Advanced Ceramics for Strategic Applications

Prof. H. S. Maiti
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

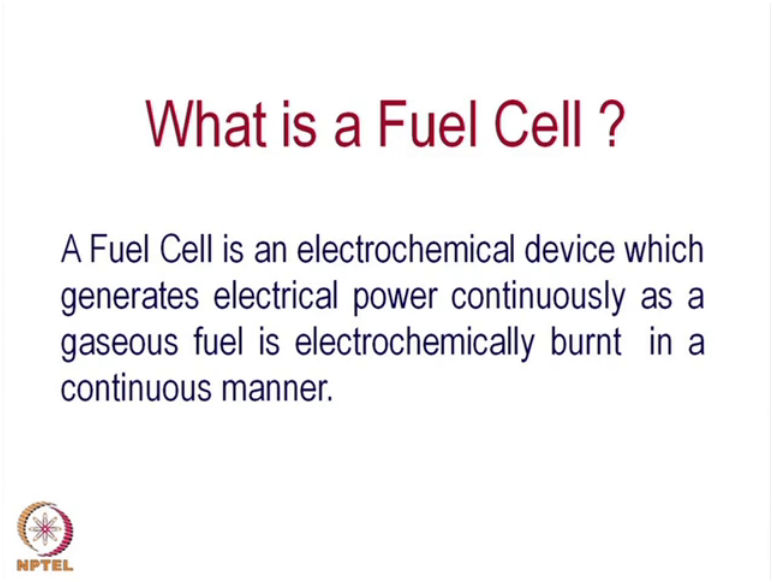
Lecture - 28
Solid Oxide Fuel Cell

Today's topic is fuel cell; in particular the solid oxide fuel cell, which is supposed to be sorry, which is supposed to be the all ceramic fuel cell and a very important area of application or advance ceramics. It is in the energy sector, environment in energy sector and let us try to discuss the materials used, the principal. And, why this particular topic is so important to us?

(Refer Slide Time: 00:55)

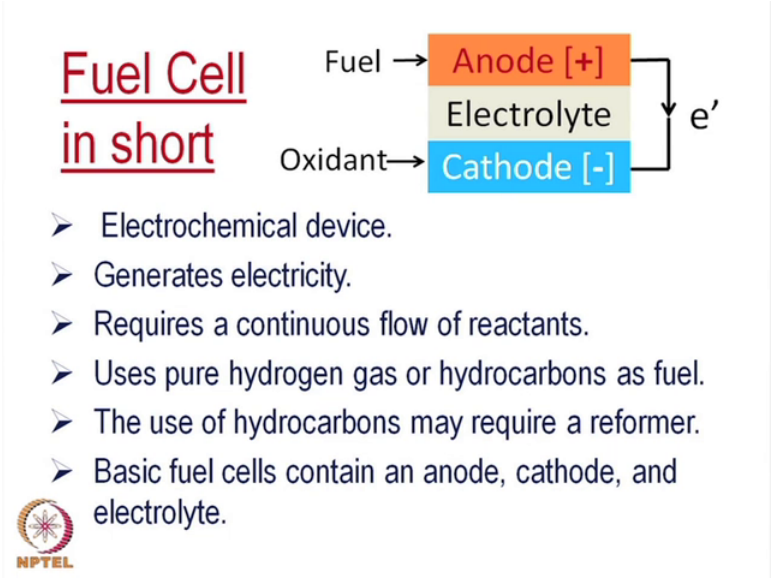
So, we will be discussing the solid oxide fuel cell.

(Refer Slide Time: 01:02)



And, first of all we must know what is a fuel cell? That is quite obvious; the fuel cell is an electrochemical cell is an electrochemical device which generates electrical power continuously as a gaseous fuel is electrochemically burnt in a continuous manner. So, as the name suggest there is a fuel which is burnt; not normally burnt, it has its own value no doubt. But it is burnt in an electrochemical system. And, therefore it is generating a power, generating a voltage. And, of course you can also draw some current through this. So, it becomes a power system or a conversion device; energy conversion device, from the fuel energy to the electrical power. So, that is what we know about fuel cell.

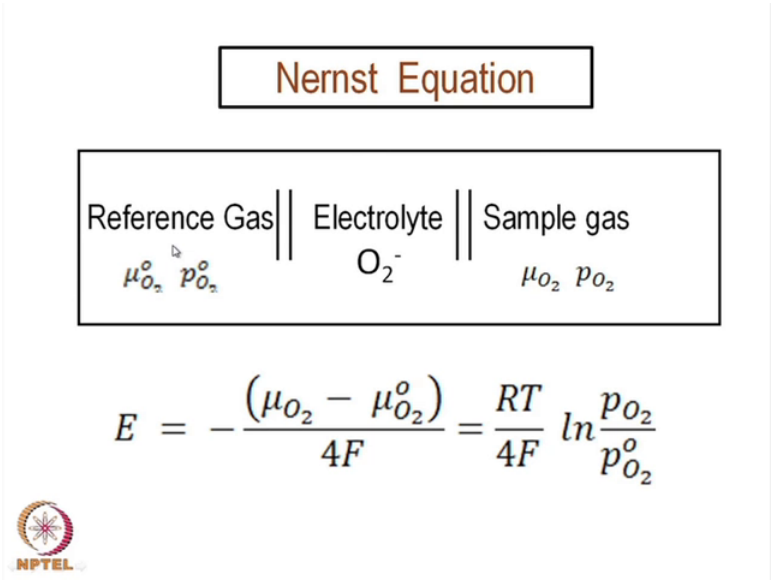
(Refer Slide Time: 02:03)



In short, what are the characteristics of fuel cell as has been mentioned? It is an electrochemical device, generates electricity, and requires a continuous flow of reactants. As we have mentioned we will have a fuel and that will be oxidized that will be burnt electrochemically. So, 2 reactants are necessary; one is a fuel a gaseous fuel, of course, not a solid fuel in this case. It can only take up gaseous fuels and a oxidant normally air; uses pure hydrogen gas or hydrocarbons as the fuel. So, depending on the particular type of variety of fuel cell, it may use hydrogen or hydrocarbons; which can be burnt electrochemically.

The use of hydrocarbons may requires a reformer. Ultimately the hydrocarbon has to be catalyzed or it has to dissociate into a mixture of hydrogen and carbon monoxide or some other hydrocarbon. So, that part is done by a s device called reformer. So, when although hydrocarbons can be used in principle, but ultimately it has to be converted into hydrogen for certain variety of fuel cells. But in other variety one can also use carbon monoxide. Basic fuel cells contain an anode, cathode and electrolyte as shown here; as that is mentioned it is electrochemical cell. So, we have to have a anode and electrolyte and a cathode.

