Process Integration
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Module - 06
Integration and Placement of Equipment
Lecture - 03
Integration of heat pump

Welcome to the lecture series on process integration, this is module six lecture number three topic of today lecture is integration of heat pump, what is the heat pump. Let us see it is a known fact that it flows naturally from higher to a lower temperature.

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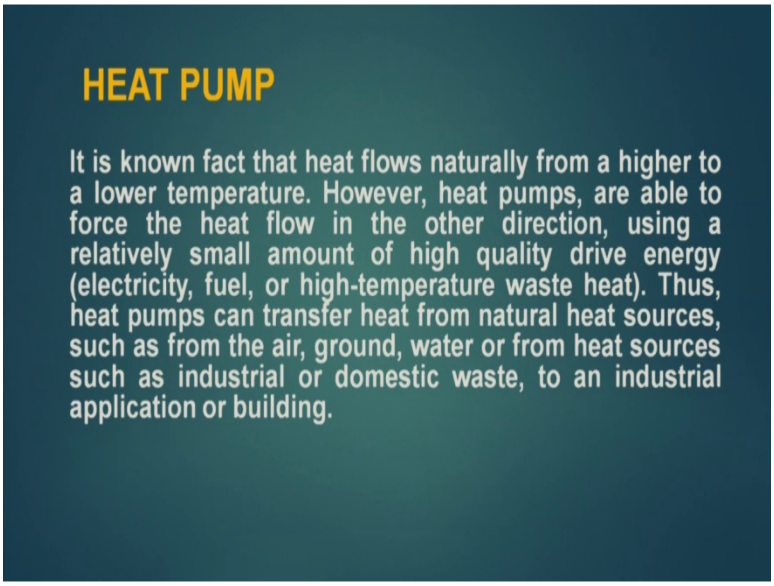

However, heat pumps are able to force the heat flow in the other direction, that is lower to higher temperature using a relative small amount of high quality drive energy. This can be electricity fuel or high temperature waste heat, thus heat pumps can transfer heat from natural heat sources such as from air ground water or from heat sources, such as industrial or domestic wastes to an industrial application or to a building. So, in sort heat pump works in opposite direction of the natural flow of heat, that is it takes it from a lower temperature and posses it at a higher temperature.

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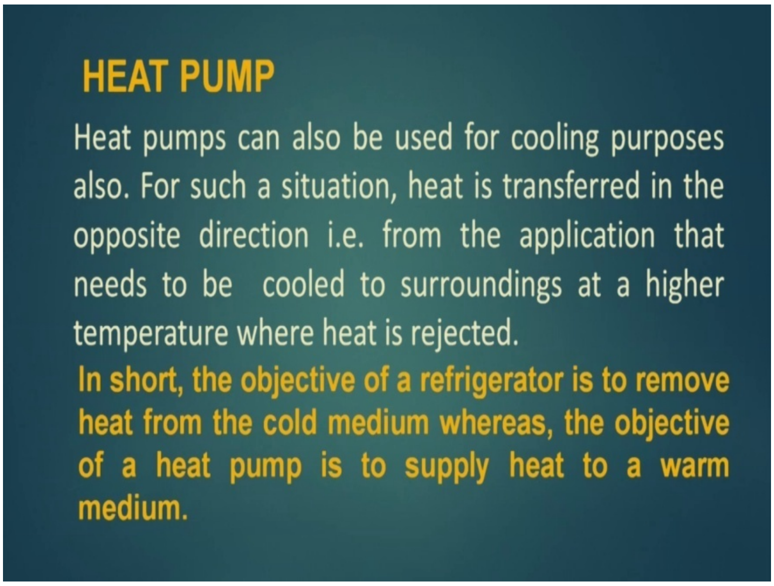

Heat pumps can also be used for cooling purposes. For such a situation, heat is transferred in the opposite direction from the application, that needs to be cooled to surroundings at a higher temperature, where heat is rejected. In short, the objective of a refrigerator is to remove heat from the cold medium whereas, the objective of a heat pump is to supply heat to a warm medium. So, this difference though technically, they are same, but as far as utility is concerned the refrigerator and heat pump have different utilities.

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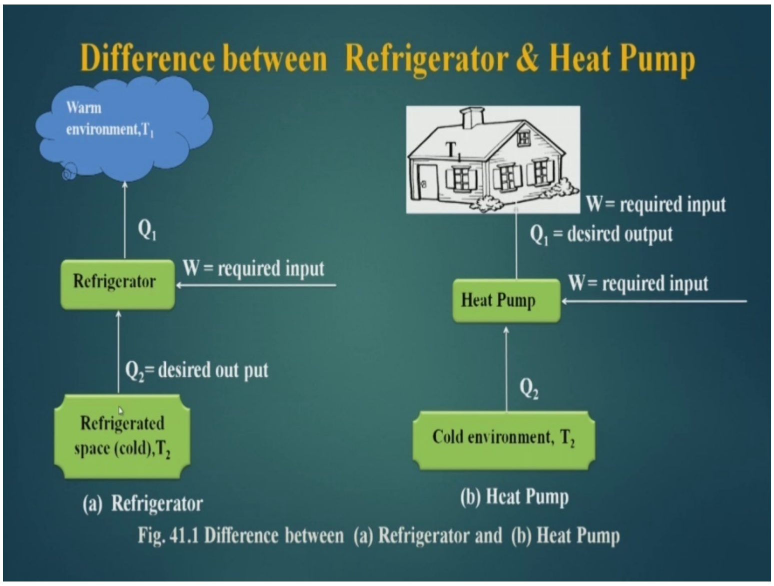

Now let us see what is the difference between refrigerator and heat pump pictorially. Now here the refrigerator, it takes of heat from a refrigerated space. It is cold at T 2 temperature and fix of Q 2 amount of heat, and then posses to environment, which is at a higher temperature at T 1, but the amount of heat is Q 1. So, there is a difference between Q 1 and Q 2. Q 1 is more than Q 2, and to transfer this heat from cold to the hot we required W amount of work, which is converted into heat and adds up to this. That means, Q 2 is less than Q 1, but here the job is the same it takes of it from a cold environment which is at T 2 fix of heat Q 2. And then discharges to a say house to warm it the amount of heat is Q 1 and to do this it spends W amount of heat, but the desired output is here Q 1, but here the desired output is Q 2. So, when it is working in a refrigeration amount the desired output is Q 2, and when it is working as a heat pump amount its desired output is Q 1 though the technology involved in doing both the jobs are almost same.

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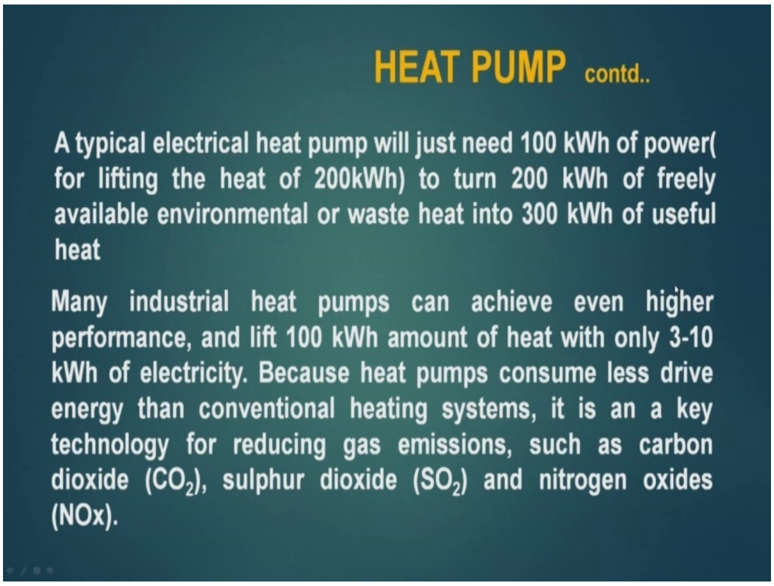

Now let us see why the heat pumping is required, why it is required to pick up the low graded heat and convert into a high graded heat and use it, why this is required. A typical electrical heat pump will just need lift 100 kWh of power for lifting, the heat of 200 kWh to turn 200 kWh of freely available environmental or waste heat into 300 kWh of useful heat. That means, while picking up a heat of 200 kWh, we have to spend around 100 kilo kWh to pump it to a higher temperature level, and that higher temperature level how much to we get, it is about 300 kWh.

Many industrial heat pumps can achieve even higher performance, and lift a 100 kWh amount of heat with only 3-10 kWh of electricity because heat pumps consume less drive energy than conventional heating systems. It is an it is a key technology for reducing gas emissions such as carbon dioxide sulphur dioxide and nitrogen oxides, because more we consume electricity or more we do the heating part of it. So, the carbon dioxide will be generated and sulphur dioxide will be generated nitrogen oxides will be generated. So, heat pump will provide heat energy at a cheaper cost also to some extend and it saves the environment from pollution.

