Chemical Process Utilities
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Module No # 11
Lecture No # 55
Refrigeration Systems

Welcome to the next section of refrigeration system now before we go into the detail let us have a brief outlook about the previous lecture. In the previous lecture we discussed about the refrigeration system and it is component. And we had a discussion about the various kinds of auxiliary devices, accumulators, receivers, oil splitters, strainers, dryers.

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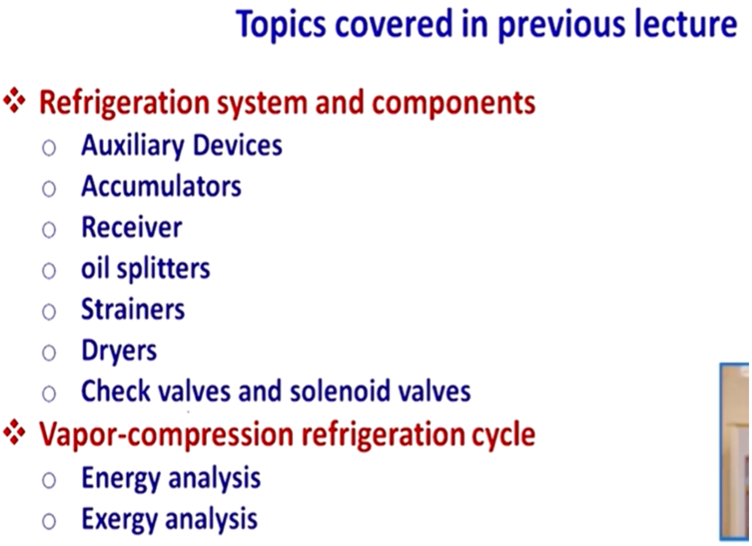

And we had a discussion about the check valves and solenoid valves. Apart from this we performed the vapour compression refrigeration cycle under the aegis of energy analysis, exergy analysis.

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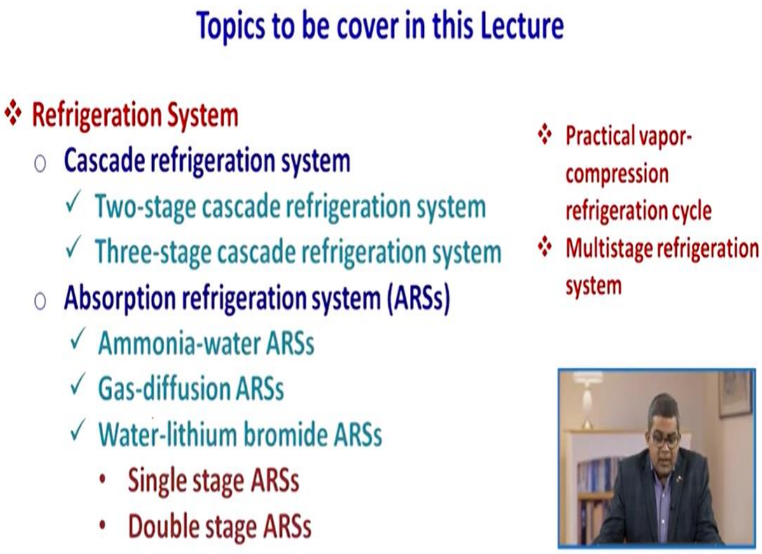

Now in this particular lecture we are going to discuss about the refrigeration system. In which we will discuss about the cascade refrigeration system, where we will discuss about the 2-stage cascade refrigeration system, or 3 stage cascade refrigeration system. Apart from this we will discuss about the absorption refrigeration system or ARS, in which we will discuss about the ammonia water ARS, gas diffusion ARS, water-lithium bromide absorption refrigeration system.

Under this we will discuss about the single stage absorption refrigeration system and double stage absorption refrigeration system. Then we will discuss about the practical vapour compression refrigeration cycle and lastly, we will discuss about the multi-stage refrigeration system.

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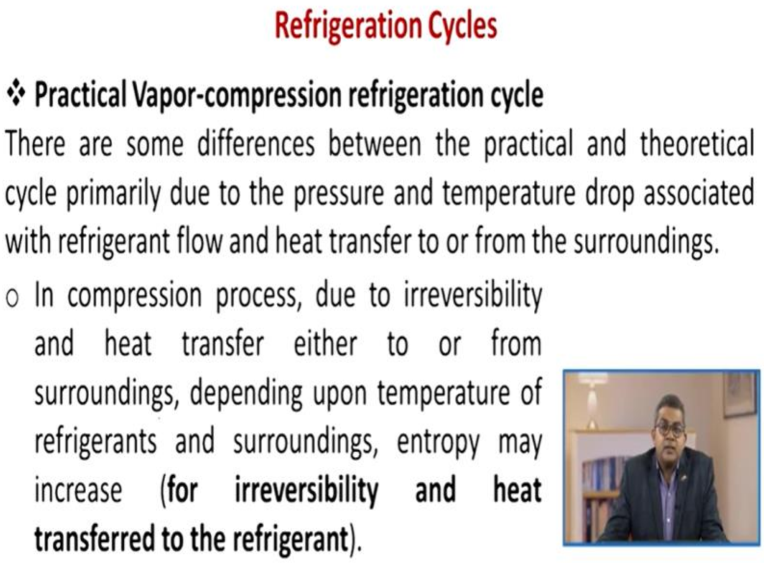

Now let us talk about first about the refrigeration cycle under this the practical vapour refrigeration cycle. Now there are some differences between the practical and theoretical cycle primarily due to the pressure and temperature drop associated with the refrigerant flow and heat transfer to or from the surrounding. Now in compression process due to irreversibility you cannot avoid the irreversibility.

So due to irreversibility and heat transfer either due to or from surrounding, depending upon the temperature of refrigerant and surrounding entropy may increase for irreversibility and heat transfer to the refrigerant.

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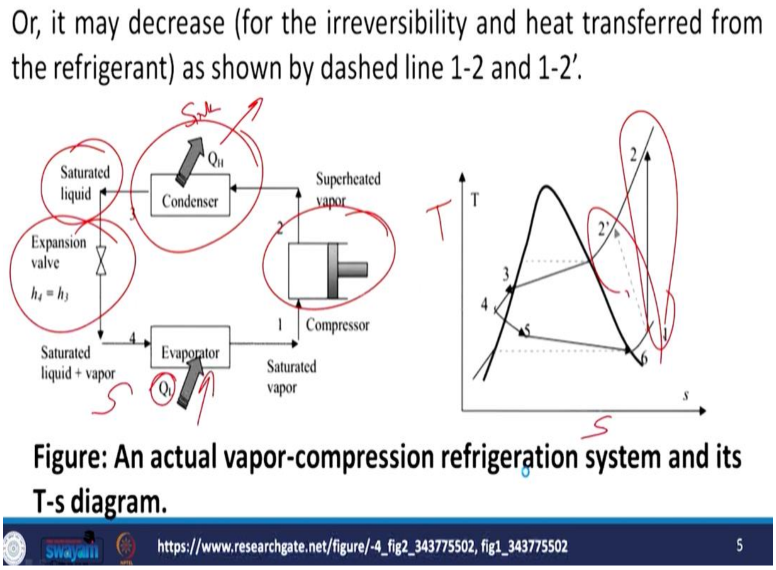

Now it may decrease for irreversibility heat transfer from the refrigerant, now here you see that in this particular figure we have shown this in the dotted line from 1 to 2 and 2 dash. Now here this is the simple refrigeration system or Vapour compression refrigeration system. Here you are extracting Q L amount of heat from a body which is maintained at low temperature. So sometimes it is referred as a source, and here this is the sink.

So, from here evaporator you are extracting Q L amount of heat and it this it subjected to the compressor, then this is a condenser through which you are discharging this Q H amount of heat to the sink or a hot surface body. And again, it restores to the saturated liquid shape through the expansion valve it again go back to the evaporator. So, this entire system thermodynamically is depicted in this T s diagram.

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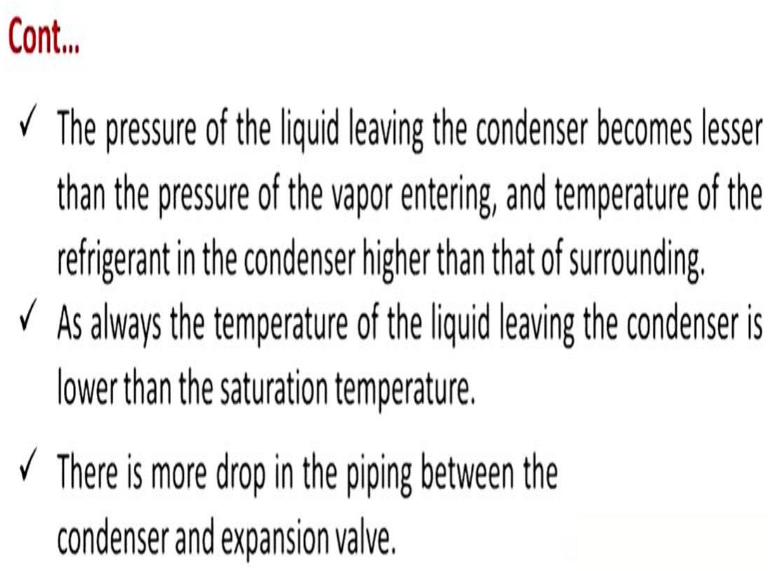

Now the pressure of the liquid leaving the condenser become lesser than the pressure of Vapour entering, and the temperature of the refrigerant in the condenser it is usually higher than that of the surrounding. So as always, the temperature of the liquid leaving the condenser is lower than the saturation temperature. Now there are more drops in the piping between the condenser and expansion valve so from 3 to this stage there are temperature drop.

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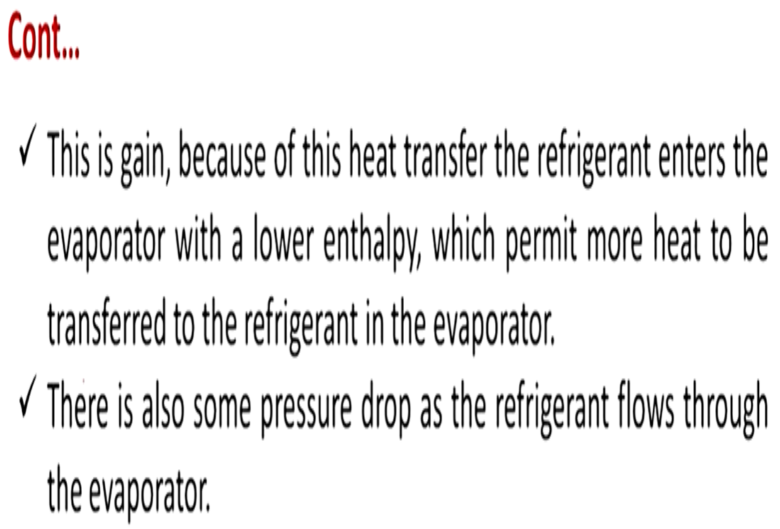

Now this is gain, because of this heat transfer the refrigerant enters the evaporator with a lower enthalpy, which permit more heat to be transferred to the refrigerant in the evaporator. So that is why, this is a gain and efficiency of your refrigeration cycle can be improvised. Now there is also some pressure drop in the refrigerant flow through the evaporator it is quite obvious.

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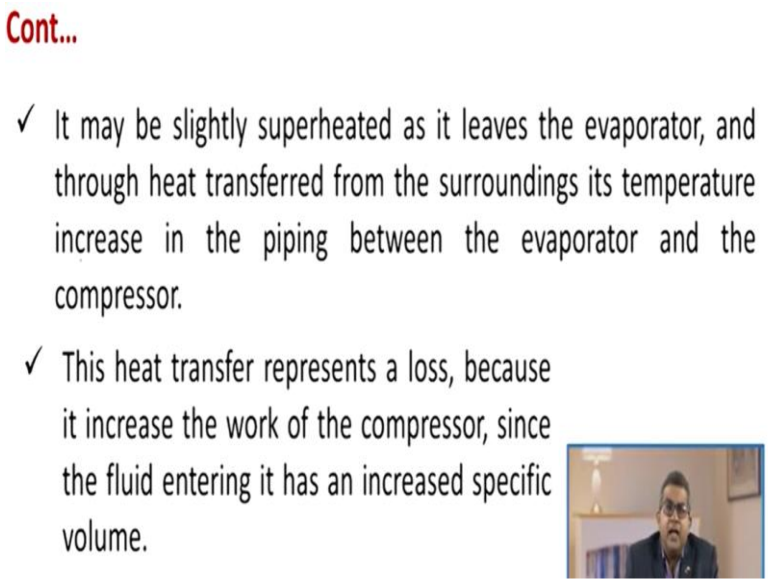

Now it may be slightly superheated as it leaves the evaporator and through heat transfer from the surrounding its temperature increase in the piping between the evaporator and the compressor. Now this heat transfer represents a loss, because it increases the work of the compressor, since the fluid entering it has an increased specific volume.