(Refer Slide Time: 04:01)

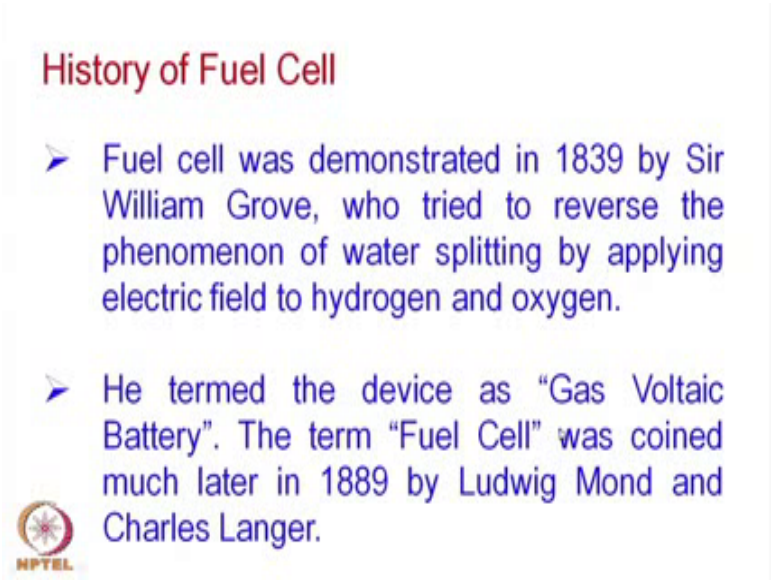


Well, we have discussed earlier, the principal of a oxygen ion conductor and measurement of oxygen partial pressure. So, the same principle applies when you talk about solid oxide fuel cell. In particular we will be discussing few other fuel cells, but

this principle or the Nernst equation. In this case it is basically applies to the solid oxide fuel cell, but very similar thing also apply to other fuel cells. So, the same equation you have a electrolyte in between incidentally it is an oxygen ion conductor here. And, you have partial pressure, one partial pressure other side or the chemical potential of the oxygen and different chemical potential on the other side. And, therefore, you will an E M F.

So, this was used in connection with the oxygen sensor using a zirconium dioxide. The basic principle is same so instead of just measuring the open circuit e m f; we can draw some current through that and that is was the called fuel cell. So, we can use the same thing as a source of power.

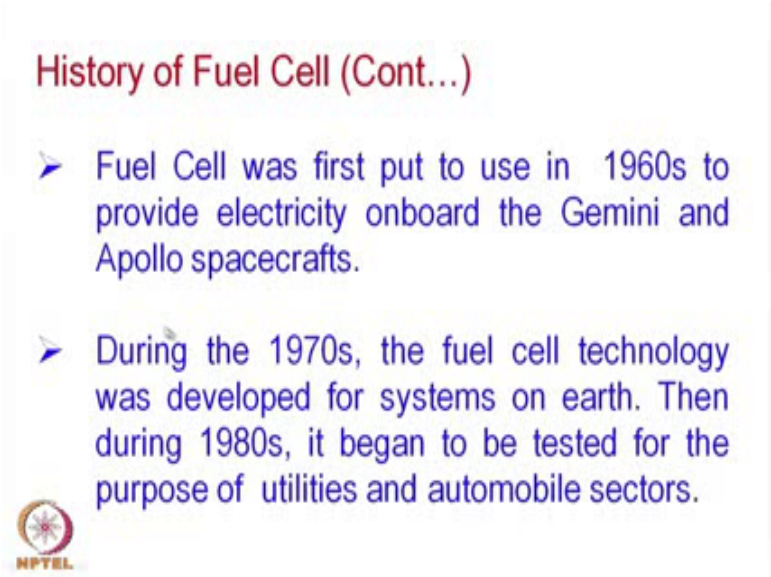
(Refer Slide Time: 05:21)



Well, we can have a look at it. The history of fuel cell it is not a very recent concept, the concept is as old as 150 years old. And, the fuel cell was first demonstrated in 1839 by Sir. William Grove, who tried to reverse the phenomena of water splitting by applying electric field and to generate hydrogen and oxygen. So, by that time the splitting water was known. And, Sir. William Grove tried to think if by supplying electricity one can generate hydrogen and oxygen is it possible to reverse the reaction. And, combine hydrogen and oxygen to get the electricity that was his idea and that is actually was successful in doing that.

He termed the device as Gas Voltaic Battery. So, by the time basically he was working on battery. So, he termed it as gas voltaic battery, but the term fuel cell was quiet much later in 1889 by Ludwig Monde and Charles Langer.

(Refer Slide Time 06:46)

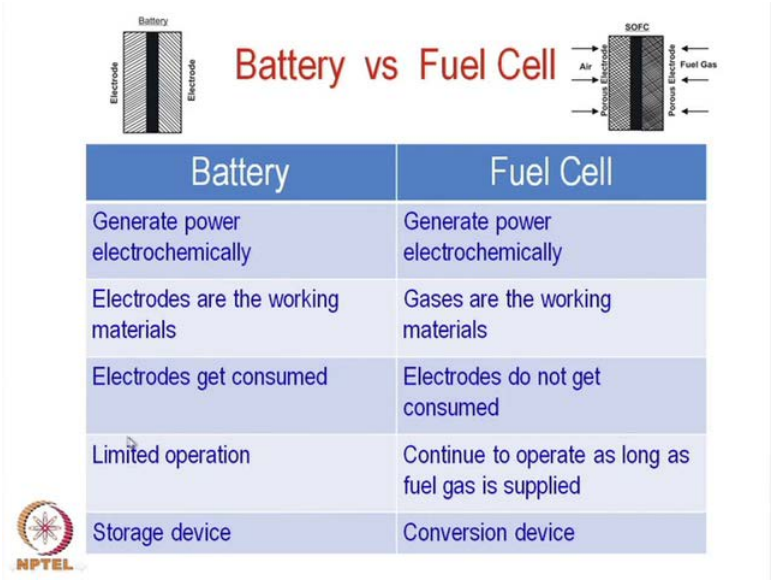


So, that was 1 part of the history and then fuel cell was first put to use in 60s. The last century 1960s to provide electricity on board the Gemini and Apollo spacecrafts. So, one of the reasons why fuel cell was used because it is power to weight ratio is very high. So, you can from the same wet per unit wet one can generate much long much larger electrical power. And, therefore one can use this on a spacecrafts where the weight is at important criteria. During the 1970s the fuel cell technology was developed for systems on earth. Looking at the success of the space mission Gemini and Apollo spacecraft missions people found that hears the technology can it be used on the on earth also for our own purposes. Because there is a shortage of fossil fuels and whether it can be an alternative source of fuel alternative source of energy.

So, that was first time in 1970's people started developing a commercial way. Of course the commercialization still to be achieved, but a very strong research activity went team for developing power systems based on fuel cells. Then, during 1980s it began to be tested for the purpose of utilities and automobile sector particularly. Because the idea of running an automobile with electrical power or a battery power was still on, but it was not successful.

