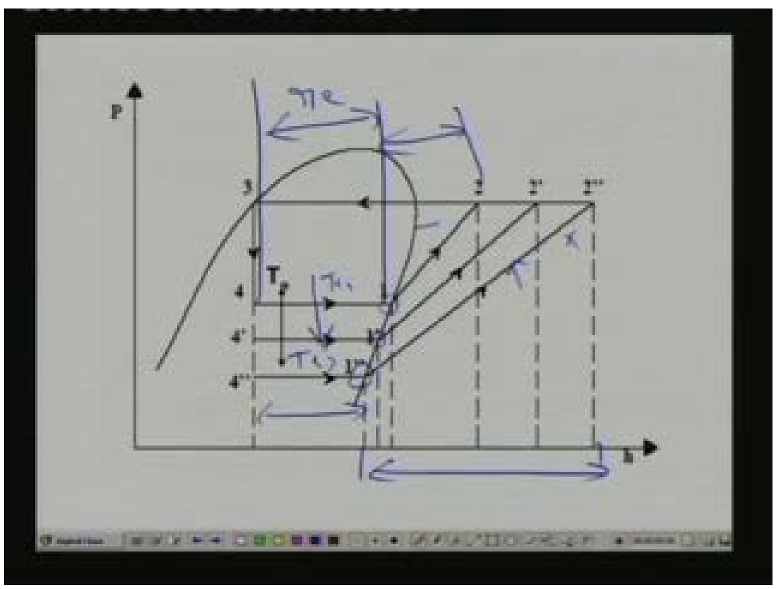

For example this is the P h diagram and the evaporator temperature is decreasing in this direction this is decreasing in this direction. And you can see that when the evaporator temperature is low, I mean when the evaporator temperature is T e one this is T e one this is your refrigeration effect okay. This is refrigeration effect and this is the work of compression okay. So when the evaporator temperature decreases let us say to T e three you can see that refrigeration effect reduces. And what is more important is your work of compression increases considerably okay. This happens because the isentropic lines they become gradually flatter as you move away from the vapour saturated vapour curve. We can see that this pressure line is much flatter compare to this one which is flatter compare to this.

So as it become flatter you can see the work of compression increases so you can see that as you are increase reducing the evaporator temperature refrigeration effect is reducing and work of compression is increasing. In addition to that you can also see that since the pressures are reducing and the specific volume at this point that increases gradually.

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So the conclusion is for a given condensing temperature as evaporator temperature decreases throttling and superheat losses increase compressor exit temperature increases amount of vapour at evaporator inlet increases. You might have noticed it from P h diagram and T s diagram that the amount of vapour or the quality of vapour at evaporator inlet temperature increases as your evaporator temperature is reduced and specific volume at compressor inlet increases. So these are the negative effects of operating the system at very low evaporator temperatures as a consequence of all these you find that the COP of the system reduces considerably and the refrigeration capacity also reduces and the life of compressor decreases rapidly. Why does the life of compressor decrease because your compressor discharge temperature increases so the lubrication becomes ineffective? That means the lubrication has evaporated very high temperature so this makes the lubrication ineffective so there will be more wear and tear as a result the compressor life reduces.

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So these are the bad effects of operating a compression system at very high temperature lift or at very low evaporator temperatures and performance also degrades as condenser temperature increases. That means if you are keeping the evaporator temperature constant and increasing the condenser temperature you will find that performance is again decreasing. So the summary is that the single stage systems are not recommended when evaporated temperature becomes very low and or condenser temperature becomes very high. In fact they become economically unviable when the temperature lift exceeds certain limits in such cases we have to use what is known as multi stage systems.

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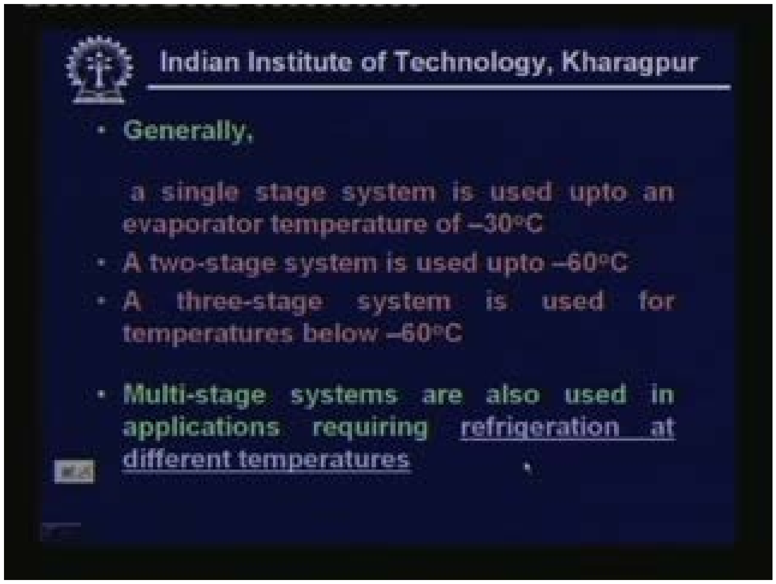

Generally a single stage system is used up to an evaporator temperature of minus thirty degree centigrade this is generally industrial practice. So as long as your evaporator temperature is above minus thirty single stage system is all right. And a two stage system is used between minus thirty to minus sixty degree centigrade and a three stage system is used when the temperature fall below minus sixty degree centigrade. And multi stage systems are also used in applications requiring refrigeration at different temperatures that means we use multi stage systems when the temperature lift is very high. And another application of multi stage system is when we require refrigeration at different temperatures. So let me give an example of it.

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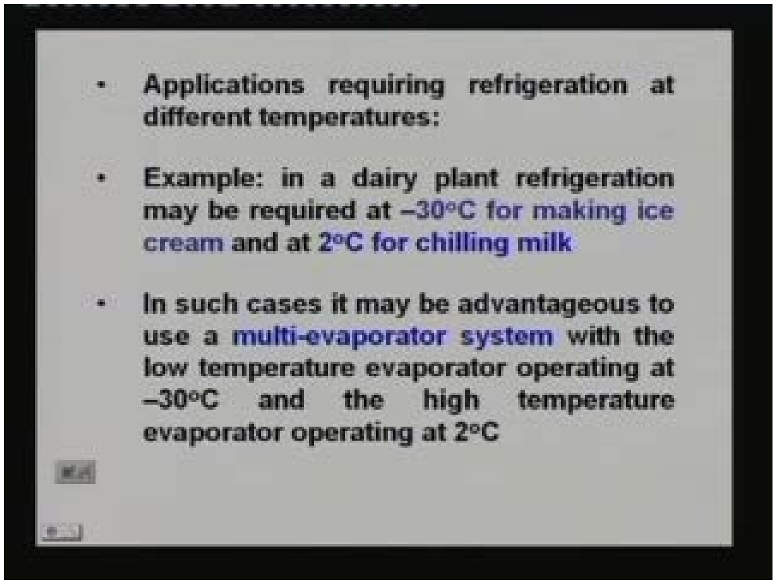

In applications requiring refrigeration at different temperature for example I give a typical application in diary plant refrigeration required minus thirty degree centigrade for making ice cream and two degree centigrade for chilling milk. That means you require refrigeration effect at minus thirty degree centigrade. So that you can produce ice cream and at the same time in the same diary plant you also require refrigeration at two degree centigrade for chilling of milk okay. So what are the options available there are several options. For example you can have two independent refrigeration systems where one refrigeration system will be catering to minus thirty degree centigrade evaporator temperature producing ice cream and the other refrigeration system will be cooling the milk at two degree centigrade this is one option.

And the other option is you can use a single refrigeration system where the evaporator is operated minus thirty degree centigrade even though you really do not required minus thirty degree centigrade for chilling the milk okay. And we shall see that this is very inefficient because you require cooling at two degree centigrade but still you operating evaporated minus thirty degree centigrade. This is inefficient from the performance point of view it can also create problems like frosting etcetera okay but this is a another option. The third option is to go for multi stage systems where you have multi evaporators that means one evaporator will be working at minus thirty degree centigrade and the other evaporator will be working at plus two degree centigrade. So this is known as a multi evaporators system.

This also comes under multi stage systems because you shall see that on the low pressure side you have two low pressures one is corresponding to minus thirty degrees and the other one corresponds to plus two degree centigrade okay. So this is a typical application of multi evaporator system of course another example is your domestic refrigerator. In domestic refrigerator also your freezer compartment has to be kept at minus eighteen minus twenty like that where as your refrigerator compartment has got to be kept at about zero to five degree centigrade okay. So normally in all the refrigerators we have a single evaporator since you require minus eighteen in freezer you have to operate the evaporator at about minus twenty-five or four so that the freezer temperature can be achieved.

So for a large part in the refrigerator even though your required temperature is five degree centigrade you are still using the same evaporator which is operating at minus thirty or minus twenty-five degree centigrade okay. This is actually thermodynamically inefficient and it leads to large irreversibility. But unfortunately in domestic refrigerator the use of multi evaporator system is generally not justified from economic point of view because you will see that a minor typical multi stage system if you will be adding more components so cost to be increasing okay. So multi evaporator system and multi stage system is economically justified when the system capacity is large and the benefits in power savings overcome the initial cost where as in typical domestic refrigeration system this may not be the case okay. But still thermodynamically that is another example where you can use a multi evaporator system okay. So as was saying instead of using single evaporator or two different systems we can use the multi evaporator system with low temperature evaporator operating at minus thirty degrees and the high temperature evaporator operating at two degree centigrade.

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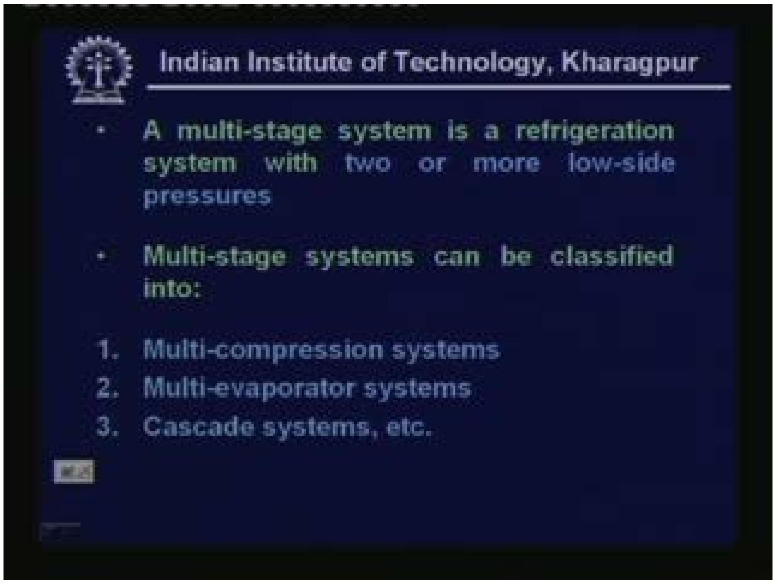

Okay. So how do we define a multi stage system a multi stage system is a refrigeration system with two or more low side pressures so in in generally it can be anything it can be a two stage three stage or more okay. It will have a single high pressure but there will be more than one low pressure. Multi stage systems can be classified into multi compression systems multi evaporator systems cascade systems etcetera.

