Hydrogen Energy: Production, Storage, Transportation and Safety
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Lecture - 39
Electrochemical and Adsorption based Compressors

In the previous class we have seen the two non mechanical compressors, cryogenic compression as well as metal hydride based compression. Today we will see two more types of non mechanical compressors the first one is an electrochemical compression where this is like the other non mechanical compressor, this does not have any moving part and the driving force for compression is the electrical energy. Now, this has a structure which is similar to polymer electrolyte membrane fuel cell.

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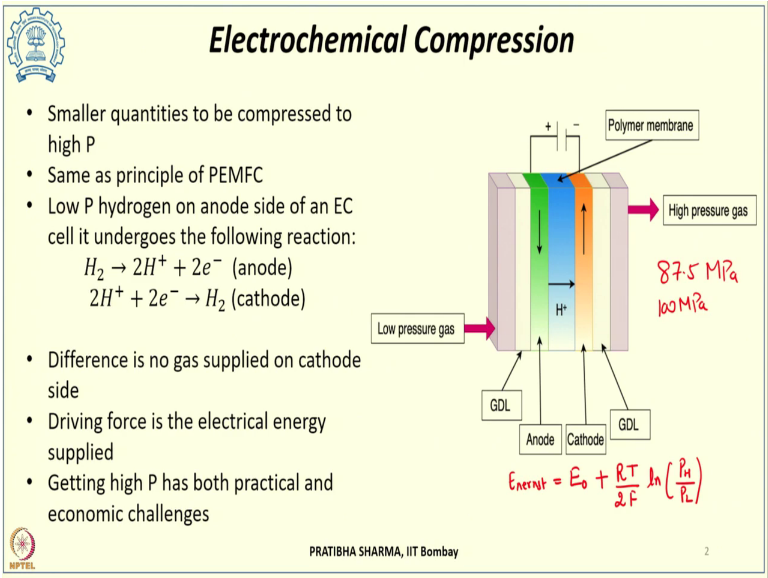

So, it has components like a PEMFC it has membrane electrode assembly where the two electrodes and membranes are integrated with electro catalyst to form an assembly MEA then there are gas diffusion layers, bipolar plates, current collectors and the end plates. The major difference of an electrochemical compressor from a polymer electrolyte membrane fuel cell is that gas is not passed on to the cathode side.

So, there is no gas flow onto the cathode side so, that the reaction of hydrogen with oxygen to produce water which used to occur in polymer electrolyte membrane fuel cell does not occur here. Principle of operation of electrochemical compression is that a low pressure gas is allowed to pass onto the anode side. Now this hydrogen gas undergoes hydrogen oxidation reaction on to the anode side producing protons and electrons.

These electrons migrate through the external circuit while the protons they permeate through the proton conducting membrane onto the cathode side. Onto the cathode side the hydrogen evolution reaction occurs. So, protons and electrons they recombine to form hydrogen. Now, a continuous pumping of low pressure gas in a closed system will increase the pressure onto the cathode side and when the delivery pressure is attained we can get high pressure hydrogen out of the compressor.

This process will continue until the driving force which is the electrical energy or current is being fed into the system. Now, more is the current being supplied, the more will be the rate of protons being transferred from the anode side on to the cathode side and the performance of such compressors also depends upon the voltage which is being supplied. So, and that is given by the Nernst voltage.

So, the E_{nernst} voltage is given by E_0 which is the standard cell voltage under the standard condition plus (RT/upon the number of electrons being transferred times Faraday's constant) times ln(the high pressure and the low pressure in the system). So, the discharge pressure over the inlet pressure.

Now, here we can see that the discharge pressure or the maximum achievable pressure it depends upon the applied voltage. Now as the applied voltage increases the high pressure or the protons which recombine onto the cathode side also increases. Now, thus we can achieve pressures in case of an electrochemical cell, this could be like 25 to 30 MPa at a current density which can vary from 0.1 to 1 amperes per centimetre square and the life of such compressor can be higher than 20,000 hours.

But the major challenges are if we want to get high pressures then it has both practical as well as economic challenges.

