Cryogenic Hydrogen Technology
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Week - 08
Lecture 38
Fuel Cell Contd.

Welcome to this cryogenic hydrogen technology. We were talking about the fuel cell and in this is actually in continuation to our earlier discussion when we were talking about the fuel cell losses. So, ah this topic is ah again PEM fuel cell and now we will be talking about the fuel cell losses and we were talking actually about the PEM fuel cell. So, this is in continuation to that earlier ah discussion. And if you remember that we have talked about this the different losses where we have talked about the ah I mean primarily activation potential we have talked about and then ah we have also talked about the polarization sorry ah ohmic losses and then of course, the gas diffusion loss.

So, these are the basically ah different I mean active in different regions. So, activation loss is dominant or prominent here at low current density the ohmic resistance or ohmic losses is ah basically ah linear and it is operated in the middle region. And when it is high current density if ah the fuel cell is operated we will find that the gas diffusion losses is dominating the performance of the cell or basically it is deciding the cell voltage at high current density. So, we have talked about ah these losses individually in the last class.

$$\eta_{act} = \frac{RT}{\alpha n F} \ln(\frac{i}{i_0})$$

$$\eta_{ohm} = i R_e$$

So, now we will try to look into that final I mean expressions and then we will move forward to you know see how they are affecting the ah ideal standard potential which we have calculated at the initially ah and let us see how they are getting affected by all this individual ah activation or ohmic or gas diffusion low potentials ah. So, in ah let us look into the expressions where we will find that there is some ah expression for the activation loss which is given by RT by n alpha F by ln i by i0. Basically, this is derived ah as a part of the Tafel equation and you will find that this i0 is the exchange current density where is i is the ah current density alpha is the charge transfer potential. So, we can ah try to estimate it if all these parameters are known ah and we have this F and n already known to us ah from the previous expressions. So, ah ohmic loss is basically as we have said it is linear and that comes ah from the movement or the resistance offered to the flow of this ah protons when it is passing through that ah what is called that media ah conducting media and proton conducting media and then it is expression is i into Re, Re is the resistance of that

membrane and here the gas diffusion loss basically it will depend on the it can also be derived from the ah diffusion equation or the Fick's law and this is ah i is the current density whereas, this iL is the limiting current and this R is of course, the ah gas constant T is the temperature.

$$\eta_{con} = \frac{RT}{nF}\ln(1 - \frac{i}{i_L})$$

So, this is the concentration expression for the concentration loss. So, with this expression ah how the fuel cell ah I mean total potential is getting changed we can have a look into it ah. So, earlier we said that ah we have an potential is you know E0 we have calculated and that is what was 1.229 volt that is corresponding to a temperature of 298 Kelvin and 1 atmospheric pressure. So, this voltage we are not ah ideally, we can expect that this will be the voltage, but in reality, you will find that we are getting much less than this potential.

So, let us see how this ah losses are affecting this ideal voltage. So, ah if we look at the different you know anode and cathode I mean ah actually what these losses are doing is ah they are changing the ah I mean what is the potential that we are supposed to get and that will be changed because of that you know a potential. So, here we have this expressions ah eta ohmic loss conduct conduct ah I mean activation potential then concentration potential and this ohmic losses. So, in the anode and cathode ah let us have a look ah how these losses are basically changing you can expect that when it is in the anode this activation potential will be there separately for the anode as well as for the cathode. Ohmic loss will only be present in this ah I mean in the membrane because ah we expect that you know this there is no ah what is called ah ohmic loss in in this side or in the anode or in the cathode, but for the electron ah movement that is again you know ah we have the ah resistance to the flow of current and that it will be Rc multiplied I mean Rc will also include the losses in the ah conducting wire which is present here.

