Cryogenic Engineering
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Lecture No. #17
Gas Liquefaction and Refrigeration Systems (contd)

So, welcome to the seventeenth lecture on cryogenic engineering, under the NPTEL program. In the last lecture, I just give you a brief out line just to see, what we did in the last lecture?

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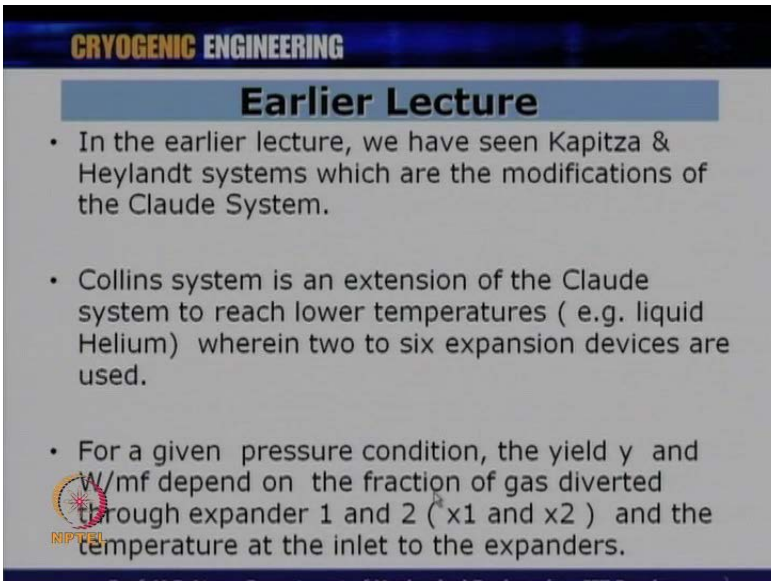

In the earlier lecture, we have seen that Kapitza and Heylandt systems which are nothing, but modifications of Claude system. In the Claude system, what we had was 2 to 3 heat exchangers and one expander. While in Kapitza and Heylandt, we had only 2 heat exchangers and one expander and it has a kind of modification from the Claude system. Then we went to Collins cycle or Collins system which is nothing, but an extension of Claude system to reach lower and lower temperature for example, liquid Helium temperatures of around 4.2 Kelvin wherein now, two to six expansion devices are used.

Collins system basically use more than one expansion device. The expansion device produce cold and in order to reach lower and lower temperature and depending on the mass flow rates or the amount of cooling effect, what one wants to have? We will decide the number of expansion devices that one wants to use in a Collins cycle, which is nothing, but a modified Claude system.

For a given pressure condition; that means, if p 1 and p 2 or the inlet pressure to the compressor and outlet pressure to the compressor are known, the yield y and the work done per unit mass of gas which is liquefied, this depend on the fraction of the gas and diverted to expander 1 and 2 which are nothing, but x 1 and x 2 as we saw last time and the temperature at the inlet to the temperature that is T 3 and T 5.

So, if you see a Collins cycle, the yield from the Collins cycle and the work that is done per unit mass of gas liquefied. It depends on what are the values of x 1 and x 2 that is what are the fractions of the gas? Which are diverted through expansion device 1 and 2, assuming that there are two expansion devices and also, at what temperatures this gas is diverted from expansion number 1 and expansion number device number 2?

Now, this is basically going to decide, what is the value of y that is the yield and the work done per unit mass of gas liquefied for Collins system? Now, in today's lecture I am again going to talk about the gas liquefaction and this is going to be last lecture now regarding Gas Liquefaction and Refrigeration.

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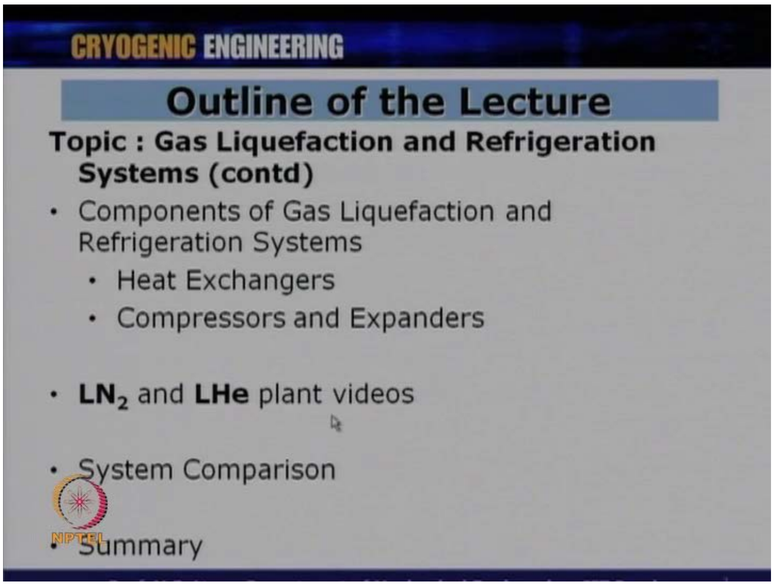

What I am going to discuss now? In brief are different components in a Gas Liquefaction cycle and also in a Refrigeration cycle. The different components are heat Exchangers, the Compressors and Expanders. In addition to that having seen all these devices having understood all this systems, having understood all this cycles, I would like to show you know how a particular cycle works? How does one get Liquid Nitrogen or how does one get Liquid Helium? That means, how does one reach 77 Kelvin to Liquefy Nitrogen and also how does one reach 4.2 Kelvin to get Liquid Helium?

So, I got some videos to show it to you, because we cannot take it to the plants, but I got some videos from these plants and let us try to understand how these cycles happen? But in cryogenics you cannot see anything closer, because everything is enclosed, everything is under vacuum condition. So, one cannot really see what is happening inside? And therefore, what you see is only from outside? Everything is under vacuum, everything is at very low temperature and not accessible from room temperature. So, you will have to see what I will tell you as to what exactly they are inside this vacuums device?

Also, I will like to have comparison of different systems too so, that one gets feel of different liquefaction cycles. There are different Liquefaction systems where, I will just show a small Comparison assuming that the pressure ratios are known to us and finally, I will summarize what all we did during the last 10 or 12 lectures? In which, we covered Gas Liquefaction and Refrigeration system.

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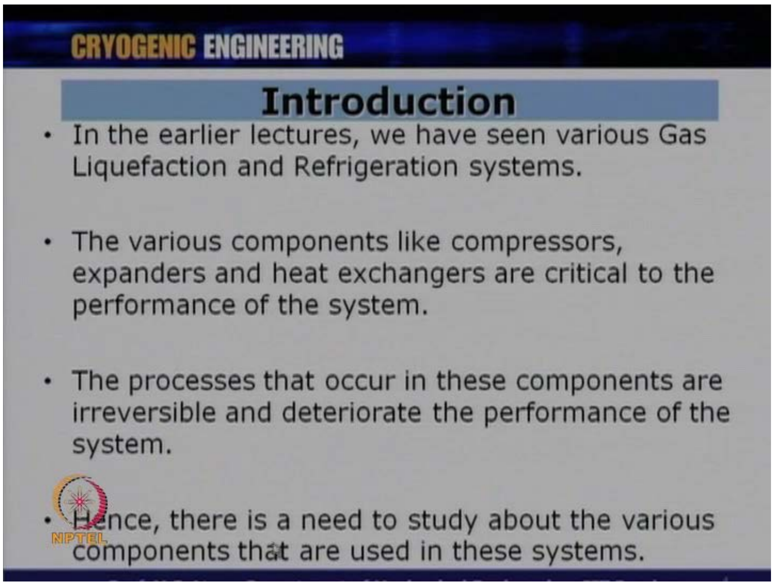

In the earlier lectures, we have seen that various Gas Liquefaction and Refrigeration system and we have seen that, the various components like compressors, expanders, heat exchangers are absolutely critical to the performance of the system. We had seen that how effectiveness of heat exchangers matter? How does it affect the yield also different efficiencies related to compressor and expanders? How do they affect the yield and the work done per unit mass of gas which is liquefied?

These processes of compression, expansion, heat exchange that occur in these components are irreversible and deteriorate the performance of the system. Hence, where we studying all this thing, because we know that these are very significant, they have very significant effect on the liquefaction and therefore, there is a need to study about these components that are used in this system.

So, we should know what kinds of heat exchangers are used? What kinds of expanders are used? What kinds of compressors are used? What are the problems with these units? Although, we cannot go in the details of all this system components at least, what we can do is? We can touch upon briefly to see how this components work.

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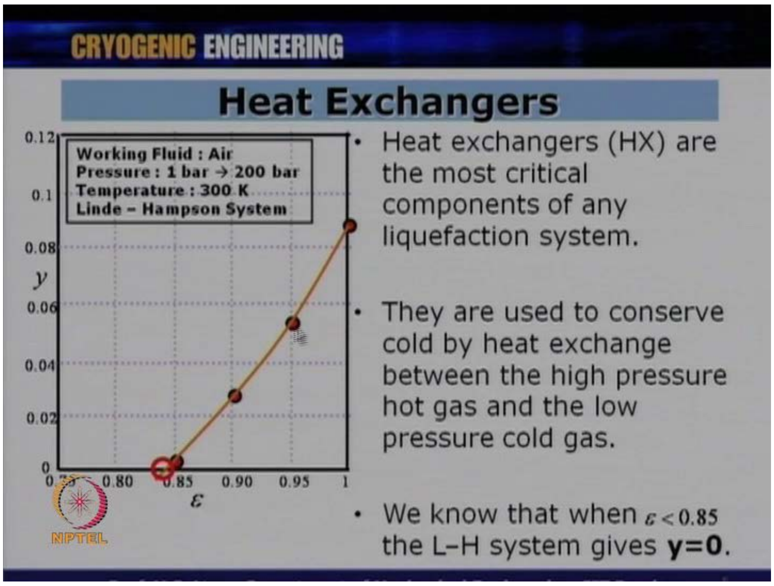

So, first we come to the heat exchangers, which is a very very important component of the liquefier. The heat exchangers are the most critical components of any liquefaction system. They are used to conserve cold by heat exchange between the high pressure hot gas and the low pressure cold gas. We know that the low pressure gas after liquefaction the remaining gas goes back and this is cold gas and therefore, whatever cold it is carrying, we use this cold to precool the incoming hot pressure gas, high pressure gas.

Now, this graph tells you, the variation in the value of y that is the yield with the epsilon value. So, you can see that if the epsilon value or the effectiveness of heat exchanger is 100 percent, we got a very high yield or the highest yield are on let us say 0.09 or something like that. But you can see, as the epsilon value goes down from 100 percent to 95 percent to 90 percent, the yield starts coming down.

So, this curve tells you how important it is? And what you can also see from this? If your epsilon value or the effectiveness value is less than 85 percent, the yield is absolutely zero; that means, it is essential that your yield or the your heat exchanger effectiveness is somewhere closed 95 percent. So, that you get a good value of y. So, that you get a reasonable value of y, definitely when one cannot reach 97 percent, 98 percent, because there are fabrication limitation, there are assembly limitations, there is pressure drop in system.

All these things have to be considered while design a heat exchanger. But at least one could strive to attain at least 95 percent effectiveness for heat exchangers and therefore, we know that the effectiveness of heat exchanger has to be more than 85 and even what should have a good y value or a reasonably good y value, the effectiveness has to be let us say more than 90 or 95 percent.

