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Comparative study of different fuel cell technologies

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ABSTRACT

Fuel cells generate electricity and heat during electrochemical reaction which happens between the oxygen and hydrogen to form the water. Fuel cell technology is a promising way to provide energy for rural areas where there is no access to the public grid or where there is a huge cost of wiring and transferring electricity. In addition, applications with essential secure electrical energy requirement such as uninterruptible power supplies (UPS), power generation stations and distributed systems can employ fuel cells as their source of energy.

The current paper includes a comparative study of basic design, working principle, applications, advantages and disadvantages of various technologies available for fuel cells. In addition, techno-economic features of hydrogen fuel cell vehicles (FCV) and internal combustion engine vehicles (ICEV) are compared. The results indicate that fuel cell systems have simple design, high reliability, noiseless operation, high efficiency and less environmental impact. The aim of this paper is to serve as a convenient reference for fuel cell power generation reviews.

Contents

1. Introduction

Fuel cells are basically open thermodynamic systems. They operate on the basis of electrochemical reactions and consume reactant from an external source [1–4]. They are favorable alternatives to conventional electricity generation methods for small-scale applications. Hydrogen and hydrocarbon fuels contain significant chemical energy in comparison with conventional battery materials; hence they are now widely developed for numerous energy applications.

Fuel cell technology is a promising substitute for fossil fuels to provide energy for rural areas where there is no access to the

Abbreviations: UPS, uninterruptible power supplies; O&M, operation and maintenance; US, United States; UTC, United Technologies Corporation; AFC, alkaline fuel cell; NASA, National Aeronautics Space Administration; PAFC, phosphoric acid fuel cell; CO, carbon monoxide; SOFC, solid oxide fuel cell; MCFC, molten carbonate fuel cell; BASE, beta-alumina solid electrolyte; PEMFC, proton exchange membrane fuel cell; MEA, membrane electrode assembly; PEM, proton exchange membrane; FCV, fuel cell vehicle; ICE, internal combustion engine; DMFC, direct methanol fuel cell; CHP, co-generation heat power/combined heat and power; FCV, fuel cell vehicle; R&D, research and development; ICEV, internal combustion engine vehicle; EV, electric vehicle; PSA, pressure swing adsorption.

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Table 1
Comparison of fuel cell with other power generating systems [8].

	Reciprocating engine: diesel	Turbine generator	Photovoltaic	Wind turbine	Fuel cells
Capacity range	500 kW–50 MW	500 kW–5 MW	1 kW–1 MW	10 kW–1 MW	200 kW–2 MW
Efficiency	35%	29–42%	6–19%	25%	40–85%
Capital cost ($/kW)	200–350	450–870	6600	1000	1500–3000
O & M cost ($/kW)	0.005–0.015	0.005–0.0065	0.001–0.004	0.01	0.0019–0.0153

public grid or huge cost of wiring and transferring electricity is required. In addition, applications with essential secure electrical energy requirement such as uninterruptible power supplies (UPS), power generation stations and distributed systems can employ fuel cells as their source of energy. Table 1 presents general comparison between fuel cell systems and other power generation systems [5–7].

Table 1 indicates that fuel cell systems perform with the highest efficiency compared to conventional distributed energy systems. They have simple design and reliable operation as well. In addition, utilizing hydrogen as the reactant makes them the most environmentally clean and noiseless energy systems [9–14]. Currently, fuel cell systems are employed widely in small scale as well as large scale applications such as combined heat and power (CHP) systems, mobile power systems, portable computers and military communication equipment.

Despite all the advantages, there are some limitations for utilizing fuel cells. For example, life span of fuel cells shortens by pulse demands and impurities of gas stream. Low power density per volume, less accessibility and less durability are other challenges for fuel cell technology development. Though, great breakthrough is yet to be seen, positive progress is witnessed throughout the recent years.