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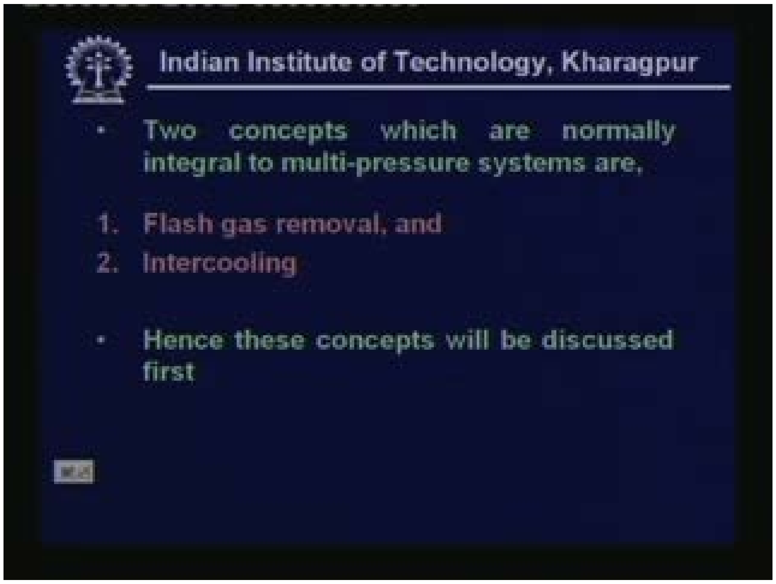

Two concepts which are normally integral to any multi pressure systems are what is known as flash gas removal and intercooling. So let us discuss these concepts first then let us move on to the systems.

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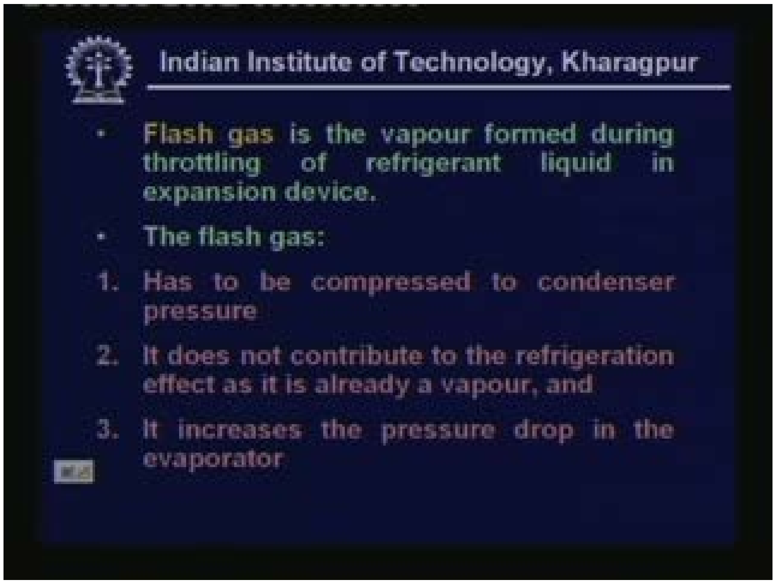

So first let us look at flash gas removal, what is flash gas flash gas is a vapour formed during throttling of refrigerant liquid in expansion device? While discussing methods of producing refrigeration we have seen that when you are expanding a saturated or a slightly subcooled liquid in such a way that some liquid flashes into vapour you can produce very temperatures. This is actually the working principle of vapour compression system where you attain very low temperatures by flashing some of the liquid into vapour okay. So flash gas generation is required to attain low temperatures and the job of the flash gas is done once the low temperatures are achieved okay so what is the problem afterwards? Afterwards the problem is the flash gas has got to be compressed back to the condenser pressure and it does not really contribute to the refrigeration effect as it is already a vapour that means it has already done its duty by reducing the temperature.

So it cannot contribute any more to the refrigeration effect so there is no point really in sending the flash gas through the evaporator because it cannot take any more heat okay. Because the refrigeration effect in the evaporator is due to the latent change okay. And since it is already a vapour form it cannot undergo any more change okay. And another disadvantage is that it increases the pressure drop in the evaporator okay these are the problems once the flash gas has reduce the temperature you see that it has to be compressed back and does not contribute refrigeration effect and it increases the pressure drop in the evaporator.

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So flash gas removal performance can improve considerably if the flash gas is removed as soon as it is formed and recompressed to condenser pressure. That means let us say that you have found a way by which you are continuously removing the flash gas as soon as it is found in the throttling device and you are compressing it back to the condenser pressure. That will give you the best performance okay. Because you are not allowing the flash gas to go to the evaporator as a result evaporator will be operating efficiently okay. But unfortunately this is not possible in practice the continuous removal of flash gas as soon as it is formed and recompressing it immediately is very difficult in practice and so far no practical means to achieve this could be found. So what is the practical way of at least reducing the damage so practical way is to remove the flash gas at an intermediate pressure is by using what is known as a flash tank. So let me explain what is the flash tank?

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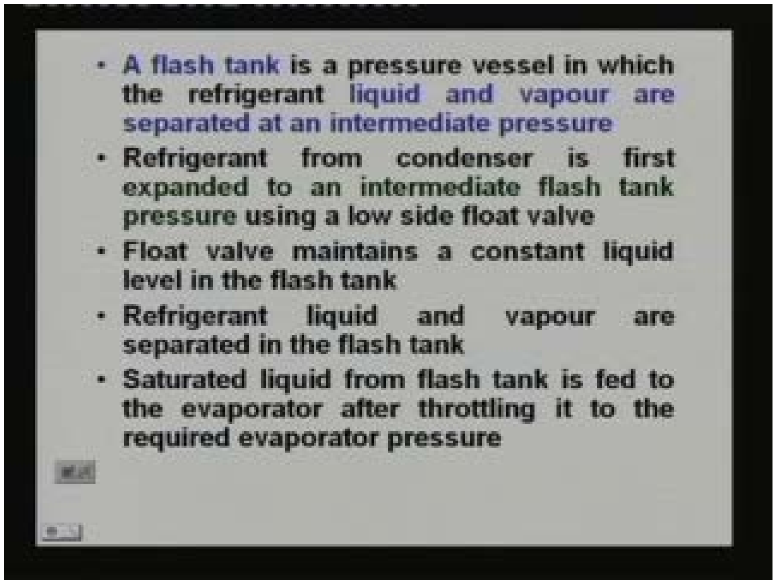

So a flash tank is a pressure vessel in which the refrigerant liquid and vapour are separated at an intermediate pressure. So it is a basically a pressure vessel where liquid and vapour are separated and this operates at a pressure intermediate between the evaporator and the condenser. Refrigerant from condenser is first expanded to an intermediate flash tank pressure using a low side float valve. That means use a float valve to reduce the pressure from the condenser pressure to an intermediate pressure corresponding to that of flash tank. This float valve maintains a constant liquid level in the flash tank refrigerant liquid and vapour are separated in the flash tank. And saturated liquid from flash tank is fed to the evaporator after throttling it to the required evaporator pressure. So this is the description of a flash tank let me show it schematic of a flash tank.

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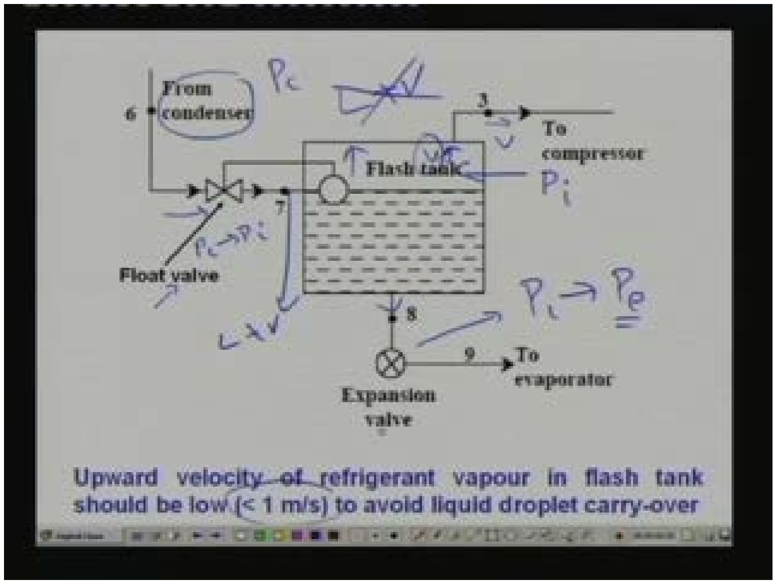

Okay. So this picture here shows the typical flash tank what we have here is high pressure refrigerant from the condenser first flow flows through a float valve okay. Float valve is an expansion device where the pressure drops from the condenser pressure P c to an intermediate pressure corresponding to the flash tank that is P i okay. So pressure drop from P c to P i takes place across the float valve okay P c to P i takes place across the float valve and the flash tank is maintained at a intermediate pressure P i. And in the flash tank what is done is you can see that only the refrigerant liquid is taken to the evaporator through the expansion valve okay. That means you separate the here what happens is the see at this point you have both liquid plus vapour okay.

Because of this is as the result of the flashing that has taken place in the float valve. So what we are doing here is we are sending the vapour to the compressor or to reduction valve and we are sending the liquid portion to the evaporator through an expansion valve. What is this expansion valve does this reduces the pressure from P i to P e P e is your required evaporator pressure okay. So this is the description of a typical flash tank normally you may have to insulate this if this temperature is lower than the surroundings okay. And typically this kind of a float valve is known as low side float valve because it maintains the liquid level on the low pressure side okay. One important requirement here is that the vapour going out of the flash tank should not carry any liquid. That means this has to be only pure vapour they it cannot be liquid plus vapour okay.

So to ensure that what you have to do is you have to maintain the upward velocity of the gas or upward velocity of the vapour less than certain value okay.

Typically it is seen that if the velocity of the vapour at this point is less than about one meter per second then the vapour cannot carry any liquid droplets. So what to have here is pure vapour okay so you have to design the flash tank in such a way that you get a low temperature here okay. Now let me show this process on P h diagram.

