Non-conventional Energy Resources
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Lecture - 34
Fuel Processing for PEM Fuel Cells

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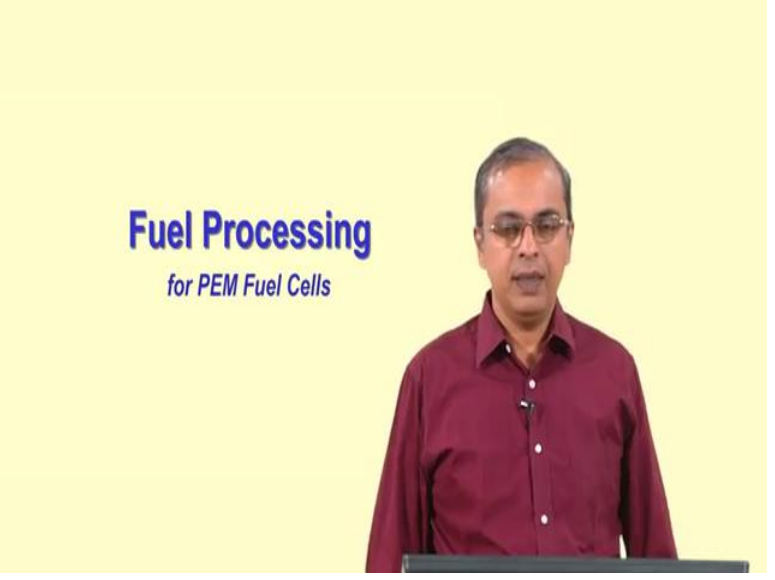

In this class we will look at a fuel processing and it will be from the perspective of PEM fuel cells. In that context it is also often referred to as reforming, reforming of the fuel.

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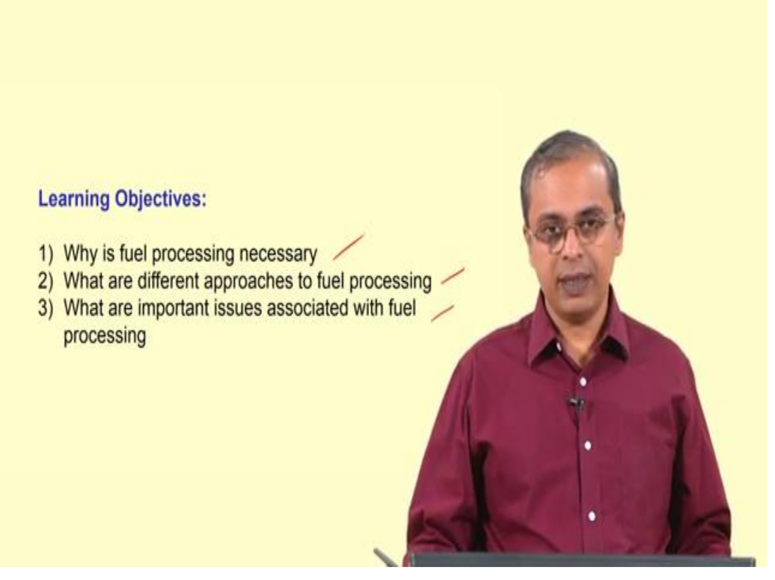

So, the learning objectives for this class are as follows. We will look at why is fuel processing necessary ok. So, we will look at, so when you complete this class you will have an understanding of that as to why is fuel processing necessary. What are different approaches to fuel processing? So, that is something that we will look at or at least the different stages involved in fuel processing. And when you get done with it, what are you know important issues associated with the fuel processing activity?

So, why is fuel processing necessary? What are different approaches or different steps involved in the fuel processing process? And what are important issues associated with this fuel processing? So, these are important things that we will look at as we proceed with this class.

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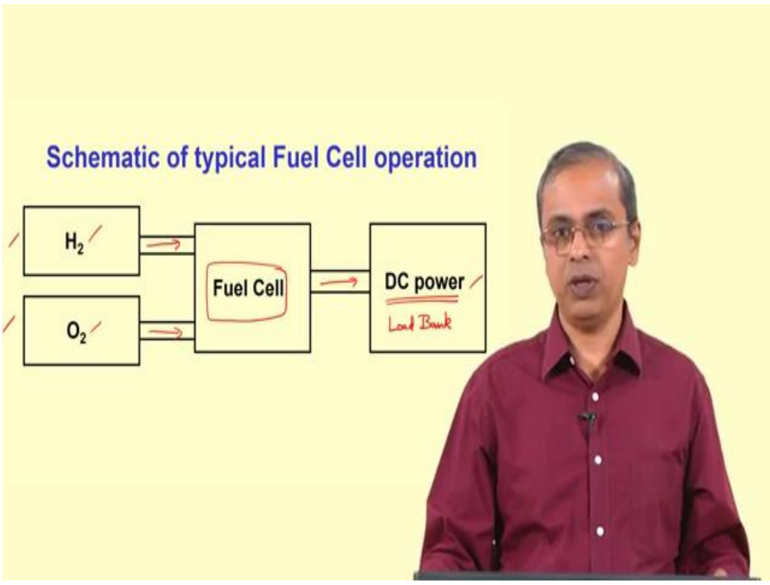

So, what we have here is the schematic of a fuel cell, and schematic of a fuel cell in the sense that if you ever visit a fuel cell lab or if you have a fuel cell lab or you get access to a fuel cell lab. In the lab the testing of the fuel cell where they are developing fuel cells, they are trying to come up with new you know materials for fuel cells trying to improve a fuel cell etcetera, in that lab you will see a set up for testing a fuel cell that once you convert it to some kind of you know outline of schematic of that set up you will see roughly what you are seeing on your screen.

So, central to it will be the fuel cell which is what you are testing in the in the test setup, but important ingredients going into it are the two reactants. So, you will have hydrogen, that is being supplied to the fuel cell and oxygen which is being supplied to the fuel cell. So, these are two important ingredients that will be getting supplied to the fuel cell. And in a lab setting this is typically in the with the help of a bottle or you know a cylinder as you may want to call it. A cylinder of hydrogen or a cylinder of oxygen which you can get commercially from suppliers of gases for research activities etcetera you can get a cylinder of hydrogen or cylinder of oxygen and this is then installed in the lab it sometimes its installed just outside the lab. So, that you have some manifold through which you can pipe this gas into the lab in a in a controlled manner that also helps you with some safety issues associated with the gas etcetera.

But fundamentally you will have a piping process, through some pipes. You will have these two gases arriving at the fuel cell and that's how the lab setup is. And then in the lab then you know operate the fuel cell you use these two gases as inputs to the fuel cell you generate electricity from the fuel cell, and that electricity is out is the output from the fuel cell. So, that's in the form of DC power. So, this is what you are getting out of the a fuel cell and usually. So, then there is a you know since you are trying to do this in a controlled setting there is a load bank there is some where there's an instrument that is referred to as the load bank. So, this is an electronic you know instrument that is put in place to which your fuel cell is connected or the output the current output coming from your fuel cell is then connected to this load bank. And using the load bank you can draw current from the fuel cell in a controlled manner.

So, you can know test it under low current conditions, under high current conditions actually the more useful parameter there is current density, so you can test it under low current density conditions and high current density conditions and a wide range of different things you can make it cycle through different you know operating conditions. All, of those things are done by controlling the input these two parameters that you see here, the two inputs that are going into the fuel cell and the DC power that you are drawing from it.