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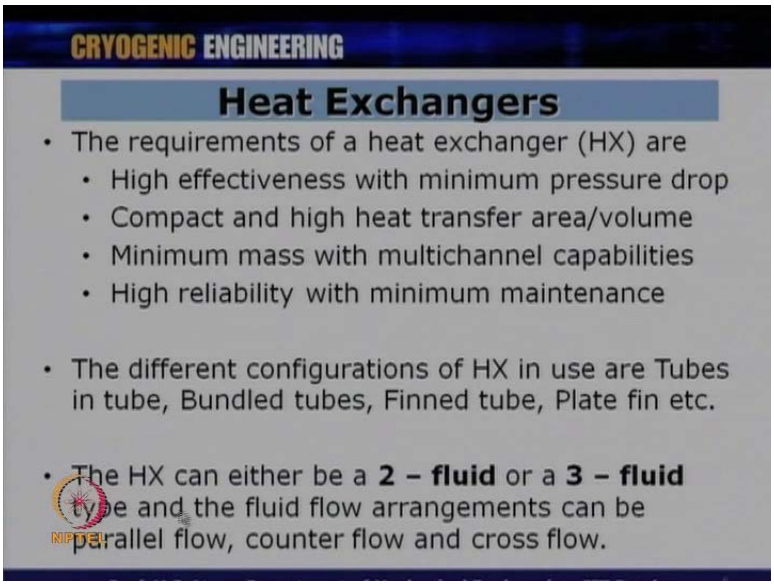

What are the requirements of heat exchangers? Now, in order to qualify to be a good cryogenic heat exchanger for gas liquefaction; it has to satisfy certain criteria; it is to satisfy certain requirements and what are these requirements? The requirements are it has to have high effectiveness with minimum pressure drop. It has to be a compact heat exchanger.

Now, this is very important, because in cryogenic, if you got a very big heat exchanger. For example, if you got a shell and 2 heat exchanger, lot of cryogen will be utilized to cool the heat exchanger itself. That means, it will have a lot of mass and therefore, in cryogenics the cold on time will be very high when you start the liquefier, it will take lot of a time when the liquefaction starts. So, therefore, one has to have very compact heat exchanger and what does it mean? It should have a high heat transfer area per unit volume. If we say that if heat transfer area per unit volume is more than 700, then it is normally called as compact heat exchanger.

So, one should strive to go in a compact heat exchanger area shown as far as cryogenics heat exchangers are concerned. We should have therefore, minimum mass with multichannel capabilities; if we got multichannel capabilities you can have more flow rates, more heat transfer area also. One should have definitely high reliability with minimum maintenance and these are very general criteria what is most important is high effectiveness and the compact heat exchanger?

Now, there are different configurations that are possible for heat exchangers to be used in the cryogenic heat exchangers and they are Tubes in tube, Bundled tubes, Finned tubes and Plate fin heat exchangers. So, different kind of heat exchanger could be used and in order to, maximize the heat transfer area 1 unit volume. We can have various structure, we can have many tubes in tube, we can see that in next slide, we can have Finned tubes, we can have Plate Fin exchangers also. And as you know from different cycles, what we have seen? heat exchanger can be of 2 - fluid or 3 - fluid types depending on the heat exchanger and cycle, we are talking about.

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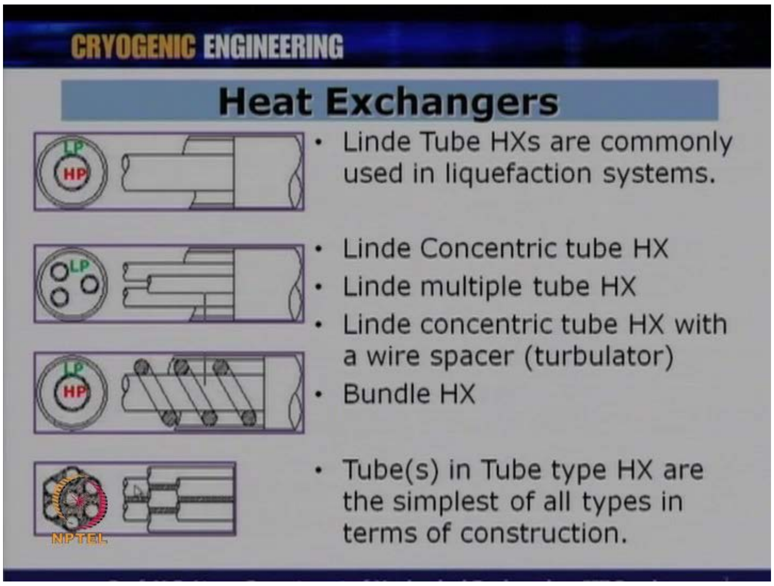

So, normally the heat exchangers are called Linde - Tube heat exchangers, which are commonly used in liquefaction systems, because they were invented by Linde and used by Linde. So, you can see here a Tube in tube heat exchanger where, the high pressure gas goes inside the tube and the the low pressure gas comes over the tube. So, Tube in Tube kind of heat exchanger or Linde Concentric tube heat Exchangers.

Then instead of one Tube, we can have 3 tubes in 1 tube. So, Linde multiple tubes heat Exchangers, they are pretty simple to understand from here. So, here we can have a coiled structure of the heat exchangers and the high pressure can gas can go in the inner tubes while the low pressure gas can come above this tube.

Now, one can have a Linde Concentric tube heat exchanger with a wire spacer. So, the low pressure gas, which is coming over can see this turbulence which is created by this wire spacer and therefore, the heat transfer area on the low pressure side could be increased in that case. We can have bundled heat Exchangers like this. So, so many solder structure is available of so many tubes over here and you can have heat transfer between different tubes.

The Tubes in tube type heat Exchangers, as you can see over here are the simplest of all types in terms of constructions. So, all these heat Exchangers are actually called Tube in Tube and they are simple heat exchanger or manufacturing point of view, they are simple, but amount of heat transfer area that is available here could be limited. They may not be classified under what you call as a compact heat exchangers, but I still use in Cryogenic heat Exchangers.

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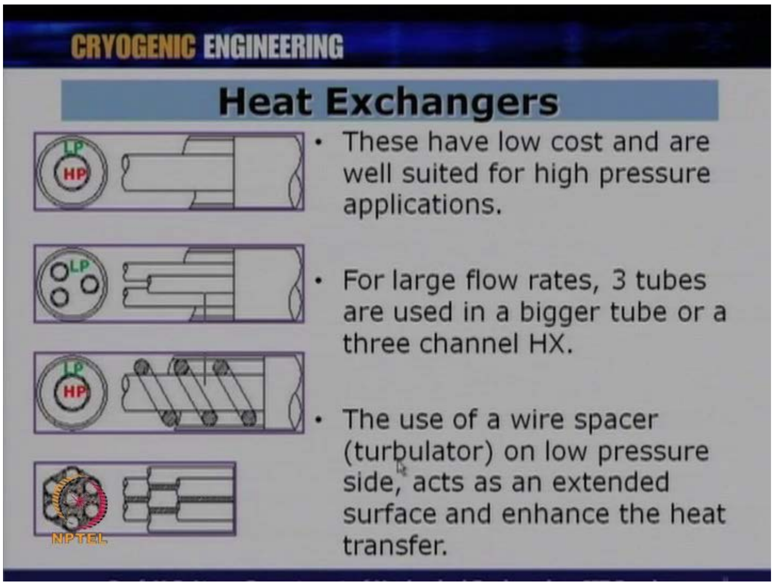

These have low cost and are well suited for high pressure applications. All this heat Exchangers for large flow rates one goes for 3 tubes are used in a bigger tube or a 3 channel heat exchanger. So, you can have different flows through different tubes also. The use of a wire spacer or a turbulator like what you can see over here? On low pressure side, acts an extended surface and enhances heat transfer on the low pressure side. I think this is mostly clear, because many of these things possibly you have understood or you have covered in a heat transfer or heat exchanger courses.

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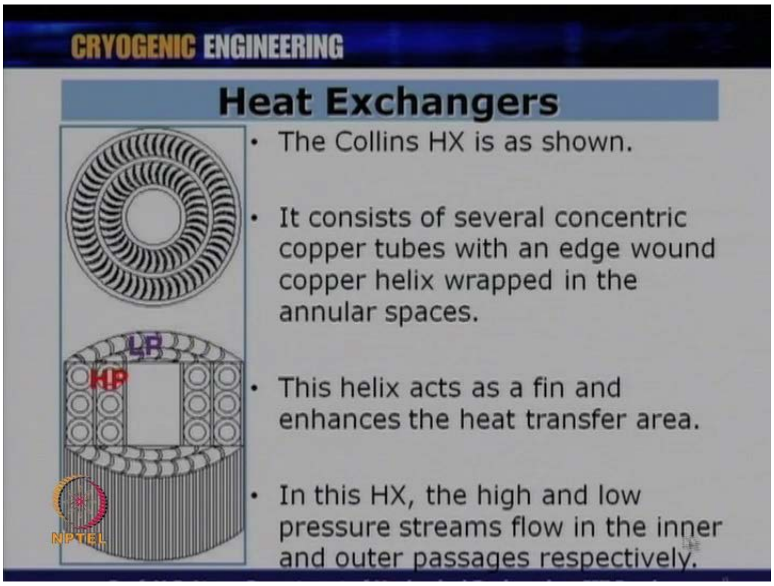

Now, very typical kind of heat exchanger which was used by Collins and therefore, it is normally called as Collins heat Exchangers and what you can see here is? A Fin Tube and shell kind of heat exchanger. Basically, what you can see are different Fin tubes bound around a mandrill. So, you can see a mandrill over here around which concentrically arrange Fin Tube are there. Which you can see in Top view here, there all Fin tubes. The high pressure Gas goes to the inner Tube over here, while the low pressure gas, the high pressure gas goes in a coiled form, it will come down the end, it will get expanded and the low pressure gas will go over this fins and then it will come out to the top and you can have various layers of this Fin tubes. So, that you get high heat transfer area available in a given volume.

So, the Collins type heat exchanger consists of several concentric copper tubes with an edge wound copper helix wrapped in another surface. So, what I am calling as fins could be an edge wound copper helix, which acts like a Fin and therefore, what is most important is? What is the contact of this copper helix with the main tubes over here? Therefore, the Fin efficiencies or the contact resistances should be 0 and the Fin efficiency should be higher in this case.

This helix acts as a fin and enhances the heat transfer area. The heat transfer area on the low pressure side, the low pressure side gas sees these fins, while the higher pressure goes inside the tube and as you can see, we can have 2 layers, 3 layers depending on the kind of flow rates which we are talking about? And corresponding to that whatever heat transfer area required, one has to calculate and accordingly design this heat exchanger. In this heat exchanger, the high and low pressure streams flow in the inner and outer passages respectively.

So, the high pressure gas goes through this inner tube, while the low pressure gas come over the fins in a coil manner, the tubes are stacked like this and the gas will come or this fin tubes.