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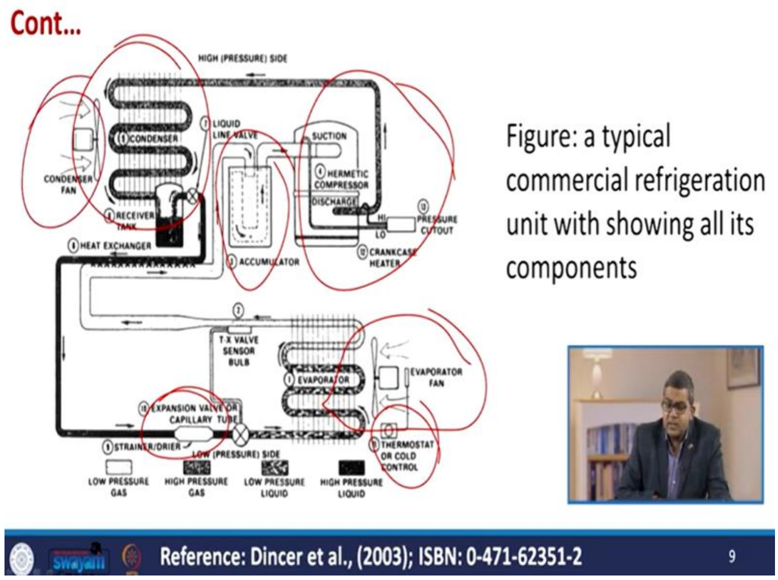

Now here you see this is a typical commercial refrigeration unit this shows all, its component. Now here you see that this is the evaporator or evaporating fan and you need to have a temperature control so thermostat control is there. Then here you see that this is the expansion valve, and here you see that this is the main compression unit with the accumulation so all kind of auxiliary setup they are there.

And this is your condenser and again you are having this condensing fan with the high-pressure side, so this is the typical commercial refrigeration unit.

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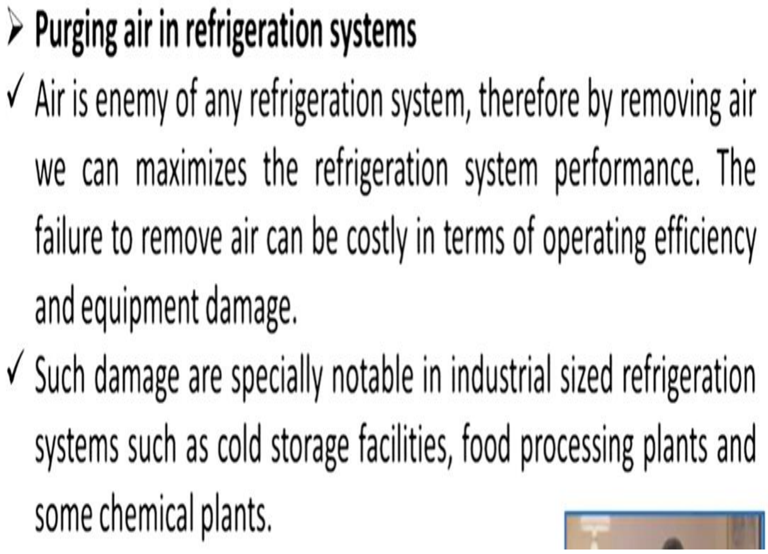

Now let us talk about the purging air in the refrigeration system. Now air is the enemy of any kind of refrigeration system, therefore you have to remove the air in case if it is entrapped. So, by removing air we can maximize the refrigeration system performance and sometimes referred with respect to the coefficient of performance. The failure to remove air can be costly in terms of the operating efficiency or sometimes it may lead to the equipment damage.

Now such damage is especially notable in industrial sized refrigeration system such as cold storage facilities, food processing plants and sometimes the chemical plants.

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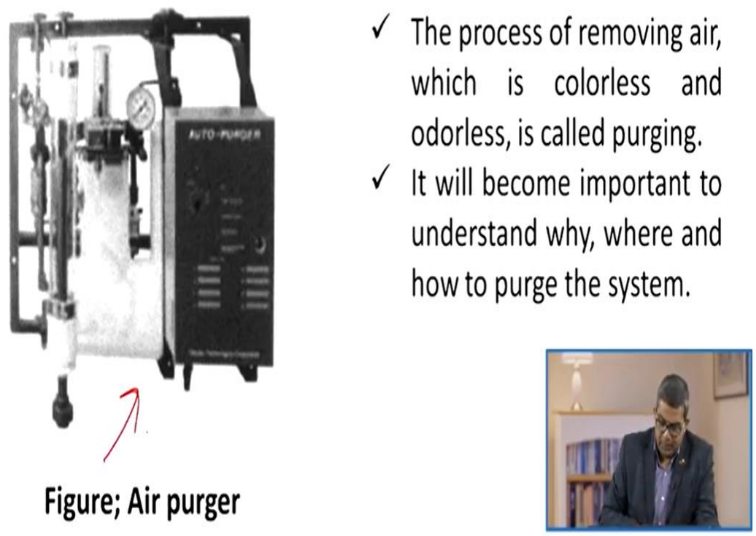

Now the process of removing air, which is colourless and odourless, is called purging. Now it become more important to understand; that why, where and how the purging of the system takes place. Now this is a typical photograph of air purge.

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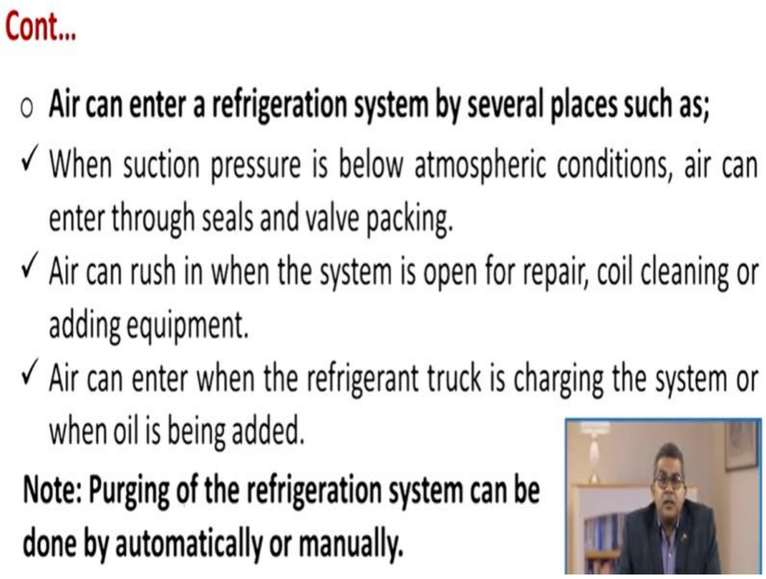

Now air can enter a refrigeration system by several ways or several places like, when suction pressure is below atmospheric condition, air can enter through seals and wall packing. Air can rush in when the system is open for repair, coil cleaning or any kind of addition of equipment. Air can enter when the refrigerant truck is charging the system or when oil is being added. So, the purging of the refrigeration system can be done by automatically or manually.

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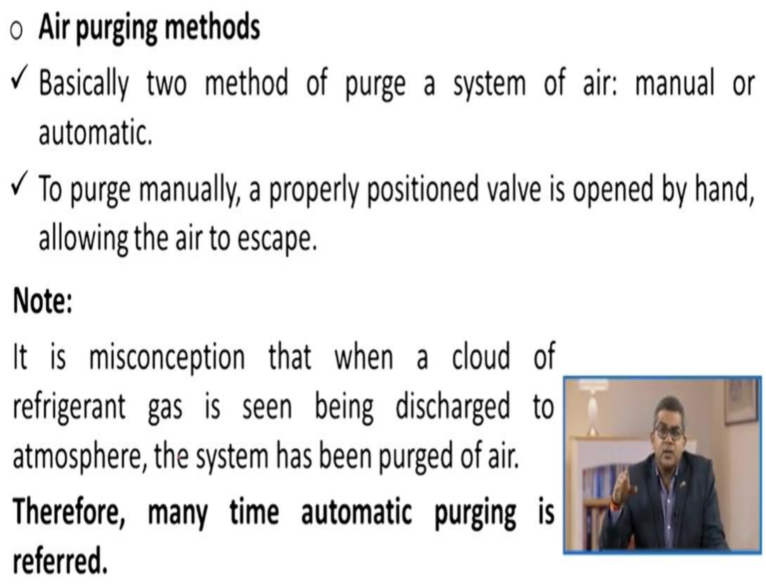

Now there are various methods for air purging and broadly you can say there are 2 methods of purging of a system one is the manual or second one is the automatic. Now to purge manually a properly positioned valve is opened by hand, allowing the air to escape. Now it is the misconception that when a cloud of refrigerant gas is seen being discharged to atmosphere, the system has been purged of gas. Therefore, many times automatic purging is required, or referred, or recommended.

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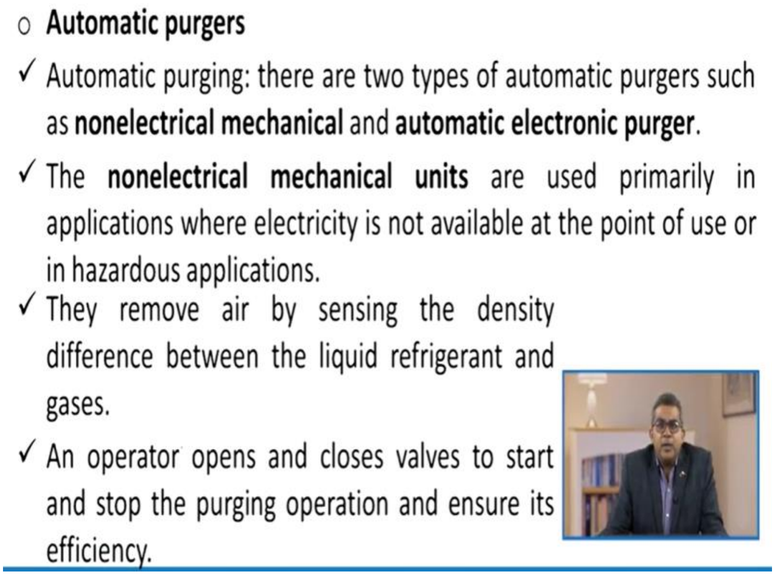

Automatic purgers, the automatic purging there are 2 types of automatic pursers such as nonelectrical mechanical and second one is the automatic electronic purger. The nonelectrical mechanical units they are used primarily in the application where electricity is not available at the point of use or in hazardous application. They remove air by sensing the density difference between the liquid refrigerant and gases. Now an operator opens and closes wall to start and stop the purging operation and ensure its efficiency.

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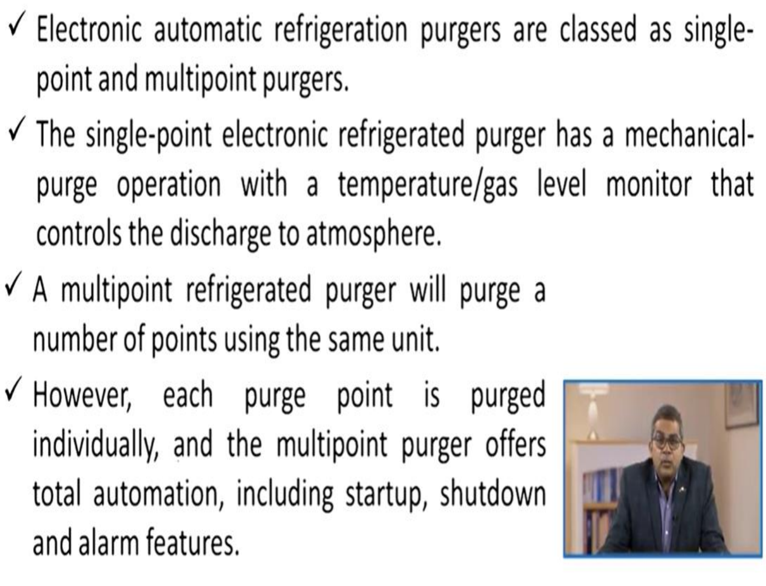

The electronic automatic refrigeration purgers are classed as a single-point and multi-point purgers. The single point electronic refrigerated purger has mechanical-purge operation with the temperature or gas level monitor that controls the discharge to atmosphere. A multipoint refrigerated purger will purge a number of points using the same unit. However, each purge unit is purged individually, and multipoint purger offers total automation, including start-up, shutdown and alarm features.

