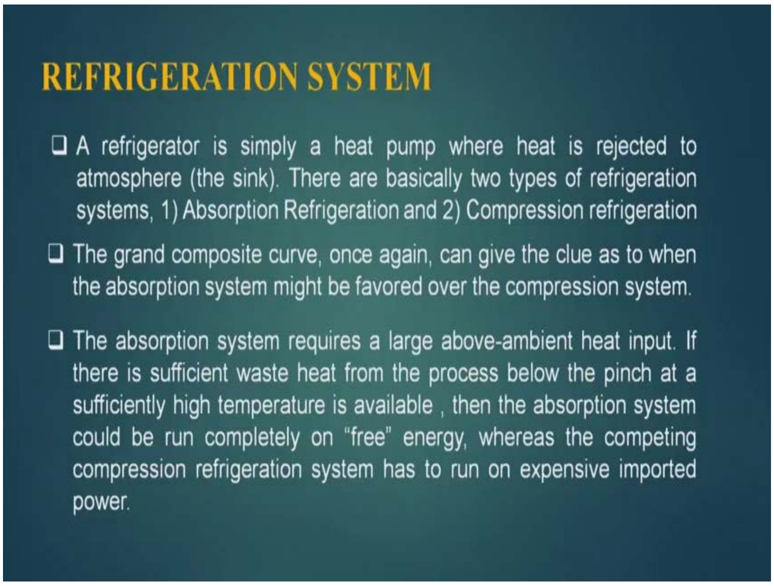
Process Integration
Prof. Bikash Mohanty
Department of Chemical Engineering
Indian Institute of Technology, Roorkee

Module - 5
Pinch Design Method for HEN synthesis
Lecture - 10
Low Temperature process Design-Part 01

Welcome to the lecture series on process integration. This is module 5, lecture number 10. And the topic of the lecture is, low temperature process design. In fact in this lecture we will be discussing the refrigeration system, and how the refrigeration system can be used as a cooling utility in a process design.

(Refer Slide Time: 01:10)



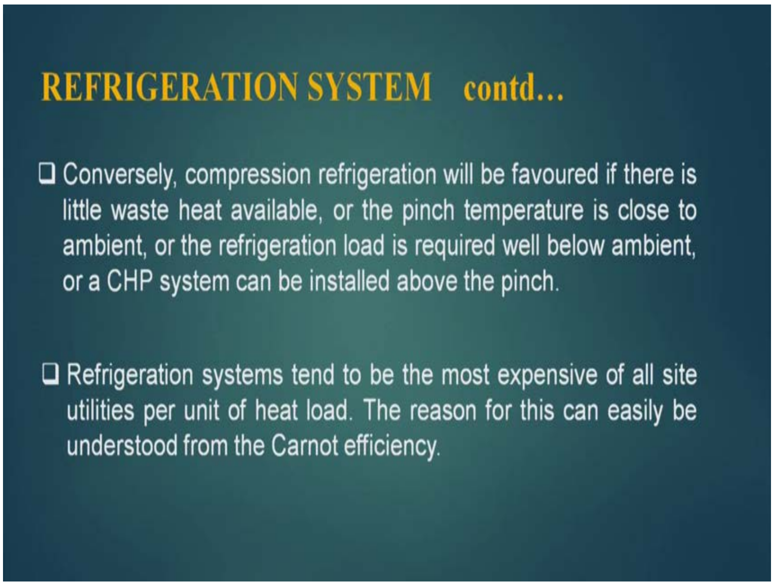
REFRIGERATION SYSTEM

- A refrigerator is simply a heat pump where heat is rejected to atmosphere (the sink). There are basically two types of refrigeration systems, 1) Absorption Refrigeration and 2) Compression refrigeration
- The grand composite curve, once again, can give the clue as to when the absorption system might be favored over the compression system.
- The absorption system requires a large above-ambient heat input. If there is sufficient waste heat from the process below the pinch at a sufficiently high temperature is available , then the absorption system could be run completely on "free" energy, whereas the competing compression refrigeration system has to run on expensive imported power.

A refrigerator is simply a heat pump, where heat is rejected to atmosphere. If you remember, you have the refrigerators in the houses; it takes heat from a lower temperature area that is called evaporator, and pumps that heat to the atmosphere, which is called a condenser. There are basically two types of refrigeration system; one is called absorption refrigeration system, and the other called compression refrigeration system

Now, let us see where absorption refrigeration system is important. In which case we should select and where the compression refrigeration should be selected. The grand composite curve, once we the process is given, we have created a grand composite curve, this gives us the clue, whether to use absorption system or a compression system. That we will discuss later on. The absorption system requires a large above-ambient heat input. Basically for cooling in absorption refrigeration system, we use heat as input; that means the heat creates the cooling effect. And if sufficient amount of heat is available in the process below the pinch, at a sufficiently higher temperature, then absorption refrigeration system can be run almost free of cost. If the situation is, so we will certainly select absorption refrigeration system. And if it is not, so then we have to go for compression refrigeration system, which needs power as a input and hence, it is costly.

(Refer Slide Time: 03:32)



REFRIGERATION SYSTEM contd…

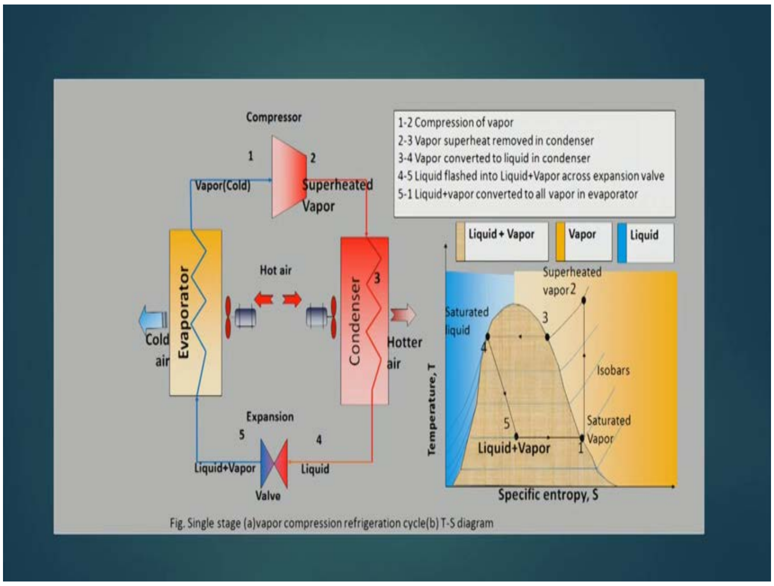
❑ Conversely, compression refrigeration will be favoured if there is little waste heat available, or the pinch temperature is close to ambient, or the refrigeration load is required well below ambient, or a CHP system can be installed above the pinch.

❑ Refrigeration systems tend to be the most expensive of all site utilities per unit of heat load. The reason for this can easily be understood from the Carnot efficiency.

Compression refrigeration will be favored if there is little waste heat available, or the pinch temperature is close to ambient, or the refrigeration load is required well below ambient, or a CHP system can be installed above the pinch. So, if these are the condition, then we can go for the compression refrigeration system. And in this talk, we will be using a compression refrigeration system for cooling purposes.

Refrigeration system tends to be most expensive of all site utilities per unit of heat load, this we should understand. There can be many utilities in a industry, steam is a hot utility, hot oil can be a hot utility, cooling water is a cold utility and refrigeration also provides cold utility. Out of these utility systems, the refrigeration system is mostly costly. And hence it should be used very intelligently and proper case should be taken while using this.

(Refer Slide Time: 05:16)



1-2 Compression of vapor
2-3 Vapor superheat removed in condenser
3-4 Vapor converted to liquid in condenser
4-5 Liquid flashed into Liquid+Vapor across expansion valve
5-1 Liquid+vapor converted to all vapor in evaporator

Fig. Single stage (a)vapor compression refrigeration cycle(b) T-S diagram

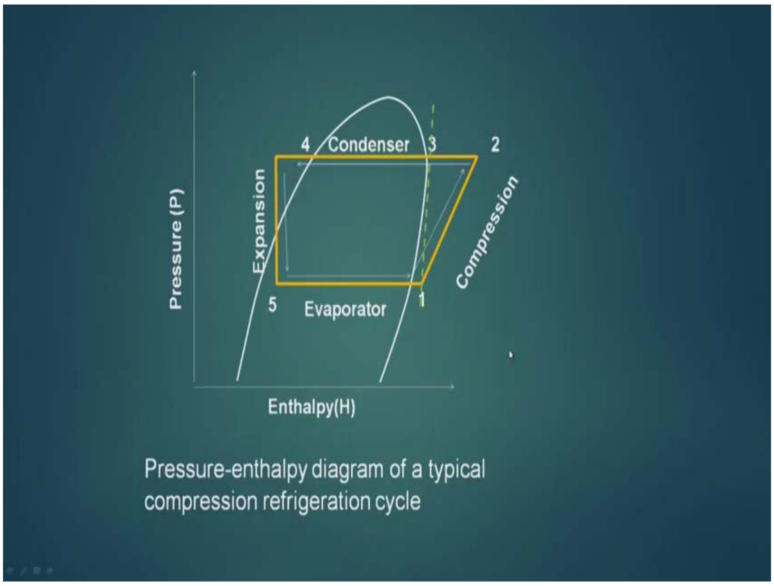
This shows a compression refrigeration system. Here this is a evaporator, if we find out an example from the refrigerator, this is the inside refrigerator vision, where the refrigerant evaporates. Vapor and liquid mixture of refrigerants are supplied to this evaporator. And this evaporator it takes heat from the materials, which are there in the evaporator and the liquid refrigerants evaporates. So, it takes latent heat of evaporation from the material and the material cools.