Because the power to weight ratio of normal lead acid batteries are very high or very low. So, it was not very commercially successful. So, with the research activities or the development of fuel cell 1 could think that a captive power stations; either a captive power station or a automobile can be run with this kind of power systems.

(Refer Slide Time: 09:11)



So, that is the history still research is going on in very very active manner and, but it is a power source basically. So, another kind of power source as mentioned is battery. The battery is also, source of power electrical power in a small way. And, fuel cell is also a very identical or a analogous way one can generate power from the fuel cell as well. So, can we have a look at what are the differences between a battery; it is not actually a battery, it is a different kind of power system. And, these are the characteristics of the battery as well as fuel cell. Battery generates power electrochemically in fact both of them generates power electrochemically both of them electrochemical cells.

Electrodes in battery are working materials whereas, working materials in the sense the electrode itself is a actually source of the energy. So, the certain amount of certain chemicals or metals are used as the electrodes here. Whereas, in case of fuel cell 1 cannot do that because basically the reactants are gases. So, gases as such cannot be used as a current collector or contacts. So, one needs a different kind other materials. So, the gases are the working electrodes, working materials.

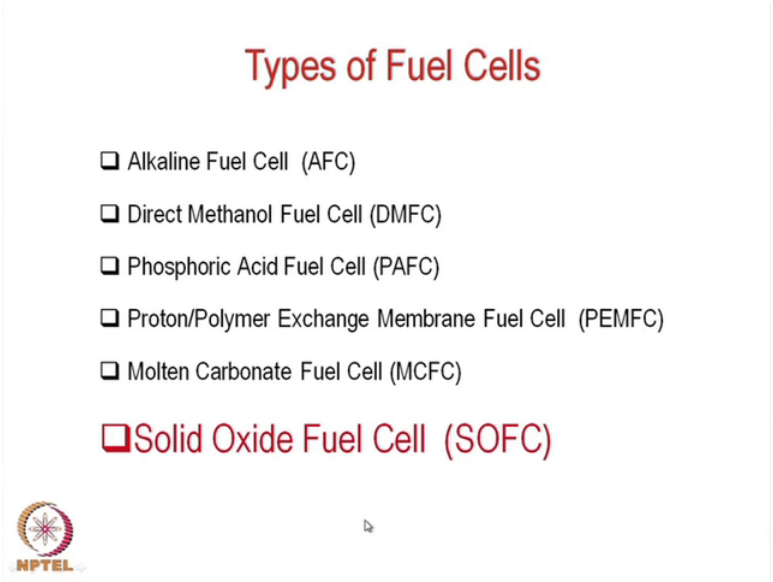
And, therefore we need an additional set of materials to act as a electrical contacts or current collectors. In case of battery electrodes get consumed whereas, in case of fuel cell the electrodes do not get consumed. If you assume that the reactants the hydrogen or the fuel as well as the oxidant are actually the electrodes they do not get consumed sorry it is not like that the electrodes are actually the contacts. Here, it is said the electrodes are the contacts. So, the contacts do not get consumed it is the reactants; the fuel and the oxidant which gets consumed to the continuous manner.

The basic electrodes remains same electrodes in the sense here we are talking about the contacts and the current collectors, limited operation because as long as particularly in a battery, as long as the chemicals are available. It will produce power once the chemicals are consumed and converted to a different kind of products then the source of power is lost. So, the power will not be available any more. In case of fuel cell 1 can get continuously generate power as long as one can supply; the fuel and the oxidant on 2 sides of the fuel cell.

So, 1 becomes a cathode another becomes the anode. So, one can say here you have supplying air from 1 side and the gas from the other side; and this is the system in which the power is getting generate. So, this is 1 electrode and that is 1 electrode, but the actual the working electrodes are actually the air and the oxygen or the fuels hydrogen or carbon monoxide. It basically a battery is basically a storage device. It is stores energy chemical potential and the chemical energy and which can be converted 1 side into a electrical power.

Whereas this is a conversion device is basically a conversion device it does not store the power. Because the chemicals the source of energy is outside the system whereas, in battery the source of energy within the system. So, that is the differences between the battery and a fuel cell although both of them are basically an electrochemical devices.

(Refer Slide Time: 13:27)



Well, based on these principles we have several types of fuel cells. They are termed in this manner Alkaline Fuel Cell, Direct Methanol Fuel Cell. That primarily depends on either the electrolyte kind of electrolyte used or the kind of fuel 1 use in this cells or a Phosphoric Acid Fuel Cell.

They are in the short term the terminology is AFC, DMFC, PAFC or proton or Polymer Exchange Membrane Fuel Cell Polymer Exchange Membrane Fuel Cell is PEMFC, Molten Carbonate Fuel Cell. And, finally the topic of our interest as ceramists are under the course of advanced ceramics. Our primary interest is here Solid Oxide Fuel Cell I will give you some characteristics of this. The this particular 1 is called alkaline fuel cell because it alkali some form of alkali, liquid alkali is actually the electrolyte here. That is why it is called Alkaline Fuel Cell. The Direct Methanol Fuel Cell although we have been talking about in the other cases it is the hydrogen; the fuel is hydrogen or carbon monoxide or the mixture of them, but methanol methanol can also be directly oxidizes in some of the fuel cell and 1 can get energy out of it.

So, because the fuel is methanol. So, it is methanol fuel cell, direct methanol fuel cell not hydrogen or gaseous fuel cell; it is actually a liquid fuel cell. A phosphoric acid fuel cell has been termed because once again the electrolyte just like here alkali is the electrolyte, here acid is an electrolyte. So, phosphoric acid is used as the electrolyte here. And,

obviously the charge carriers here is the hydroxylamine whereas, the charge carrier here is the hydrogen.

And, so this is a liquid liquid acid which becomes the electrolyte here. Proton or the polymer exchange membrane fuel cell just like phosphoric acid fuel cell. Here, is also a hydrogen ion conductor, but this is not in the liquid form. This is a polymer a particular polymer which is having a sufficient amount of hydrogen ion conductivity and that is used as the electrolyte. So, here compared to phosphoric acid this is a solid electrolyte, but both of them the conduct in species or the charge carrier is basically hydrogen ion. So, the protons are the basic charge carriers and one can make membranes impact the electrolyte in this case is called the membrane.

