Hydrogen Energy: Production, Storage, Transportation and Safety
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Lecture - 34
Thermodynamics of Hydrogen Compression Part - 1

Now, in this part, we will consider the hydrogen compression and expansion. Now, the hydrogen compression or expansion that will depend upon which thermodynamic process has been used and thus the final state of the gas will also be determined by the process used.

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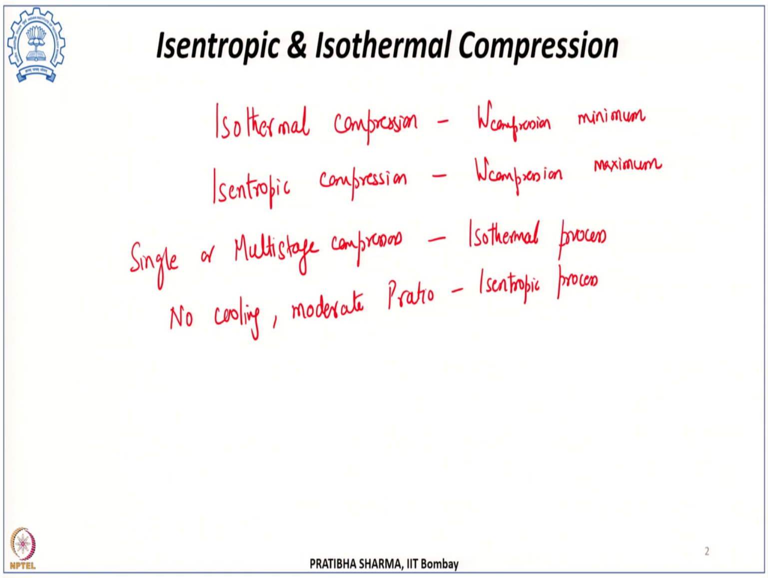

In actual practice it is very difficult to identify the process, actual process that occurs in the compression and it requires a lot of efforts. So, what is done is, actual process is in fact mapped to a reference thermodynamic process, which closely approximate the actual process. So, we can consider the process to be either an isentropic compression or we can consider it to be an isothermal compression.

Now, if the process of compression is considered to be an isothermal compression, in that case the work of compression required is minimum. If it is isothermal compression, then the compression work required is minimum and that we know from the knowledge of thermodynamics. If the process of compression is modeled to isentropic process, in that case the compression work is maximum.

Now, single stage or whether it is multi stage compressors, when they are compressing hydrogen gas and cooling is involved or cooling is being considered during the compression process; then they can be modeled as isothermal or the process can be modeled as isothermal process. However, there is no cooling involved during the compression process or for moderate pressure ratios; the process can be modeled as an isentropic process.

And if there is no efforts being put, in so as to remove the heat which is generated during the compression process, then in that case this is a adiabatic process. So, the process can be modeled according to the, whether the process involves cooling, whether it is it does not involve cooling; so accordingly the process can be modeled to the appropriate thermodynamic process.

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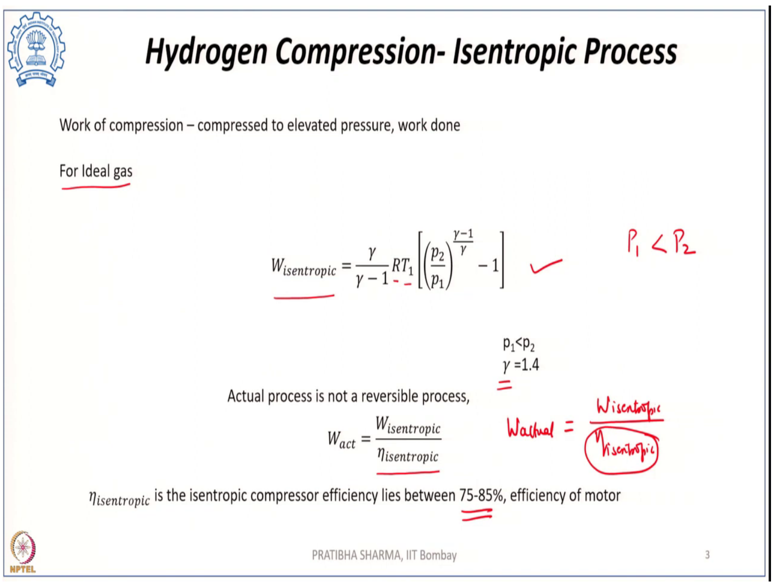

