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Challenges and future developments in proton exchange membrane fuel cells

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Abstract

Fuel cell system is an advanced power system for the future that is sustainable, clean and environmental friendly. The importance of fuel cell as the future power system is discussed in the light of future fossil fuel depletion, impending international law on green house gases control and the national renewable energy policy. The modern development of the proton exchange membrane fuel cell (PEMFC) for the last 20 years is then briefly reviewed and the current status of international and national research and development of this type of are established. The review also discuss the remaining research and development issues that still need to be resolved before these fuel cells are available for commercial application. The main thrust in PEMFC research and development is to lower the cost of the fuel cell by reduction in membrane and electrocatalyst costs. Although Europe, USA, Canada and Japan are leading fuel cell research and development as commercialization, it is not too late for Malaysia to master this technology and to apply it to niche markets in the future.

Keywords: Polymer electrolyte membrane fuel cell; Research and development trends; Bipolar plates; System design; Commercialization; Issues and challenges

1. Introduction

The first working fuel cell was invented by Sir William Grove in 1843 by reacting oxygen and hydrogen on separate platinum electrodes that were immersed in dilute sulfuric acid inside five cells of a gas voltaic battery and using the current produced to electrolyze water in another similar cell. Fuel cell technology was too crude and inefficient then and could not compete with

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the dynamo invented by von Siemen. Since then, there have been several attempts to apply it for more than 100 years but none was very successful. In the 1920s, early German fuel cell research developed primitive carbonate and solid oxide fuel cells and from 1932 to 1959, Francis T. Bacon developed a fuel cell that used alkaline electrolyte and nickel electrodes [1].

It was only after a more efficient design of the fuel cell was made in the 1960s for the Gemini and Apollo space missions that fuel cell technology came of age. General Electric produced the fuel cell powered electrical power system for NASA's Gemini and Apollo space capsules that also provides drinking water for the crew. In developing the fuel cell technology, NASA funded more than 200 research contracts that finally brought the technology to a level now more viable for commercial application.

Fossil fuel reserves are finite and will be depleted in 70–150 years time. By the year 2015, the world fossil fluid fuel demand will outstrip the world fossil fluid fuel production (Fig. 1) and will precipitate an energy shortage crisis unless a sustainable alternative fuel will be available by then and will also face an energy shortage crisis in 2015 [2]. In addition, continued use of fossil fuels will generate green house gases that will cause global warming and climate change. The Kyoto protocol that regulates the reduction of green house gases has now become a binding international law when its ratification was approved by the Russian Republic. Solar and hydrogen energy could also be used but at a much lower total capacity. The contribution from both solar and hydrogen energy will grow in the future as the shortfall between the demand and the production of energy resources grow. While hydrogen powered internal combustion engines will continue to be used in the near term, the fuel cell will slowly be introduced first in hybrid power systems but ultimately in the long term in hydrogen energy systems at the advent of the so called hydrogen economy.

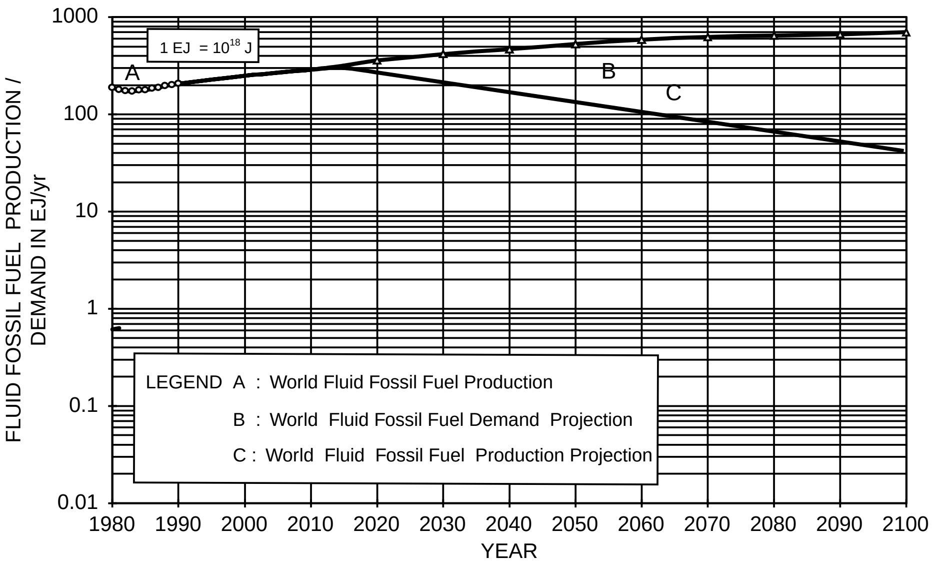

Fig. 1. Fluid (petroleum & natural gas) fossil fuel world production/demand estimates.

