Hydrogen Energy: Production, Storage, Transportation and Safety
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Lecture - 28
Tutorial - 04

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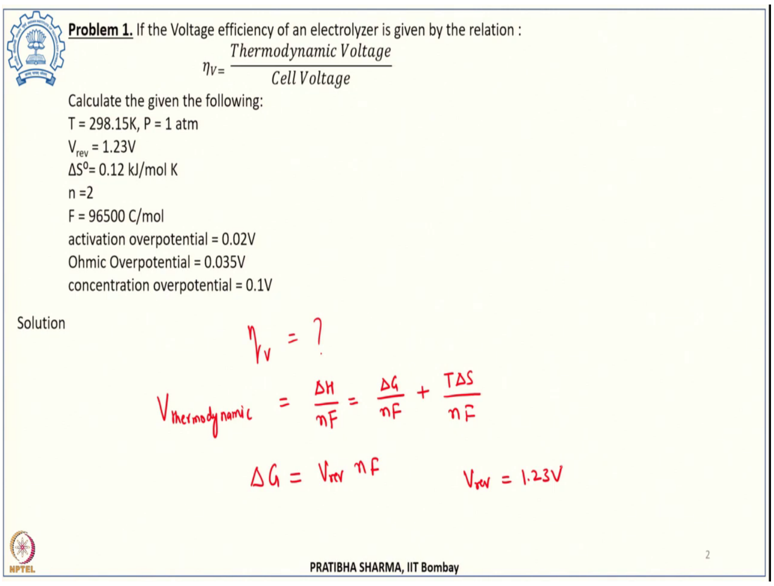

So, this is a Tutorial class on water electrolysis and we will solve problems related to electrolysis. To start with the first problem states that if the voltage efficiency of an electrolyzer is given by the relationship as efficiency equal to thermodynamic voltage divided by the cell voltage and it has also provided the information that the temperature is 298.15 kelvin, pressure 1 atmosphere, the reversible cell voltage is 1.23 volt.

Standard entropy change is 0.12 kilo joule per mole per kelvin, n number of electrons participating in the reaction = 2, Faraday's constant 96500 coulombs per mole, activation over voltage for the cell is given to be 0.02 volt, ohmic over voltage as 0.035 volt and concentration over voltage as 0.1 volt. Now given these conditions we have to find out what is the voltage efficiency value.

So, what we have to find out is η_v? Given these conditions we know that the thermodynamic voltage, which is delta H the enthalpy change over number of electrons participating into Faraday's constant and that is also written as delta G over nF plus T delta S over nF. Also we know that delta G the change in the Gibbs free energy is V reversible times nF. Now it is already given that V reversible is 1.23 volt.

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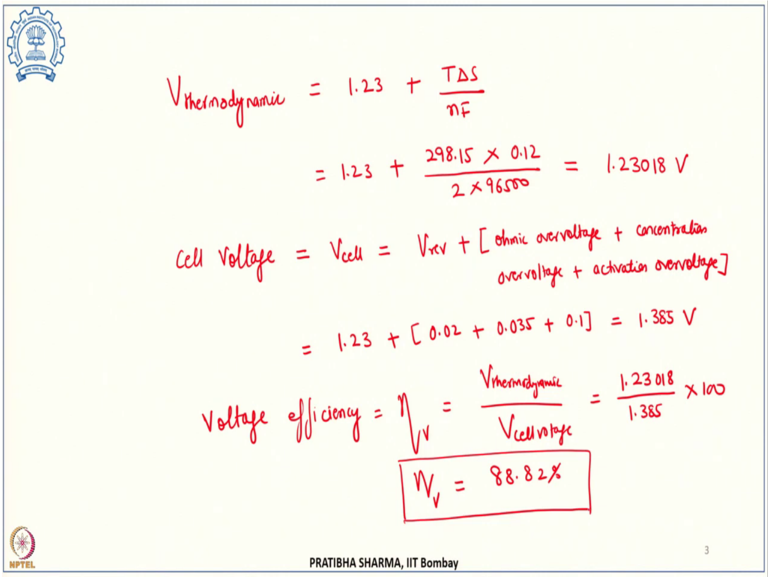

So, using this we can write down the V thermodynamic as the V reversible voltage 1.23 volt plus TΔS/nF, that is 1.23 plus temperature is 298.15 kelvin change in the entropy is 0.12 number of electron transfer 2, Faraday's constant is 96500 and on solving this we can get the value of the thermodynamic voltage as 1.23018 volt.

Now, the denominator in η_v finding the efficiency is cell voltage and the cell voltage is given as the reversible voltage plus the voltage arising due to over voltage; whether it is ohmic over voltage, concentration over voltage and activation over voltage a sum of these three. Reversible cell voltage is 1.23 volt and we sum up the rest of the over voltages.

So, ohmic over voltage, the concentration over voltage and activation over voltage and this comes out to be 1.385 volt. So, the question in the problem is we have to find out the Voltage efficiency which is η_v and it is the ratio of thermodynamic voltage and the cell voltage.

We have calculated it to be thermodynamic voltage as 1.23018 over the cell voltage 1.385 and that comes out to be 88.82 percent that is what is asked in the problem.