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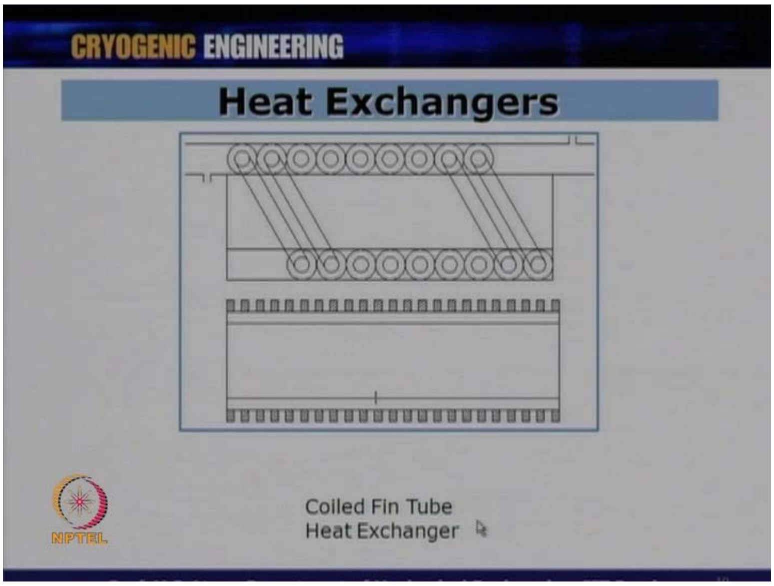

We can see the same thing over here, where you can see that the coiling is done over here? The higher pressure gas will come through this tube while the low pressure gas will go over this tube and this is basically kind of a shell, what you can call it? And therefore, sometimes these are also called as not only Coiled Fin Tube heat exchanger, but Fin Tube and shell also can be this can be referred as.

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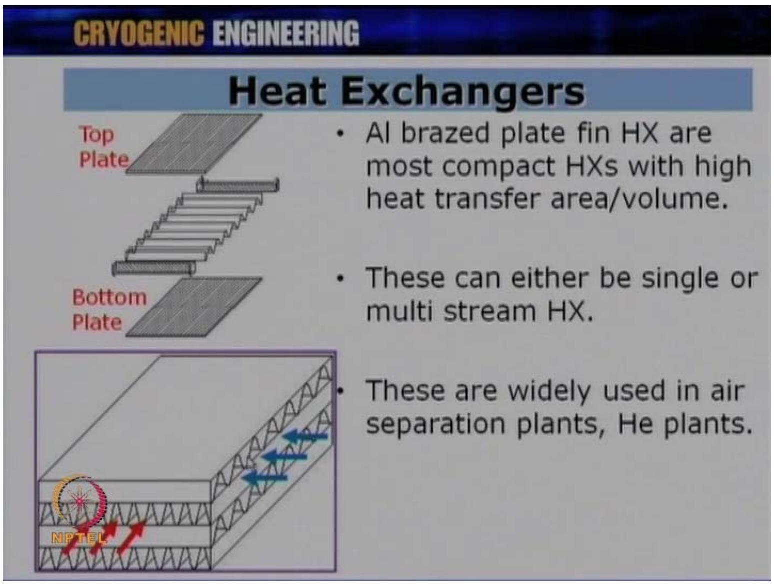

The most important or most momently used heat exchanger is normally, which is called as aluminum brazed plate fin heat exchanger. This is very costly item and very difficult to manufacture. However, this has a very compact heat Exchanger; that means, it has got a heat transfer area more than 700 meter square per unit volume.

So, aluminum brazed plate fin heat Exchangers are most compact heat exchanger with high heat transfer area to volume. These can either be single or a multi stream heat exchanger. These are widely used in air separation plants and Helium plants. Now, how does it work? What you can see here is?

You have got a fins over here, it could be normal fins, could be u type fins, could be of different characteristic fins over here and this fins has a top plate and a bottom plate and a side plate also. So, this makes one layer of the fin and here you can see that, they are mades in layers and there could be 10 layers or 20 layers depending on the flow rate and all these are basically arrange alternately. So, that high pressure gas goes through or the hot stream can go through one layer and if it is a cross flow heat exchanger, above it comes the other gas.

So, there are 2 fluids; 1 fluid this way, 1 fluid this way and therefore, you can find, you can understand that is a cross flow kind of a aluminum brazed plate plate fin heat exchanger. I got a small unit to show to you here and this unit can be seen over here. So, this is basically what you can see on if I show like this, you can see as I have just shown in the figure that you have got a one layer over here and this is the one layer. So, you got a top plate, bottom plate in which what you have got is a kind of… this kind of a model basically not for this for experiments and you can see different fins, which are kept over here and the whole thing is aluminum material and it is a brazed structure.

So, gas can go in this direction, all this will be having one header and higher pressure can gas can go through this layers. While alternatively, you can see that there is other gas, which can go through here. So, hot gas can go in direction, other gas the cold gas can go in this direction which is alternate to this. So, this minimum thickness is basically through which the other gas is going, this is what you can see between this two layers, is the other gas which is going from this direction.

So, I hope you are understanding, that one gas is going in this direction below and above of these two layers and they are alternately staked. So, one gas goes this way, the other gas can also come down from this, if it is a counter flow in this particular what you can see model? It is a cross flow arrangement. So, one gas is going this way and then alternate layer one gas is going like this.

So, all this things can have one gas in a couple through a header, the gas can go in this direction one header can here and other gas is going through this direction. Now, there are different fluids that that could go in this directions also. So, we can have one fluid going through this top 2 layers, the other fluid is going bottom 3 layers also. Similar thing can happen over here. So, you can have a multiple fluid facilities heat Exchange over here, in a plate fin heat exchanger and one can see how compact it is? And you can imagine such units made in big length of 1 meter or something like that with 10 layers something like that, then you will have a tremendous heat transfer area that is available in a given unit volume and this is what we call as a aluminum brazed plate fin heat exchanger.

So, coming back the critical requirement in this is the thermal design and fabrication. Because aluminum brazing is not a very simple process and therefore, because aluminum gas oxides immediately and for the aluminum brazing requires lot of preprocessing and post processing. So, thermal design is very important depending on the fins, fin efficiency types of fin etcetera.

At the same time, the fabrication process is also a very demanding process and aluminum brazing as it is done in a vacuum environment or a controlled environment and therefore, this is a very special class of manufacturing or brazing. But this is a very important device; because plate fins heat Exchangers are very compact heat exchanger. There are definitely are used for all the liquefaction, high flow liquefaction system, they are commonly used.

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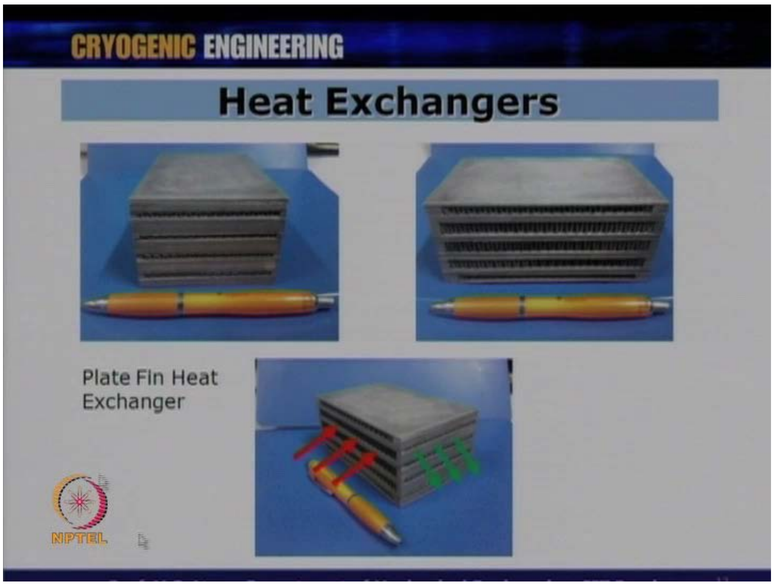

So, the same thing I have just shown you are in a photographic manner. So, that this is always with you. So, you can see one gas is going over here; the other gas is coming through in this direction. Having seen heat Exchangers let us come to compressors and in compressors we can see now.

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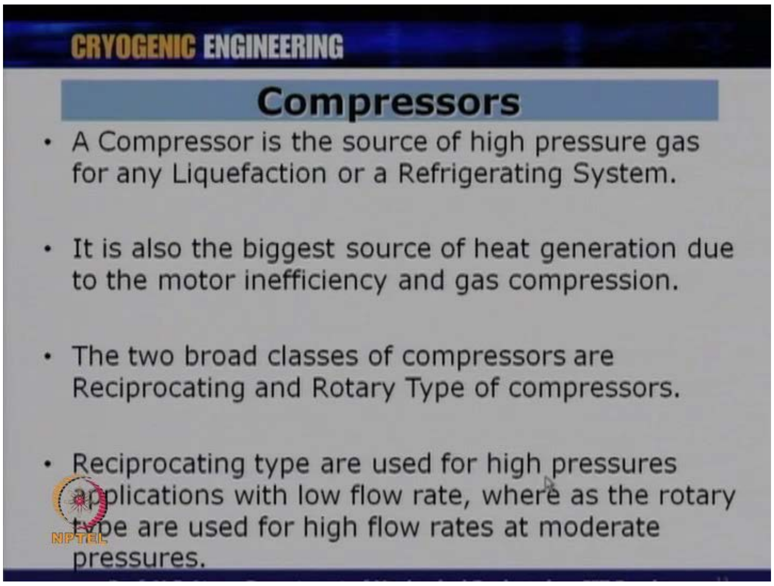

A Compressor is a source of high pressure gas for any Liquefaction or a Refrigerating system. So, it is clear to us that compressor has to be there. So, that we get high pressure gas. It is also the biggest source of heat generation due to the motor inefficiency and the gas compressor.

Again, this is known to us that the Isothermal efficiency of a compressor is a very important thing, overall compressor efficiency also the very important parameter. The two broad classes of compressors are Reciprocating compressor and the Rotary Type of compressors. Any of this could be used depending on the flow rates and pressure ratio, which we are talking about.

The Reciprocating types are used for high pressures applications with low flow rates, whereas the rotary types are used for high flow rates and at moderate pressures. So, you can have reciprocating as well as rotary depending on the flow rates and the pressure ratios we are talking about.

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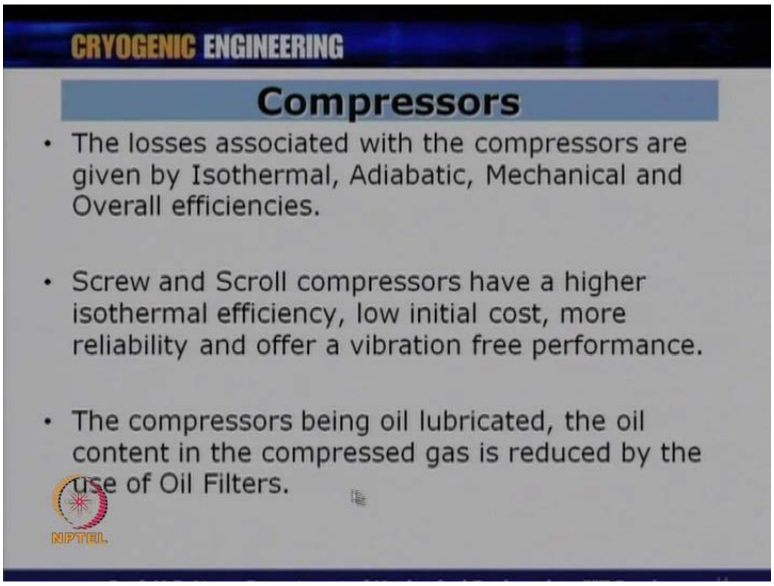

The losses associated with the compressors are given by Isothermal efficiency, Adiabatic efficiency or Mechanical efficiency or Overall efficiencies. All this efficiency have to be taken into account in order to calculate the work input to the compressor. Normally, Screw compressors and Scroll compressors are used for Helium gas or Nitrogen gas. So, Screw and Scroll compressors higher isothermal efficiency, low initial cost and more reliability and they offer a vibration free performance.

