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A Survey of Fuel Cell Types and Its Applications

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Abstract

Energy efficiency and alternative power play a big role in sustainability The use of fossil fuels as a major energy source has given rise to several concerns such as the effect of harmful emissions and sustainability. Due to these reasons lot of efforts have been placed on finding alternative energy sources. One of the promising environmentally benign alternative for large scale electricity production involves the use of fuel cells. Several countries are partnering to advance research and development efforts in fuel cell technologies . Fuel cells are being used by major corporations today – in applications varying from local generation of heat and electricity to materials handling to transportation.

Keywords: Distributed Generation , Fuel Cell, Hybrid vehicle , Automobile,Cogeneration.

I. INTRODUCTION

Fuel cells generate electricity with minimum to zero emissions and provide not only environmental savings, but also favors productivity improvements like time, cost and manpower savings. No other energy generation offers the product range and combination of pros than fuel cells can[1].

Fuel cells are basically more efficient than the combustion systems, because it achieves more than 40- 50% efficiency in converting fuel to electricity with hydrocarbon fuels or pure hydrogen, depending on the type of fuel cell and the application[2]. High efficiency is an important advantage for fuel cells because they use the chemical energy of the fuel directly, without combustion. Hybrid systems that combine high temperature fuel cells with a turbine, can operate at more than 60% estimated electrical efficiencies, which is higher than the most efficient combined cycle turbine plants[3].

II. FUEL CELL

In principle, a fuel cell operates like a battery. Unlike a battery , a fuel cell does not run down or require recharging. It will generate electricity and heat as long as fuel and an oxidizer are supplied. Both batteries and fuel cells are electrochemical devices. Both of them have a positively charged anode, a negatively charged cathode and an ion-conducting material in between the two plates called an electrolyte. The fuel cell itself has no moving parts – making it a noiseless and reliable source of power. Since the hydrocarbon fuel in fuel cells is transformed directly to electricity, a fuel cell can work at much higher efficiencies than internal combustion engines, deriving more electricity from the same amount of fuel[4].

Fuel cells are electrochemical devices which convert the chemical energy in the fuel directly into electrical energy. Figure 1 shows the reactants flows and reactions in a fuel cell. Unlike ordinary combustion, fuel (hydrogen-rich) and oxidant (air) are delivered to the fuel cell separately. Fuel cells consist of two electrodes (anode and cathode) and an electrolyte in between them . Oxygen (air) continuously passes over the cathode (positive electrode) and hydrogen passes over the anode(negative electrode) to generate electricity. Electrochemical oxidation and reduction reactions take place at the two electrodes to produce electric current. The by- products of fuel cell reaction are water and heat[5].

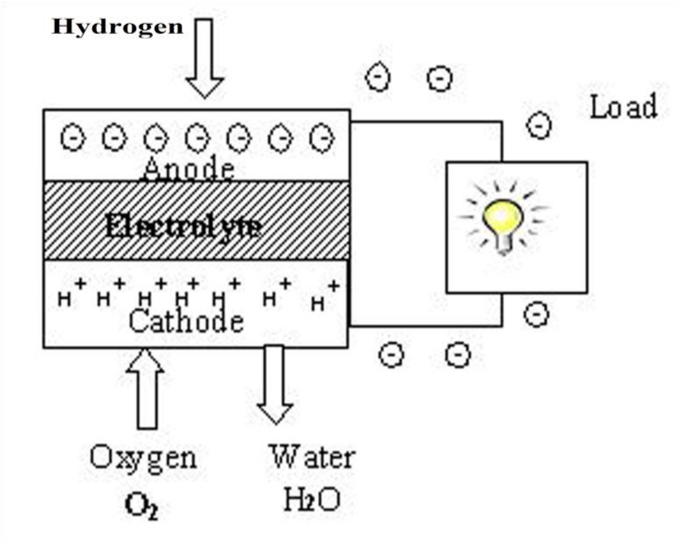

Fig.1. Fuel Cell Architecture

The electrolyte which separates the anode and cathode is an ion-conducting material. At the anode, hydrogen get separated into hydrogen ions (protons) and electrons, in which the protons move through the electrolyte while the electrons move through an external electrical circuit as a Direct Current (DC) that can power useful devices. The hydrogen ions combine with the oxygen at the cathode and recombine with the electrons to form water[6].