Here we get at the end of the evaporator or we said at the exit of the evaporator, we get vapor and this vapor is in cold state. We can have a saturated vapor or we can have a superheated vapor, depending upon how the evaporator is being designed. Then this vapor goes to a compressor and from a low pressure to a high pressure compression takes place here. So, here mostly we get superheated vapor and then this superheated vapor is cool down. This vapor is at a higher temperature and pressure. And this is cool down by either by air. Here, we have shown that there is a fan it pushes air into this condenser. So, at ambient temperature, it condenses to liquid. So, when it comes out this vapor, which is at a higher temperature and pressure converts into a liquid, that this liquid is at a higher temperature.

So, this liquid goes to a valve, which is a expansion valve, it reduces its pressure. And then it converts into a low temperature liquid and vapor mixture. And this node temperature liquid and vapor mixture is pumped to the evaporator. And in this evaporator, the liquid part of this mixture evaporates. And for that the latent heat of vaporization is supplied by the material, which is inside the refrigerator. And then it converts into a complete vapor and then again it goes to the compressor.

So, this cycle goes on. This shows a temperature entropy diagram, how the cycle goes on. This is the cycle and this is the saturated liquid region, this is the saturated vapor region, this line shows saturated vapor region. This shows 1 to 2 compression of vapor 2 to 3. 2 to 3 here the vapor superheating is removed in the condenser, and then 3 to 4 the vapor converted into liquid in the condenser. And then 4 to 5 the liquid flashes into liquid vapor across the expansion valve, and then 5 to 1 the liquid vapor converts to all vapor in the evaporator.

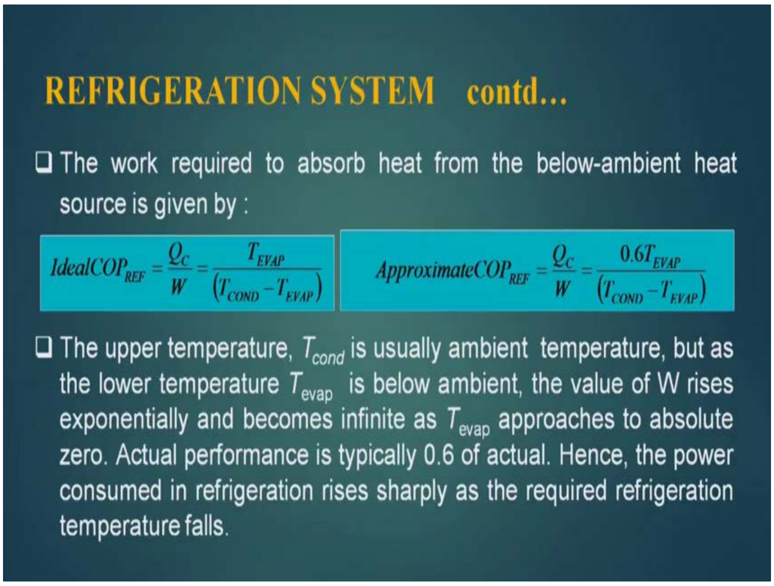
(Refer Slide Time: 09:16)



Pressure-enthalpy diagram of a typical compression refrigeration cycle

Now, if I see a pressure-enthalpy diagram, this was my cycle. So, 5 to 1 is the evaporator, where the vapor liquid mixture converts into vapor, and then there is a compression takes place from 1 to 2 the pressure increases. Now, due to this compression, this much of heat is added to the condenser. So, this much of heat we are taking from the evaporator, but when we are rejecting heat into the condenser, this much amount of heat is being rejected. That means, the amount of heat which is being rejected into the condenser is more than what we pick up from the evaporator. And this is because we have to spent energy in the compression from 1 to 2 and this energy is converted into heat. So, the condenser always rejects more heat than what it picks up from the evaporator, and this happens in a refrigeration system.

(Refer Slide Time: 10:48)



REFRIGERATION SYSTEM contd...

- The work required to absorb heat from the below-ambient heat source is given by :

$$IdealCOP_{REF} = \frac{Q_C}{W} = \frac{T_{EVAP}}{(T_{COND} - T_{EVAP})} \qquad ApproximateCOP_{REF} = \frac{Q_C}{W} = \frac{0.6T_{EVAP}}{(T_{COND} - T_{EVAP})}$$

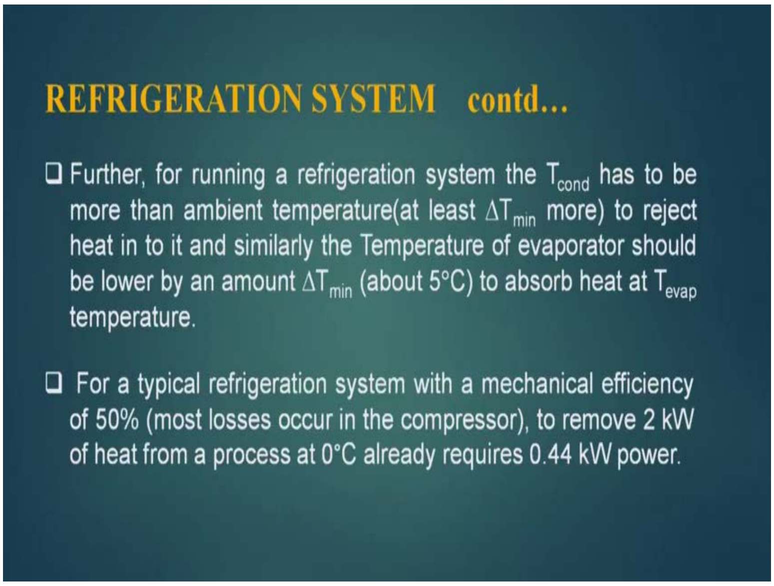
- The upper temperature, T_{cond} is usually ambient temperature, but as the lower temperature T_{evap} is below ambient, the value of W rises exponentially and becomes infinite as T_{evap} approaches to absolute zero. Actual performance is typically 0.6 of actual. Hence, the power consumed in refrigeration rises sharply as the required refrigeration temperature falls.

The work required to absorb heat from the below-ambient heat source is given by this. We define a COP and this is Q c that is heat rejected into the condenser divided by work done to leave the heat from a lower temperature to a higher temperature. And this is equal to this T evaporator divided by T condenser minus T evaporator. Now, this is a ideal COP, but if we see a non-ideal COP that means actual sort of a COP or a approximate COP, then a efficient c factor being added to this is 0.6.

So, the upper temperature T condenser is usually the ambient temperature, but as the lower temperature, that is the T evaporator is at a lower temperature is below ambient, the value of W rises exponentially and becomes infinite as T evaporator approaches to absolute zero. This will happen, because if I take here, this will be W is equal to Q c divided by this much. Even T evaporator moves to zero, this W exponentially it will increase. The actual performance is typically 0.6 of the actual performance, basically 0.6 of the ideal performance.

Hence, the power consumed in refrigeration rises sharply, as the required refrigeration temperature falls. This has to be kept in mind and that is why we will see that, in the refrigeration system the delta T minimum is very less, say around 5 degree centigrade or so. And for each degree of lowering the refrigeration temperature, we have to invest more and more heat when we go towards the lower temperature. So, much care has to be taken while designing a refrigeration system.

(Refer Slide Time: 13:15)



REFRIGERATION SYSTEM contd...

- ❑ Further, for running a refrigeration system the T_{cond} has to be more than ambient temperature(at least ΔT_{min} more) to reject heat in to it and similarly the Temperature of evaporator should be lower by an amount ΔT_{min} (about 5°C) to absorb heat at T_{evap} temperature.
- ❑ For a typical refrigeration system with a mechanical efficiency of 50% (most losses occur in the compressor), to remove 2 kW of heat from a process at 0°C already requires 0.44 kW power.

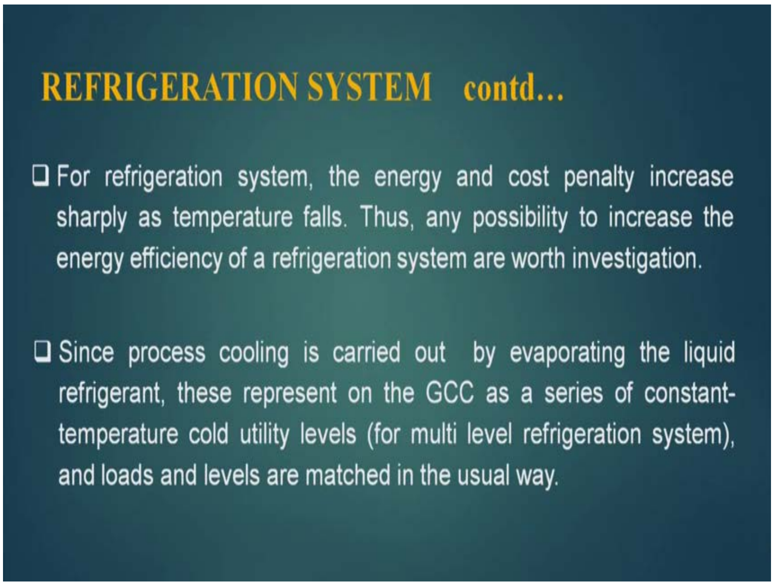
Now, this is a important factor, further for running a refrigeration system, the T condenser has to be more than the ambient temperature, at least delta T minimum a more or above. Say, the ambient temperature is 20 degree centigrade. Now, the heat has to be rejected to the ambient temperature. And if the heat has to be rejected, the stream which will reject heat to the ambient temperature should be more than the ambient temperature, only then naturally the heat will be pushed to the ambient temperature.

