Cryogenic Hydrogen Technology
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Lecture 37
Application: Fuel Cell

Welcome to this lecture on cryogenic hydrogen technology. We were talking about hydrogen production, hydrogen liquefaction, storage and transfer. So, now, we are going to move towards the application part and this applications that there are I mean multiple applications where we find that hydrogen will be used. Particularly we are interested about using hydrogen as fuel. So, in that connection what we are going to learn is about the fuel cell and in this lecture, we will be talking about PEM fuel cell that is proton exchange membrane fuel cell and then we will ah slowly move to other applications if possible. So, ah the topic of this lecture is PEM fuel cell then the keyword is also PEM fuel cell.

And now to start with ah or to talk about the fuel cell ah the naturally the question will arise whether it is how is it different from the battery. So, we are familiar with the use of ah replication of I mean use of battery in our daily life, but fuel cell we are not that much convert ah I mean we are not accustomed to ah ah while talking about the production of hydrogen we have said that solid polymer electrolyzer and during that time we you know talked about the history of this fuel cell or the solid polymer electrolyzer. So, I am not ah not going into that ah, but this is where has I mean this application initially started for the space application by NASA. But it is different from battery in the sense ah that the battery is basically we can say it is a chemical ah storage or energy storage device whereas, this fuel cell is basically the energy conversion device ah where we will find that the ah maximum energy that we can you know achieve with a battery is so long as the chemical or the reactants will be available.

And once that is you know exhausted you know what we have to do is that we have to either recharge it or you know just we have to ah throw it out ah, but in case of fuel cell as long as you have the ah you know the supply of say the reactants particularly we are talking about the ah PEM fuel cell. So, where you will find that the hydrogen and oxygen or air ah is used. So, so long as this two are available I mean both hydrogen and oxygen is available and if there is no deterioration ah with the or the corrosion in the fuel cell etcetera ah which is comparatively ah having a long life. So, it can you know maintain or it can run the or it can give you the voltage. So, that is the basic difference between this battery and the fuel cell.

So, once we ah are having this idea about fuel cell we can look into the ah fundamentals of this process where we find that we have we we are rather you know habituated of burning the fuel like if we have some fuel like hydrogen or any other carbonaceous ah material. So, we burn it and then we get thermal energy and from that thermal energy we generate ah most of the time we generate the steam and the steam runs the turbine and we get power. But here what happens ah in fuel cell ah what we find that it is an electrochemical device, but that electrochemical device will directly change or you know the chemical energy it will convert into electrical energy. That means, we are having this ah hydrogen and oxygen we are not burning it please mind that we are just combining it in such a way that we will ah harness the energy from it and I mean the total reaction would be again hydrogen plus oxygen, but you will get electricity, but I mean and as a byproduct we will have water. So, that is ah you know thereby we can avoid many multiple steps ah where we have to generate the heat then we have to you know produce the steam or we have to generate power then we have to put it in the grid and then we will have it you know ah we can ah you know use it use that electricity.

So, all those intermediate steps being absent we can see that ah you know it is probably ah now it is it has a chance of ah becoming more efficient. So, what happens ah in this ah we will find that in the anode and in the cathode particularly we will have in case of solid oxide sorry in ah what is called proton exchange membrane we have ah this exchange membrane on both sides we will have the electrode and what we use is the fuel that is in our case is hydrogen and from this side we have the oxygen ah you know or air or oxygen ah I mean both can be used, but air will create some you know because it is mixed with nitrogen. So, it will have its associated problem, but if it is ah you know oxygen then we can ah find that this hydrogen and oxygen will you know combine together to give us the water, but along with that we will have the electrical ah energy or electrical current ah electrical energy we are getting. So, this electrical energy we will achieve in the form of electricity. So, that we can you know run ah this ah I mean external load can be connected this is ah we have shown it in the form of an electric bulb.