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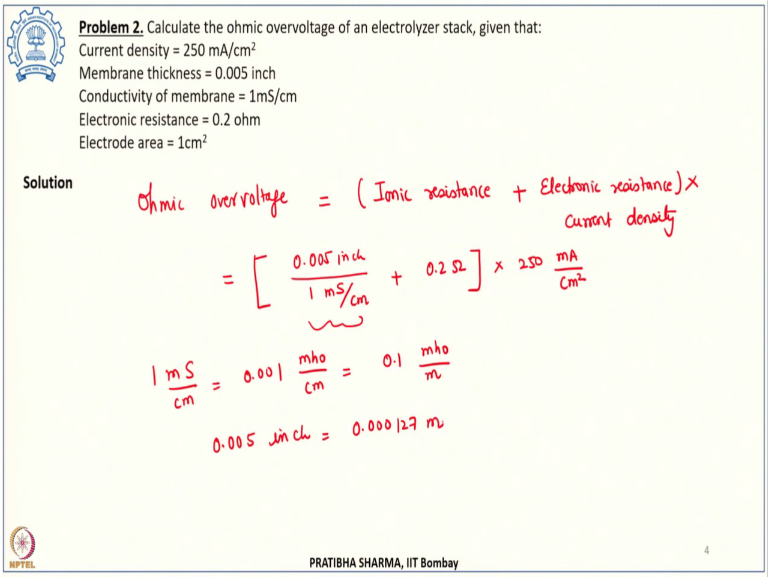

Now, the 2nd problem is it is asked to calculate the ohmic over voltage of an electrolyzer stack.

It is given in the problem that the current density of the electrolyzer is 250 milli amps per centimeter square, the thickness of membrane is 0.005 inch, it is conductivity is 1 millisiemens per centimeter, electronic resistance is given as 0.2 ohms and the electrode area is 1 centimeter square and we have to find out the ohmic over voltage of the electrolyzer stack. Now let us see how we are going to solve this problem? Now the ohmic over voltage is given by the resistance, which is both sum of ionic resistance and electronic resistance times the current density.

So, if we write the values of ionic resistance then it is given as 0.005 inch is the thickness divided by the conductivity, which is 1 millisiemens per centimeter plus the electronic resistance, which is given as 0.2 ohm and times the current density, current density is given as 250 milli amps per centimeter square. So, some conversion will be required now for the first term 1 millisiemen per centimeter and that we will get as 1 mho per meter.

Also, we need to convert inch the thickness, which is given in inch into meter, it is 0.000127 meter.

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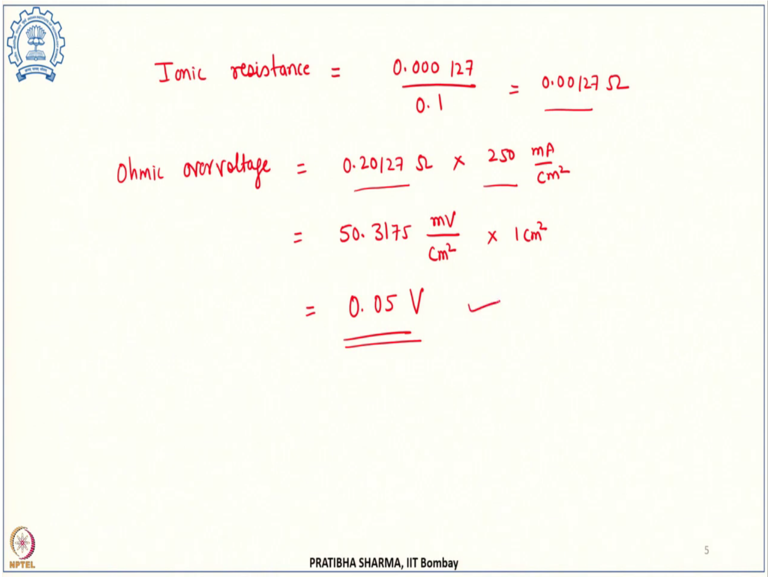

Now, when we substitute that we can get the ionic resistance as 0.000127 ohm and the ohmic over voltage in that case is the sum of the two resistances times the current density, which makes it 50.3175 milli volt per centimeter square or we can also convert it into volts.

So, given that the area is 1 centimeter square. So, this value comes out to be 0.05 volt of the ohmic over voltage. So, in this problem what we have done is we have ohmic over voltage, which is sum of both the ionic resistance and electronic resistance times the current density, we found these terms just some conversions. So, as to get the ionic resistance and finally we have converted it into ohms, the ionic resistance added that to the electronic resistance to get the total resistance times the current density and that gave us the ohmic over voltage in the problem.