So, most of the places we will find either Screw or Scroll compressor, they are actually rotary kind of a compressors and they are being used for most of the cryogenic applications. The compressors being oil lubricated, both these compressors are oil lubricated. The oil content in the compressed gas is reduced by using Oil Filters.

As you know cryogenics cry coolers or cryogenic heat Exchangers or liquefiers do not like oil, because oil will get frozen and therefore, all the gas which is coming out of this compressor should be free of oil and therefore, Oil Filters are a must. This is a very important requirement that this gas has to be stripped of the oil and only oil free gas should go to the low temperature area.

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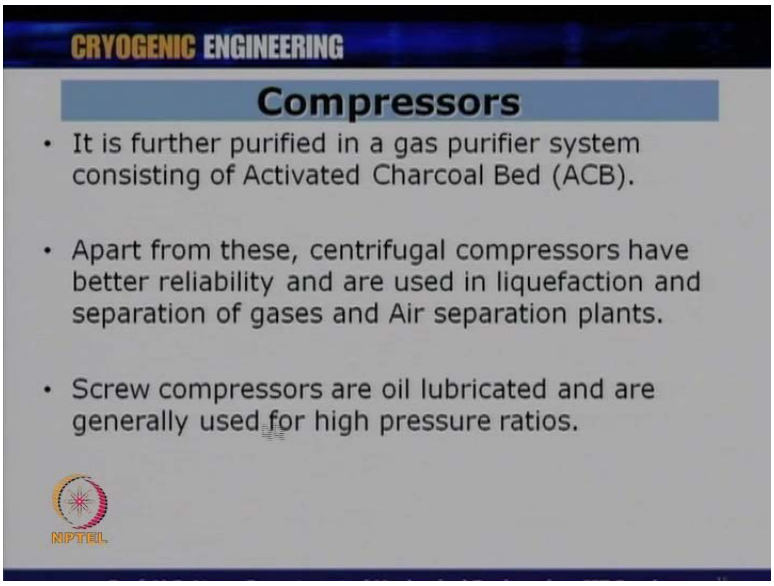

It is further purified in a gas purifier system consisting of Activated Charcoal Bed. So, that all the moisture etcetera is removed from this gas and therefore, only dry gas without moisture, without oil should go to the heat Exchangers and Expanders. Apart from these, centrifugal compressors have better reliability and are used in liquefaction and separation of gasses and Air separation plants.

Depending on the again for a very high flow rates, centrifugal compressors could be used. They are also reliable and all used for liquefaction. Screw compressors are oil lubricated and are generally used for high pressure ratios. I just said Screw compressors and Scroll compressors generally used for liquefaction of a moderate quantity of gases. So, having seen a heat exchangers and compressors now, let us come to the expanders in short and I will have 3, 4 slides on the Expanders.

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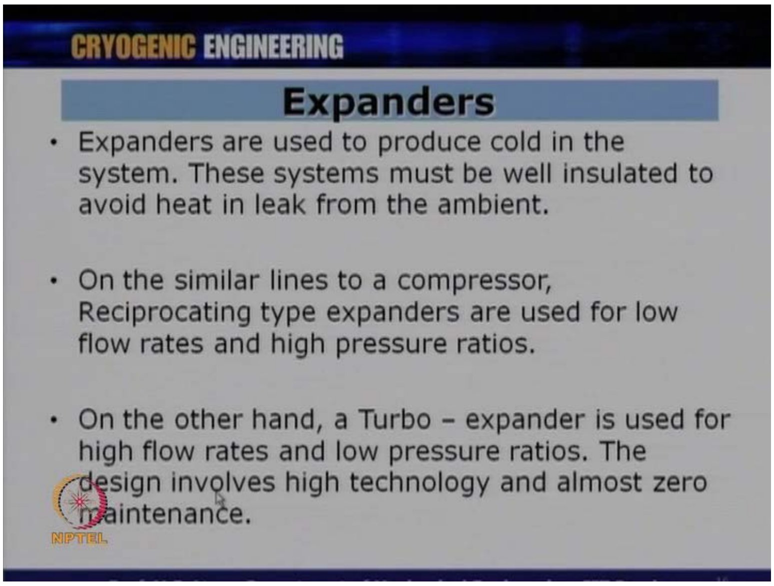

Expanders are used to produce cold as you know that expanders are very important, because it is the one, because of which the gas undergoes isentropic expansion and which produces cold in the system. These systems must be well insulated to avoid heat in leak from the ambient. In fact, the all the heat Exchangers, all the Expanders should be well insulated here, because the heat should not come from the ambient.

On the similar lines to a compressor Reciprocating type expanders are used for low flow rates and high pressure ratio. If you want to expand the gas from for a high pressure ratio, then one should go for a Reciprocating expander, but then it can take a limited flow rate in this case.

On the other hand, a Turbo - expander is used or a rotary - expander is used for high flow rates and low pressure ratios. The design involves high technology and almost zero maintenance and mostly a new technology is using Turbo – expanders, which run at a very high speed. They are really very good for high flow rates. However, the technology demand is too much, the design is very sophisticated sometimes almost zero maintenance requirements.

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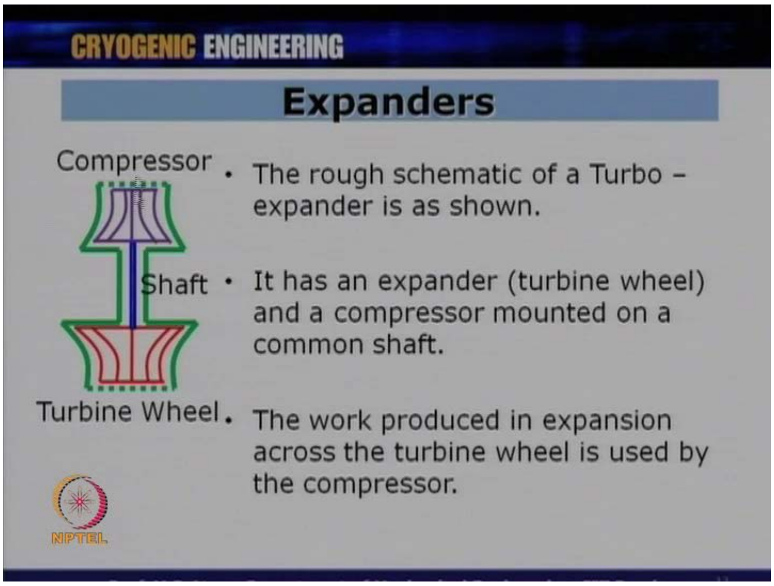

There are schematic of a Turbo - expander I am showing over here. So, you got a Shaft, which is moving at a very high RPM. One end is a Turbine Wheel, which could be very small reveal, there has been compressor. On this side basically, this compressor is kept to basically control the speed of this turbine over here. This turbine speed is very high; the RPM could be of the order of 1 lakh, 2 lakhs or around 6000 to very high RPM in this case.

It has an expander turbine wheel and a compressor mounted on a common shaft. The work produce in expansion across the turbine wheel is used for the compressor. So, basically compressor is the amount of work, which is produced by turbine is not substantial and therefore, normally these work actually dumped in a alternator or sometime and the compressor is basically used to control the speed of this turbine.

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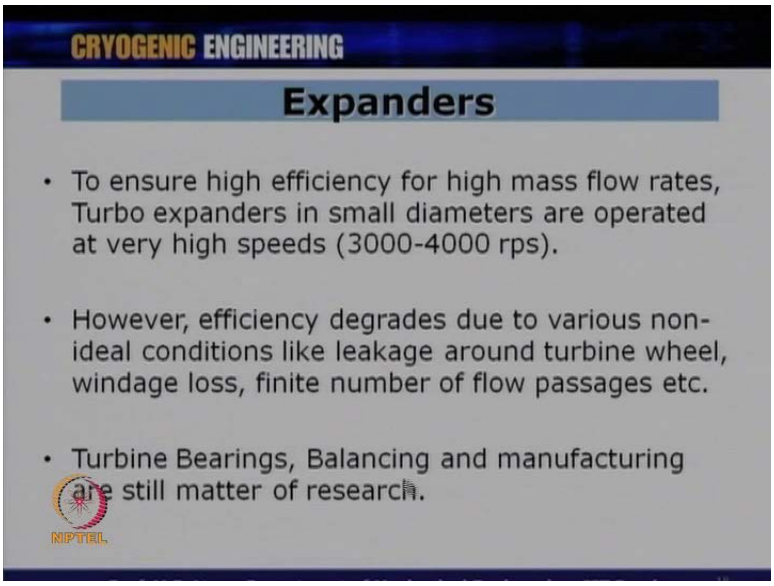

To ensure high speed, high efficiency for high mass flow rates, Turbo expanders in small diameters are operated at a very high speeds. So, I just said 3000-4000 rps, which means around 2 lakhs above kind of a RPM which we are talking about and such a small turbo expander is going to be running at very high speed. And this is the most important design requirement for as soon as we talk about very high speed, the Shaft has to have correct bearings and therefore, very high technology requirements will be there in order to basically take loads of this kind.

However, efficiency degrades due to various non ideal conditions like leakage around turbine wheel, windage loss, finite number of flow passages etcetera. So, therefore, as the result of all this losses you will have some expander efficiency, which could be (( )) 75 percent, 70 percent like that or sometimes it could be as a 80 percent also and this has to be taken into account while designing the expander.

Turbine bearings, Balancing and manufacturing are still matter of research. So, lot of work is still being carried out. In order to, design Turbine bearings, Balancing of Turbine on a Shaft, manufacturing anything like that. So, lot of research work is being carried out on the Turbo expanders.

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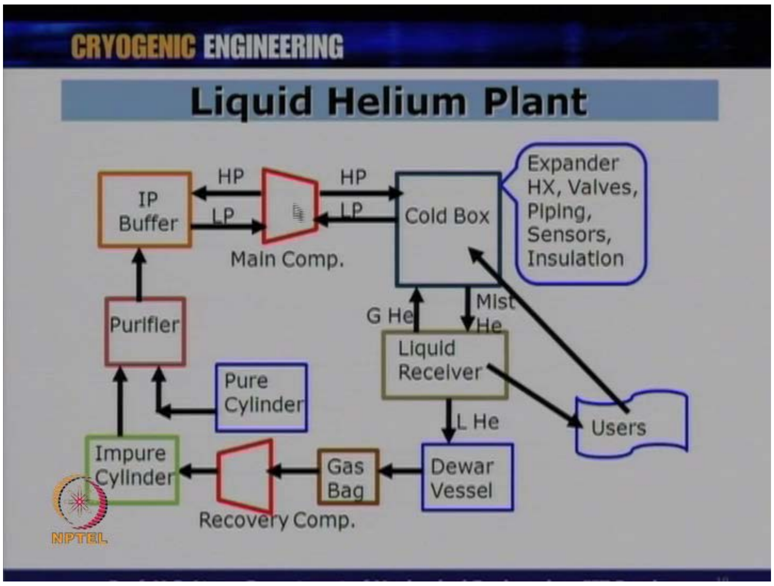

With this background have in done compressors heat Exchangers, Expanders, let us now see the working of Liquid Helium Plant and Liquid Nitrogen Plant. We can see here Liquid Helium Plant I got a schematic of the Liquid Helium Plant and this is the Cold Box, which basically houses, Expanders, heat exchanger, valve, piping, sensors and insulation. So, it has got everything as I said different heat Exchangers and Expanders.