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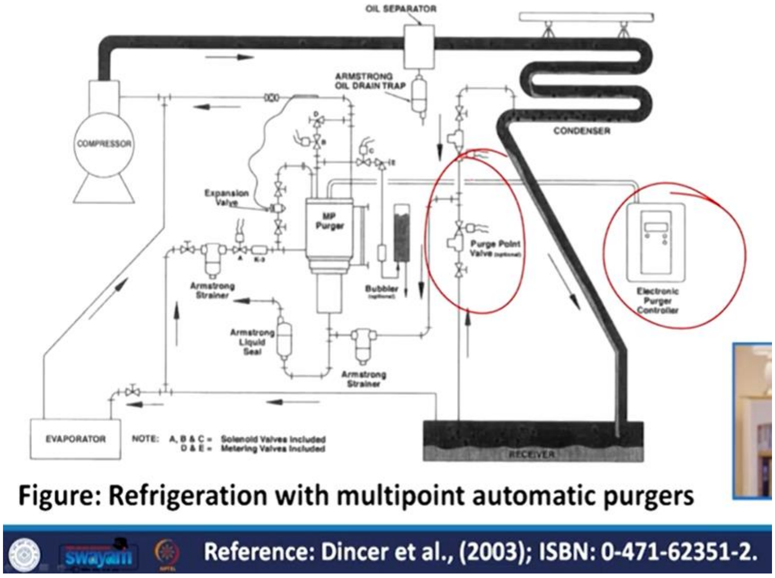

Figure: Refrigeration with multipoint automatic purgers

Now here you see that the refrigeration with the multipoint automatic purger. Now this is the electronic purger control and you see all the major operations are enlisted, and this is the purging valve so you can see that the attachment of purging device in this particular refrigeration apparatus.

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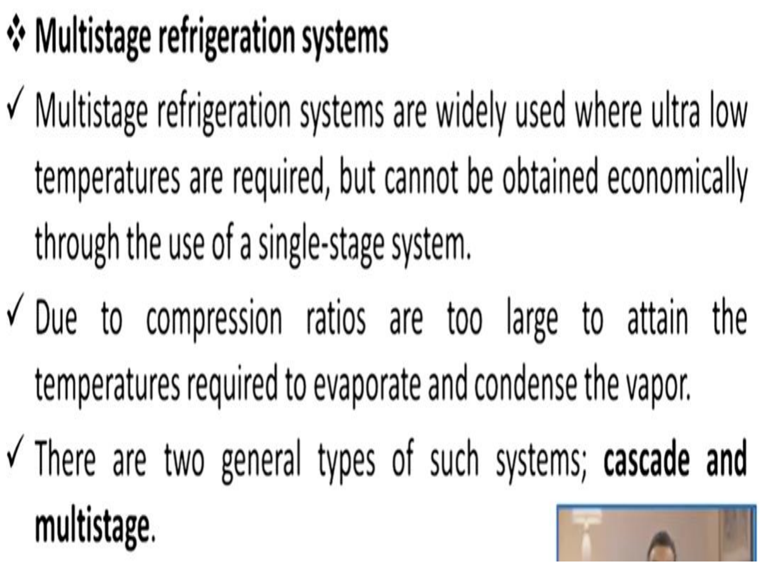

Now let us talk about the multistage refrigeration system. The multi stage refrigeration system they are widely used where ultra-low temperatures are required, but cannot be obtained economically through the use of a single-stage system. Now due to compression ratio they are too large to attain the temperature required to evaporate and condense the Vapour. Now there are 2 general type of such system one is the cascade and second one is the multi stage.

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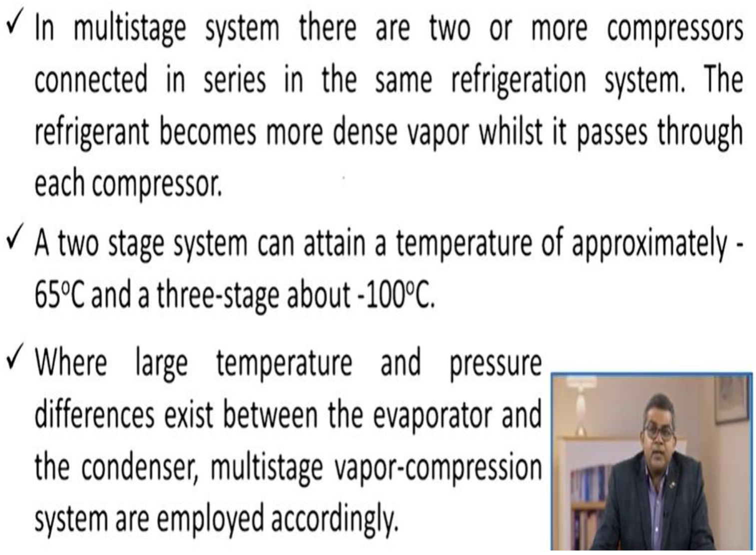

So, in a multi-stage system there is 2 or more compressor they are connected in series in the same refrigeration system. The refrigerant becomes more, dense vapour while it passes through each compressor. A 2-stage system can attend a temperature of approximately 65 degrees Celsius and 3 stage about -100 degree Celsius. Where large temperature and pressure differences exist between the evaporator and the condenser, the multi stage Vapour-compression system are employed accordingly.

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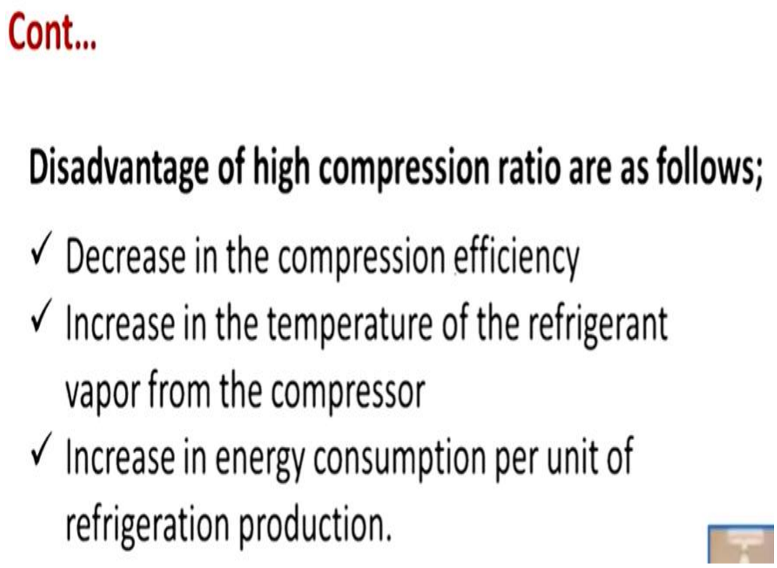

Now there are various disadvantages of high compression ratio, one is that the decrease in the compression efficiency second is the increase in the temperature of the refrigerant Vapour from the compressor. And third one is the increase in the energy consumption per unit of refrigeration production.

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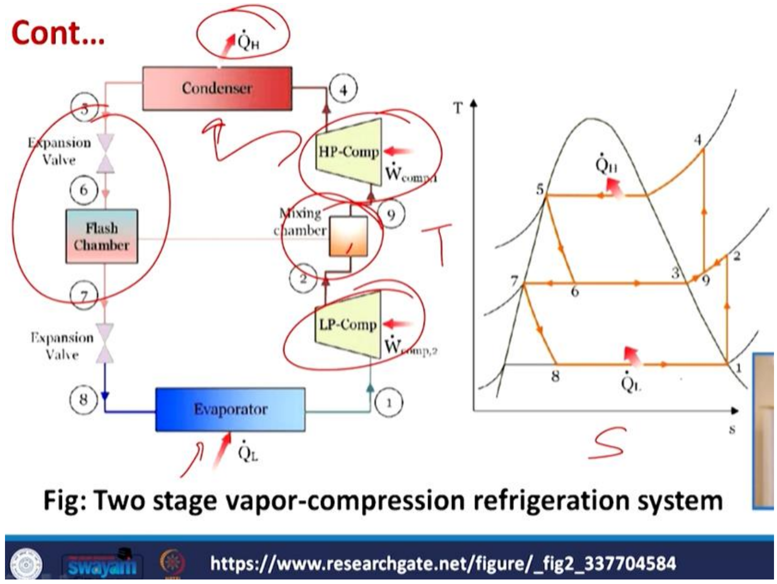

Now here you see that this is the 2-stage vapour compression refrigeration system. Now here this is the evaporator through which you are extracting the Q L amount of energy from a low temperature source, and this is the 2-compression unit. One is the low-pressure compression units and second one is the high-pressure compression unit. So, and this is the mixing chamber it is quite obvious, and this is subjected to the condenser where you are discharging the Q H amount of the heat to the sink.

Apart from this the expansion valve this is attached with the flash chamber. Now if you wish to represent this particular entire operation into the T s diagram, here you see that all the steps are demarcated.

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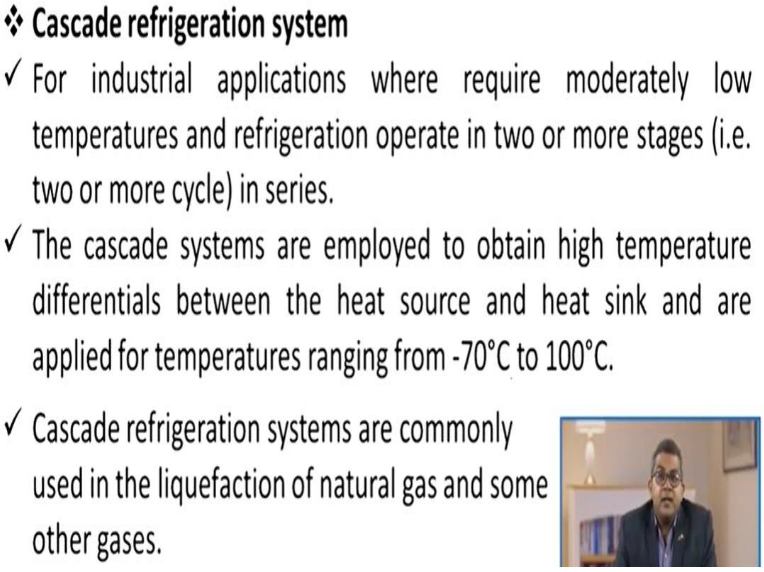

Let us talk about the cascade refrigeration system. Now for industrial application where which requires sometimes moderately low temperature and refrigeration they operate in 2 or more stages, that is sometimes called that is 2 or more cycle in series. The cascade system they are employed to obtain high temperature differential between the heat source and heat sink and applied for temperature ranging from -70 degree Celsius to 100 degrees Celsius.

The cascade refrigeration system they are commonly used in liquefaction of natural gas and some other gases.

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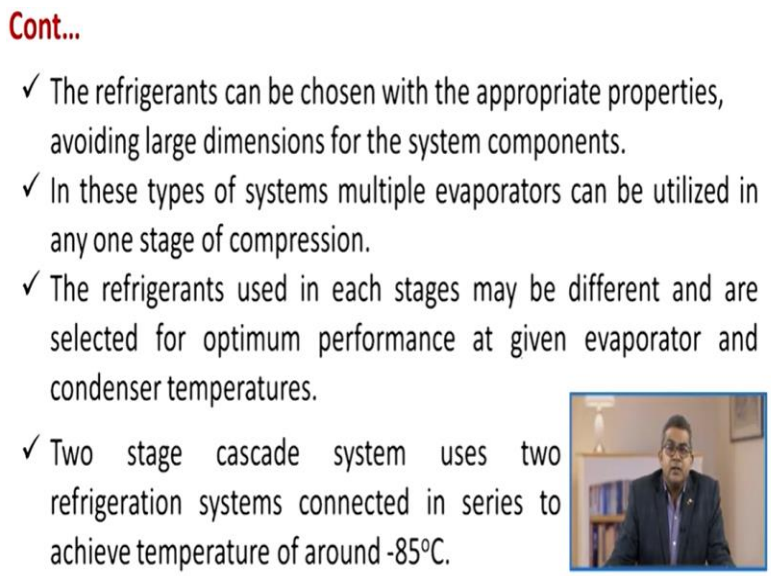

The refrigerants can be chosen with the appropriate properties, avoiding large dimensions for the system component. Now in this type of system multiple evaporators can be utilized in any one stage of the compression. The refrigerant used in each stage may be different and are selected for optimum performance at given evaporator and condenser temperatures. 2 stage cascade system can be used in 2 different refrigeration system they are connected in series to achieve the temperature of around say -85 degree Celsius.