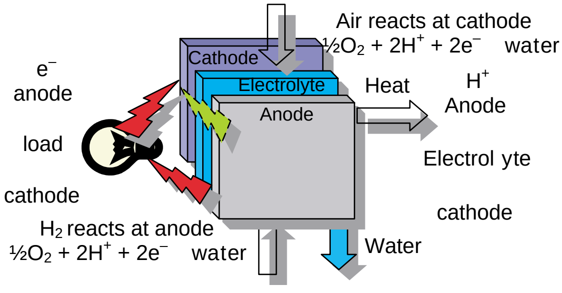

Fig. 2. A proton exchange membrane fuel cell.

2. The fuel cell

The fuel cell as shown in Fig. 2 is an electrochemical energy conversion device that converts chemical energy of hydrogen and oxygen into electricity and heat by electrochemical redox reactions at the anode and the cathode of the cell, respectively, that produces water as the only byproduct. It is the chemical engineering way of producing energy.

The fuel cell has a high-energy conversion efficiency of more than 40–50% that is higher than a coal fired power station or an internal combustion engine. It has no moving parts apart from the air and fuel blowers and is therefore more reliable and less noisy, has a lower maintenance cost and a long operating life compared to an equivalent coal-fired power station or internal combustion engine. Its modular compact design enables the consumer to increase or decrease

Table 1
Types of fuel cells

Fuel cell	Temperature (°C)	Efficiency (%)	Application	Advantages	Disadvantages
Alkaline fuel cell (AFC)	50–90	50–70	Space application	High efficiency	Intolerant to CO_2 in impure H_2 and air, corrosion, expensive
Phosphoric acid fuel cell (PAFC)	175–220	40–45	Stand-alone & combined heat & power	Tolerant to impure H_2, commercial	Low power density, corrosion & sulfur poisoning
Molten carbonate fuel cell (MCFC)	600–650	50–60	Central, stand-alone & combined heat & power	High efficiency, near commercial	Electrolyte instability, corrosion & sulfur poisoning
Solid oxide fuel cell (SOFC)	800–1000	50–60	Central, stand-alone & combined heat & power	High efficiency & direct fossil fuel	High temperature, thermal stress failure, coking & sulfur poisoning
Polymer electrolyte membrane fuel cell (PEMFC)	60–100	40–50	Vehicle & portable	High power density, low temperature	Intolerant to CO in impure H_2 and expensive
Direct methanol fuel cell (DMFC)	50–120	25–40	Vehicle & small portable	No reforming, high power density & low temperature	Low efficiency, methanol cross-over & poisonous byproduct

power by simply adding or removing the modules to the required power without having to redesign and reconstruct the whole plant. It is a clean technology and therefore, has very low chemical pollution. It could use pure hydrogen fuel or a variety of primary fuels such as natural gas and methanol that could be used directly or used to produce the hydrogen fuel instead. In a high temperature fuel cell, combined heat and power would increase its efficiency.

There are six main types of fuel cell of commercial importance: alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), polymer electrolyte membrane fuel cell (PEMFC) and direct methanol fuel cell (DMFC). Table 1 shows briefly their characteristics, advantages and disadvantages.

3. Research trends in PEMFC

The proton exchange membrane fuel cell (PEMFC) is a rugged, quite, clean and efficient energy conversion means for transportation application [3,4]. The capital cost of PEMFC originally used in space, at USD2000/kW is too expensive for terrestrial application and must be reduced in order to make it more competitive. Cost reduction is directed in order of priority, on polymer electrolyte membrane and catalyst electrodes (membrane electrode assemblies, MEA), fuel cell stack, fuel cell processor, power conditioner and air supply system [5–7].

3.1. Membrane cost reduction

Reduction of membrane cost could be achieved by using non-fluorinated polymer electrolytes with a cheaper sulfonated polymer backbone. Sulfonation of poly(ether ketone), poly(styrene) and related materials produces high proton conductivity polymers free of fluorine. Grafting of short sulfonate terminated side groups would increase thermal stability. Extensive research has been done to produce cheaper membranes to replace DuPont's Nafion 117 [8,9] use of commercially available polymer membranes such as PTFE, FEP, and PFA to produce new electrolyte membranes by grafting them with styrene and sulfonic acid through irradiation, looks very promising and further development is underway to improve performance of the membrane [10,11]. The research group in UKM and The Asahi Chemical Co. studied on alternative membranes available in the market like the Aciplex membrane from Asahi but found that the Dupont's Nafion 117 is still superior [12,13]. Extensive tests by Asahi on another promising electrolyte membrane, flemion, shows it is also a viable alternative [14].