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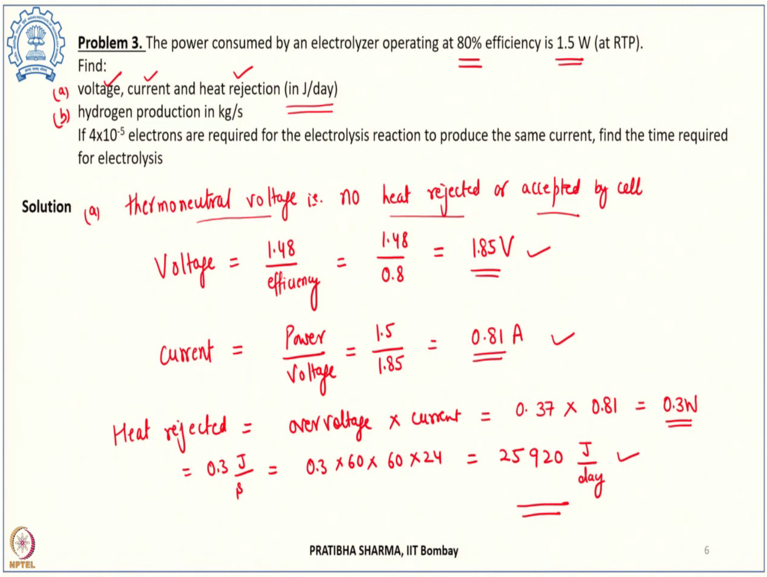

Now, let us look at the 3rd problem statement an electrolyzer, which is having an efficiency of 80 percent and it consumes power of 1.5 watt and that is at room temperature pressure condition. What is required to be found in the problem is what is the corresponding voltage, current and how much is the heat rejected and that is required to be found in joule per day of heat being released?

Also we need to find out what is the hydrogen production and that too in kg per second, it is also provided that let us say if 4×10^{-5} electrons are required for the electrolytic reaction and it produces the same current, which we have calculated in the earlier step. How much is the time required for the electrolysis to take place?

So, these three things we need to find out among the first part we have to find out voltage current and heat rejected, let us see how we are going to solve that? Now let us consider that the, thermo neutral voltage we have studied during the course that this is the state where there is no heat rejection or acceptance. So, in this condition when it is the thermoneutral voltage there is no heat rejected or accepted by the cell by the electrolytic cell, when it operates at this voltage.

So, the voltage is 1.48 divided by the efficiency and that is given by 1.48 and efficiency is already given to be 80 percent. So, divided by 0.8 and that comes out to be 1.85 volt. So, that much is the voltage which is required to be found in the problem. Now the second thing we need to find out for the electrolyzer is the current and that is nothing but the power divided by voltage and power is given as 1.5 watt, voltage we have find out 1.85 volt, so it comes out to be 0.81 ampere.

So, this is the current which is asked in the first part of the problem. Now it is required to found the heat rejection? So, the heat rejected by the electrolytic cell is over voltage times the current. Since for thermo neutral voltage there is no heat rejected or accepted. So, anything above that we will have a heat being formed in the process and that will be rejected.

So, the over voltage here is the difference and that is 0.37 volt times the current 0.81 amps and that makes it 0.3 watt. So, this much amount of heat is rejected by the electrolytic cell. Now it is being asked that we have to find out how many joules of heat is rejected per day. So, to convert it into joule per second it is 0.3 joule per second.

Now we have to convert it into joule per day. So, 0.3 into 60 into 60 into 24 and that gives us 25920 joules per day, that is what is being asked as the third quantity in the part of the problem. So, the amount of voltage current and heat rejected we have found. Now the second thing, which is asked is the hydrogen production how much amount of hydrogen is being produced in units of kg per second.

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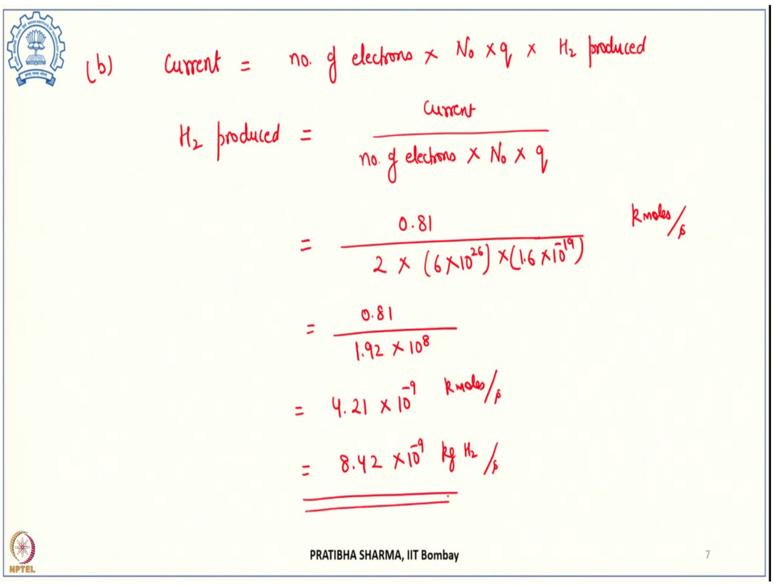

So, let us calculate that part, so in part b we have to calculate the amount of hydrogen being produced. Now we know that the current that flows through the spell is number of electrons times the Avogadro number times the charge on the electron times the hydrogen being produced and this will give us hydrogen is being produced is in kilo moles per second.