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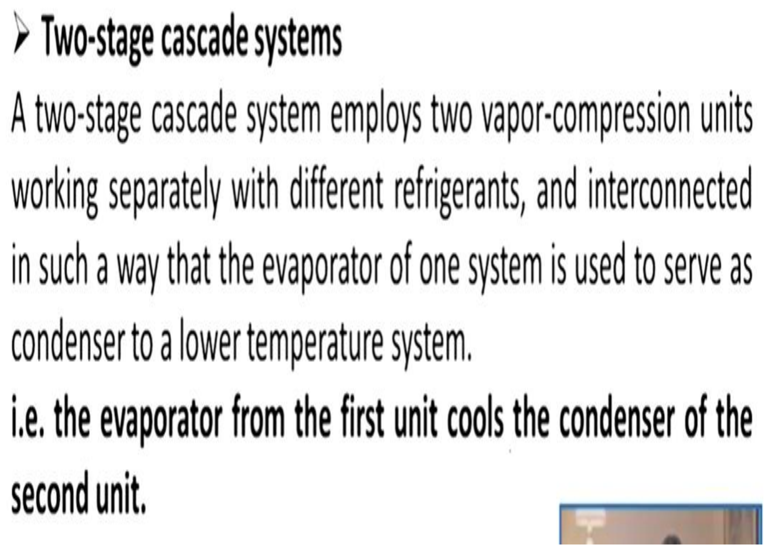

Now let us talk about the 2-stage cascade system. The 2-stage cascade system employs 2 vapour compression units working separately with the different refrigerants. And interconnected in such; a way that the evaporator of one system is used to serve as the condenser to a lower temperature system. And that is evaporator from the first unit cools the condenser of the second unit.

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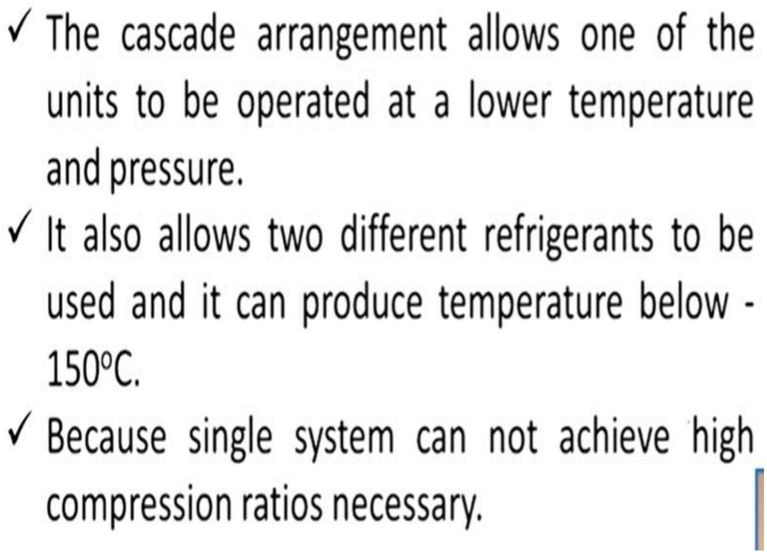

Now the cascade arrangement this allows one of the units to be operated at a lower temperature and pressure. It also allows 2 different refrigerants to be used and it can produce temperature below -150 degree Celsius now because single system cannot achieve high compression ratio necessarily.

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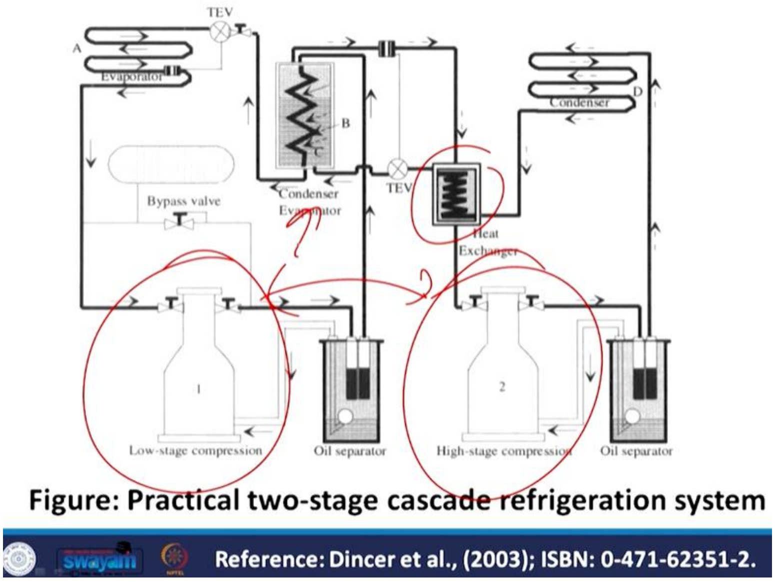

Figure: Practical two-stage cascade refrigeration system

Now here you see that the practical 2 stage cascade refrigeration system. Now here this is the lowest stage compression and this is the high stage compression so by this way you see that we are using 2 stage cascading refrigeration systems. Apart from this heat exchanger and the condenser and evaporator so what we discussed in the previous slides it is obviously it is quite obvious in this particular figure.

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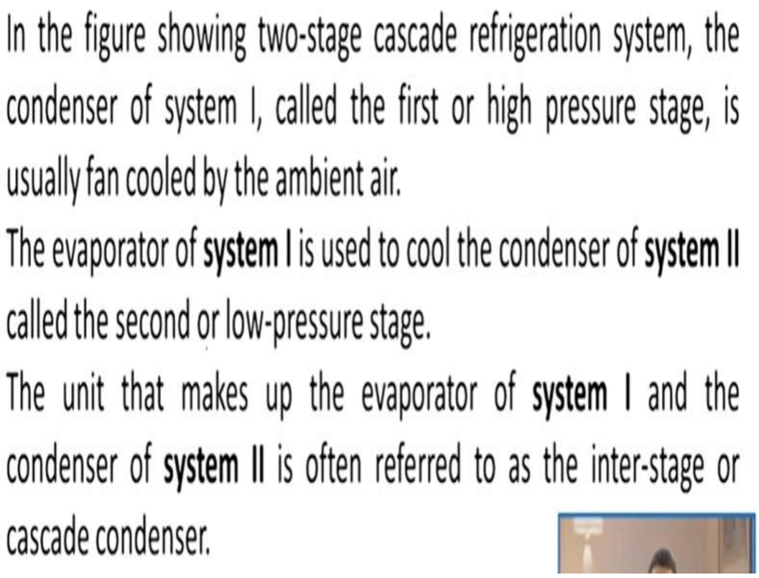

Now here we showed that 2 stage cascading refrigeration system. The condenser of system one now, this is the system one the condenser of the system l, called the first or high-pressure stage, is usually fan cooled by the ambient air. The evaporator of system 1 is used to cool the condenser of system 2 and that is called the second or low-pressure stage. The unit that makes up the evaporator of system 1 here and the condenser of the system 2 is often referred to as an inter-stage or cascading condenser system.

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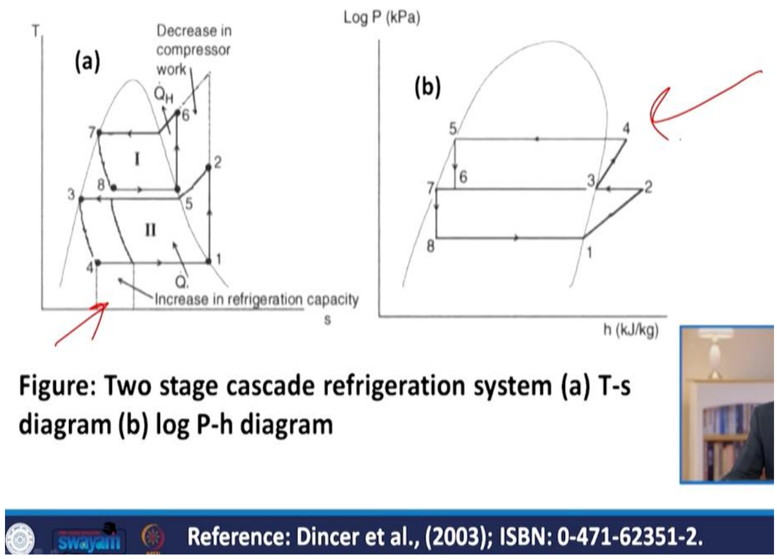

Figure: Two stage cascade refrigeration system (a) T-s diagram (b) log P-h diagram

Now here you see the T s diagram of the 2-stage cascade refrigeration system, and the log P-h diagram of 2 stage cascade system.

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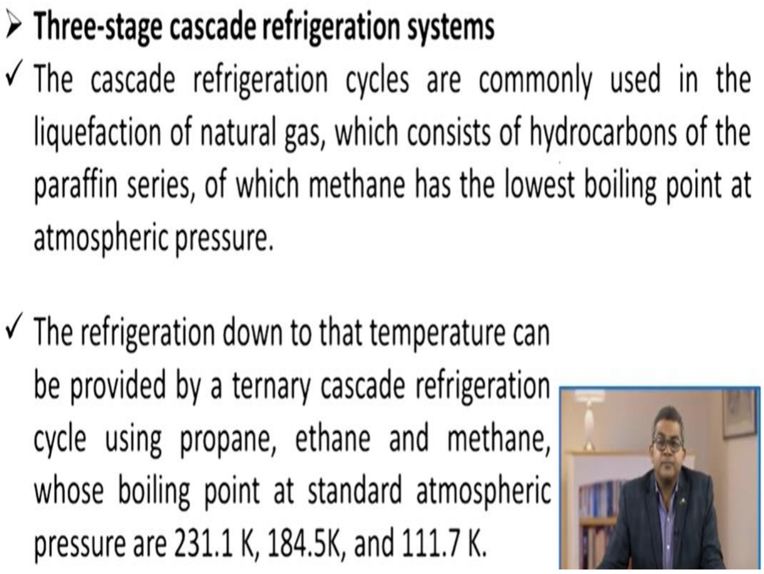

Now let us talk about the 3-stage cascade refrigeration system. The cascade refrigeration cycles they are commonly used in the liquefaction of natural gas, which consists of hydrocarbon of the paraffin series, of which methane has the lowest boiling point at atmospheric pressure. The refrigeration down to the temperature can be provided by the ternary cascade refrigerator cycle using propane, ethane and methane, whose boiling point at a standard atmospheric pressure are 231.1 kelvin, 184.5 kelvin, and 111.7 kelvin respectively.

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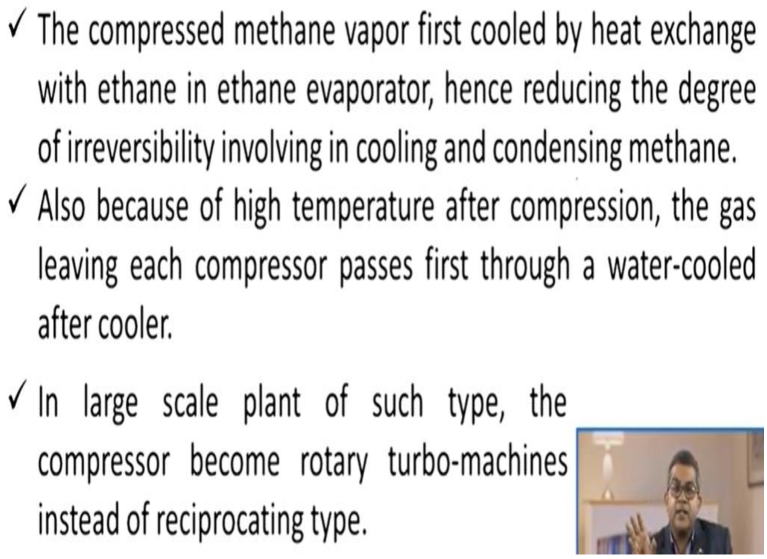

The compressed methane vapour first cooled by the heat exchanger with ethane in the ethane evaporator, has reducing the degree of irreversibility involving in cooling and condensing methane. Also because of high temperature after compression the gas leaving such compressor passes first through ah water cooled after cooler. In large scale plant of such type, the compressor; become rotary turbo-machine instead of reciprocating type.