A.Anode Reaction

When hydrogen gas is supplied to the system, the catalyst surface splits hydrogen gas molecules into protons and electrons.

$$2H_2 \Rightarrow 4H^+ + 4e^- \quad (1)$$

B.Cathode Reaction

The protons move through the membrane to react with oxygen in the air (forming water).

$$O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O \quad (2)$$

C.Overall Cell Reaction

$$2H_2 + O_2 \Rightarrow 2H_2O \quad (3)$$

III .FUEL CELL STACK

A single fuel cell can produce less than one volt of electrical potential [7]. To generate higher voltages, fuel cells are stacked on top of each other and are connected in series. Individual fuel cells can therefore be combined into a fuel cell "stack." The Fuel Cell stack consists of many fuel cell units, each comprised of an anode, cathode, electrolyte, and a bipolar separator plate[6]. The number of cells in the stack depends on the desired power output and individual cell performance; stacks range in size from a few (less than 1 kW) to several hundred (250+ kW).

The number of fuel cells in the stack decide the total output voltage, and the surface area of each cell decides the total current .The product of voltage and the current will give in the total electrical power generated.

$$\text{Power (W)} = \text{Voltage (V)} * \text{Current (A)} \quad (4)$$

IV. TYPES OF FUEL CELLS

A, Alkaline Fuel Cells (AFC)

Alkaline fuel cells (AFC) are one of the most developed types and have been used since 1960s by NASA in the Apollo and Space Shuttle programs. The fuel cells on board these spacecraft generate electrical power for on-board systems, as well as drinking water. AFCs are one of the most efficient type of fuel cells in generating electricity at nearly 70% [4].

Alkaline fuel cells contains an electrolyte that is an aqueous (water-based) solution of potassium hydroxide (KOH) retained in a porous stabilized matrix. The concentration of KOH can be varied with the fuel cell operating temperature, which ranges between 65°C to 220°C. The charge carrier for an AFC is the hydroxyl ion (OH-) that passes from the cathode to the anode where they get reacted with hydrogen to produce water and electrons. Water produced at the anode migrates back to the cathode to regenerate hydroxyl ions(OH-).The set of reactions in the fuel cell generates electricity and water and heat are the by- products evolved in this reaction.

An important characteristic of AFCs is they are very sensitive to CO_2 that may be present in the fuel or air. The CO_2 reacts with the electrolyte, poisoning it , and severely degrading the performance of the fuel cell. Therefore, AFCs are limited to closed environments, such as space and undersea vehicle. Molecules such as CO, H_2O and CH_4, which are harmless or even work as fuels to other types of fuel cells, are poisons to an AFC.Compared with other fuel cells ,AFCs are the cheapest fuel cells to manufacture. This is because the catalyst required on the electrodes can be any of a number of different materials that are relatively inexpensive compared to the other types of fuel cells.

Since AFCs are sensitive to poisoning, AFCs are not being considered for automobile applications. Conversely, AFCs operate at relatively low temperatures and are among the most efficient fuel cells, they would be a quick starting power source and provide high fuel efficiency

B. Phosphoric Acid Fuel Cells(PAFC).

Phosphoric Acid Fuel Cells (PAFC) are the first fuel cells to be commercially used. Developed in the mid-1960s and field-tested since the 1970s, they shown improved significance in stability, performance, and cost. Such characteristics have made the PAFC a good option for early stationary applications[4].