So, this two ah losses or the resistances through the membrane plus the resistance through the ah ordinary wire that is our connecting wire that includes in Rc, but for the anode and cathode part ah both activation potential and separately this concentration potential will be separately there. For the in the cathode what we find is that ah this is where you know O2 is coming and in the anode, we have the H2. So, this diffusion of the molecules ah in that you know ah when we are trying to we said that when we are trying to you know have a large current density that means, we are trying to you know use lot of hydrogen and oxygen ah at a time and we are trying to ah you know draw a large ah amount of current density basically. So, you will find that this activation sorry this concentration potential is dominating this activity and you will find that this O2 and H2 they will be present both in the cathode as well as in the anode. So, this gas diffusion part will be ah actively ah participating in both the anode and cathode whereas, ah this activation potential will also

be present ah in separately for the sluggish kind of you know ah movement of the hydrogen or O2 because this hydrogen things will be coming this H plus ion will be coming over here then you know it will be mixing with the O2 and then finally, we will have H2O as the product here.

So, we can see that both this activation and ah concentration are present separately in the cathode and the anode. So, we can say that as a summing if we ah summing up these losses for the anode we will have this activation ah part and ah separately this A stands for the anode and activation ah you know for this and then we have the concentration potential or concentration losses ah separately for this anode. Then we also have it for the cathode that means, this activation potential loss for in the cathode and concentration loss in the cathode. So, this is ah for the 2 cells, but for the I mean ah this part we have only IR loss I iRc basically. So, what will happen because of these separate losses we will find that the electrode potential is you know ah getting changed.

So, if it was earlier ah this is the ah potential that we had. So, now, that potential will give you a separate new voltage the depending on this ah new you know electrode that activation potential or say activation ah polarization or activation losses. So, what we can expect is that ah the for the ah anode say the V anode and V cathode will be different and earlier say if it was V anode ah was say V electrode for the anode ah say it was E anode if we denote it then we will have ah a different one. So, it will be added by V eta anode ah. So, let us write it in separately in the next slide.

$$V_{anode} = E_{anode} + |\eta_{anode}|$$

$$V_{cathode} = E_{cathode} - |\eta_{cathode}|$$

So, the effect on the cell voltage we can then write as V of anode as this is the new one. So, earlier it was E anode and then ah it will be the magnitude ah it would be eta anode. So, this eta anode includes both the activation potential and ah what is called the concentration potential for the ah what is ah now we will try to write it for the cathode. So, for the cathode it would be earlier it was that voltage ah potential that was there along with that there would be say negative cathode. So, this will reduce the you know the basically this was the potential and now we are getting as if because of that losses it is getting reduced.

$$V_{cell} = V_{cathode} - V_{anode}$$

$$V_{cell} = E_{cathode} - E_{anode} - [|\eta_{cathode}| + |\eta_{anode}|] - iR_c$$

So, the overall effect ah I mean if we look at the entire V cell if we try to calculate we will see that the cell voltage would become V cathode minus the V anode. So, that means, you will finally, find that whatever voltage that we are supposed to get ah that is E cathode

minus E anode then there is a negative and let us put it in the bracket say the eta cathode plus eta anode and there actually the magnitude we are you know subtracting. But along with this ah actually the voltage that we will get ah we have ah not you know included another term here and that is this is only we have talked about the V cathode and anode, but we have not included in it the resistance through the cell. So, this is the ohmic loss. So, that will also be you know that has to be excluded.