So, we can find out from here how much amount of hydrogen which is being produced and that will be given by this expression current divided by the number of electrons transferred in the electrolysis process, the Avogadro's number the charge on an electron. And that can be written as current we know 0.81 amperes we have found in the first part the number of electron transfer in the electrolysis is 2, value of $N_0 = 6\times10^{26}$, charge on one electron 1.6×10^{-19} and this will give us hydrogen produced and the unit will be kilo moles of hydrogen produced per second.

So, it is $0.81/ (1.92 \times 10^8)$ and that makes it 4.21×10^{-9} kilo moles per second or we can make it into kg per second, so multiplying by 2×10^{-9} kg of hydrogen being produced per second. So, this is the answer to the part 2 where, it is asked how much amount of hydrogen is being produced per second.

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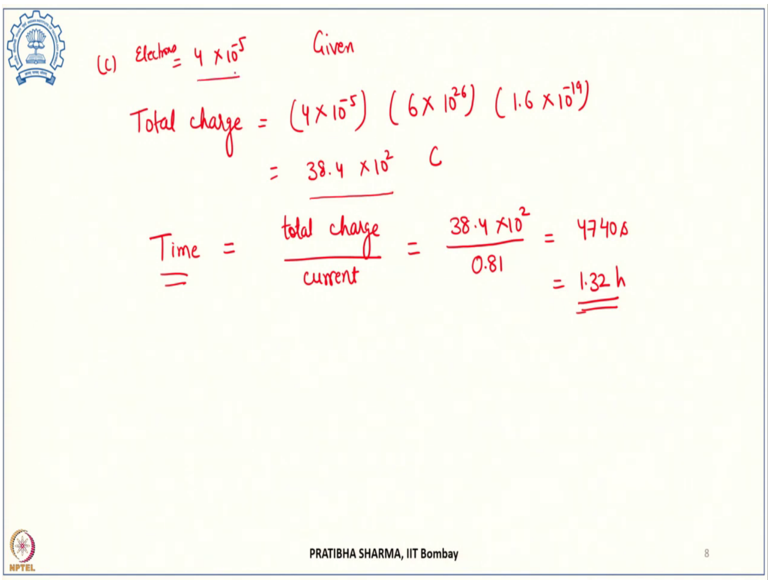

Now, let us look at the part 3 of the problem where it is given that the number of electrons is 4×10^{-5} electrons are required for electrolysis to produce the same current. So, we have to find out the time required for electrolysis in this process and number of electrons is given as 4×10^{-5} this is given in the problem.

Now, the total charge we can find out, which is 4×10^{-5} electrons times the Avogadro's number 6×10^{26} times the charge on each electron 1.6×10^{-19} and that makes it 38.4×10^{2} coulombs of charge, so that is the total charge. So, time for electrolysis is nothing but the charge total charge which we have calculated in this step divided by the current.

Because the current is total charge divided by the time from there we can find out the time and this is 38.4×10^{2} coulombs and the current we have found in the first part of this problem as 0.81 amperes and that makes it 4740 second or converting it into hours 1.32 hour. That is what is being asked in this problem to find out how much time it takes for that much amount of hydrogen which is being produced, when you pass total charge of this much coulomb or these many electrons.

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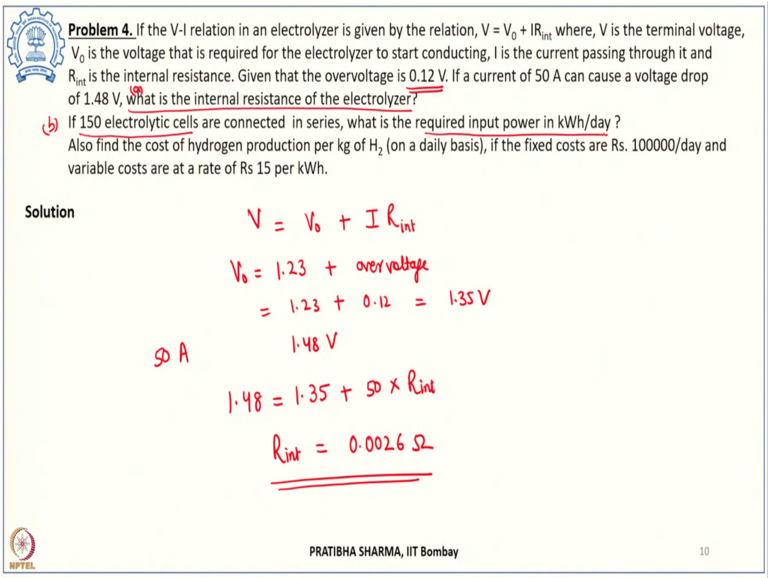

Now, let us see the next problem the problem statement is that if the voltage current relation in an electrolysis is given by $V = V_0 + IR_{internal}$, I is the current passing through it , R is the internal resistance, V is the terminal voltage and V_0 is the voltage, which is required for the electrolyzer to start conducting, the minimum voltage required. Now it has also provided that the over voltage is 0.12 volt and if a current of 50 amperes it can result into a voltage drop of 1.48 volt.

We need to find out under these conditions when a current of 50 amperes resulting into a voltage drop of 1.48 volt. What is the internal resistance of the electrolyzer? Also if a stack is made by connecting 150 electrolytic cells in series what will be the required input power and that we have to express in kilowatt hour per day. So, the input power required to run the electrolytic electrolyzer and also we have to find out the cost of hydrogen being produced per kg of hydrogen on a daily basis per day basis.