So, you can have you know excess gas going in you can be drawing low power you can have just the right amount of gas for the right amount of power that you are trying to draw or you send in a little less of one gas and try to draw more power. Obviously, you would be limited by the gas that is coming in, so you cannot draw more power then what the gas can support, but you can make it you know deficient in one gas versus deficient in the other gas and lot of such tests you can do to understand what is the fuel cell doing, how is the anode of the fuel cell behaving, how is the cathode of the fuel cell behaving, how is the electrolyte of the fuel cell behaving.

So, these gases in fact, depending on the type of fuel cell you are testing. So, for example, if you are testing a proton exchange membrane fuel cell or a PEM fuel cell then these two gases that that I am referring to here that the hydrogen and oxygen would also go through a humidifier which will then humidify the gas and so in a humidified manner they will enter the fuel cell and you can also use that level of humidity as a parameter that you can control.

So, you can run the cell in you know fully humidified condition in which means that the hydrogen is running at 100 percent relative humidity and the oxygen is also running at 100 percent relative humidity or rather it’s entering the cell at 100 percent RH for that operating point. So, in the cell maybe tested at 60 degree C or at 70 degree C and so on. And so at that temperature whatever is the relative humidity it will reach 100 percent relative humidity and with that you send it into the cell and, so you can test it a 100 percent RH, you can test it at 80 percent RH, you can test it at 50 percent RH.

Basically meaning you are testing the cell in either a fully wet condition or in a I mean relatively drier condition. So, the extent of dryness in the cell use is something that you can control. So, these are all the things you can control. You can control the gas flow rates individually, you can control the humidity individually. So, one gas could be running dry, one gas could be running wet you can control the you know the temperature at which the cell is sitting and you can control the power that is being drawn from the cell. So, lot of parameters you can control and using this you test the cell. So, this is how you test in a laboratory condition.

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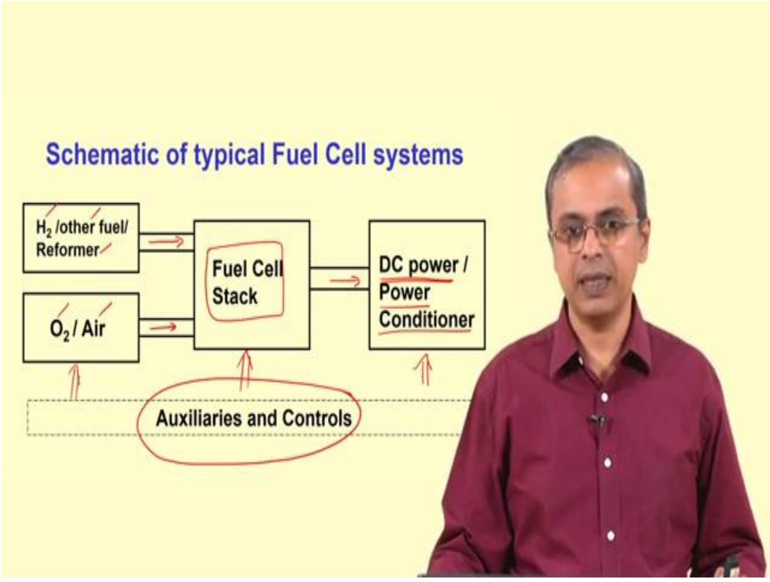

However if you so that is something that is in a lab condition that kind of you know test setup where you have many things under control and your testing it and it is really necessary only then you truly understand what is possible with the fuel cell, you understand what are the limits of the fuel cell that you can operate within and how you can consider pushing the you know boundary with respect to the fuel cell. So, these are all things that you can do if you do it in a lab setting.

Now, from there if you move to a real life system so, then it is say let’s say it is sitting in an automobile or you are deploying it in a you know residential sector. So, now, that is not a test setup it’s not a test setup in a lab. It is actual utilization of this fuel cell in a real life condition. So, there you have a complete system that is sitting there and that gets referred to as a fuel cell system and what you see on your screen is a schematic of a typical fuel cell system.

So, if you compare against what we previously had there are some variations between what you would do in the lab versus what you will do in a in the real life situation. Of course, in the lab also you can create the same situation you can now, is because lab is completely in under your control you can simulate this real life situation in your lab and in fact, normally when they develop fuel cells that’s exactly what they do.

First they will test it under these kind of controlled conditions where you have hydrogen, and oxygen and the fuel cell and the power bank or the load bank which is drawing your

DC power. And then once you understand what it is doing under these control conditions you will mimic real life conditions and then you will create some slightly different setup which is what this schematic shows you in which you can test the real life conditions. Once you are satisfied that your fuel cell system is working well under real life conditions you would deploy it on the field. So, this is sort of the you know gradual progression of how you study a fuel cell, understand it and then send it out to the to the field.

This is exactly what is going on in you know even in battery industry for example, some similar analogy analogous conditions you can think of, but this is what goes on in any fuel cell company for example. You will have an R&D part I mean there will be some scientists who work on the individual cell, trying to understand how well to improve it. And then there will be people who will also be looking at what is required to move this into the field and so they will look they will do the testing under the simulated you know field conditions and then finally, you take it out to the field. So, that is what you do.

So, now, when you look at this schematic of what you did in the lab which is a typical fuel cell operation versus what you do in the field which is the typical fuel cell system that is out there, there are specific differences that are of interest. So, let’s just see what those differences are. So, the first thing is the reactant, reactant stream. So, what we had previously in the lab was pure hydrogen and pure oxygen and as I said these are coming off of two bottles. So, you have two cylinders, one cylinder is hydrogen one cylinder is oxygen then you have a flow meter later the in the pathway which controls the flow and then you send the gases.

Now, in real life conditions you don’t only use hydrogen you have the choice of using hydrogen or you can use some other fuel and in this case you have the option of sending that other fuel maybe for example, methanol directly into the fuel cell. So, you can take hydrogen send it directly into the fuel cell or you can take some other fuel such as methanol and send that also directly into the fuel cell. So, that depends really on the capability of the fuel cell whether it can handle methanol.

So, some fuel cells may handle it some may not, but but basically that is the idea you can either send hydrogen in or you may consider sending methanol in or you will take some other fuel and send it through another unit called a reformer and in fact, in today’s class that is exactly what we are going to talk about what is this reformer and what does it do and what are some issues associated with it. So, you can take some other fuel which could be methanol, it could be methane, it could be some other gas and you can send it into this reformer. The output from the reformer will be a stream which will consist of a bunch of a mixture of gases that gas that mixture may be further processed in to clean up certain you know some ingredients of that mixture and then that output is then sent into the fuel cell.

So, that kind of an output. So, some processing is done to some other gas the output of that processing is then sent to the fuel cell ok. So, that is the activity that is happening on the fuel side of the fuel cell. On the oxygen side the oxidant side of the fuel cell as I said you could you have that you still have the choice of sending in pure oxygen, but more generally in order to you know look at you know convenience of operation and many other operational details which we will see.

From the point of view of convenience of operation it makes sense to actually just send air ambient air into the fuel cell. So, even in your automobiles for example, existing automobiles which are not running of a fuel cells you need to send an air into the engine for the engine to work and that air is being taken from the ambient air. So, normally in your typical automobile car or any other you know automobile you can get a chance to look at they will have something called an air filter.