So, this can also run ah if this is a single cell we have talked about, but if there are multiple cells we know we can get generate larger ah. So, ah since you know it is generated ah the electrical energy is generated ah we can run ah what is called ah I mean we can use it for lighting a bulb or we can also even you know depending on the size of the ah fuel cell we can also run a car. So, here ah what we are you know ah trying to learn about is the PEM fuel cell and that fuel cell is supposed to ah drive a vehicle. So, that is what we ah you know thought of because ah I mean there is a potential use of this hydrogen for ah as a I mean fuel or vehicular fuel. So, we have you know thought of using it as a fuel cell driven car and we have stored it and now we are now talking about how do we ah use it ah in the fuel cell.

So, let us see how it works ah before that let us look into the different type of fuel cells because it is not only the ah proton exchange membrane fuel cell ah that exist there are different ah fuel cells. Say for example, we have talked about the alkaline ah I mean ah oxygen sorry hydrogen generation system or ah alkaline what is called electrolysis, but the just it is if you look at it is basically a reversible process where we have seen that we are breaking we were earlier breaking the water into it is constituent hydrogen and oxygen. Now, it is just exactly the reverse process where we are combining hydrogen and oxygen and of course, one of the product would be water, but ah along with that either we were supposed to get thermal energy or electrical energy. So, here in the I mean fuel cell ah we can also have ah the alkaline fuel cell where we find that you know the k o h can again be used, but here the ah combination would be hydrogen and oxygen will be combined in a fuel cell and if it is an alkaline fuel cell it will generate the electricity or we will get electrical voltage. Then we have the phosphoric acid fuel cell then molten carbonate ah fuel cell and of course, there is another one solid oxide fuel cell or ceramic fuel cell.

So, we will let us have ah the ah I mean the ah the ions are basically the charge carriers ah are like this we have the for PEM fuel cell we have the hydrogen plus or proton is the charge carrier ah for alkaline fuel cell it is OH minus and for phosphoric acid again you have the H plus or proton for molten carbonate it is CO3 double minus and for ceramic or the solid oxide fuel cell it is O2 minus. So, these are the different charge carriers we are not going to talk about the ah all all this type of fuel cells, but we ah at least we should know that what is the typical operating temperature. So, the operating temperature for the PEM fuel cell is around 80 degree ah because you see this the normal boiling point sorry the boiling point of water is 100 degree centigrade. So, we want to you know operate it below that temperature. So, ah, but whereas, this alkaline fuel cell that is typical operating temperature is between 60 and 220 and for phosphoric acid again around 200 carbonate is slightly on the higher side 650 degree centigrade, but for the ceramic one it is ah about 600 to 800 or sometimes more than that.

So, depending on the temperature if we classify this ah you know fuel cell often you will find that this are termed as hot fuel cell compared to that you know this is you know below 100 degree centigrade and that is why ah we call it so called cold you know fuel cell though it is at operating temperature is around 80 degree centigrade. So, now, the point is that for vehicular application you can understand that these are not you know ah acceptable ah generally we try to restrict the temperature on ah the below I mean ah 80 degree centigrade. So, that is why this PEM fuel cell would be suitable for the vehicular application. So, we are going to talk about it in ah some more details. So, the PEM fuel cell ah if you can I mean remember the operation of the solid polymer electrolyzer there you have seen that similar structure was ah I mean presented before you where we have a solid polymer which is basically ah conducts the proton or it allows the proton to pass through it, but not the I I mean ah other ions like or the reactants like H2 or O2 or water ok.

So, the molecules will not pass through it or any other ion will not be allowed to pass through it except the proton that H plus. So, in that solid polymer electrolyzer we were using the water we were breaking it into hydrogen and oxygen here in this case what we are putting here is hydrogen and on the other side anode we are putting oxygen. So, ah what will happen this fuel ah will this you know hydrogen will come in and then we have ah if you again remember that we have said that there are solid you know catalyst and that is the catalyst is ah mostly you know ah novel materials like ah platinum etcetera. So, ah that platinum if it is you know coming in contact to this in presence of that catalyst this hydrogen will break into hydrogen plus and hydrogen plus. So, these are the hydrogen plus by releasing ah you know one electron.