Given that the fixed cost associated with the electrolyzer is 1 lakh rupees per day and the variable cost is to be calculated considering the rate of 15 rupees per kilowatt hour. So, the first part is we have to find out the internal resistance of the electrolyzer, then the input power and then what is the cost of hydrogen production under these conditions?

So, let us try to attempt that now it is given that $V = V_0 + IR_{internal}$ and R is the internal resistance. Now V_0 we have to find out V naught is 1.23 that is the reversible cell voltage plus the over voltage and over voltage in the problem is given as 0.12 volt. So, that is 1.23 plus 0.12 that makes it 1.35 volt and it is mentioned that 50 amperes can cause a voltage drop of 1.48 volt.

So that means, the voltage drop of 1.48 caused by 50 amperes of current given that the V naught is 1.35 volt we have found 50 amperes into the internal resistance of the electrolytic cell and that can give us internal resistance of the cell and that is found from solving this as 0.0026 ohm and that is what is desired in the first part.

So, we had to find out the internal resistance of the electrolyzer. Now the second part says if we have an electrolyzer with 150 electrolytic cells connected in series, we have to find out the required input power and that has to be found in kilowatt hour per day.

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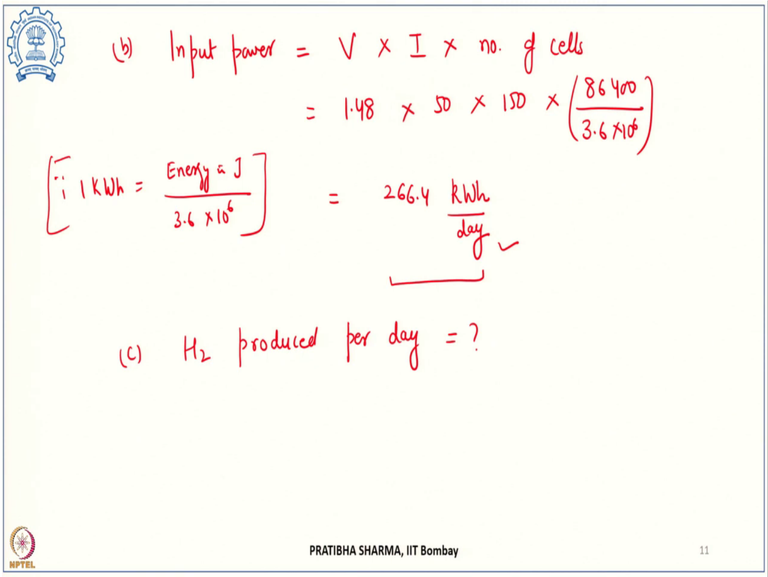

Now, input power we know can be found as the voltage times current times number of cells connected in the electrolyzer. So, number of electrolytic cells connected in series, voltage we have found 1.48, current is 50 amperes, number of cells connected given is 150.

Now, we will require a conversion factor, the reason of including is we have to convert it into kilowatt hour per day. Now 1 kilowatt hour is equivalent to energy in joule energy in joule divided by 3.6×10^6. So, that is the conversion which is required to convert it into kilowatt hour per day. So, again going back to the same problem input power is if we solve this then we get the input power as 266.4 kilowatt hour per day.

So, this much is the kilowatt hour per day of the required power to the electrolyzer, this is the 2nd part. While in the third part it is asked how much amount of hydrogen is being produced per day that is need to be found.

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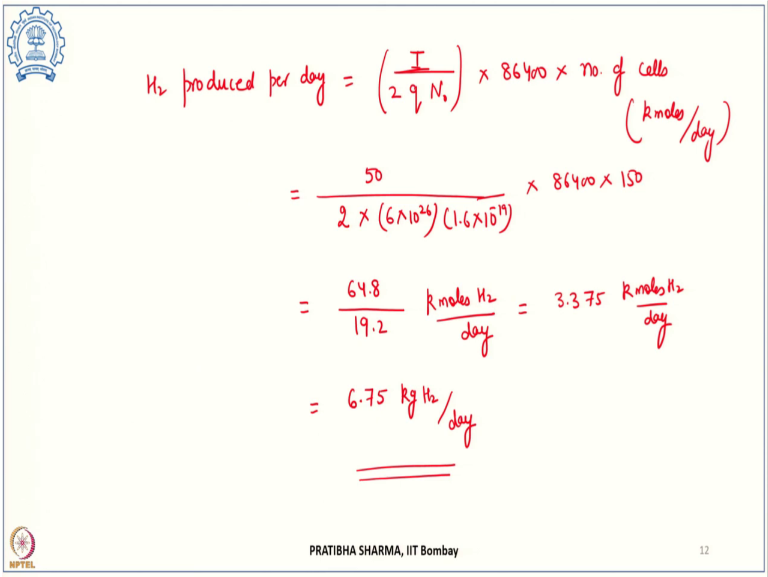

Now, to find out that much amount of hydrogen per day we can write it as this is current divided by the number of electron transfer, charge on the electron, Avogadro's number N_0 and this will give us hydrogen produced in kilo moles per day.