Now, let us first consider the hydrogen compression process to be an isentropic process. So, as mentioned it is very difficult to find out what the actual process would approximate to; however it can be modeled to be isentropic process, where when the compression is done to a elevated pressure, the work of compression we can calculate.

If we consider the gas to be an ideal gas, then the isentropic work involved is given by the specific heat ratio (γ/γ-1),R is the gas constant T is the initial temperature, p2 is the discharge or the final pressure, p1 is the initial pressure or the inlet pressure and again to the power (γ-1/γ)-1. So, this is the isentropic work considering the gas to be an ideal gas.

Here since the process is of compression, so the initial pressure is lower than the delivery or the final discharge pressure. Now, considering the gas to be diatomic; because hydrogen is diatomic gas, the specific heat ratio is 1.4. Now, this is the process considering an isentropic process, which is reversible; but in actual process, the process is not a reversible process, there are several irreversibility involved. To account for those irreversibility, we can consider an isentropic compressor efficiency.

So, this is considering the ideal process which is reversible; but if in order to account for the irreversibility involved in the process, we can include the isentropic compressor efficiency in the denominator. So, the actual work done is the ratio of the two; the isentropic work and the isentropic compression efficiency. This isentropic compressor efficiency this lies in the range of 75 to 80 percent; besides that, we have to also include the efficiency of the motor which lies in the range of 90 percent.

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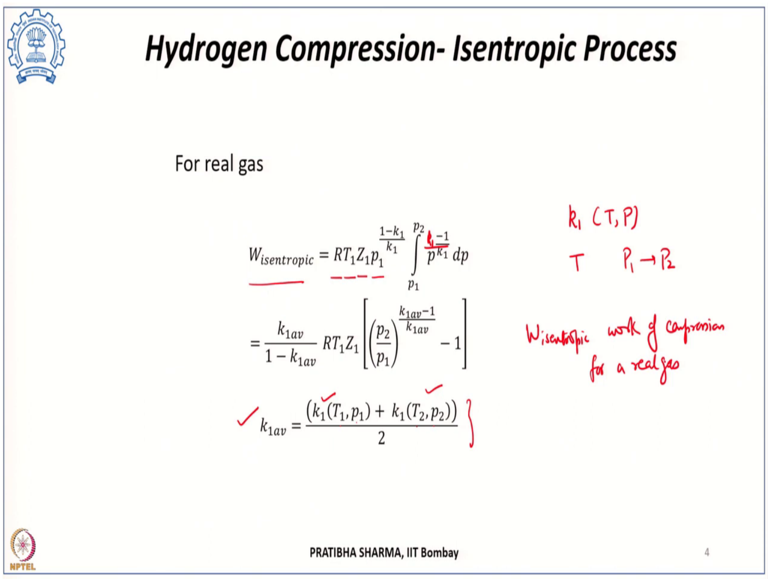

Now, ideal gas we know this is a theoretical concept, where we know that we consider that the gases these are made up of hard molecules, which have negligible volume, solid spheres and they have no interaction between the gas molecules. However, in actual case, the real gases they have an interaction, attractive or a repulsive interaction that exists. So, the behavior of the gas as we have seen in the earlier class, for a real gas it is different from the ideal gas.

Now, in order to calculate the work which is required for compression using an isentropic process; for a real gas, we can find the work that is given by the gas constant R, T_1 the initial temperature, the compressibility factor Z_1 and the initial pressure p_1. So, $RT_1Z_1p_1^{1-k1/k1}$; k1 is the isentropic coefficient, which relates the pressure, volume equation of state. And then there is an integration from initial pressure, p_1 to the final pressure p_2, $p^{k1-1/k1}$ integrated over the pressure dp.