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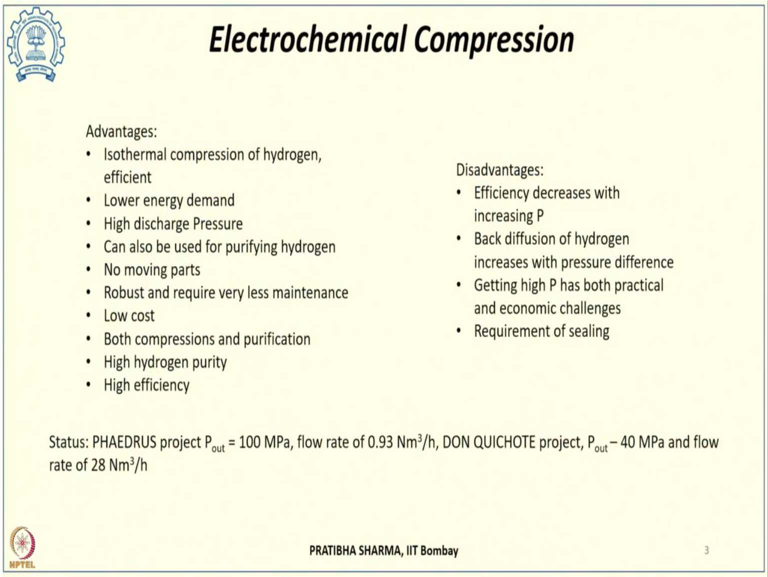

The reason being what happens is as we increase the pressure the Nernst voltage becomes almost of the same order of magnitude as that of the ohmic losses and as such the efficiency decreases. Secondly, if we further increase the pressure, in that case the permeation of hydrogen from the cathode side onto the anode side the process which is known as back diffusion will also increase.

Now, if we want to address this back diffusion process, in that case the membrane which is being used that can be made thicker, but if that membrane is thickened in that case the membrane resistance will also increase and as such ohmic losses will increase and finally, the efficiency will decrease.

So, we can say that if we want to get a higher pressure, the efficiency for higher pressures as well as for higher flow rates the efficiency of the electrochemical cell that reduces. So, now we can get a higher pressure from electrochemical compressors by cascading several single stage electrochemical cells.

So, a multi stage electrochemical cell which consists of several such electrochemical cells being cascaded together that can produce higher pressures and we can get pressures of the order of like 87.5 MPa or even 100 MPa have been demonstrated. Now if it is say for example, if we are operating in a lower pressure condition at a lower flow rate with a lower voltage then efficiencies are very high efficiency could be as high as 90 percent.

If it is operating under isothermal conditions which is usually the case in case of electrochemical compressors being operated at a lower pressure say 1 MPa in that case we can achieve efficiencies as high as 95 percent. But as the pressure increases the efficiency decreases like for example, if we go to 10 MPa or higher than 10 MPa in that case the efficiency can drop to 60 percent or even below.

So, the major advantages if we see with this particular process is that since the operation of electrochemical compressors this is almost isothermal as such these are more efficient they consume less amount of energy because of this isothermal compression process. We can achieve high discharge pressures using electrochemical compressors they do not have moving parts as such no vibrations and noise with these compressors they are quite robust and they require very less maintenance.

As such the operating cost as well as the CAPEX is also lower for these type of compressors we can achieve high hydrogen purity high efficiency with these compressors, but high efficiency at comparatively lower flow rate. So, these are for low flow rate operations.

At the same time these electrochemical compressors can be used for both compression as well as purification. So, we can separate out hydrogen from a mixture of gas. As the membrane which is used is a proton conducting membrane only protons gets permeated through the membrane and they recombine on the cathode side to separate the hydrogen from the mixture of gases. So, it can be used to get high purity hydrogen.

However, the major disadvantages associated with electrochemical compressors is the efficiency decreases with the increasing pressure. Also we have seen that there is a back diffusion of hydrogen as the pressure difference between both the electrode side increases and that increased permeation is undesirable.