Now, we will substitute the different values it is given that the current is 50 amps, number of electron transfer in the electrolysis process is 2, Avogadro's number 6×10^{26}, charge on 1.6×10^{-19}, number of cells connected 150 and that much is the kilo moles per day. Now if we solve this we get it as 64.8 divided by 19.2 this is kilo moles of hydrogen produced per day.

Now, we can convert it into kg per day also, so this value is 3.375 and we can convert it into kg of hydrogen being produced per day as double of it 6.75 kg of hydrogen being produced per day. So, this much is the hydrogen produced per day by connecting these 150 electrolytic cell in series.

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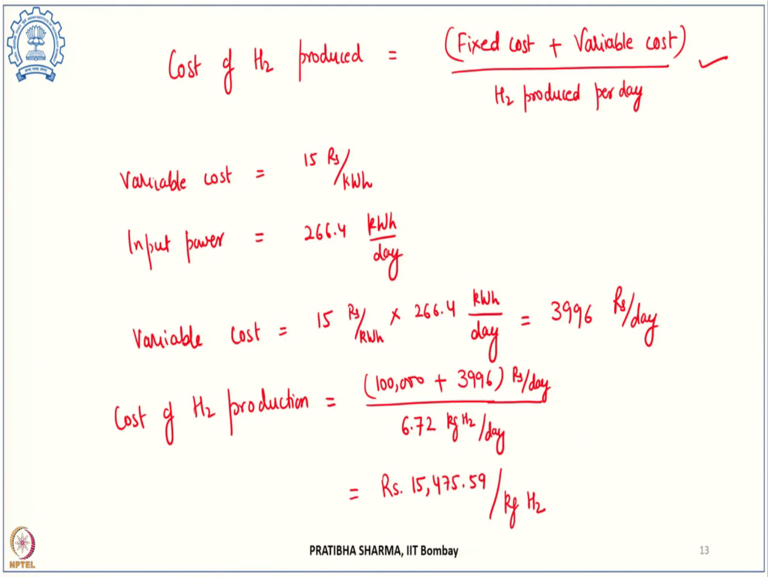

Now, the another part is we have to find out the cost of hydrogen being produced per kg of hydrogen.

So, cost of hydrogen which is being produced we have to find out in per kg of hydrogen. Now we have already studied in the course that it is the total cost including the fixed cost and the variable cost divided by the total hydrogen being produced. So, you will be calculating it as fixed cost plus the variable cost and that is divided by the hydrogen being produced per day.

Because the fixed cost it is given in rupees per day and variable cost we will convert it into rupees per day, now to first let us convert the variable cost. So, the variable cost is given as 15 rupees per kilowatt hour and the input power we have found in the earlier section as 266.4 kilowatt hour per day.

So, we can find out the variable cost in rupees per day is given by 15 rupees per kilowatt hour times the input power and that gives us 3996 rupees per day, this we will use in the above equation to substitute for variable cost. So, that we can get the cost of hydrogen production as fixed cost 1 lakh rupees plus the variable cost 3996 divide by the hydrogen being produced.

Which we have found in the earlier section as 6.72 kg of hydrogen produced per day and this is rupees per day numerator. So, using this we can find the cost of hydrogen production as rupees 15475.59 per kg of hydrogen being produced. So, that is per kg of hydrogen being produced. So, we have solved all the parts of this problem.

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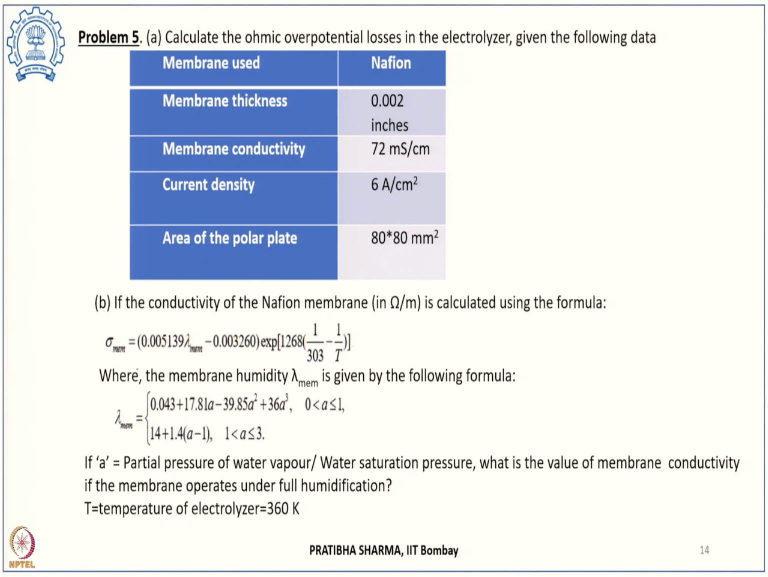

Now, let us see another problem which states that the ohmic over voltage losses we need to calculate for an electrolyzer. So, the over potential, which arises due to ohmic losses in the electrolyzer provided that we are given the details about the membrane, membrane used is Nafion its thickness is 0.002 inches it is conductivity is 72 millisiemen per centimeter, current density is given as 6 amperes per centimeter square and the area of the plate is 80 × 80 millimetre square.