So, in other words they pull air in from the from the ambient conditions, and that air goes through the air filters primarily removing dust and other such you know things that they would like to prevent going into the engine and then the cleaned up air is then sent into the engine and then the engine runs. So, the same idea can be used even in a fuel cell, if you can just take ambient air that of course, contains oxygen. So, we have you know 21 percent oxygen there you just take that air you send it through some filter and then you send it into the fuel cell. So, that is the other possibility that you have here and that is the way in which you would do this. So, you then turn air and this reformed fuel or some other fuel and that goes into the fuel cell stack.

So, that, so these are the ingredients that have now, gone into your fuel cell stack. Now, once they are in the fuel cell stack again you have you know power generation that is going on and now, the characteristics may be slightly different from what you tested in the lab in the original condition where you had pure hydrogen versus pure oxygen, but in any case you would have tested it also under simulated conditions. So, hopefully you have a good understanding of how your fuel cell is going to behave. And then the output from that fuel cell is the same DC power. So, that you get DC power which is you know. So, some current and some voltage which you will get from the fuel cell and it turns out that most of our households are all set up for AC power, right.

So, somehow the infrastructure that we have all gotten used to over the years has been AC power primarily because you can you know go to high voltages and then transmit it over long distances and that way you can control losses and that's why we use AC power in many of the situations. And then when it comes home you just comes closer to home you just drop the voltage to something that's acceptable internationally its typically somewhere between 110 volts and 220 volts and then that is sent into your household appliances.

So, often DC power is not directly being used in the household. So, or in many other places, so the output from the fuel cell is often not directly usable. You can make it directly usable if you accordingly design your appliances that run off of a fuel cell, but generally speaking if you come and you know if some fuel cell supplier would like to supply a system that works in your household they would need to set it up such that your existing appliances will work with the fuel cell system that they are supplying. Your existing appliances are all more or less all of them are uniformly working off of AC power supply. And therefore, you need to take the DC output of the fuel cell and then convert that to an AC kind of signal and then that is what is being sent into your house or your appliances.

So, that process is done using this device referred to as the power conditioner. So, there is a lot of electronics involved in that and there are typically electrical engineers design these power conditioners. And they have to design the power conditioner such that it is capable of taking the typical output coming off of a fuel cell. So, that could be you know maybe some you know 30-40 volts in current I mean sorry in voltage and then you can have you know maybe even 50 to 100 amps coming off of the fuel cell. So, it's a high current maybe a little lower voltage then what is there on our household circuit. So, you have to change that to you know something like 110, 120 volts and then change the current rating. So, that you are you know back to this 5 amp kind of situation and then you also have to do AC power supply converter to AC. So, all of this is being handled by this power conditioner ok.

So, in in know to control all of this set up this entire setup of you know the fuel supply the fuel cell and the power conditioner you have these auxiliaries and controls. So, this, these auxiliaries and controls actually interface with everything they interface here, they interface here, and they interface here. So, they interface with all of these parts of the fuel cell and that's how they control the functioning of the fuel cell and so this is the complete system that is going to be sitting out there in on the field trying to you know power some end use.

So, if you come if you look at this system and you look at this idea that you actually have a reformer here the question that we need to address immediately is why do we want to do this reforming or in this case the more general term being fuel processing. Why do we need to do this fuel processing? Why cannot we you know in the lab we use hydrogen and oxygen why cannot we just continue doing that. So, that's a valid question that we need to consider and as we look at these issues associated with fuel processing.

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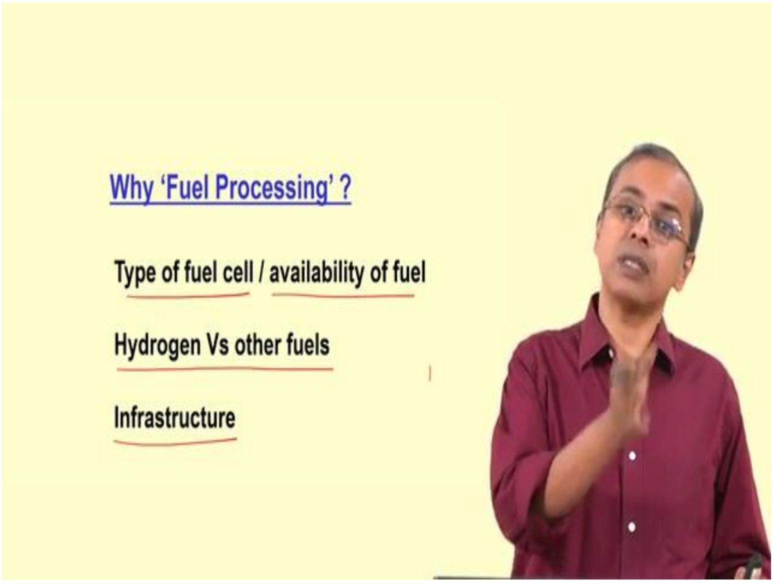

The first is the type of fuel cell. So, some types of fuel cells will operate with certain fuels only they will not operate with certain other fuel cells other will operate with certain types of fuel only and will not operate with certain other types of fuel.

So, you have to also look at what is available. So, you may have a particular version of fuel available to you and that may not be the type of fuel that the fuel cell will accept. So, this does not mean that you cannot use the fuel cell under those conditions. So, you have to find a way to make that fuel acceptable to the fuel cell. So, you do this conversion of that fuel you take the fuel you process it in some way, you convert it to a form that is acceptable to the fuel cell and then you send that into the fuel cell ok. And you have all these other fuels available you have hydrogen available, but hydrogen typically we have we are trying to make it from some source could be you know electrolysis of water, you could be catalytically splitting, photocatalytic catalytically splitting water etcetera and there are other fuels which you can actually basically get off of you know the existing carbon based fuels that hydrocarbon based fuels that we are already having available.

So, you have to keep in mind the availability of the fuel both of these are there some may be more readily available. So, the other types of fuels are typically more readily available and therefore, it from a commercial perspective from an ease of use perspective using fuel that is readily available is of interest. Of course, then you may ask then what is the purpose of using the fuel cell it is just that it takes this other fuel and uses it with much more efficiency, so you can use less fuel and get more work done and therefore, a fuel cell is still meaningful to have even though you are using some other fuel. And there is always this question of infrastructure. So, you have existing infrastructure all over the world. That existing infrastructure already deals with supply of specific types of fuel. So, you have gasoline or petrol, you have diesel, you have compressed natural gas all of these are available in in you know in a wide extend extended version of infrastructure that is there in many countries.

So, this is readily available. So, now, suppose you want to deploy a new technology in the automotive sector it really helps if you are using the infrastructure that is already there. If you are going to ask for a you know complete overhaul of the infrastructure naturally there is going to be a lot of resistance it’s going to take a lot of time to enable that to happen. So, it makes sense to try and use the infrastructure that is already there and that infrastructure usually helps works very well with a lot of fuels that are already being used. So, that is therefore, it makes sense to look at fuel that is already available and then do some fuel processing with it. So, that the fuel cell can use it and therefore, you get the benefits of the fuel cell without doing a large scale overhaul of the infrastructure which is being set up for some other fuel. So, therefore, we do fuel processing. So, that's the whole idea of fuel processing.