So, high pressure gas from compressor get into the Cold Box and the Liquid is produced in the Cold Box, which goes to the Liquid receiver. So, the mist Helium that is the vapor plus Liquid come over here, the Liquid gets received over here, it is stored over here and the remaining gas goes back at low pressure and the cycle continues.

Now, this is basically cycle of which we have talked till now. This is the closed cycle compressor, expander and heat Exchangers the Liquid is stored here and the Gas goes back and the cycle continues. So, from here the users take Liquid use the Liquid or the Liquid is transferred from here to even Dewar vessels, which are taken by different laboratories for in usage.

So, Liquid Helium is directly used by the users right here in the site or they could be transferred to different Dewars and different Dewars are take taken to different labs. Now, this Helium being a very costly gas, wherever it is used, this Liquid will get connected to gas. This gas cannot be left to atmosphere and therefore, this gas is recovered and this is the… therefore, there are lot of recovery lines may attach to different utility points. So, all the gas or all the liquid which get gets evaporated, which become gas is toured in a gas bags with this recovery lines.

So, here gas bag is normally a kind of a rubber bag, in which the gas is stored and once it has recovered most of the gas. The gas goes to a recovery compressor and it is then pressurized by using a recovery compressor which is different from the main compressor. And this actually this gas is normally called as impure gas, because this is collected from various end users and therefore, they are stored impure cylinder over here.

Now, this impure gas stored in impure cylinder has to be first purified, and the pure cylinder has also sometimes needs some purification. The Purification is a very important phenomenon, because you have to remove all the possible contaminates like Air moisture, carbon dioxide etcetera from this gas. So, the Purifier will purify the gas and then it will go to some intermediate pressure buffer and it will store at this point and from here the Gas will be supplied to be in the compressor and the cycle continues.

So, what is important to see here? The Liquid Helium whatever Liquid Helium is used, the Helium is not let allowed to go outside to the atmosphere all this liquid in fact, one says that almost 98 percent gas which is given in the liquid form should be collected. So, that are recovery is almost 98 to 99 percent.

So, whatever liquid is given to the users, the Helium liquid will get evaporated. All this evaporated gas now, should be stored, it should be stored in a gas bag, it should be purified using liquid compressor stored in a cylinder, the gas should purified and again the cycle continues and this is what a Liquid Helium Plant will look like?

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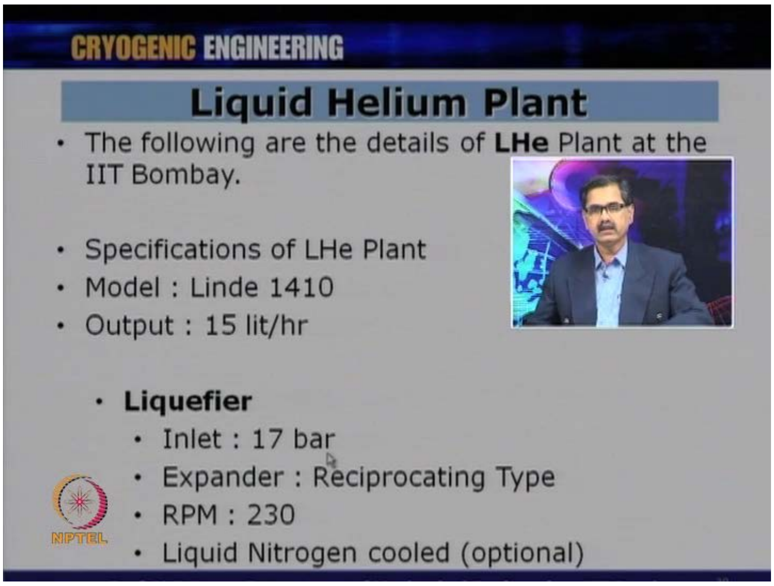

Now, let see the Liquid Helium Plant and some specks associated with this. At IIT Bombay, we have got a Liquid Helium Plant and the specifications of these plants are this is basically Linde 1410 machine model number belonging to Linde company, the output is 15 liter per hour that in 1 liter it produces 15 liters. The Liquefier inlet pressure is 17 bar, 17 bar is basically inlet pressure to the heat Exchanger; that means, the gas gets compressed from almost 1 bar to 17 bar and the Expanders in this case are Reciprocating type to understand that they are not basically the Rotary Type there is no Turbo – expander, because we are talking only about 15 liter per hour.

The moment I talk about having around 100 liter per hour or 200 liter per hour. It will be justified to go for a high flow rate system that is Turbo-expanders. Now, it is even for 15 liter per hour Turbo-expanders are being used. The RPM of these expanders around 230 and sometime they could be Liquid Nitrogen cooled also. So, you can have precooling done on this gas.

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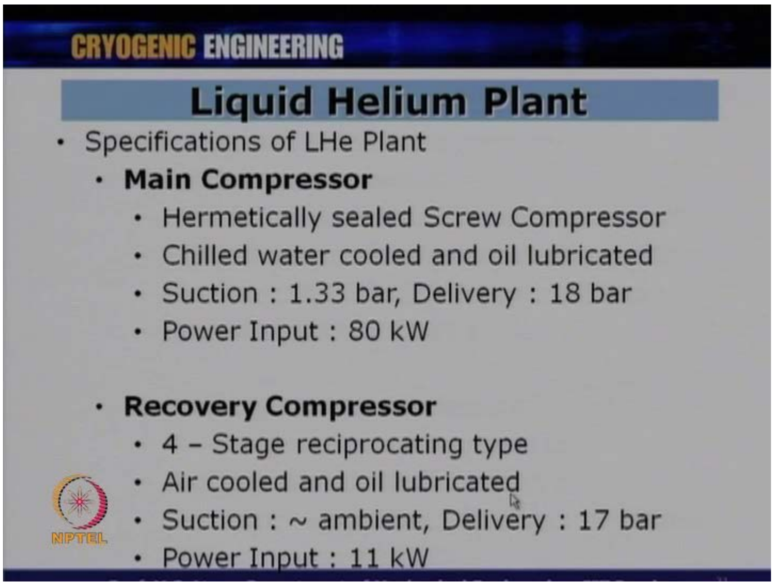

The Liquid Helium Plant has a Main Compressor, which is Screw type Compressor. It has got to have a chilled water cooling, because the compressor needs cooling, oil lubricated, the Suction is 1.33 bar and Delivery is 18 bar and the power input is 80 Kilo Watt. Now, we can see that 80 Kilo Watt power input electrical power input is given to get 15 liter per hour Liquid Helium of this plant. It is a very it demands lot of power basically.

In addition to this main compressor, we got other compressor which is recovery Compressor; it is a 4 - Stage reciprocating type, Air cooled and oil lubricated, the Suction is around ambient and Delivery 17 bar and this also requires electrical power input of 11 kilo watt. So, once you are operating both the plants you got a… Both the compressors you got to have 80 Kilo Watts over here and 11 Kilo Watts, the recovery for the recovery compressors so, the power input is of the order of 90 kilo watt in this case.

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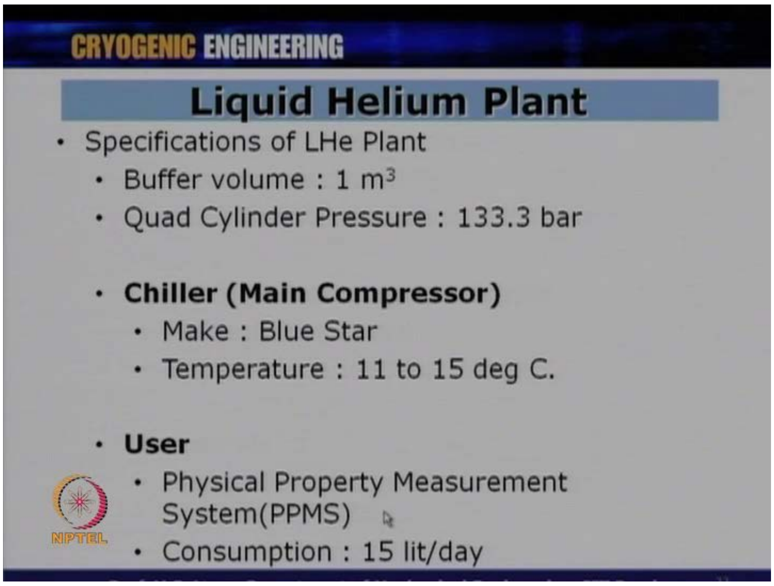

Then we have got a Buffer volume of 1 meter cube capacity, the Cylinder pressure are 133.3 bars. Chiller for the Main Compressor is Blue Star, the temperatures of the water which comes out is 11 to 15 degree centigrade over here. The Liquid Helium which we are producing used for various kind users, one of which is PPMS or physical property measurement system, the Consumption is 15 liter per day while there are other system like n m r apparatus, which requires continuous replenishments of the Liquid Helium.

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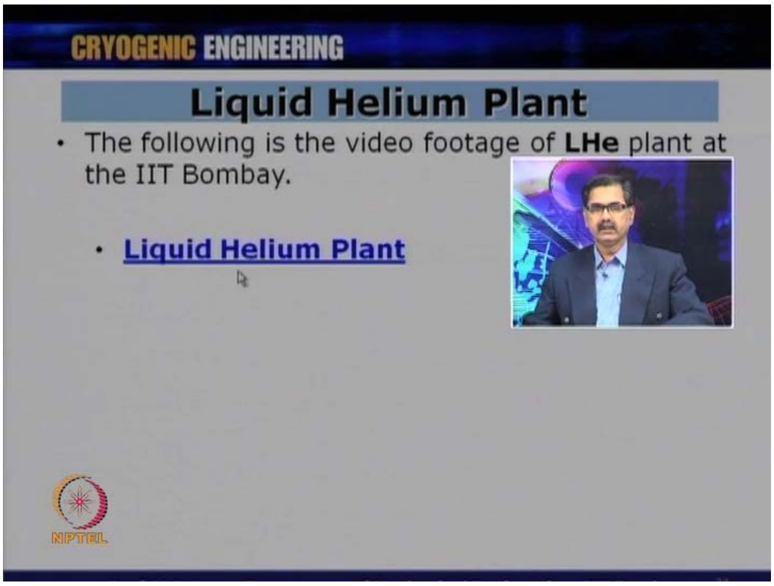

With this background I would like to show you a video of the Liquid Helium Plant right.

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So, with this background, with this specification which you just saw of the Liquid Helium Plant, let us have a look at actual Liquid Helium Plant that is we have with IIT. This is a Liquid Plant giving you around 15 liters per hour and what you can see on the screen is? Basically, the all the containers or the Dewar's in which the Liquid Helium which is produced is kept. So, what we can see here are different containers and this is around let us 200 liter capacity, around 100 liter capacity and this is around less than 100 around 80 liter capacity for Liquid Helium.

So, these are different Dewars and when you add Liquid Helium to this. Some Liquid Helium will get evaporated, which is then taken care of in the recovery bags. This is stored in the recovery bags and this is what you will see now?

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So, this is a video and this is around 200 liter and you can see this is a kind of experimental Dewar, where some experiments could be carried out. From all this things, what you see is a there are recovery lines. So, some Helium will always get evaporated, when you are doing experiment or when you are filling Liquid Helium to this? Or the Helium will always get boiled off. So, on every Dewar wherever you see a Helium Dewar, you will see some recovery line and the Helium which is getting boiled off from this is getting stored in a Recovery Bag, which is stored above this and we will see that later at the end of this video.