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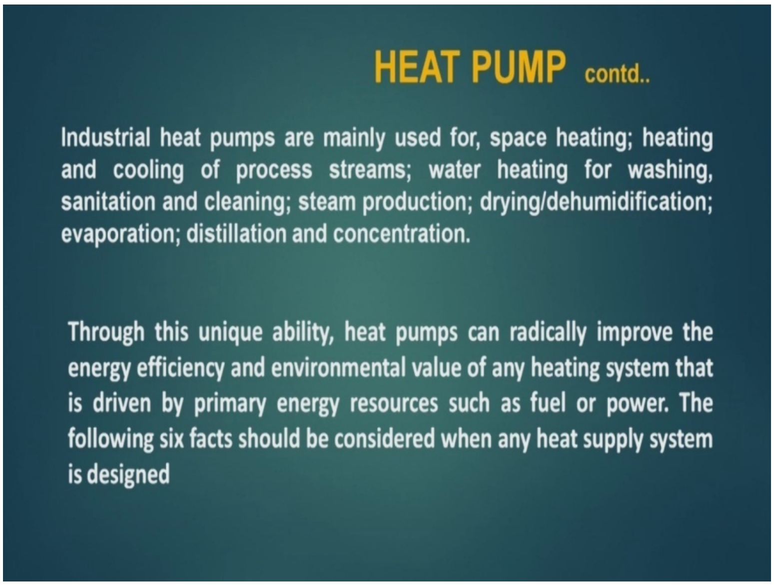

Industrial heat pumps are mainly used for space heating and cooling of process streams water heating or washing sanitation, and cleaning steam production drying dehumidification evaporation distillation and concentration. So, a large area of technology is serviced by this heat pumps though this is the unique technique, and it has got unique ability heat pumps can radically improve the energy efficiency, and environmental values of any heating systems. That is driven by primary energy resources such as fuel or power, the following six factors should be considered when any heat supply system is designed. So, if I am designing a heat supply system by heating it by a fuel. So, I should consider all these things six points before planning a heat supply system.

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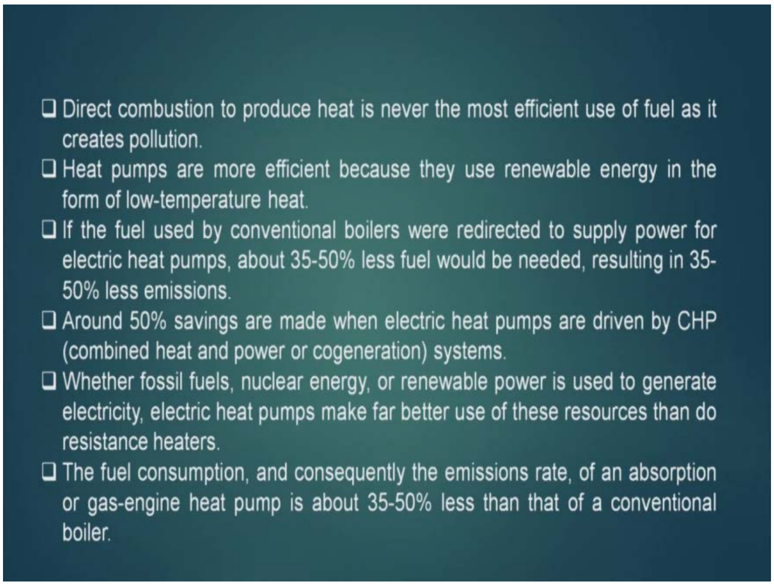

What are those direct combustion to produce heat is never the most efficient use of fuel as it creates pollution. The second point is heat pumps are most efficient, because they use renewable energy in the form of low temperature heat. The third point is if the fuel used by conventional boilers were redirected to supply power for electric heat pumps, about 35-50 percent less fuel would be needed resulting in 35-50 percent less emission. The fourth point is around 50 savings are made, when electric heat pumps are driven by CHP, that is combined heat and power cogeneration system. The fifth point is whether fossil fuels nuclear energy or renewable energy is used to generate electricity electric heat pumps make far better use of these resources. Then do resistance heaters the sixth point is the fuel consumption and consequently the emission rates of an absorption or gas engine heat pump is about 35-50 percent less than that of a conventional boiler.

So, these points should be taken into account, when we are considering a heating system if the temperature lift is low may be that most suitable form of heating will be using heat pumps. Now the heat pump is a reverse form of heat engine a heat engine running in reverse direction is basically, a heat pump from the first law of thermodynamics. The W-work will be Q 1 into n c the carbon efficiency by n mechanical, that is Q 1 T 1 minus T 2 divided by n mechanical into T 1 the overall efficiencies of heat engine, and heat pumps are W into heater into Q 1.

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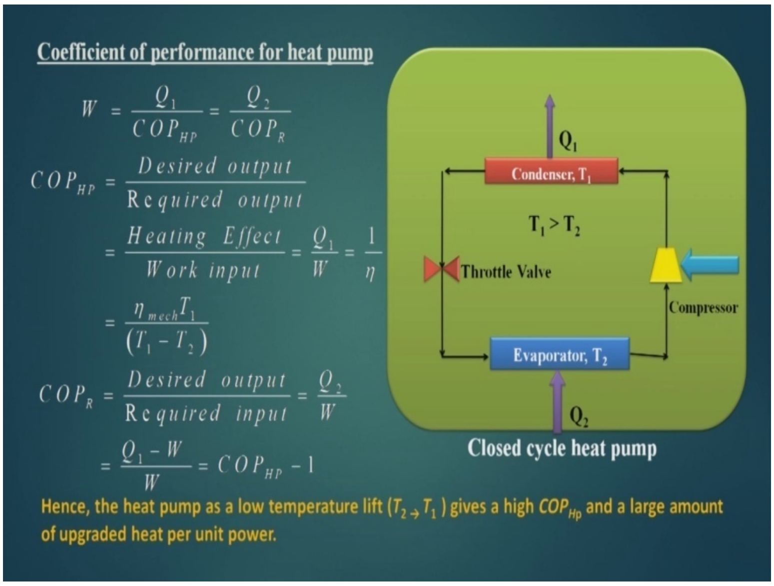

And from the first law of thermodynamics W is equal to Q 1 minus Q 2, where for heat engines the converse efficiency is greater than the n for heat engines, and it is n is greater than n c for heat pumps. Now this heat pumps will be coefficient of performance and W is equal to Q 1 divided by COP H P, that is for heat pump and Q 2 is equal to COP R for refrigerator COP R stands for refrigeration COP H P. That is for heat pump is a desired output divided by required output heating effect by work input Q 1, W is equal to 1 by n and is equal to n mechanical T 1 minus T 2. And COP R for refrigeration is desired output which is Q 2 in this case and required input is W So, if I find out the relationship between COP R and COP H P which is COP R is equal to COP H P minus 1.

Hence the heat pumps of the heat pump as low temperature lift you want T 2 tends to T 1 gives high COP; that means, ft lift is less this COP of heat pump is high and large amount of upgraded heat per unit of power. We will get now how the heat pump works let us say evaporator here, that is a liquid represent which takes of heat at a certain lower temperature T 2 it takes of Q 2 amount of heat, and then this evaporates here the vapors are pump the vapors are compressed and some external work W is given here.

The compressed vapors are cool down in a condenser, where it rejects it at a T 1 temperature, which is evaporator the T 2 temperature and the rejection is Q 1, which is more than the Q 2 and then this liquid goes here across with forty valve where the pressure is reduced. And this converts into a vapor and liquid mixture and goes into the evaporator, this is a cycle and this cycle goes on, and this is how the heat pump takes of heat at a lower temperature the Q 2 amount of heat and rejects Q 1 amount of heat is more than Q 2 at a higher temperature.

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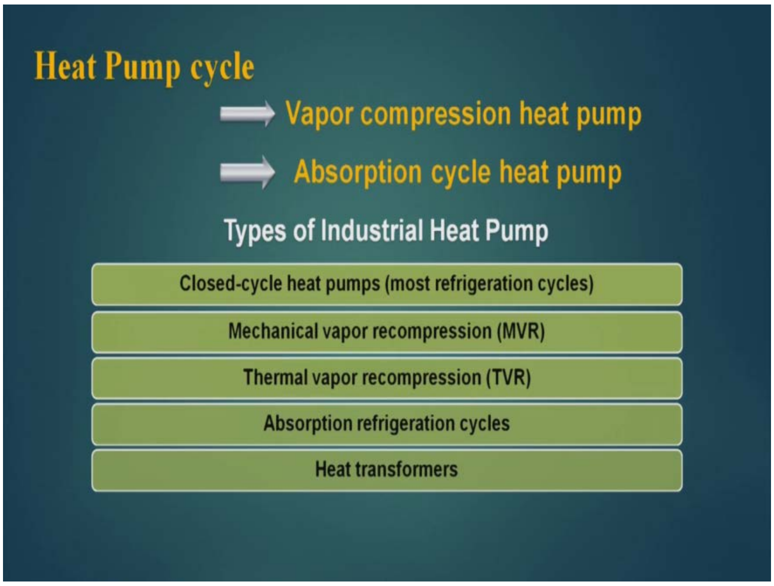

Now, that can be many type of heat pump cycles to measure cycles are vapor compression heat pump, and the other is absorption cycle heat pump the different types of the industrial heat pumps are closed cycle heat pumps mostly refrigeration cycles mechanically vapor compression MVR. Thermal vapor compression TVR and then absorption refrigeration cycles and then heat transformers. So, these are the different type of heat pumps, they have different COP values different efficiency values and they are used in different places the fourth is reverse Brayton cycle heat pumps.