2. Working principle of fuel cells

Fuel cells generate electricity and heat via electrochemical reaction which is actually the reversed electrolysis reaction. It happens between the oxygen and hydrogen to form the water. There are a range of designs available for fuel cells; however, they all operate with the same basic principles. The main difference in various fuel cell designs is the chemical characteristics of the electrolyte [3]. Eq. (1) shows the electrochemical reaction and Fig. 1 depicts the operating principle of a fuel cell.

$$\begin{array}{l} 2H_2(g) \quad + O_2(g) \quad \rightarrow 2H_2O \; + \text{energy} \\ \text{hydrogen} + \text{oxygen} \rightarrow \text{water} + (\text{electrical power} + \text{heat}) \end{array} \quad (1)$$

A fuel cell has four main parts: anode, cathode, electrolyte and the external circuit. At the anode, hydrogen is oxidized into protons and electrons, while at the cathode oxygen is reduced

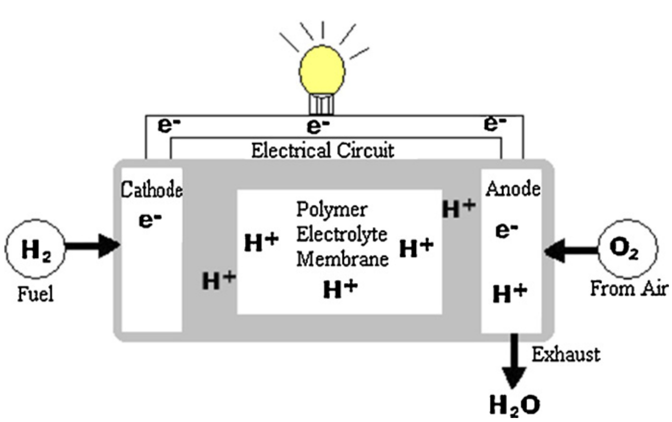

Fig. 1. Operating principle of a fuel cell [13].

to oxide species and reacts to form water. Depending on the electrolyte, either protons or oxide ions are transported through an ion-conductor electron-insulating electrolyte while electrons travel through an external circuit to deliver electric power [4]. Nevertheless, fuel cells often produce only very small amount of current due to diminutive contact area between electrodes, electrolyte and the gas. Another problem to be considered is the distance between electrodes. To improve the efficiency of fuel cells and maximize the contact area, a thin layer of electrolyte with flat porous electrodes is considered for electrolyte and the gas penetration.

The reaction between oxygen and hydrogen to generate electricity is different for various types of fuel cells. In an acid electrolyte fuel cell, electrons and protons (H+) are released from hydrogen gas ionizing at the anode electrode. The generated electrons pass though an electrical circuit and travel to the cathode while protons are delivered via electrolyte. This exchange releases electrical energy. Simultaneously at the cathode side, the water is forming as a result of the reaction between electrons from electrode and protons from electrolyte. The reactions happening at the anode and cathode are shown in (2) and (3), respectively.

$$\text{Anode}: \quad 2H_2 \rightarrow 4H^+ + 4e^- \quad (2)$$

$$\text{Cathode}: \quad O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \quad (3)$$

Acid electrolytes and certain polymers that contain free H^+ ions are often called “proton exchange membranes”. They serve more properly and effectively for proton delivering functions since they solely allow the H^+ ions passing through it. The electrical current is lost in the case of delivering electrons through the electrolyte [6].

3. Types of fuel cells

Fuel cells are different according to their operating temperature, efficiency, applications and costs. They are classified based on the choice of fuel and electrolyte into 6 major groups [8]:

- Alkaline fuel cell (AFC)
- Phosphoric acid fuel cell (PAFC)
- Solid oxide fuel cell (SOFC)
- Molten carbonate fuel cell (MCFC)
- Proton exchange membrane fuel cell (PEMFC)
- Direct methanol fuel cell (DMFC)

3.1. Alkaline fuel cell (AFC)

The AFC generate electric power by utilizing alkaline electrolyte potassium hydroxide (KOH) in water based solution. The presence of the hydroxyl ions travelling across the electrolyte allows a circuit to be made and electrical energy could be extracted. Fig. 2 illustrates an alkaline fuel cell.

At anode, 2 hydrogen gas molecules are combined with 4 hydroxyl ions with a negative charge to release 4 water molecules and 4 electrons. The redox reaction taking place is oxidation as in (4) [16,17]:

$$(\text{Oxidation}) \quad 2H_2 + 4OH^- \rightarrow 4H_2O \; + \; 4e^- \quad (4)$$

Electrons released in this reaction, reach the cathode through the external circuit and react with water to generate (OH^-) ions.