So, these are all the recovery line, which are where boiled off Liquid Helium Gas, will be you know stored. It is not let go to the atmosphere, as what you see otherwise in Nitrogen and these are the piping and now, let us come to the actual Helium Liquefier machine.

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So, this is the Helium Liquefier machine and here you can see that in this it houses, heat Exchangers as well as the Expanders. Let us see the video of ahead and this is the most important place where all the action takes place.

So, this is our Cold Box. This Cold Box houses, heat Exchangers, the entire liquefier works on Collins cycle. So, you know that there are 5 or 6 heat exchangers and there are 2 Reciprocating expansion engines. So, this is the Cold Box which houses all the heat exchangers and the expansion engines and there will be inside Dewar, outside Dewar and there is a vacuum in between with insulation and the vacuum is always you know wherever you want to start the plant, the vacuum will be made first on. So, that the vacuum is always maintained over there and is a rotary pump and whenever you want to start the plant first you will start the vacuum rotary vacuum pump. So, that you get a good vacuum out there and then start the compressor later.

So, this is the this is normally called as Cold Box which houses, the heat exchanger and the expansion engines and there are various pressures which are recorded, the vacuum which is recorded all those dials are shown over there. Many times now it is these are all digital dials also.

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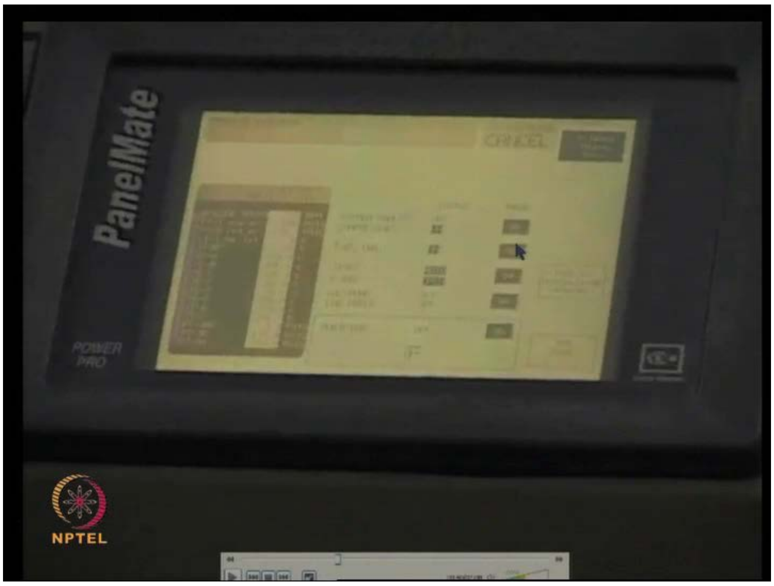

So, just have a closer of the machine and what you see now here is a some display. So, you can see the display, where you can always see what are the temperatures at various points in the machine? For example, the inlet temperature, the J-T temperature or the gas temperature before the J-T expansion also what you can see is? What is the RPM of the expansion engine number 1 and expansion number engine number 2 and thing is like that?

So, all that data which what is essential for an operator to know? Just to know that if the machine is working properly or not, what are the temperatures at various locations? What is the RPM of the expansion engines? All this data can be seen over there and accordingly, the action may be automatically taken or in some cases, if the plant is of older generation, the action has to be taken manually right.

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So, this is the display which will be there and this is now the Liquid Helium which is produced in the Cold Box, it will be transferred using this transfer line to the Main Dewar.

Now, this Main Dewar is of around 500 liter capacity. So, this is a transfer line, which transfers Liquid Helium from your Cold Box through this and enters the Main Dewar and from this Dewar, if suppose somebody want to take Liquid Helium from our laboratory, it will be transferred from this to the user. This is never touch, this will never go, this always will be associated using this transfer line to the cold box.

So, this part is always untouched from this Main Dewar or sometimes called as mother Dewar, it will transfer the Liquid Helium to other device. So, let us see the video ahead and here you will have some Liquid level indicator.

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Which tells you how much is the Liquid Helium contained over there in the Dewar? Now, what you see here are the moving components? And what you see now here? In this direction, we can see now these are the two expansion engines and the engines are basically kept open in the Cold Box below which which just saw and these are the 2 Reciprocating expansion engine 1 on this side, 1 on the other side and that side there are always two expansion engines, they could be 4 expansion engine depending on the flow rates and the flywheel here.

Like any IC engine you have got an inlet and outlet walls. So, there are puppet type walls you can see here on either side. There is the inlet wall to the gas, the outlet wall to the gas and this expansion engine may be moving at 250 RPM, 300 RPM and as the gas gets cooler and cooler the gas becomes denser and denser and in that case the RPM of this will be as low as around 60 RPM. So, that feedback control look will be there and depending on the temperatures inside, the RPM of this machine will change. So, you can see this two expansion engines, which are moving right now here. So, essentially what you have is a heat exchanger and the expansion engines.

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So, now let us come to the compressor that was what the Cold Box was all about? And this is now the compressor which is the most important thing and this compressor now is a Screw type compressor and it compresses the gas from around 1.2 bar to around 17 or 18 bar, which some flow rate of 12 to 18 gram per second of Helium. So, you can see this compressor, this compressor is going to be water cooled, because the temperature after compression going to be very high.

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Now, what is most important is? We just solve the other time in from the form the Dewar, from different user device that the gas goes to the Recovery Bag and the Recovery Bag will get inflated as the gas comes over there and this inflation is major in some terms of height of the Recovery Bag.

So, as soon as this insulation of the bag exceeds a particular value. The recovery gas now is going to will be compressed in a recovery compressor and it will then be stored in impure cylinder and this cylinder gas also will be used for liquefaction over a period of time. So, what you see? This is the recovery line and this is the recovery line connection, which indicates gets connected to the Recovery Bag meant out of rubber and this gas, because it is flexible, because being in the rubber material of rubber material, it gets inflated.

So, you can see now, this is a Recovery Bag and as the Recovery Bag become bigger and bigger, then it will be the gas will be getting transferred to recovery compressor and this is the recovery compressor.

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This is around 11 Kilo Watt recovery compressor and what you see now here is? A user. Some property measurement is being done over here, in this container here, the Liquid Helium is transferred and again the recovery line of that will be connected to the recovery bag.

So, you can see normally wherever Helium production is done, the user also has to normally preferably sit near the Liquid Helium Dewar. So, that you will not have losses in transferring Helium Liquid Helium from place A to place B. The uses are normally kept in nearer to the Liquid Helium production and whatever Liquid Helium boiled off will be there, it will be collected in the recovery bags and the recovery will be faster and efficient.

Whatever Helium is delivered all that Helium Gas has to be recovered, we should have a recovery ratio of above 98 percent; that means, we should not lose any of the Helium that has been delivered in the Liquid form. So, this is a users community, who is now nearer to the Liquid Helium production and you can see again that the Helium gas will go to the recovery connection later. So, that piping, clumping has to be taken care of properly to ensure that gas.

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And they need to have chiller and Cylinders there are infrastructure required, what you saw earlier was? Water chiller which supplies chiller water from the compressor and these are the different Cylinder, Helium Cylinder these are actually manifolds of Pure Cylinder and impure Cylinder.

The Gas form the recovery compressor is actually stored in the impure Cylinders while there are Pure Cylinders with which we start the plant. So, we will have a Pure Cylinder manifold, we will have the impure Cylinder manifold, and they both are put to action while operating the Helium Plant and this is what in short? The video tells you how the Helium Plant operates? Having seeing the Liquid Helium Plant?

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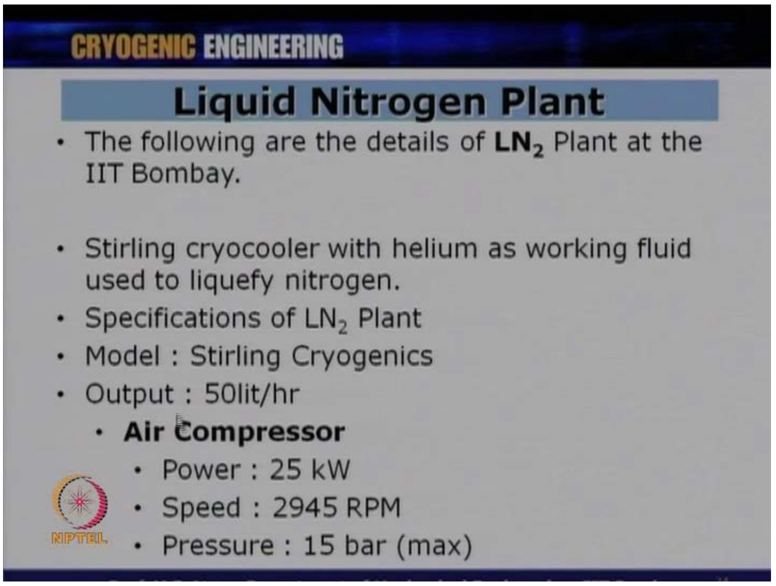

Now, let us see Liquid Nitrogen Plant at IIT Bombay. Following are the details now this Liquid Nitrogen Plant is not an open system over here, it uses a Stirling cryocooler with Helium as working fluid used to liquefy Nitrogen. So, this works on a different principle, it is not an open look system. This cryocooler generates cooling effect at 77 Kelvin and it has got a condenser. The Nitrogen Gas comes on this condenser and it gets liquefied. So, this is close cycle cryocooler which is running all the time and the Nitrogen Gas will come from the top, it will get condensed and what you get is a Liquid Nitrogen. So, these are completed different system as compared to what you saw? For Liquid Helium or whatever systems we have studied earlier.

So, basically is a close cycle while all are the earlier systems where open cycle; that means, the working fluid itself use to get liquefied. Here the working fluid just produces cold while other fluid Nitrogen comes over there gets liquefied and therefore, you get Liquid Nitrogen from here. Now, what do the specifications of this unit? The specifications of this Plant are the Model is Stirling cryogenics, the Output is 50 liter per hour. So, we can see the production rates are higher over here.

Now, it has to (( )) first produce Nitrogen from air. So, Air Compressor is used and then from Air, Oxygen and Nitrogen are separated and Nitrogen is then sent to the cryocooler to get liquefied or to get condense. So, one has to have an Air Compressors the power input to Air Compressor 25 Kilo watt and the pressure is 15 bar.

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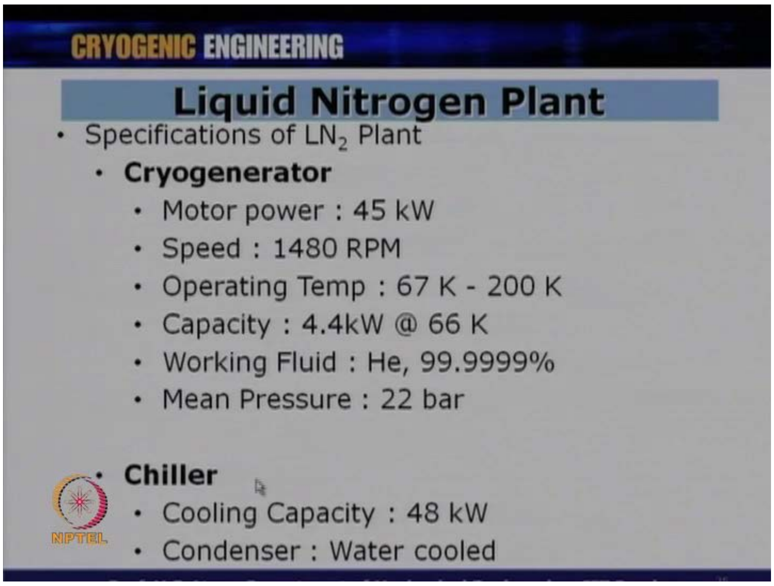

The Nitrogen Plant has a motor power of 45 Kilo Watt, if the gas input is of the Nitrogen it will take 45 Kilo Watt to condense, this Nitrogen in order to get 50 liter per hour production. The speed is 1480 RPM; the operating temperature could be 67 to 200 Kelvin, what we have in this case? We will be 77 Kelvin to liquefy Nitrogen.