PAFC uses phosphoric acid(H_3PO_4) as an electrolyte that can achieve 100% concentration. Since Phosphoric acid has low ionic conductivity at low temperatures, they can be operated in the range of 150ºC–220ºC.Hydrogen ions are the charge carrier in this type of fuel cell. This is similar to PEMFC where hydrogen is introduced at the anode and it splits into its protons and electrons. The protons passes through the electrolyte and combine with the oxygen (air)at the cathode to form water. The electrons pass through an external circuit where they can operate a load. The set of reactions in this type of fuel cell produces electricity and byproducts are water and heat.

The PAFC operates with more than 40% efficiency in generating electricity. While operating in cogeneration applications, the overall efficiency is approximately 85%.At the operating temperature of PAFCs, the waste heat is capable of heating water or generating steam at atmospheric pressure.

The high efficiency of the PAFC when operated in cogeneration mode is an important advantage of this fuel cell. In addition, CO_2 does not affect the electrolyte or cell performance as in AFCs and can therefore be easily operated with reformed fossil fuel. Simple construction, low electrolyte volatility and long-term stability are the additional advantages in this fuel cell.

C. Molten Carbonate Fuel Cells (MCFC)

Molten Carbonate Fuel Cells (MCFC) belongs to the class of high-temperature fuel cells. The higher operating temperature allows them to use natural gas directly without the need for a fuel processor[4].They are developed in the mid 1960s, improvements have been made in fabrication methods, performance and endurance.

MCFCs are quite different from other types of fuel cells. These cells uses an electrolyte composed of a molten mixture of carbonate salts. Two mixtures are currently used: lithium carbonate and potassium carbonate, or lithium carbonate and sodium carbonate. MCFCs operate at high temperatures (650ºC) to melt the carbonate salts and achieve high ion mobility through the electrolyte.

While heated to a temperature of about 650ºC, these salts melt and become conductive to carbonate ions (CO_3^{2-}). These ions migrate from the cathode to the anode where they combine with hydrogen to produce water, carbon dioxide and electrons. These electrons pass through an external circuit then back to the cathode, generating electricity and the by-product as water and heat.

The higher operating temperature of MCFCs has both advantages and disadvantages compared to the lower operating temperature of PAFC and PEMFC. At the higher operating temperature, the fuel reforming of natural gas can take place internally, eliminating the need for an external fuel processor. The other important advantages include the ability to use standard materials for construction, such as stainless steel sheet, and allow use of nickel-based catalysts on the electrodes. The heat generated as a by-product in an MCFC can be used to generate high pressure steam and can be used in many industrial and commercial applications.

The high operating temperature and the electrolyte chemistry also has disadvantages. The high temperature requires significant time to reach the operating conditions and responds slowly to the fluctuating power demands. These characteristics make MCFCs more suitable for constant power requirements. The carbonate electrolyte can also corrode the electrodes. Since CO_2 is consumed at the anode and transferred to the cathode ,the introduction of CO_2 and its control in air stream places an issue for achieving optimum performance .

D. Solid Oxide Fuel Cell (SOFC)

The Solid Oxide Fuel Cell (SOFC) is the highest-operating temperature fuel cell in development and can be operated over a wide temperature range from 600ºC–1000ºC. In SOFC the electrolyte is a thin, solid ceramic material (solid oxide) that is conductive to oxygen ions (O^{2-}). The SOFC has been in development since 1950s and has two configurations that are being investigate-planar (flat panel) and tubular.

Since a solid electrolyte is used, it is impervious to gas cross-over from one electrode to another when liquid electrolytes usually consist of the electrolyte contained in some porous supporting structure. The charge carrier in the SOFC is the oxygen ion (O^{2-}). At the cathode, the oxygen molecules from the air split into oxygen ions with the addition of four electrons. The oxygen ions migrate through the electrolyte and combine with hydrogen at the anode, releasing four electrons. The electrons travel through an external circuit providing electric power and producing water and heat as by-products.