Now, we know that the exponent k_1 also changes when pressure changes. So, we know that it is a function of both temperature and pressure; at a particular temperature let us say T, when the pressure changes from p_1 to p_2, the exponent also changes. Now, since the variation is linear, we can take average of the exponent in these 2 states. So, the k_1 average we can use.

So, if at pressure p_1, temperature T_1, the value is k_1; at temperature T_2, pressure p_2, the 2 values and we can take it is average. Now, this average exponent $(k_{1average}/1-k_{1average}) \times RT_1Z_{1\times}[(p2/p1)^{(k1average-1/k1average)}-1]$ this gives the isentropic work for compression for a real gas.

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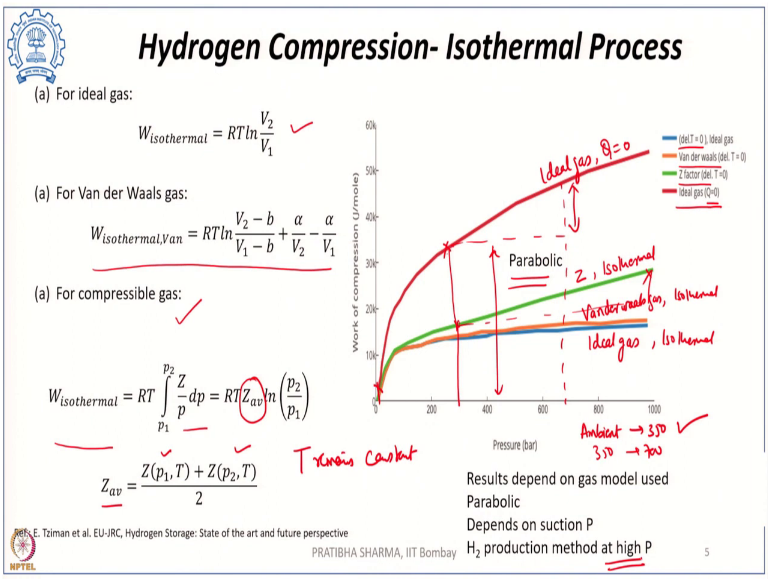

The another possibility is, if the actual process is modeled to be isothermal process; that means we are removing the heat during the compression. So, whatever is the heat generated during the compression that is removed, such that, the temperature of the process remains constant.

Now, here again we can consider either the gas to be ideal gas; if we consider the gas to be ideal gas, the work of isothermal compression is RT × $\ln(V_2/V_1)$. We can have different models for real gas and considering the Van der Waals gas model, we can also get the isothermal work for the Van der Waals gas as RT× $\ln(V_2\text{-}b/V_1\text{-}b) + (\alpha/V_2)\text{-} (\alpha/V_1)$

So, this is the required work of compression considering the process to be isothermal. However, if we include the compressibility factor as a deviation between the real and ideal gas behavior; we can write the isothermal compression work as RT integration over the initial pressure to final pressure, compressibility factor Z upon p integrated over dp. So, RT integration p_1 to p_2 (Z/p) dp; on integration we can get a value of $RTZ_{average} \times \ln(p_2/p_1)$, so the pressure ratio.

Now, again this Z average is the average compressibility factor, we have already seen the variation of compressibility factor for different temperature and pressure. Now, in this case since it is an isothermal process, the temperature remains constant. So, the average compressibility factor is found as an average of the compressibility factor in the 2 different states, where the pressure was different; in one state where the pressure was p1, in another state when the pressure was p2. And then we can find out the isothermal work for the compressible gas.

Now, this figure shows that depending upon which gas model we have used, the work of compression may differ. So, whether we have used an ideal gas model, whether we have considered it to be a real gas, whether it is an isothermal process, whether it is an isentropic process, whether we have considered a Van der Waals gas or we have considered it to be a compressible gas considering the compressibility factor, the different curves are obtained.