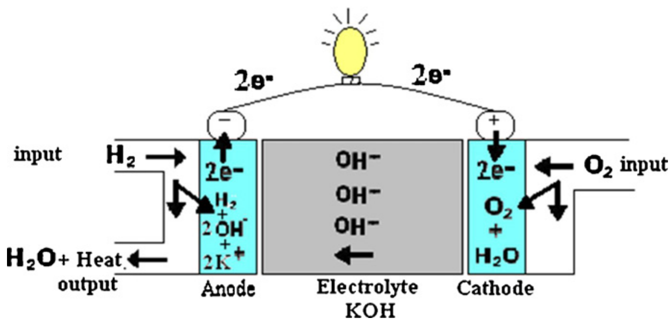

Fig. 2. Alkaline fuel cell (AFC) [15].

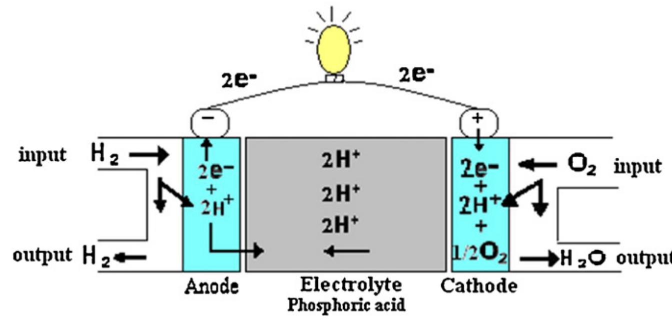

Fig. 3. Phosphoric acid fuel cell (PAFC) [15].

At cathode, oxygen molecule and 2 water molecules combined and absorbed 4 electrons to form 4 negatively charged hydroxyl ions. The occurring redox reaction is reduction as below [16,17]:

$$\text{(Reduction)} \quad O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{5}$$

AFCs generally perform in temperatures between 60 and 90 °C; however, recent designs can operate at low temperatures between 23 and 70 °C. AFCs are classified as low operating temperature fuel cells with low cost catalysts. The most common catalyst to speed up electrochemical reactions in cathode and anode side in this type of fuel cell is nickel. Electrical efficiency of AFCs is about 60% and CHP efficiency is more than 80%. They can generate electricity up to 20 kW [18,19].

NASA has first used AFCs to supply drinking water and electric power to the shuttle missions for space applications. Currently, they are employed in submarines, boats, forklift trucks and niche transportation applications [20]. AFCs are considered as the most cost efficient type of fuel cells since the electrolyte used is a standard chemical potassium hydroxide (KOH). The catalyst for the electrodes is nickel which is not expensive compared with other types of catalysts. AFCs have simple structures due to eliminating bipolar plates. They consume hydrogen and pure oxygen to produce portable water, heat and electricity sources. The by-product water produced by AFC is the drinking water which is very useful in spacecrafts and space shuttle fleets. They have no green house gas emissions and operate with a high efficiency of about 70%. In spite of all the advantages of AFCs, they are defeated by getting easily poisoned with carbon dioxide. The water based alkaline solution (KOH) used in AFCs as electrolyte, absorbs CO_2 through the conversion of KOH to potassium carbonate (K_2CO_3) and consequently poisons the fuel cell. Therefore, AFCs typically use purified air or pure oxygen which in turn increases the operating costs. Hence, one concern is to find a substitute for KOH [6,18].

3.2. Phosphoric acid fuel cell (PAFC)

Phosphoric acid fuel cells (PAFC) use carbon paper electrodes and liquid phosphoric acid (H_3PO_4) electrolyte. H_3PO_4 (3.09% H, 31.6% P, 65.3% O) is a clear colourless liquid used in fertilizers, detergents, food flavouring and pharmaceuticals. The ionic conductivity of phosphoric acid is low at low temperatures, so PAFC can operate at the range of 150–220 °C temperature. The charge carrier in this type of fuel cell is the hydrogen ion (H^+ or proton). They pass from the anode to the cathode through the electrolyte and the expelled electrons return to the cathode through the external circuit and generate the electrical current. At the cathode side, water is forming as the result of the reaction between electrons, protons and oxygen with presence of platinum catalyst to speed up the reactions. Expelled water is usually used in heating applications. Continuous operation and system start-up is a concern at 40 °C due to solidity of phosphoric acid at this temperature [21–24]. Fig. 3 shows a PAFC.