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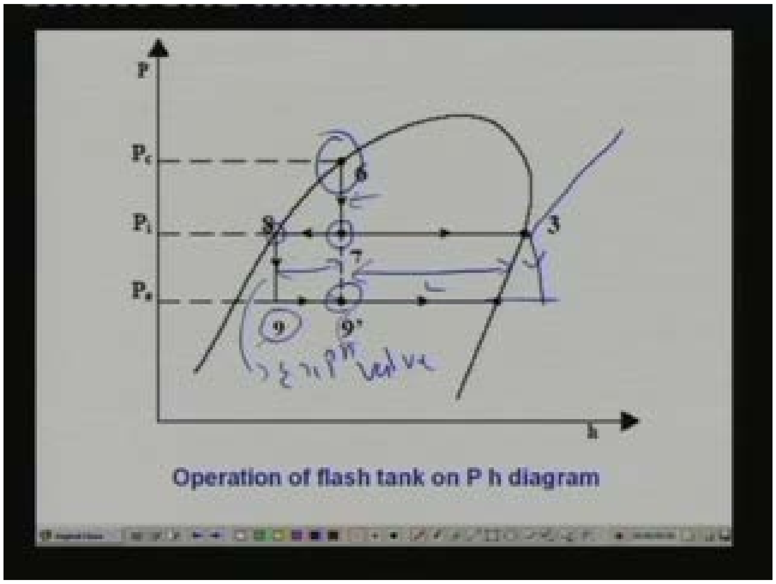

So this is the process on the P h diagram this is the inlet this is your inlet to the float valve it is entering at point six in the float valve and in the float valve the pressure has reduced from P c to P i okay. So this is operation in the float valve and at the this is the point at which the refrigerant enters into the flash tank so you can see that at this point it consists of this much fraction of vapour and this much fraction of liquid. So what you are doing is you are taking the liquid fraction which exits at this point to the evaporator through another expansion valve this is the expansion valve okay, between the flash tank and the evaporator okay. So the saturated liquid goes to the evaporator and the vapour that has formed at this point goes to either compressor depending upon the system or it may be reduced in pressure and again mixed with the low pressure evaporator gas okay. So one thing you can see it that if you do not have this flash tank and all the quality at the entry to the evaporator would have been nine dashes okay. By using the flash tank you could reduce the quality considerably. So you can see that at the inlet to the evaporator point nine has more liquid than vapour compare to point nine dash okay so this is the briefly the working principle of a flash time.

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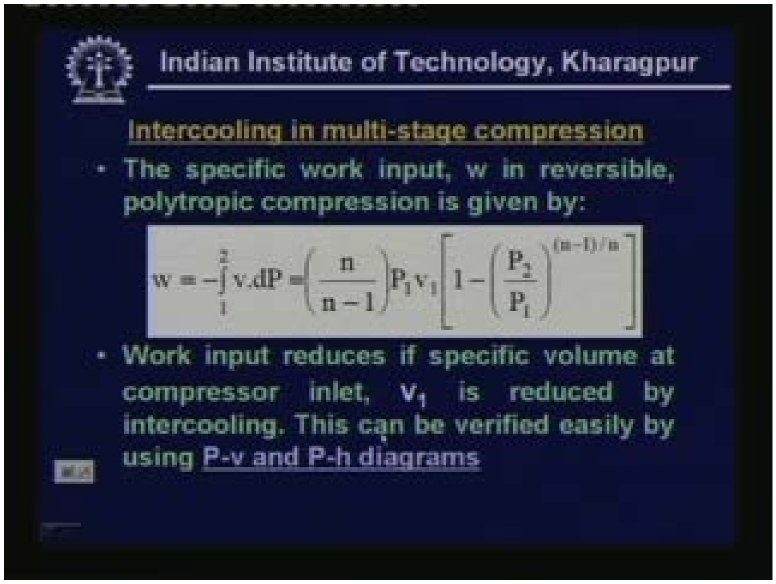

Now let us look at intercooling the other concept of intercooling the specific work output input to a compressor in a reversible polytropic compression is given by this expression okay. This expression basically is obtained by integrating this and all polytropic process if you remember follow this equation P V to the power of n is constant okay. So if you substitute that and integrate it you get you get this expression okay. So this is the work input to compressor in a polytropic reversible polytropic compression. So you can see from this expression that the work input can be reduced if you reduce the specific volume V one okay.

And normally you may not any control on the pressures because these are typically for example the high pressure may be decided by the condenser temperature and the low pressure is decided by your evaporator temperature over which you may not have much control okay. And n is typical process parameter and also it also depend upon the refrigerant. So you do not have much control on these parameters but one parameter where you can you have some thought of a control is the specific volume at the inlet to the compressor that is V one okay. So work input can be reduced if you are reducing V one how can you reduce this V one by reducing the temperature at this point that means by cooling the vapour in between the compressions okay. So that is the principle of intercooling. This is very clear if you look at P v and P h diagrams so let me show the P v and P h diagrams okay.

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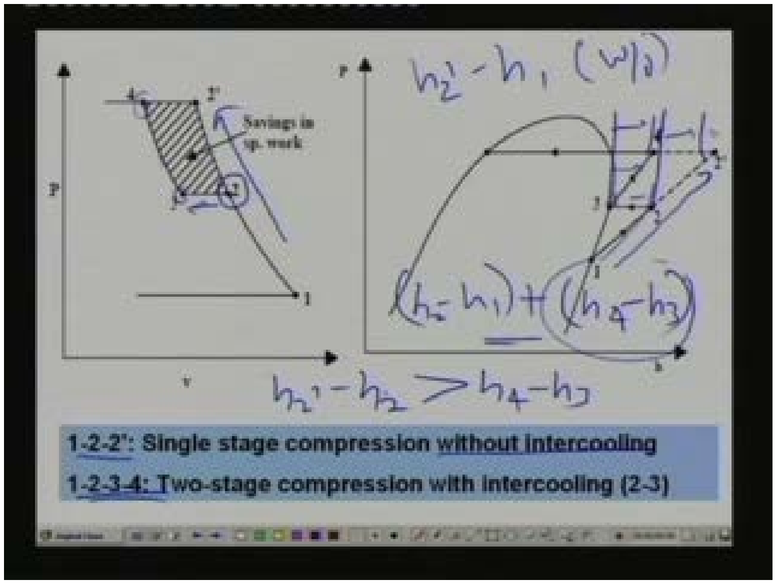

Okay. So in the on the P v and P h diagrams process one to two dash one to two dash is a single stage compression without intercooling okay. If you are not using any intercooling this would have been the process okay, one to two dash okay. And the work done you we will see is the area under this P v curve if the process is reversible okay. So integral V D P that means the area under this P v curve will give you the specific work input to the compressor okay. And the same thing you can see on P h diagram if you are not using any intercooling one to two dashes is the compression process and specific work input is h two dash minus h one this is without any intercooling okay. Now if we are using intercooling that means what you are doing is you are stopping compression midway at point some pressure two and you are cooling the refrigerant vapour okay refrigerant vapour or a gas.

So the temperature reduces so specific volume reduces again at this point you are compressing back to the required pressure so the process becomes one two three four with intercooling okay. The same thing is shown on a P h diagram one two is the compression the low stage compressor two to three is the process of intercooling and three to four is compression in the high stage compression okay. So as you can see from this there is considerable savings in specific work that can again be shown on this one for example with intercooling what is the specific work input with intercooling specific work input is h two minus h one.

This is the work input in the low stage compressor plus h four minus h three okay. This is the work input with intercooling you will see that h four minus h three will be much less than h two dash minus h two that means h two dash minus h two will be greater than h four minus h three. This is because as I have already mentioned the isentropic lines on P h diagram become flatter as you move away from the saturated vapour dome as a result this enthalpy difference will be much less than this enthalpy difference okay. Ultimately this will give rise to savings in specific work input so this is the principle of intercooling in between compression stages.

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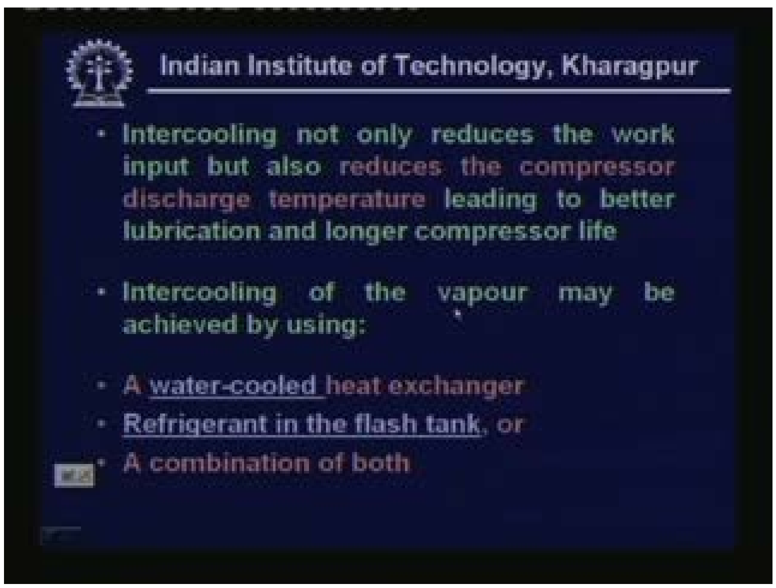

Now the benefit of intercooling it not only reduces the work input but it also reduces the compressor discharge temperature. This is the important in practical systems because as I have already mentioned if once you reduced compressor discharge temperature the lubrication will be better. And this will ultimately lead to longer compressor life and intercooling can be achieved by two way by two three ways. The first one is by using what is known as water cool heat exchanger the second method is by using refrigerant in the flash tank or you can also use a combination of both. That means the combination of water cool heat exchanger as well as refrigerant in the flash tank so let me show what is the typical water cooled heat exchanger based intercooling.