So, for an ideal gas, considering it to be an isentropic process; we are getting the highest amount of work of compression. Similarly, for considering it to be a compressible gas with the compressibility factor, the model which uses the compressibility factor and considering it to be isothermal; the third one is considering it to be a Van der Waals gas and under isothermal conditions and finally, considering it to be an ideal gas under isothermal conditions.

This shows that depending upon the gas modeled used, the work of compression varies with the pressure. Now, important thing to be noted here is that, other than the gas model the effect of the gas model used; the curve is not linear that is to be noted, it shows a parabolic nature.

So, the curve shows a parabolic nature and that is very important consideration; because the work of compression it is variation with the pressure, the delivery pressure or the discharge pressure is showing a parabolic nature.

That means it depends upon the suction pressure. How? Let us say if we have compressed it to 350 bar. So, if we compare the work of compression which is required to compress from ambient pressure to 350 bar is much higher; if we see the variation, this is much higher as compared to the amount of work, which is required to compress it from 350 to 700 bar. So, this work is much higher compared to the amount of energy, which will be required to compress it from 350 to 700 bar.

And thus this makes it very important that the method of hydrogen production which is used, whether it is reformer based hydrogen production or whether it is the hydrogen, which is being produced is from electrolyzer; whatever production route is giving hydrogen at a higher pressure, we can save in terms of the work of compression or the process can get more and more energy efficient, if the suction pressure for the compressor is available at a higher pressure. And that is the importance when the delivery from the production plant is at a higher pressure.

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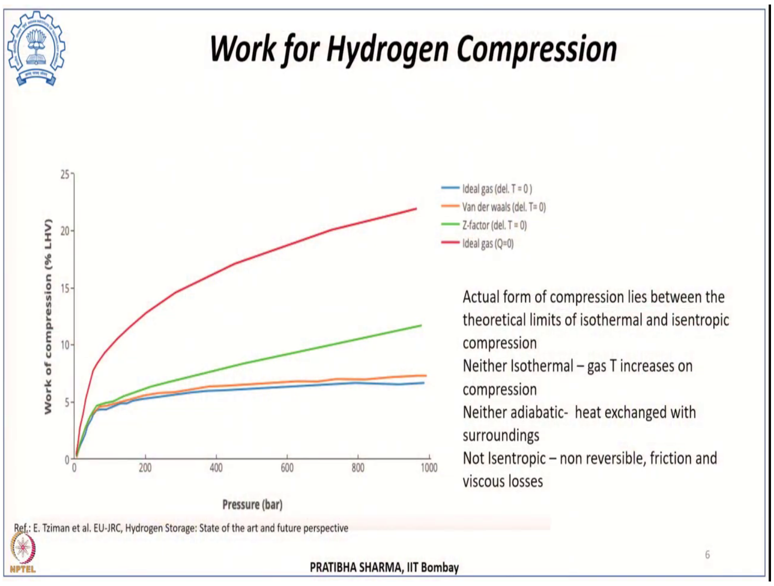

Now, as mentioned, the theoretically the work required to compress hydrogen in an isothermal process is minimum and to compress it through an isentropic process, it is maximum. But the actual work of compression it lies between the 2 theoretical limits of isothermal and isentropic compression.

So, the actual process of compression it is neither isothermal; the reason being as we compress the temperature of the gas increases on compression, so we cannot keep it isothermal; neither it is adiabatic, because there will be heat exchange with the surroundings; neither it is isentropic, because in isentropic process, the process is considered to be reversible, but the actual process is a non reversible process.

There will be losses associated because of the friction, there will be viscous losses. So, all these make the actual process neither isothermal, nor adiabatic, nor an isentropic process. So, some of the reports, some of the researchers they have even modeled the process to be a polytropic process.

Here in this curve the work of compression has been plotted. So, the same curve has been plotted as a percentage lower heating value, that the how much energy content of hydrogen would be required in compressing the hydrogen to a higher pressure.