And for that reason, the stream which will reject heat to the ambient temperature should be at least delta T minimum above than the ambient temperature. This we will see while fixing the condenser temperature. Similarly, in evaporator we suck heat. So, the fluid which will suck heat in the evaporator has to be at least 5 degree less than the evaporator temperature. So, we have to make that fluid or bring down the temperature of the fluid to such a level, that it is about 5 degree less than the temperature of the evaporator. And accordingly the compression ratio has to fix.

For a typical refrigeration system with a mechanical efficiency of 50 percent or so most losses occur in the compressor, this is a fact. And the example is to remove 2 kilo Watt of heat from a process at 0 degree centigrade, this requires 0.4 kilo Watt power. That means from a when I am pushing up a heat from a lower temperature to a higher temperature. I am working against the natural flow of heat, because natural flow of heat is from a higher temperature to a lower temperature.

So, when I do reverse, from a lower temperature to higher temperature I push the heat, and then we have to do work for that. And if you want to push 2 kilo Watt of heat from a 0 degree centigrade to a higher temperature, say ambient temperature. We have to spend around 0.44 kilo Watt of power. More is the gap for pushing up the heat; more will be the energy requirement.

(Refer Slide Time: 16:12)



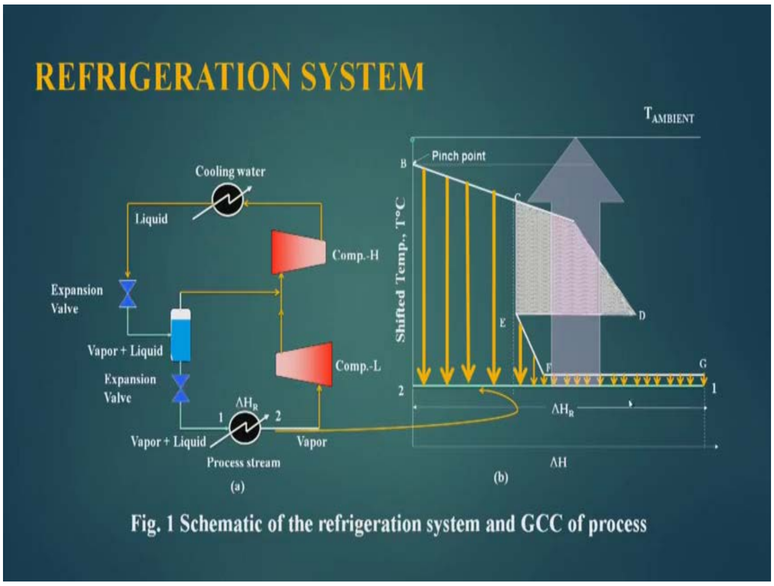
REFRIGERATION SYSTEM contd...

- ☐ For refrigeration system, the energy and cost penalty increase sharply as temperature falls. Thus, any possibility to increase the energy efficiency of a refrigeration system are worth investigation.
- ☐ Since process cooling is carried out by evaporating the liquid refrigerant, these represent on the GCC as a series of constant-temperature cold utility levels (for multi level refrigeration system), and loads and levels are matched in the usual way.

For refrigeration system, the energy and cost penalty increase sharply as temperature falls. This we have to keep in mind, when we design. Thus, any possibilities to increase the energy efficiency of a refrigeration system are worth investigation. Since, process cooling is required carried out by the evaporating the liquid refrigerant, this represents on the GCC as a series of constant-temperature cold utility levels. As the cooling takes place by the evaporation of refrigerant liquid.

So, till the liquid is present, the temperature does not change because the liquid takes latent heat of vaporization from the system and converts itself into vapor. This fact is similar to the fact, when we are boiling water on a stove or on a gas; we must have seen that the temperature of the liquid will not increase till the last drop of liquid is there in the pot. Similarly, when the liquid refrigerant evaporates, its temperatures remain constant. And that is why we see a series of temperature levels in the GCC, when you are using multi level refrigeration systems.

(Refer Slide Time: 18:13)



REFRIGERATION SYSTEM

Fig. 1 Schematic of the refrigeration system and GCC of process

Now, this shows a GCC and this is the pinch point, and this is lower part of the GCC. And in this GCC this area marked by the white is a process to process heat exchange area. Now, here the heat is rejected to the coolant, which is refrigerant in this case. And this is the temperature level of the refrigerant or we should say that, this is the evaporator temperature. The heat from here is rejected to this refrigerant. So, heat is being rejected to this refrigerant.

So, here this is the area of the evaporator, where vapor and liquid is coming to the evaporator and this vapor plus liquid takes heat from the process streams here to here. They reject heat on to this evaporator and this heat evaporates the liquid part of the refrigerant. And hence the temperature remains constant in this evaporator. Now, when all the liquids are converted into vapor, this goes to a compressor, which is low compressor, and then vapor is generated at a high pressure.

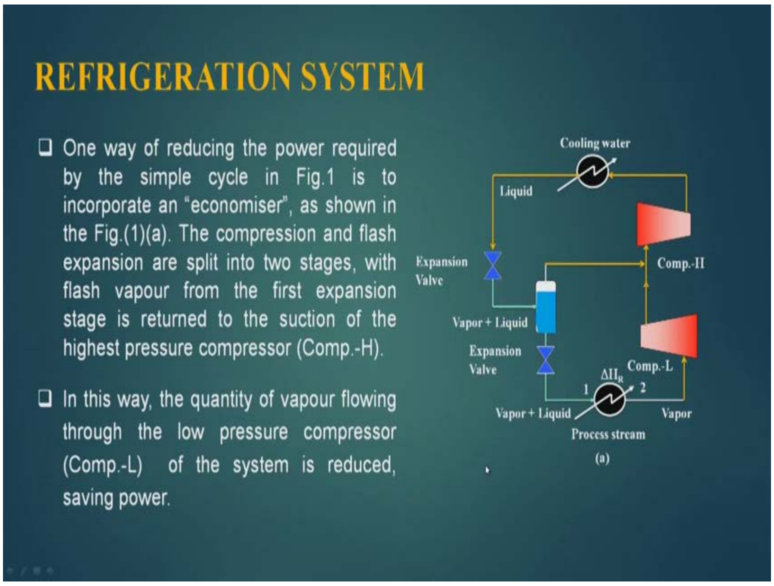
It again goes to a compressor, which is called high compressor, and then it is compressed further. And then it goes to a cooler or is a condenser, where cooling water passes, cooling water takes the heat from the compressed vapor at a higher pressure and it converts into the liquid. The liquid comes here through a expansion valve, it is expanded it converts into vapor and liquid mixture and then the liquid goes here. And then this converts into vapor. So, this is again a expansion valve, it expanse the liquid further that means brings down the pressure of this liquid.

Once it brings down, it again converts into vapor liquid mixture is goes to the evaporator. So, this cooling utility is provided by evaporating the liquid refrigerant. Now, here the vapor goes to here, this is basically a economizer. And now the heat which is absorbed by the evaporator is push to the T ambient here. So, basically this is the cooling water lying of the condenser, and this heat is taken out from this level, and ejected at this level or rejected at this level, which is the atmospheric temperature of the cooling water.

So, basically the lifting heat from here to this point, if the distance between this is and this is less, it will take less energy of compression here, if it is more it will take more energy for the compression. That this is how, a refrigeration system is integrated with GCC system and this refrigeration system provides the required cooling of the GCC system. Now, this is a base case, now we will see that, if it is possible to improve the energy consumption of the system, that means with low energy can this cooling can be done.

This is the question, and we will see that the answer is yes. We can do it with a lower power; we can offer the same amount of cooling. Now, the trick is that if you see here the delta T available is very large whereas, delta T available is here is small and here is little bit large. So, we should not operate the cooling system with such large delta T and you can decrease it by providing multiple cooling utilities or multiple refrigerant cooling utilities. And by doing so we can save the energy, we will see in the next figure.

(Refer Slide Time: 24:26)

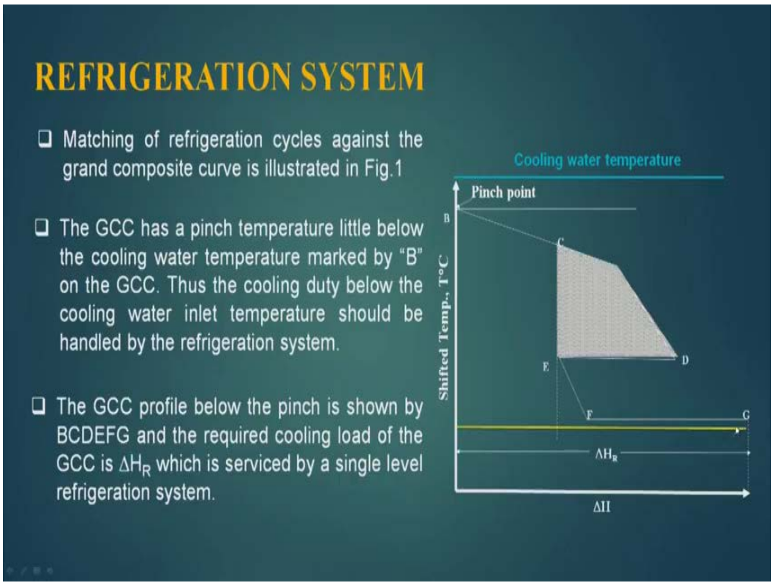


REFRIGERATION SYSTEM

- ❑ One way of reducing the power required by the simple cycle in Fig.1 is to incorporate an "economiser", as shown in the Fig.(1)(a). The compression and flash expansion are split into two stages, with flash vapour from the first expansion stage is returned to the suction of the highest pressure compressor (Comp.-H).
- ❑ In this way, the quantity of vapour flowing through the low pressure compressor (Comp.-L) of the system is reduced, saving power.