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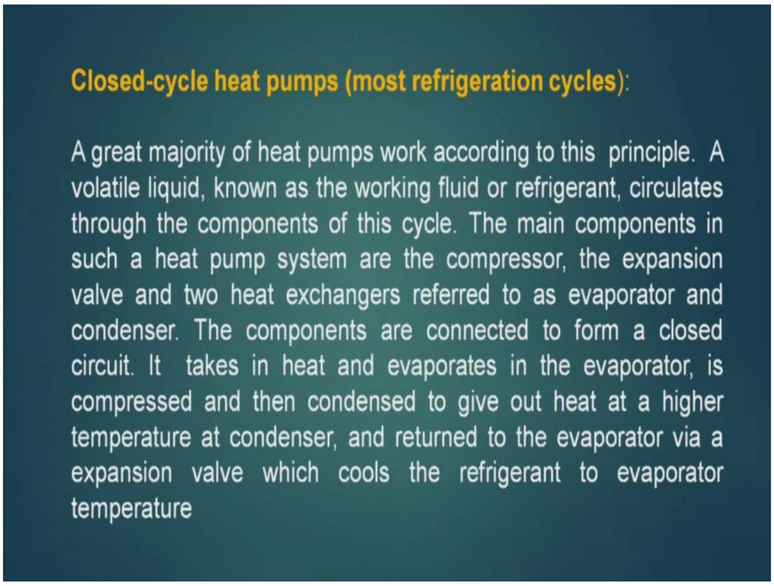

Now, let us see these different heat pumps. How they and work what are that way of working the closed cycle heat pumps mostly refrigeration cycles a great majority of heat pumps work according to this principle, which we have also explained a volatile liquid known as the working fluid or refrigerant circulates through the components of this cycle. The main components in such a heat pump system are the compression the expansion valve, and two heat exchangers referred to as evaporator and condenser the components are connected to form a closed circuit. It takes heat and evaporates in the evaporator then the vapor is compressed, and then condensed to give out heat at a higher temperature at the condenser and returned to the evaporator via a expansion valve, which cools the refrigerant to evaporator temperature. So, this is the philosophy or this the working principle of a closed cycle heat pump, now in a mechanical vapor rep recompression unit which is called short form is MVR.

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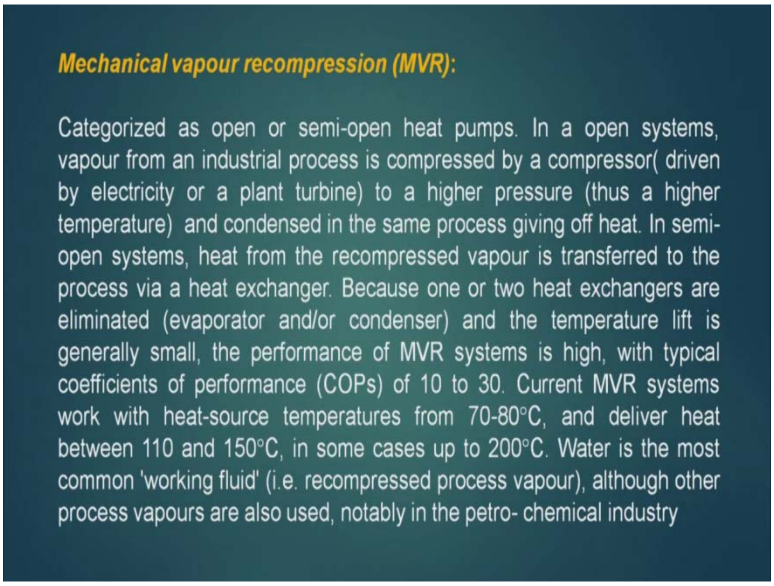

That is categorized as open or semi open heat pump in a open system vapor from an industrial process is compressed by a compression. This compression is either driven by electricity or plant turbine to a higher pressure. Thus a higher temperature and condensed in the same process giving of heat in semi open system heat from the recompressed vapor is transferred to a process via a heat exchanger, because one or two heat exchangers are eliminated evaporator or condenser or and condenser. And the temperature lift is generally small the performance of MVR system is high with typical COP values ranging from 10-30, which is a very high value current MVR systems work with heat source temperatures from 70-80 degree centigrate and deliver heat between 110 and 150 degree centigrade. In some cases up to 200 degree centigrate water is the most common working fluid although other process vapors are also used notably in the petro chemical industry.

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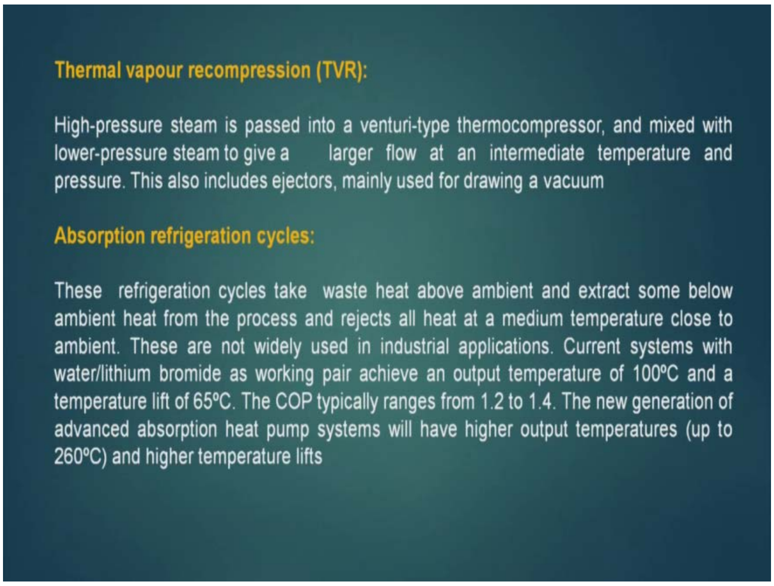

Now, thermal vapour compression which is called TVR high pressure steam is passed into a venturi type thermo compression, and mixed with the low pressure steam to give a larger flow at an intermediate temperature and pressure. This also includes ejectors mainly used for drawing a vacuum the absorption refrigeration cycle. These refrigeration cycles take waste heat above ambient and extract some below ambient heat from the process, and rejects all heat at a medium temperature close to ambient. These are not widely used in industrial applications current systems with water and lithium bromide as working pair achieve an output temperature of about 100 degree centigrade. And a temperature lift of about 65 centigrade, the COP typically ranges from 1.2 to 1.4 this is very low sloppy as we have seen from mechanically vapour recompression systems. The new generation of advanced absorption heat pump systems will have higher output temperatures up to 250 degree centigrade and higher temperature lifts.

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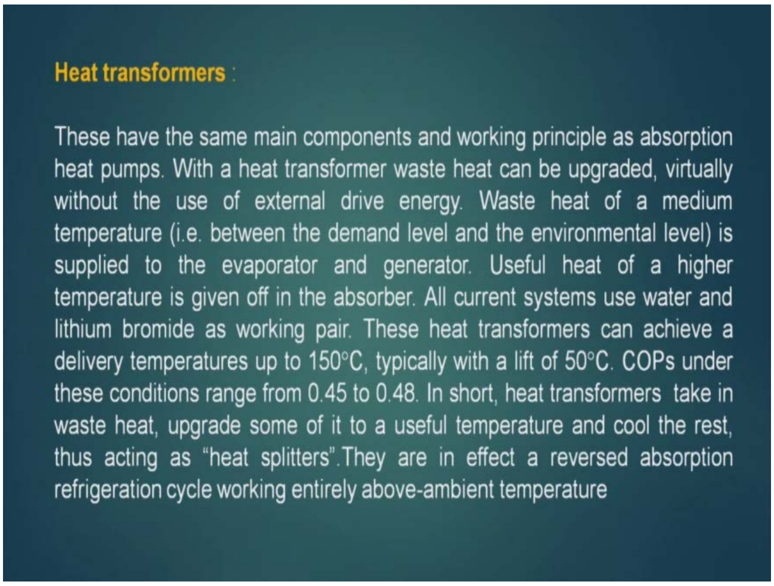

Now, that is another category of heat pump which is called heat transformer. Though it is COP is very less these have the same main components, and working principle as absorption heat pumps with a heat transformer. Waste heat can be upgraded virtually without the use of external drive energy waste heat of a medium temperature is supplied to the evaporator. And generator useful heat to a higher temperature is given up in the absorber, all current systems use water and lithium bromide as working pair. These heat transformers can achieve a delivery temperature up to 150 degree centigrade typically with a lift of 50 degree centigrate also COP under these conditions range from 0.45 to o.48, which is a very low value in short heat transformers take in waste heat upgrade some of it to a useful temperature and cool the rest. That means, whatever heat it picks up some part of heat is upgraded and some part of heat is degraded, thus acting as a heat splitter they are in effect a reversed absorption refrigeration cycle working entirely above ambient temperature.

