Hydrogen Energy: Production, Storage, Transportation and Safety

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Lecture - 36
Reciprocating and Diaphragm compressors for Hydrogen Compression

Hydrogen compression is an integral; it is an indispensable and fundamental part of hydrogen energy value chain. It is actually if the hydrogen is being produced in a centralized industrial scale hydrogen plant, in that case compressors are required prior to the distribution network whether it is by means of pipelines or tube trailers. However, if hydrogen is produced in a decentralized plant, then it is required downstream, after the electrolyzer or reformer.

Now, the mechanical compressors are actually the most widely used compressors and the most mature technology. They can also provide very high hydrogen flow rates of the order of thousands of normal meter cube per hour. Now, the major challenges that are associated with hydrogen compression is hydrogen because it is very light, it has the lowest density, it requires a lot of energy to compress it to a higher pressure. At the same time, when metals, they are exposed to hydrogen over a period of time at high pressures and corresponding temperatures, then hydrogen embrittlement can result.

Hydrogen is the smallest molecule as such diffusion of hydrogen or hydrogen can leak from the seals end joint and that is the major concern, when considering the different mechanical compressors. Now, that not only reduces the efficiency, decreases the pressure; but at the same time, can pose safety concern because hydrogen it has a low auto ignition energy, it has a wide flammability range. So, as such, this leakage is not desired when we consider the different hydrogen compressors.

Now, when it comes to select a particular technology for hydrogen compressor, then we have to look at the various process variables like these includes the capacity, flow rate, then what is the suction pressure, what is the discharge pressure to which the end use, what is the demand for the end use application.

At the same time, thermodynamics wise that we have seen in the previous classes a compressor technology which requires minimum amount of work is the most preferred one.

So, in today's class, we will look at the different hydrogen compressors. We will be starting with the mechanical compressors.

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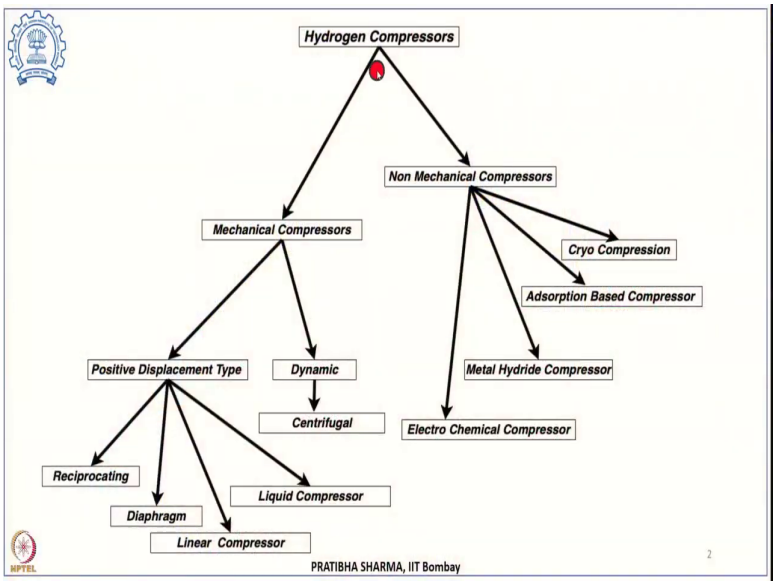

Now, if we try to categorize the hydrogen compressors, then, they are broadly divided into mechanical compressor and non-mechanical compressors. Among the different mechanical compressors, these are further sub-divided into positive displacement type compressors and the dynamic compressors. Among the dynamic category is the centrifugal compressor; while the positive displacement type compressor includes reciprocating type, diaphragm type, linear compressor, liquid compressor.

And then, non-mechanical compressors can be subdivided into electrochemical compressor, metal hydride based compressor, adsorption based compressors and the cryo compressors. So, today, we will look at the various mechanical compressors.

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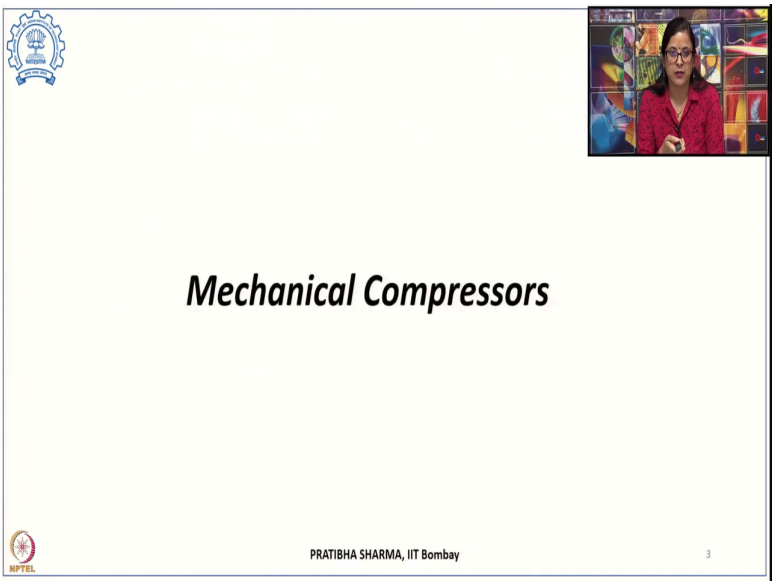

Now, these mechanical compressors as I mentioned, this is the most widely used compressors and the most mature as well. They in fact, convert the mechanical energy into gas energy. Now, among the different topologies which can be used for mechanical compressor, the positive displacement topology is most is the usual one which is being used.