So, that will be taken at iRc So, this is what is that you know ah total ah voltage that we will get. Now this is what we were supposed to get ah ΔE ah that is we have now I mean earlier we have estimated it, but imagine that all these losses if are not there then you know this would be say this cathodic and anodic loss say eta cathode and ok eta anode eta ok. So, ΔE and then we have this plus eta anode this two are getting minus i Re. So, now if you look at if these losses are not there then this goes to you know the ideal you whatever voltage that we are supposed to get this is supposed to be ah you know ideally what we have ah calculated it to be 1.229 volt or say nearly 1.23 volt. So, that we have estimated earlier. Now as we understand that because of this losses we will have a difference in the cell voltage and that will be like this expression as we have already talked about say here if it is the current density is low ah here this ah activation potential will be dominating and on this side this ah what is that ah x I am sorry that resistance will be dominating on this side and here this concentration ah part will be dominating. So, now this is the cell voltage that we have obtained if we have to design or you know operate this ah this ah fuel cell we will find that ah there is a performance analysis of course, but if we before going to that part if we look at it is operation we will find that this ah let us go back to that slide here let us slightly clean it ah what we try to you know if we want to find out how is the operation of this ah fuel cell ah then we will find that depending on your our requirement we have to ah look for ah a current density say if someone wants to operate at a particular current density ah either one will be trying to you know operate it at a ah low current density or if I want to operate it at a high current density or somewhere in the middle we have to compromise with certain things.

So, as you can understand that when this cell density is at a low value ah the cell voltage would be ah comparatively higher ah and if someone is operating at a low current sorry high current density ah the operating corresponding operating voltage is quite small I mean much smaller than the ideal voltage. So, what are the advantage and disadvantage advantages are there like you know when we are operating it at a low current density ah the problem is that we are getting a cell voltage high cell voltage, but the low current density means ah the size of the ah fuel cell will be quite large. On the other hand, if ah we are operating it at a large current density we will have the system compact, but we will have some other losses we will talk about that part ah maybe later on. So, before that we just try to have a look into the cell performance and the cell performance is generally

defined in terms of the ah I mean it is the effectiveness or efficiency we call it ah the cell ah efficiency it is basically the useful energy per unit the ΔH or the change in enthalpy. So, what is that in useful length energy that we are getting in case of fuel cell ah it is basically the ΔG we can say related to the ΔG because the voltage that we are getting ah if you remember that this it is equivalent is basically the ah non-PV work that we are getting.

$$\eta_{eff} = \frac{\Delta G}{\Delta H}$$

So, that is related to ah this ΔG. So, we have you know we can finally, correlate it as ah the efficiency as ΔG by ΔH. Now, ah this ΔH and ΔG ah ah though we are writing it you know from our previous experiences, but truly speaking ah this should be a negative and this should also be a negative value. Why because ah if you remember that we have told that this is H2O and H2O was break broken into H2 plus O2 sorry ah it was broken into H2 and half of O2 and you know here we had to spend energy and when we have calculated the ah you know reaction enthalpy ΔH we found it to be ΔH was positive. But ah since it is just the opposite and this ΔG ΔH was positive and from there we have ah calculated that ΔG was also positive.

$$\eta_{eff,act} = \frac{Useful\ energy}{\Delta H} = \frac{Useful\ energy}{(\Delta G/0.83)}$$

So, this ΔG when it is positive that gives energy ah change ah that also is related to you know the spontaneity of equation so or reaction. So, it is not a spontaneous reaction I mean if you have some water it will not spontaneously break into hydrogen and oxygen. But here ah this you know H2 plus O2 if you are mixing and with a small you know ah energy you can see that it is going to burn and then what you have you are getting energy and in this case if you are calculating the Δah H or the ΔG from there you will find this is coming to be you know 285.8 kilo joule per mole and and basically what you can say that you know when we are taking this ΔG here if it you if you are taking it as ah this this value it is actually the ah mod part or the magnitude part of it. And the ΔG for this reaction ah it is to be you know negative of that value minus 237.1 kilo joule per mole and the voltage corresponding voltage equation that will be actually ΔV equals to minus n ah I mean it will be related to that minus n F ok. So, now ah I hope you understand it here if you take you know the only the magnitude or even if you put it with the sign you will find that it is coming out to be 0.83. So, this ideal thermodynamic efficiency of this fuel cell is supposed to be 0.83, but first about the actual one ah then again, we can ah try to ah correlate it with respect to this ideal efficiency and with respect to the actual part.

