# Solid Oxide Fuel Cell: A Review

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**Abstract -** *The generation of energy by clean, efficient and environmental-friendly means is now one of the major challenges for engineers and scientists. Fuel cells convert chemical energy of a fuel gas directly into electrical work, and are efficient and environmentally clean, since no combustion is required. Moreover, fuel cells have the potential for development to a sufficient size for applications for commercial electricity generation. Fuel cells and hybrid systems present a promising future but in order to meet the demand, high amounts of hydrogen will be required. Until now, probably the cleanest method of producing hydrogen has been water electrolysis. In this field, solid oxide electrolysis cells (SOEC) have attracted a great interest in the last few years, as they offer significant power and higher efficiencies compared to conventional low temperature electrolysers. Their applications, performances and material issues will be reviewed*

***Key Words***: SOFC; renewable energy; power generation; electrode….

## 1.INTRODUCTION

Fuel cell is an energy conversion unit that converts a gaseous fuel to electrical energy and heat by electrochemical combination of a fuel with an oxidant. Since it is operated electrochemically and is not limited by the Carnot cycle, lower emissions such as NOx or CO2 are produced from fuel cells compared to the cleanest combustion process. Due to its high conversion efficiency and environmental acceptability, the fuel cell is regarded as an effective process to produce electricity from chemical components.

The application of fuel cell technologies to advanced power generation systems signifies the most significant advancement in energy conservation and environmental protection for the next decade [1]. One such technology is the solid oxide fuel cell (SOFC), which is one of the most efficient and environmental-friendly technologies available for generating power from hydrogen, natural gas, and other renewable fuels. Large-scale, utility-based SOFC power generation systems have reached pilot-scale demonstration stages in the US, Europe, and in Japan. Small-scale SOFC systems are being developed for military, residential, industrial, and transportation applications [2]. SOFC is an energy conversion device that converts the chemical energy of the fuel gas directly into electricity and therefore very high electrical efficiency can be achieved. SOFC uses an oxide-ion conducting ceramic material as the electrolyte. It is therefore simple in construction than all the other fuel cell system as only two phase are required (gas and solid). The electrolyte management issue that arises with other fuel cell is absent here. Moreover because of their high temperature of operation (600°–1000°C), natural gas fuel can be easily reformed within the cell, promotes rapid electro catalysis with non-precious metals and produce high quality by product heat for cogeneration/tri-generation etc. Also pressurized SOFC can be successfully used as replacement for combustors in gas turbine or steam turbine. Such combined SOFC–GT or ST power system is expected to have efficiency over 70%. One of the main advantages of SOFC over other fuel cell is their ability to handle a wide range of hydrocarbon fuel. Quite vibration free operation of SOFC also eliminates noise usually associated with conventional power generation system.

### 1.1. History

Water electrolysis to produce hydrogen and oxygen gases is a well-known established process. Basically, the principle of a water electrolyser is to convert water and DC electricity into gaseous hydrogen and oxygen, that is to say the reverse of a hydrogen fuel cell. This process was firstly demonstrated by Nicholson and Carlisle in 1800. In the 1820s Faraday clarified the principles and in 1934 he introduced the word “electrolysis”. Electrolysis was not used commercially to produce hydrogen from water until 1902 by the Oerlikon Engineering Company. During the same period, Nernst developed the high-temperature electrolyte ZrO2 with 15% Y2O3, this being the basis for solid oxide electrolysis (SOEC) and solid oxide fuel cells (SOFC). In 1951, the first commercially available high pressure electrolyser (30 bar) was presented by Lurgi. Nowadays, low temperature electrolysis technology is available with at least 13 manufactures (3 using alkaline electrolysers and 10 using polymer membranes). On the other hand, SOEC technology is still under development. This technology attracted great interest in the 1980s because of the studies curried out by Donitz and Erdle [3], where they reported the first SOEC results within the HotElly project from Dornier System GmbH using electrolyte supported tubular SOEC. In this program, single cells have been operated during long-term periods with current densities of −0.3Acm−2 and 100% Faraday efficiency at a voltage as low as 1.07V. In addition, Westinghouse Electric Corporation Research and Development Centre contributed to the development of SOEC. They reported Area Specific Resistance (ASR) values of about 0.6 cm2 per cell in a seven-cell stack at 1003 ◦C [4]. Research in high temperature electrolysis has increased significantly in recent years, as will be described in the present review.