In that particular topology, the gas at fixed amount of gas is compressed such that the volume associated is decreased by using a piston or some other arrangement, in such a way in that particular confined volume, in the reduced volume the impact or the collision of gas molecules onto the walls of the compressor chamber, it increases and that results into an increase of pressure.

So, that is the functioning or the principle of a positive displacement type of compressor. Now, let us start looking at the first of these type of mechanical compressor which are the reciprocating compressor.

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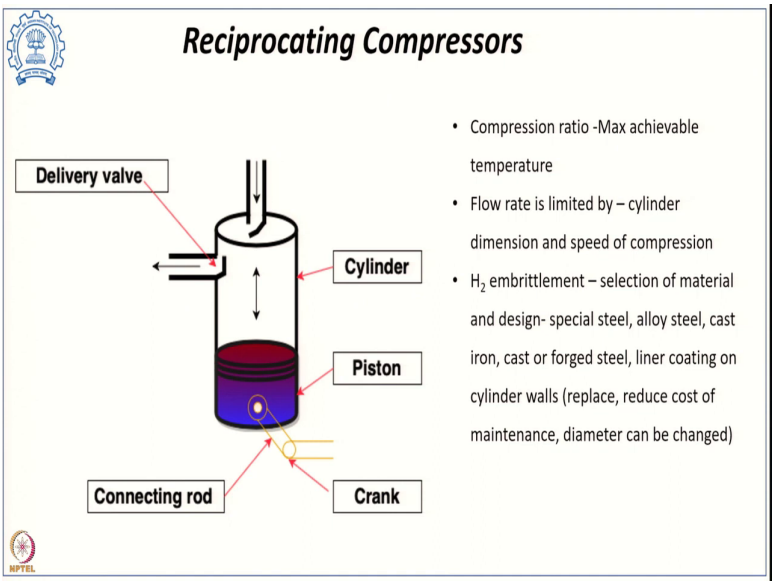

The simplest one being a single stage reciprocating compressor and this compressor is usually taught in the thermodynamics class and this is widely being studied in the previous classes. So, a single stage reciprocating compressor consists of a piston, cylinder, there is an inlet valve, these are the automatic valves, inlet valve and a discharge valve or the delivery valve. Then, the piston is connected by means of a rod to a crankshaft. So, these are the major components. Now, in reciprocating type of compressor, the compression is in fact achieved by the pulsating action of the piston.

Now, in this, the piston which is attached to a crankshaft, its rotator motion which is connected by a rod is converted into a linear motion by the piston. That is why this is also known as reciprocating type of device. Now, in the single stage compressor, when the piston it moves from the lower position which is also known as the bottom dead center towards the top dead center, compression is achieved.

Now, if we look at the working principle of the single stage reciprocating compressor, during the suction stroke the inlet valve opens and the piston moves from the top dead center towards the bottom dead center taking in the gas charge inside and that is what is suction stroke. Now, during the compression, the piston moves from the bottom dead center towards the top dead center and thereby, reducing the confined volume in which the gas is enclosed.

When it reaches to the top dead center, the delivery valve or the discharge valve opens and that pressurized gas is discharged through the outlet valve. So, this completes one cycle of the

reciprocating compressor and similarly, several cycles are carried out so as to compress to get the desired amount of hydrogen at a particular pressure.

Now, in such type of compressor, the major limitation is in terms of the compression ratio that we can achieve with a single stage reciprocating compressor, we can achieve a compression ratio of 3:1, 4:1 or with a well-designed compressor, we can reach about 6:1 compression ratio. This compression ratio other than the cylinder dimension or the speed of compression, it is also related to the maximum achievable temperature.

Because of the compression, there will be an increase in temperature and that maximum temperature is allowable in the compression that is restricted and that limits to which we can achieve the maximum compression usually, about 250 degree centigrade. Other than that, the flow rate which can be achieved using the single stage reciprocating type of compressor, this is limited by the cylinder dimension and speed of compression.

By speed of compression, we mean number of cycles per unit time. Now, cylinder dimension, if we want a higher flow rate, if we try to increase the cylinder dimension, the system will become heavier. It will become bulkier and then, there will be inertia forces involved. At the same time, with a higher cylinder dimension, if a higher speed of compression is tried; in that case, there will be more of vibration, noise, then there will be several sort of mechanical stresses that will arise.

And in that case, we will have to again reduce the speed of compression. So, in fact, that limits the flow rate in case of a higher cylinder dimension. So, we can achieve a better speed of compression in smaller cylinders. But that again limits the flow rate. So, with these reciprocating type of compressor, there is a limit to which the maximum flow rate which we can achieve.

Other than that because hydrogen has a specific property that when it comes in contact with metals, it can result into embrittlement and that requires that a special material should be selected which for which the embrittlement is as low as possible so, both the selection of appropriate material as well as the design of these type of compressors plays a very important role.