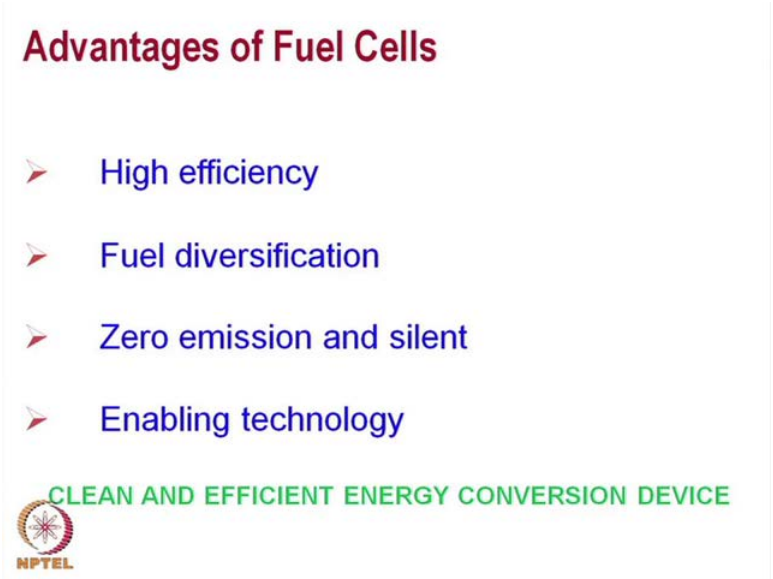
Because it preferentially allow hydrogen ion to pass through. Then, there is a another type of fuel cell where electrolyte is once again liquid, but at a sufficiently high-temperature is fairly high-temperature about 600 to 800 centigrade. So, this is a carbonate liquid, carbonates and that carbonate ion is the charge carrying species. And, this is a high-temperature a moderate temperature you can say moderate temperature fuel cell were molten carbonates are normally used as the electrolyte.

The operating temperatures of these at different temperatures. This is small as room temperature this are again slightly above room temperature I will see give you some temperature range. But they operate at different temperature ranges and solid oxide fuel cell is once again a all solid state all solid state device where the electrolyte is a solid, the electrodes are also solid and the fuel is only gas. So, the fuel is either hydrogen carbon monoxide or some hydrocarbons like natural gas mixture of hydrocarbons like natural gas and so on. It can be used quite easily 1 of the reason is it operates at a fairly high temperature.

The originally it used to operate 900 to 1000 degree centigrade primarily because the electrolyte zirconium; does not have very high ionic conductivity or the overall conductivity is relatively low. So, sufficient conductivity is a obtained only at high temperature. So, that is the reason this is the kind of operating temperature highest among all the fuel cells listed here. Of course there is a tendency to or the research is going on to reduced operating temperature will see look at it. So, this is a all solid state fuel cell and the all ceramic fuel cell. So, all the components are ceramic components

and they must withstand fairly high-temperatures. So, our topic of discussion is primarily concentrated will be concentrated on the solid oxide fuel cell.

(Refer Slide Time: 19:28)



Well, advantages of fuel cells in general are as follows. High efficiency will explain; why it is high efficiency? The converse in efficiency the chemical to electrical energy conversion efficiencies is extremely high impact higher than any other system one can think of. Fuel diversification remains in some of the fuel cells not all. There are different kind of fuels can be used. Although they are all gaseous fuels except in DMFC all the gaseous fuels, but different kind either hydrocarbon hydrogen can be used, carbon monoxide can be used or a mixture of hydrogen and carbon monoxide or in some cases hydrocarbons can be directly fed into the system.

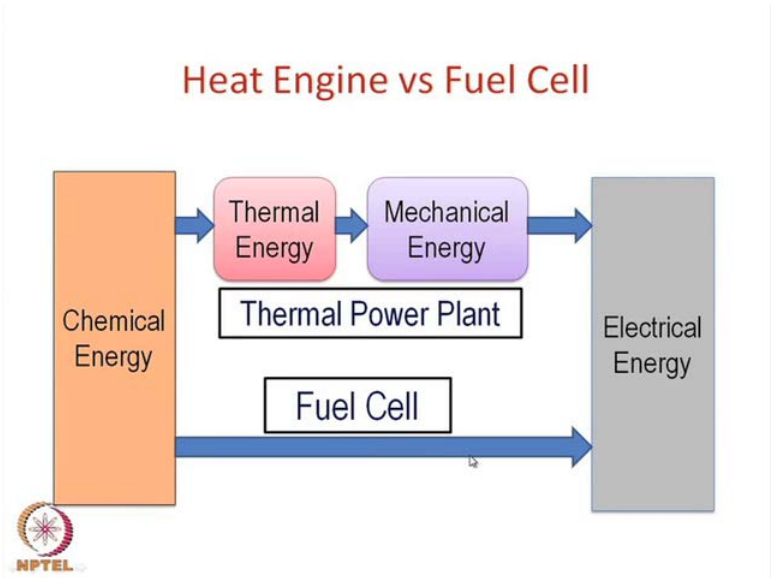
So, one can have different kind fuels, but the most important characteristics is its high efficiency. 0 emission and silent well compared to many other mechanical systems like generators; in gas generators and so on or steam generators. You do not have a moving part here. Your basic it is basically a stationary system except for gas supply and air supply you need some blowers so on or the otherwise the basic system is stationery. You do not have a moving part that is why it is also silent, but 0 emission that is another very important. Zero emission in the sense here we are basically talking about carbon dioxide emission provided of course provided of course 1 uses hydrogen as the fuel. Because how an hydrogen gets burnt it actually the products of combustion is nothing but H2O.

So, we do not generate a carbon monoxide or carbon dioxide that is 1 environmental issue other emission there is no particulates.

If you are talking about a thermal power plant where solid fuel is burnt. You generate huge amount of particulates particulate emission and that emission is not there this in case so you can say it is a 0 emission. So, it is a basically a clean energy system. It is a clean energy system environmentally (( )) system and those are the reasons. Why fuel cell research has become a very important and fascinating in these days? Enabling technology because it gives you some other technology. For example, fuel cell technology is also giving it to automobile research because how the fuel cells can be used in battery-operated or electric vehicles; electric vehicles is another area where fuel cell or that a independent on the fuel cell technology development.

So, these are some of the advantages where most important advantage it is high efficiency. That means, the conversion efficiency most of the chemical energy of the fuel is converted into electricity or electrical power well we do that. So, of course finally as I mention have explained that it is a clean and efficient energy conversion device. So, when you are talking about environmental pollution and also we are talking about the carbon economy to the hydrogen economy. That means, we have to burnt or generate less of carbon dioxide in the environment. This is the one of the techniques by which one can reduce carbon dioxide in the environment.