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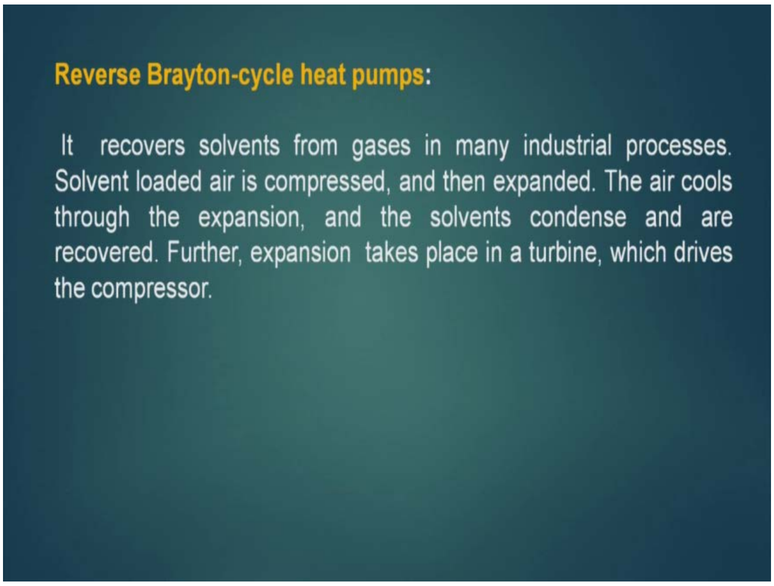

Reverse Brayton-cycle heat pumps it recovers solvent this pump recovers solvents from gases in many industrial processes solvent loaded air is compressed, and then expanded the air cools through the expansion, and the solvent condense and are recovered further expansion takes place in a turbine which drives the compression.

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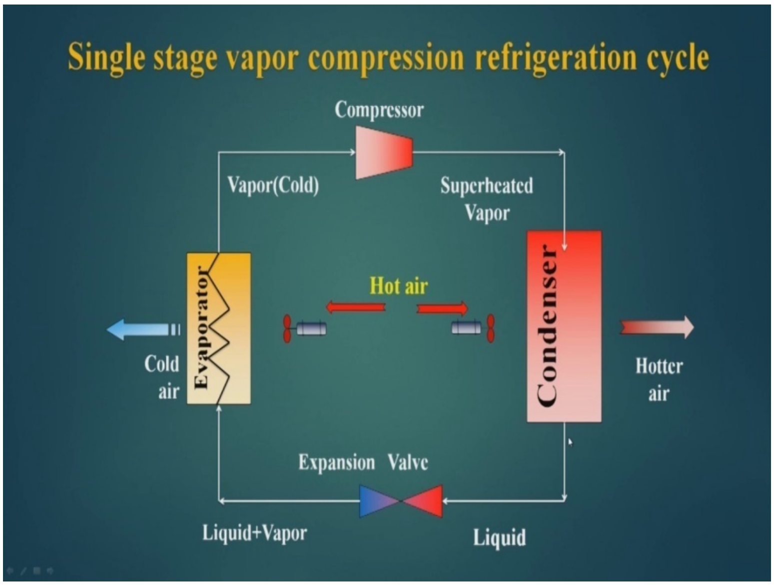

So, after seeing the different type of heat pumps let see the compression refrigeration and the absorption refrigeration which is a compression refrigeration cycle, this is the evaporator in which the liquid and vapour mix is evaporated. So, it cools and the liquid vapor goes to here, it cools down and then vapour is created here. Vapour is compressed, the superheated vapour goes to the condenser. While it condensed, then it goes to the expansion valve, here the expansion takes place, that a special drop express and we get a low pressure liquid and vapour mixture that goes to the evaporator, and the liquid part evaporates here and then we get vapour. So, this is how the compression refrigeration cycle works.

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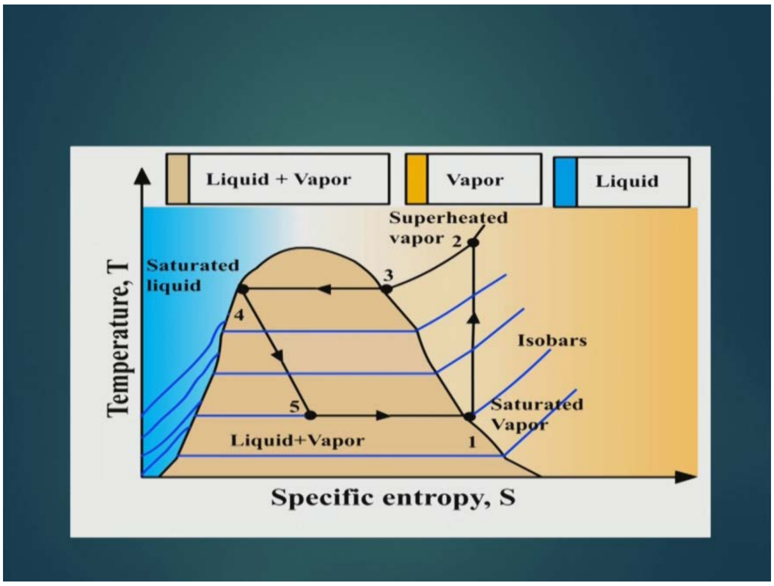

This is the entropy-temperature, entropy diagram. This is the compression part then superheating then condensing then expansion then vaporization takes place.

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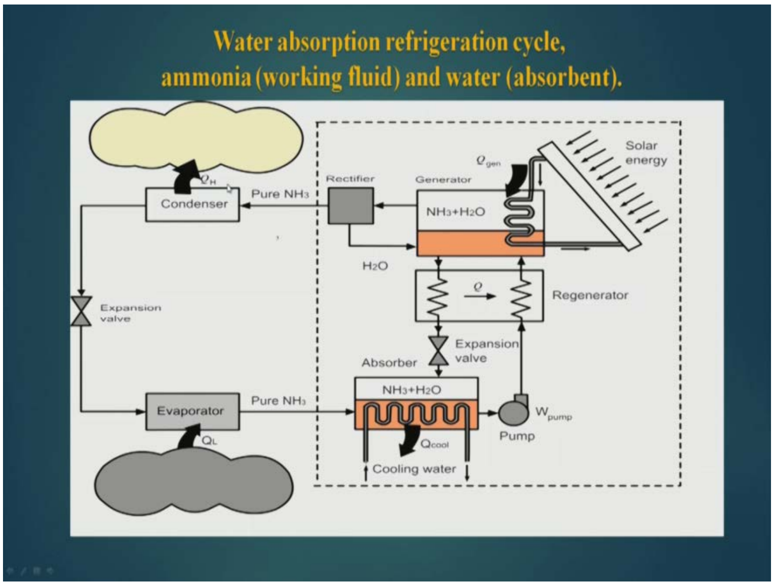

Now this gives you an absorption refrigeration cycle. This is the evaporator where we are using the NH3 and H20 combination here. So, here the liquid n h three is evaporated you get a vapour is absorbed in a H20, and the absorbed vapour and liquid is pumped through a regenerated to here. The heating takes place the vapours come out with water, they go for rectification. From rectification almost pure NH3 at a higher pressure goes to the condenser, where it condenses to the liquid and the heat is pumped to the atmosphere, and then expansion takes place. The temperature comes down the liquid, and vapour mixture of N H 3 goes to evaporator where it evaporates basically, and then you will get again pure almost pure NH3 that is ammonia and then it is being absorbed by H2O. So, this is shows a absorption refrigeration system and the driving force is the heater here, the solar heater it provides the energy for cooling. So, with low temperature heat these system can work, but you need a large amount of low temperature heat.