So, they will release this electron and this electron e minus will find a path through the external circuit whereas, this proton as we have said that proton you know will move from one end to the other end because this polymer or this electrolyzer electrolyte this will allow the or membrane will allow the ah migration of the protons from one end to the other end. So, this hydrogen ion will move from here to here here it will combine with this electron and this O2. So, that we will have H2O and this electron when it is you know travelling through the external circuit this will ah you know generate that electricity and which can be and on that electrical circuit you can put your load and you know it will either this will drive the car of a fuel I mean the wheel of a car and then you know it can also light ah bulb or you can use it for different application power applications also. So, now we have the cathode here and on this side we have the anode. So, if we look at these electrons are you know flowing and lighting the bulb.

So, if we ah look at in details now ah how is the ah I mean things operating. So, we on the anode we are putting hydrogen as we have said this hydrogen will break up ah this hydrogen is breaking up if we have taken to ah H2. So, we will have 4H plus or proton and there it will be giving you 4 electrons. So, then you know this electrons ah sorry the proton will be passing through the electrolyte. So, this protons are as we have said this protons will be moving through this electrolyte they are you know passing through this electrolyte, but this you know electrons ah that will pass through the external circuit and in the process it will have its electrical load or you know the load which you will run either a bus or or a small car or you know it will give you the power for lighting a bulb and etcetera.

Now, what happens ah this hydrogen is coming over here then electron is also joining and you know this O2 is combined here to have the product gas or say if it is operated below 100 degree centigrade. So, it will be in the form of liquid sorry it will be in the form of liquid, but if it exceeds 100 degree centigrade you can expect that it will be in the ah vapour form. So, that is about the ah PEM fuel cell working ah the ah details of this you know fuel cell you will find we are not ah I mean we will be giving the details here ah, but before that we just look into the advantage of ah this PEM fuel cell. So, first of all this power generation ah we are ah we can achieve without ah any moving part. So, as I have pointed out earlier that we are trying to you know convert this or combine this hydrogen and oxygen ah and without any moving part means there is no ah turbine or etcetera we are not heating any water or we are not generating steam to produce the electricity.

Instead without any moving part we are able to generate the power. So, there is ah I mean if there is no moving part obviously, the maintenance part will be there is a little. So, that we have the advantage ah if it is you know ah there is no moving power movement part in any kind of ah devices. So, ah in terms of efficiency as we have said that since there are ah definitely the number of steps are less it is supposed to give you more efficient power particularly with with respect to an IC engine. So, ah in terms of the clean products ah we have ah there is no NOx or SOx generation.

So, it is generating only the water ah and little bit of heat will be generated ah we will come to that part and of course, it is generating the clean electricity. Now comes the pollution as we have said that the conventional pollution like NOx or SOx are absent ah in this fuel cell ah. So, it is ah obviously, benign to the ah ambient or I mean to the mother nature ok. So, ah these are the advantage of this fuel cell then as we are talking about the construction we will not get into the details of it, but I hope you ah just if you compare it with the ah solid oxide poly I mean electrolyzer it is almost similar to that we have the the polymer membrane and on both sides you have the catalytic ah you know thin layer of catalyst and sometimes if you look at you will find this geometry would be something like this on the on other side I mean this is if this is the membrane there would be ah platinum disperse this black colored ones are the platinums. Then we have this carbon support and the porous electrode.