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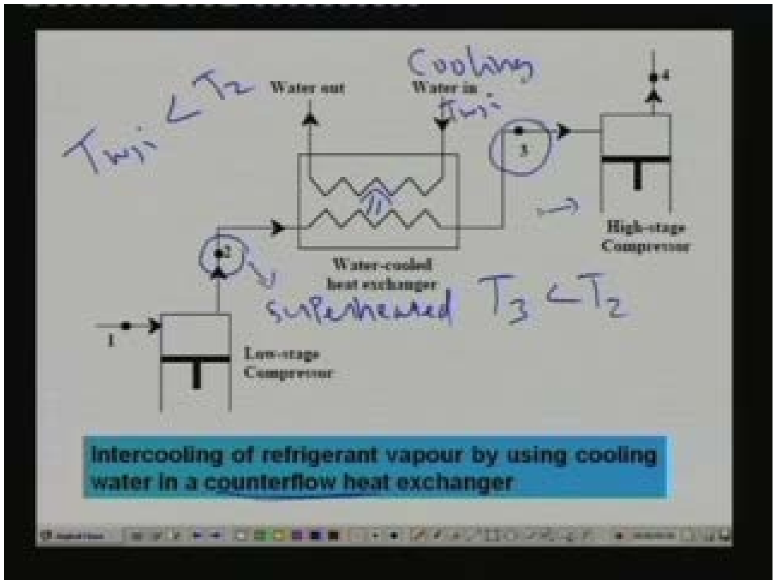

Okay. So what we are doing here is we are compressing as i have already shown the refrigerant to an intermediate pressure P two so at this point the refrigerant exists as a superheated vapour okay. This is superheated. So suppose you have cooling water which sufficiently low temperature let us say that this temperature is much lower than this temperature okay. That means T water inlet is lower than T two then you can cool this refrigerant vapour by exchanging heat between the refrigerant vapour and the cooling water in a heat exchanger what I have shown here is a counter flow heat exchanger. So you can use a heat exchanger where the cooling water comes in thermal contact with the refrigerant vapour and because of the temperature difference refrigerant vapour rejects heat to the cooling water. In this process it gets cooled that means T three will be lower than T two depending upon this temperature T three could be a saturated vapour or it could be again superheated but with less superheat okay. So in this process ultimately what we are doing is we are reducing the temperature of the refrigerant vapour and the low temperature intermediate pressure refrigerant vapour is sent to the high stage compressor for further compression okay.

So this is the principle of intercooling using a water cool heat exchanger let me show the
Principle of intercooling using a flash tank.

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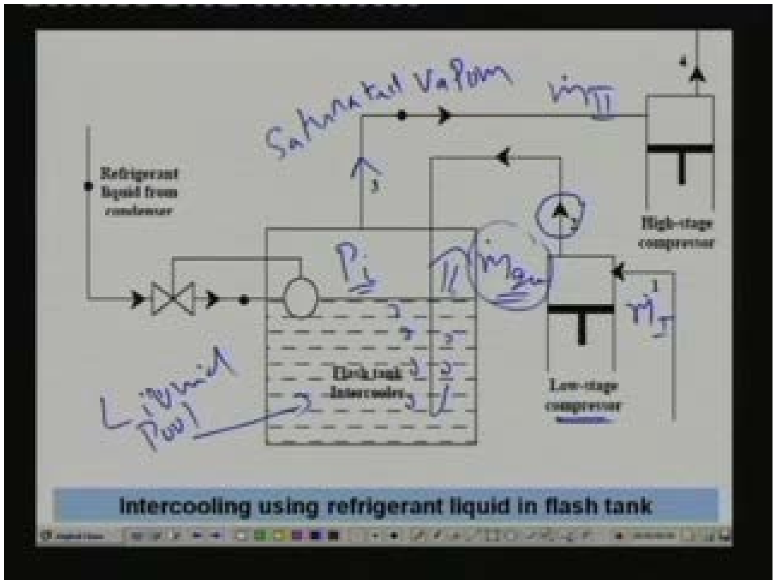

Okay. So this is again we use a flash tank here so what is done here is this superheated vapour from the low stage compressor is bubble through this okay. So it will be bubbling the vapour will be bubble through the liquid in the liquid pool in the flash tank okay. As a result since this temperature will be lower than this temperature the refrigerant vapour gets de-superheated in this process okay. Because the vapour bubbles come in contact with the liquid and their temperature reduces. And in an ideal case what you have here is a saturated vapour okay. if you have a perfect contact between the vapour and the liquid then this temperature will be corresponding to the saturation temperature at this pressure okay.

So but one thing you must see here is what is happening to the heat this is rejecting heat to the liquid here so some extra vapour will be generated okay. So this is a negative this thing of intercooling using a flash tank since you are rejecting the heat not to an outside fluid but to the refrigerant itself you end up with a little more refrigerant vapour. That means the refrigerant vapour handled by the high stage compressor will be greater than the refrigerant vapour handled by the low stage compressor because of the vapour generation due to de-superheating okay. So this is the principle of intercooling using refrigerant liquid in a flash tank.

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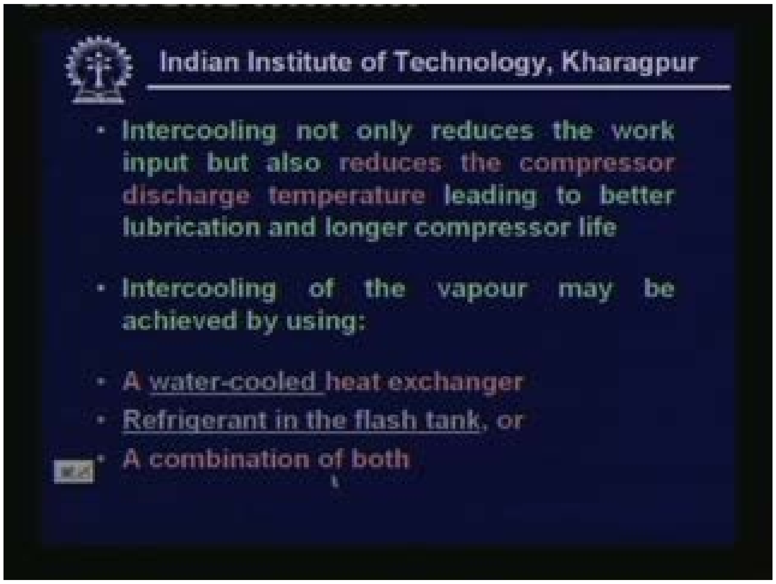

Of course you can also use a combination of both.

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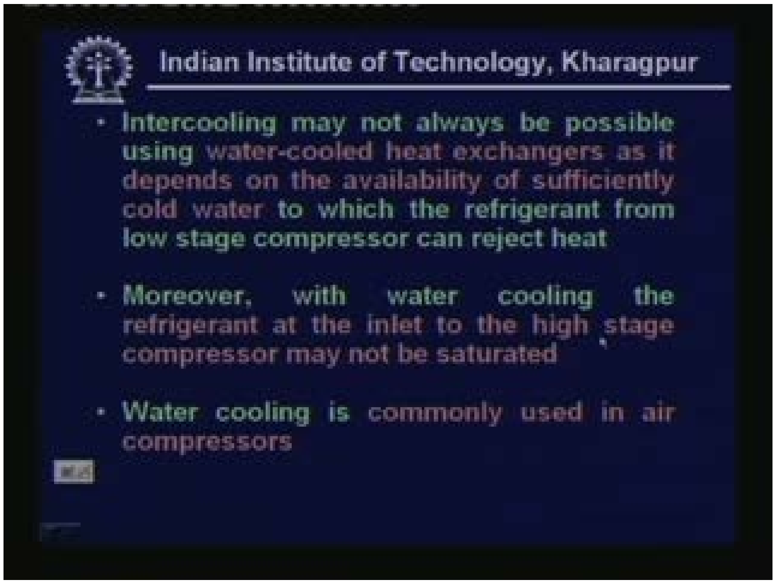

And intercooling may not be possible always using water cooled heat exchangers as it depends upon the availability of sufficiently cold water to which the refrigerant from low stage compressor can reject heat. So ultimately whether water cooling is possible or not depends upon what you have in hand okay. You have to have sufficiently cold water okay. As I have already discussed the refrigerant vapour should be able to reject heat to it okay. This again depends upon what is the discharge temperature of the refrigerant vapour after the low stage compression okay, which in turn depends upon the nature of the refrigerant okay.

And another problem is as I have already mentioned with water cooling the refrigerant at the inlet to the high stage compressor may not be saturated. And water cooling is generally used in air compressors it is normally you might have seen air compressors with water cooled jackets it is possible in air compressors because the discharge temperature in a typical air compressor is much larger due to higher C P by C V ratio okay.

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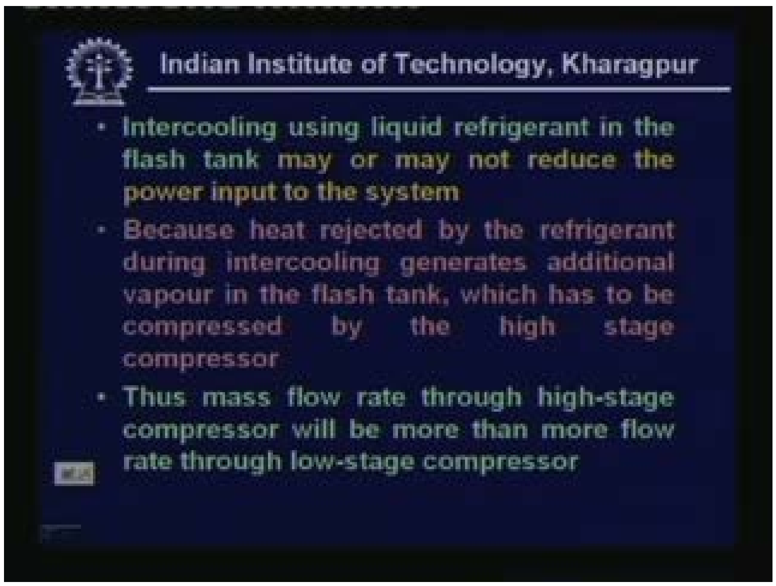

And intercooling using liquid refrigerant in the flash tank may or may not reduce the power input to the system okay. We will see why it may or may not reduce the power input. This is because as I have already mentioned heat rejected by the refrigerant during intercooling generates additional vapour in the flash tank which has to be compressed by the high stage compressor. Since the high stage compressor has to handle more amount of refrigerant vapour obviously the total power input to it increases even though the specific work input reduces okay. So you have to see whether the additional whether the benefit of reducing the specific work of compression compensates the increase in the mass flow rate okay. Depending upon the balance of these two you whether the total power input increases or not depends okay. This is the same thing thus the mass flow rate through high stage compressor will be more than the mass flow rate through the low stage compressor.