Now, here basically this structure here, we have used a economizer to save energy. One way of reducing the power required by the simple cycle in figures one. This is basically figure one is to incorporate a economizer as shown in this, this is economizer part. The compression and flash expansions are split into 2 stages with flash vapor. From the first expansion stages returned to the suction line of the compressor H. Here in this way the quantity of vapor flowing through the low pressure compressor that is compressor L of the system is reduced and the energy is saved. So, here some sort of energy saving has been created in the circuit, but more saving can be done with more or different designs of this compression refrigeration system, that we will see.

(Refer Slide Time: 25:49)



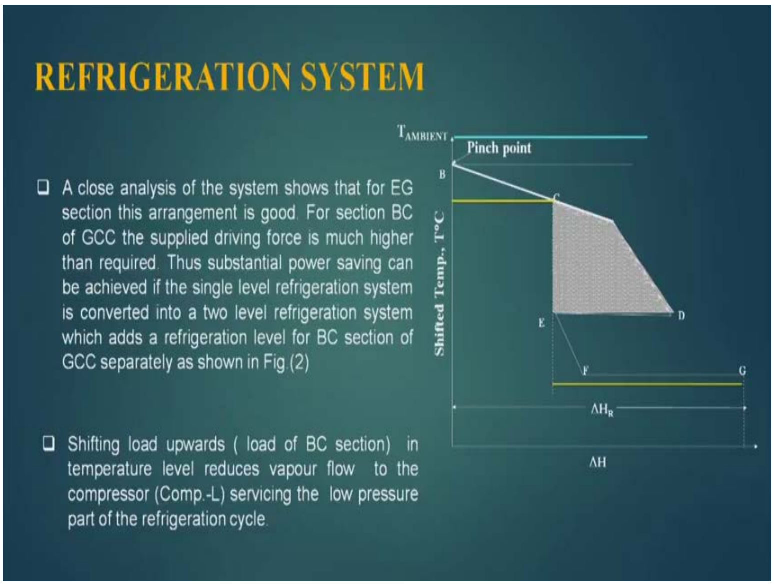
REFRIGERATION SYSTEM

- ❑ Matching of refrigeration cycles against the grand composite curve is illustrated in Fig.1
- ❑ The GCC has a pinch temperature little below the cooling water temperature marked by "B" on the GCC. Thus the cooling duty below the cooling water inlet temperature should be handled by the refrigeration system.
- ❑ The GCC profile below the pinch is shown by BCDEFG and the required cooling load of the GCC is ΔH_R which is serviced by a single level refrigeration system.

Now, the job of this refrigeration system or the aim of this refrigeration system is to provide cooling to this lower part of the GCC. This is below pinch area, this is the pinch and this pinch is below the atmospheric temperature. And hence the cooling, which requires is refrigeration, but the heat which is available from this to this, and from this to this, and this has to be rejected to a refrigeration system.

Now, this refrigeration system which has been designed has to meet this purpose. Now, here we see that the cooling load is from here to here that is delta H r, but the delta T here is less, delta T here is still more and delta T is still more here. So, by giving a cooling utility here, from here to here, what we can do, we can decrease the what we can say that, the decrease the pumping or we can say that a high temperature refrigerant or a high temperature level can be created here. So, the energy to put a temperature level here will be far less than, to created temperature level of refrigerant here. So, further we see this.

(Refer Slide Time: 28:11)



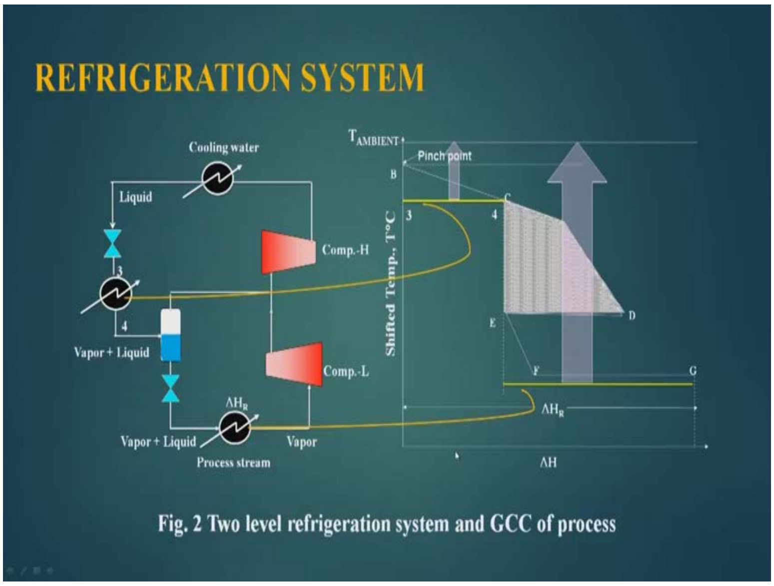
REFRIGERATION SYSTEM

- ❑ A close analysis of the system shows that for EG section this arrangement is good. For section BC of GCC the supplied driving force is much higher than required. Thus substantial power saving can be achieved if the single level refrigeration system is converted into a two level refrigeration system which adds a refrigeration level for BC section of GCC separately as shown in Fig.(2)
- ❑ Shifting load upwards (load of BC section) in temperature level reduces vapour flow to the compressor (Comp.-L) servicing the low pressure part of the refrigeration cycle.

So, this shows here I am created a temperature level here by giving a refrigeration system, which creates evaporator at this temperature and another evaporator is created at this temperature. Now the cooling has divided into 2 parts. This is some sort of high temperature cooling; this is a low temperature cooling. Now, by doing so we can save energy, why? Because the heat available at this temperature will be pumped to this temperature, because it will be rejected at this temperature, but the heat which will be picked up at this temperature level will be rejected to this temperature.

So, it will take less energy to reject the heat whereas, it will take more energy to reject at this temperature, because the distance between these two temperature levels are far more than the distance between these two temperature levels. So, heat is being taken from here and rejected here. So, it has to do more work, it has to do less work in comparison to this, when heat is picked up from here and is rejected here. So, when this is broken into 2 parts, then my energy consumption decreases the shifting. The load upwards in the temperature level reduces the vapor flow to the compressor L, which is servicing the low pressure area and hence the work done is less.

(Refer Slide Time: 30:26)



REFRIGERATION SYSTEM

Fig. 2 Two level refrigeration system and GCC of process

Now, how this will be created actually. Now, let us see how it is being created this evaporator, which is working at this temperature level will pick up heat from the process streams, which are available from E to F and F to G. So, here I have written process stream, so process streams are going through this evaporator. So, they are discharging, the process stream is discharging heat to this evaporator. And which are these process streams, these are from here to here and here to here.

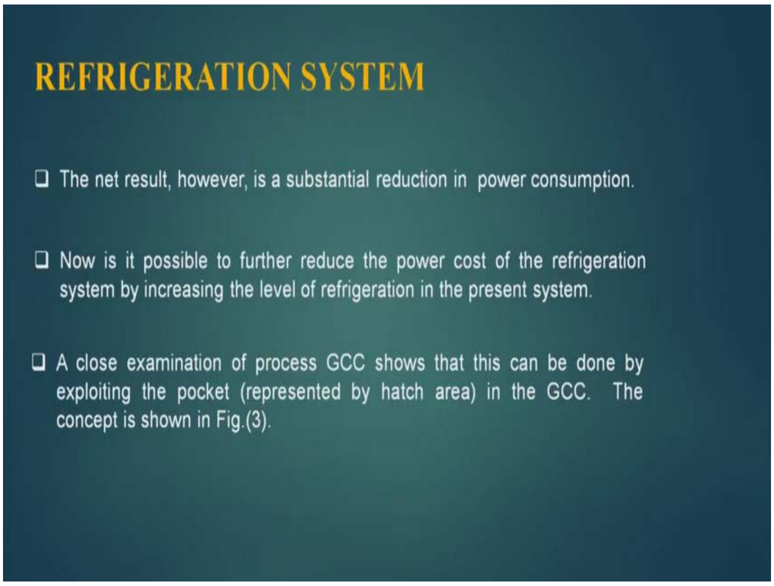
Now, the process stream which are available from B to C, they are rejecting heat into this evaporator 3 to 4. They are rejecting heat and the process streams, which are here from C to D, they are rejecting heat to E to D. So, this is a process to process heat transfer and I do not have to bother much for it. Now, the heat which is available here is rejected at this level and the heat which is available from here to here is rejected into this level. So, obviously more work will be done for this level and less for this level.

Now, this is the condenser, where at T ambient temperature, the heat is being rejected. So, this is how the compression refrigeration part of the system will work, to satisfy the cooling load of this GCC. And we are always talking about the below pinch part of the GCC, because at the below pinch part, it rejects heat to the coolant not above the pinch part. So, we are not talking about above pinch area here, because the below pinch area is of the area concerned to us. And that is why we are always talking about the below pinch area.