Among the different materials that can be used, this can be either a special steel, it could be alloy steel, it could be cast iron, cast or forced steel. Now, since they are these type of

compressors they have moving parts and that will result into a lot of wear, there will be repair that will be required; lot of maintenance that will be required.

We can have an inner coating a liner coating onto the cylinder walls in the inside surface of the cylinder and that helps in not only we can during the maintenance, we can replace if there is a wear, if there is any worn out of that layer; at the same time, that can reduce the cost of maintenance. So, no major replacement of the moving parts will be required, if that coating is there, the change of that coating would be good enough. At the same time, with that coating we can change the diameter of the cylinder and that provides a lot of versatility and flexibility in the operating conditions.

So, having a coating in the inner surface of cylinder has several advantages. Now, as we have seen that there is a limit to which we can achieve a compression ratio using a single stage compressor. So, if there is a limit to that, then we can go for adding stages to the compressor reciprocating compressor.

So, in that case, we can have two stage compression, three stage compression or more than that. That depends upon as we have discussed in the prior class, in the earlier class during the thermodynamics of the compression process that we can keep on adding stages to save the work of compression at this to increase the pressure.

But at the same time there will be a trade-off; trade-off in terms of the amount of energy saved as against the expenditure as against the further addition of cost which we are doing in terms of adding a stage. So, there lies an optimum depending upon which technology we are using.

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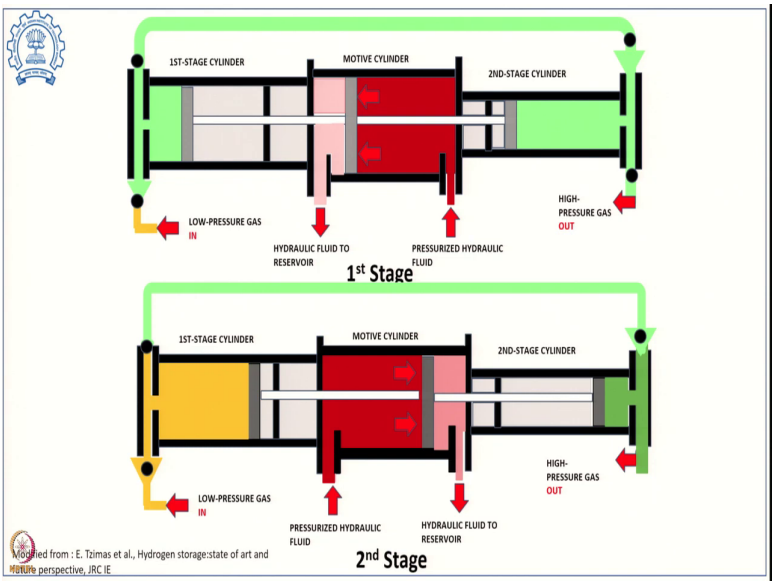

Now, to consider a two stage compression, for a reciprocating type of compressor, this figure shows the first figure shows the 1st stage of compression; the second figure shows the 2nd stage of compression. To explain the principle of operation in the beginning, a low pressure gas which is hydrogen in our case is taken in the first stage of compression. So, the first stage cylinder, this is having a higher diameter compared to the second stage cylinder.

So, during the suction stroke, when low pressure hydrogen is taken inside the first stage cylinder, the piston moves towards the right hand side. This hydraulic fluid is such that that makes the piston move towards the right hand side during the suction stroke and the gas is taken in the first stage.

Now, after it reaches to its maximum displacement, the compression stroke starts with the movement of the piston towards the left hand side and that decreases the volume and increases the pressure. Once it reaches to the top dead center that high pressure the pressurized gas for the first stage, it goes to the second stage of compression.

Now, during this, this transfer from first stage to second stage of compression, we can have an intercooler in between. As we have learnt in the previous class, in the thermodynamics part by having an isothermal or the work of compression required for an isothermal process is minimum. We can achieve near isothermal conditions, if we increase the number of stages. So, there could be multi-stage compression with inter cooling in between. Other than that we can also have cooling in the walls of the compressor.

So, other than the cooling, adding the cooling by means of intercooler; cooling can be achieved in the compressor chamber in the walls of the compressor. Now, once the gas is compressed by the 1st stage, it enters into the 2nd stage of compression. So, during the suction stroke, the piston moves towards the left hand side to take the gas charge inside and for compression, during the second stage the piston moves on to the right hand side to decrease the volume and increase the gas pressure.

Once it reaches to the top dead center, the gas at a higher pressure is taken out from the 2nd stage. So, this is the process of compression using two stage compression. The movement of piston is provided by a hydraulic fluid circuitry.