The operating efficiency of SOFCs is the highest of the fuel cells at about 60%. This high operating temperature allows cogeneration applications to create high-pressure steam that can be useful for many applications. Combining a high-temperature fuel cell with a turbine to form a hybrid fuel cell further increases the overall efficiency of generating electricity (more than 70%). [3]

Since SOFCs operate at extremely high temperatures (600ºC–1000ºC) a significant time is required to reach the operating temperature. Therefore they respond slowly to the changes in electricity demand. So SOFCs are considered to be a leading option for high-power applications including industrial and large-scale central-electricity generating-stations.

The very high operating temperature of the SOFC has both pros and cons. The high temperature enables them to tolerate relatively impure fuels, such as those obtained from the gasification of coal or gases from industrial process and other sources. However, the high temperatures require more expensive materials for construction.

E. Proton Exchange Membrane Fuel Cells (PEMFC)

Proton Exchange Membrane Fuel Cells (PEMFC) are said to be the best preference of fuel cell for vehicular power source which can replace gasoline and diesel internal combustion engines in terms of its efficiency. They are first used in the 1960s for the NASA Gemini program, PEMFCs are currently being developed and demonstrated for applications ranging from 1W to 2kW.

PEM fuel cells use a solid polymer membrane (a thin plastic film) as their electrolyte. This polymer is permeable to protons when it is saturated with water, but it does not conduct electrons.

The fuel for the PEMFC is hydrogen rich fuel or hydrocarbon based fuel and the charge carrier is the hydrogen ion (proton). At the anode, the hydrogen molecule split into hydrogen ions (protons) and electrons. The hydrogen ions migrate across the electrolyte to the cathode while the electrons flow through an external circuit and generate electric power. Oxygen, usually in the form of air, is supplied to the cathode and they combine with the electrons and the hydrogen ions to produce water.

PEMFCs generate more power based on the given volume or based on the weight of fuel cell. The high-power density ratio characteristic of PEMFC makes them compact and lightweight. In addition, the operating temperature is less than 100ºC, which allows rapid start-up[4]. These traits and the ability to rapidly change the power output are some of the characteristics that make the PEMFC the leading choice for automotive power applications.

One of the disadvantages of the PEMFC for some specific applications is that the operating temperature is low. Temperatures near 100ºC are not high enough to perform useful cogeneration. Also, since the electrolyte is required to be saturated with water to operate optimally, careful control of the moisture of the anode and cathode streams are important.

PEMFCs are currently being developed primarily for sizes less than 500 kW. The applications for PEMFCs include:

- Light duty (50–100 kW) and medium duty (200 kW) vehicles
- Residential (2–10 kW) and commercial (250–500 kW) power generation
- Small and/or portable generators and battery replacements

V. APPLICATIONS

Stationary fuel cells are widely used for commercial, industrial and residential primary and backup power generation[10]. Fuel cells are very useful as power sources in remote locations such as spacecraft, remote weather stations, large parks, communications centers, research stations, and in certain military applications. A fuel cell system which uses hydrogen as fuel can be compact and lightweight, and have no major moving parts. As fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability[9].

Since fuel cell electrolyzer systems do not store fuel in themselves, but rather depend on external storage units, they can be successfully applied in large-scale energy storage. There are many different types of stationary fuel cells with varying efficiencies, but most are between 40% and 60% energy efficient. However, when the fuel cell's waste heat is used to heat a building in a cogeneration system this efficiency can increase to 85%.This is significantly more efficient than traditional coal power plants, which are only about one third energy efficient[11]. Fuel cells can save 20-40% on energy costs when used in cogeneration systems. Fuel cells are also much cleaner than traditional coal power generation; a fuel cell power plant using natural gas as a hydrogen source would create less than one ounce of pollutants (other than CO_2) for every 1,000kW produced, compared to 25 pounds of pollutants generated by conventional combustion system. Fuel Cells also give out 97% less nitrogen oxide emissions than conventional coal-fired power plants[1] .