Now, if we want to get higher pressure then there are both practical as well as economic challenges associated with it and then there is a requirement of sealing so, as to avoid the hydrogen leakage. If we consider the current status of these compressors, then there are several projects which have demonstrated the use of electrochemical compressors like the PHAEDRUS project where in the output pressure that was achieved was 100 MPa at a flow rate of 0.93 normal meter cube per hour another project that was DON QUICHOTE project that offered a output pressure of 40 MPa and a flow rate of 28 normal meter cube per hour.

Now, the another non mechanical compressor is adsorption based compressor. Now again adsorption based compressors these are non mechanical. So, they do not have any moving part; however, the compression is derived by means of temperature swing. Now if we look at the process of compression in these adsorption based compressors then this is adsorption desorption based.

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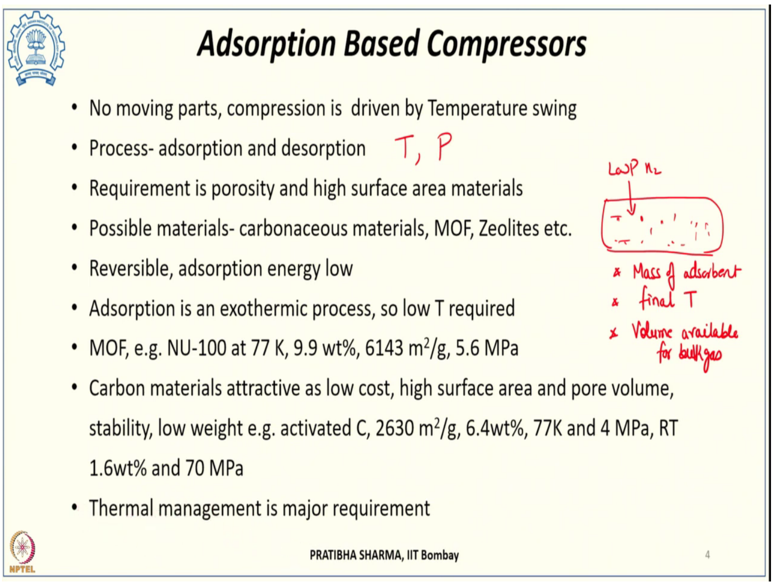

Now, if we consider a tank a closed system when a low pressure gas is introduced into a tank which consists of high surface area materials and high porosity in that case hydrogen gets adsorbed onto the surface of high surface area materials. Now this adsorption is a surface phenomena and once it reaches saturation then we can have a desorption process so, as to get the high pressure hydrogen.

Now, for desorption heat energy input has to be provided which increases the temperature of the system which increases the temperature of the adsorption bed thereby desorbing hydrogen. Now both the adsorption and desorption occurs at a specific temperature and pressure conditions. Now, since hydrogen when it is in the adsorbed state that is a very dense state during desorption the desorbed hydrogen enters into the bulk gas phase and that increases the pressure.

So, the pressure in this way is increased. Now the maximum achievable pressure from such devices that depends upon how much is the mass of absorbent used, what is the final temperature which we have supplied and at the same time the volume which is available for the bulk gas.

So, the final achievable pressure, the maximum pressure that we can obtain depends on all these three. The mass of absorbent, what is the final temperature and what is the volume which is available for the bulk gas. Also, there is an important requirement in such adsorption based compressor and that is of high surface area materials which has porosity into the system.

Now, this is the reason because the adsorption increases or the rate of adsorption becomes higher and it depends upon the high surface area of the bed. Now there are different materials which have shown very promising for having high adsorption capacities like some of these materials are carbon based materials, carbonaceous materials, these could be carbon nanotubes activated carbon or fullerenes, there are materials like metal organic frameworks, zeolites and many such materials which are high surface area materials and have very high adsorption capacity.

Now, this adsorption desorption process the adsorption is a completely reversible process with the interaction energy involved being 0.01 to 0.1 electron volt. This is also an exothermic reaction as such this is preferred at low temperature. Now the interaction involved in the adsorption process is a weak Van der Waals interaction and as such the thermal motion energy which is involved and that is that can be of the same order of magnitude as that of the adsorption energy or the Van der Waals interaction as such we need to cool down the system to get sufficient adsorption.