Now the second part is we have been given the relationship of membrane conductivity and the humidity. So, the conductivity of the Nafion membrane, which we have used in this electrolyzer is expressed in ohm per meter and it is given by the formula that conductivity is ($0.005139\lambda_{membrane}$ which is the membrane humidity minus 0.003260) times exponential (1268 ((1/303) – (1/T))); T is the temperature of the electrolyzer.

And the relationship between the membrane humidity as well as the partial pressure is given as when the partial pressure is in the range of 0 to 1 then the first expression it is 0.043 plus 17.81 partial pressure minus 39.85 a square plus 36 a cube. However, when the value of a is higher than 1, but less than or equal to 3 then the value is of the membrane humidity is 14 plus 1.4 a minus 1, a is partial pressure of water vapour or water saturation pressure.

Now, what is required to find out in the second part is the membrane conductivity. Considering that the membrane operates under full humidification, provided the temperature which we will require for the membrane conductivity is given as 360 K. So, the first part we are going to find out ohmic over voltage and for the second part we have to find out the membrane conductivity under full humidification condition.

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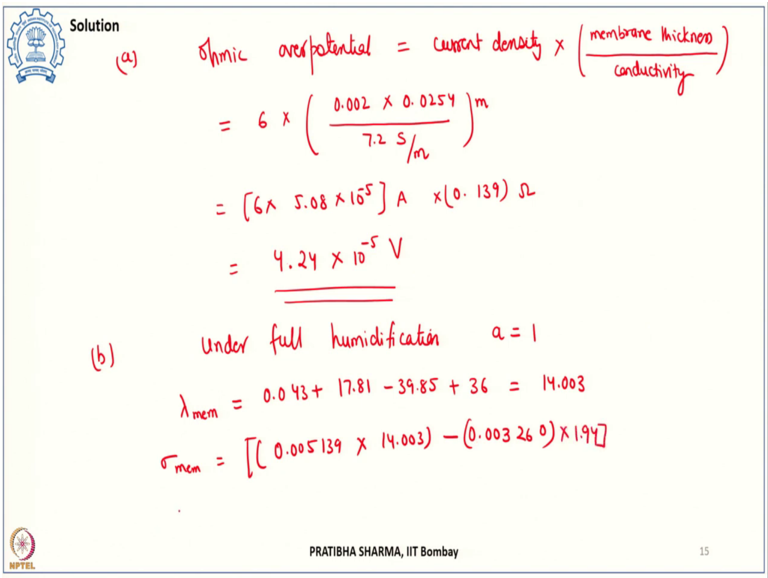

Now, let us solve this problem. So, the first part is we need to find out ohmic over potential and that is given by the current density times membrane thickness divided by the conductivity of the membrane. Current density is given as 6 amps times the membrane thickness divided by the conductivity 7.2 siemen per minute per meter. So, that is $6 \times 5.08 \times 10^{-5}$ and that is all in amps into 0.139 ohm that makes it a value of 4.24×10^{-5} volt.

This is the value of ohmic over voltage that we can calculate. In the second part it is asked that under full humidification condition for the membrane, by full humidification means the value of a being 1 and when value of a is substituted in the humidity value for the membrane to be 1 we get a value of 0.043 plus 17.81 everywhere we have substituted a equal to 1 minus 39.85 plus 36 and that comes out to be 14.003.

Now, this we can substitute for finding out the conductivity of the membrane and that is 0.005139 into this value of 14.003 minus 0.00326 into 1.94.

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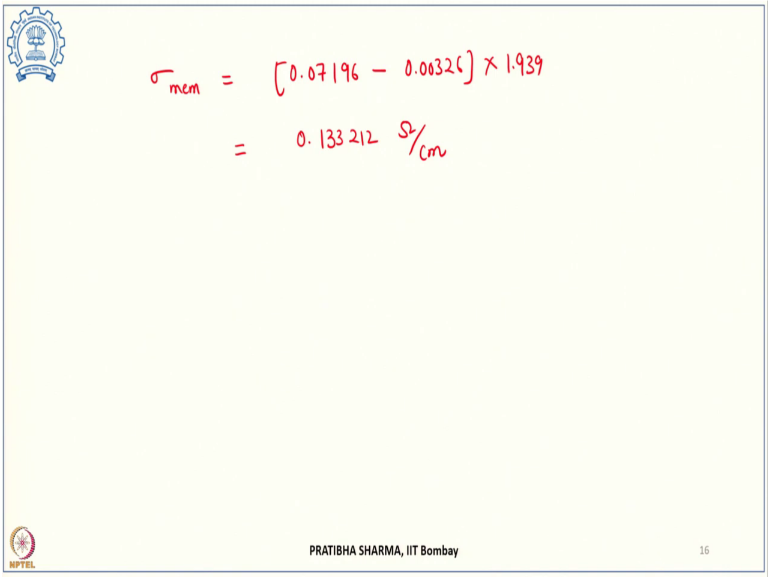

So, the conductivity of the membrane we can write down as this value comes out to be 0.07196 minus second term 0.00326 times the exponential part its value is 1.939. Finally, we get a value of 0.133212 ohm per centimeter. So, that is the conductivity of the membrane that we can find out using the condition that it is under the full humidification condition.