Cooling effect is around 4.4 Kilo Watt at 66 Kelvin, but what we want at 77 Kelvin and the capacity could be around 5 Kilo Watt in this range. The working fluid inside the cryocooler is Helium and it is a very high Purity Helium of six 9 99.9999 Purity. So, very high Purity Gas is used to run this cryocooler with a mean pressure of 22 bar.

So, pressure of Helium inside the cryocooler is 22 bar and therefore, the high pressure could be around 30 bar and the low pressure could be around 12 to 15 bar. The chiller is used to cool the cryogenerator and the cooling capacity requirement around 48 Kilo Watt the condenser is water cooled.

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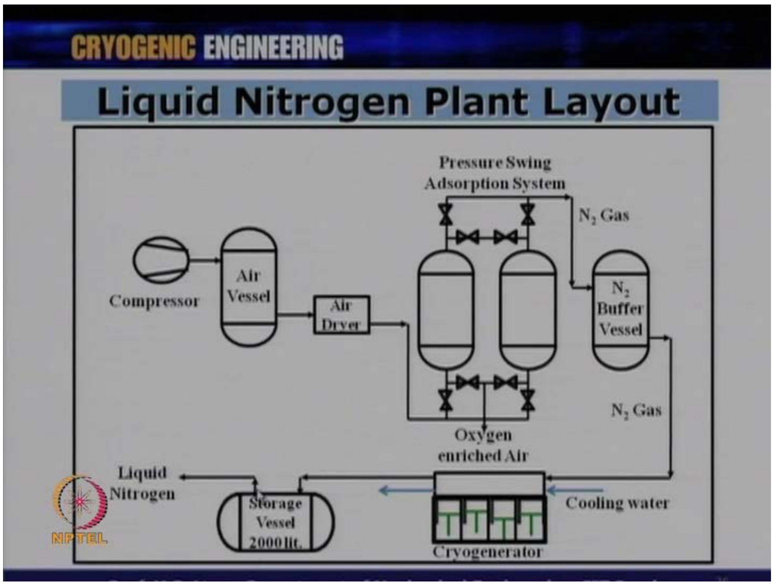

And here is what a schematic looks like? This is the air compressor which takes air form atmosphere; the air gets compressed to around 8 bar and stored in 8 air vessel. This air then is dried so, that all the moisture is taken off from here and then it goes to a something called as a PSA system or pressure swing absorption system. And here only Nitrogen is allowed to go ahead, while oxygen is not allowed to go ahead. Assuming that here is a mixture of Nitrogen, Oxygen, because of different valve arrangement over here, only Nitrogen comes sort of this system.

The Nitrogen gets stored in the Buffer Vessel at this point and this Nitrogen gas, then come to the cryogenerator where continuous 77 Kelvin temperature is produced and the cooling effect of around 5 Kilo Watt is produced. So, that when this Nitrogen Gas come from this side, it will get converted to Liquid and this Liquid is stored in the storage Vessel and from the storage Vessel, the Liquid is given to all the users. So, this is the schematic of the entire Liquid Nitrogen Plant and now, I will show the video of the Liquid Nitrogen Plant.

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So, let us see the video of our Liquid Nitrogen Plant, which we have recently brought at IIT Bombay and what you see here, is a 4 cylinder cryogenerator, which works on stirling cycle and this is the common condenser to all the 4 cylinder machine. This is the stirling cryogenerator and the Liquid Nitrogen is produced from this side and it is stored in this 2000 liter mother Dewar and from here it will be transferred to anybody who wants to take Liquid Nitrogen from our laboratory.

Now, this crank case you can see the crank case houses the crank Shaft, which drives which compressors the gas and does the compression of the Helium gas inside this cryogenerator and this is driven by one motor. Under specification of this motors as you know is around 45 Kilo Watt. The Liquid Nitrogen generator from this is around 50 liters per hour while the gas is charged here at 22 bar. So, that means around 10 to 12 liters per hour from each cylinder.

Now, what you see from other side is? The outlets of the air, which are going out the hot gas, the hot air, because this air which is taken form atmosphere to cool the compressor at this point and to cool the chiller at other point. This is the water chiller requirement, because the gas when it gets compressed over here. The temperature increases and there is the chilled water requirement, which is supplied by the chiller which is sitting over here and the air which is getting compressed, basically get Nitrogen from is also having a air compressor which also needs to be cooled.

So, cooling is done by air only and the hot air which leaves this place is you know left outside at some higher points that people around will not be getting affected. So, this the overall structure of the plant, the air gets compressed over here, then air gets in the P S A plant here, which is pressures been absorption. The Nitrogen is allowed to flow ahead while oxygen is not allowed to go over here. Here, the Nitrogen Gas comes and Nitrogen Gas enters the cryogenerator, we will get condensed and condense Nitrogen or the Liquid Nitrogen will stored in this Dewar. This is the in general the plant structure.

Now, let us see (( )) component from closed distance. So, these are all the outlet for the air, the hot air which leaves our laboratory importantly, we can see that it is a very well ventilated laboratory. This is the air outlet, when it cools the compressor. This is the air compressor around 25 Kilo Watt is the electrical power requirement for the compressor and 45 Kilo Watt for the cryogenerator here and then we need... So, this is a compressor.

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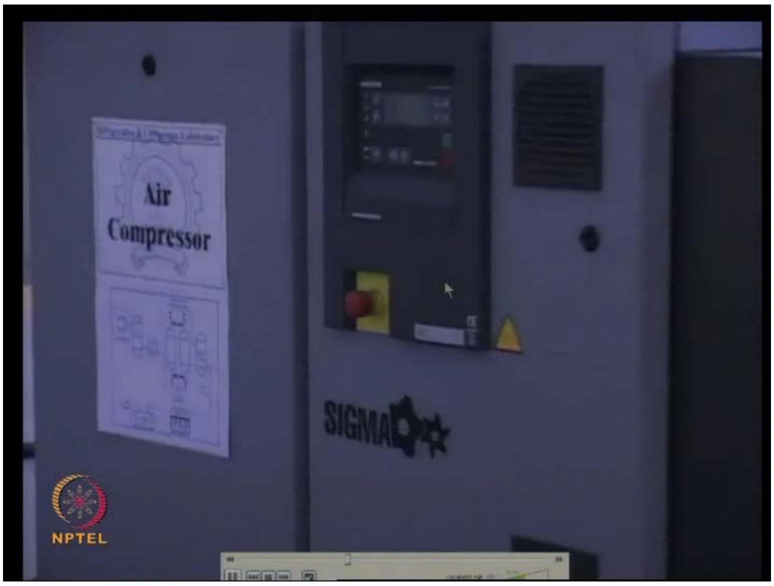

So, you can see this is the air compressor, which takes air from outside here and the compressor also uses the outside air to cool this compressor and the hot air will leave from here, we just saw earlier.

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So, once the air gets compressed to around 8 bar, this air will be stored in this air vessel. You can see it here also in this small schematic over there. So, when air is getting stored over there.

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The Air then will be dried; that means, whatever water component is there moisture is there, it will be taken care off. So, we want only dry air to go after that from from the Air Buffer and from that dry air, this air will go to pressure swing absorption devices PSA system and as you know that PSA will not allow assuming that Air to be mixture of Nitrogen and Oxygen.

The P S A will not allow Oxygen to go ahead and only Nitrogen will be allowed to go and this is done by using molecular sieves, it is like a filter mechanism wherein Oxygen cannot go through the sieves only Nitrogen can go through and once whatever gas leaves this PSA, it will be 100 percent Nitrogen.

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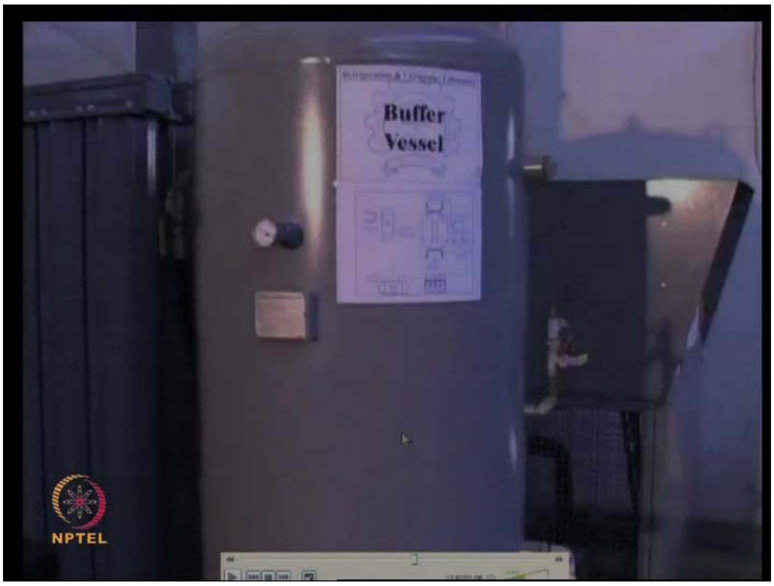

So, now what is coming out is Nitrogen and this Nitrogen is now stored in the Buffer vessel. So, here at the end of P S A Nitrogen will be stored and it will be Nitrogen Pure Gas. This Nitrogen Gas then will go to the cryogenerator for condensation. So, this Nitrogen Gas will come over here and it will get condensed due to the cold, which is produced by this stirling cryocooler and it will be stored in this.

And then we have got a chiller also to get chilled water from this machine, and again chilled water plant is cooled by the air and hot air leaves the laboratory at some higher temperatures. So, this is chiller very important device and this machine and this is our Liquid Nitrogen Plant functions and you can see Liquid Nitrogen being delivered form the Main Dewar and put it some 5 liter cryocan cryo containers.

Having seen both the videos of Liquid Helium and Liquid Nitrogen now, I will actually summarize various systems which we have studied right now. Till now, during all the last almost 10 to 11 lectures.