Besides the adsorption process takes on the surface of the high surface area materials and it forms a sort of mono layer on the absorbent as against in case of metal hydrides where a strong chemical bond is formed and that is the volume phenomena here this is the surface phenomena which requires a low temperature.

So, as such for the adsorption we have to have a lower temperature and this can be easily achieved at liquid nitrogen temperatures because that becomes economical and easily available liquid nitrogen usage. There are materials like metal organic frameworks a typical example nu 100 if we see at the liquid nitrogen temperature 77 K it was observed that it has a surface area of 6143 meter square per gram a pure volume of 2.82 meter cube per gram and at

77 K 5.6 MPa, it could adsorb 9.9 weight percent. So, and that is the highest achievable capacity like for such materials.

Even we can use the different carbon based materials. They are very attractive because they have sort of moderate cost they can provide very high surface area, pore volume, they show stability, they have a lower weight like for example, if we see the activated carbon then one of the result it is shown that with a area specific surface area of 2630 meter square per gram at 77 K, 4 MPa we could get an gravimetric capacity of 6.4 weight percent. So, this is at 77 K.

However, if the temperature is room temperature we can achieve 1.6 weight percent at 70 MPa. So, that clearly shows the advantage of reduced temperature in case of adsorption based compressor besides that as we have seen that it is an exothermic process the heat which will be released during adsorption need to be taken out or removed from the storage tank.

So, a lot of thermal management is required not only the heat which is generated during the process at the same time heat has to be supplied for the desorption and the heat which is produced during the adsorption has to be removed. So, for both there is a very major requirement is that of thermal management.

Now, if the heat which is being produced in the process of adsorption is not being removed in that case that will increase the temperature of the bed and that will reduce the rate of adsorption and we will not get good efficiencies. So, if we look at the advantages that we can get from adsorption based compressors.

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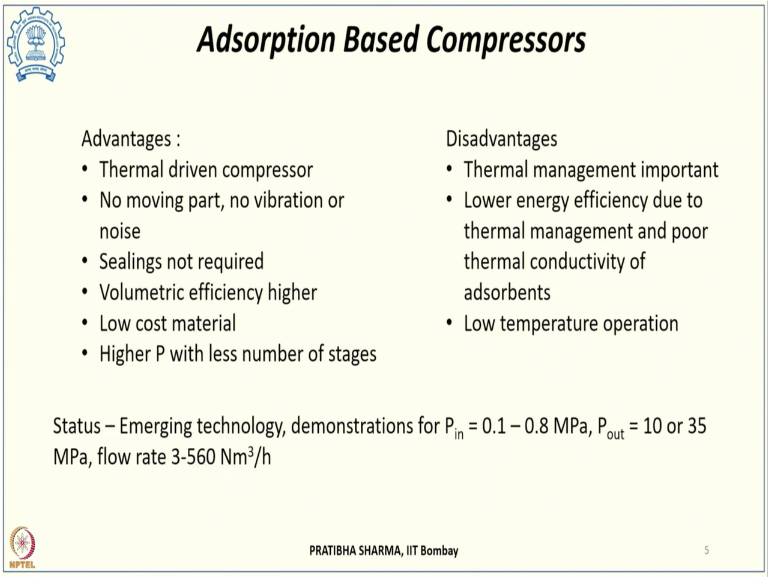

These are thermal driven devices and even the waste heat which would be available like the industrial waste heat we can utilize for desorption. Since they do not have any moving part. So, no vibration or noise is observed we do not require sealings like as it was required for electrochemical compressors since the hydrogen, they have a very high energy density, volumetric energy density as such the volumetric efficiency is higher for such devices, the cost of material is also low as such the overall cost is reduced they have both CAPEX and OPEX cost which is less.

The higher pressure can be achieved using these devices by including less number of stages, but the major disadvantages with these devices is the thermal management becomes very essential and we need to consider both the heat removal as well as heat supply mechanism so, as to have a uniform bed temperature. There is a lower efficiency observed if there is a poor thermal management and this is also associated with the poor thermal conductivity of the absorbents which are used in the compressor and we require a low temperature operation that adds up to the cost and reduces efficiency.