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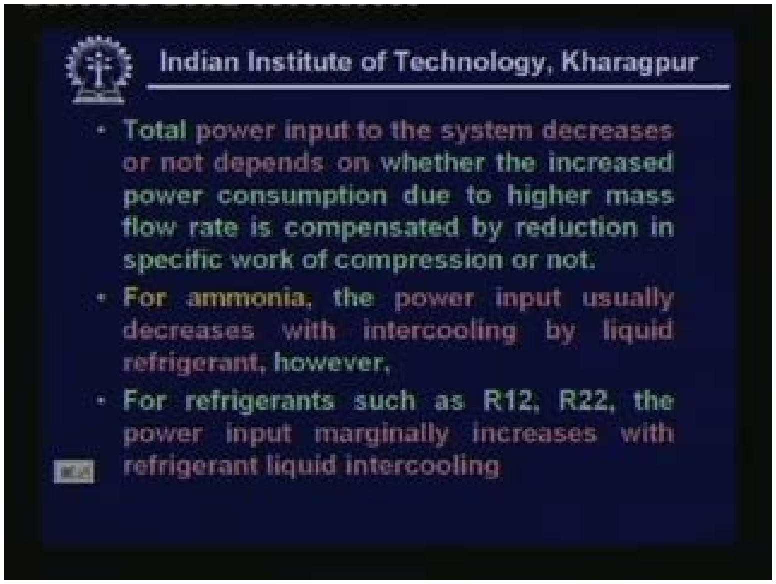

And total power input to the system as I have already mentioned decreases or not depends on whether the increased power consumption due to higher mass flow rate is compensated by reduction in specific work of compression or not. And it is observed that in ammonia system the power input usually decreases with intercooling by liquid refrigerant that means liquid intercooling using liquid refrigerant in the flash tank may be beneficial in ammonia systems okay. This is because of two reasons first reason is for the same pressure ratio the discharge temperature with ammonia is quite high compare to halocarbon refrigerants okay so you have high discharge temperature.

So there will be a large amount of de-superheating at the same time ammonia has large latent heat of vaporization okay. So the amount of vapour generated will be less compare to halocarbon refrigerants okay so you will find that the benefit of intercooling is more than the disadvantage of generating more refrigerant vapour okay. But it is observed that in refrigerant halocarbon based refrigerants such as R twelve and R twenty-two the power input marginally increases with refrigerant liquid intercooling. So intercooling using refrigerant liquid may not be very effective in the halocarbon base systems.

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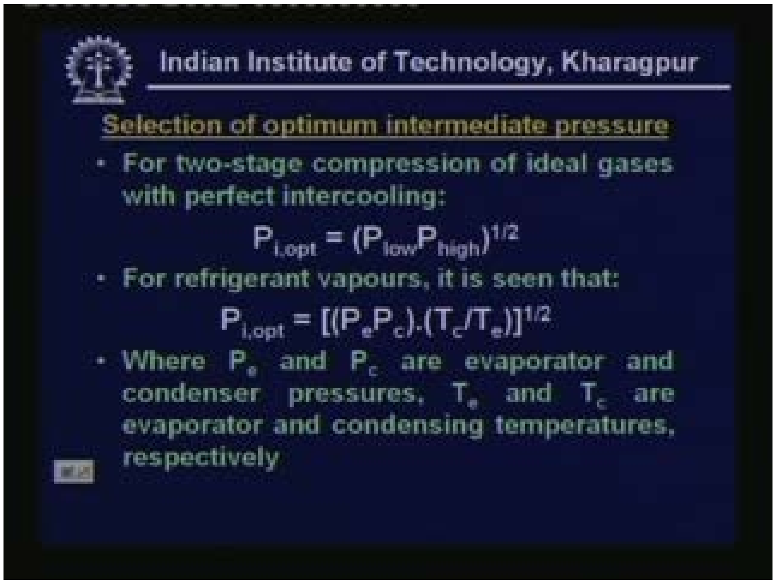

And the one problem common to any multi stage compression system or multi stage system is the selection of suitable intermediate pressure. Normally as I have already mentioned the evaporator pressure and condenser pressure are fixed by condenser and evaporator temperatures.

But designer has to decide what should be the intermediate pressure okay because that does not depend upon the application or the available of heat sink. So normally you have to optimize this intermediate pressure. So the total power input to the system is reduced and it is observed that if you are talking about multi stage compression using an ideal gas with a perfect intercooling okay.

Then the intermediate pressure is the geometric mean of the low and high pressures. That means the intermediate pressure with perfect intercooling is simply equal to square root of the product of low pressure and high pressure okay P i optimum is P low into P high to the power of half okay. But it is observed that with real gases especially with refrigerant vapors and all you have to have a small correction factor. So normally people used this expression where the P i optimum is given by P e into P c into T c by T e to the power of half where P e and P c are evaporator and condenser pressures T e and T c are evaporator and condensing temperatures respectively okay.

So the you have to add a small correction factor T c and T e are have to got to be in absolute temperature scale.

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Now let us look at some systems it is possible to device large combination of multi stage system so i shall discuss very few system okay typical multi stage systems. First system is that, I am going to discuss is with flash gas removal and intercooling. First let me describe the system the system uses a combination of water cooling and flash intercooling the superheated vapour from the water cool heat exchanger bubbles through the refrigerant liquid in the flash tank. It is assumed that the vapour at the exit of flash tank is saturated okay so now let me describe the system.

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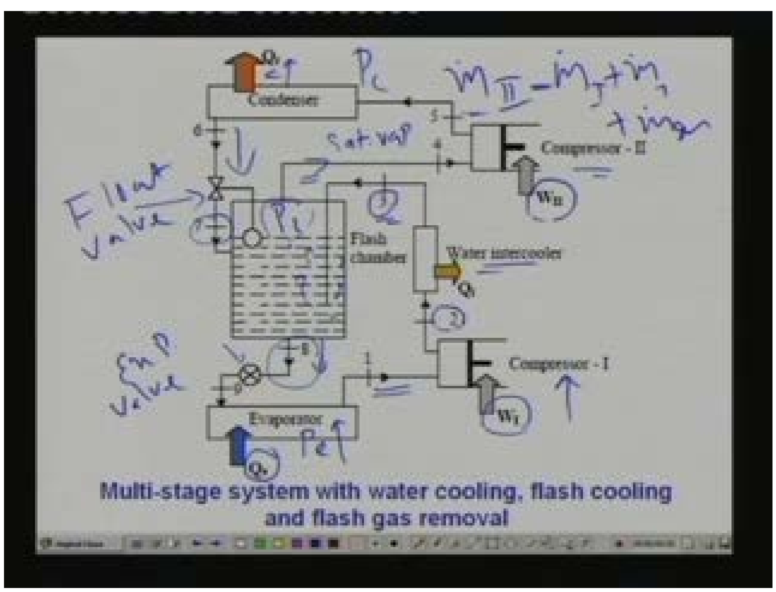

It is a complete system okay. So you have all the components let me begin at this point high pressure refrigerant liquid from the condenser first flows through a float valve where its pressure is reduced to an intermediate value P i corresponding to the flash tank pressure okay. And in the flash tank liquid and vapour are separated liquid goes to the expansion valve here and where it is pressure is further reduced to the required evaporator pressure P e okay. So if you have to notice here that what is going to the expansion valve is saturated liquid okay and its pressure is reduced in the expansion valve to the evaporator pressure. In the evaporator the refrigerant takes heat load Q E and it becomes a vapour and this low temperature low pressure vapour is compressed to the intermediate pressure using the low stage compressor one.

So you have to supply work of input W I to the first compressor. Then this superheated vapour at the intermediate pressure is first cooled in the water inter cooler from temperature T two to temperature T three okay. So some amount of intercooling takes place in the water intercooler then further intercooling takes place in the flash chamber as I have already mentioned this is also superheated so this superheated vapour um bubbles through this flash tank okay. And where its temperature is reduced further and you are assuming that there is a perfect intercooling. Here what you have here is a saturated vapour corresponding to this pressure okay. So what is the vapour here? Here the mass flow rate consists of three parts first part is what is the vapour generated in this stage okay. That means the fraction at this point then the mass flow rate of low stage this is the compressor plus what is the mass generated here okay.

So if you are writing this as m two that is the mass flow rate of compressor two this consists of mass flow rate of low stage compressor plus mass of vapour at point seven plus mass of vapour generated okay so this is higher than this. So this is compressed in the second stage compressor from the intermediate pressure to condenser pressure P c and you have to supply work of compression W two to the second stage compressor. Then this entire mass is condense in the condenser and heat is rejected Q C and the cycle continues okay so now let me show this on P h diagram.

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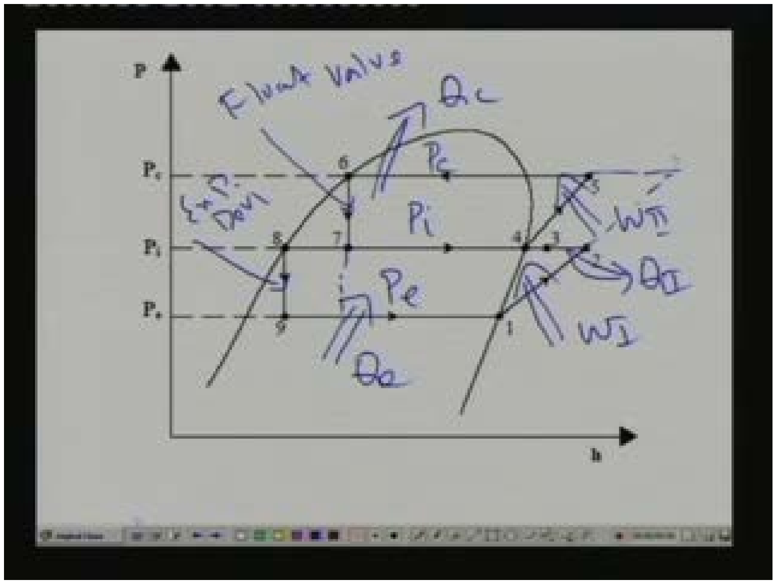

Okay this is the process on P h diagram what you have here is the condenser pressure intermediate pressure and evaporator pressure okay. So this is where you are taking in heat Q e and this is where is you are rejecting heat Q c okay. And this is the work input to the low stage compressor this is the work input to the high stage compressor and some amount of heat is rejected in the intercooler here. And this is your expansion in float valve and this is the expansion in the expansion device and as I said if you are not doing these things your cycle if you are with single stage cycle it will be something like this okay. So single stage cycle will be something like this now let us look at typical performance of this how do you analyze the performance of this.