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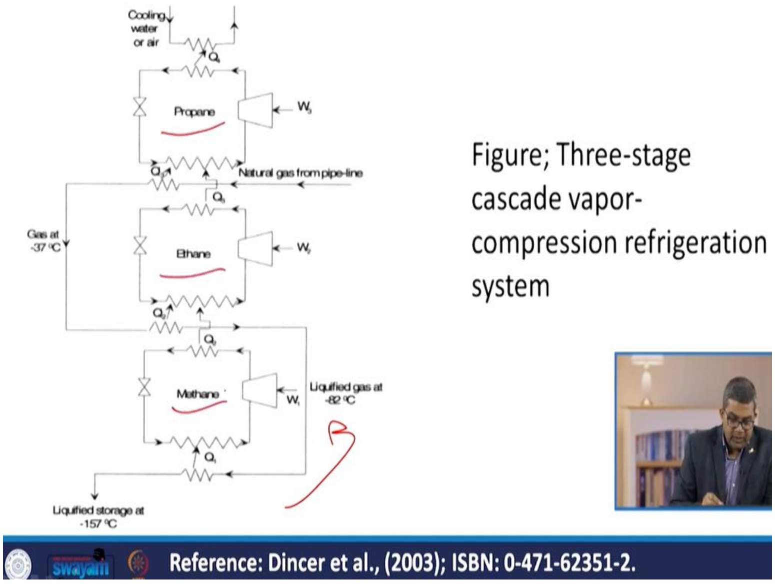

Now here you see this is the typical figure of 3 stage cascade vapour compression refrigeration system this is the propane, ethane, and methane.

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- **Energy and Exergy analysis of cascade refrigeration systems**

In this analysis, the methodology for writing the mass, energy and exergy balance equations is the same as for vapor compression refrigeration system except the work input to the compressor will be total work input which is the summation of all compressor work.

Now let us talk about the energy and exergy analysis of cascade refrigeration system. Now in this analysis, the methodology of writing the mass energy and exergy balance equation, is the same as for the vapour compression refrigeration system except the work input to the compression compressor will be total work input which is the summation of all compression work.

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The COP becomes different e.g., the overall COP for a three-stage cascade refrigeration system can be defined as:

$$\left(1+\frac{1}{COP_T}\right)=\left(1+\frac{1}{COP_1}\right)\left(1+\frac{1}{COP_2}\right)$$

Where,

COP_T is less than either of COP_1 and COP_2 because the COP of a refrigeration cycle decrease with increase in reservoir temperature.

Thus, coefficient of performance or COP this becomes different that is the overall COP for 3 stage cascade refrigeration system this can be defined as, 1 + 1 upon COP T = 1 + 1 upon COP 1 into 1 + 1 upon COP 2. Now COP total that is less than either of a COP 1 and COP 2 because the COP of a refrigeration cycle decrease with increase in reservoir temperature.

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Liquefaction of gases

- ✓ It is important area of refrigeration as many of engineering processes at cryogenic temperature below -100oC depends upon the liquefied gases.
- ✓ Some examples includes; separation of oxygen and nitrogen from air, preparation of liquid propellants for rockets.
- ✓ The substance exits in the form of gas phase only at temperature above of critical point.
- ✓ The critical temperature of some of the gases such as helium, hydrogen and nitrogen are -268, -240, -147^{o}C respectively.

Thus, let us talk about the liquefaction of gases. Now it is important area of refrigeration as many of the engineering processes are cryogenic temperature below -100 degree Celsius depends upon the liquefied gases. Some examples include the separation of oxygen and nitrogen from air preparation of liquid propellant for rockets. The substance exists in the form of gas phase only at temperature above the critical point.

The critical temperature of some of the gases such as helium, hydrogen and nitrogen are 268, - 240, -147 degree Celsius respectively.

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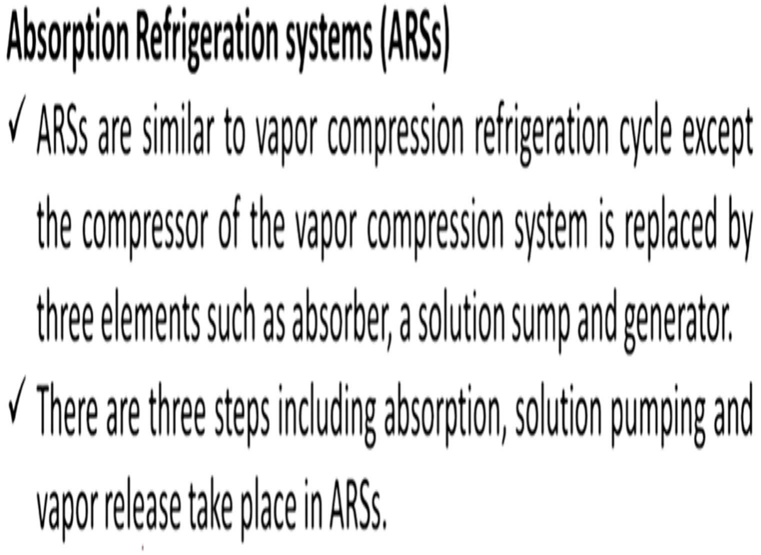

Now let us talk about the absorption refrigeration system or ARS. Now absorption refrigeration systems are similar to the Vapour compression refrigeration cycle except the compressor of the Vapour compression cycle is replaced by 3 elements such as absorber, a solution sump and a generator. Now there are three steps including absorption, solution something and Vapour release takes place in ARS.

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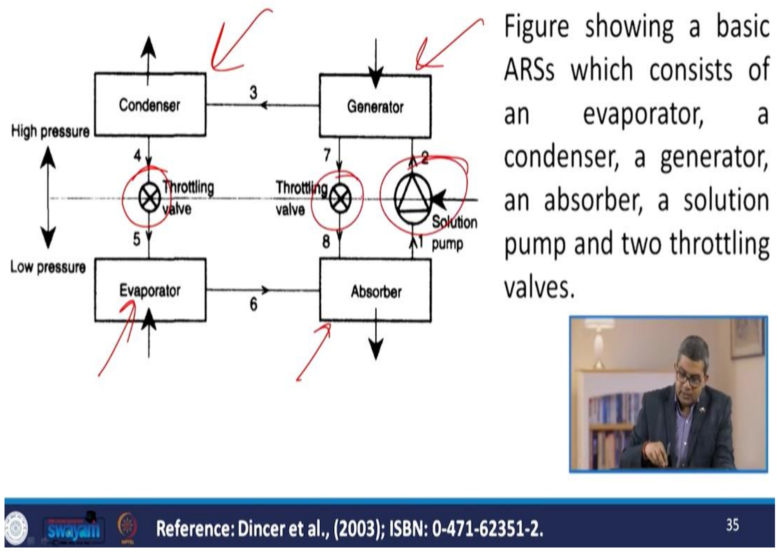

Now here you see the basic ARS which consists of an evaporator, a generator, a condenser, and an absorber, apart from this a solution pump and 2 throttling valves. Now here you see that we are having 2 throttling valves and this is the solution pump.

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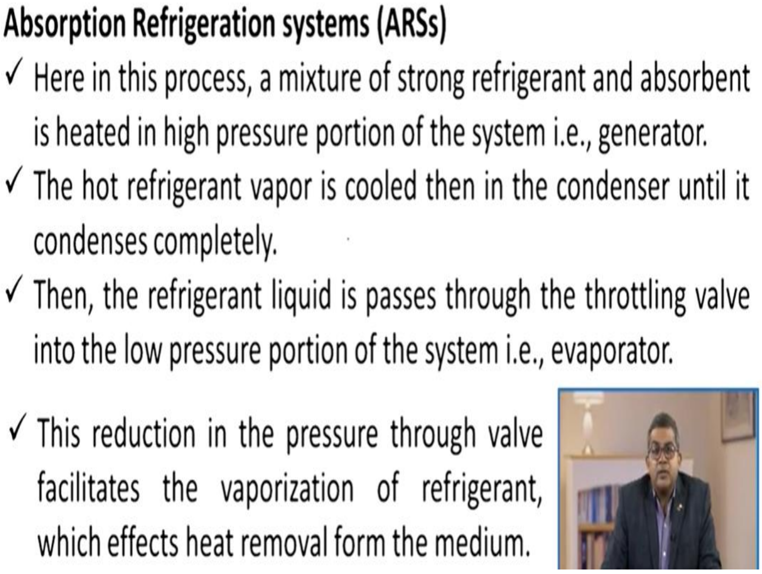

Now in this particular process, a mixture of strong refrigerant and absorbent is heated in a high-pressure portion of the system and that is called the generator. The hot refrigerant vapour is cooled then in the condenser until it condenses completely. The refrigerant liquid is then passed through the throttling valve into the low-pressure portion of the system and that is evaporator. Now this reduction in the pressure through the wall facilitates the Vaporization of refrigerant, which affects the heat removal from the medium.

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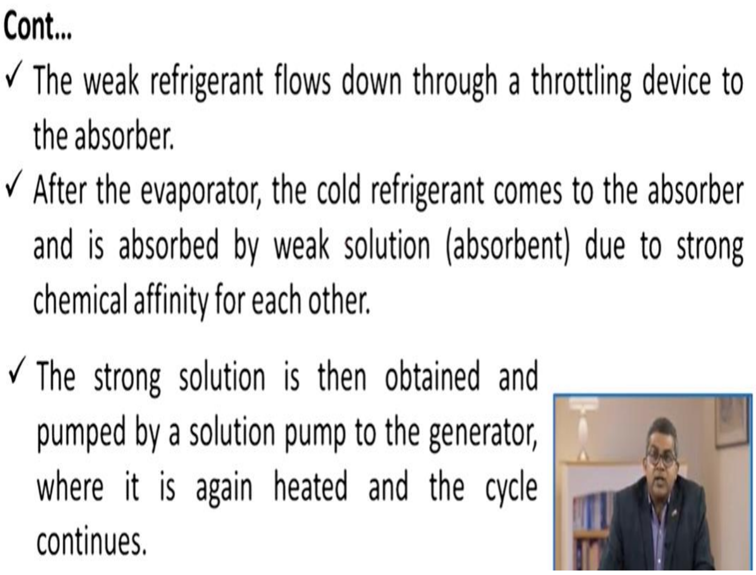

The weak refrigerant flows down through a throttling device to the absorber. Now after the evaporator the cold refrigerant comes to the absorber and absorbed by the weak solution that is absorbent and due to strong chemical affinity of each other. The strong solution is then obtained and the pump by a solution pump to the generator, where it is again heated and the cycle continues.

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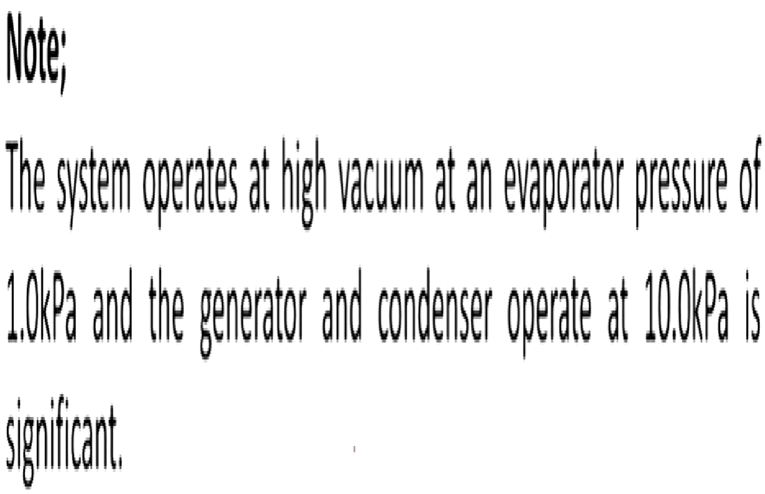

Now the system operates at high vacuum at an evaporator pressure of 1.0 kilo Pascal and generator and condenser operates at 10 kilo Pascal and that is significant.