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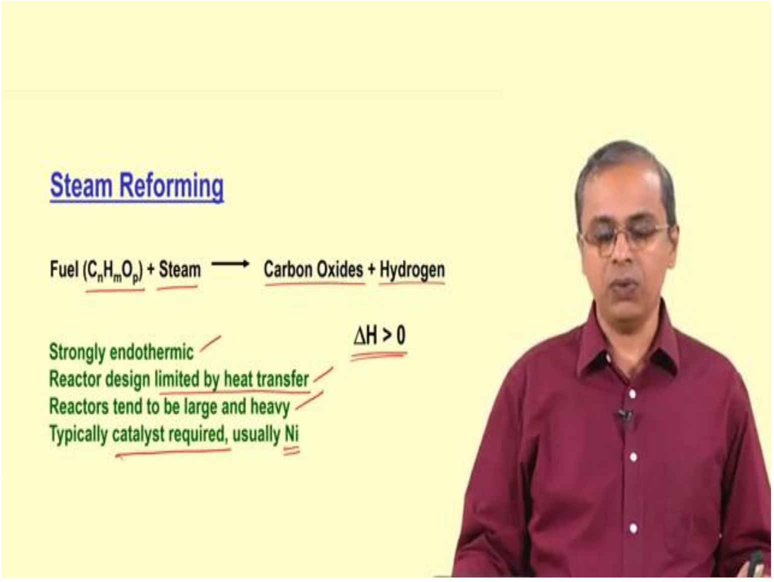

So, what is fuel processing? So, if you take the basic idea with respect to at least the fuel cell you want the inlet of the fuel cell to receive a stream of fuel that is rich in hydrogen ok. So, as opposed to the lab setting where you are testing just pure hydrogen you now want a situation where the inlet is some processed fuel and that output of that processing step is a fuel stream that has a lot of hydrogen in it and therefore, the fuel cell can work with that hydrogen ok.

So, the hydrogen may not have been inherently present as a separate entity in the original fuel you process it to separate the hydrogen out and then with that hydrogen you send it into the fuel cell. So, that's the basic idea. So, there are certain ways of procedures that are used for fuel reforming from the perspective of fuel cells. So, the first one is referred to as steam reforming ok.

So, you take some fuel here. So, for example, you have in general it would be some you know carbon, hydrogen and oxygen containing entity which would be your fuel. So, in generic way I have simply put C_n H_m and O_p as the generic formula that the fuel would represent, you may have a mix of fuel level it may not even necessarily be one single molecule so to speak, and you mix some steam with it. The output you will get when you do this is basically a system of gases which will contain different types of carbon based oxides. So, you could have carbon dioxide, you could have carbon monoxide etcetera and then you will have hydrogen.

So, you are not going to get pure hydrogen. So, that's something that you would keep in mind. The reforming processes that we are talking about generally are not going to give you pure hydrogen stream ok, so at least not immediately. What comes off the reformer will not be pure hydrogen. It will typically have hydrogen and some other byproducts of the reforming process typically those byproducts are carbon based oxides which is what you will have. And this whole this reaction is basically an endothermic reaction. So, delta H is greater than 0 which means you have to provide heat. So, the whatever is that processor you have to keep supplying heat. So, it is strongly endothermic. You have to provide a fair bit of heat for this process to occur and naturally when you when you have a reformer which is strongly a very when you have a reaction that is strongly endothermic and you have some kind of a reactor in which this endothermic reaction is happening the heat which you are supplying externally has to find a way to reach all the locations where the reaction is happening.

So, the reactor design is limited by the heat transfer process ok. So, the reactor design is limited by the heat transfer process primarily because heat has to reach the various locations where the reaction is likely to occur. And therefore, if you simply look at steam reforming the reactors tend to be large and heavy you have to have lot of you know heat exchange processes involved to for the heat to go in and come out and all these reaction to be distributed throughout this region and so on, and that is how this steam reforming based reactor is set up. And, but that does take an existing fuel and converts it to a stream that is hydrogen rich and therefore, creates a stream that is acceptable to a fuel cell ok.

So, at least in general sense maybe some further processing is required, but you are getting closer to a fuel that is acceptable to the fuel cell ok. And usually this will require some catalyst to enable you know these you simply cannot just mix the fuel and a and the steam and expect things to happen the way you are hoping for. Usually a catalyst is required to ensure that the reaction occurs at some appreciable rate and in the manner that you wanted to proceed and typically that catalyst is nickel.

So, clearly I mean nickel is not expensive it's quite you know cheap inexpensive metal to work with relatively speaking and therefore, this is you know a very acceptable process it is not you know prohibitive in some fundamental sense. The only issue here is that you are supplying heat. So, naturally you are now, wasting some energy, you are use creating energy somewhere you are using that energy to do this splitting process and then you know taking this hydrogen rich stream to use it for some other process.

Generally in all you know energy circumstances say energy related technologies we are always interested in knowing how effectively we have done the process and how efficiently we have done the process. So, you have to look at the process as a whole. You cannot simply look at the efficiency of the fuel cell alone. If you are going to spend a lot of energy creating the fuel stream that goes into the fuel cell that energy should also be included in your calculation as wasted energy because that energy is not driving whatever is your end goal. Now, if it is supposed to power the house that energy is not powering the house that energy is being used by the fuel cell to create electricity and that electricity is used to power your house. So, this energy should also go in as energy that has been consumed in the process of running your house ok. So, these are things that we have to look at.

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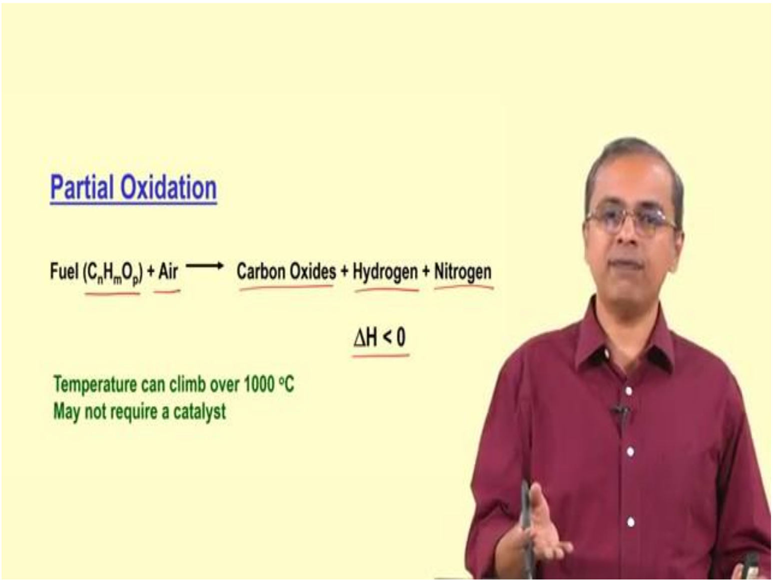

There is another way in which you can do this reforming and that is referred to as partial oxidation ok, partial oxidation of the fuel ok. So, you are sort of doing a little bit of burning of the fuel, but partial oxidation is what it is referred to. So, in some controlled circumstances you mix the fuel and air. So, again fuel is this generic formula that we have here and in that in some controlled circumstances in a reactor you mix it with a little bit of air.