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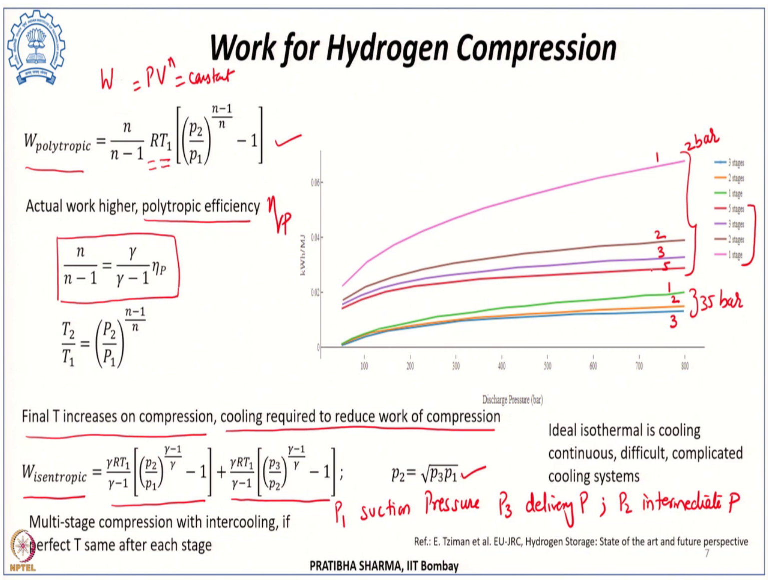

Now, as mentioned some researchers consider the compression process to be a polytropic process. So, if we consider the process to be a polytropic process; then it is PV^n = constant and that n is the polytropic index. So, the polytropic work is (n/n-1), n is the polytropic index; RT_1 the initial temperature gas constant times the p_2/p_1 pressure ratio to the power (n-1/n)-1.

So, this is the work of compression which will be required, if the process is considered to be a polytropic process. This is considering an ideal process; however the actual work of compression will be higher and that can be accounted for by considering a polytropic efficiency η_p. And this polytropic efficiency is related to both the polytropic index and the specific heat ratio as n is the polytropic index, $n/n-1 = (\gamma/\gamma-1)\times\eta_p$, where gamma is the specific heat ratio, η_p is the polytropic efficiency.

Now, considering the process of compression, the temperature the final temperature of the gas on compressing it from pressure P1 to P2 can be obtained as T2 will be the final temperature. So, T2 upon the initial temperature T1 is the pressure ratio $(P2/P1)^{(n-1/n)}$; usually in the compression process, the temperature increases, so on compression we know that.

Now, since the temperature increases, if we cooled down the gas on compression, the increase in the temperature and we reduce the temperature of the gas, the required work of compression will also reduce. So, if we cool the gas on compression, the work of compression reduces. Now, ideally what is required is, as we know that the isothermal process if we make the process to be completely isothermal, an ideal isothermal process is very difficult to attain.

The reason being by means of isothermal process and ideal isothermal process is, we remove the heat from the gas or during the compression process at the same rate as it is being produced in the process or we consider that the temperature is uniform throughout the compression.

So, it is ideally it is very difficult to achieve, it is a very complicated cooling system will be required. So, actually we can approximate it by considering a multi stage compression or including an inter cooling stage, so that the temperature at each stage of the gas attains it is initial temperature. So, if this inter cooling which is introduced between the different stages, if it is perfect; in that case the temperature of the gas will become same, it will be identical after each stage of compression.

Considering an ideal gas undergoing an isentropic compression including 2 stage of compression; if the initial pressure or the suction pressure is p1, the delivery pressure is let us say p3 or the discharge pressure is p3 and there is an intermediate or an optimal pressure, this is an intermediate pressure on optimal pressure.