(Refer Slide Time: 23:35)

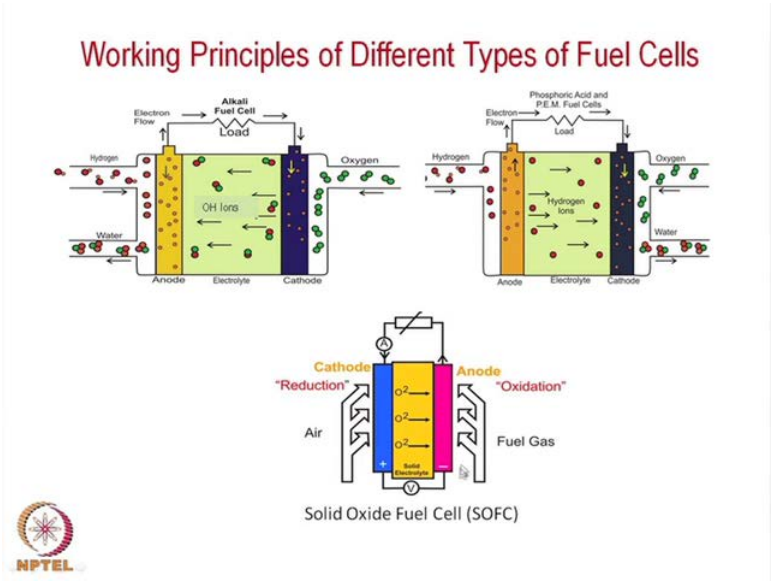


This is the reason why it is highly efficient system system of energy conversion. If you are talking about thermal power plant. Then, the chemical energy of the solid fuel; coal is first converted to thermal energy because it is normal burning to generates thermal energy. So, that thermal energy generates steam and that steam again goes to the steam turbine and generates electricity. So, it goes through a large number of conversion steps. So, directly chemical energy is not getting converted into the electrical energy. So, at each step there will be lot of loss.

And, therefore the overall efficiency is not very high. Only 30 to 35 percent of the chemical energy is basically converted to the electrical energy and 65 to 70 percent is actually lost. So, it is huge loss. So, for as when you are talking about the power generation; whereas, if you talk about a fuel cell it is an electrochemical conversion it is the 1 step process. So, it does not go through a multiple step. So, it is a 1 step process of chemical energy is directly getting converted to electrical energy. And, therefore the theoretically it is a very very efficient process.

So, of course there are will be losses for because of many other reasons, but in principal it is a 1 step process. And, therefore the conversion efficiency has to be very high. The electrical efficiency as such can be as high as 80 to 90 percent, but the overall plant efficiency depending on many other features; it can come down to about 40 to 50 percent. We look into that later on why such losses take place and where exactly we lose some the energy. But in principle it is very high compared to thermal power plant because both of them are basically looking at the energy generation.

(Refer slide Time: 25:56)



The conversion of chemical energy to the electrical energy. Well, these are some of the working principle of different types of fuel cells. To start with the alkaline fuel cell or alkali fuel cell basically you have 2 different compartments. 1 is the fuel compartment and the other is the oxidant compartment either it can be pure oxygen or mostly air. You have electrodes; this is 1 electrode and this is another electrode. So, this is an anode and this is a cathode. So, there is interfacial reactions and this is of course the electrolyte. So, this is the electrolyte some kind of alkali and that actually as OH ions which are mobile in this case. So, OH ion because it is a negatively charged.

So, it is actually takes the oxygen from this side and then it goes to the other side. And, then 1 can also look at from the other point of view a hydrogen here. Hydrogen actually combines with the OH, here oxygen is actually goes to the oxygen ion; and it takes up electron from here whereas, hydrogen gives the electron there. So, the electron goes to this and then this electron gives donates the oxygen atom. So, it becomes oxygen ion. So, and then hydroxyl ion moves to this and combines with hydrogen. So, and becomes no water. So, this the reaction or alkali fuel cells.

And, if you have hydrogen ion or hydrogen ion is conductor it moves to the opposite direction. And, then you have a electrolyte with may be a phosphoric acid fuel cell. A phosphoric acid has the electrolyte or as a I mentioned earlier a polymer. Incidentally it is a very commercially available particular very specific polymer having a very high

hydrogen ion conductivity which is called (( )). And, that is the most efficient hydrogen ion conductor so far as the solid polymers are concerned.

Then, this is their source of hydrogen and hydrogen gets ionized there. Then, it is become hydrogen ion it moves to this direction it combines with the oxygen on this side. And, it releases it takes up the electron from there and the electron moves in the outer circuit and hydrogen ion moves in the internal circuit. So, internally it is a charge carrier is a hydrogen and externally of course there is a electron flow. So, you can generate current and the load can be attached.

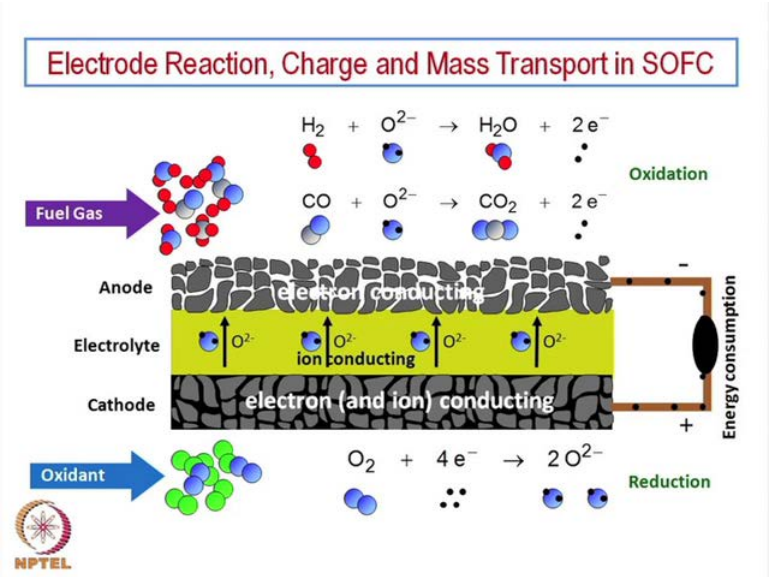
So, oxygen comes from one side, hydrogen comes from the other side and they combine electrochemically and ultimately water goes there. So, on this side hydrogen and water goes in the same side whereas, or this system oxygen and water is only on same side. So, hydrogen comes from the other side combines with oxygen and religious water has the product of combustion. Here, oxygen comes from other side and it combines with hydrogen and a water is released on the same side as the hydrogen.

So, there is a continuously flow of hydrogen here, there is a continuous flow hydrogen there also and on this side there is a continuous through flow oxygen. So, as long as these flows are maintain. You can generate electrons or you can generate current on the outer circuits and a load can be connected with that. The particular electron fuel cell which we are interested in is a solid oxide fuel cell. And, that is as a said it is all solid-state fuel cell everything is solid here an electrolyte is an oxygen ion conductor. This is an OH ion conductor, this is an hydrogen ion conductor and this is an oxygen ion conductor. So, because we are talking about a electrochemical system.

So, there may be possibilities of different electrolytes and according we choose the electrodes. So, this is hydroxyl ion, this is hydrogen ion and this an example of oxygen ion. So, oxygen ion is the conducting conduction is the electrolyte conducts oxygen ion. And, on this side you have anode this is a cathode on this side you supply air. And, here it is a reverse to this because this is hydrogen and this is oxygen. So, the cathode and anode will be different. So, here oxygen air is supplied to this and this is get ionized on this side. And, then oxygen moves there oxygen moves there and combines with the fuel may be hydrogen carbon monoxide.