Now, if we see the status then this is an emerging technology there are some demonstrations available in literature where in if the input pressure is used is 0.1 to 0.8 MPa we could get an output pressure of 10 MPa or 35 MPa with flow rates shown in literature to be 3 to 560 normal meter cube per hour.

Now, if we compare all the compressors that we have learned so far both the mechanical as well as non mechanical compressors we do a techno economic analysis.

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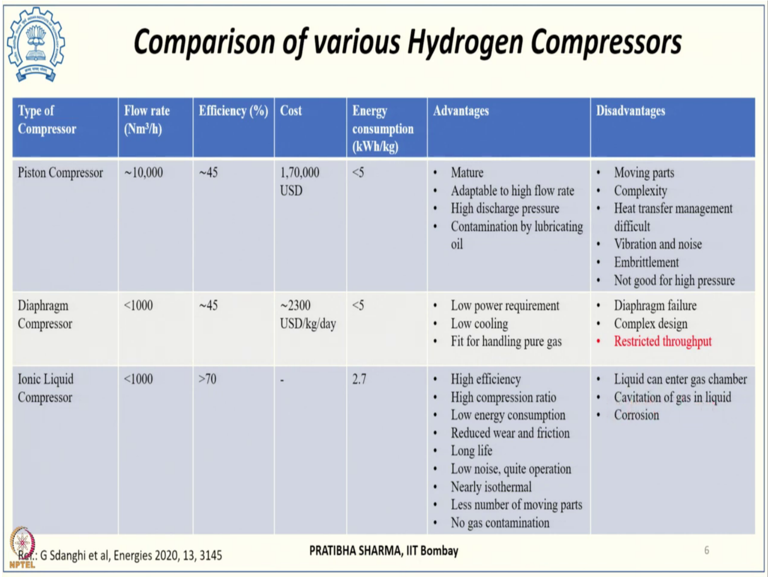

Comparison of various Hydrogen Compressors

Type of Compressor	Flow rate (Nm³/h)	Efficiency (%)	Cost	Energy consumption (kWh/kg)	Advantages	Disadvantages
Piston Compressor	~10,000	~45	1,70,000 USD	<5	• Mature • Adaptable to high flow rate • High discharge pressure • Contamination by lubricating oil	• Moving parts • Complexity • Heat transfer management difficult • Vibration and noise • Embrittlement • Not good for high pressure
Diaphragm Compressor	<1000	~45	~2300 USD/kg/day	<5	• Low power requirement • Low cooling • Fit for handling pure gas	• Diaphragm failure • Complex design • Restricted throughput
Ionic Liquid Compressor	<1000	>70	-	2.7	• High efficiency • High compression ratio • Low energy consumption • Reduced wear and friction • Long life • Low noise, quite operation • Nearly isothermal • Less number of moving parts • No gas contamination	• Liquid can enter gas chamber • Cavitation of gas in liquid • Corrosion

Ref.: G Sdanghi et al, Energies 2020, 13, 3145

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Then we can see that the piston compressors we can achieve very high flow rate of the order of 10,000 normal meter cube per hour their efficiencies is low approximately 45 percent the cost this is CAPEX that is 1,70,000 US dollars. The energy consumption is approximately 5 kilowatt hour per kg the advantages associated with piston type of compressor is this is a mature technology we can get high flow rates high discharge pressure, but the challenge is that it can get contaminated with the lubricating oil.

They have moving parts that adds up to the complexity in the design, heat transfer required that heat transfer management becomes difficult. And since they have moving parts there is vibration and noise associated there could be challenges associated with the embrittlement and they are typically not very good when it is very high pressures are required.

Diaphragm compressors we can achieve flow rates which are comparatively lower than the piston compressors less than 1000 normal meter cube per hour, efficiency 45 percent if we see the cost then it is 2300 USD per kg per day energy consumption of the same order as the piston compressor they have lower power requirement, lower cooling requirement that we have seen in more detail in the previous classes and they are fit to handle the pure gases.

The reason being the diaphragm separates both the piston chamber and the gas handling chamber. The disadvantages are there could be stresses on to the diaphragm and that could lead to diaphragm failure design is complex and there is a restricted throughput.