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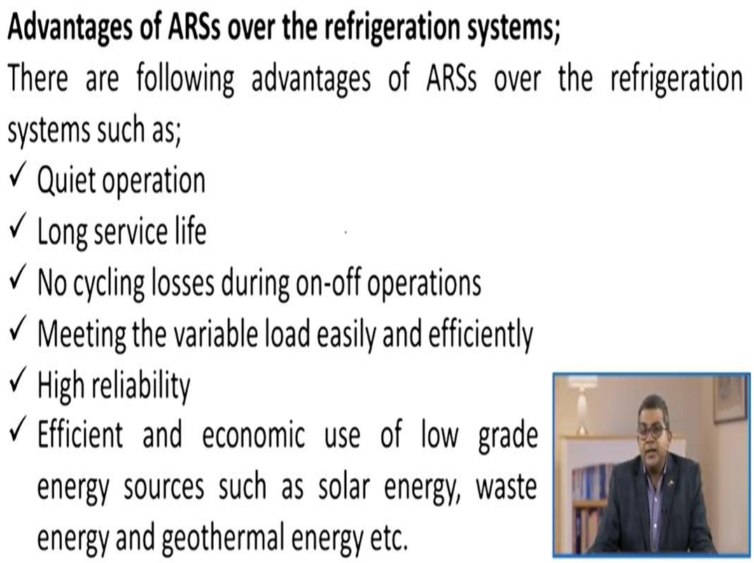

The advantage of ARS over the refrigeration system, there are different type of advantages attributed to the ARS over the refrigeration system. Such as, they are having a quiet operation noiseless. They are having the long service life, no cycling losses due to on off operation, they make the variable load easily and efficiently, they possess the high degree of reliability. And they are efficient and economic with respect to the use of low-grade energy source such as solar energy, waste energy and geothermal energy.

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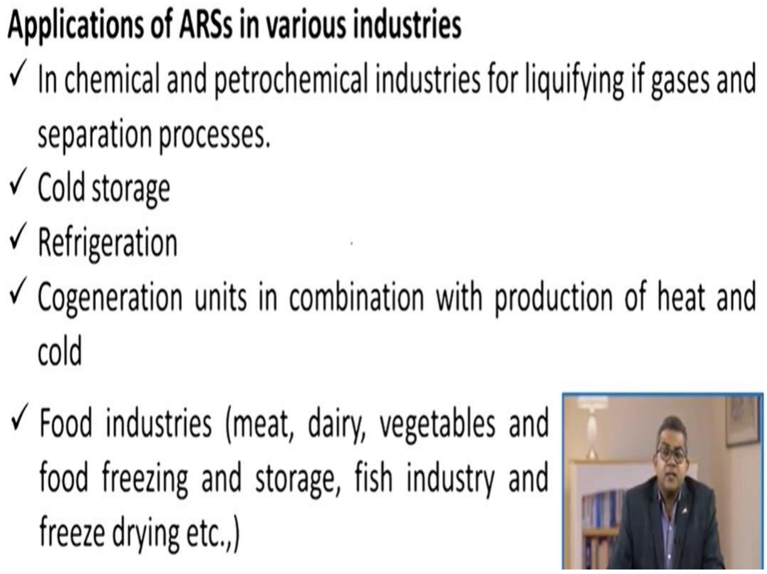

Now when; we talk about the application of various ARS in different industries. One is petrochemical or chemical industries for liquefying of gases and separation processes cold storage, refrigeration system, co-generation units in combination with the production of heat and cold. Food industries like meat, dairy, vegetable and food freezing and storage, fish industry and freeze drying.

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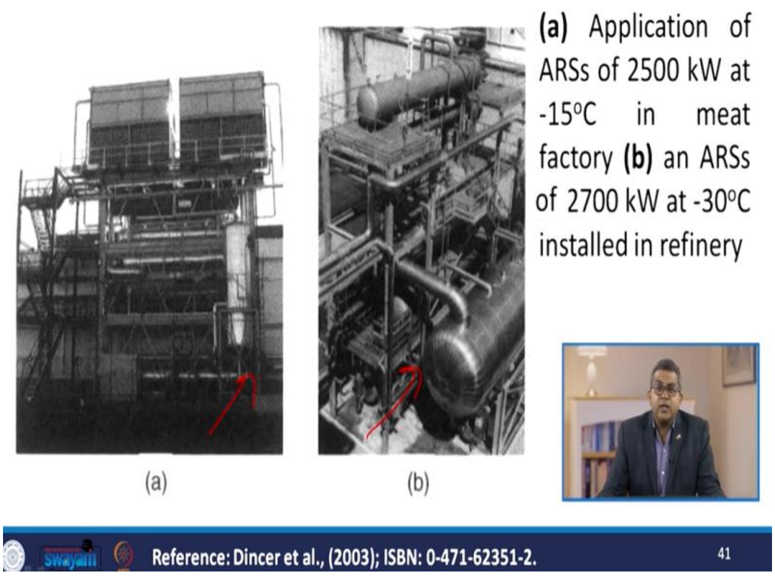

Now here you see that application of ARSs in 2500 kilowatt at -15 degree Celsius in meat factory, and this ARS is installed in a refinery of 2700 kilowatt.

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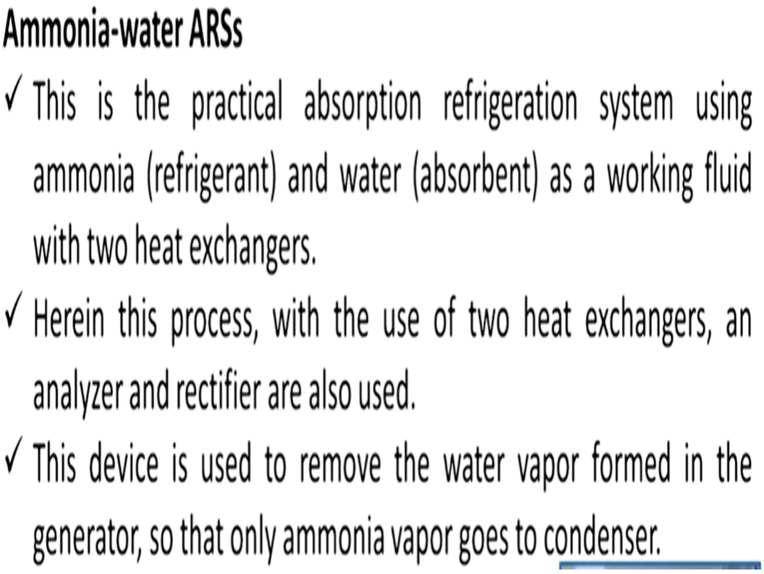

Now let us talk about the ammonia water ARS. Now this is the practical absorption refrigeration system using ammonia as in refrigerant and water as an absorbent as and they are as a working fluid with the 2 heat exchangers. Now in this process with the use of 2 heat exchangers, an analyser and rectifier are also used. And this device is used to remove the water vapour formed in the generator, so that only ammonia vapour goes to the condenser.

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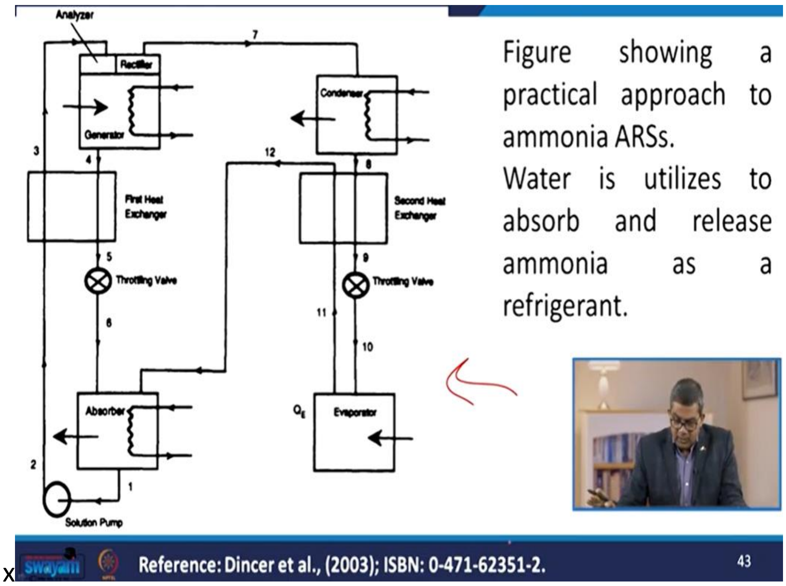

Now in this particular figure this shows a practical approach to ammonia ARS water is utilized to absorb and release the ammonia as a refrigerant.

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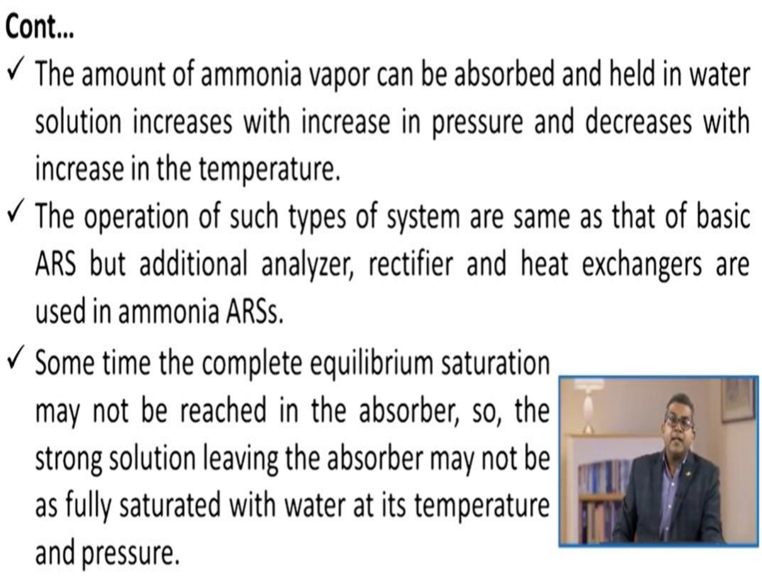

The amount of ammonia vapour can be absorbed and held in water solution increases with the increase in the pressure and decreases with increase in the temperature. The operation of such type of system is same as that of basic ARS but additional analyser, rectifier and heat exchanger are used in ammonia ARS. Sometime the complete equilibrium saturation may not be reached in the absorber, so the strong solution leaving the absorber may not be as fully saturated with water at its temperature and pressure.

The strong solution obtained from the absorber enters into the solution pump we are raising the pressure and delivers the solution into the generator through the heat exchanger. The strong solution pumped into the generator via heat exchanger where a strong solution is preheated before being discharged into the ammonia generator. The generator which is heated by an energy source raises the temperature of a strong solution and causing the ammonia to separate from it.

The remaining weak solution it absorbs some of the water vapour coming from the analyser rectifier which is in combination and flows down to the expansion wall through the heat exchanger.

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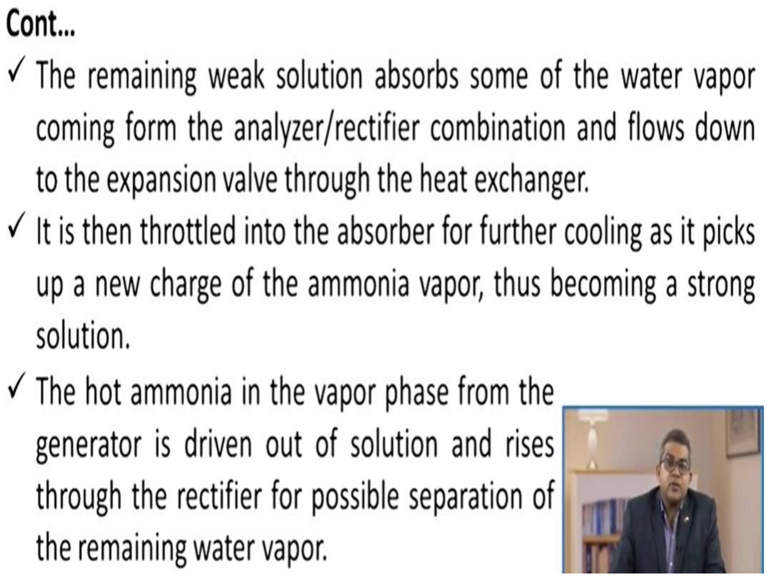

It is then throttled into the absorber for further cooling as it picks up a new charge of ammonia vapour, thus becoming a strong solution. The hot ammonia in the vapour phase from the generator is driven out of solution and rises through the rectifier for possible separation of the remaining water vapour.