So, once again the product of combustion is on the hydrogen fuel side and air comes from the other side. And, you produce a voltage here and this is the load on the external circuit. Otherwise the basic principle is same only thing they difference here is the mobile species or the charge species of the electrolyte is oxygen ion and there all solid-state. So, we will see what are the different materials we use for this kind of a system? But this is the basic principle by which one can generate electricity or power, electrical power from the chemical potential the chemical energy of the fuel of this fuel.

(Refer Slide Time: 32:56)



Well, referring to the solid oxide fuel cell will go the little details the electrode reaction, charge and mass transport in SOFC or Solid Oxide Fuel Cell. Now, once again this is the schematic of this cell. This is basically a what we call the electrode or the membrane electrode assembly. So, this is only a part of the main reaction side. The main reaction side where you have the cathode; you have a electrolyte and the anode all in the solid-state oxygen is moving. Now, cathode both cathode because you have a gaseous fuel and gaseous oxidant. So, the reaction electrochemical reaction or the charge transfer is basically taking place at this interface electrolyte electrode interface either the cathode electrolyte interface or the anode electrolyte interface.

So, the gaseous fuel or the gaseous oxidant as to come in contact with this interface. And, the triple phase boundary that means 1 is the cathode electrolyte and the gaseous and movement. So, these are the triple phase boundaries like this. These are the reaction

sites where this kind of reaction is taking place the oxygen because this is the oxidant side oxygen the cathode side. So, the oxygen plus 4 electrons give rise to 2 oxide o minus. So, at this interface this reaction is taking place. So, the reaction sides are very important higher is the reaction side, higher is the conversion and better is the current carrying capacity or the current generating capacity. So, more electrons will be generated and one can draw more and more current.

So it cannot be a it cannot be a completely dense material it has to be a porous material. So, that through the porous molecular deficiency takes place oxygen comes to this surface; then gets atomized and its gets the electron from this and gets ionized. So, once the oxygen gets ionized this material the electrolyte is an specifically an oxygen ion conductor. So, oxygen because there will be a potential difference there will be high oxygen potential on this side and there is a low oxygen potential because there is a fuel has a reducing condition low oxygen potential. So, from high oxygen potential there is a there is a kind of tendency of driving force impact.

A driving force will be there for the oxygen to move from this side to that side; from the higher oxygen potential on this side to the lower oxygen potential on this side. So, oxygen ion will move along the through the bulk of the electrolyte. Now, this can move because this electrolyte has been chosen in such a way that it has a very high oxygen ion conductivity, there is no electronic conductivity in this. So, the electrolytes can be used or electrolytes as per definition they will have only ionic conductivity and no electronic conductivity. And, so the oxygen ion move there and then it will combine with hydrogen in this manner hydrogen plus oxygen ion will generate water and then it will release electron.

The electron will flow from this side to this load to this side and this will continue. So, that is the kind of principle what we have discussed earlier also. The only thing we want to introduce here or had is both cathode and the anode as to be pores; has to be a porous material whereas, the electrolyte has to completely dense.

So, this is one of the major requirements of this kind of a system. The membrane electrolyte assembly 1 can say this compact there it can be called as a membrane electrolyte assembly. Membrane base basically electrolyte, membrane electrode assembly not electrolyte membrane electrode assembly membrane basically because it

has a semi permeability through only through oxygen no hydrogen can go through. No other gas can pass through only oxygen ion can pass through. So, it is basically acting as a membrane although physically it is a very dense material. This oxygen permeability is because of the oxygen vacancy. So, it is a lattice oxygen is going through there is no physical force. So, this electrolyte has to be completely dense.

So, that oxygen molecular oxygen definition is avoided molecules, oxygen molecule can should not pass through. And, then combined with hydrogen if that that becomes so then it is only a thermal combustion, it is not in the electrochemical combustion. So, electrical energy cannot be generated by that process. So, there should not be any porous or continuity of the force even if some small pore is there it has to be discontinuous or a interrupts force. So, this is 1 of the major requirements. So, for as the solid oxide fuel cell is concerned the both the cathode and the anode material has to be porous material whereas, the electrolyte has to be completely dense material. And, it has to be it because some such material is already available with us like zirconium oxide, zirconium dioxide.

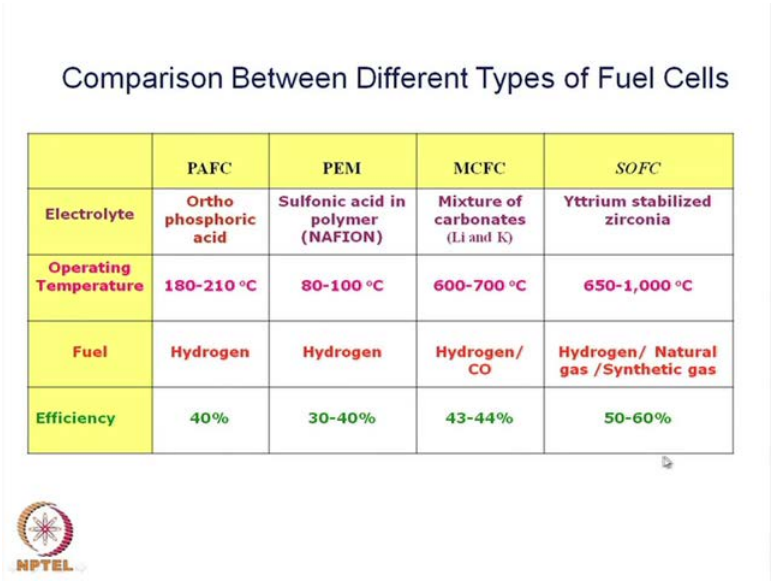
We have seen earlier calcium stabilized or it is yttrium stabilized zirconium dioxide can act as a very good oxygen and conductor. And, therefore, these are the materials 1 can use will come to that what are the different materials possible to use either as a cathode material or the anode material. In case of carbon monoxide this is again very similar reaction takes place. Instead of hydrogen 1 can have carbon monoxide and then high oxygen an carbon dioxide. So, it again releases to electrons here. So, whether it is the fuel is hydrogen or carbon monoxide or a mixture of them these are the oxidation reaction which is taking place on the anode side and there is a ionization of the oxygen ion on the cathode side.

So, there is a very high oxygen potential on the cathode side were are there is a low oxygen potential on the anode side. And, this is reducing highly reducing condition and these is highly oxidizing condition. So, these also another requirement of this electrolyte because on one side of the electrolyte is a very high oxygen and potential very high oxidizing condition. On the other side it is a very high reducing condition because hydrogen is highly highly reducing. This electrolyte must be thermodynamically stable both a oxygen high oxygen potential as well as low oxygen potential otherwise this material will get reduced or oxidized.