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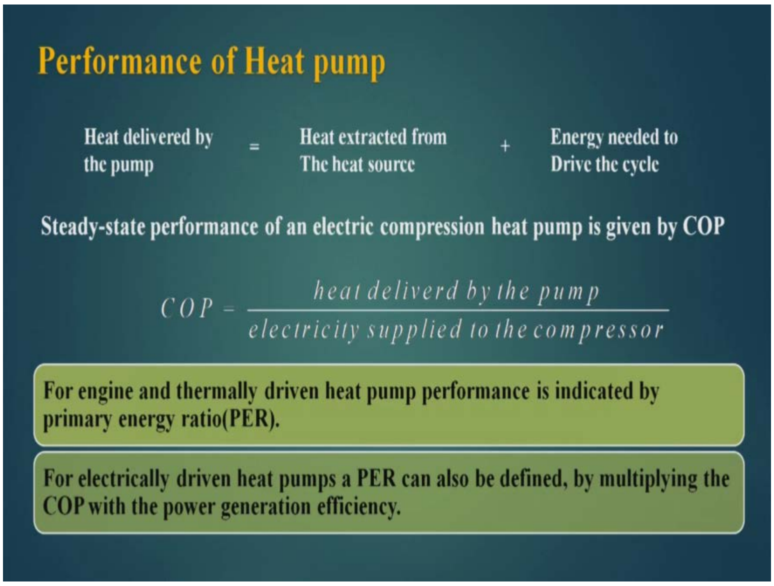

Now, the performance of heat pump the heat delivery by the heat pump is equal to heat extracted from the heat source plus energy needed to drive the cycle. So, this Q 1 is equal to Q 2 plus W. The steady state performance of an electric compression heat pump is given by this COP, which is defined like this heat delivered by the pump divided by the electricity supplied to the compression for engines, and thermally driven heat pump performance is indicated by primary energy ratio PER for electricity driven heat pumps. A PER can also be defined by multiplying this COP with the power generation efficiency.

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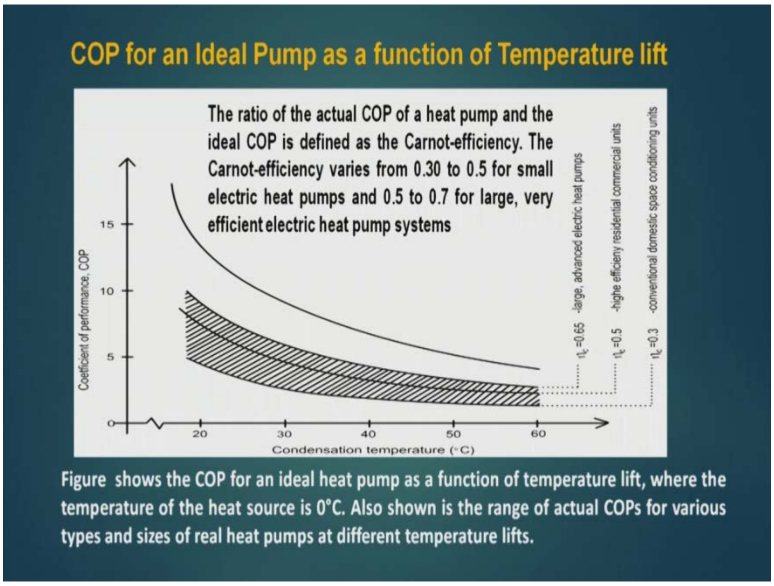

Now, this source that with different type of heat pumps or different size of heat pumps how this COP with a changes with the temperature lift, now here this figure shows the COP of an ideal heat pump as a function of temperature lift, where the temperature of the heat source is 0. So, it is picking up heat from a 0 degree heat source and condensing at different temperatures. So, whatever temperature here it is written is practically heat lift because my bottom line is at 0 degree centigrade. So, here we see that the n c is point 0.65 for large advanced electric heat pumps, and for it is 0.5 for highly efficient residential commercial units and 0.3 for conventional domestic safe conventional units. So, the receiver of the actual COP of a heat pump and the ideal COP is defined as the Carnot efficiency varies from 0.30 to 0.5 for small electric heat pumps and 0.5 to 0.7 for large and very efficient electric heat pump systems. So, here we see that it is the function of the lift as well as size of the heat pump, and the type of the technology which is used for heat pumps.

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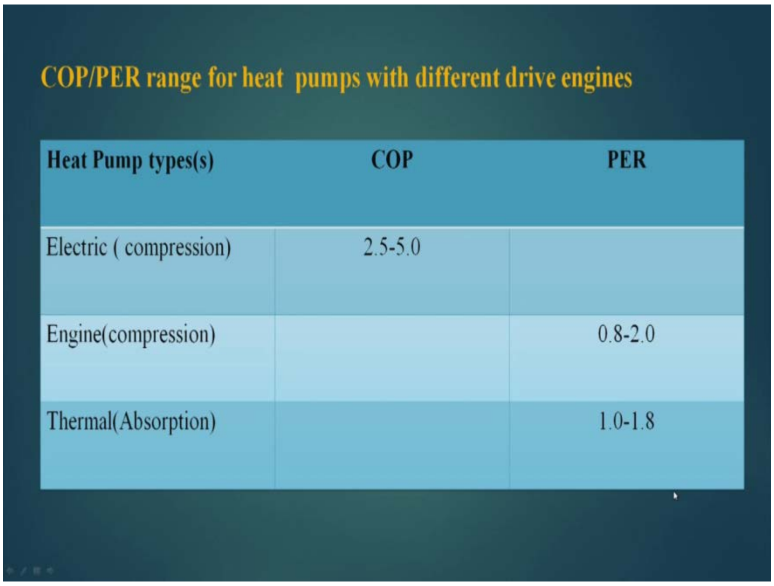

COP/PER range for heat pumps with different drive engines

Heat Pump types(s)	COP	PER
Electric (compression)	2.5-5.0	
Engine(compression)		0.8-2.0
Thermal(Absorption)		1.0-1.8

Now this shows the COP and PER range for heat pumps with different drive engines. If I take a electric compression is used for heat pump, this COP is 2.5 to 5.0. If I use a engine compression, it is 0.8 to 2.0 p e r and thermal, if I use its very low is 1.0 to 1.8 for others.

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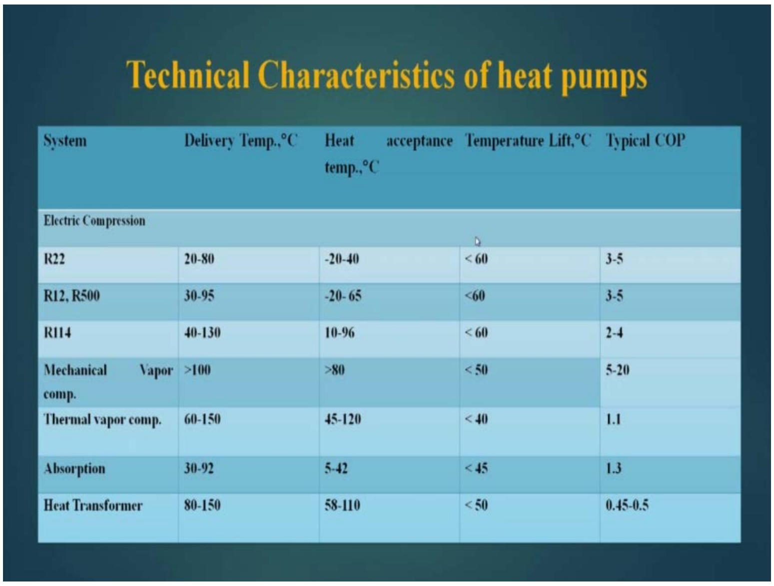

Technical Characteristics of heat pumps

System	Delivery Temp.,°C	Heat acceptance temp.,°C	Temperature Lift,°C	Typical COP
Electric Compression				
R22	20-80	-20-40	< 60	3-5
R12, R500	30-95	-20- 65	<60	3-5
R114	40-130	10-96	< 60	2-4
Mechanical Vapor comp.	>100	>80	< 50	5-20
Thermal vapor comp.	60-150	45-120	< 40	1.1
Absorption	30-92	5-42	< 45	1.3
Heat Transformer	80-150	58-110	< 50	0.45-0.5

If you see this electrical compression, I am using R 2 2. If I use the delivery temperature is 20 to 80, and the heat acceptance temperature which is basically the evaporated temperature is minus 20 to minus 40, and temperature is lift is about less than 60 degree centigrade, and this COP is 3.5. Similarly for R 1 2 this is 3.5 also. And temperature lift is also same R 1 1 4, this is 60. And this is 224 and mechanical vapour compression, if you take the lift is 50 little bit less, but the COP value is very large 5 to 20. And thermal vapour compression it is 1.1, and lift is also less 40 absorption, it is less than 45 degree and the COP is 1.3. And heat transformer this is less than 50 degree, and if it is very low 0.4 to 0.5. So, here see that mechanical vapour compression the lift is little bit less for this COP is very high.