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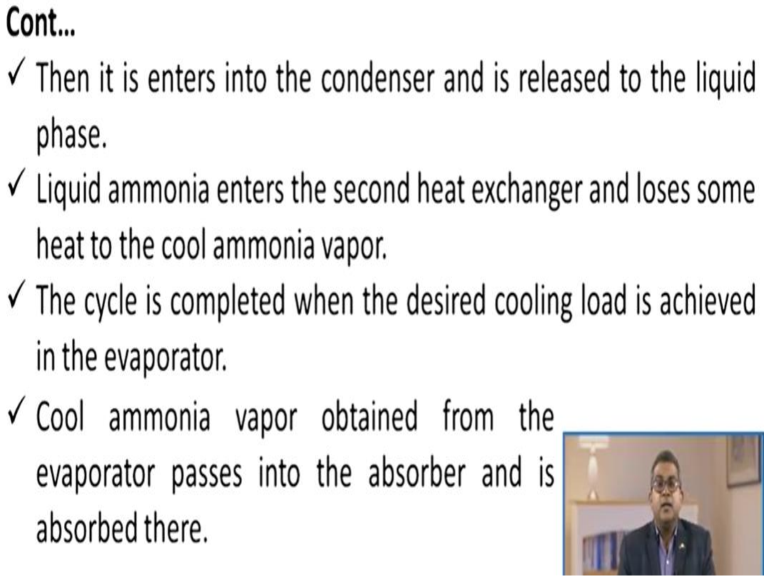

Now then it enters into the condenser and released to the liquid phase. The liquid ammonia enters the second heat exchanger and loses some heat to cool ammonia vapour. The cycle is completed when the desired cooling load is achieved in the evaporator. Cool ammonia vapour obtained from the evaporator passes into the absorber and is absorbed there. Now when the vapour goes into the liquid the solution it releases both its latent heat and heat of dilution. The heat introduced into the absorption system in the generator from steam heat.

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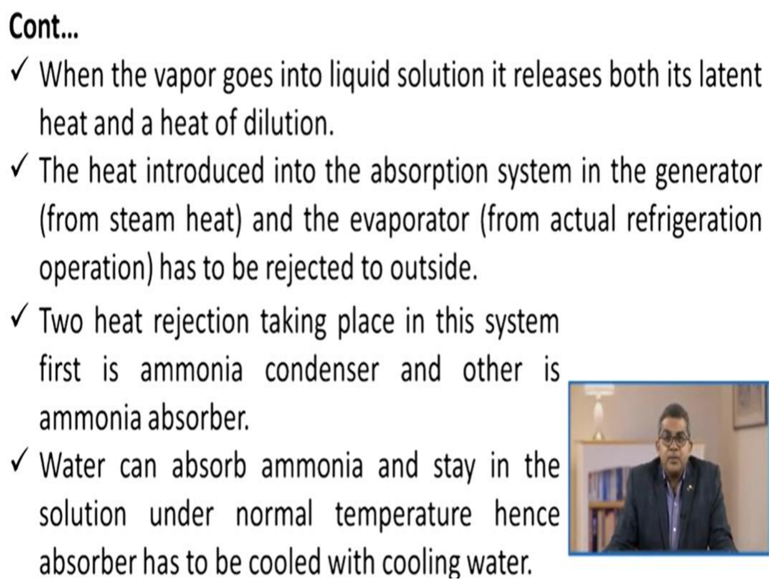

And the evaporator that is from the actual refrigeration operation has to be rejected to outside that is to the sink. Now 2 heat rejections take place in the system first in ammonia condenser and other is an ammonia absorber. Water can absorb ammonia and stay in the solution under normal temperature therefore; absorber has to be cooled with the cooling water. The evaporated ammonia in the generator is passing through the distillation column where ammonia is concentrated into the pure ammonia vapour before going to the condenser.

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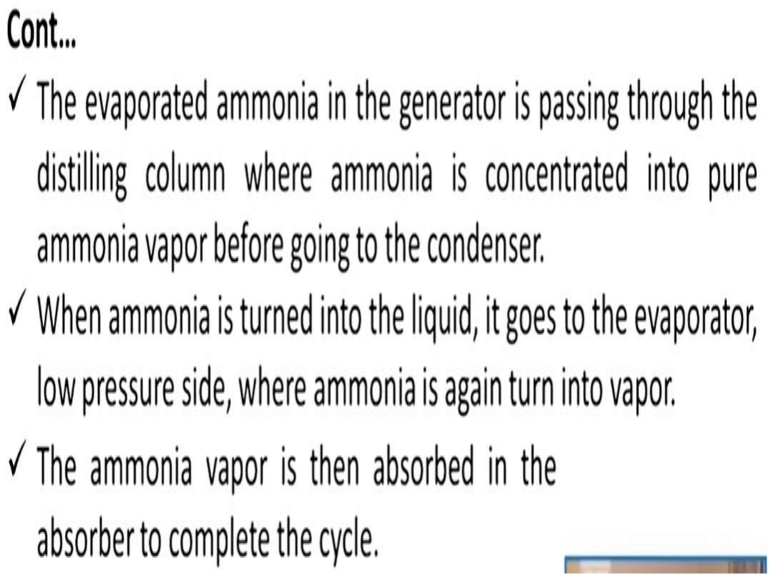

When ammonia is turned into the liquid, it goes to the evaporator, low pressure side, where ammonia is again turned into vapour. The ammonia vapour is then absorbed in the absorber to complete the cycle. Now let us talk about the gas diffusion or three fluid ARS in such type of system there are 3 fluids used as a working media. The most commonly used fluid in question they are ammonia as refrigerant, water as absorbent, and hydrogen as carrier gas.

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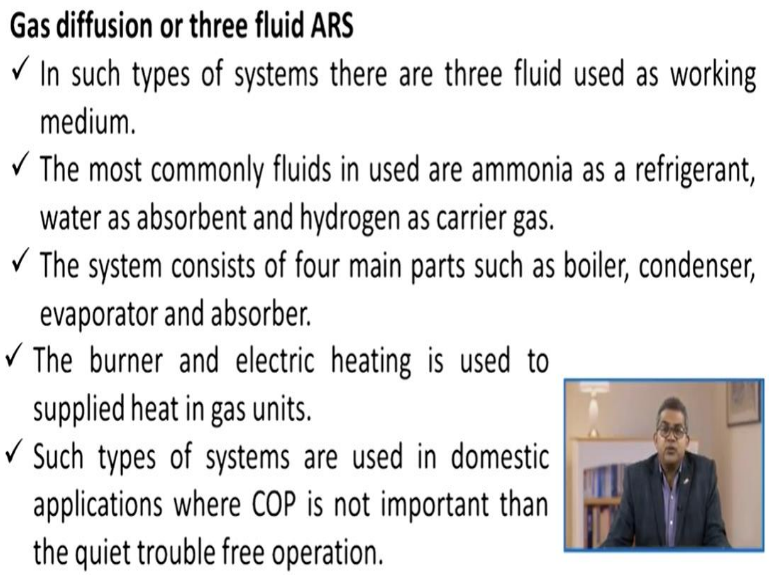

The system consists of 4 main parts such as boiler, condenser, evaporator and absorber. The burner and electric heating are also used to supply the heat in the gas unit. Such types of systems are used in the domestic application where coefficient of performance is not important then quite trouble-free operation.

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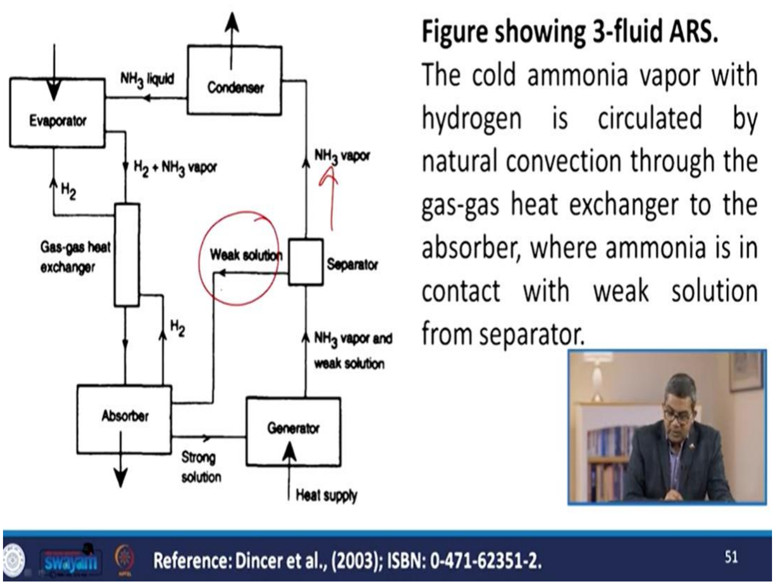

Now here you see the cold ammonia vapour with hydrogen is circulated by natural convection through the gas-gas heat exchanger to the absorber where ammonia is in contact with the weak solution from the separator.

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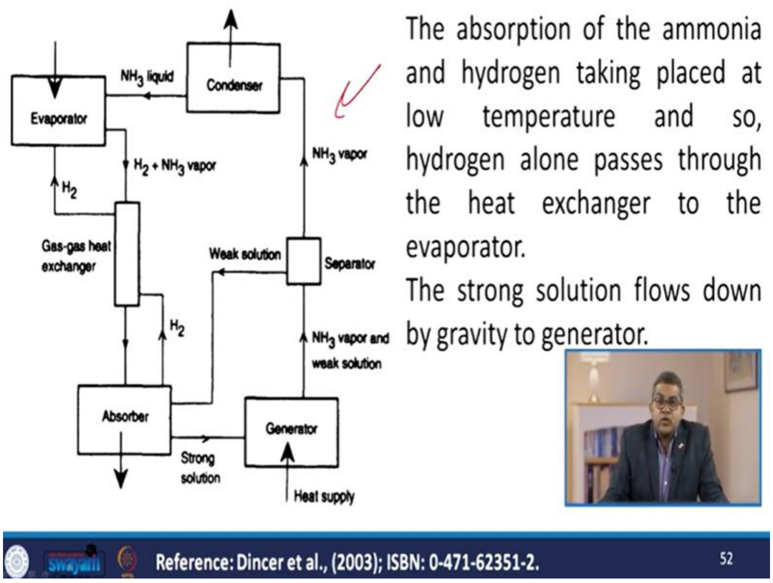

Now the absorption of ammonia and hydrogen takes place at low temperature and so hydrogen alone passes through the heat exchanger to the evaporator. The strong solution flows down by the gravity.

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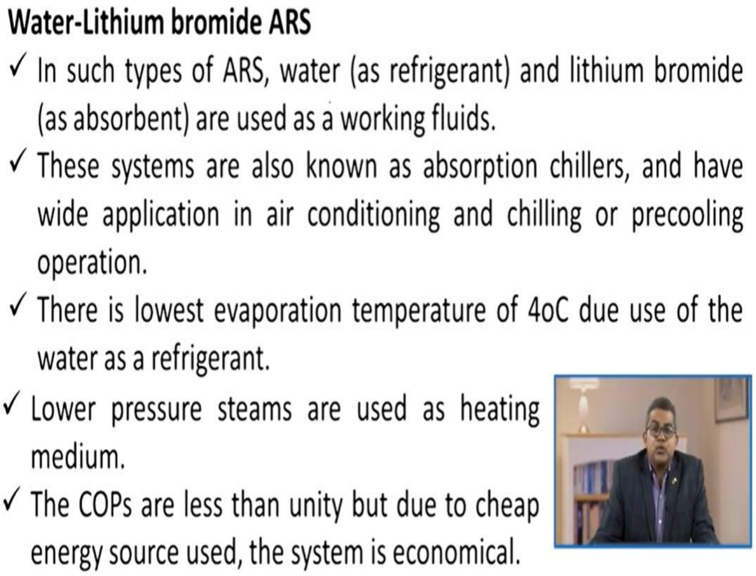

Let us talk about the water-lithium bromide. Now in such type of ARS, water that is as a refrigerant and lithium bromide as absorbent they are used as working fluid. Now these systems are also known as absorption chillers and have wide application in air conditioning and chilling or pre-cooling operation. Now there is lowest evaporation temperature of say 4 degrees Celsius due to use of the water as refrigerant.

Lower pressure steams are used as a heating media. The coefficients of performance are less than unity but due to cheap energy source used, the system is economical.