So, there will be non-stoichiometric set in because many of the oxides many of the oxides in presence of hydrogen can be reduced to corresponding metal. So, 1 has to choose a particular electrolyte which should not be reduced even in presence of hydrogen. A reducing gas like hydrogen should not reduce it is corresponding metal. And, that is also at a higher temperature normally many of the oxide will get reduced at a high-temperature in presence of hydrogen. But 1 is to choose a electrolyte in this case or solid oxide fuel cell to be successful are operating 1 is to choose a very stable oxide. Which is a stable not only highly oxidizing condition like pure oxygen or high reducing condition like your hydrogen.

So, this is once again a challenge, but fortunately fortunately we have that kind of material in the form of stabilize zirconium. Zirconium is a highly stable oxide it is melting point is very high and at the same time it is non stoichiometric is extremely low. That means, it does not get stable the that does not get oxidizes or reduced either in the presence of hydrogen or the presence of oxygen. So, it is that is how solid oxide fuel cell has been really a success. Success in the sense one can demonstrated at least in the large scale that is certain things happening commercial success is still to come. But many prototypes are available several kilowatts 100s of kilowatts of power can be generated from such systems.

(Refer Slide Time: 42:56)



Well, next comes, there are few comparisons, few in terms of the materials used, temperature operation, the kind of fuel one can use in different kind of fuel cell. We have already introduced few variety of fuel cells. So, these are some comparison between them. How, where exactly Solid Oxide Fuel Cell stands? Is it a good one, so bad one in this? Where exactly, how exactly it is compared with other systems of energy conversion like fuel cells? So, fuel cell is not unique that way, SOFC is not unique; there are many variety of fuel cells. So, one should have a comparison between them. This is PAFC the Phosphoric Acid Fuel Cell. This is Phosphoric Acid Fuel Cell, the electrolyte as I mention is the Ortho Phosphoric Acid.

Whereas, PEM that is the proton or Polymer Electrolyte Membrane Fuel cell; sometimes called proton membrane fuel cell. It is actually as I mention it is the Sulfuric acid in some polymer and that is the NAFION. Its freed name is NAFION and is produced by (( )) and it is a worldwide famous polymer, which has a sufficient hydrogen ion conductivity. And, can be used very easily in Polymer Electrolyte Membrane Fuel Cell. And, there has been extensive research whether a alternative polymer can be found out. Unfortunately, so far no other polymer as been found with that kind of properties. So, there have been some atoms, there are some other polymers available. But the performance is not as good as that of nation. In case of MCFC, that is the Molten Carbonate Fuel cell; it is a molten carbonate, it is actually a mixture of lithium and potential carbonate which melts at relatively low temperature. And, that is the electrolyte whether carbonate ion is this species which is conducting.

And, Solid Oxide Fuel Cell is basically one can be use calcium oxide no doubt. But as we have seen earlier, the yttrium stabilized zirconium as a much higher ionic conductivity or overall conductivity compare to zirconium calcium stabilized zirconium. So, although yttrium is slightly costlier, but one can get the advantage of higher conductivity. So, yttrium stabilized zirconium is the standard material used as the electrolyte. And, as we have just discuss few minutes back, that it has to be stable both that reducing as well as of oxidizing condition and that satisfy this particular material satisfied that condition.

The operating temperature of PAFC or the Phosphoric Acid Fuel Cell is about 180 to 200 degrees. Whereas, pain fuel cell or polymer electrolyte fuel cell has an operating temperature of around 80 to 100 degree centigrade. Because beyond that, the polymer is

not stable; so, one has to limit to this kind of operating temperature. MCFC, although it is mention 600 to 700 it can go up to 800 degree also, but normal temperature is around 600 to 700 degree centigrade, where this liquid carbon; the mixture of carbonate actually melts in a new tactic mixture. This operating temperature is normally is written here as 650 to 1000.

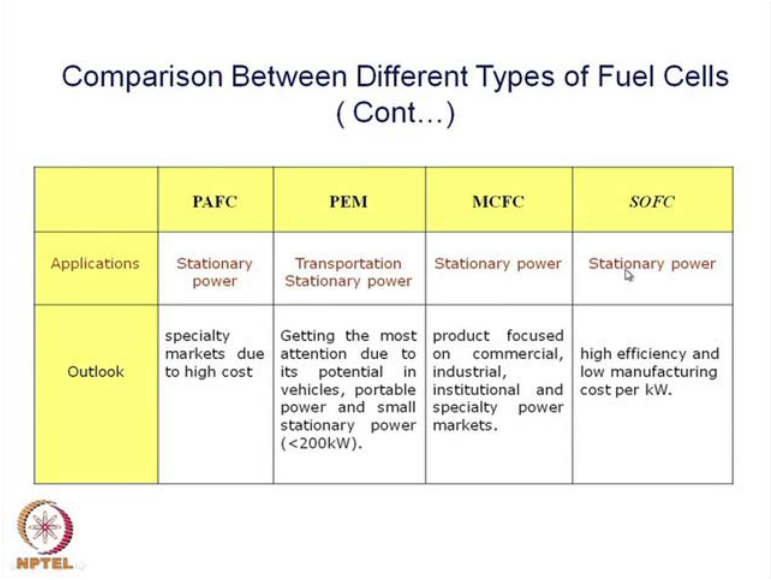
Actually, when we start, when people started using solid oxide fuel cell the temperature operation was quite high over 900 to 1000 degree centigrade. And, though because of various kinds of research, than materials, invention or discovery of different materials or development of different materials the temperature is going coming down slowly. Currently, it is about 650 to about 800 degree centigrade mostly; 800 is limit now, still research is going on whether the temperature can be further lower down to about 500 to 400 degree centigrade.

So, there are certain advantages although some disadvantages also there. But operating with a high-temperature system is always a difficult to operate and therefore, there is always a tendency to lower the temperature. So, we have at this point a group of Solid Oxide Fuel Cell, what is called LTSOFC that means low-temperature or intermediate temperature fuel cells and so on. So, LT or IT, IT SOFC means intermediate temperature which is the order of about 600 to 800 degree; whereas, l t means below 600 degrees. So, there is always a attempt to reduce temperature of operation of as much as possible.

Fuel, what is the kind of fuel? In all this particularly this 2, phosphoric acid fuel cell and pain fuel cell, a polymer electrolyte fuel cell; one needs a very pure hydrogen, very very pure hydrogen not contaminated with certain species like a carbon monoxide and so on. So, this is 1 of the limitations one can say that you need very pure hydrogen to operate. Because there are some catalysts and those catalysts are getting poison by presence of carbon monoxide. Whereas, this high-temperature or the MCFC Molten Carbon Fuel Cell can operate both with hydrogen and carbon monoxide. So, there is no problem. So, far as the carbon monoxide is concerned, there is no platinum catalyst here; all this both of them need some platinum catalyst. We are not going to details, why the platinum is needed, but without the platinum catalyst verifying this present of platinum catalyst, this kind of system do not work.