So, when you do this again you get the same kind of output you have carbon based oxides you have hydrogen as an output and of course, you have nitrogen because you started with air and air is you know 79 percent nitrogen. So, you are going to have nitrogen in your stream right. So, this is the general output that you are going to have.

But the difference between say steam reforming and this is the fact that now, you are actually doing some amount of combustion and therefore, you have a strongly exothermic reaction. So, delta H is negative it is just releasing energy into the process and therefore, the temperature can climb up very high. So, you can have a temperature climbing past 1000 degrees C very rapidly ok. So, that is the issue here with partial oxidation and in fact, it happens so easily that you may not even require a catalyst to enable it to happen. So, you carry you can even do it without a catalyst and you can have this situation happening. So, a one point you have to remember in both let's say the steam reforming as well as the you know partial oxidation is the fact that you no longer have a pure hydrogen exit stream. So, here you had carbon oxides with hydrogen and in partial oxidation you have carbon oxides you have hydrogen and you have nitrogen ok.

So, if you want to look at it from a technical perspective what this means is that the partial pressure of hydrogen is not 1 ok. So, even if this whole thing is 1 atmosphere you know gas that you have generated gas at 1 atmosphere the partial of pressure of hydrogen is not 1 ok. So, it's going to be much a gas with much lower partial pressure of hydrogen. If you were testing this in a lab and you were trying to run it under ambient conditions and you sent in pure hydrogen the partial pressure of hydrogen would be 1 atmosphere at that point in time whereas, in these two cases if you send this same stream let's say you simulate this stream in the lab and you send this into the cell with an ambient exit pressure. So, then the partial pressure of hydrogen will not be 1, if it is only 20 percent hydrogen the partial pressure of hydrogen is only 0.2 atmospheres, right.

So, this changes the thermodynamics of the cell and therefore, changes the voltage associated with the cell the open circuit voltage associated with the cell or at least the the wave manner in which the voltage of the cell will change as you draw current from it. So, all these parameters associated with the cell will start changing because your partial pressure of the gas is not 1 and all these parameters are dependent on that. But at the same time as I said in real life this is what you have, so this is what you have to work with ok.

So, now, that you have seen partial oxidation and steam reforming and you realize that in one case it is strongly endothermic and in the other case it is strongly exothermic there is an interesting way you can do this where you mix both of these processes. So, that you are you are you are setting up a situation where the heat released by 1 process assists the other process.

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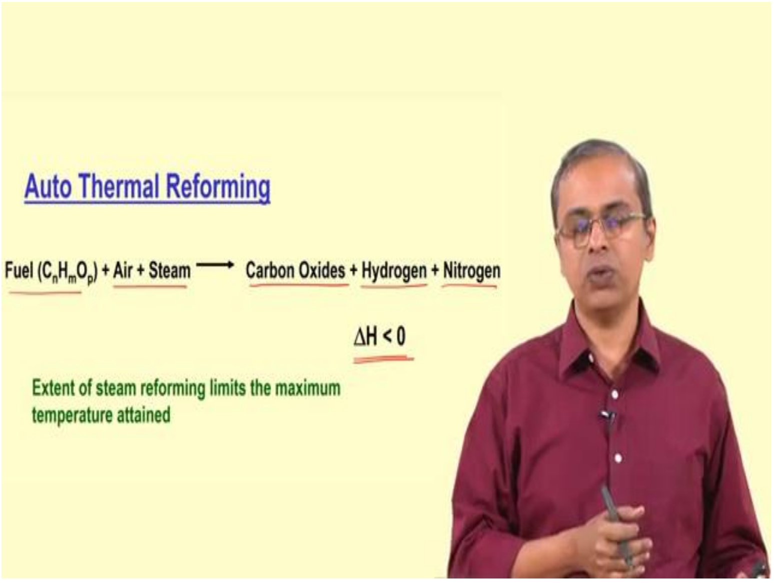

So, suddenly you don’t need as much of heat exchangers etcetera relatively speaking because you now, take the fuel you mix both air as well as stream steam to the fuel both of them are being added to the fuel, and you take this complete mix and allow it to undergo this process of reforming. Again now, the output will contain carbon oxides it will have hydrogen, it will also have nitrogen because after all you are sending in air. So, this is what you do.

But the advantage is that you don’t have to separately do any heating process and you basically you know take the heat from one reaction and supply it to the other reaction and both reactions are doing reforming. So, in both cases you are always assisting the reforming process. So, you are not generally burning some other fuel to create the reforming process, it is happening simultaneously both reactions are doing the reforming process of fuel processing activity and therefore, the end goal is being served by both reactions. And the nice thing is since one is consuming the heat the temperature doesn't climb up in an uncontrolled manner. So, you can set it up. So, that it is slightly exothermic. So, that you have some control on the temperature and you can manipulate that temperature.

So, this is the way in which you can set it up so that you know you can manage the temperature and hold the temperature and then continue the reaction. And then based on the amount of steam reforming you are doing you can limit the maximum temperature to which the you know the reactor begins to climb. So, this is called auto thermal refining, rifts or reforming autothermal reforming. And as the name suggests it basically means, you don't have to supply heat externally, you don't have to remove heat using some other process it is all happening internally. So, that therefore, that and hence the autothermal reforming your name. So, this is an interesting way in which you deal with the reforming processes.

So, this is these are 3 different ways that I have told you 3 different approaches to do the reforming steam reforming and partial oxidation and this auto thermal reforming. So, 3 different ways in which you can do the reforming.

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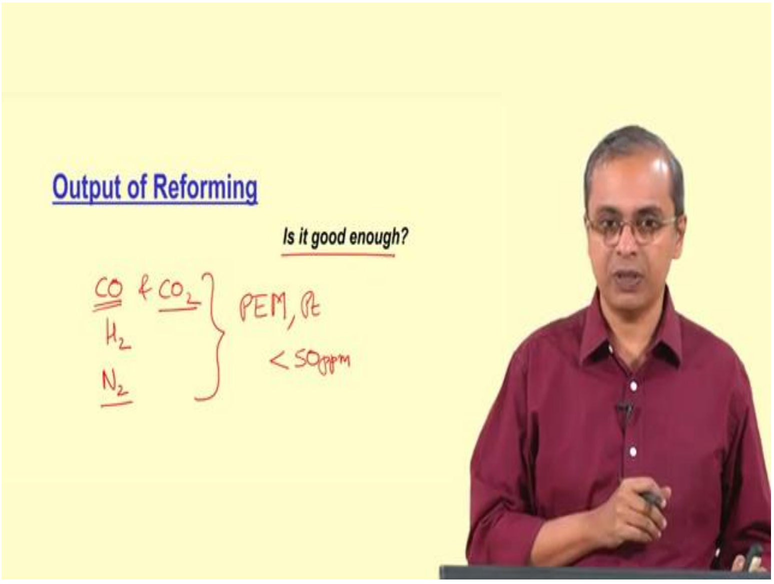

So, what is the output of this reforming process? So, as I said you have typically carbon based oxide. So, let's just say CO and CO_2 and you have hydrogen and you have nitrogen. Largely this is what you are looking at as the output from the reformer. Now, the question is it good enough ok? So, that is a question that is for which the answer really depends on what fuel cell is this output going to ok. So, so that is very dependent on that, based on that this itself may be good enough ok.