So, like that ah this whole structure will be building up ah this is of course, an unit cell and it is extremely you know ah magnified. So, because this is you know there only few microns ah in a layer and this polymer is also not more than you know 200 to 300 ah micrometers. So, that also we have talked in our ah previous class. So, we will not talk about it in details about the construction, but what we have not talked about ah this ah solid oxide ah I mean ah electrolyzer that we need to ah just we have mentioned that ah that bare minimum voltage is not ah or the thermodynamic ah minimum voltage that is not sufficient to split the water ah. Ideally that is the ah ok voltage that will be necessary, but in practice you will find that practically you do not ah it that voltage is not sufficient to electrolyze the water.

In that connection we have said that we need an over potential that are a larger than the ah thermodynamic minimum voltage. So, now just if we talk about the fuel cell. So, if we are combining hydrogen and oxygen conversely ah we will not necessarily get that you know minimum ah voltage or the ah thermodynamically ideal voltage that is expected from here rather we will get ah some you know smaller value. So, that part we will be talking ah about in this class or in this lecture. So, before that ah we again ah want to talk about another part where we will try to just look into the ah pressure and temperature dependence of this reaction where we are ah you know ah talking about a combination of hydrogen and oxygen and ah it is going to generate ah water along with that we are getting the electricity ah, but this ah Ernst equation will tell you what is the dependence of this ah electric ah or voltage that we will get ah or the potential that we will achieve from this.

This is the voltage that we have calculated for if you remember this is 1.229 volt for ah you know it was ah how much 298 kelvin 298.15 kelvin exactly this is the temperature and one atmospheric pressure. So, that was the kind of voltage that we said that will be necessary to you know ah split water when we talked about the electrolysis. Now, just exactly in the reversible process when we are combining hydrogen and oxygen and if we check the reaction enthalpy you will find that ah the same reaction enthalpy the magnitude of the reaction enthalpy is exactly the same, but there is you know ah difference in the ah actual value of it and this time it is going to be a spontaneous reaction.

So, there would be a proportional I mean there is a change in the Gibbs free energy ah associated with that and with a different ah difference in the magnitude I am sorry the ah what is called the negative ah Gibbs energy will be generated ok. So, that means, what we ah have is the same voltage the thermodynamically same voltage will be ah generated ah, but here we find that the reaction ah activities or activity coefficients will be there. So, this is generally we put it in the form of ah the in terms of the pressure of water and if we are putting it below ah 100 degree centigrade ah we take it as 1 and this is ah you know the pressure of partial pressure of hydrogen and partial pressure of oxygen to the power half because there is an half ah you know of oxygen. So, this is how we ah you know can correlate how this is going to change with the ah temperature and pressure. So, let us now look into the equation and this will tell you ah if we want to find out say the partial pressure of oxygen ah in this reaction say if we ah assume that instead of pure oxygen if you are using air at atmospheric pressure.

So, if it is air we will find that you know this partial pressure it is ah will be 21 and say if we are using air at 1 atmospheric pressure and this hydrogen is at you know again it is coming with say 1 atmospheric pressure you will find that this equation if you put all these values. So, this value is already we have talked about 1.229 and this R value is 8 point say 1.229 minus 8.314 temperature is 298.15 then this 2 into 96485 then this is the ah I mean ah this value. So, then we have the this has been taken as 1 and this is also 1 and this is 0.21 that is the partial pressure. So, here we will find that this is ah you know 1.2194 that is not much ah I mean ah drastic change in the ah I mean value ah of this potential ah particularly if you are using ah instead of pure oxygen, but please note that this is only the thermodynamic calculation we are talking about in reality we will find that use of air will have ah different kind of you know complicacies when it were using it in the actual fuel cell other than oxygen.