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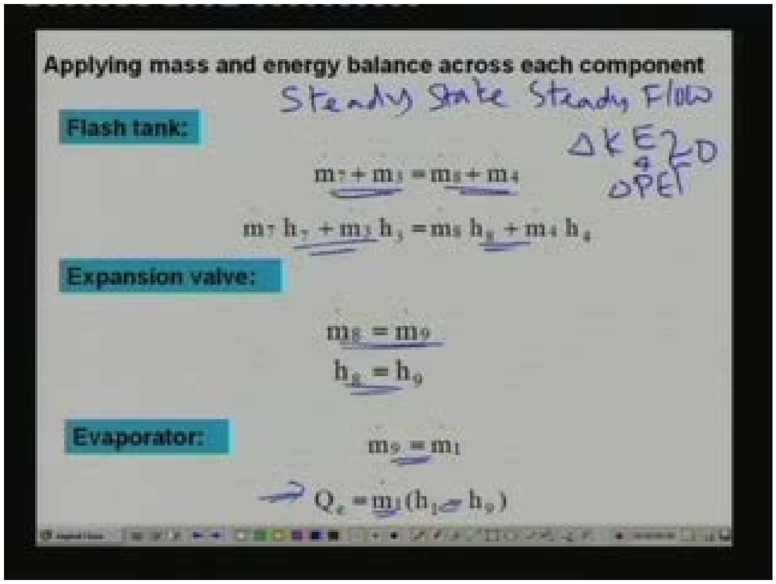

So what we do here is we apply mass and energy balance across each component and we assume steady state okay. That means basically we apply steady states steady flow energy equation steady state steady flow energy equation okay. And we also assume that delta K E and delta P E are they are negligible okay. Under these assumptions we are carrying out this simple analysis.

First let us take the flash tank if you take a control volume across the flash tank this is the mass balance mass coming in is mass going out okay. And this is the energy balance energy coming in is energy going out okay.

Then look at the expansion valve okay this is the expansion valve between the flash tank and the evaporator mass balance is whatever mass is entering is simply leaving and since this is an isenthalpic process enthalpy remains constant okay. This is the throttling device then comes the evaporator again mass balance whatever mass is coming has to go out and this is the energy balance this is the refrigeration effect. I am sorry, this is the refrigeration capacity which is equal to mass flow rate of the refrigerant into the refrigerant effect okay now so this is these are the equations for flash tank expansion valve and evaporator similar equations.

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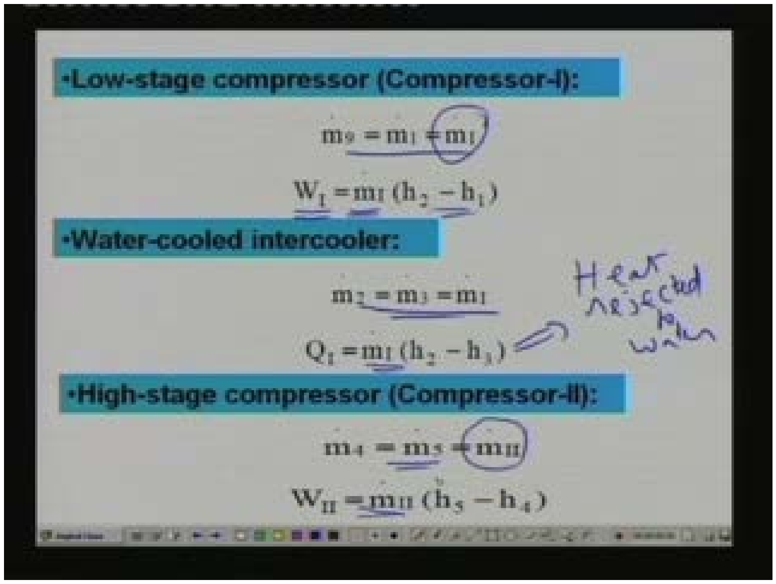

You can find out for low stage compressor okay. This is the mass balance this is the work input to the low stage compressor which is nothing but mass flow rate through the low stage compressor m dot i into the work of compression okay. Now if you are applying this to the energy and mass balance water cooled intercooler this is a simple mass balance this is the energy balance this is the heat rejected to the water okay, heat rejected to water in the intercooler okay. Now we apply this to high stage compressor in the high stage compressor this is the mass balance this is mass flow through the high stage compressor, you can, as I have already explain this will be much larger than this. And this is the power input to the high stage compressor product of mass flow rate into specific work of compression for the for this compressor.

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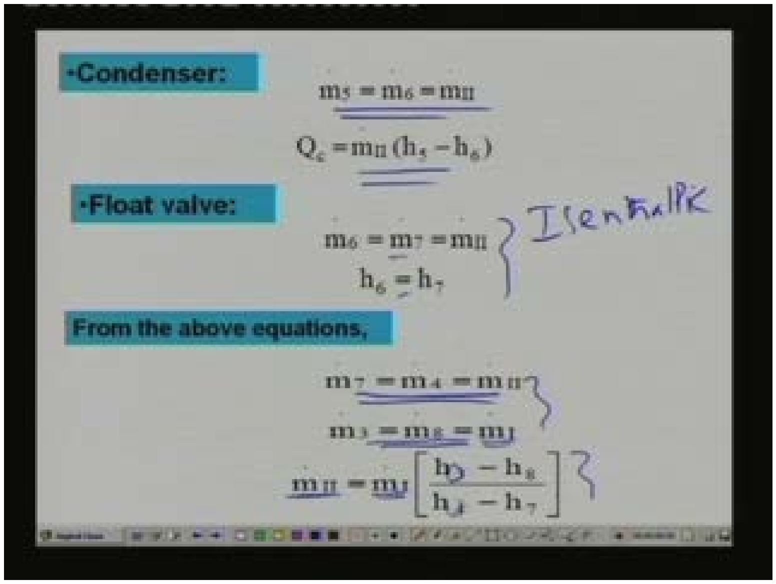

And further condenser again same simple equations mass balance energy balance then float valve this is again an isenthalpic process okay. So it is the mass balance and enthalpy remains constant. From the above equations if you are clubbing these equations it is very easy that you can easily show that m dot seven is equal to m dot four equal to m dot two this is nothing but the mass flow rate through the second stage compressor okay. Similarly this is m dot three is what is going to the evaporator is what is compress in the low stage compressor okay. So this you can easily see by looking at these equations and you can also easily show that the mass flow rate through the second stage compressor is equal to mass flow rate through the low stage compressor into the product of the ratio this enthalpies. One thing you can notice here is this ratio reduces that means m difference between m dot two and m dot one will be less as h three approaches h four.

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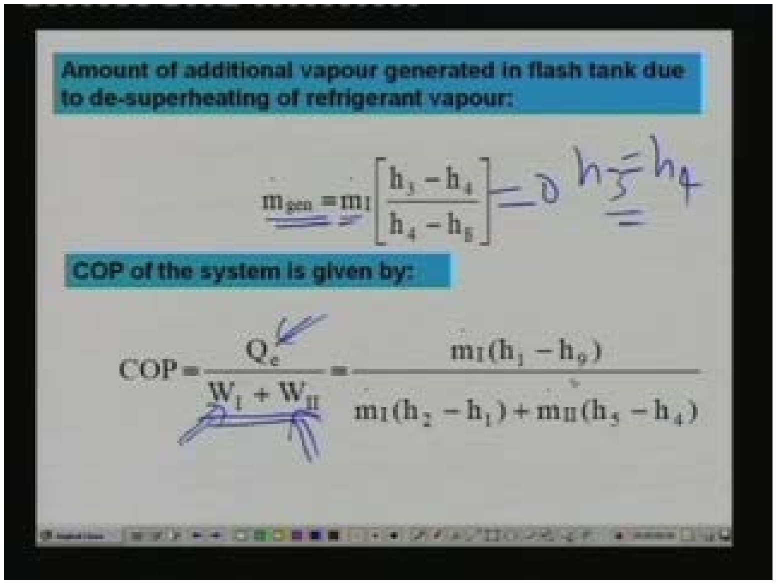

And this is the mass of vapour generated because of the de-superheating in the flash tank okay. So again this is expressed in terms of the mass flow rate through the evaporator and enthalpies.
Again you can see that this becomes zero when h three is equal to h four that means in the water cooler. If you can cool the refrigerant vapour in the water cooler to such a state that it enters into the flash tank as a saturated vapour and then there will not be any further vapour generation okay. But this may not be possible as I have already explained and finally the COP of the system is written as the cool refrigeration capacity divided by work input now the work input consist of work input to the first stage compressor plus work input to the second stage compressor. And this is written in terms of various mass flow rates and enthalpy differences. So this is the typical this is the way how typical thermodynamic analysis of a multi stage system can be carried out okay.
So what is required in the analysis of these problems is that first you have to look at the systems schematic carefully and you have to translate the various processes onto a P h diagram. Because typically P h is very useful if you can correctly plot the P h diagram of the system. Then all that you have to do is take each component and apply mass balance and energy balance across the component okay. Then you have a set of equations and you will have a set of unknowns and from the set of equations and from the set of unknowns you can find out what whatever is required okay.

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So as I have already mentioned steady state performance is obtained by applying mass and energy balance across each component.

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Now what are the advantages of this system this system obviously repeatedly I have explained first advantage is that quality of refrigerant at evaporator inlet reduces leading to lower pressure drop and better heat transfer in the evaporator this is an obvious advantage a very desirable advantage. Second advantage is you have already seen that throttling losses are reduced as vapour generated is separated in the flash tank and recompressed by compressor okay. You are not allowing that vapour to go to the right down to the evaporator pressure and then compressing it. You are compressing it from the intermediate pressure okay. So there by you are save saving some power and there will be high compressive volumetric efficiency because each individual compressor is operating at a reduced pressure ratio okay. So this will reduce the size of each individual compressor and considerably reduced compressor discharge temperature. So this is another benefit.

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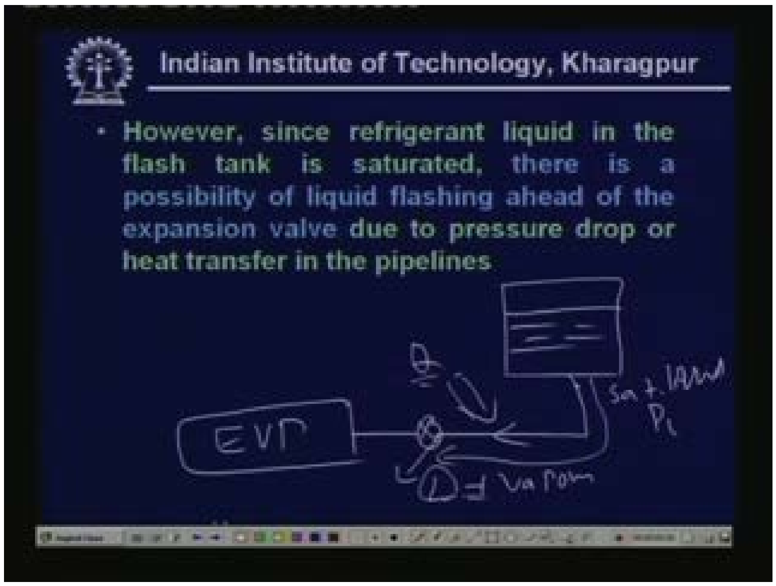

However this particular system has one small problem this problem is that since the refrigerant liquid in the flash tank is saturated there is a possibility of liquid flashing ahead of expansion valve due to pressure drop or heat transfer in the pipelines. Let me explain this one you have the flash tank here okay. So what you are doing is you are taking the saturated liquid and then you are sending it to the evaporator okay. So at the entry here this point you have saturated liquid corresponding to the intermediate pressure P i so if you have a long pipeline let us say that this pipeline is very long and in addition to that you have some heat transfer to the pipeline. Then what happens is at this point you will have liquid plus some vapour okay. That means some flashing takes place not in the throttling device but in the pipeline itself because of the pressure drops and because of the heat transfer okay. That means this throttling device has to handle both liquid and vapour typically throttling devices are designed to handle only liquid. So if you have any vapour at the inlet they malfunction okay. So this is a disadvantage of this system right.