Now, here the liquid vapor mixture gets evaporated here and the vapor is created. This is compressed the vapor goes to the inlet of the higher compressor and then it is further compressed it goes to the condenser. Here it is rejecting heat at this temperature level and then the liquid is expanded. And here we create a temperature level, which is this. Then liquid and vapor goes here, it is separated vapor separated out here, liquid comes here, again it is expanded the pressure goes down.

And a still lower temperature level is created in this evaporator, which is this temperature level. By breaking the whole system into 2 evaporator systems, we are increasing the complexity of the design, but at the same time, we are able to save some valuable electrical energy, which has to be invested in the compressor. Now, it appears that this design has been saturated and no more saving can be done, but if is analyze it further, we can see that a new design can be evolved, which will say more energy for this part of the GCC than what we are observing here. So, let us see the third part of the design.

(Refer Slide Time: 35:12)



REFRIGERATION SYSTEM

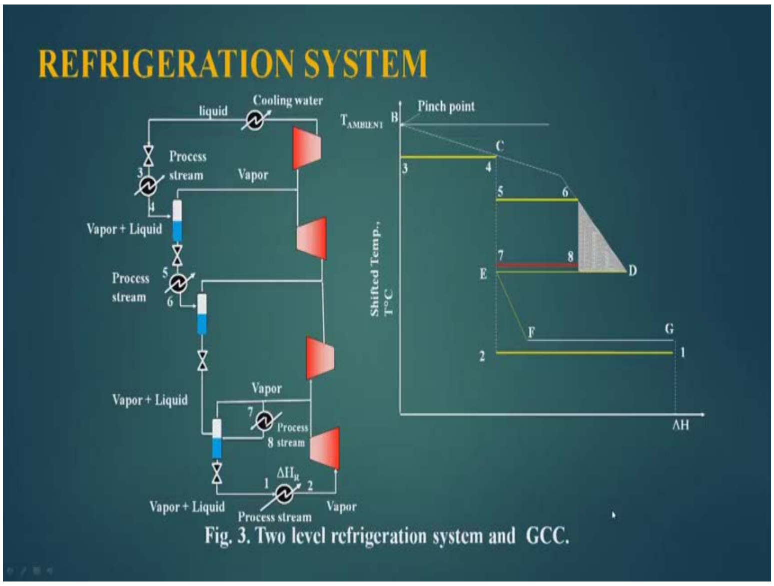
❑ The net result, however, is a substantial reduction in power consumption.

❑ Now is it possible to further reduce the power cost of the refrigeration system by increasing the level of refrigeration in the present system.

❑ A close examination of process GCC shows that this can be done by exploiting the pocket (represented by hatch area) in the GCC. The concept is shown in Fig.(3).

The net result however is a substantial reduction in the power consumption for the earlier figure. Now, it is possible to further reduce the power cost of the refrigeration system, by increasing the level of refrigeration in the present system. A close examination of the process GCC shows that, this can be done by exploiting the pocket represented by the hatched area in the GCC. The concept is discussed in figure 3. So, we will see a new concept, which will further decrease the energy consumption of the system.

(Refer Slide Time: 35:58)



REFRIGERATION SYSTEM

Fig. 3. Two level refrigeration system and GCC.

Now, this is a new system in which will saving far more energy, how because now we are providing cooling at 3 different temperature levels. This is one temperature level, which is at the highest temperature, then this is the second temperature level 5 to 6, which is being created by this evaporator, this is 3 to 4 which is created by this evaporator and then 2 to 1, which is created by this evaporator. And here we are creating 2 condensers, 1 condenser is this 7 to 8 where heat is being rejected.

And the 7 second condenser is this, where it heat is being rejected to the cooling water. What we have done, whatever heat these streams are from B to C, they are being rejected at 3 to 4. So, this heat is being rejected from 3 to 4, which is this evaporator. Then the heat available from this to this is rejected here from 5 to 6, so this is this evaporator. Now, the heat available from this to this is rejected from this to this point. So, this is a process to process heat exchanger. Now, we have to satisfy this part because this parts needs heat. Earlier, this heat was satisfied from this to this the process streams, which were from this to this where giving heat to this.

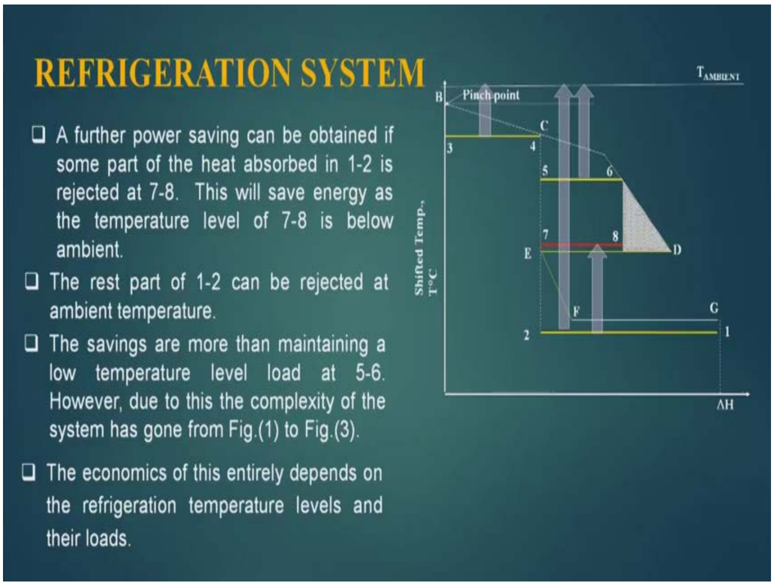
Now, I have provided a new temperature level to cool down the streams from this to this and hence, heat is required here. So, I am providing a extra level of condenser here 7 to 8 to provide heat. Now, this way we have created 3 different cooling levels, one by this evaporator, this is by this evaporator and this is by this evaporator. And a new condenser here 7 to 8, what it is doing? It is taking this vapor, and it is rejecting this heat, and this is being transfer to here. That means the heat which is available with this vapor is rejected to this area. And cooling is done and the liquid and gas mixture is separated here.

Now, if we start from the lowest level this is vapor and liquid, the liquid gets evaporated by giving heat from 1 to 2 have a vapor, this is being compressed here and the output is send to here. This vapor from this vapor liquid separator also goes to this and input to this compression, but a part of vapor is being cooled by the process stream, which is available from here to here, and liquid vapor mixture may be sent to here.

Now, whatever vapor goes here, they are compressed as sent upwards to this compressor and the vapor from here mixes here at this compressor. And the out of this compressor goes to here and vapor comes from here. They add together and go to here and it compresses. Now, it takes to the highest temperature level, where this is being cooled by cooling water and the liquid is formed. This liquid is at highest pressure, then it expanded, a vapor liquid mixture is being created.

This goes to the evaporator 3 to 4 here and cooling level is being created here, then the vapor liquid goes here. Vapor is separated, push backed here, liquid is further expanded that means pressure is brought down and a new temperature level which is 5 6 is being created. And then the vapor goes here, the liquid comes here. It is further expanded to a lower temperature and goes here, this is separated and then it is further expanded and a lower temperature is created here 2 to 1. So, this is how the system works.

(Refer Slide Time: 42:35)



REFRIGERATION SYSTEM

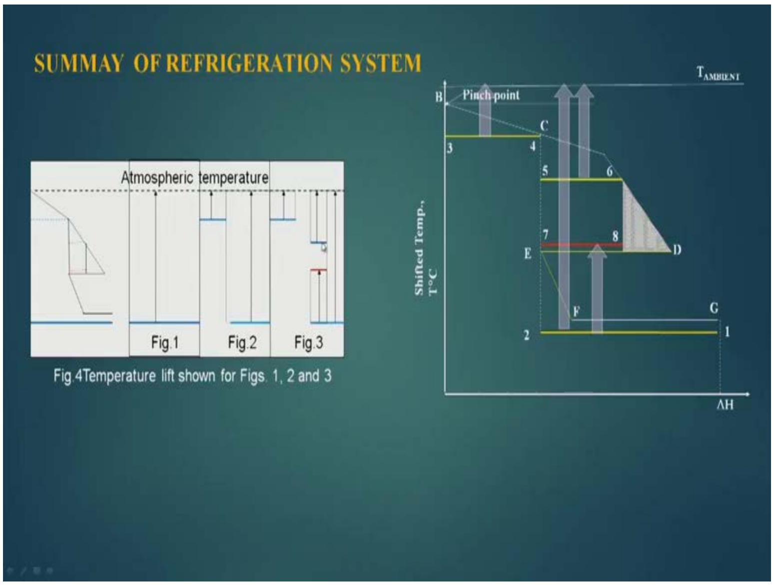
- ❑ A further power saving can be obtained if some part of the heat absorbed in 1-2 is rejected at 7-8. This will save energy as the temperature level of 7-8 is below ambient.
- ❑ The rest part of 1-2 can be rejected at ambient temperature.
- ❑ The savings are more than maintaining a low temperature level load at 5-6. However, due to this the complexity of the system has gone from Fig.(1) to Fig.(3).
- ❑ The economics of this entirely depends on the refrigeration temperature levels and their loads.

So, by creating more temperature cooling levels, we can say further energy, but the design becomes more complicated. Now, if we see the heat rejection schemes, then the picture becomes clear, why such a system takes lower energy? The heat which is absorbed by this evaporator is rejected to the atmosphere here. So, lift is very less, it is lifting the heat from here to here. The heat which is being rejected here into this evaporator 5 to 6, this is lifted from this to this where, this is T ambient. Basically, this is the cooler, which is called condenser and that cooler we are using cold water, which is at ambient temperature.