So, again we start with the actual efficiency and then you have the useful energy, but this time is is the actual ah useful energy. So, actual useful energy we can you know put it and ΔH here in this case what we will try to correlate it as this is equals to 0.83. So, ΔH would

be ΔG by ah we can also write it like this ah we can write it as ΔH would be ah ΔG by 0.83. So, we will replace that ΔH here and we can say that ah this eta effective for the actual one or efficiency for the actual one is this total useful energy divided by ΔG by 0.83. So, if we write it in terms of the ah power ah basically what you will find that ah this is the ah you know useful energy to power if we are writing and this ΔH has been converted to ΔG and this can again be written as you know the in terms of the voltage actual voltage and the current and this will be on the other side ah basically this is the ah v into the current part and then we have basically this is the useful power if we have converted into ah then we have this ah effectiveness or efficiency of the actual one ah given by this I will cancel out and we will ah write it this v ideal if you ah see it will become basically the ah 1.23 volt as we have obtained earlier this corresponds to 298 kelvin or 25 degree centigrade and one atmospheric pressure. So, ah now if we put this value of 1.23 ah. So, the efficiency of the actual fuel cell would be 0.675 multiplied by this actual voltage. So, as we can understand that when we are operating this ah fuel cell at different ah I mean what is called the current density we find that we had a curve like this and if the operating point is at different location say as we have said that this is this like this and this is the current density on this side you have the voltage on this side cell V cell and different locations if ah if it is designed for a high current density or if it is designed for a low current density corresponding to that we have different ah cell voltages. So, actual that cell voltage ah if it is operated at the different locations you can understand that this ah ah efficiency of this fuel cell will be different. So, ah as we have talked ah I mean this cell potential corresponding to high density or cell potential at the low-density ah they are going to be quite different and ah.

So, we will ah write we will write it here once again that this is the V cell and this is the current density if we have this curve when we are ah operating it at this high current density we can see that the effectiveness of the cell ah is basically low though we are achieving ah compactness when you know it is with the large current density what will happen that large current density will of course, ah you know the corresponding voltage will be small, but large current density will definitely allow it to be operated at a compactness or it will render compactness of the fuel cell particularly that will be a good ah for say the vehicular application or so, but for the when we are looking for when we are looking for a stationary application for example, ah you will find that the voltage is quite large with the you know large I mean small current density, but small current density what will we do it will make the system large ok or bulky system, but we can afford to you know have it a bulk system particularly for the stationary power application for example, but it is ah it is ah you know efficiency will be efficiency wise as we said that you know this is related to the voltage. So, we have ah the efficiency part will be on the higher side on the contrary ah here if we are operating it at ah low I am sorry large current density it will render effect I mean render compactness, but you have to compromise with the effectiveness or efficiency of the fuel cell. So, let us ah try to look at the refer I mean ah references and then of course, the

conclusions. So, these are the this reference already we have talked about you can also refer to this ah paper ah where it is basically a review paper you can read you will have lot of informations and then ah we can then conclude that to conclude with that ah the fuel cell operation at high current density what we have understood that we have looked into the fuel cell efficiency and the different losses and we understand that it is a curve which will basically govern the total operation or ah the design of the simulation if we want to look at we have to look into this characteristic curve and if someone wants to you know operate it at high current density as we have understood that this will be ah operating it at high current density this will give you a not a large size this will be giving you a small size of the cell. But high current density will make it compact, but ah or it is giving you a small size, but at the same time you will be ah losing in terms of its efficiency, but if we are talking about ah you know ah ah fuel cell operation at small current density or you know when you are very near to that curve if you are operating it at the small current density you will have ah a large efficiency it is exactly the reverse we have written it is having a large efficiency, but you know this will be giving a very large cell size.

 So, but you know efficiency wise you will have ah large efficiency ok. So, that is ah all about the fuel cell for time being ah. Thank you for your attention.