Considering that the isentropic work of compression is given by $(\gamma RT_1/\gamma-1)\times[(p2/p1)^{(\gamma-1/\gamma)}-1]$, this is corresponding to the first stage plus the temperature remains constant after the first stage $(\gamma RT_1/\gamma-1)\times[(p3/p2)^{(\gamma-1/\gamma)}-1]$, where the pressure p2, which is the intermediate optimal pressure is given by under root of p3 and p1.

So, ideally it is considered that the pressure ratio should be same between the different stages. Now, if we consider a multi stage compression with inter cooling in between; so what we are doing is after each stage, we are cooling down the gas to it is initial temperature by introducing an intercooler. And using that it is not becoming ideal isothermal process; but we are trying to keep the temperature same after every stage and using that we can reduce the work of compression.

Now, if we consider the electrical work, which is required for compression as against the variation in the pressure for 2 different suction pressure, this is being plotted in this curve. So, for 2 different pressures, 35 bar and 2 bar considering different stages of compression. For 2 bar there have been 5 stages, which has been considered; considering 1 stage, considering 2 stage, 3 stage and 5 stage compression. For 35 bar 3 stages has been considered; 1 stage, 2 stage, and 3 stage.

Now, from this curve we can see that, introducing an additional stage with inter cooling in between, it reduces the amount of work of compression. As we go from stage 1 to stage 5, the work of compression required reduces at the same time this curve also emphasizes that the importance of the suction pressure. So, if the initial pressure for compression is higher, the required amount of work for hydrogen compression will be lower.

Usually there is a tradeoff between the number of stages that we can add to the amount of energy being saved like. If we add more number of stages, then there will be a requirement of infrastructure and additional cost associated with it. And that needs to be considered against the energy, which is being saved or energy work of compression, which is being saved by adding an additional stage of compression.

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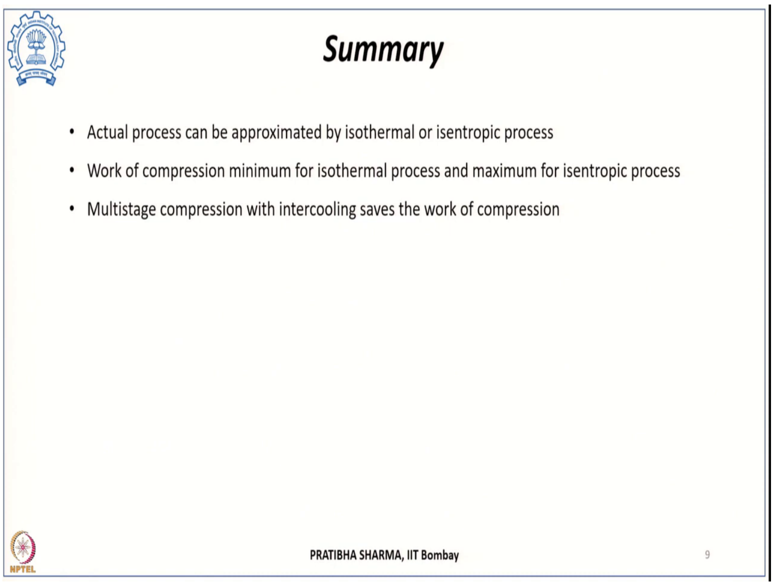

To summarize this part, we have seen that it is difficult to approximate the actual process; it requires a lot of efforts, as such the actual process could be approximated by a reference thermodynamic process. It could be an isothermal process or an isentropic process, depending upon whether the compression is done with cooling or whether the heat is not removed during the compression process.

We know from the basic thermodynamics that the work of compression required is minimum, if the process is an isothermal process; however it is maximum, when the process is an isentropic process. So, we have in this class also seen that work of compression considering whether the gas is ideal gas or whether it is a real gas, which type of thermodynamic process we have modeled and also we have looked at the compression work which is required, when it is multistage compression with inter cooling.

Multistage compression with inter cooling has an advantage that, it can save the work of compression and it can approximate it to be an isothermal, nearly isothermal process, such that, the temperature of the process is same after every stage of compression.

Thank you.