Another category of mechanical compressor that we have seen was the liquid ionic compressor or ionic liquid compressor with a flow rate of around 1000 normal meter cube per hour, efficiency was very high that we have seen that was 70 percent energy consumption is very low because they work very close to the isothermal conditions. So, about 2.7 kilowatt hour per kg.

The advantages are they have very high efficiency, we can achieve higher compression ratios energy consumption is lower there is a reduced wear and friction associated with these compressors, we can get long life, less of noise and quiet operations they operate near isothermal conditions and then there is no gas contamination that can take place in these type of compressors.

But the major problem is that the liquid can enter into the gas chamber as such the condensation of the liquid or removal of the liquid from the gas is required even the reverse can happen cavitation of gas into the liquid is also possible and then the associated corrosion.

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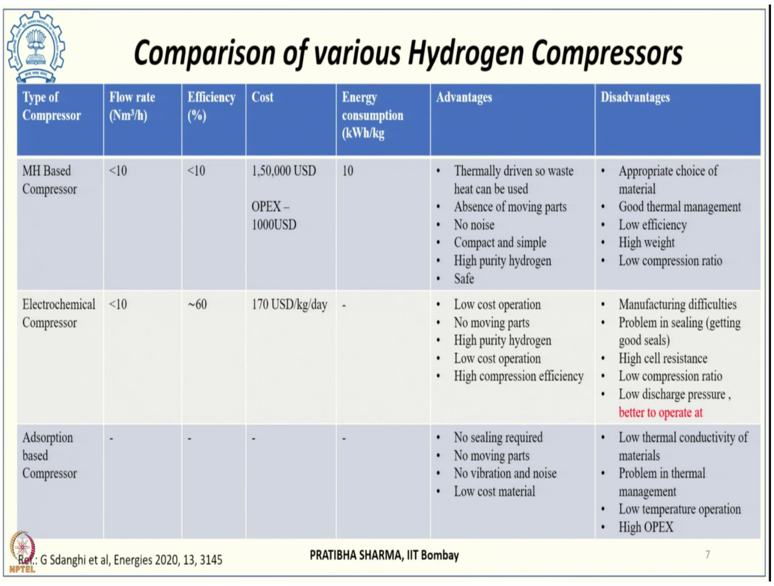
Comparison of various Hydrogen Compressors

Type of Compressor	Flow rate (Nm^3/h)	Efficiency (%)	Cost	Energy consumption (kWh/kg	Advantages	Disadvantages
MH Based Compressor	<10	<10	1,50,000 USD OPEX – 1000USD	10	• Thermally driven so waste heat can be used • Absence of moving parts • No noise • Compact and simple • High purity hydrogen • Safe	• Appropriate choice of material • Good thermal management • Low efficiency • High weight • Low compression ratio
Electrochemical Compressor	<10	~60	170 USD/kg/day	-	• Low cost operation • No moving parts • High purity hydrogen • Low cost operation • High compression efficiency	• Manufacturing difficulties • Problem in sealing (getting good seals) • High cell resistance • Low compression ratio • Low discharge pressure , better to operate at
Adsorption based Compressor	-	-	-	-	• No sealing required • No moving parts • No vibration and noise • Low cost material	• Low thermal conductivity of materials • Problem in thermal management • Low temperature operation • High OPEX

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Then non mechanical compressors we have seen were metal hydride based compressors, electrochemical and adsorption based compressors metal hydride compressors they are suited for lower flow rate 10 normal meter cube per hour, their overall efficiency is poor. Cost is lower than the reciprocating type of compressors 1,50,000 USD that is the CAPEX even the OPEX cost is also lower for metal hydride based compressors like if we compare then it is 1000 USD for metal hydride based compressor and 9000 USD for reciprocating type of or the mechanical compressors.

Energy consumption 10 kilowatt hour per kg, advantage is the metal hydride compressors they are thermal driven devices and even the waste heat can be used for deriving the absorption desorption process. There is an absence of moving part no vibration and noise they are very compact and simple we can get high purity hydrogen no contamination these are safe to operate.