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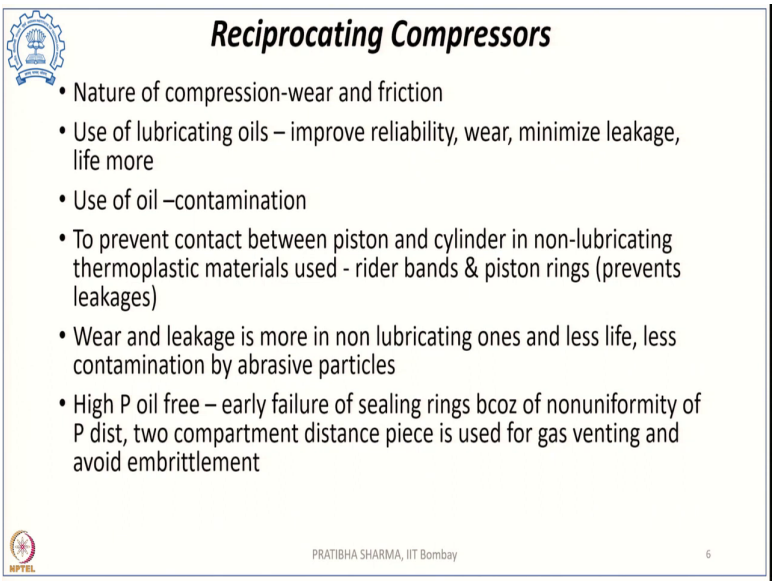

Now, if you look at the reciprocating type of compressors, we have seen that there are several moving parts involved. Because of the moving parts and because of the nature of the compression, there is a wear associated with the process as well as there will be friction losses. We can reduce that wear and friction with the use of lubricating oils. With the use of lubricating oils, not only we will improve the reliability of the process; the friction wear will reduce. At the same time, these lubricating oils presence of that will minimize the leakage.

And that leakage, we know it is undesirable; highly undesirables. The reason being when there is a hydrogen leakage, the corresponding pressure of hydrogen reduces; at the same time, efficiency reduces and that also leads to safety challenges. With the use of lubricating

oil since the wear is reduced, the life of the compressor will also increase. It is found that the life of lubricating compressors is higher than the life of non-lubricating compressors.

But at the same time, the problem associated with these type of compressor is because of the presence of oil that may enter into the compression chamber and that may contaminate the gas, the hydrogen present in the compression chamber and that is thereafter, we will require then a separation of hydrogen or removal of the contaminants so as to get pure hydrogen.

Now, in order to prevent this type of contamination, what can be done is we can use a non-lubricating type of compressor. But then, if it is non lubricating one, then there will be definitely wear in friction associated with it. That can be still reduced if a non-lubricating layer is introduced that is of thermoplastic materials.

These materials have high thermal and chemical stability and then, we can introduce the different rider bands or the piston rings. These will not only reduce the wear the improve the life of the compressor; but at the same time, presence of these will also prevent the leakages of hydrogen. But still if we compare these wear and leakage, it is more in case of non-lubricating compressors compared to the lubricating compressor and as such the life is also less of the non-lubricating type of compressor.

But the major reason, we have considered the non-lubricating compressor is to avoid the contamination. However, there still can be certain amount of contamination in the non-lubricating ones as well. And that arises because of the abrasive particles which may be because of these materials which we have used as bands or rings.

With completely oil free compressors, we can achieve high pressures; but then, there are chances of early failure of ceiling rings. These are because there will be non-uniform distribution of pressure inside. And for that to address that, there could be two compartment distance piece that can be used and that can do the gas venting and that gas venting can reduce the embrittlement.

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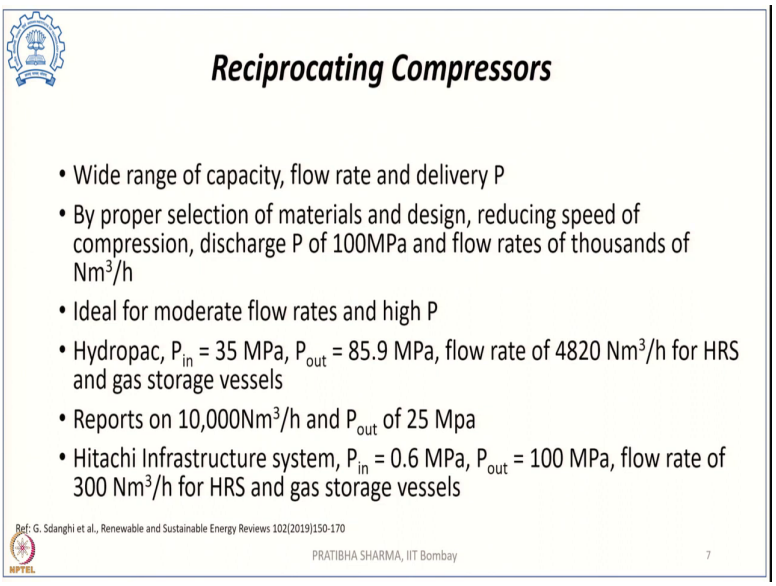

So, with the reciprocating type of compressor, we can achieve wide range of capacities, flow rates and the delivery pressure. So, high pressures can also be achieved and for that, an appropriate selection of material as well as the design of the compressor plays a very important role.

At the same time, by reducing the speed of compression, we can still achieve a higher discharge pressure and it has been reported that about 100 MPa pressure can be achieved with flow rates of thousands of normal meter cube per hour. Usually, these compressors are preferred for high pressures and a sort of moderate flow rates.