As the figure shows, the hydrogen expelled at the anode splits into its 4 protons and 4 electrons. The redox reaction taking place in anode is oxidation as in (6). While at cathode, the redox reaction is reduction (7) where 4 protons and 4 electrons combine with the oxygen to form water [22–24]:

$$\text{(Oxidation)} \quad 2H_2 \rightarrow 4H^+ + 4e^- \tag{6}$$

$$\text{(Reduction)} \quad O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{7}$$

The electrons and protons pass through the external circuit and the electrolyte, respectively. The result is generation of electrical current and heat. The heat is usually exploited for water heating or steam generation at atmospheric pressure; however, steam reforming reactions produce some carbon monoxide (CO) around the electrodes which might poison the fuel cell and affect the PAFC performance. The solution to reduce the CO absorption is to increase the anode temperature tolerance. The higher tolerance for CO means higher temperature tolerance at anode. At high temperatures, the CO is desorbed in reversed electro-catalyst reaction at cathode. Contrary to other acid electrolytes that need water for conductivity, PAFC concentrated phosphoric acid electrolyte is capable of operating in temperatures higher than boiling point of water.

PAFC does not require pure oxygen for its operation since CO_2 does not affect the electrolyte or cell performance. They run on air and can be easily operated with reformed fossil fuels. Besides, H_3PO_4 has lower volatility and long-term stability. The initial cost is high since PAFC uses air with ~21% oxygen instead of pure oxygen resulting in 3 times reduction in the current density. Therefore, PAFC is designed in stack bipolar plate to increase electrode area for more energy production which implies high initial cost for this technology. Currently, PAFC systems are in commercial stage with capacity up to 200 kW and systems with higher capacities (11 MW) are already tested. The PAFCs are expensive to manufacture due to the need for finely dispersed platinum catalyst coating the electrodes. Unlike AFCs, hydrogen steam impurity (CO_2) does not affect the PAFCs. Electrical efficiency of this type of fuel cells is between 40 and 50% and CHP efficiency about 85%. They are typically used for on-site stationary applications [21–24].

3.3. Solid oxide fuel cell (SOFC)

Solid oxide fuel cells (SOFCs) are high temperature fuel cells with metallic oxide solid ceramic electrolyte. Fig. 4 shows a SOFC.

SOFCs generally use a mixture of hydrogen and carbon monoxide formed by internally reforming hydrocarbon fuel and air as the oxidant in the fuel cell [4]. Yttria stabilized zirconia (YSZ) is the most commonly used electrolyte for SOFCs because of its high chemical and thermal stability and pure ionic conductivity [25,26].

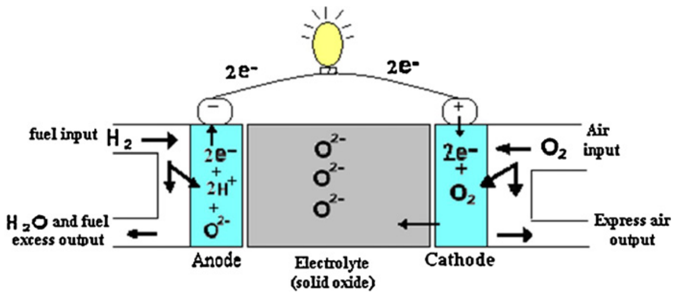

Fig. 4. Solid–oxide fuel cell (SOFC) [15].

Oxygen is oxidized in reduction reaction at the cathode (air electrode) at 1000 °C, while, fuel oxidation happens at the anode. The anode should be porous to conduct fuel and transport the products of fuel oxidation away from the electrolyte and fuel electrode interfaces [27–29].

$$\text{(Oxidation)} \quad (1/2)O_2(g) + 2e^- \rightarrow O^{2-}(s) \tag{8}$$

$$\text{(Reduction)} \quad O^{2-}(S) + H_2(g) \rightarrow H_2O(g) + 2e^- \tag{9}$$

SOFCs are well adopted with large scale distributed power generation systems with capacity of hundreds of MWs. The by-product heat is usually used to generate more electricity by turning gas turbines and hence increasing the CHP efficiency between 70 and 80%. SOFC systems are reliable, modular and fuel adaptable with low harmful gas (NO_x and SO_x) emissions. They can be considered as local power generation systems for rural areas with no access to public grids. Furthermore, they have noise free operation and low maintenance costs.