A part of heat of this evaporator is rejected here and the remaining part is taken to the condenser, which is operated by cooling water. So, if we see the lifts then we will find that this system will consume less energy because if I am rejecting heat taking from here to here I will consume more energy, if I reject heat which is available here to this level I will consume less energy. So, on this basis of this argument, we see that this system will consume less energy than the earlier system.

So, what we have seen? We have seen 3 different designs, which will consume different levels of power to operate, but this also we have seen that, when we are saving energy we are making the design more complicated. So, there has to be a trade up between the complications of the design or the fix cost of the design and the savings. This is the summary. Here in the first figure all the heats where picked up at this level and rejected to the atmosphere.

(Refer Slide Time: 45:32)



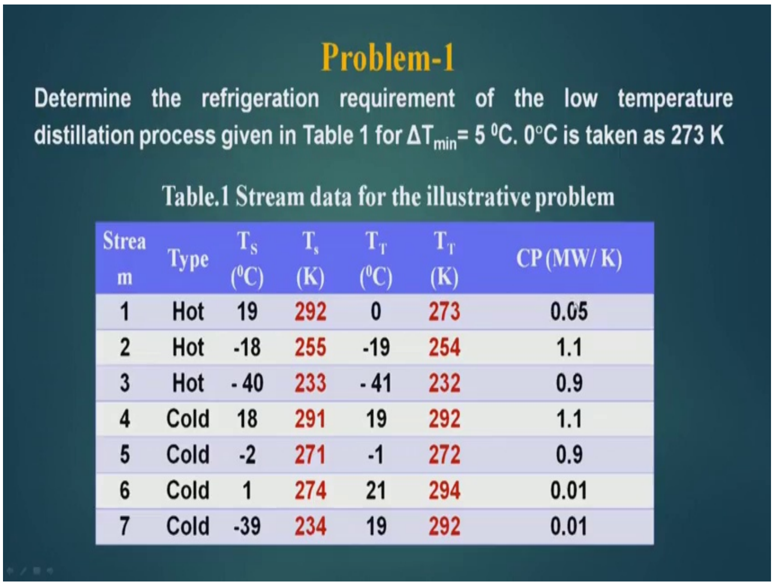
SUMMAY OF REFRIGERATION SYSTEM

Fig.4Temperature lift shown for Figs. 1, 2 and 3

In the second figure, we broke down this to 2 temperature levels this and this then we lifted this heat from here to here, and this amount of heat from here to here. So, the lifting was less, so this was improvement over this. Now, here what we did? We broke it into 3 levels, this level heat is rejected at this level, and this level heat is rejected at this level. And this is further broken into 2 parts, some part of heat is rejected to this level and the remaining part is rejected to this level. So, this arrangement is improvement over this, but if you see here that the number of evaporators here is 1, condenser is 1, here there are 2 evaporators and 1 condenser, here there are 3 evaporators and 2 condensers.

So, the complexity is increasing the number of equipment is increasing, but we are able to save the electricity, which will be used into the compressor. Numbers of compressors are also increasing because in many cases, we cannot work on high compression ratios. If the compression ratio is high, we have to break into 2 compression ratios and 2 compressions have to be used because adiabatic compression takes more energy than isothermal compression. After learning this that how through different designs energy can be saved in a refrigeration system. We will take a problem and we will apply the knowledge, which we have gained in this lecture. On this problem and we will see the actual savings, which can be done through different designs. For this purpose, we have taken a stream data for this illustrative purpose.

(Refer Slide Time: 48:10)



Problem-1

Determine the refrigeration requirement of the low temperature distillation process given in Table 1 for $\Delta T_{min} = 5\ ^0C$. 0°C is taken as 273 K

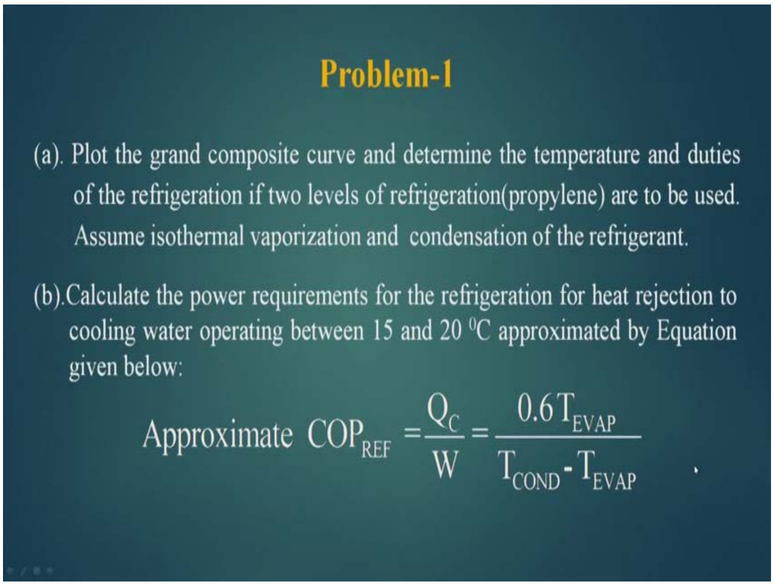
Table.1 Stream data for the illustrative problem

Stream	Type	T_S (^0C)	T_s (K)	T_T (^0C)	T_T (K)	CP (MW/ K)
1	Hot	19	292	0	273	0.05
2	Hot	-18	255	-19	254	1.1
3	Hot	- 40	233	- 41	232	0.9
4	Cold	18	291	19	292	1.1
5	Cold	-2	271	-1	272	0.9
6	Cold	1	274	21	294	0.01
7	Cold	-39	234	19	292	0.01

It has got 3 hot streams and 4 cold streams. And we have to find out a refrigeration requirement for this example problem. In this case, we are taking delta T minimum is equal to 5 degree centigrade because I have already told you that, for refrigeration systems delta minimum taken are very low. Because, the cost of refrigeration is very high and that is why delta T minimum considered here is low. And if we do the optimization of delta T minimum also for refrigeration system, we will see that the delta T minimum will come out to be low.

Here negative temperatures are there, so we will convert into Kelvin, by adding 273. In actual fact, it is 273.15, 0 degree is equal to 273.15 Kelvin, but here for the simplicity reason we have taken 273 Kelvin. So, we have added to this temperature 273 and converted into Kelvin. Now, this is supply temperature, this is target temperatures are also converted into Kelvin and these are the CP values, which is basically MCP.

(Refer Slide Time: 49:47)



Problem-1

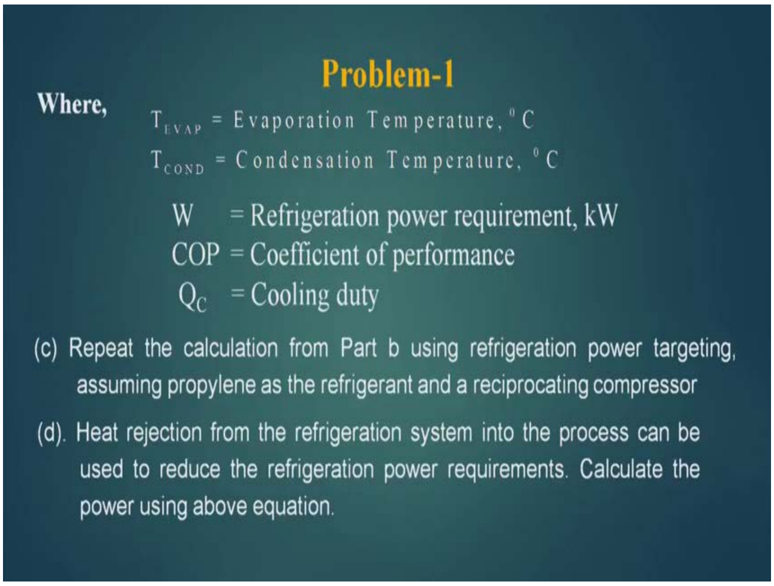
(a). Plot the grand composite curve and determine the temperature and duties of the refrigeration if two levels of refrigeration(propylene) are to be used. Assume isothermal vaporization and condensation of the refrigerant.

(b).Calculate the power requirements for the refrigeration for heat rejection to cooling water operating between 15 and 20 ^{0}C approximated by Equation given below:

$$\text{Approximate } COP_{REF} = \frac{Q_C}{W} = \frac{0.6T_{EVAP}}{T_{COND} - T_{EVAP}}$$

Now, what is the requirement of this problem, the part is plot the grand composite curve and determine the temperature and duties of the refrigeration if two levels of refrigeration and the refrigerant is propylene are to be used. Assume isothermal vaporization and condensation of the refrigerant. The b part is, calculate the power requirement of the refrigeration for heat rejection to the cooling water operating between 15 and 20 degree centigrade approximately. The equation which will be used to calculate the approximate COP or the practical COP will be this. Here we have use the efficiency factor.