**Table -1:** Characteristics of different fuel cell systems

| Types of fuel cell | Electrolyte | Operating Temperature | Fuel | Oxidant | Efficiency |
|---|---|---|---|---|---|
| Alkaline (AFC) | potassium hydroxide (KOH) | 50–200°C | pure hydrogen, or hydrazine | $O_2$/Air | 50–55% |
| Direct methanol (DMFC) | polymer | 60–200°C | liquid methanol | $O_2$/Air | 40–55% |
| Phosphoric acid (PAFC) | phosphoric acid | 160–210°C | hydrogen from hydrocarbons and alcohol | $O_2$/Air | 40–50% |
| Sulfuric acid (SAFC) | sulfuric acid | 80–90°C | alcohol or impure hydrogen | $O_2$/Air | 40–50% |
| Proton-exchange membrane (PEMFC) | polymer, proton exchange membrane | 50–80°C | less pure hydrogen from | $O_2$/Air | 40–50% |
| Molten carbonate(MCFC) | molten salt such as nitrate, sulphate, carbonates | 630–650°C | hydrocarbons or methanol | CO2/O2/Air | 50–60% |
| Solid oxide (SOFC) | ceramic as stabilised zirconia and doped perovskite | 600–1000°C | natural gas or propane | $O_2$/Air | 45–60% |
| Protonic ceramic (PCFC) | thin membrane of barium cerium oxide | 600–700°C | hydrocarbons | $O_2$/Air | 45–60% |

### 1.2. Fuel cell

A fuel cell is an energy conversion device that converts the chemical energy of a fuel gas directly to electrical energy and heat without the need for direct combustion as an intermediate step, giving much higher conversion efficiencies than conventional thermo-mechanical methods. The operating principles of fuel cells are similar to those of batteries, i.e., electrochemical combination of reactants to generate electricity, a combination made of a gaseous fuel (hydrogen) and an oxidant gas (oxygen from the air) through electrodes and via an ion conducting electrolyte. However, unlike a battery, a fuel cell does not run down or require recharging. A fuel cell operates as long as both fuel and oxidant are supplied to the electrodes and the influence it exerts on the surrounding environment is negligible.

### 1.3. Types of Fuel Cells

Fuel cells are generally classified by the chemical characteristics of the electrolyte used as the ionic conductor in the cell, as summarized in Table 1. The first five types are characterized by their low to medium

temperature of operation (50–210°C), their relatively low electrical generation efficiencies (40–50% when operated on readily available fuels such as methanol and hydrocarbons, 50% when using pure hydrogen fuel). The latter three types are characterized by their high temperature of operation (600–1000°C), their ability to utilise methane directly in the fuel cell and thus their high inherent generation efficiency (45–60% for common fuels such as natural gas, 90% with heat recovery) [9]. There are also other types of fuel cells which are less employed, but may later find a specific application. Examples are the air-depolarized cells, sodium amalgam cells, biochemical fuel cells, inorganic redox cells, regenerative cells, alkali metal–halogen cells, etc. Present materials' science has made the fuel
cells a reality in some specialized applications. By far the greatest research interest throughout the world has focused on
Proton Exchange Membrane (PEM) and Solid Oxide (SO) cell stacks. PEMs are well advanced type of fuel cell that are suitable for cars and mass transportation. SOFC technology is the most demanding from a materials standpoint and is developed for its potential market competitiveness arising from:

- SOFCs are the most efficient (fuel input to electricity output) fuel cell electricity generators currently being developed world-wide.
- SOFCs are flexible in the choice of fuel such as carbon-based fuels, eg, natural gas.
- SOFC technology is most suited to applications in the distributed generation (ie, stationary power) market because its high conversion efficiency provides the greatest benefit when fuel costs are higher, due to long fuel delivery systems to customer premises.
- SOFCs have a modular and solid state construction and do not present any moving parts, thereby are quiet enough to be installed indoors.
- The high operating temperature of SOFCs produces high quality heat byproduct which can be used for co-generation, or for use in combined cycle applications.
- SOFCs do not contain noble metals that could be problematic in resource availability and price issue in high volume manufacture.
- SOFCs do not have problems with electrolyte management (liquid electrolytes, for example, which are corrosive and difficult to handle).
- SOFCs have extremely low emissions by eliminating the danger of carbon monoxide in exhaust gases, as any CO produced is converted to CO2 at the high operating temperature.
- SOFCs have a potential long life expectancy of more than 40000–80000 h.