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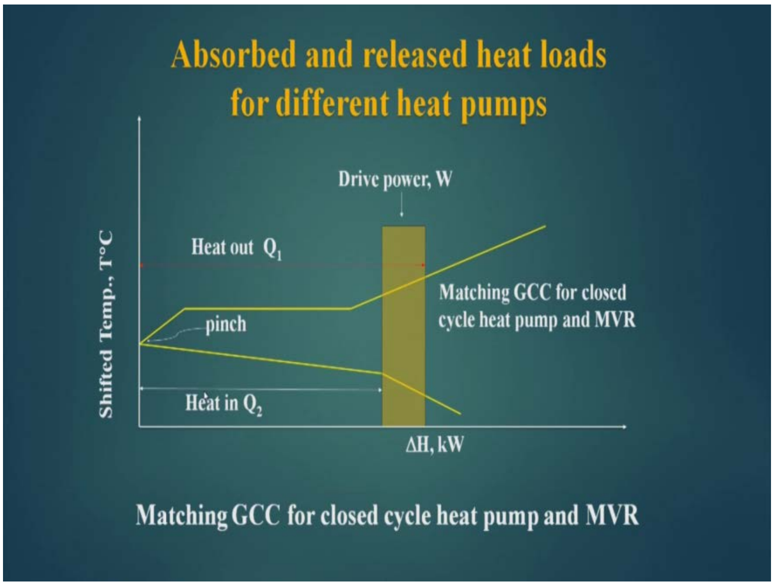

Now, if you see that absorbed and released heat loads of different heat pumps, if I am using a closed cycle heat pump. So, this is the amount of Q 2 it picks up the distance between this and this is the amount of Q 2 its picks up, and deliver is from here to here; that means, this band is for driving power. So, this much amount it will pick up and this much amount it will deliver.

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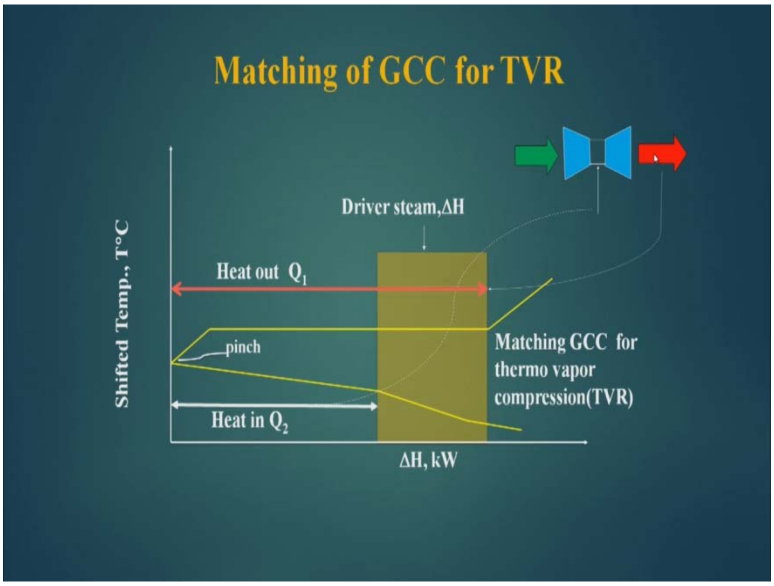

Now, for thermal vapour compression units this much amount it picks up, and this much amount it delivers and it is the driver steam systems delta H. So, it adds up to this Q 2 and forms its Q 1. So, this is amount of heat it delivers and this is amount of heat it picks up. So, this is a TVR, where the high pressure and high temperature steam is injected its struck vapour from here they mix together, and then we get a mix steam which deliver seat.

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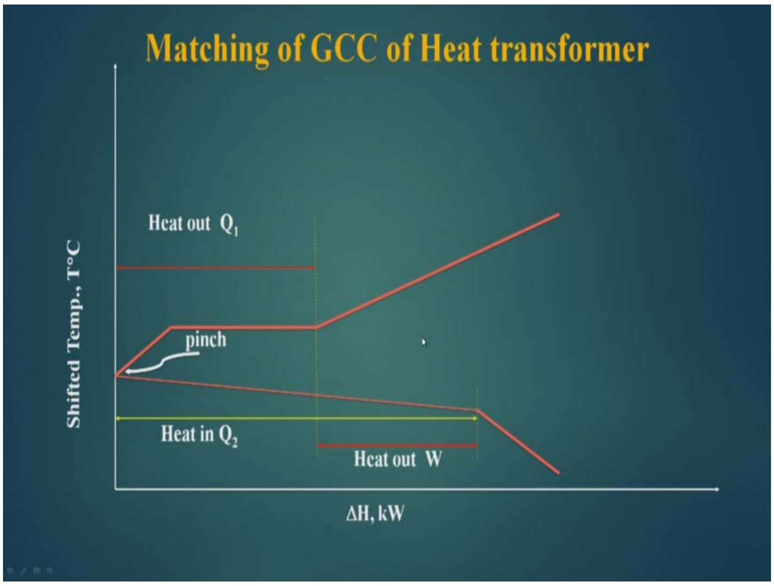

This is for heat transformer this is the amount of heat, which is available a part of heat this much is upgraded and this is a downgraded. So, we get less heat here in a heat transformer which is a upgraded heat.

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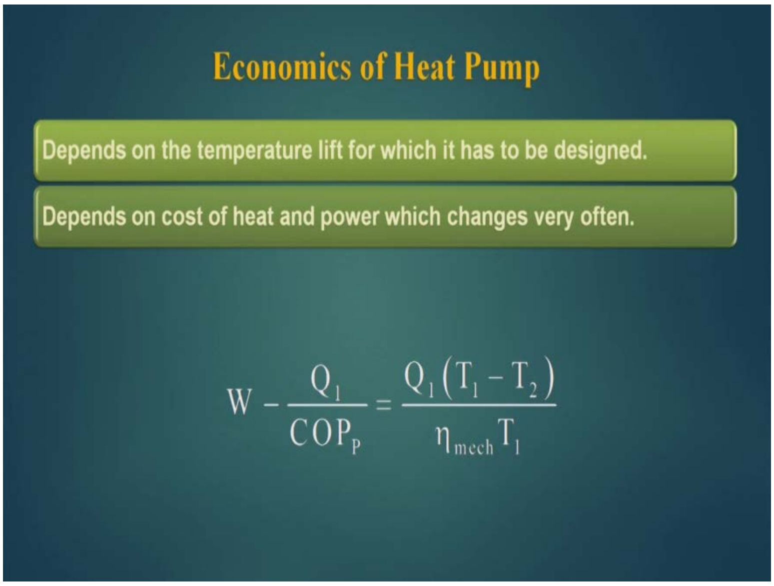

Now the economics of heat pump will depend on the temperature lift for which it has to be designed. Because if the temperature lifts are very high, the economy does not support it the economics, and depends on cost of heat and power which changes very often it is a interesting part the cost of heat, and the cost of power is varying. So, is may be possible if the today the heat pump is not economical after few years it will be economical. So, the warden is given by this Q 1 by COP is equal to this is W equal to Q 1 by COP.

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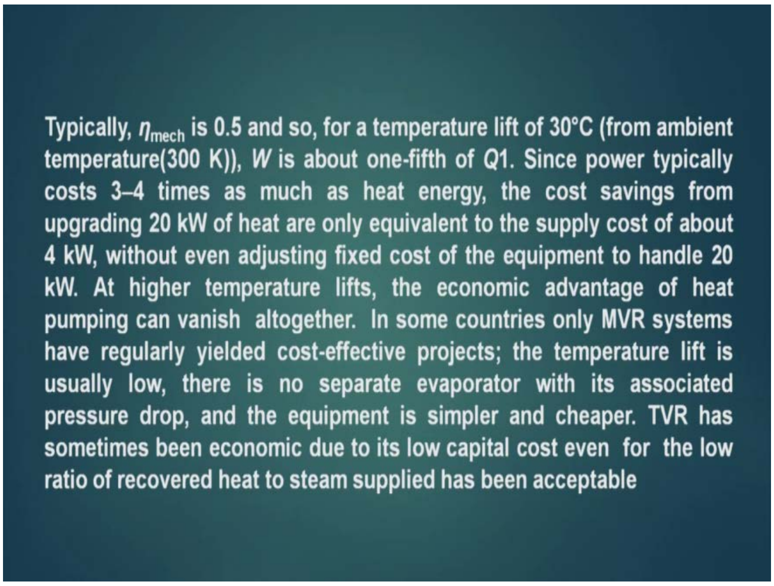

Now to get a fairly good idea how the efficiency of this heat pump works typically the n mechanical is about 0.5 and. So, for a temperature lift of 30 degree centigrade from ambient temperature W is about 15 of Q 1 ; that means, whatever heat I am delivering its 15 is the power requirement to lift it for about 30 degree centigrade. Since power typically costs 3-4 times as much as the heat energy the cost saving from upgrading 20 KW of heat are only equivalent to this supply cost of about 4 KW without even adjusting fixed cost of the equipment to handle 20 KW at higher temperature lifts. The economic advantage of heat pumping can vanish altogether this we have seen because the economics is a is highly sensitive to the temperature lift.