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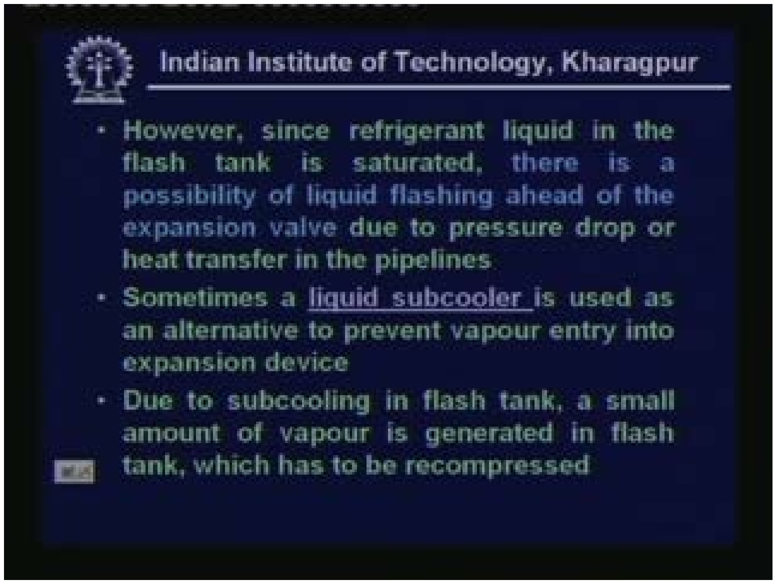

So what is done typically is sometimes if you have long pipe lines or if you have some heat transfer and if you expect there will be some flashing if you are using this flash tank then you can use what is known as a liquid sub cooler okay. So this is an alternative way to prevent vapour entry into expansion device. So let me explain liquid sub cooler okay let me explain this Remiroy schematic.

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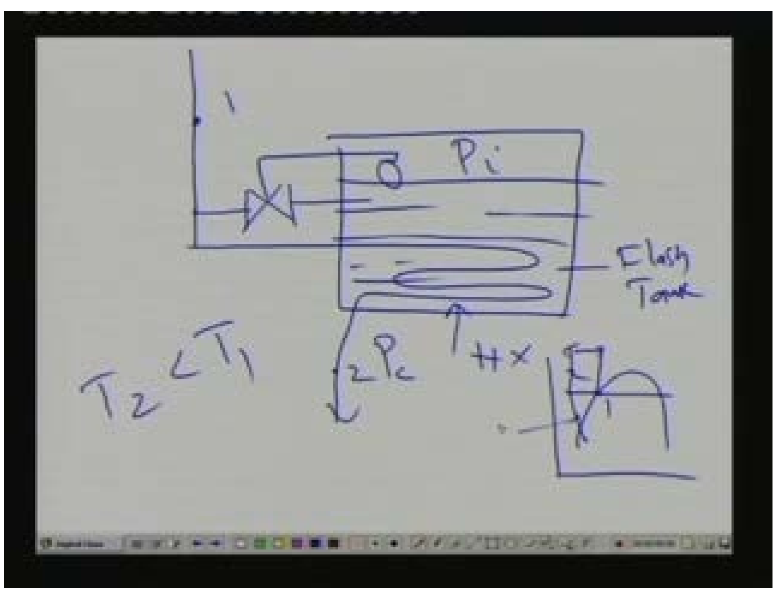

Okay. So what do you have in a liquid sub cooler is you have a flash tank here refrigerant vapour from the condenser comes here first using a float valve okay. Some amount of liquid is expanded in the float valve so you have an intermediate pressure here.

Then what is done is the rest of the liquid goes through a heat exchanger which is submerged in the flash tank okay so this is your flash tank okay. So what are you doing is you are not allowing this to come into direct contact with the liquid in the flash tank but you are exchanging heat in an indirect manner okay. So this is the heat exchanger right. So if this is a point let us say one and if this is point two you will find that T two will much less than T one because of the heat exchange that has taken place in the flash tank okay. So this is what is known as liquid sub cooler now what is the pressure here is still same as condenser pressure okay. So if you will look at this one on P h diagram it is very easy to show that for example if the point one is this what is happening in the liquid sub cooler is it is getting sub cool to a state two. And at this point it enters into your expansion device. So you can see that you are able to provide good amount of sub cooling and thereby you are preventing the possibility of vapour entering into the expansion device here so this is the principle of liquid sub cooler.

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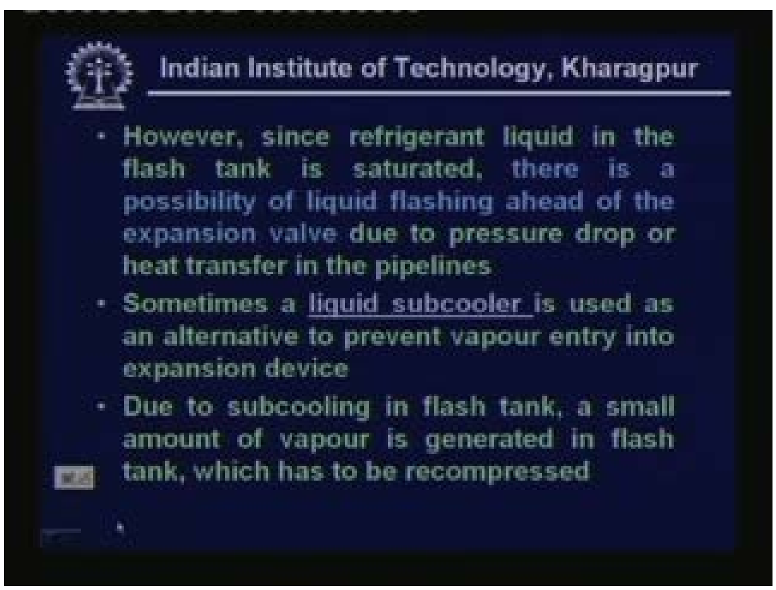

So of course what is the penalty you have to pay due to sub cooling in flash tank a small amount of vapour is generated in flash tank which has to be recompressed so this is the penalty.

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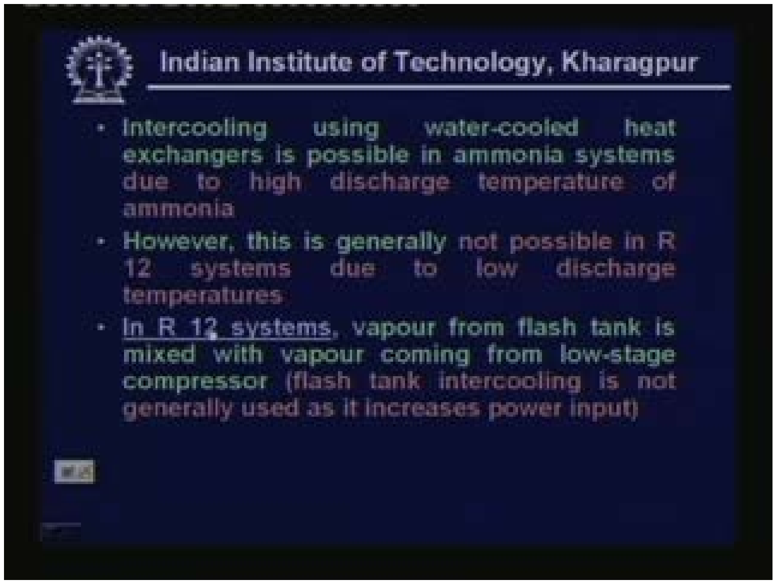

Okay so intercooling using water cool heat exchanger is possible as I have already mentioned in ammonia systems due to high discharge temperature of ammonia okay. And generally this is not possible in R twelve system due to low discharge temperatures. In fact this I have already mentioned while discussing the typical T s diagrams of various refrigerants. So we have seen that typically in R twelve systems the superheat losses are very small and the discharge temperature at the end of compression is typically very small okay.

So if you are trying to you cool that one using water cool heat exchanger then you have a sufficiently cold water okay which may not be possible always. So that is the reason why normally water intercooling is not used with R twelve systems and other halocarbon systems.

But in ammonia base system the discharge temperature is quite high so maybe you can use the tap water for example and you can have some kind of an intercooling using a water cool heat exchanger okay.

Now in R twelve systems in addition to this we have already also seen that intercooling using the liquid refrigerants is also not very effective. Because if you remember i have mentioned that intercooling using refrigerant liquid increases the mass flow rate through the high stage compressor okay. Even though it reduces the specific work of compression okay in the in case of halocarbon refrigerants the rate of increase in the mass flow rate does not compensate the reduction in the specific work input so as a result it is not effective. So normally in R twelve systems and in other halocarbon systems intercooling using water cooling or flash tank refrigerant is not used. So what is done here is the vapour from the low stage compressor is simply mixed with the vapour from the flash tank okay. This is typical practice in halocarbon systems such as R twelve.