On the other hand, long start-up and cooling-down times as well as various mechanical and chemical compatibility issues limit the use of SOFCs. Authors in [26–31] have studied possible solutions to reduce the operating temperature and claimed if successful and sustainable counter-measures are built up, SOFC may bring energy production to a new generation.

3.4. Molten carbonate fuel cell (MCFC)

Molten carbonate fuel cells (MCFCs) are high-temperature fuel cells. They use molten carbonate salt mixture as electrolyte suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte (BASE) [32]. A MCFC is illustrated in Fig. 5.

In MCFC, the reaction at the hydrogen electrode occurs between hydrogen fuel and carbonate ion, which react to form carbon dioxide, water and electrons. At the anode, the feed gas (usually methane CH_4) and water H_2O are converted to hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2).

$$\text{(Reform1)} \quad CH_4 + H_2O \rightarrow CO + 3H_2 \tag{10}$$

$$\text{(Reform2)} \quad CO + H_2O \rightarrow CO_2 + H_2 \tag{11}$$

Simultaneously, two electro-chemical reactions consume hydrogen and carbon monoxide and generate electrons at anode. Both reactions in (12) and (13) use carbonate ions ($CO_3{}^{2-}$) available in the electrolyte:

$$\text{(Oxidation1)} \quad H_2 + CO_3{}^{2-} \rightarrow H_2O + CO_2 + 2e^- \tag{12}$$

$$\text{(Oxidation2)} \quad CO + CO_3{}^{2-} \rightarrow 2CO_2 + 2e^- \tag{13}$$

The reduction happens at cathode and expels new carbonate ions from oxygen (O_2) and carbon dioxide (CO_2). Hereby, the carbonate ions produced at cathode are transferred through the electrolyte to the anode. Electric current and cell voltage can be collected at electrodes [33].

$$\text{(Reduction)} \quad (1/2)O_2 + CO_2 + 2e^- \rightarrow CO_3{}^{2-} \tag{14}$$

MCFCs are currently employed for natural gas and coal-based power plants in electrical utility, industrial and military applications. The advantages and disadvantages of MCFCs are closely related to its high operating temperature. MCFC may be directly fuelled with hydrogen, carbon monoxide, natural gas and propane. They do not require noble metal catalysts for electrochemical oxidation and reduction. They also do not require any infrastructure development for installation; however, long time is needed to reach to the operating temperature and generating power [33–36].

4. Proton exchange membrane fuel cell (PEMFC)

In PEMFCs, the hydrogen is activated by catalyst to form proton ion and eject electron at the anode. The proton passes through the membrane while electron is forced to flow to the external circuit and generate electricity. The electron then flows back to the cathode and interact with oxygen and proton ion to form water. The chemical reactions occurring at each electrode are presented in (15) and (16). The PEMFC is illustrated in Fig. 6.

$$\text{Anode}: \quad H_2(g) \rightarrow 2H^+ + 2e^- \tag{15}$$

$$\text{Cathode}: \quad (1/2)O_2(g) + 2H^+ + 2e^- \rightarrow H_2O(l) \tag{16}$$

$$\text{Overallreaction}: \quad H_2(g) + (1/2)O_2(g) \rightarrow H_2O(l) \tag{17}$$

Basically the PEMFC is comprised of bipolar plates and membrane electrode assembly (MEA). The MEA is composed of dispersed catalyst layer, carbon cloth or gas diffusion layer and the membrane. Membrane is to transport protons from anode to cathode and block the passage of electron and reactants. Gas diffusion layer is to access the fuel uniformly. Electrons at anode pass through the external circuit and generate electricity.

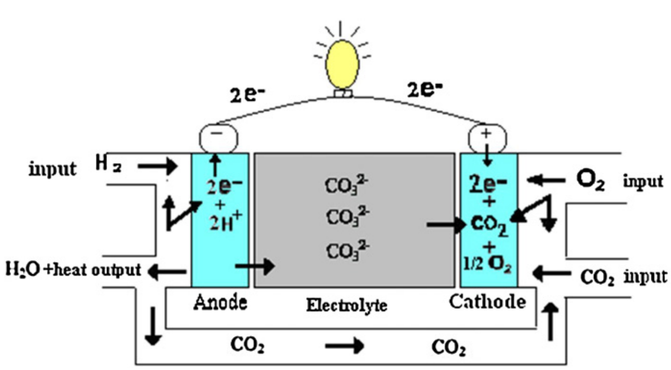

Fig. 5. Molten carbonate fuel cell (MCFC) [15].