So, now, ah if it is so that you know if we are ah using for example, ah some ah hydrogen at elevated pressure say if we take it as a say 3 atmospheric pressure hydrogen and that is mixing with ah you know pure ah oxygen at say 5 atmospheric pressure. So, this will this value will change to ah ln of 1 by 3 into ah 0.21 multiplied by 5. So, this would be the value and along with that other things will come in picture this value will be coming over here and minus it would be 1.229. So, this if you are calculating then you will find that this is coming out to be 1.254 volt. So, that is ah I mean ah that is how you can think of increasing the ah cell voltage, ah but this is again ah thermodynamically ah you know ideal voltage if you are operating it at elevated pressure and you can try to change or you can try to get a higher ah voltage ah obtained from this PEM fuel cell. Now, ah let us look into this equation, but these are all you know the ideal conditions, but in reality when you are going to use it and in practice you will find that ah it is it is more of ah more like ah it is more like ah then ideal voltage or say the 0 load voltage. The moment you will connect ah with some load you will find that ah you know the fuel cell loss will start.

So, there are different losses and ah these losses will be related to the current density and this is the cell voltage. So, this is the ideal standard potential that we have talked around and this is you know at ah 298 Kelvin this is this much ah volt ok, but the moment you are ah you know trying to find out or draw you know current you will find that this you know cell voltage is decreasing steadily. So, there are different kind of losses ah the when you know and that also depends on the current density. So, here we will find that we have the activation losses and ah we will learn about what is the activation loss, where it is prominent, then we have the ohmic loss and finally, we say that there is a diffusion gas diffusion losses. So, ah let us try to understand what is that activation loss, ah ohmic loss and gas diffusion loss.

This activation loss is prominent at the low current density and this ah ohmic loss will be mostly prominent into this ah you know this is a linear one you can see and this is prominent at the moderate to the higher one, but when the current density is ah very ah high you know if we are trying to draw large amount of current from it there will be obvious the you know less ah cell potential, but you will find that the gas diffusion ah you know losses are prominent. So, we will try to learn about this in details in the following classes, but before that we will just tell you what is an activation loss ah. The hydrogen that is coming or say in terms of the solid polymer electrolyzer they were coming to the activation site or the reaction site, then you know here in this case ah the ah hydrogen is coming to that reaction site then it is getting dissociated. So, if this kinetics is getting slow or say the electrons are moving to the through the electrical outer circuit. So, if this all this ah electrode kinetics may you know be sluggish to reduce the electrochemical reaction.

And then ah ohmic loss is basically ah if you can understand that this migration of the electron is taking place through the electrode and the flow of electron through the ah I mean electro ah through the external circuit. So, it is basically ah giving some losses and that is proportional to the current density and ah we have the ohmic loss. Then finally, ah when you are trying to you know receive a large amount of I mean what is called current density if you are trying to increase you will find that this ah migration of this what is called the reactants or the ah I mean the protons or the gases etcetera they will they has to reach to the point of interaction or say at the reaction site they have to you know reach. And there the diffusion will be the dominating ah will play a dominating role the migration will become different I mean difficult if you have a kind of concentration gradient and that is where you have the gas diffusion loss. So, all these losses will you know finally, try to ah reduce the cell voltage and you have to judiciously choose the cell voltage depending on your ah current density.

Current density will also determine the overall size of the fuel cell ok. But other than that we have ah you know though limited ah it is called the reactant crossover or the internal current loss. We have said that the polymer allows only the ah protons to pass through, but not the electrons. Sometime it may so, happen that both the electrons or the reactants are crossing this polymer ok. So, if it is crossing then what will have that hydrogen you know migration if it is taking place that there will be a direct combustion of hydrogen and oxygen, but it will be very small amount and there will be liberation of heat.

But if the electrons are also flowing through the electrode that also you know it is considered to be a loss and that is what is called the reactant crossover or internal current loss. So, these are the typical losses are present in a fuel cell. So, now let us look into the references. So, there are plenty of references you will find I have just noted one of them here ah you can read from this book. And then to conclude we have the we have talked about the p m fuel cell and we said that this is good for the vehicular application because it is a so, called low temperature ah you know operation takes place.

And we have also seen that the seal voltage is different from the actual ideal voltage that we have talked about or learned about. So, there are in reality we find that there are ah I mean losses and that has to be you know taken into consideration while designing the ah fuel cell. So, thank you for your attention.