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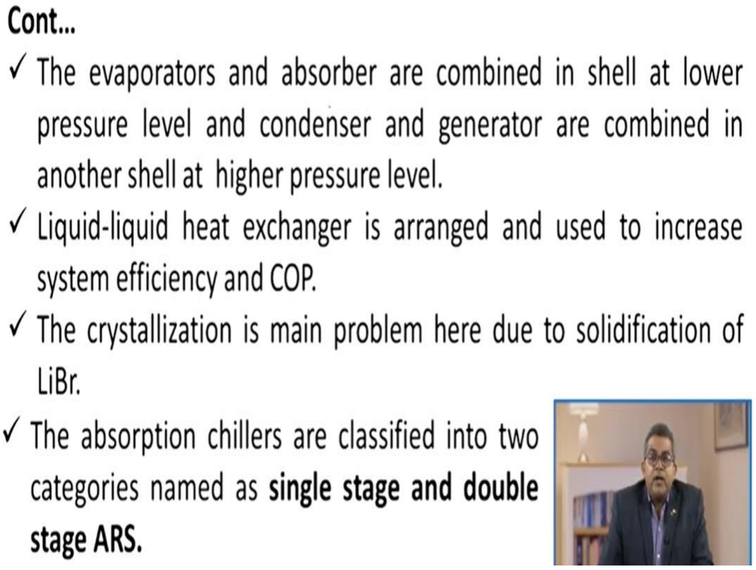

The evaporator and absorber are combined in shell at lower pressure level and condenser and generator are combined in another shell at higher pressure level. Liquid-liquid heat exchanger is arranged and used to increase the system efficiency and coefficient of performance or COP. The crystallization is the main problem in this particular case due to the solidification of lithium bromide.

The absorption chillers are classified into 2 categories one is the single stage and next one is the double stage ARS. Let us talk about the single stage or single effect ARS.

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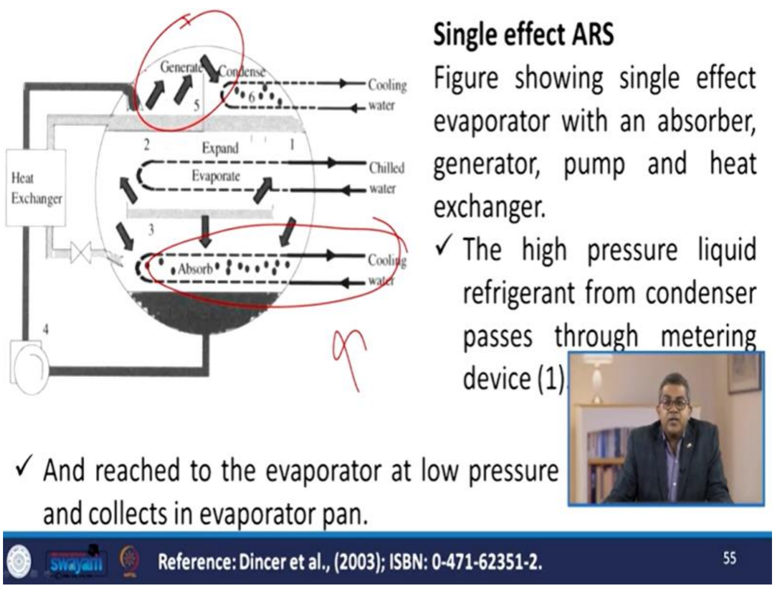

Now this particular figure shows, the single effect evaporator with an absorber, there is a generator, and a pump and a heat exchanger. The high-pressure liquid refrigerant from condenser this passes through the metering device.

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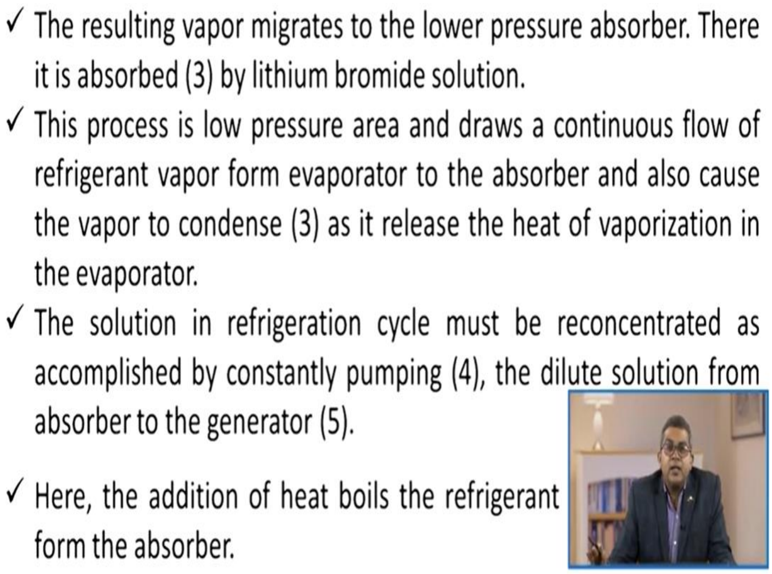

The resulting vapour nitrates to the lower pressure absorber there it is absorbed by lithium bromide solution. Now this process is low pressure area and draws a continuous flow of refrigerant vapour from evaporator to the absorber and also cause the vapour to condense as it releases the heat of Vaporization in the evaporator. The solution of in the refrigeration cycle must be reconnected as accomplished by constantly pumping, and the dilute solution from the absorber to the generator. Now here, the addition of heat boils the refrigerant from the absorber.

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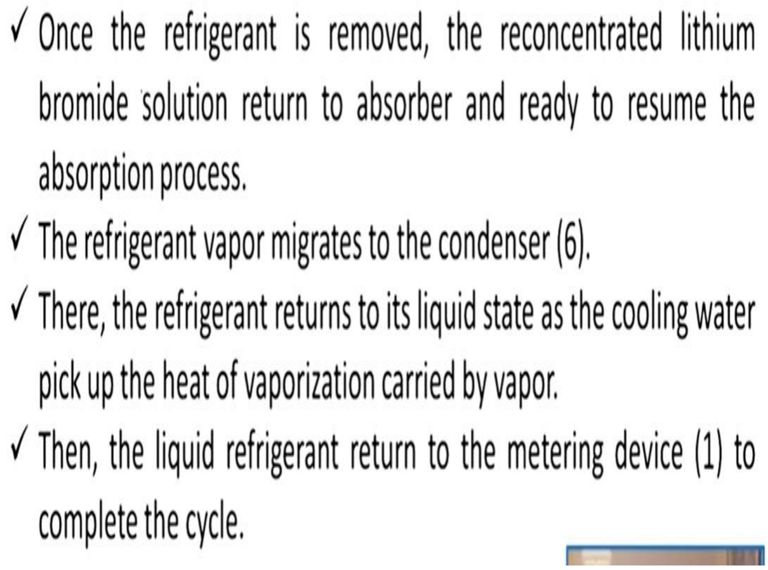

Once the refrigerant is removed the re-concentrated lithium bromide solution returns to absorber and ready to resume the absorption process. The refrigerant vapour migrates to the condenser and there, the refrigerant returned to the liquid state as the cooling water picked up the heat of Vaporization carried by vapour. Then, the liquid refrigerant returned to the metering device to complete the cycle.

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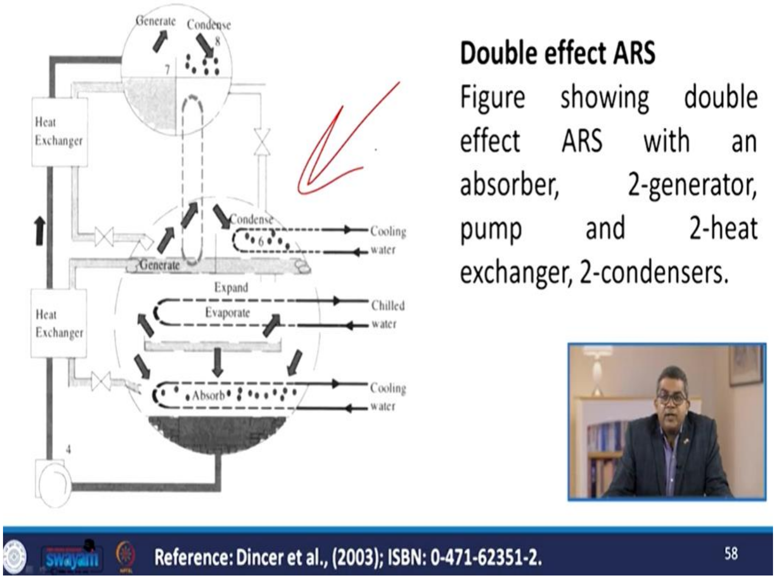

Now let us talk about the double effect here is this particular figure shows the double effect ARS with an absorber, 2 generator, pump and 2 heat exchanger, and 2 condensers.

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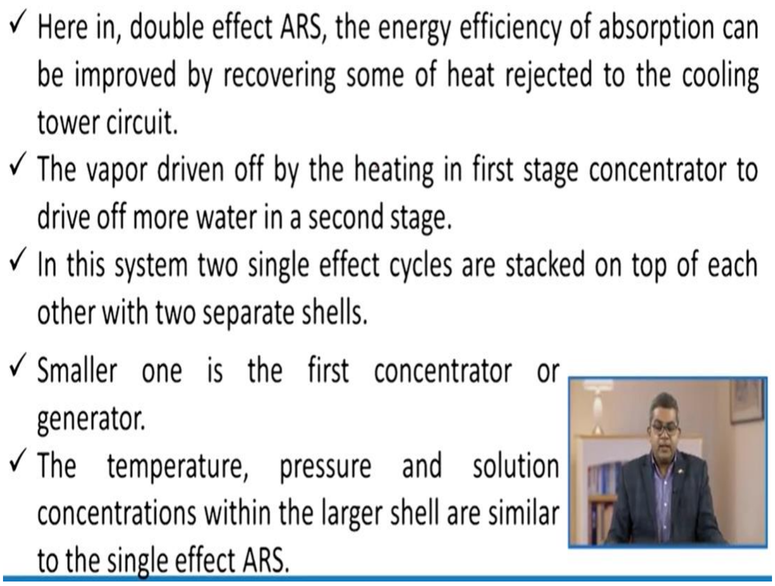

Now here in, the double effect ARS the energy efficiency of absorption can be improved by recovering some of the heat rejected to the cooling tower circuit. The vapour driven off by the heating in first stage concentrator to; drive off more water in second stage. In this system 2 single effect cycles are stacked on top of each other with 2 separate shells.

Smaller one is the first concentrator or generator. The temperature, pressure and solution concentration within the larger shell are similar to single effect ARS. The cycle on the top is driven either directly by natural gas, or oil burner, or indirectly by using steam. The heat is added to the generator on the top of the cycle which generates the refrigerant vapour at higher temperature and pressure.

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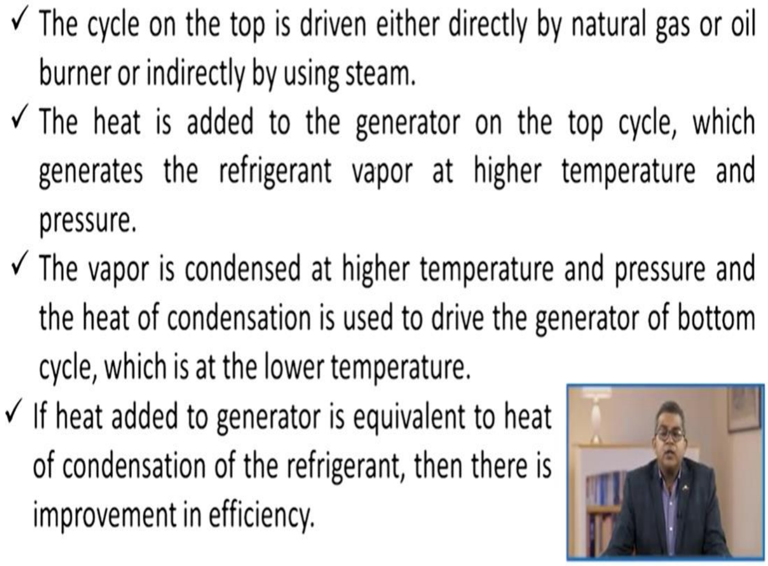

The vapour is condensed at higher temperature and pressure and the heat of condensation is used to drive the generator of bottom cycle which is the lower temperature. Now if heat added to the generator is equivalent to the heat of condensation of the refrigerant, then there is an improvement in the efficiency. So, in this particular lecture we discussed the different type of ARS, keeping in view of vapour compression refrigeration cycle.

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References

- Ibrahim Dincer, Refrigeration systems and applications, John Wiley & Sons, Ltd.,(2003), ISBN 0-471-62351-2.
- A.C. Bryant, Refrigeration equipment, Elsevier Science & Technology Books, (1998); ISBN: 0750636882.

And for your convenience we have been listed couple of references you can go through all these references if you need the further knowledge or information, thank you very much.