(Refer Slide Time: 50:53)



Problem-1

Where,

T_{EVAP} = Evaporation Temperature, ^{0}C
T_{COND} = Condensation Temperature, ^{0}C

W = Refrigeration power requirement, kW
COP = Coefficient of performance
Q_C = Cooling duty

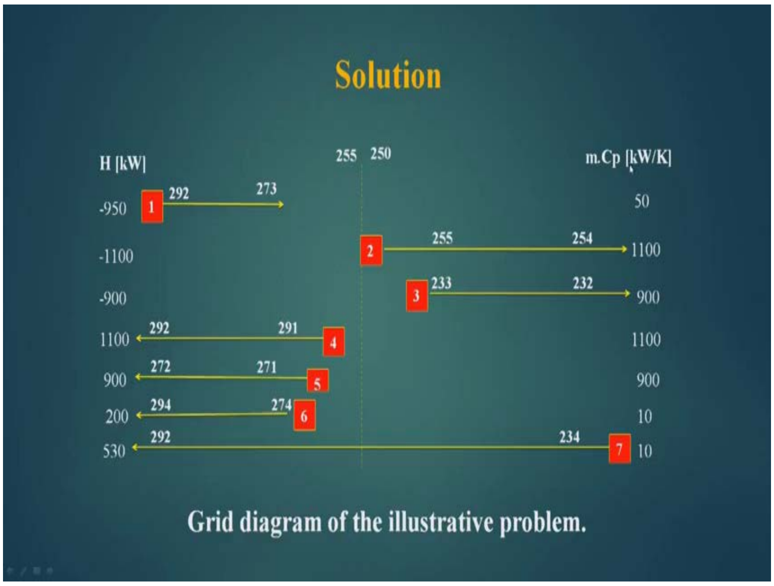
(c) Repeat the calculation from Part b using refrigeration power targeting, assuming propylene as the refrigerant and a reciprocating compressor

(d). Heat rejection from the refrigeration system into the process can be used to reduce the refrigeration power requirements. Calculate the power using above equation.

Now, in the part c, we have to repeat the calculation from part b using refrigeration power targeting. Once we calculate the actual power required for the refrigeration system, and then will simulate the whole system. And based on the model, which will be developed simulation model, we will do the refrigeration power targeting. And the refrigeration power targeting will create a new design. We will see what sort of design will have minimum power and minimum usage of hot utility. In the d part, the heat rejection from the refrigeration system into the process can be used to reduce the refrigeration power requirements. Calculate the power using above equation. You will use that equation, which just we talked about.

(Refer Slide Time: 51:54)

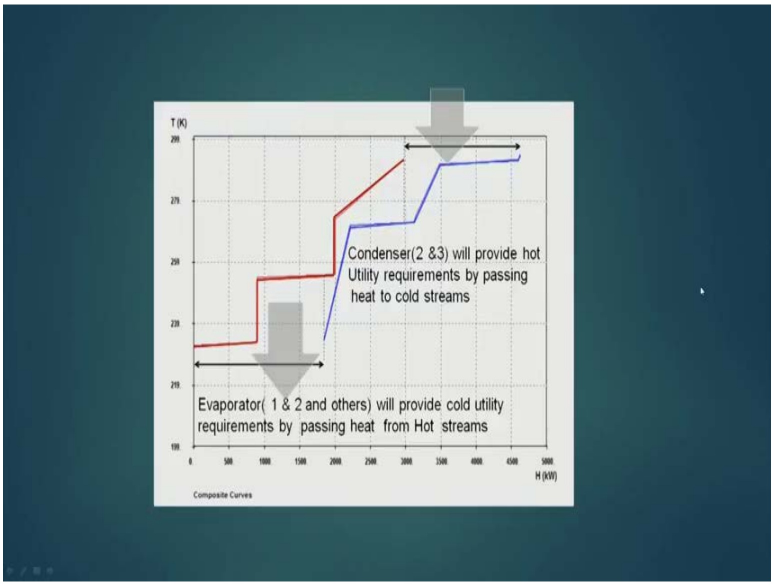
Solution



Grid diagram of the illustrative problem.

So, this is the grid diagram of the illustrative problem. Now, here 255 and 250 is the pinch temperature, this is hot pinch and 250 is the cold pinch. So, difference being 5 degree centigrade, we have taken delta T minimum to be 5 degree centigrade. So, here this is being kilo Watt per Kelvin and the problem this is in given in mega Watt. So, there is some difference in the unit research, this has to be remembered. So, here also it is in kilo Watt.

(Refer Slide Time: 53:13)



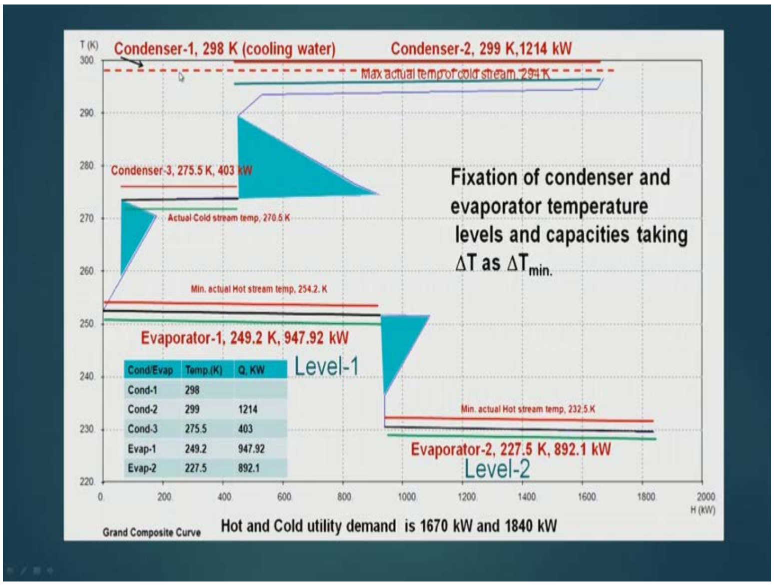
Condenser(2 &3) will provide hot Utility requirements by passing heat to cold streams

Evaporator(1 & 2 and others) will provide cold utility requirements by passing heat from Hot streams

Now, this is the composite curve of the problem. Now, here from this to this is the hot utility requirement and this hot utility will be pass to the cold streams. So, in the problem we will see that we are using condenser 2 and 3, to pass the hot utility. And the hot utility will be transfer to the cold streams only. So, when calculating temperature of the condenser, this will keep in mind that my condensers, which will be using the process stream, will pass on the heat to the cold streams only.

Similarly, here this heat, this much amount of heat has to be pass to the cold refrigerant streams, so they only pass to the evaporators. So, here we will use evaporator number 1, 2 and others will provide the cold utility requirements by passing heat from hot stream. So, this heat from the hot streams will be passing to the evaporator. So, while fixing up the evaporator temperatures, we will keep this in mind that the evaporator will treat only the hot streams. Now, here we are fixing up the evaporator temperatures and condenser temperatures.

(Refer Slide Time: 55:25)



Fixation of condenser and evaporator temperature levels and capacities taking ΔT as $\Delta T_{min.}$

Cond/Evap	Temp.(K)	Q, KW
Cond-1	298	
Cond-2	299	1214
Cond-3	275.5	403
Evap-1	249.2	947.92
Evap-2	227.5	892.1

Hot and Cold utility demand is 1670 kW and 1840 kW

Now, there is a water is available here at 20 degree centigrade. So, we add 5 degree delta T to this and the temperature of the condenser number 1, which is using cooling water comes up to be 298 Kelvin. So, if I am passing heat to the cold water in condenser number 1, then my refrigerant temperature will be vapor state has to be at 298 degree Kelvin or say 298 Kelvin not degree Kelvin it is Kelvin.

Now, there is a condenser number 2, where heat is passing to the cold streams. We are here not passing heat to the cooling water, but we are passing heat to the cold streams. And if I am doing so then I am saving my hot utility. Now how to calculate that temperature and the maximum temperature of the cold stream is 294 Kelvin. So, if I add 5 degree to this, becomes 299 Kelvin. So, my condenser number 2, which will pass the heat to my process streams, which are available from this to this and this, the condenser temperature will be 299, then how heat will be passing through this condenser?

This is given by the distance between this and this extreme point. If I calculate this distance through this axis, I can convert it how much kilo Watt I have to pass, then it comes out to be 1-2, 1-4 kilo Watt, that means the condenser 2 will operate at 299 Kelvin, and its capacity is 1-2, 1-4 kilo Watt. Now, this is another condenser. Here also heat is required to heat the GCC. Now, this is here the actual cold stream temperature is 270.5 because heat will pass to the cold stream.

So, the temperature here, this is the shifted temperature, so actual temperature will be below this for the cold streams, this is 27.5. So, I add 5 degree delta T minimum to this, becomes 270.5 Kelvin and the size of this condenser, which is the distance between this and this or the load of this condenser is 403 kilo Watt. Now, this is the pinch and below this we will be putting evaporators. Now, evaporators will take heat from the hot streams, so they will service only hot streams.

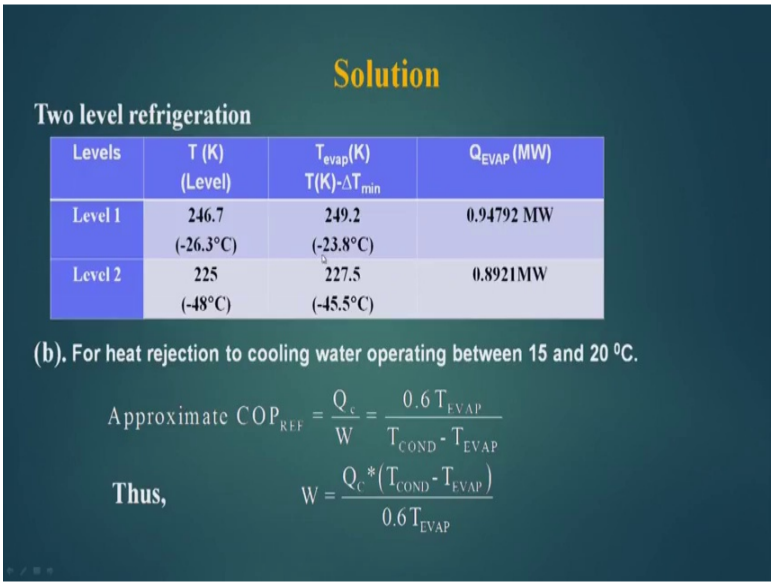
So, this temperature is the shifted temperature, so hot stream temperature with respect to this shifted temperature is here 254.2 Kelvin. Now, if I reduce 5 degree to this temperature, then my evaporator 1 temperature becomes 249.2 Kelvin and load on this evaporator will be distance between this and this. And I can calculate from this axis form here, this comes out to be 947.92 kilo Watt. And I will call this level 1, this temperature level I will call this level 1 in which, evaporator number 1 is operating at level one.