There have been several demonstrations for these reciprocating compressors, there are companies which provide these reciprocating compressors for various end use applications. Like Hydropac Inc, they have their compressors which having an inlet pressure of 35 MPa; it can give a deliver pressure of 85.9 MPa with a flow rate of 4820 normal meter cube per hour and such compressors have been installed at hydrogen refueling stations and they are used for storing hydrogen in the compressed gas vessels.

There have also been reports, where in very high flow rates could be achieved like 10,000 normal meter cube per hour with outlet pressure of 25 MPa. Another well-known company Hitachi Infrastructure Systems, they also have high pressure compressors, where the inlet pressure at as low as 0.6 MPa, has delivered pressure of 100 MPa with a flow rate of 300

normal meter cube per hour and these are also used for hydrogen refueling station and for storing gas in the compressed hydrogen tank.

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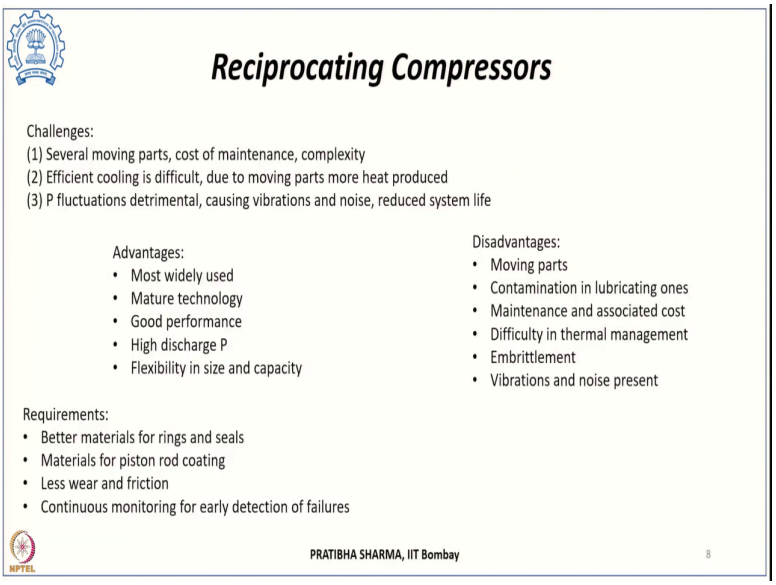

So, if we see the major challenges which are associated with these reciprocating machines is they have many moving parts and that adds up to the complexity, that adds up to the wear, that adds up to the friction, heat produced and all those are the major challenges associated with these machines and since there are several moving parts, there will be there will be maintenance required and that adds up to the cost. At the same time because of these moving parts a lot of heat is generated and that heat needs to be removed.

So, an efficient cooling is required; but with the speed of compression, it is very difficult to achieve efficient cooling in these devices. With pressure fluctuation arising in the compression chamber, this can be highly detrimental because that can induce different vibrations and noise into the system. At the same time, this can even reduce the life of the system. So, these are the major challenges that needs to be handled with the reciprocating compressor. But they have at the same time, they have many advantages also.

Advantages that this is the most major technology for hydrogen compression. They give good performance; they are most widely used; they can even give high delivery pressures; they can be made in different sizes and capacity. So, flexibility in size and capacity exist.

At the same time, the presence of moving parts, if we are using lubricating type of compressors and the contamination by the oil; the required maintenance and associated cost which is high, the requirement of thermal management which is very difficult to obtain, hydrogen embrittlement that can result, presence of vibrations and noise all these are the major disadvantages with these types of compressors.

So, if we look at what is required in the area of reciprocating compressor is we require better materials for both rings and seals. Piston rod coating materials are required. There should be design as well as materials, which could reduce the wear and friction in these materials.

At the same time, there is a requirement of continuous monitoring so that an early detection of any fault or failures could be carried out. Now, another category of these reciprocating machines is a diaphragm compressor. Again, this is a piston driven device; but it do not have any moving part in the gas compression chamber.

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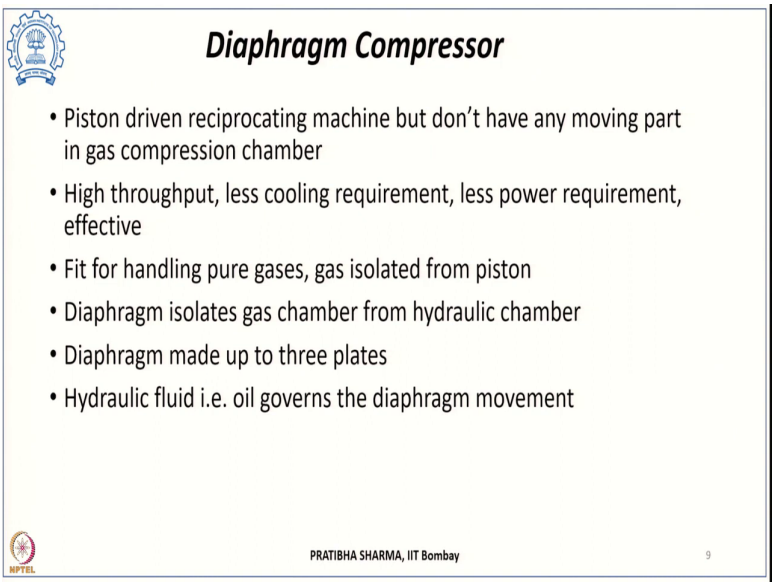

So, these diaphragm compressors with their high throughput, less cooling requirement, less power requirement, they are very effective towards hydrogen compression. They are also specially fit for handling pure gases; chemically pure gases. The reason being in diaphragm compressor, the gas is completely isolated from the piston or the two are separated and the movement of the piston that is provided to the hydraulic fluid in the hydraulic chamber.