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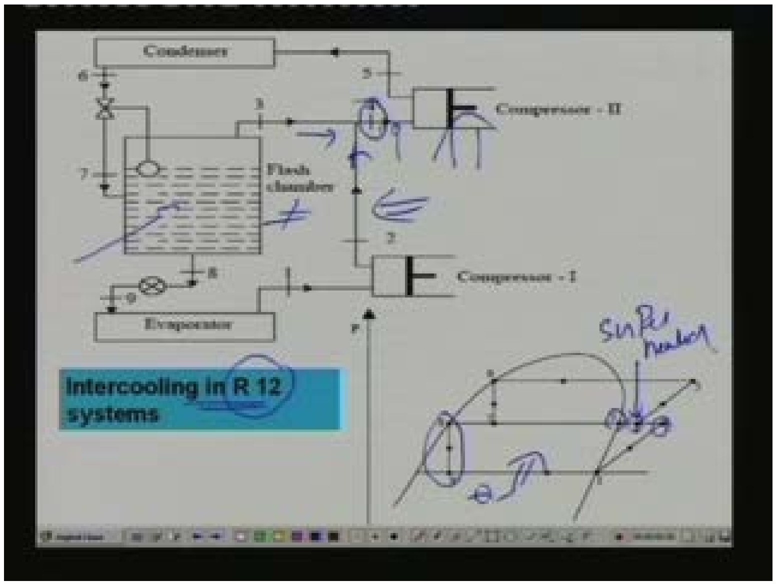

let me show that, okay, so that this is the typical inter cooling system with R twelve. So what we are doing here is we are doing the flash tank here normally okay. So this process is same as the compression system we are taking saturated liquid from flash tank and evaporation process is taking place here okay. The difference is at this point what we are doing is the vapour from the low stage compressor it does not go to here it does not go to this point what you are doing is this you are mixing with the vapour from the flash tank okay. So these two vapors are getting mixed this is getting mixed with this okay and you are getting a resultant vapour at this point the same thing is shown on P h diagram.

This is the exit vapour from the low stage compressor this is the vapour from the flash tank these two are mixed and the resultant condition is point four at this point you are compressing it in a high stage compressor okay. So you can see that since your mixing superheated vapour with a saturated vapour the condition to the inlet of the high stage compressor is also superheated okay.

So you have a superheated vapour here but this is all right here because typically the discharge temperatures are lower in R twelve systems okay. So even though you have superheated vapour at the inlet to the compressor you do not lose much okay.

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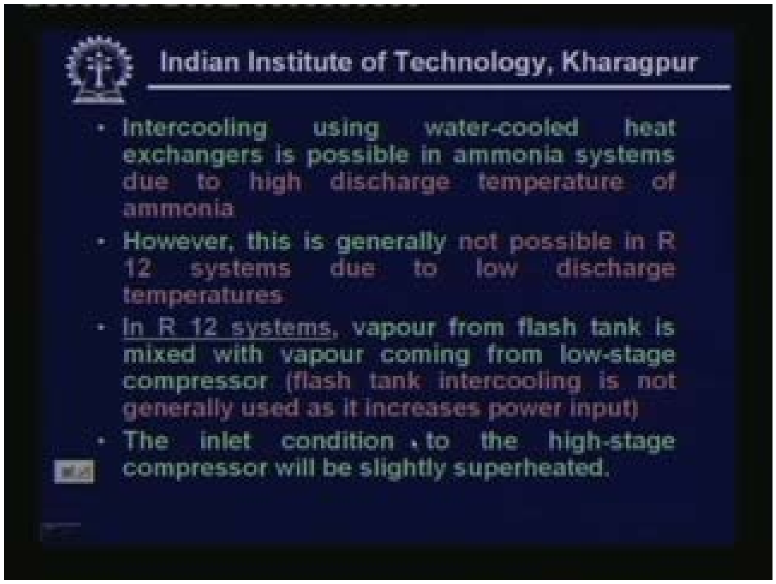

So the inlet concern to the high stage compressor as I said will be slightly superheated.

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Now let me describe another system what is known as use of flash tank for intercooling alone okay. So some times the flash tank is used for intercooling of the refrigerant only it is not used for flash gas removal. And flash tank for intercooling alone can be used in ammonia systems as it reduces the power input. So let me explain use of flash tank for intercooling alone.

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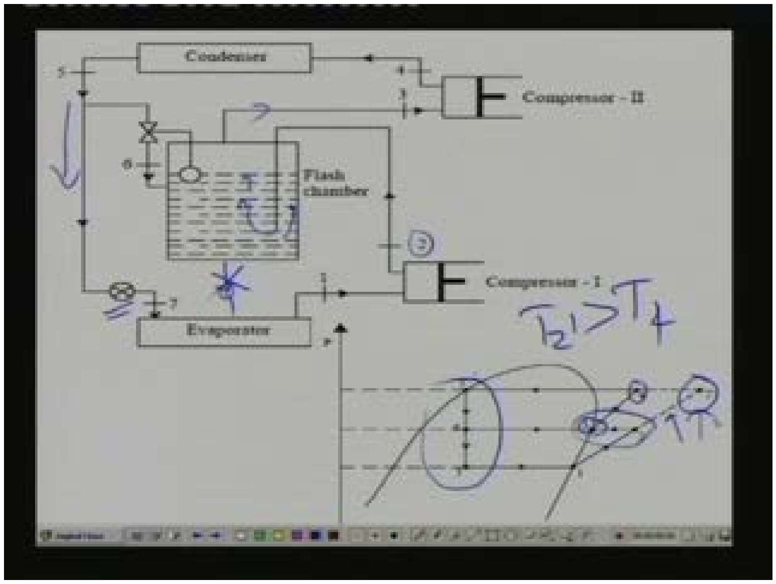

So what you are seeing here is you are not taking any refrigerant vapour from this point okay. So this you are not doing so whatever entering into this expansion device is straight from the condenser okay. So you are not using the flash tank for flash gas removal okay. So what you are using the flash tank for you are using it for intercooling of the refrigerant vapour from the low stage compressor that means this refrigerant vapour is bubble through this flash tank and its temperature is reduced. And it typically if you are assuming perfect contact then you have a saturated condition at this point okay.

So this process remains same as before and only change compare to single stage system is at this point so obviously you can see that your you are able to reduce the work of compression okay, because these lines are flatter okay. In addition to that this temperature will be much lower much higher than this that means T two dash will be much higher than T four so the benefit is you are reducing the specific work of compression. And you are also reducing the discharge temperature. This is a typical problem in ammonia systems typically all ammonia compressors due to this high discharge temperatures they are, they have water jackets. That means water will be running through this compressors and they are cooled the compressors are cooled so that the temperature does not go very high. Because as I have already said its temperature becomes very high lubrication gets effected then with the compressor gets effected okay.

So this problem becomes more severe as the temperature lift increases. So when you have high temperature lift ammonia systems you have to have intercooling you have to somehow reduce the discharge temperatures okay. So even though you are really bothered about the flash gas removal if that is the case then you can use this system. That means you are using flash tank only for intercooling not for flash gas removal okay.

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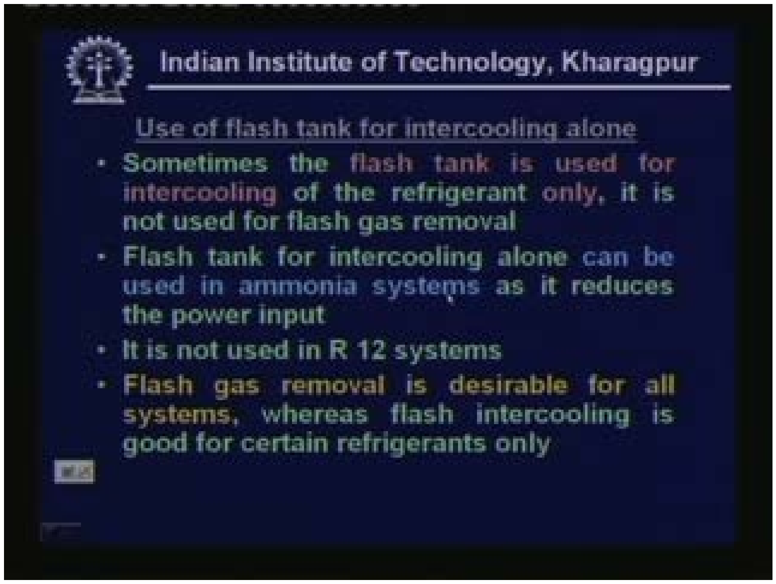

So as I said this is used in ammonia system but it is not used in R twelve systems because there is no advantage in using this in R twelve system because it generates additional refrigerant vapour okay. So one thing you must notice here at the end of this lesson is that flash gas removal is desirable for all systems okay flash gas removal is desirable whereas flash intercooling is good for certain refrigerants only okay. That means whether it is ammonia base system or halocarbon system if you are using a flash tank or some other device for removing the flash gas it is always good and it always desirable. But if you are using a flash tank for intercooling only then whether if the system is good or not depends upon the nature of the refrigerant. And typically it is good for systems like ammonia and it is not very good for halocarbon base systems like R twelve R twenty-two okay.

Now let us conclude what we have learned in this lesson.

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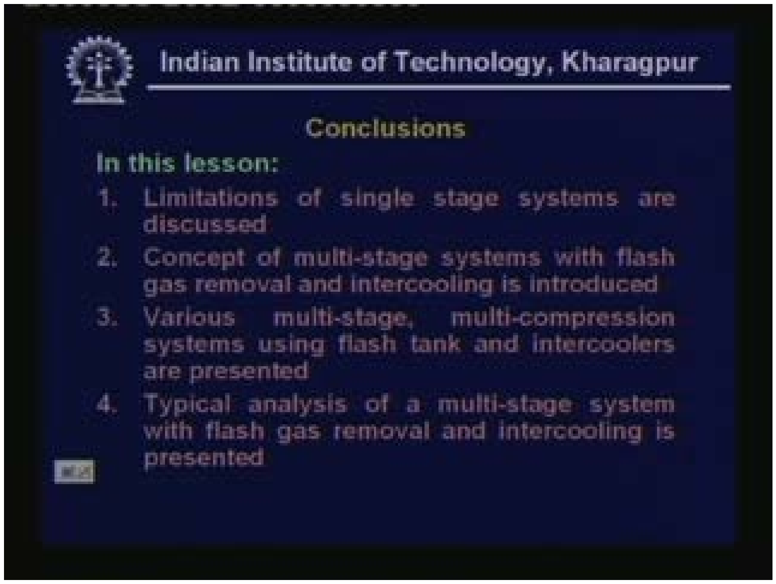

In this lesson we have seen the limitations of single stage systems and we have introduced the concept of multi stage systems with flash gas removal and intercooling. And we have discussed various multi stage multi compression systems using flash tank and intercoolers. And we have presented the typical analysis of multi stage system with flash gas removal and intercooling okay. So in this particular lesson i have discussed only two stage systems okay. So but the principle remain same so you can apply the same principle for higher stage systems that means the three stage compression system or three stage with flash gas removal etcetera okay.

The principle remains exactly same. So that is the one thing keep in mind and another thing is that i have presented steady state analysis for only one system okay. But you can follow the same procedure and you can carry out the steady state analysis of other systems and you can find out what is the COP and work of compression etcetera okay the principle remains same right and in this particular lesson we have discussed only multi compression systems with flash tank or water intercoolers okay. In the next lesson we shall discuss a multi evaporator multi stage system and we shall also discuss what is known as cascade refrigeration system okay.

Thank you.