Coca-Cola, Google, Sysco, FedEx, UPS, Ikea, Staples, Whole Foods, Gills Onions, Nestle Waters, Pepperidge Farm, Sierra Nevada Brewery, Super Store Industries, Brigestone-Firestone, Nissan North America, Kimberly-Clark, Michelin and more have installed fuel cell stacks to meet their power requirements. In Washington State the Stuart Island Energy Initiative has built a complete, closed-loop system: Solar panels power an electrolyzer which makes hydrogen. The hydrogen is stored in a 500

US gallons (1,900 L) at 200 pounds per square inch (1,400 kPa), and runs a ReliOn fuel cell to afford full electric back-up to the off-the-grid residence.

A. Cogeneration

Combined heat and power (CHP) fuel cell systems, including Micro combined heat and power (MicroCHP) systems are used to generate both electricity and heat for homes ,office building and factories. These are stationary fuel cells for mass production. This system generates regular electric power and at the same time produces hot air and water from the waste heat. MicroCHP is usually less than 5 kWe for a home fuel cell or small scale business[1].

Co-generation systems can reach 85% efficiency (40% -60% electric + remainder as thermal). Phosphoric-acid fuel cells (PAFC) comprise the largest segment of existing CHP products worldwide and they can provide combined efficiencies close to 90%. Molten Carbonate (MCFC) and Solid Oxide Fuel Cells (SOFC) are also used for combined heat and power generation and they have electrical energy efficiencies around 60%[7].

B. Fuel Cell Electric Vehicles (FCEVs)

(1)Automobiles

Even though there are no Fuel cell vehicles available for commercial sale at present, over 20 FCEVs prototypes and demonstration cars have been released since 2009. Demonstration models include the Honda FCX Clarity, Toyota FCHV-adv, and Mercedes-Benz F-Cell. As of June 2011 demonstration FCEVs has driven more than 4,800,000 km (3,000,000 mi), with more than 27,000 refueling. Demonstration fuel cell vehicles has produced a driving range of more than 400 km (250 mi) between refueling. They can be replenished in less than 5 minutes. http://en.wikipedia.org/wiki/Fuel_cell - cite_note-58 EERE's Fuel Cell Technology Program claims that, as of 2011, fuel cells achieved 53–59% efficiency at ¼ power and 42–53% vehicle efficiency at full power,http://en.wikipedia.org/wiki/Fuel_cell - cite_note-progressreport-59 and a durability of over 120,000 km (75,000 mi) with less than 10% degradation, which is double that of achieved in 2006. In a Well-to-Wheels simulation analysis, General Motors and its partners estimated that per mile traveled, a fuel cell electric vehicle running on compressed gaseous hydrogen produced from natural gas use about 40% less energy and emit 45% less greenhouse gasses than an internal combustion vehicle[8].

(2) Buses

Totally there are over 100 fuel cell buses deployed around the world today. Most buses are produced by UTC Power, Toyota, Ballard, Hydro genics , and Proton Motor. UTC Buses have already achieved over 970,000 km (600,000 mi) of driving. Fuel cell buses have a 30-41% higher fuel economy than diesel buses and natural gas buses. Fuel cell buses have been deployed around the world including Canada, San Francisco USA, Hamburg Germany, Shanghai China, London England, São Paulo Brazil as well as several others. The Fuel Cell Bus Club is a global cooperative effort in deploying trial fuel cell buses. Notable Projects Include:

- Around 12 Fuel cell buses are being deployed in the Oakland and San Francisco Bay area of California.
- Daimler AG, with 36 experimental buses powered by Ballard Power Systems fuel cells completed a successful three-year trial, in eleven cities, in January 2007.
- A fleet of Thor buses with UTC Power fuel cells was deployed in California, operated by Sun Line Transit Agency.

(3)Forklifts

Fuel cell powered forklifts forms one of the largest sectors of fuel cell applications in the industry. Most fuel cells used for material handling purposes are powered by PEM fuel cells, although some direct methanol fuel forklifts are available in the market[4].