And that hydraulic chamber transfers that movement to the diaphragm and from diaphragm that movement is transferred to the gas or the gas gets compressed in the region, which is separated from the hydraulic chamber or from the piston. Now, this diaphragm is in fact a metallic membrane which consists of three plates. So, it is made up of three plates; one plate which is on to the hydrogen side that is known as process plate, the another plate which is on to the hydraulic oil side that is known as the hydraulic plate.

And then, there is a middle plate that intermediate plate or the middle plate that not only provides strength to the diaphragm; but also prevents hydrogen leakage. So, in the case of diaphragm compressor, the hydraulic fluid used is oil and that governs the movement of diaphragm.

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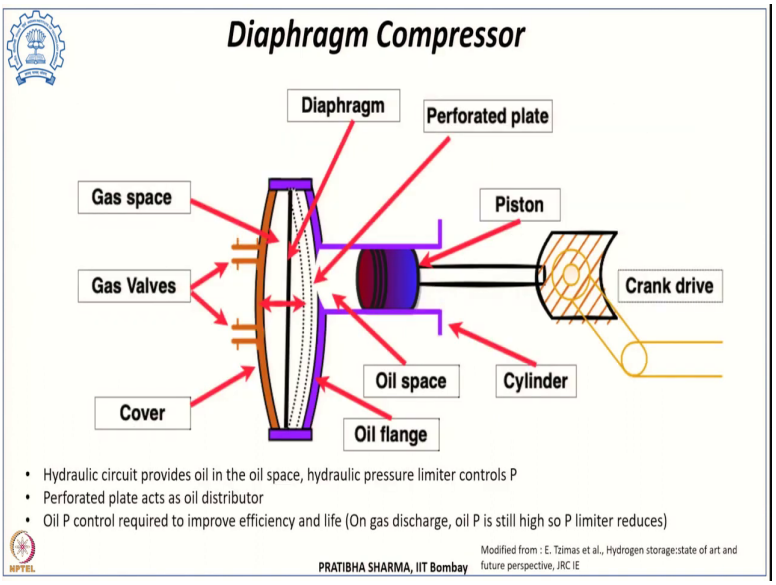

Now, if we consider the principle of diaphragm compressor, there is a diaphragm which separates the oil chamber or the hydraulic circuitry from the gas circuitry. So, there is a gas space and then, there is an oil space. Now, the piston movement that creates a pressure in the hydraulic circuitry that deflects the diaphragm. Now, during the suction stroke from the inlet valve, the gas is taken into the gas chamber and the diaphragm deflects towards the right hand side that is the suction stroke.

Now, during the compression stroke, the piston moves on to the left hand side and then, the pressurized hydraulic fluid that deflects the diaphragm to the left hand side thereby, compressing the gas. Once it has reached to its maximum, the delivery valve opens and the

pressurized hydrogen could be obtained. So, now, that is the biggest advantage that since the two are separated, there is no direct contamination of the gas by the oil here. At the same time, the hydraulic oil which is used that provides oil in the oil space.

But the major challenge that lies is the hydraulic pressure is such that say for example, when the compression is done, the diaphragm moves towards to its maximum position towards the surface of the gas chamber. In that case, the pressure on to the hydraulic side is higher; in such a way that still the piston has not reached to its top dead center. So, that pressure has to be restricted; it has the pressure difference between the gas space and the hydraulic space needs to be limited.

So, there is always a hydraulic pressure limiter which controls this pressure. At the same time, to increase the life of this diaphragm, there is a perforated plate which acts as an oil distributor and provides a uniform pressure across the diaphragm. So, this oil pressure control, the presence of perforated plate that is very much required to not only improve the efficiency of the process; but at the same time, to increase the life of the compressor.

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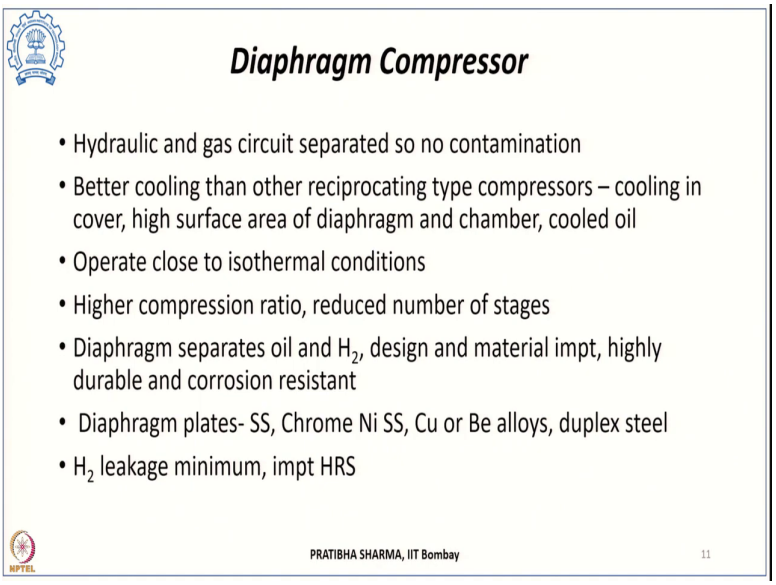