But in many cases let's say a typical PEM fuel cell, if you send this into a PEM fuel cell which is the one that as I said you know you have solid oxide fuel cells or PEM fuel cells being actively looked at for you know deployment of this fuel cell technology. In a PEM fuel cell which is what would be typically looked at for automotive sector. This is not this kind of a mix of gases needs to be looked at carefully to understand whether it is acceptable or not. Most specifically since it operates less than 100 degree C the CO is an issue, carbon monoxide is an issue. Issue to what degree? Even even if you have you know say 1 percent carbon monoxide it will completely kill the operation of the cell, kill meaning it will completely stop the operation of the cell within minutes of the cell starting.

Basically what it does is the carbon monoxide goes and sits on the catalyst sites platinum is the catalyst, that is being used in the in the PEM fuel cell let's say typically platinum or some other catalyst also may be there. Typically when platinum is used the the carbon monoxide goes and sits on top of the platinum and does not leave the site of the platinum. So, every location of platinum that it sits on it blocks the hydrogen from reaching the platinum site and then as even if you have 1 percent CO in the fuel stream in a matter of minutes it will completely block all the platinum sites that are available in the within the fuel cell and then the hydrogen will be sort of you know uselessly traveling through the fuel cell it will not undergo any reaction. It will also come to the surface of the fuel cell, it will find all sides are blocked and simply go out the exit. So, it will come in and go out without getting utilized. If it doesn't get utilized you do not get any current. So, that is the problem.

So, CO is a issue. So, as opposed to something like a percent or so that will come out as on the exit side of the reformer the fuel cell itself can tolerate only ppm of several let's say less than less than say 50 ppm ppm be parts per million. So, you should have a fuel stream that has less than 50 parts per million of CO for the fuel cell to tolerate it whereas, what is coming off the reformer is typically 1, like 1 or 2 percent of CO. So, you may have something like that maybe half a percent, 1 percent something like some reasonably large quantity which is distinctly larger than this 50 ppm that I am mentioning ok.

So, therefore, you need to do something to this exit stream. You have to further process this exit stream before it can go into the fuel cell, you cannot just directly put this into the fuel cell. These other gases CO_2 and nitrogen basically end up diluting the gas I spoke about partial pressure and that is exactly what happens here. So, if you end up with a stream that is say 40 percent hydrogen and say 20 percent CO_2 and another 40 percent nitrogen something like that, then 60 percent of the gas that is present there which is nitrogen and carbon dioxide are useless with respect to the fuel cell. So, 60 percent of the gas that goes into the fuel cell actually does nothing it just goes in and it comes out ok, and and it basically dilutes the 40 percent hydrogen that is going in and. So, in terms of you know statistically the hydrogen reaching the catalyst site these other gases are getting in the way. So, basically that’s the issue here.

So, they just get in the way and you know eventually you still have to use the hydrogen you find a way to use the hydrogen, but basically these are acting as diluting the gas stream and then that naturally affects the you know voltage current characteristics of the fuel cell. But generally speaking nitrogen and carbon dioxide are not you know poisonous from the perspective of a proton exchange membrane fuel cell. I told you that CO_2 is not good for an alkaline fuel cell, but in this case it is for a proton exchange membrane fuel cell it is not an issue, CO_2 is not an issue, nitrogen is not an issue it generally goes through without any impact on the fuel cell. So, these to act as diluting agents, but they don’t make any other impact CO is the one that you have to deal with much more carefully because it would poison the fuel cell and stop the fuel cell from operation.

So, more generally it is not good enough. The output of the reforming process is not good enough to be directly used in the fuel cell. So, you have to do something more to the output to make it usable in the fuel cell.

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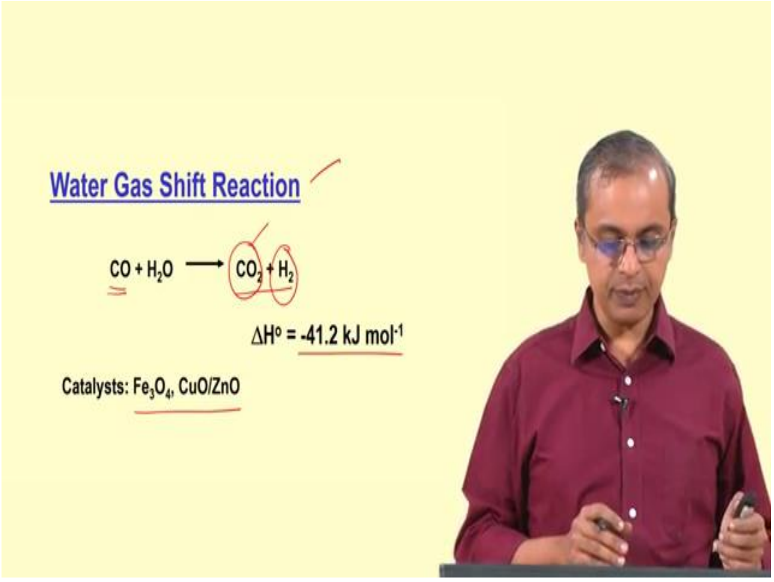

So, what we do is we enable you know two, other two more processes are often made available in a fuel cell reforming you know set up which then helps you to do cleaning of the gas stream cleaning from the perspective of reducing the CO content. So, one is called a water gas shift reaction which is what we have put here a water gas shift reaction which basically takes CO and gives it an opportunity to react with water moisture in this case and then that converts that to CO_2 plus hydrogen.

And interestingly this means that when you do the water gas shift reaction you are actually getting a little bit more hydrogen into your stream. So, this is a very welcomed reaction to have in your system. So, if you encourage this to happen and this is also slightly exothermic you get some you know exothermic reaction that's going on here. So, so it is something that you know without having to put in some energy you can get this process running.

And it does require some catalyst. So, typically you know Fe_3O_4 , copper oxide, zinc oxide etcetera is a catalyst that is used for this process and you take steam you take water you get them to react you get hydrogen and carbon dioxide. So, now, what has happened is you have slightly increased the amount of hydrogen that is present and you have taken CO and converted that to CO_2. So, CO as I said is poisonous for the fuel cell, but CO_2 is actually basically a dilutant that is it doesn't affect the fuel cell in any way. So, this poisoning process has now been stopped.

So, using this reaction you can drop from you know percentage down to you know several ppm kind of range. So, this is one way in which you can enable this drop of amount of carbon monoxide that is present in the fuel cell.