## 2. SOLID OXIDE FUEL CELL

SOFCs have recently emerged as a serious high temperature fuel cell technology. They promise to be extremely useful in large, high-power applications such as full scale industrial stations and large-scale electricity-generating stations. Some fuel cell developers see SOFCs being used in motor vehicles. A SOFC system usually utilizes a solid ceramic as the electrolyte and operates at extremely high temperatures (600– 1000°C). This high operating temperature allows internal reforming, promotes rapid electrocatalysis with non-precious metals, and produces high quality byproduct heat for co-generation. Efficiencies for this type of fuel cell can reach up to 70% with an additional 20% as heat recovery. SOFCs are best suited for provision of power in utility applications due to the significant time required to reach operating temperatures.

### 2.1. Design and operation of SOFCs

SOFCs differ in many respects from other fuel cell technologies. First, they are composed of all-solid-state materials. Second, the cells can operate at temperatures as high as 1000°C, significantly hotter than any other major category of fuel cell. Third, the solid state character of all SOFC components means that there is no fundamental restriction on the cell configuration. Cells are being constructed in two main configurations, i.e., tubular cells or rolled tubes, such as those being developed at Westinghouse Electric Corporation since the late 1950s, and a flat-plates configuration adopted more recently by many other developers and employed today by the electronics industry. A SOFC consists of two electrodes sandwiched around a hard ceramic electrolyte such as the remarkable ceramic material called zirconia. Hydrogen fuel is fed into the anode of the fuel cell and oxygen, from the air, enters the cell through the cathode. By burning fuel containing hydrogen on one side of the electrolyte, the concentration of oxygen is dramatically reduced. The electrode on this surface will allow oxygen ions to leave the electrolyte and react with the fuel which is oxidized, thereby releasing electrons ($e^-$). On the other side of the plate, which is exposed to air, an oxygen concentration gradient is created across the electrolyte, which attracts oxygen ions from the air side, or cathode, to the fuel side, or anode. If there is an electrical connection between the cathode and the anode, this allows electrons to flow from the anode to the cathode, where a continuous supply of oxygen ions ($O_2^-$) for the electrolyte is maintained, and oxygen ions from cathode to anode, maintaining overall electrical charge balance, thereby generating useful electrical power from the combustion of the fuel. The only byproduct of this process is a pure water molecule ($H_2O$) and heat, as shown in Fig. 1.
The electrochemical reactions that take part in an SOFC are the inverse reactions to those thattake partin an SOFC. Cell polarization is the opposite and anode and cathode interchange their roles. In an SOEC, water acts as a reactant and is supplied to the cathode side of the cell (anode electrode in SOFC mode). Oxygen ions are transported to the anode through the electrolyte, and

hydrogen is produced in the cathode side, as shown in Fig. 1.

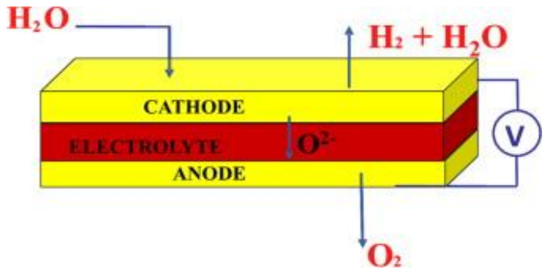


**Fig.1.** Scheme of a SOFC cell operating under electrolysis mode

The overall reaction of the water electrolysis is:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (1)$$

The reactions in the cathode and anode sides are:

$$H_2O + 2e^- \rightarrow H_2(g) + O^{2-} \quad (2)$$

$$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^- \quad (3)$$

There are mainly two types of electrolysers, depending on their operation temperature: low temperature electrolysers (LTE) and high temperature electrolysers (HTE). LTE are also divided into alkaline and proton-exchange membrane, and these devices are proven technologies that can achieve energy efficiencies of about 75% [5]. The major problem associated with LTEs is the high electric energy consumption which can degrade the competitiveness of the process. Although LTE is a mature technology, HTE presents a greater potential as the electrolysis of water is increasingly endothermic with increasing temperature. The required electrical power is reduced at higher temperatures as the unavoidable joule heat of an electrolysis cell is used in the H2O splitting process. Another advantage of the high temperature is the reduction of electrode over potentials which cause power losses in the electrolysis cell.