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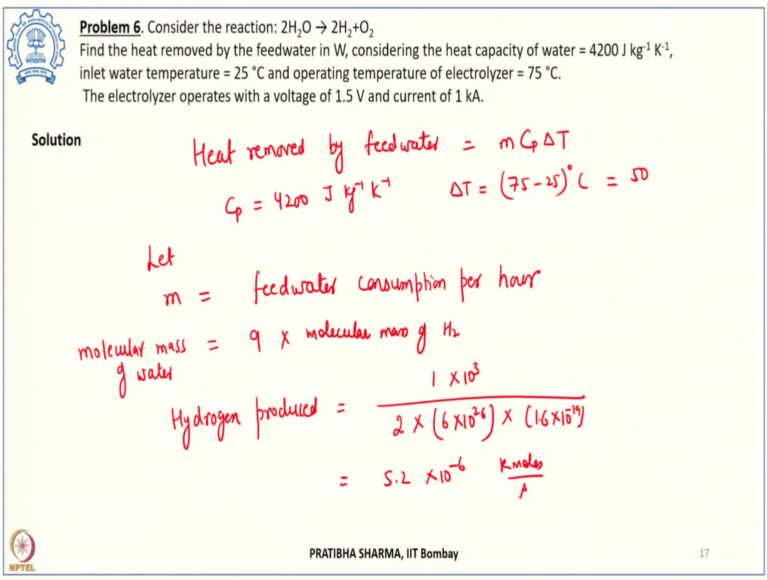

So, the last problem that we will do today is the reaction for water splitting into hydrogen and oxygen is given in which takes place in the electrolyzer. It is considered that the feed water is used to remove the heat and the amount of heat which is removed we have to find out by the feed water in watt. Considering that the heat capacity is given as 4200 joule per kg per kelvin, provided that the water when at the inlet side was at 25 degree centigrade and the electrolyzer operates at 75 degree centigrade.

The electrolyzer operates at a voltage of 1.5 volt and current of 1 kilo amps. So, under these conditions we have to find out how much amount of heat is being removed by the feed water? Now let us do that problem it is a simple problem that the heat removed by the feed water is nothing but by given by $mC_p\Delta T$, C_p is already given in the problem 4200 joule per kg kelvin and ΔT is 75 minus 25 degree that is 50 degree a difference of 50 degree centigrade.

Now, let us assume that the feed water consumed per hour is given by m. So, the molecular mass of water we can say is 9 times the molecular mass of hydrogen. So, the hydrogen which is produced in the process of electrolysis is when we passed a current of 1 kilo amps. So, 1×10^3, 2 electrons participated in the electrolysis, Avogadro's number 6×10^{26}, charge 1.6×10^{-19} and that gives 5.2×10^{-6} kilomoles of hydrogen produced per second.

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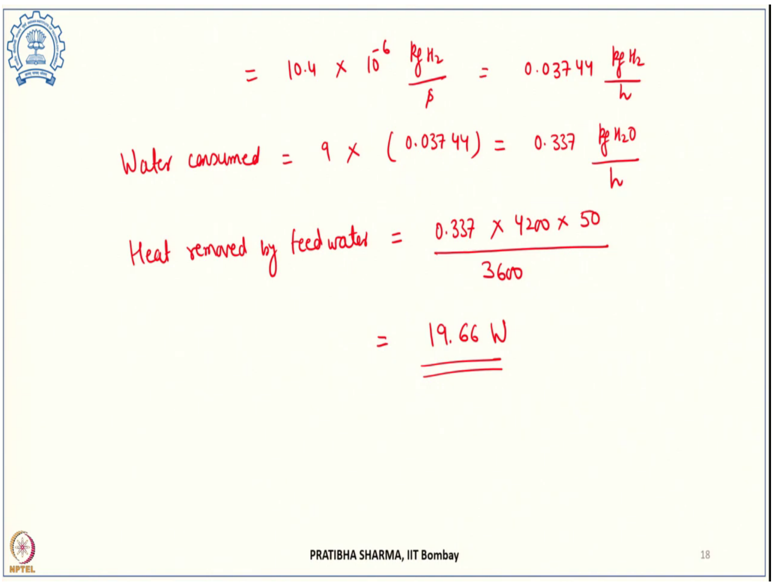

Or it is 10.4×10^{-6} kg of hydrogen being produced per second. So it is equal to 0.03744 kg hydrogen when expressed in terms of per hour. So, the same quantity we can use here 0.03744 this is the kg of hydrogen being produced per hour times 9 that gives a value of 0.337 kg of water being consumed in the process per hour. So, the heat which will be removed when this much amount of feed water is fed is given by $mCp\Delta T$.

So, mass 0.337, Cp is given as 4200, change in temperature is 50 degree and we will have to convert it into watt. So, this is 19.66 watt, this much amount of heat is being removed by the feed water in the electrolytic process. So, these are some of the simple problems that we have seen in this tutorial which were based on water electrolysis.

Thank you.