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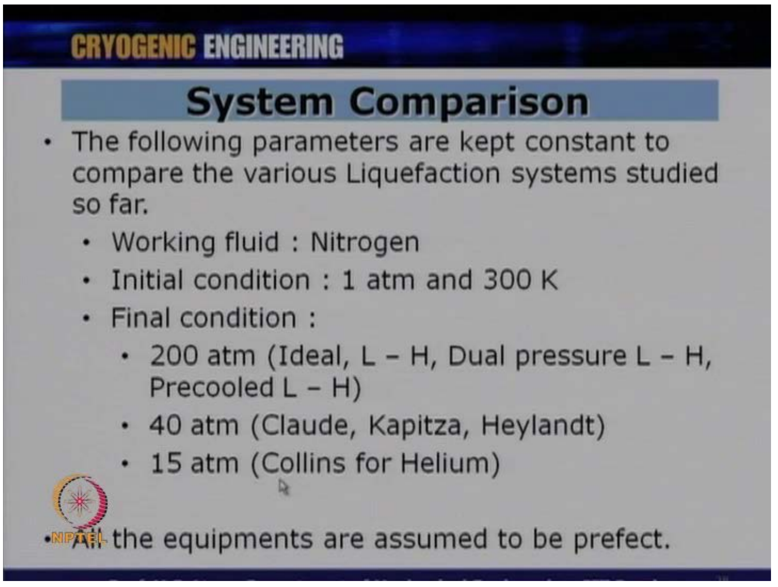

The following parameters are kept constant to compare a various Liquefaction systems studied so, far. Working fluid is Nitrogen and initial condition is 1 atmosphere 300 Kelvin, the final condition is around 200 atmosphere for these cycles, 40 atmosphere for Claude Kapitza and Heylandt cycle while 15 atmosphere around Collins and for Helium cycle… for Collins cycle using Helium as a working fluid. All the equipments are assumed to be perfect.

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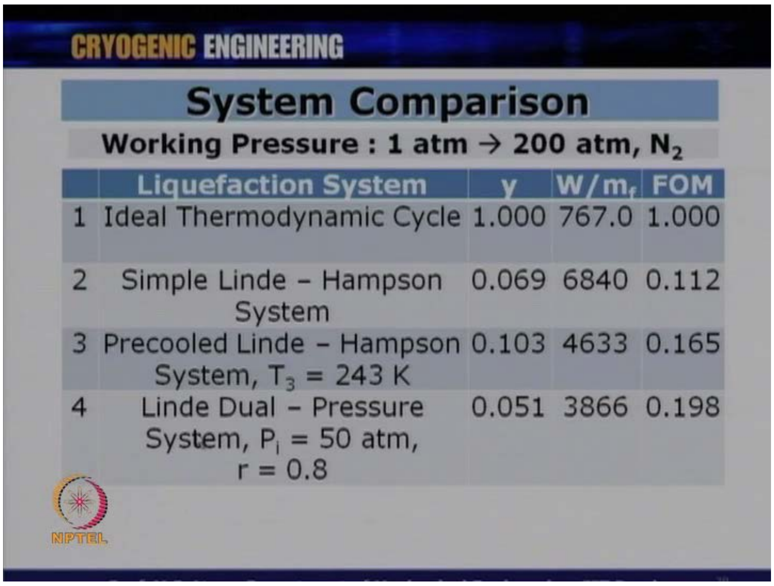

So, if I see this table now here. So, first we had an Ideal Thermodynamic cycle where we get y as 100 percent and these are the FOM value and w y m f value. Then I went from Ideal to Simple Linde - Hampson system and y got reduced my work of Liquefaction also got increased and FOM decreased.

Then I went to a Precooled Linde - Hampson cycle at T 3 is equal to 243 Kelvin what you can see the y increased over here, at the same time w by m f decrease as compared to Simple Linde - Hampson system, but what I have to do is a Precooling.

Then I went for Linde Dual - Pressure system where the intermediate pressure was taken at 50 atmosphere and here while decreases, but what is the important is? w by m f decreases that the work per unit mass of gas liquefied decreases and this was basically the advantage of Linde Dual - Pressure system.

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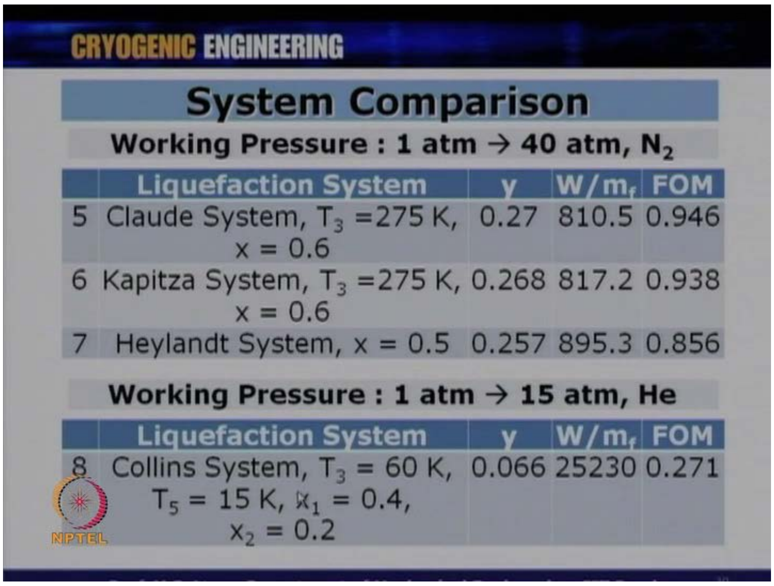

If I go for now 1 atmosphere to 40 atmosphere Nitrogen is a working fluid. The Claude cycle I get y of almost 27 percent, which is very high w by m f is 810 while figure of merit also is very high. Then I had the Kapitza system and Heylandt system where you can again see that y value is quite high, w by m f is quite low and FOM is also quite good basically in this case. But there are all giving me temperature of around 80 Kelvin, they are all using single expansion device.

If I go for now 1 atmosphere to 15 atmosphere using Helium as a working fluid, which is now I am using Collins cycle and Expanders are having inlet temperature of 16 Kelvin and 15 Kelvin is the ratio of 0.4 and 0.2, you get y at 4.2 Kelvin around 6 percent w by m f is of course, very high because you got a very small value of y and the Figure of Merit in this case is 0.271.

All this calculations, I would ask you basically to calculate yourself and compare in this table. The table is shown basically to compare different systems for different end pressure conditions and just to give you feel of what could be the y w by m f and Figure of Merit for these cycles.

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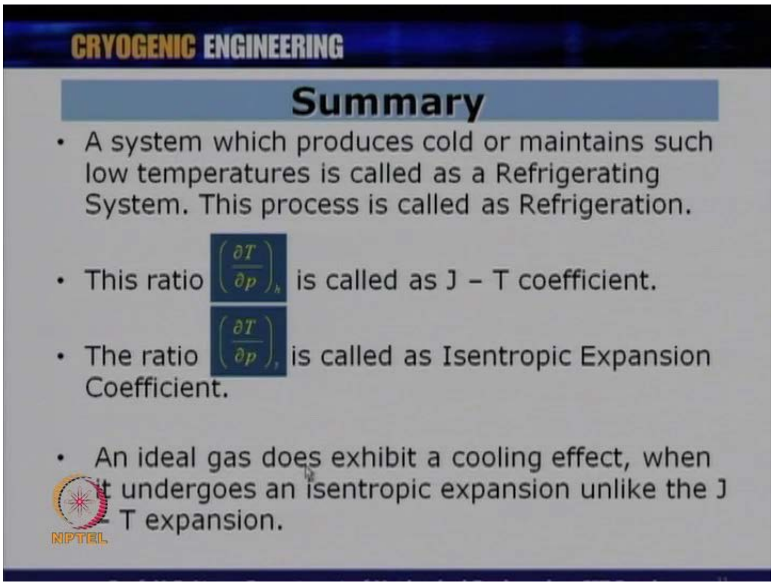

In Summary, a system which produces cold or maintains such low temperature is called Refrigerating system. This process is called as Refrigeration. This ratio of delta T by delta p at constant enthalpy is called as J - T coefficient. The ratio delta T by delta p at constant entropy is called isentropic expansion coefficient. An ideal gas does exhibit a cooling effect, when it undergoes isentropic expansion unlike J - T expansion, J - T expansion has to worry about the inversion temperature of the gas.

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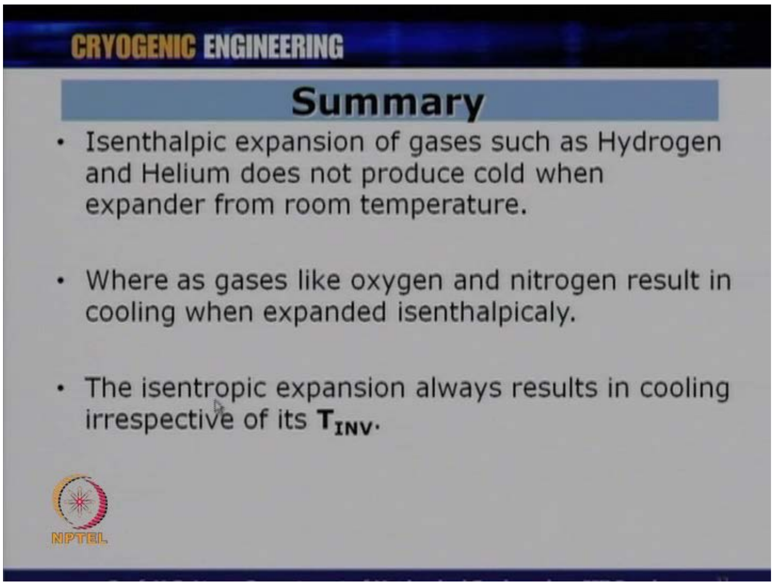

Isenthalpic expansion of gases such as Hydrogen, Helium does not produce cold when expanded from room temperature, because their inversion temperatures are less than room temperature. Whereas, gases like Oxygen, Nitrogen result in cooling when expanded isenthalpicaly. The isentropic expansion always results in cooling irrespective of it is T inversion.

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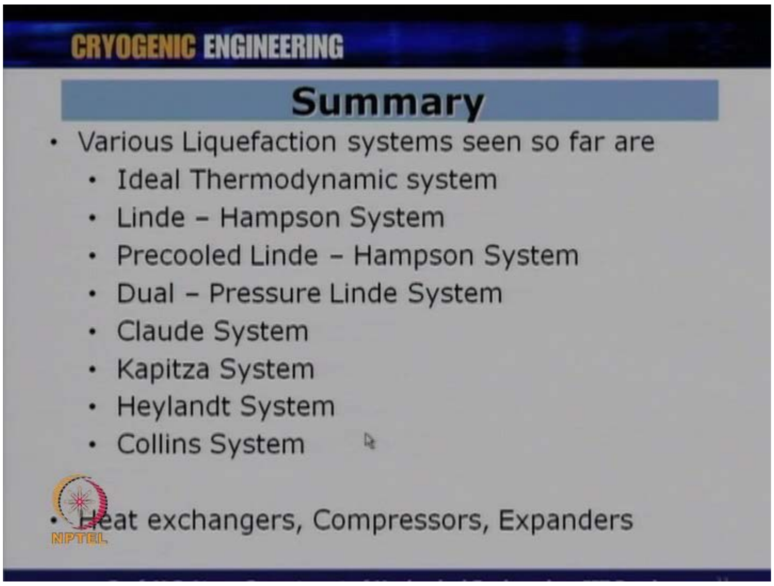

Now, what we have studied are various Liquefaction cycles? And they are ideal thermodynamic cycles, Linde - Hampson cycle, Precooled Linde - Hampson cycle, Dual - pressure Linde system, then Claude system, Kapitza system, Heylandt system and Collins system.

So, we have studied all this systems with their T - s diagram with the schematic of those things and we had solved various problems or we have taken various tutorials to understand, how is cycle got evolved? How is cycle become better and better or how one reaches lower and lower temperatures using various expansion devices etcetera?

Also, we studied the effect of compressors heat Exchangers and Expanders and the effect of those efficiency on the performance of this systems. So, what is important is to understand? How these systems function? And one has to be able to do Minimum calculations like to complete y w by m f, Figure of Merit for all this systems. Thank you very much.