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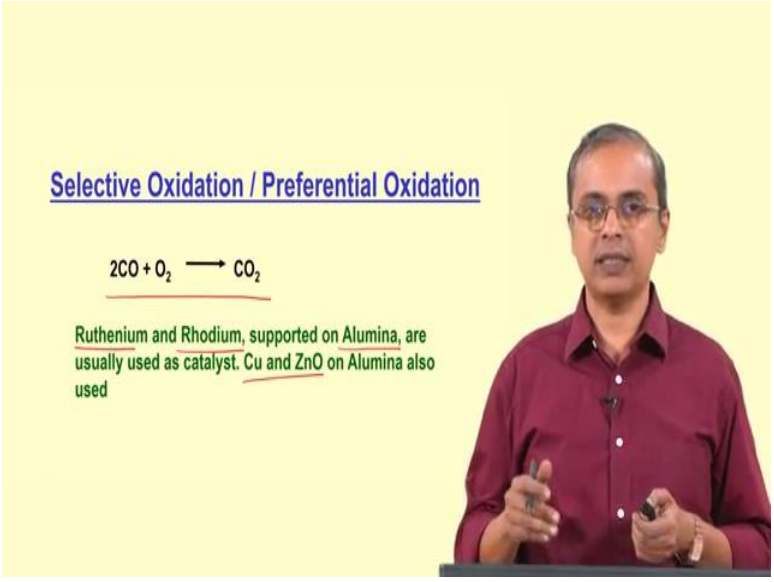

The other way in which you could do it is called selective oxidation or preferential oxidation and they are also you take CO and then you mix it with oxygen and then you get CO_2. So, you are sort of oxidizing the CO to get CO_2 and that again convert CO to CO_2 and therefore, what was previously poisonous to the fuel cell is no longer poisonous to the fuel cell. But you have to be careful. So, when you introduce oxygen into the stream it is not going to work selectively only on the carbon monoxide, it may react with the hydrogen too, right. In fact, it is a statistical process you are providing some carbon monoxide you are providing some hydrogen and in fact, you are providing a lot of hydrogen you 40 percent of the stream is already hydrogen and you have you know let's say 1 percent CO sitting somewhere.

So, now, when you introduce oxygen it has you know 40 times more a chance that it will find hydrogen then it will find the CO. So, you are going to waste some fuel also in this process. It's not going to be that you know you will only remove the CO you will you will go it wastes some fuel some hydrogen is going to get wasted in this process and so you have to look at this a little bit carefully, but it is done it is necessary in some ways because you have to really get this CO off the system and so we do have this selective oxidation or partial oxidation, preferential oxidation so to speak being done to take care of this activity. And you do need some catalysts to enable this and so usually ruthenium or rhodium are used and they are supported on alumina this supporting process is something which basically ensures that the catalyst is nicely dispersed and it does not you know collect at one location, but gives you a much wider area.

You can also use copper and zinc oxide, also on alumina and so you have some options there on what can be done and so when you do all this you get this process. So, you now, get a stream from the reformer, that has then been analyzed and then we understood that there is you know it is a step in the right direction, but not a completely solved issue you still have some cleaning that you have to do and so we are now, done some cleaning. And hopefully at this point we have a stream that is distinctly cleaner and also acceptable to the proton exchange membrane fuel cell.

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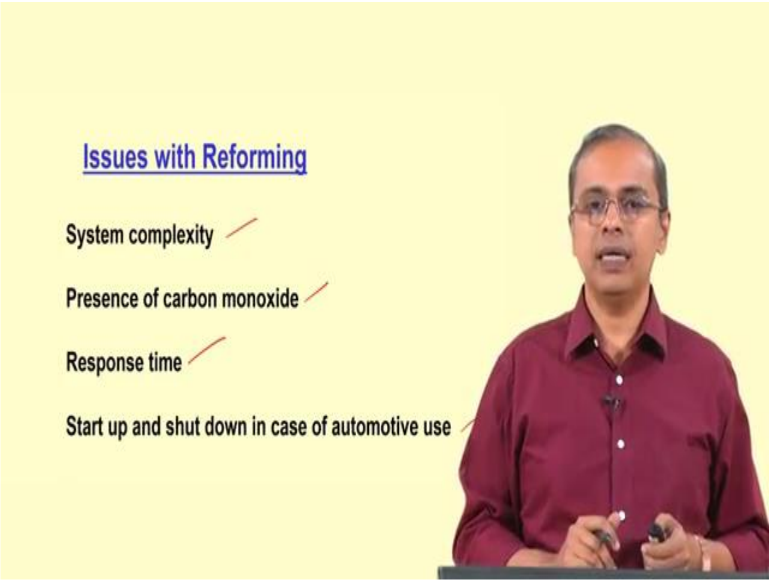

So, having come this far it is interesting to actually take a moment to look at some issues associated with the reforming process.

The first is the system complexity. See ultimately if you want any technology to you know become prevalent in large scale, across you know wide range of uses across various locations in the world system complexity is a very important parameter to look at. The more complex the system is there is more there is a greater likelihood that some part of the system will fail and when some part of the system fails you need a service engineer to visit the site and set it right. So, generally speaking it the expenses associated with the system, the inconvenience are associated with the system, all of those go up when you have highly complicated systems which are represented. I mean it turns out that you know with the advances of science and engineering we are able to get by with lot of complicated systems we use you know sophisticated aeroplanes, we use automobiles that are highly sophisticated they are quite complicated systems.

So, there is nothing that says that you cannot have a complicated system, but if you step back and look at the options available, if you have a simpler system versus a complicated system that does a particular activity any industrial process will tend to prefer the simpler system. So, that is one thing that we have to keep in mind. And so when you put in a reformer when you say that you know directly I cannot send this fuel into the fuel cell I need to put in a reformer. Once you take that kind of a decision the just that decision has distinctly increased the complexity of your fuel cell fuel cell system. So, reforming does improve the sorry does increase the complexity associated with the fuel cell system.

As I told you there is carbon monoxide. So, you you have to do cleaning you and which is what we discussed we have a process by which we have to clean the fuel cells stream and create a much cleaner stream which can then go into the fuel cell, and so we have to do something, and we are doing something to deal with the carbon monoxide that is coming off the stream with the through the reformer. And even then we are not completely done with the carbon monoxide we just drop it to several ppm because beyond that it becomes difficult the more you try to push it down towards 0, more energy, and time and complexity you will start putting into the system just to keep moving it lower and lower and lower and you know content. So, you stop somewhere and you make some you know accommodation for it and you handle it and go.

People do look at catalysts that are more tolerant to CO which don’t you know which don’t hold on to the CO that strongly and so there is a lot of research that goes on, on that as well. So, to look at catalysts that do not care as much about CO and therefore, you can send in the stream directly.

There is another very critical performance parameter that you have to look at when you are looking at this as a system that is being deployed in say automobile or in a house. So, when you come to your house let’s say in your house you come in, I mean let’s say the house has been sitting idle you have gone out to work you come home may be let us say at 6 pm you have come into your home. You come home and you start switching on lights, you switch on a lot of lights, you switch on let's say the air conditioner, you switch on the television, and then let's say you want to get something to eat, you may be put on a microwave oven or something. Let's assume that all the activities you are doing in start switching on various electrical devices.

So, suddenly the power demand that you are placing on the source of power is going up ok. So, whereas, previously it was just using say a few 100 watts to some base power you know powering your refrigerator quietly or something it was running suddenly you come and turn on a whole bunch of things you maybe you turn on even your washing machine etcetera, and suddenly you climbed up from few 100 watts to let's say 2 kilowatts of power you say just to give you an example ok. So, you have gone up you know an order of magnitude in power usage suddenly. And this change has happened in the matter of let's say couple of minutes you walk in and you just start flipping up this is a flipping on the switches at different different places you switch on the TV, you just quickly walk into the kitchen you turn something on, you turn on your washing machine in a couple of minutes suddenly you have changed to the complete power demand on the power source in your house.