Basically, SOFC have been investigated as an innovative technology that can be integrated with traditional electrical power plants or to supply electricity as on-site power generators [6]. Due to the fast development of industrial and social structure, the diverse application of SOFC in different field has been investigated. There are three main application of SOFC such as combined cycle power plant, cogeneration/trigeneration and residential application. Due to its high operating temperature, SOFC are not suitable for portable application and transportation. But now researchers are investigating in the areas to reduce the operating temperature of SOFC to make it suitable for portable application. There are six different types of fuel cells available in the market. Out of these only PEMFC (80°C) and SOFC (1000°C) have captured the most part of

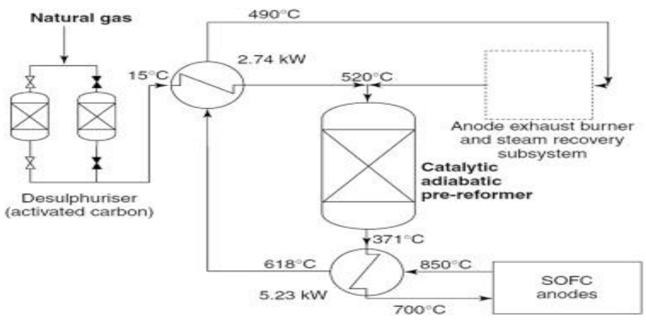


**Fig. 2.** Pre-reformer system devised for a Siemens 50-kW SOFC demonstration [6].

the market share. As these two types of fuel cells are targeted for commercialization in the residential (1–10 kW), power generation (several MW) and commercial (25–250 MW) end use markets, system studies in this area are of great interest. The basic components of a SOFC power plant consist of a fuel processor, desulphurizer, fuel cell power module, power conditioning equipment for DC-AC converter and process gas heat exchanger. Depending upon the operating temperature SOFC fuel cell produce varying grades of waste heat that can be recovered for heating, cooling, cogeneration or trigeneration application purpose. It can significantly impact the system efficiency, economics and environmental issues. Hydrogen and carbon mono oxide are used as the fuel for SOFC. In order to supply these components to the fuel cell, steam reforming reaction is used to reform hydrocarbon fuels such as natural gas. Due to the high temperature of SOFC, reforming can be done very efficiently. Natural gas contains organic sulphur that can deactivate the steam reforming catalyst. So to ensure long life of the fuel processor unit, desulphurization is done before reforming shown in Fig. 2 [6]. Reforming can be internal or external. The external feed such as methane (natural gas) is converted to hydrogen and CO at the reformer section. In external reforming, the endothermic steam reforming reaction and the fuel cell reaction are operated separately in different units and there is no direct heat transfer between both unit operations. In case of internal reforming, the endothermic reaction from the steam reforming reaction and the exothermic reaction from the oxidation reaction are operated together in single unit and therefore there is no need of separate reforming unit. There are two internal reforming concepts: direct and indirect internal reforming. Indirect internal reforming physically separates the reforming process from the electrochemical process, making use of the cell-stack heat release either by radiation heat transfer [6] or by direct physical contact between the cell hardware and the reforming unit. In direct internal reforming, the hydrocarbon fuel–steam mixture is admitted directly into the anode compartment and the fuel is reformed on the porous, nickel-based anode layer.

## 2.2. Components of the SOFCs

A SOFC is mainly composed of two electrodes (the anode and the cathode), and a solid electrolyte. The fuel is also important as the principal parameter but independent of the other as it is most of the time converted into hydrogen. The SOFC, which relies on O2- oxygen ion transport, also works with high purity hydrogen, but it does not rely upon this fuel, which is expensive to produce and difficult to handle. The main function of the electrode is to bring about reaction between the reactant (fuel or oxygen) and the electrolyte, without itself being consumed or corroded. It must also bring into contact the three phases, i.e., the gaseous fuel, the solid electrolyte and the electrode itself. The anode, used as the negative post of the fuel cell, disperses the hydrogen gas equally over its whole surface and conducts the electrons, that are freed from hydrogen molecule, to be used as a useful power in the external circuit. The cathode, the positive post of the fuel cell, distributes the oxygen fed to it onto its surface and conducts the electrons back from the external circuit where they can recombine with oxygen ions, passed across the electrolyte, and hydrogen to form water. The electrolyte determines the operating temperature of the fuel cell and is used to prevent the two electrodes to come into electronic contact by blocking the electrons. It also allows the flow of charged ions from one electrode to the other to maintain the overall electrical charge balance. It can either be an oxygen ion conductor or a hydrogen ion (proton) conductor, the major difference between the two types is the side in the fuel cell in which the water is produced: the oxidant side in proton– conductor fuel cells and the fuel side in oxygen-ion-conductor ones.