In some countries, only MVR systems have regularly yielded cost effective projects, because we have seen that the MVR and COP is very high. The temperature lift is usually low, there is no separate evaporator with its associated pressure drop, and the equipment is simpler and cheaper. TVR has sometimes been economic due to its low capital cost even for the low ratio of recovered heat to steam supplied has been acceptable. So, what we see here the MVR’s are very cost effective, but they can only be used or we can say that they are only be economical for lower temperature lift may be below 50 degree centigrate.

Now, let us come to the design part of it for the design we have to integrate this heat pumps with. The GCC. So, the heat pumps has to be described in a shifted temperature and entholbrid diagram as GCC also expressed in a shifted temperature and delta t diagram now let us see how two. GCC’s physically when I say two GCC I mean that one GCC for the heat pump, and other GCC for the process now let us see that how to integrate two G C C’s.

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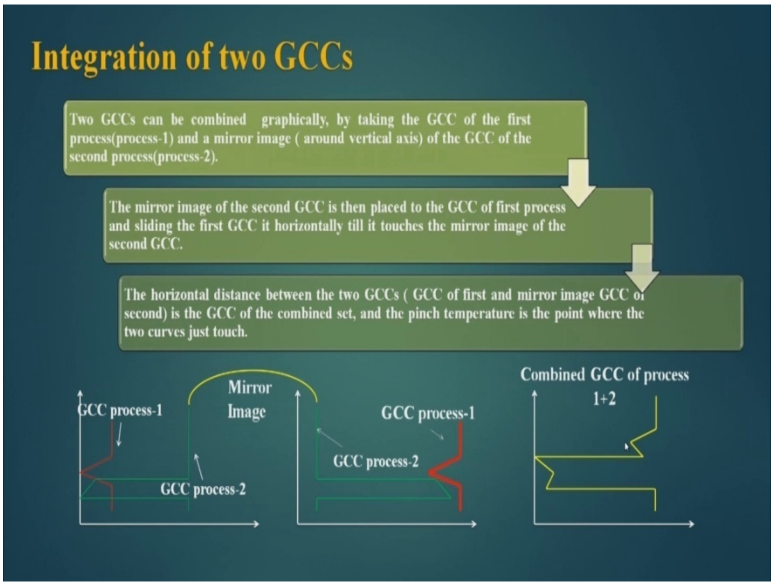

Now, these are two GCC, one GCC for the process and the other GCC for the process two. And basically this will be the heat pump. Now what we have to do we have to find out the mirror image of the second GCC, and then placed to the GCC of the first process and sliding the first GCC to it horizontally till it touches the mirror image of the second G C C. So, if I see the mirror image of the second GCC process here this is this. So, basically on this axis have to rotate it. So, when I rotate it I get this GCC, which is the mirror image of this GCC process two and then I put my first GCC here and this touches at this point. Now the horizontal distance between the two GCC’s that is GCC of the first, and mirror image GCC of the second is the GCC of the combined set and the pinch temperature is the point where the two curves just touch. So, this is the point where it is touching.

So, this will be pinch and the distance between this GCC and this GCC is measured and plotted. So, if I do so my combined GCC of the process one and two will look like this. So, this point here the touching point is this which is the pinch point. So, this pinch point of the combined GCC will be different than the pinch point of the individual GCC, that is process one and process two. Let us see what we have done this two GCC‘s are to be combined GCC of process one, and GCC of process two then process two GCC has to be its mirror image has to be taken. So, I took the mirror image of the process two GCC here and then slide the process one GCC tively touches at one point and once it touches, I stop it then this gap between this r plotted here that they take different temperature levels. So, I get a combined GCC. Now what I will do with of this combined GCC now, because my aim is to integrate the heat pump with the GCC. So, one of the process of this heat pump say process two and process one is the actual process which I am using.

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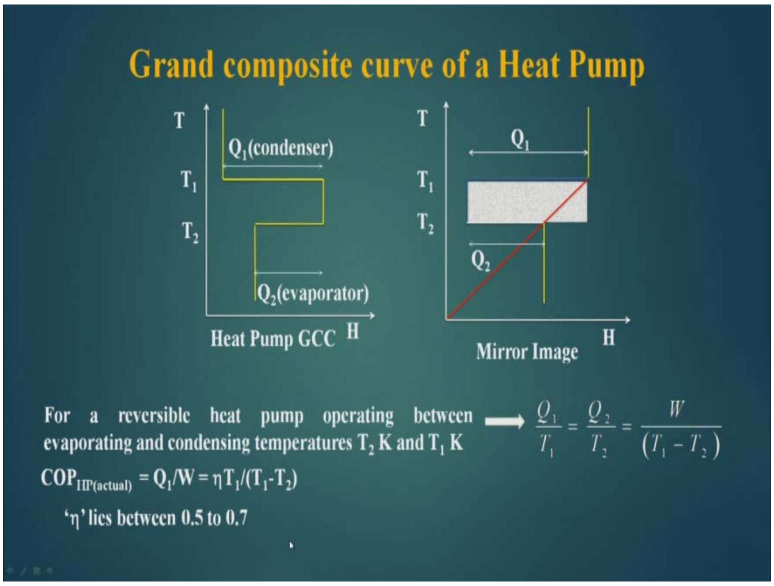

Now let us see the a heat pump, now the if I plot the heat pump this will look like this this is the evaporator and this is the condenser because the less heat, that is Q 2 will be taken from the evaporator and more evaporator will producing the condenser. So, this look like this. So, if I get a mirror image of this. So, this will look like this now for reversible heat pumps operating between evaporating and condensing temperatures T 2 and T 1. This holds good Q 1 by T 1 is equal to Q 2 by T 2 is equal to W by T 1 minus T 2 and COP of the heat pump actual is this where n lies between 0.5 to 0.7.

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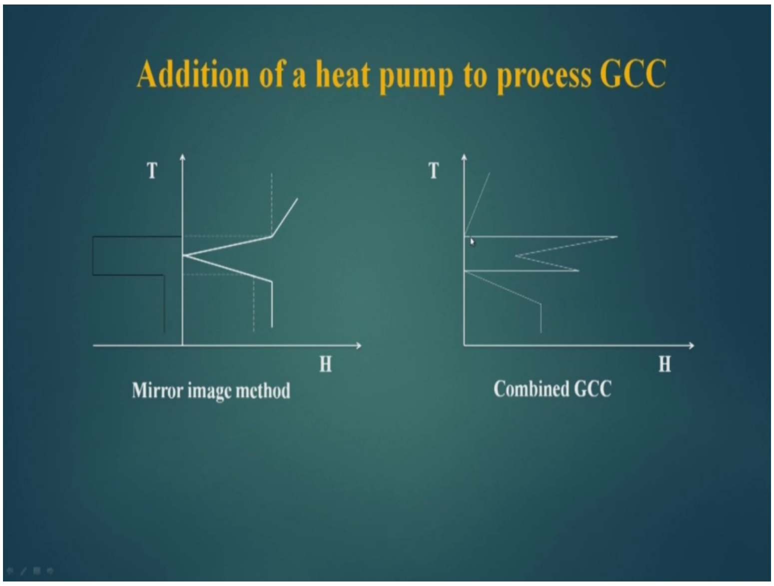

Now let us see how this we have to integrate the heat pump with GCC. So, this is the mirror image of the GCC and this is our process. So, this touches at this two point. So, what I am expecting a two pinch combined GCC, now if I analyze this GCC what I am finding that the heat, which is available here is going down up to this without working no full full work is done. So, at this part I can use a cannot engine to recover some of the energy; that means, the heat pump, which I am using to pump the heat from a lower temperature to a higher temperature is not working very efficiently.