3.2. Non-hydrated membrane

Current polymer electrolyte membranes must be fully hydrated for good proton conduction. The PEMFC system therefore requires the provision of a water management system that consists of air and fuel gas humidifiers and water recovery system. PEMFC system complexity could be reduced by the development of 'water-free' electrolytes that do not require hydration. It also enables the PEMFC to be operated under 'warm' conditions (i.e. above 100 °C) thus further improving its efficiency. Capital cost could also be further reduced because at warmer conditions less Pt could be used. Acid–base polymer complexes where a strong acid is coupled to a highly basic polymer are good proton conductors without hydration. Basic polymers such as PEO, PVA [poly(vinylalchohol)], PAAM [poly(acrylamide)], PVP [poly(vinylpyrrolidone)], PEI poly(-ethyleneimine), poly(aminosilicates), and PBI [poly(benzimidazole)] in combination with sulfuric, phosphoric and various halide acids could also be used [15]. Replacement of water in sulfonated polymer by a less volatile ionic liquid such as heterocyclic amines such as imidazole (pyrazole) and benzimidazole [16]. Better still, the ionic liquid should be linked to the polymer backbone to prevent lost of the ionic liquid. However, performance of these non-hydrated membranes is a very long way from that of Nafion

3.3. Low Pt loading electrodes

The lowering of the platinum loading on the electrodes has become the subject of many research [17–23]. Although a variety of electrode catalyst layers such as PTFE bound catalyst layer, sputtered thin catalyst layer by sputtering and electrodeposition have been made [24], it is still more efficient and cheaper to use PTFE bound catalyst layer with a gas diffusion layer. It is found that low-platinum electrode with a diffusion layer gives better performance than those without the latter [25–28]. Carbon nanotube based gas diffusion layer are now being developed. Complete elimination of Pt in electrodes could dramatically reduce PEMFC cost. The Pt could be replaced with metal oxides such as mixed conducting oxides, hydrous, amorphous $FePO_x$ but research is still very low.

3.4. CO tolerant anode electrocatatlysts

Since Pt is still the best electrocatalyst, its low CO tolerant has been improved by using bifunctional catalysts such using alloys of Pt with Ru, Mo and Re [29]. Electro-oxidation of CO, which would otherwise remain strongly absorbed onto Pt, is catalyzed by oxygen-like or hydroxyl species absorbed onto neighboring Ru sites. However, bifunctional catalysts are more effective if it is arranged in a specific way but alloy molecules are arranged in random. Intermetallic compounds such as Pt–Bi may have more regular and more thermodynamically stable structure but no extensive work has been done in this area.

3.5. Bipolar plate material

The cost of bipolar plates could be reduced by substituting the graphite plates with composite plates formed by pressing a mixture of conducting and non-conducting polymer powders [30,31]. Non-porous graphite is the standard material for bipolar plates but graphite bipolar plates are expensive to manufacture because of the long time required to machine the plates using a CNC machine. Metal bipolar plates have been used but dissolution of plate due to highly acidic environment renders the plate having a short operating life. This problem could be solved by coating the metal plate. Coated bipolar metal plates, however, tend to crack due to unequal coefficient of expansion of the metal and the coating. A variation of the metal bipolar plates is the porous metal bipolar plates, which could function both as a bipolar plate and a gas distributor without further forming processes [32]. Metal–carbon–polymer composites are better both in terms of material and manufacturing costs. Most suitable polymers are thermoplastics such as polyethylene, polypropylene & poly(vinylidene fluoride) [33] and thermoset resins such as penolics, epoxies & vinyl esters.

3.6. Stack and bipolar plate design

The proper design of flow distribution of gases in the bipolar plates making up the internally manifolded stack is also important to ensure mass transfer limitations is reduced to a minimum

Table 2
Current fuel cell materials

Fuel cell	Anode	Cathode	Electrolyte	Interconnect material (SOFC) /bipolar plate (PEMFC)
SOFC	$La_{1-x}Sr_xMnO_{3-\delta}$ (lanthanum strontium manganite or LSM) $0.15<x<0.25$	Ceramic metal composite (cermet) comprised of Ni+YSZ	Yttria stabilized zirconia (YSZ), with 8 mol% Y	Alkali doped LaCrO3 (lanthanum chromite), with specific dopant (typically, Sr, Ca or Mg)
PEMFC	Pt nano particles supported on carbon	Pt nano particles supported on carbon	Polymer electrolyte membrane (Nafion)	Graphite or graphite-polymer composite
DMFC	Similar to those of PEMFC			

[34,35]. The distribution topology also known as the flow field include parallel, serpentine and interdigitated as well as various combinations of them [36].