Now, if a fuel cell system is the only thing that is powering your house the fuel cell system should suddenly ramp up in power, for it to ramp up in power everything going into the fuel cell should get ramped up. So, if suddenly you have increased the power demand on the fuel cell by a factor of I mean one order of magnitude by a factor of 10, 10 times more fuel has to go into the fuel cell, 10 times more air or oxygen has to go into the fuel cell. For the air or oxygen to go into the fuel cell by for that to go up by a factor of 10 is actually quite easy because you usually just have a blower, blower is you know a different form of a fan you can think of it as a different form of fan and that just blows more air into the you just you know you just change the power setting on it suddenly it just blows 10 times more air into fuel cell system. So, that is very quick.

But the reformer on the other hand may take several minutes ok. So, it may take several minutes for it to suddenly go from whatever was the previous setting to a value that is you know 10 times as high ok, as an output ok. You can send sender suddenly you can increase the input, but it still takes some time to do all the processing and then send you an output that is you know now, 10 times higher. So, the response time of your power supply power source is actually much less its much I am sorry much longer and therefore, its much slower the response time then what you can do by just coming in and turning on switches. So, if this were the only thing that is powering your house you will have a problem, you cannot just turn things on, if you turn things on your circuit breaker will go it will just say no not possible and then only some 10 minutes later it will allow you to do that, right.

So, that is why in many fuel cell systems they actually have some other way in which they can augment the power supply for those critical few minutes during which there is a transition in power ok. So, the response time of the fuel cell system is an important parameter that you have to look at, either you have to use grid power or something more that you have stored in a battery which you throw in into the system for several minutes till everything stabilizes and then you run. So, it adds to the system complexity and it comes from this basic concept then there is a response time, associated with the system and to the extent that you have put a fuel processor or a reformer in the system the response time has now gone up and therefore, the system is a lot slower.

And then finally, there is this issue of startup and shutdown. So, startup and shutdown also sort of are associated with this response time because when you start up suddenly from a cold start when you start up; suddenly lot of gasses to enter all the reformer locations in the reformer get reformed get ready get into the fuel cell and start. And we being who we are we want the vehicle to start immediately, you don’t want to get into the vehicle and then switch it on and then sit there for about 5 minutes before the engine warms up and then you know it’s ready, and it says yes, I am ready to move.

I mean maybe we do that in winter time in some countries where you know it is so cold that you have to get the engine to warm up a little bit, but generally we are all impatient because we have so many busy, I mean we have very busy lifestyles, we have so many other things to deal with we want the instrument to respond to us instantaneously. We just get in you want to switch on and keep moving, you just want to backup your back you vehicle a lot of wherever you are parked it get it out of the parking space and move you don’t want you do not have 5 minutes for that. So, startup and shutdown is has to be really fast.

And when you have a reformer or a fuel processor in line it slows down this whole startup process and when you shut down also there is still gas sitting in the system you have to figure out what you want to do with it I mean how we want to handle it. Some, some gas will be there the system it is not just a valve that suddenly shuts off there is something there you got to figure out what you want to do with it. So, these are some issues that you have to deal with when you are looking at a reform.

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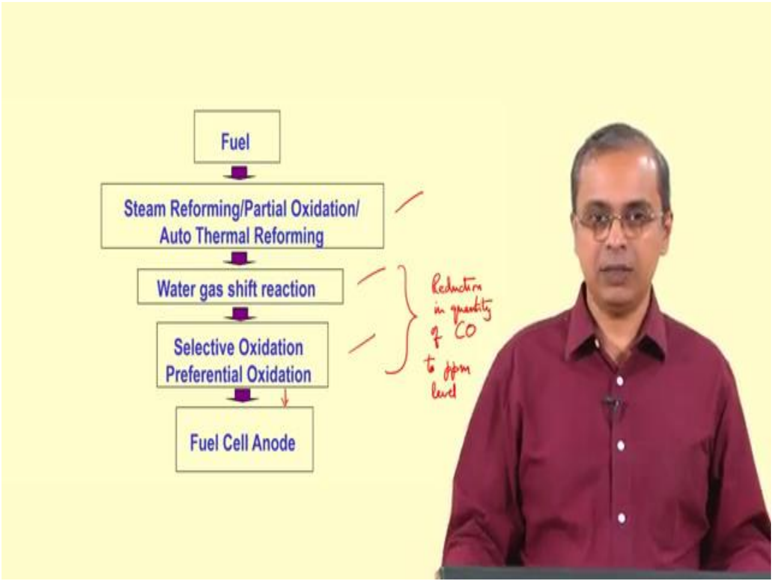

So, to sum up what we saw here is that you take you have fuel that has to go in a fuel and oxygen that goes into a fuel cell system for us to generate power. Generally speaking the fuel is what is easily available to us in many situations it is not a fuel that can directly go into a fuel cell and therefore, there is a need for this fuel cell I mean fuel to be reformed or processed as a fuel cell processing is a necessary step. Simply, because of the availability of the types of fuel that are available and the idea that you don't want to complicate things by demanding only one particular type of fuel to be made available.

And so a fuel processing the fuel is now, an integral step that we have to accept and then we have to deal with. And to do that, so we have to either do steam reforming or partial oxidation and more slightly we would do an auto thermal reforming which would then you know make it such that it is a self contained system with or with less complexity you will have the reforming process occurring without having to worry too much about the heat transfer etcetera that is involved.

What comes out of this reforming process is not something that is directly usable, because primarily because of the carbon monoxide that is present and therefore, we do the water gas shift reaction. And often we follow that up with another reaction step which is either referred to as self selective oxidation or preferential oxidation. Both of these are focused on reduction of CO, reduction in quantity of CO to ppm level. So, that is the critical thing to drop it to the ppm level not from not in the percentage level. You could have it in percentage level coming off the reformer that's not acceptable you have to drop it into the ppm level, and once you do that you can send that into the anode, which is basically what we would do.

So, to sum up this is the basic idea of fuel processing from the perspective of a fuel cell, certainly from the perspective of a proton exchange membrane fuel cell. As I said these are this is what why it is needed because of the type of fuels that are available. We have discussed the various steps involved in the fuel processing activity, and we have also looked at some of the issues associated with this fuel cell processing activity. And you have to sort of embrace the idea that this is necessary and be aware that it is going to be part of the overall fuel cell you know deployment process, and sort of you know mentally be prepared for it technologically be prepared for it and address it accordingly. So, so this is the overall process.

So, with this we will halt this discussion on the fuel processing. And we will look at other aspects associated with the fuel cell.

Thank you.

KEYWORDS:

Reforming of Fuel; Processing of Fuel; Load Bank; Relative Humidity; Reformer; Power Conditioner; Steam Reforming; Partial Oxidation of the Fuel; Auto Thermal Refining, Rifts; Reforming Autothermal Reforming; Water Gas Shift Reaction; Selective Oxidation; Preferential Oxidation

LECTURE:

The fuel fed into Fuel cell Technology needs some processing to increase the percentage of Hydrogen content in the fuel and to further reduce the impurities present in them which will either poison the catalyst or dilute the Hydrogen fuel. The methods used for processing the fuel to make it Hydrogen rich are discussed. The techniques followed to reduce the CO content which poisons the catalyst are elaborated. The feasibility of such processes in the perspective of Fuel cells specifically SOFC & PEMFC are detailed.