Now, in this as we have seen in the diaphragm compressor, the gas circuit and the hydraulic circuit is separated so, as such there is no contamination of the hydrogen which is being compressed by the oil since the diaphragm separates the two. At the same time, there is better cooling observed in these type of compressor as against the other reciprocating type of

compressor. The reason being the diaphragm surface area is higher, the gas chamber surface area is higher; at the same time, we can also provide cooling onto the cover of the diaphragm.

So, there are different ways in which we can achieve better cooling, using the cover cooling, surface area as well as the oil which is supplied in the hydraulic circuit can also be cooled so as to achieve conditions which are near isothermal and that improves on to the efficiency reduces the work of compression.

So, with these type of compressors, we can achieve higher compression ratio even with the reduced number of stages. Now, the important thing here is the diaphragm which separates the oil and the hydrogen circuitry that design of this diaphragm as well as what material it will be made up of that is very important and that needs to be highly durable this diaphragm and it should be corrosion resistant at the same time.

So, specialized materials need to be used for making this diaphragm. So, diaphragm plates, these are usually made up of stainless steel or chrome nickel stainless steel or copper beryllium alloys or duplex steel. In these type of compressors, since there are no seals which could or moving parts in the compression chamber and the diaphragm this is hermetically sealed as such the leak which used to be in the reciprocating type of compressor, this is very less in the diaphragm type of compressor.

So, the minimum leakage that is an advantage of the diaphragm compressor, when the application in the hydrogen refuelling station is being considered. Now, a major change from the diaphragm compressor could be the movement of the diaphragm by means of piston can be replaced by an electrostatic by supplying a DC voltage.

So, that it is an electrostatic diaphragm compressor. Now, in these type of compressor, still the diaphragm is going to move; but in between the diaphragm and the compressor chamber, the surface of the compressor, a DC voltage is connected.

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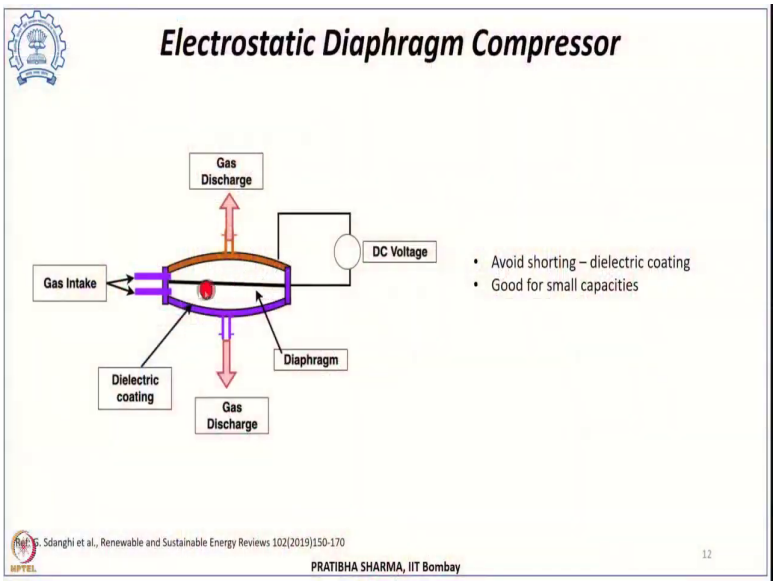

Now, this voltage connected is such that the electric field which is produced in the compressor chamber will deflect the diaphragm and during the compression stroke, the diaphragm will move towards the surface of the compression chamber and it will compress the gas. So, in this process during the suction stroke, the diaphragm will move away from the surface of the compressor chamber and gas will be taken in.

During the compression stroke, the diaphragm will move towards the surface of the compressor chamber and the gas will be discharged at a higher pressure. Now, the polarity of the voltage could be changed so as to have the compression and expansion associated in the two cavities; the gas cavities. So, these are the two gas cavities, wherein with the reversal of the polarity we can achieve the complete cycle.

Now, this diaphragm when it moves towards the surface of the compressor chamber, it can come in contact with the compressor chamber and that can lead to sorting. In order to avoid that a dielectric material coating is there in the inner surface of the compressor chamber. But these type of compressors these are better suitable for small capacities. Now, the major problems associated with these compressors is the durability.