Disadvantages, appropriate choice of material is required that plays a crucial role, thermal management again is very important, they have a lower efficiency, weight is higher gravimetric capacity of these metal hydrides which are used that is lower and we can achieve a lower compression ratio.

Electrochemical compressors they can give a flow rate of around 10 normal meter cube per hour, they have efficiency of 60 percent. 170 USD per kg per day is the cost advantages again low cost operation, no moving parts, high purity hydrogen we can get, low cost operation, high compression efficiency.

The problems are there are manufacturing difficulties which are associated with these electrochemical compressors, the scaling up problem in sealing getting very good seals, high cell resistance, low compression ratio, low discharge pressure and they are better to operate at lower flow rate and lower pressure.

And the last one that we have seen are adsorption based compressors. This is a relatively new technology and there are not much data available, but the advantages with these type of compressors is we do not require ceiling, they do not have moving parts, no vibration and noise, the low cost material are used in these compressors.

The major disadvantages are the poor thermal conductivity of the materials which are used and then that increases the problems associated with thermal management at the same time the requirement is of low temperature 77 K and that adds up to the operational cost OPEX.

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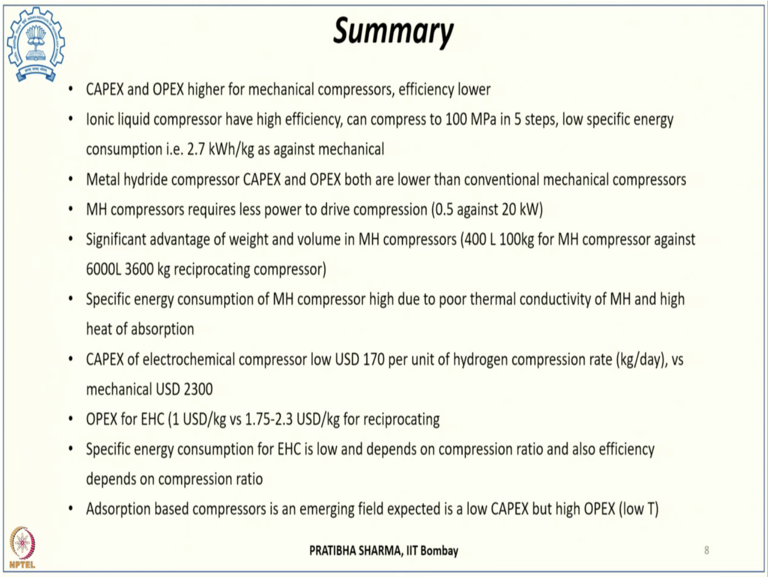

To summarize the CAPEX and OPEX is both higher for mechanical compressors they have many moving parts, maintenance cost is higher their efficiency is lower. We have seen the ionic liquid compressors which have high efficiency and we can achieve higher compressions higher pressures like 100 MPa in five steps, they require low specific energy like 2.7 kilowatt hour per kg and that is as against the mechanical which require high energy.

Metal hydride compressors they have both CAPEX and OPEX which are lower than the mechanical compressors. metal hydride compressors require less of power like 5 kilowatt per kg as against 20 kilowatt for the reciprocating type and there is a significant advantage of weight and volume in metal hydride compressors like a typical example if 400 litres 100 kg for metal hydride compressor then 6000 litres 3600 kg for reciprocating compressor thus they require a larger footprint area.

Specific energy consumption for metal hydride compressors is high that is the overall energy requirement and that is because of poor thermal conductivity of metal hydride and high heat of absorption which is required high heat of desorption and then the thermal management which is required.

CAPEX associated with electrochemical compressors is low like USD 170 per unit of hydrogen compression that is in kg per day versus the mechanical compressor that is 2300 USD and the same units. OPEX with the electrochemical hydrogen compressors is low like 1 USD per kg against 1.75 to 2.3 USD per kg for reciprocating type of compressors and the specific energy consumption is low and that depends upon the compression ratio efficiency also depends upon the compression ratio.

Adsorption based compressors these are emerging this is an emerging technology it is expected that they will have a lower CAPEX, but high OPEX this is because of the requirement of low temperature.

Thank you.