3.7. PEMFC system design

System design of the fuel cell has long been neglected and it was only towards the end of the last decade and early this century that greater efforts have been made to improve fuel cell system design in order to improve further the efficiency [37–39]. The application of process system engineering technology such as pinch technology is now being applied to fuel cell systems [40]. One problem in process system engineering of fuel cell systems is the lack of good models for most of the fuel cell system components such as the fuel stack itself, gas humidifier, pressure swing adsorber, membrane reactor fuel cell processor and membrane gas separator. Simpler model of the fuel cell for use in conceptual design of PEMFC system is developed by Masdar et al. [41]. Iyuke et al., 2001 proposed a model for the humidifier [42] while Hassan et al., 2003 develops the water management system models for the PEMFC system [43]. Kamaruddin et al., 2003 developed a model for the gas membrane separator to separate the hydrogen from CO (Table 2) [44].

4. Fuel cell system demonstration and commercialization

The PAFC has reached commercialization stage mainly for central stationary power of up to 11 MW. The MCFC and SOFC have been demonstrated for stationary central power of up to 250 and 100 kW, respectively, since late 1990s. Both are now entering commercial markets in the next 5 years. Although PEMFC has been demonstrated in buses, cars, motorcycles and portable power units of up to 250 kW all over the world since the early 1990s, there are still many unresolved commercialization issues especially manufacturing cost. The PEMFC are expected to be fully commercialized in the next 10–15 years. Table 3 shows the commercialization status and future trends of the various fuel cell types [45].

The USA, Europe, Canada and Japan are leading the world in fuel cell research and development and in fuel cell commercialization (Table 4) [45]. Iceland has taken the bold step of converting to the hydrogen economy in 2003. A hydrogen future act was passed in the US Senate to prepare the USA for a future hydrogen economy. More than USD one billion from the USA government will be spent in the next 5 years to commercialize fuel cells and prepare the USA's infrastructure for the future hydrogen economy.

Table 3
Commercialization status and trends of various types of fuel cells

Fuel cell	Commercialization status	Future trends
Phosphoric acid fuel cell (PAFC)	Commercial: 50–200 kW & 1–11 MW units Total: 65 MW worldwide, Technology leader: United Technologies	Increase PAFC installations Expand PAFC markets
Molten carbonate fuel cell (MCFC)	Demonstrator plant in California, 1997, 2 MW Production capacity of 250 kW prototypes at 400 MW in 2004 Technology leader: Fuel Cell Energy Inc.	Increase stationary applications
Solid oxide fuel cell (SOFC)	Demonstrator plant in Netherlands, 1998 100 kW Technology leader: Siemen Westinghouse	Increase stationary applications
Polymer electrolyte membrane fuel cell (PEMFC)	Ballard PEMFC powered bus demonstrator, 1993	Improve PEMFC performance for bus fleet operations
	Xcellsis commercial PEMFC powered bus by 2005 All major car manufacturers has PEMFC powered car prototypes Stationary (250 kW) & domestic power (1–50 kW) prototypes Technology leader: Ballard	Expand PEMFC markets

5. Conclusions

Fuel cell will be the technology of choice of the future hydrogen economy that will certainly be a reality when our fossil fuel runs out. The first three older fuel cells (AFC, PAFC and MCFC) were well developed and there are no more research and development issues to address. The developments of both fuel cell technologies have already reached the top plateau of the S-curve of technological development. In contrast, the technologies for the last three types of fuel cells (SOFC, PEMFC and DMFC) are still developing rapidly at the acceleration part of the S-curve and there are numerous opportunities for innovations before both types of fuel cells are available for commercial applications. Contemporary research and development in fuel cells are therefore now focused mainly on SOFC, PEMFC and DMFC. Although fuel cell technologies has been studied for many years in USA, Europe, Canada and Japan, other smaller countries could still contribute to the development of fuel cell technologies particularly PEMFC and DMFC technologies, and to commercialize them in niche markets.

Table 4
Commercialization status and trends of fuel cells in different countries

Country	Commercialization status	Future trends
USA	Light duty fuel cell vehicle R&D on direct methanol fuel cell (DMFC) & SOFC Stationary power demonstrator	Improve fueling infrastructure Increase PAFC installations
Europe	PAFC, PEMFC & DMFC for portable & mobile applications SOFC & MCFC for stationary power R&D on advanced multi-fuel processor	Improve mobile applications
Canada	PEMFC for transit buses and cars	Improve PEMFC for fleet operation
Japan	PEMFC, MCFC & SOFC for stationary and mobile applications	Increase PAFC installations Expand PAFC market

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