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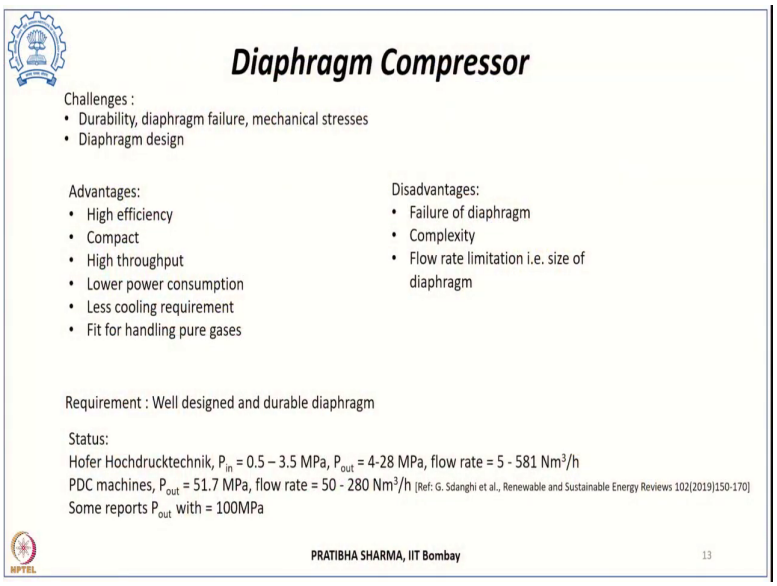

The diaphragm undergoes several mechanical stresses and that could lead to diaphragm failure. So, the major challenge is the design of this diaphragm, the associated material used for the diaphragm should be appropriately selected. So, that diaphragm failure could be avoided.

So, that is the biggest disadvantage as well of the diaphragm compressors. The other disadvantage lies that it is a complex system; there is a limitation of flow rate. This is because of the size of the diaphragm to the maximum which we can have the diaphragm size that limits the flow rate.

But there are several advantages also associated with these type of compressors, like we can achieve high efficiency with less number of stages. This is more compact. We can get high throughput. This requires lower power consumption, less of cooling is required and these are very good for handling pure gases. So, the major requirement in these compressor is a well-designed and durable diaphragm which has a long life and it works without failure is the requirement for such compressors. There have been demonstrations.

So, like the company Hofer, a German based company that has that supplies these diaphragm compressors and these diaphragm compressors have an inlet pressure of 0.5 to 3.5 MPa with an outlet pressure of 4 to 28 MPa and a flow rate of 5 to 581 normal meter cube per hour has been installed at several places.

Another company which supplies diaphragm compressors is the PDC machines, which can supply compressors which have an outlet pressure of 51.7 MPa, flow rate of 50 to 280 normal meter cube per hour and there have been several reports, where even the outlet pressure which could be achieved using these compressors is 100 MPa.

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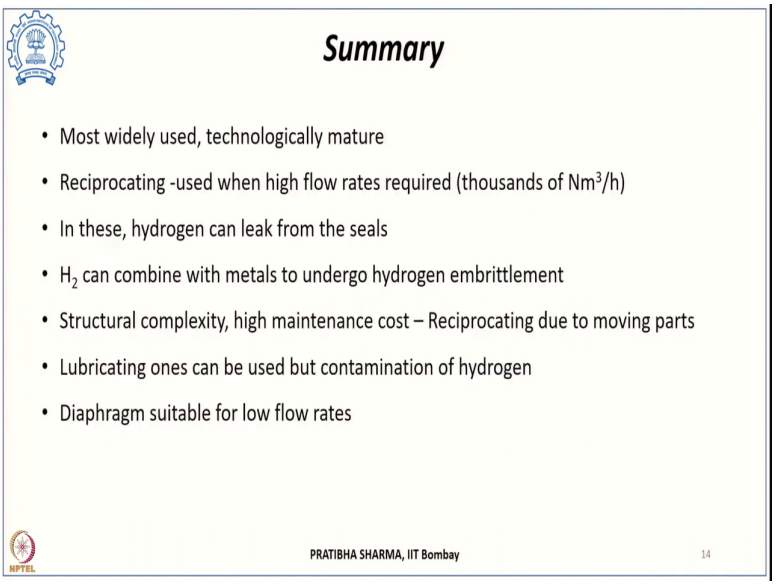

So, to summarize this part, we have seen two compressors, these mechanical compressors or the reciprocating type of compressors, these are the most widely used one in the major technology. They are used when high flow rates are required; even they can provide flow rates of the order of thousands of normal meter cube per hour. In them, the major problem that lies is since they have moving parts, there is a requirement of seals and hydrogen being the smallest molecule can leak through these seals.

And that can have many challenges; these challenges could be not only in terms of safety, we can also have a relatively lower efficiency, lower pressure because of the hydrogen loss. Hydrogen can even combine with metals and can result into hydrogen embrittlement. So, the selection of material is very important, when considering the compressors. The structural complexity and high maintenance cost because of the moving parts is again another concern in the reciprocating type of compressors.

So, the cost, cost of maintenance is relatively higher and the design is again important part. Using the lubricating type of compressors, we can reduce the wear, we can reduce friction, leakages; but then, there is a contamination of hydrogen and the gas needs to be purified after

compression. With the diaphragm type of compressors, these compressors are well suited for low flow rates. So, in the next lecture, we will see the other mechanical type of compressors.

Thank you.