Similarly, for level 2 which will service the hot process streams this is the shifted temperature, actual temperature of the hot stream will is this 232.5 Kelvin. So, I deduct 5 degree from 232.5 Kelvin, I get 227.5 Kelvin here. So, evaporate a 2 will operate at 227.5 Kelvin and the load on this evaporator part can be found out from here, by projecting these 2 lines. And that load is 892.1 kilo Watt and I will call it level 2. This temperature level is called as level 2. So, my evaporator 1 is operating at level 1, its temperature is 249.2 Kelvin and its load is 947.92 kilo Watt.

Evaporator 2 is operating at level 2 temperatures, its temperature is 227.5 Kelvin and its load is 892.1 kilo Watt. Similarly, my condenser 2 is working at 299 Kelvin and its load is 121.4 kilo Watt and condenser 3 is operating at 275.5 Kelvin and load is 143 kilo Watt. And I have not calculated the load for condenser 1 because whatever, load is left has to be rejected to this. So, it is not required to calculate the load of condenser 1. If I am rejecting the heat which is available from here and here to condenser 1 obviously, its load will be this 947.92 plus 892.1 kilo Watt.

As this heat which will be rejected to condenser 1 is not further used, and then I am not keeping any calculation for this. Now, all these data are being computed from the GCC of the process. So, this is the GCC which we see and from this GCC, all these temperature levels are fixed. Now, if I do the PT of this problem, then hot utility demand is 1 6 7 0 kilo Watt and cold utility demand is 1840 kilo Watt. So, with this analysis, now we will move ahead and we will solve the problem. So, we are using 2 levels of refrigeration.

(Refer Slide Time: 63:24)



Solution

Two level refrigeration

Levels	T (K) (Level)	T_{evap}(K) T(K)-ΔT_{min}	Q_{EVAP} (MW)
Level 1	246.7 (-26.3°C)	249.2 (-23.8°C)	0.94792 MW
Level 2	225 (-48°C)	227.5 (-45.5°C)	0.8921MW

(b). For heat rejection to cooling water operating between 15 and 20 °C.

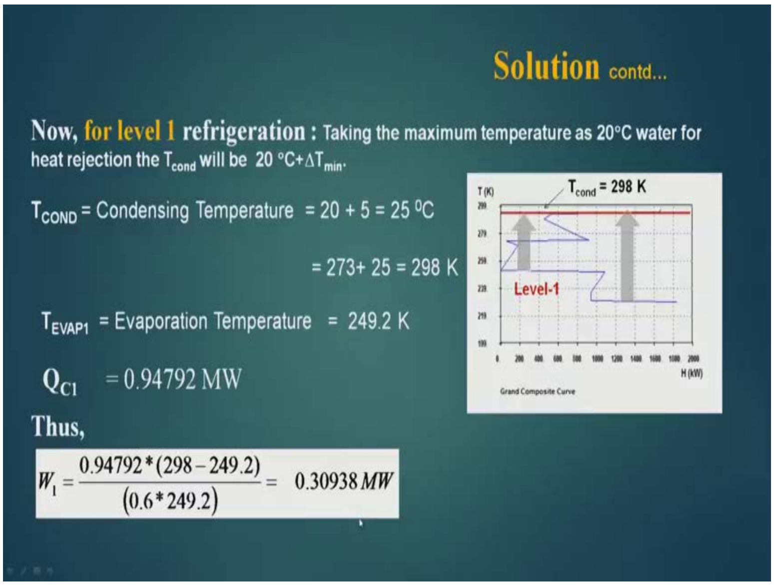
$$\text{Approximate } COP_{REF} = \frac{Q_c}{W} = \frac{0.6\,T_{EVAP}}{T_{COND} - T_{EVAP}}$$

Thus,

$$W = \frac{Q_C * (T_{COND} - T_{EVAP})}{0.6\,T_{EVAP}}$$

First level is operating at this temperature, which is the shifted temperature basically and this is actual temperature of the evaporator, we have calculated. Here this is in Kelvin, this is in degree centigrade and this is the loads, we have already seen. Now, the COP is computed using this equation, which is basically practical COP because the efficiency factor is being involved here. So, this will be actual COP, this is not ideal COP, so to calculate this W, this is the equation which will be using.

(Refer Slide Time: 64:11)



Solution contd...

Now, for level 1 refrigeration : Taking the maximum temperature as 20°C water for heat rejection the T_{cond} will be 20 °C+ΔT_{min}.

T_{COND} = Condensing Temperature = 20 + 5 = 25 ^{0}C

= 273+ 25 = 298 K

T_{EVAP1} = Evaporation Temperature = 249.2 K

Q_{C1} = 0.94792 MW

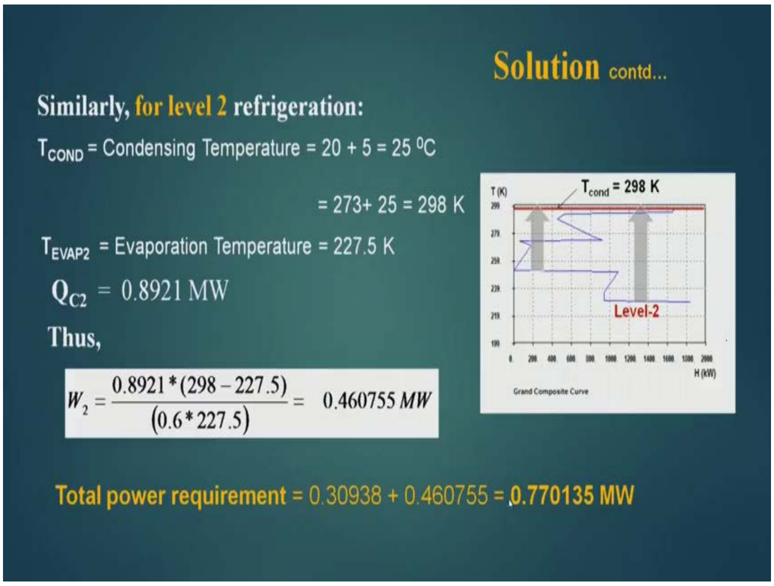
Thus,

$$W_1 = \frac{0.94792*(298-249.2)}{(0.6*249.2)} = 0.30938\,MW$$

Now, here what we are doing, we are transferring the heat, which we are picking up from level 1 and level 2 to the cold water, which is this line and the temperature is 298. So, the condenser temperature will be fixing, this is the maximum temperature of the cooling water. So, for the design purpose, we have taken the maximum temperature. So it will be a conservative design and it will always satisfy, because of the winter the temperature will down and in the summer the temperature will rise to 20 degree centigrade.

So, if I design for the winter taking it to be 15 degree centigrade, then this condenser will not work in the summer. And that is why we have taken the maximum temperature 20 degree centigrade and then we have added the delta T minimum value, so it becomes the 25 degree centigrade. So, we add 273, it converts into 298 K, so this is the temperature of the condensing stream, which is obviously will be a refrigerant in this case. So, T evaporator is 249.2 Kelvin and Q which will be taken up from this level to this condenser is 94792 mega Watt. So, we can calculate our power requirement, this comes out to be 0.3938 mega Watt. So, to take the heat from level to the condenser, which is operating at 298 Kelvin, the work required will be this much 0.30938 mega Watt.

(Refer Slide Time: 06:08)



Solution contd...

Similarly, for level 2 refrigeration:

T_{COND} = Condensing Temperature = 20 + 5 = 25 ^{0}C

= 273+ 25 = 298 K

T_{EVAP2} = Evaporation Temperature = 227.5 K

Q_{C2} = 0.8921 MW

Thus,

$$W_2 = \frac{0.8921 * (298 - 227.5)}{(0.6 * 227.5)} = 0.460755\ MW$$

Total power requirement = 0.30938 + 0.460755 = **0.770135 MW**

Similarly, for level 2 we can calculate same condenser, so the same condenser temperature. Here also we are heat from level 2 and putting up into this same condenser. So, the temperature remains same 298, but the evaporation evaporated temperature is 227.5, this we have fix in the GCC, if you remember. And the Q, which is lifted from this level to this level, is 0.8921. So, work require to lift is 0.8921 mega Watt from this to this level condenser level is 0.6075 mega Watt.

Though here heat is less number, because the distance is more from here to here, I am consuming more power. So, total power requirement is the first one W 1 plus W 2 it comes out to be 0.770135 mega Watt. So, actually in actual case this, 0.770135 mega Watt will be consume to operate this or to provide the cooling levels at 2 levels, level 1 and level 2. To provide this I will be needing 0.770135 mega Watt of energy and this will be consumed in the compressors of the compression refrigeration system.

Thank you.