Fuel cell powered forklifts has significant benefits over both petroleum and battery powered forklifts as they produce no local emissions, and can work for a full 8 hour shift on a single tank of hydrogen, can be refueled in 3 minutes and have a lifetime of 8–10 years. Fuel cell powered forklifts are frequently utilized in refrigerated warehouses as their performance is not tarnished at lower temperatures. Many companies do not prefer petroleum powered forklifts, as these vehicles work indoors where emissions can be controlled. Fuel cell forklifts offer green house gases, product lifetime, maintenance cost, refueling and labour cost benefits over battery operated forklifts.

(4)Motorcycles and bicycles

In 2005 ,the British firm Intelligent Energy produced the first ever working hydrogen fuel based motorcycle called the ENV (Emission Neutral Vehicle). This motorcycle holds enough fuel to run for four hours, and travel upto160 km (100 mi) in an urban area, at a high speed of 80 km/h (50 mph).http://en.wikipedia.org/wiki/Fuel_cell - cite_note-86 In 2004,Honda developed a fuel-cell motorcycle which utilized the Honda FC Stack. Hydrogen fuel cell engine based bikes and bicycles are also available[8].

(5)Airplanes

Boeing researchers and industry partners throughout Europe conducted experimental flight tests in February 2008 on a manned airplane powered only by a fuel cell and lightweight batteries. The Fuel Cell Demonstrator Airplane, employed a Proton Exchange Membrane (PEM) fuel cell/lithium-ion battery hybrid system to initiate an electric motor, which was coupled to a conventional propeller. In 2003, the world's first propeller driven airplane has been powered entirely by a fuel cell[4,8].

Several fuel cell powered unmanned aerial vehicles (UAV). A Horizon fuel cell UAV placed the record distance flow for a small UAV in 2007.http://en.wikipedia.org/wiki/Fuel_cell - cite_note-93 The military is especially interested in this application because of the low noise, low thermal signature and the ability to reach high altitude. In 2009 the Naval Research Laboratory's (NRL's) Ion Tiger employed a hydrogen-powered fuel cell and they run for 23 hours and 17 minutes. Boeing completed tests on the Phantom Eye, a high-altitude, long endurance (HALE) research and surveillance flying at 20,000 m (65,000 ft) for up to four days at a time. Fuel cells are also being employed to endow with auxiliary power for aircraft, replacing fossil fuel generators that were formerly used to initiate the engines and power the on board electrical requirements. Fuel cells can help airplanes to reduce CO_2 and other pollutant emissions and noise.

(6)Boats

The world's first Fuel Cell Boat HYDRA used an AFC system with 6.5 kW net output. For each liter of fuel consumed, the average outboard motor produces 140 times the hydrocarbons produced by the modern car. Fuel cell engines have higher energy efficiencies than combustion engines, and therefore they offer better range and significantly reduced emissions .Iceland has committed converting its vast fishing fleet to use fuel cells to provide auxiliary power by 2015 and, eventually, to issue primary power in its boats. Amsterdam recently introduced its first fuel cell powered boat that ferries people around the city's famous and beautiful canals[4].

(7)Submarines

The latest fuel cell submarine is the U212A—an ultra-advanced non-nuclear sub developed by German naval shipyard Howaldtswerke Deutsche Werft.The system consists of nine PEM (polymer electrolyte membrane) fuel cells, providing between 30 kW and 50 kW each. Fuel cells provide some distinct advantages to submarines, in addition to being completely quiet, and can be distributed throughout a ship to improve balance and require far less air to run, allowing ships to be submerged for longer periods of time. Fuel cells offer a good alternative to nuclear fuels[4].

VI. CONCLUSION

The Operational Characteristics and the applications of the different types of fuel cells are discussed in this paper. Fuel cells should meet the demands of rapid start up, fast pick up, high power density ,easy and safe handling and greater fuel efficiency. Unfortunately all these requirements cannot be satisfied by any of the fuel cell type .However some of them can be used in present day technologies. The PEMFC can satisfy requirements like rapid start up, acceleration, power density. Even though it is not economically acceptable it will be best for light duty vechicles.The PAFCs application is limited to buses and trucks because of its size and weight. AFCs are limited because of its inability to tolerate CO_2 contamination in fuel as well as oxidant.

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