### 2.3.SOFC component requirements

Each component of the SOFC serves several functions and must therefore meet certain requirements such as [7]:

- Proper stability (chemical, phase, morphological, and dimensional)
- Proper conductivity
- Chemical compatibility with other components.
- Similar thermal expansion to avoid cracking during the cell operation.
- Dense electrolyte to prevent gas mixing.
- Porous anode and cathode to allow gas transport to the reaction sites.

## 3. SOFC BENEFITS AND LIMITATIONS

SOFCs have many advantages: they can be modular, they can be distributed to eliminate the need for transmission lines, they operate quietly and are vibration free. SOFCs could provide higher system efficiency, higher power density, and simpler designs than fuel cells based on liquid electrolytes. At low enough costs, they could compete with combined cycle gas turbines for distributed applications. The high cell operating temperature enables high reactant activity and therefore facilitates fast electrode kinetics (large exchange currents) and reduced activation polarization. This is especially advantageous as precious platinum electrocatalysts are not required and the electrodes cannot be poisoned by carbon monoxide. As a result, carbon monoxide is a potential fuel in SOFCs. Moreover, the operating temperatures are sufficiently elevated, thereby performance issues are not related to kinetics (activation over potentials) but to ohmic losses due to charge transport across components and component interfaces [8]. The benefits of SOFCs also include:

- Energy security: reduce oil consumption, cut oil imports, and increase the amount of the country's available electricity supply.
- Reliability: achieves operating times in excess of 90% and power available 99.99% of the time.
- Low operating and maintenance cost: the efficiency of the SOFC system will drastically reduce the energy bill (mass production) and have lower maintenance costs than their alternatives.
- Constant power production: generates power continuously unlike backup generators, diesel engines or Uninterrupted Power Supply (UPS).
- Choice of fuel: allows fuel selection, hydrogen may be extracted from natural gas, propane, butane, methanol and diesel fuel.

Up until now, SOFCs have been most fuel-efficient operating at 1000°C. Unfortunately, this high temperature decreases the cell lifetime and increases the cost of materials, since expensive high temperature alloys are used to house the cell, and expensive ceramics are used for the interconnections, increasing the cost of the fuel cell substantially. Lower operating temperature has been recognized worldwide as the key point for low-cost SOFCs. The reduction in the temperature will therefore allow the use of cheaper interconnecting and structural components, such as stainless steel. A lower temperature will also ensure a greater overall system efficiency and a reduction in the thermal stresses in the active ceramic structures, leading to a longer expected lifetime of the system and make possible the use of cheaper interconnect materials such as ferritic steels, without $LaCrO_3$ protective coatings, as already mentioned. For some years, scientists and researchers throughout the world have been on a quest to drop the operating temperature of SOFCs without sacrificing their performance. The 600–1000°C operating temperature of the SOFC requires a significant startup time. The cell performance is very sensitive to operating temperature. A 10% drop in temperature results in 12% drop in cell performance, due to the increase in internal resistance to the flow of oxygen ions [9]. The high temperature also demands that the system include significant thermal shielding to protect personnel and to retain heat.

## 4.APPLICATIONS OF SOFC

Combined with low noise and ability to utilize readily-available fuel such as methane and natural gas, SOFC generators are best suited for the provision of power in utility applications, due to the significant time required to reach operating temperatures, and can have broad applications ranging from large-scale power plants to smaller home-scale power plants and portable/emergency power generators. SOFCs could be used in many applications. Each proposed use raises its own issues and challenges. Their most needed uses are:

- High power reliability: computer facilities, call centers, communication facilities, data processing centers high technology manufacturing facilities.
- Emission minimization or elimination: urban areas, industrial facilities, airports, zones with strict emissions standards.
- Limited access to utility grid: rural or remote areas, maximum grid capacity.
- Biological waste gases are available: waste treatment plants, SOFC can convert waste gases (methanol from biomass) to electricity and heat with minimal environment intrusion.

## 5.CONCLUSIONS

Energy exploitation of fossil fuels is reaching its limits. Future alternatives must therefore be developed for long-term and environmental-friendly energy supply needed by a constantly growing world population. SOFCs provide highly efficient, pollution free power generation. Their performance has been confirmed by successful operation power generation systems throughout the world. Electrical-generation efficiencies of 70% are possible nowadays, along with a heat recovery possibility. SOFCs appear to be an important technology for the future as they operate at high efficiencies and can run on a variety of fuels, from solar hydrogen to methanol, from biomass to gasified coal. As the technology develops, and if the cost of fossil fuels continues to rise, this clean, efficient alternative will stimulate the thermo-mechanical engineers, despite their Carnot and Rankine limitations, to even greater efforts for the SOFCs to find more and more practical uses.

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