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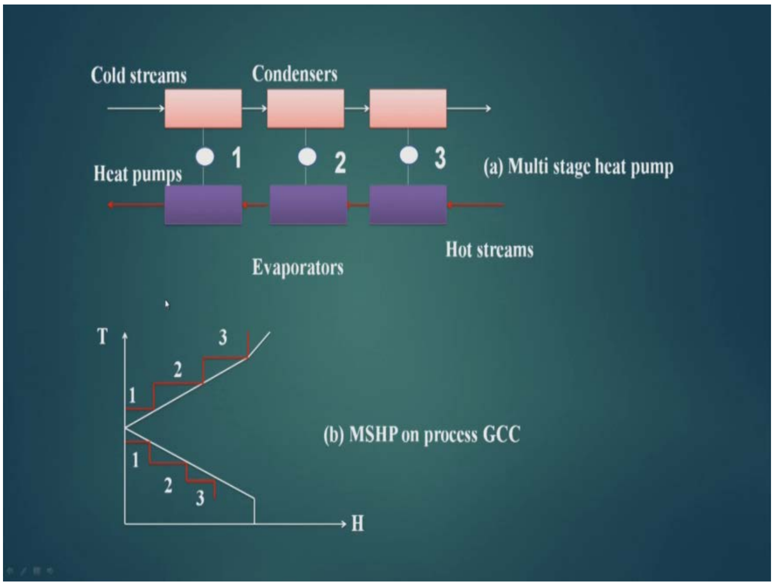

Now, this can be solved to some extend if I am using multi stage heat pumps. So, in the multi stage heat pump will look something like this. And then this is the process GCC, it a has got a better fit with multi stage heat pump and; that means, if I am using a multi stage heat pump though the complexity of the design will increase the cost will increase, but it will be more energy efficient than the single stage heat pump. Now this shows that the heat pump is catching this extreme boundary of this GCC of the process. So, this shows the maximum saving which can be done, because if I pump more energy to this then it will start cooling this part of the GCC, which is not required. Because I am using a heat pump to pump energy that means, to cool that to heat the cold process streams and if I increase here the amount; that means, this line will cut it here o in this direction. So, this will start heating this output of the h p heat pump. So, it is not required.

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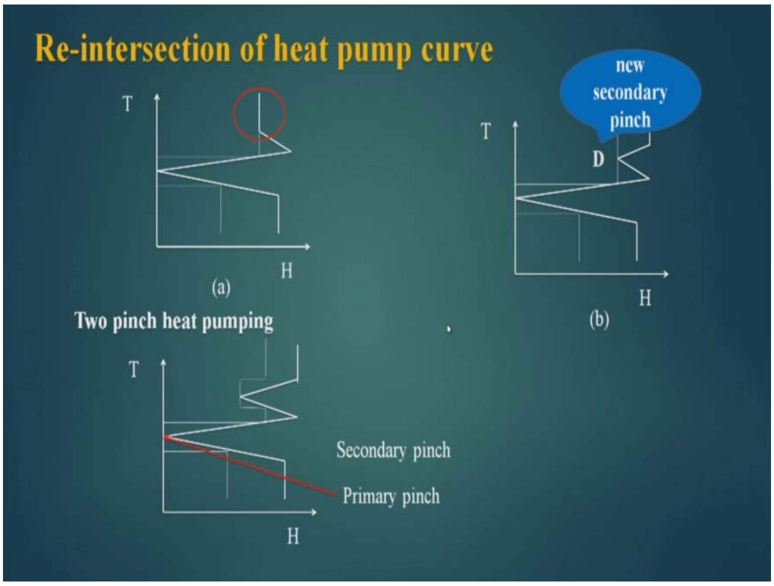

So, this shows the maximum heating which can be done by using a heating pump similarly I cannot increase the condenses also because it will give the reverse effect, but if I have got two pinches here one pinch here and one pinch here this heat can be upgraded. A and can be put here for heating purposes similarly heat available from here can be put here for heating purposes, but in this case there is no scope for improvement, but here there is a case for improvement where the heating can be done. So, here in the third part we can see that we can have this part of heat can pick up and put it here. So, this can be improved.

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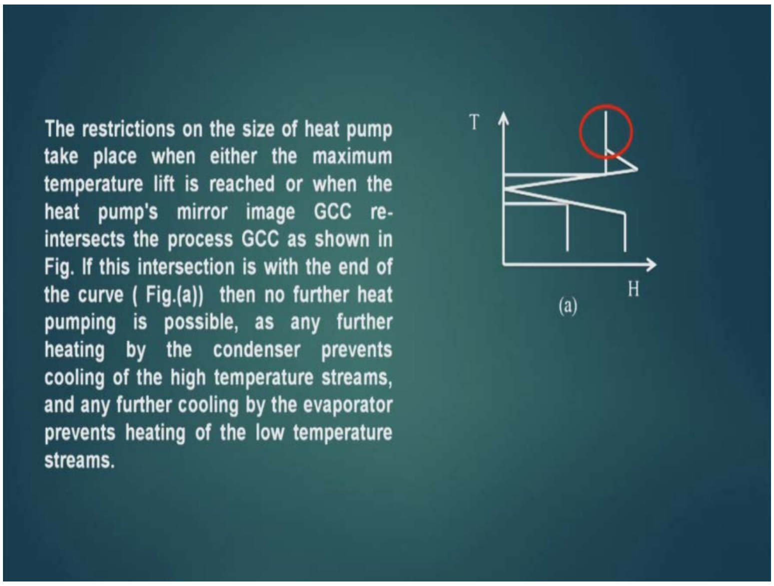

Now let us see it. The restrictions on the size of heat pump take place, when either the maximum temperature lift is reached or when the heat pump mirror image GCC re-intersects the process GCC as shown in the figure here. If this intersection is with the end of the curve as shown in the a-part, this is end of the curve this intersection. No further heat pumping is possible as any further heating by the condenser prevents cooling of the high temperature streams, and any further cooling by the evaporator prevents heating of the low temperature streams.

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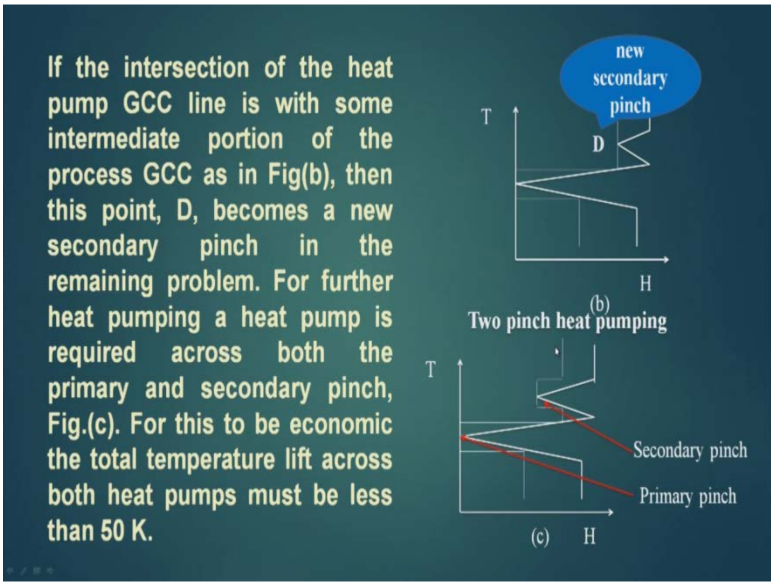

So, if it touches like this then this is the maximum heating, which we can do if the intersection of the pump GCC is with some intermediate portion of the process GCC as shown in the figure b. Then this point, which is called d point, becomes a new secondary pinch in the remaining problem for further heat pumping. A heat pump is required across both the primary and secondary pinch, because we have seen that the integration of heat pump is beneficial when is integrated across the pinch. So, here across the pinch I am putting of a heat pump. And if is secondary pinch here also I can heat pump across of the pinch, and it is shows in the c part or this will be done. So, here we can employee a secondary pumping as shown here.

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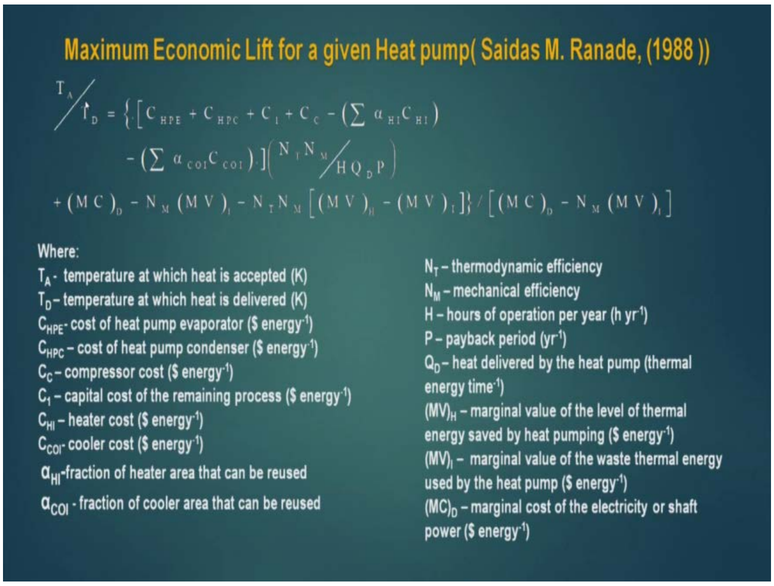

Saidas M Ranade has derived an equation to give what is the maximum economic lift for a given pump. So, this is the equation which is available where these are the input parameters T A a is the temperature at which heat is accepted, and T is the temperature at which heat is delivered. So, if I am able to know this two temperatures I can find out the lift. So, it gives you the ratio when pertinent parameters are entered into this F b this economic parameter are also there the operating parameters are also there. So, find out a maximum lift for a given heat pump from this and can apply to a problem. So, these are the references.

Thank you.