We do not need any platinum catalyst here; will the catalyst is oxide catalyst. So, the this can operate with hydrogen, natural gas even synthetic gas. So, one can generate core synthetic gas from coal and burn it. One has to find out what is the total overall efficiency. So, because efficiency is one of the dragon force for developing this kind of systems. Here these are efficiencies, the bulk per efficiencies been put here; is about 40 percent here 40 percent overall efficiency 30 to 40 percent and then 40 to 44 percent or 40 to 45 becomes all that has been mention 43, 44 specifically. That is around 40 to 45 percent and solid oxide fuel cell can go as high as 50 to 60. So, this of course, has some conditions because one has to have utility of the thermal energy also; we will look into that, what exactly it means.

(Refer Slide Time: 51:00)



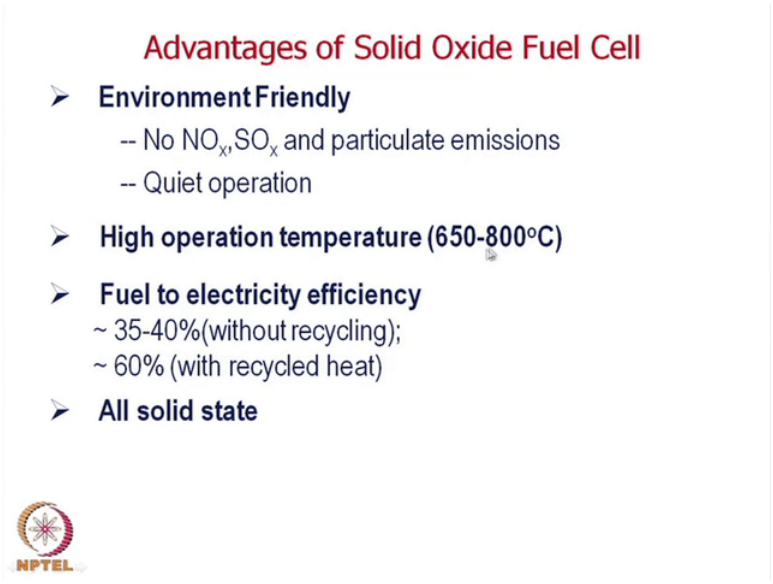
There are few other aspects on which the comparison can still be been made with the same set of fuel cells, for applications, stationary, power systems, transportation system. As I have said PEM, the polymer electrolyte fuel cell at the primarily getting developed for the electrically operated automotive systems. And, the prototypes are already available for a large number of last 10 years or so. The prototypes are running in many of the many countries particularly in Canada and some of the European countries; transportation systems are available, Japanese cars are also being run with PEM fuel cells. So, that is one of the driving force; the application area is concern.

But in addition one can also uses a stationary power, auxiliary power systems and so on. This is again a stationary power system; even MCFC have been developed to large extent almost of 1 megawatt of power systems can be has been demonstrated. But commercial commercially, many of them are still not available. If they are available, but it is not economic all the time. So, under specific conditions, one can always use that. SOFC is being considered once again as a stationary power source because of his high, conversion efficiency; 50 to 60 percent conversion efficiency is fairly high. And, one can use it force power auxiliary systems, because it contents ceramic materials. So, it cannot take lot of vibrations as well as fluctuations of temperature. So, there brittle materials and one as to, that is one of the major limitations otherwise the driving force for developing such kind of system is basically the high energy efficiency.

These are some of the other remarks specially markets, specialty markets due to high cost. Then, getting the most attention due to its potential on the vehicles, portable power and small stationary powers less than 200 kilo watt. So, several 100 kilowatts or power station or energy systems can be has been built with fuel cells. Infact, phosphoric acid fuel cell has gone up to megawatts again. MCFC, the product focus on commercial industrial and institutional as well as facility power markets. So, once again there are large number of areas, industrial situations were you need auxiliary power, you need continuous power, you need captive power. So, those things can be thought of from MCFC and this is once again or high-efficiency and low manufacture; well, relatively low manufacturing cost per kilowatt. But running costs will low, but power and the total overall cost is not that low; so, one has to have question mark here.

Oh, this is already going down.

(Refer Slide Time: 54:47)



Well, I will complete our discussion for the class, for this class with what are the specific advantages of fuel cells, solid oxide fuel cell in particular. This is environment friendly; in the sense, it is does not produce No NO x, SO x and particulate emissions and quiet operation which is true for many of the fuel cells. High operating temperature; this is an advantages in some cases and for some considerations it is an advantage. Because the kinetics of the process is very high; so, one can draw very high currents. So, actually current is one of the limitations; most of the fuel cells the operating voltage or the open circuit voltage or each cell is low. It is within 1 vote, but one has to draw a very large current; so, the kinetics must be fast enough. And, operating temperatures of 652 to 800 degrees are actually high-temperature; where kinetics is so quite fast and therefore, one can get high efficiency, that is an advantage.

But the operating temperature is also a disadvantage; high operating temperatures is also disadvantage from the materials point of view and the construction point of view or fabrication of view. Fuel cell, fuel to electrical efficiency, particularly for Solid Oxide Fuel Cell there are 2 situation. one is 35 to 40 percent, without recycling of the thermal energy and it can go up to 60 percent with the recycling of heat. Which means, you see whenever this chemical reaction is taking place H 2 plus O 2 equal to H 2 O. These has 2 ways or 2 different types of output; 1 is the thermal energy ,it is the Exothermicity of the process as well as the electrochemical combustion. So, the electrochemical combustion

of the free energy change free energy change give rise to the electrical E M F. But there is a exothermic reaction; so, it also gives rise to a lot of heat.

Now, whenever that reaction is taking place all the energies not getting converted into electrical energy loss; quite a few quite a fraction of that also goes to the heat energy. So, it continuously generate heats. So, that is also, there is also possible way to use that heat and maybe use it for some other purposes not to generate electricity. But one can also generate electricity using some micro turbines. When they call micro turbines that means the heat can be used are the combustion, the product of combustion is basically a hot gas. That hot gas can be used to generate a gas turbine or move gas turbine and from that also electricity can be generated. So, this is what if you combine that, what we call sometimes called the combined cycle, solid oxide fuel cell. So, by that recovery the heat energy also one can generate electricity. And, by that the total efficiency can be as high as 60 percent.

So, the last one is all solid-state because everything is solid, everything is high-temperature stable. Basically, there are ceramic materials; so, they are stable. And, as solid-state, that is one advantage. Primarily, the corrosion resistance; in a liquid electrolytes, if the liquid are there is electrochemical reaction and whatever is in coming in contact the cathodes and the anodes, one has to find out choose the right kind of material. So that there is no corrosion. So, as phospher whether you talk about phosphoric acid or alkaline; their corrosive liquids and one has to be free, I mean causes about choosing the particular material. However, when it is all solid-state that kind of liquid corrosion is not there, but the problem will be there for high temperature. So, both the systems have his own progeny cons but the advantage is we can have a very high conversion efficiency. So, with this we come to the end of this class, we will continue discussion in the next class.

Thank you, thank you for your attention.