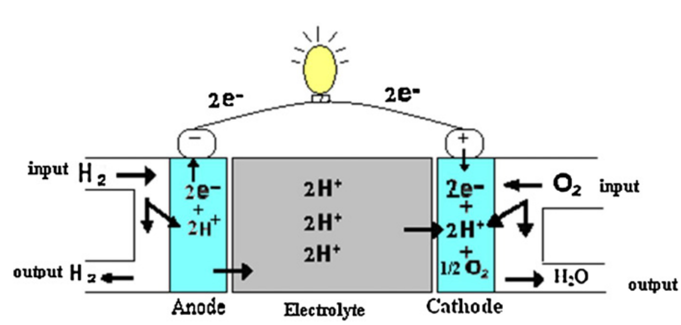

Fig. 6. Proton exchange membrane fuel cell (PEMFC) [15].

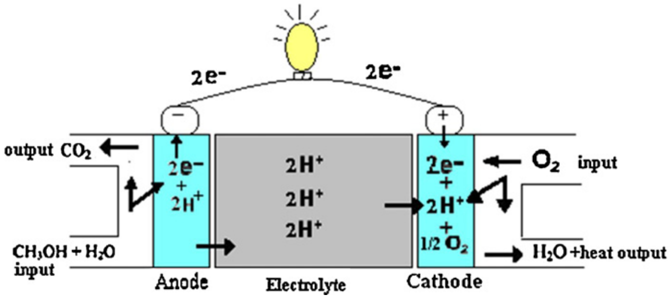

Fig. 7. Direct methanol fuel cell (DMFC) [15].

PEMFCs are low temperature fuel cells with operating temperature between 60 and 100 °C. They are light weight compact systems with rapid start-up process. The sealing of electrodes in PEMFCs is easier than other types of fuel cells because of solidity of the electrolyte. In addition, they have longer lifetime and cheaper to manufacture [37–39].

The total cost of car with the FEMFC system is 500–600 $/kW which is 10 folded compare with cars using Internal Combustion Engine (IEC) [40]. Total cost of the PEMFCs includes the costs of assembly process, bipolar plate, platinum electrode, membrane and peripherals.

From efficiency point of view, the higher the working temperature the higher efficiency can be gained. This is due to the higher reaction rate. Nevertheless, working temperature above 100 °C will vaporize the water causing dehydration to the membrane which leads to the reduction in the proton conductivity of the membrane. Electrical efficiency of PEMFCs is between 40 and 50% and the output power can be as high as 250 kW.

PEMFC systems are usually used in portable and stationary applications. However, among applications of PEMFCs, transportation seems to be the most suitable since they provide continuous electrical energy supply at high level of efficiency and power density. They also require minimum maintenance because there are no moving parts in the power generating stacks of the fuel cells. Fuel cell vehicles are the most promising application of PEMFC systems. The reason is the observability of technology development by people which can significantly improve the acceptability of such systems among communities. A report from McNicol et al. [41] states that a FCV can successfully contend against conventional ICE vehicles. However, the initial cost for FCV is higher than that for ICE vehicles.

5. Direct methanol fuel cell (DMFC)

Direct methanol fuel cell (DMFC) is promoted type of the PEMFCs. It is a suitable source of power for portable energy purposes due to low temperature operation, long lifetime and rapid refuelling system characteristics. In addition, they do not need to be recharged and are addressed as clean renewable energy source. Fig. 7 illustrates a direct methanol fuel cell (DMFC).

Energy source of the DMFC systems is methanol. At anode, methanol is reformed into carbon dioxide (CO_2) while at cathode steam or water is formed using oxygen available in the air. The reactions are shown in Eqs. (18) and (19):

$$\text{(Anode)} \quad CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \tag{18}$$

$$\text{(Cathode)} \quad (3/2)O_2 + 6e^- + 6H^+ \rightarrow 3H_2O \tag{19}$$

DMFC systems are generally classified into active and passive. Active DMFCs are high efficient and reliable systems consisting of methanol feed pump, CO_2 separator, fuel cell stack, methanol sensor, circulation pump, pump drivers and controllers. Using pump for water circulation can significantly increase the efficiency of such systems. Active DMFCs are usually used in control applications for quantities such as flow rate, concentration and temperature.

In the passive DMFC systems, the methanol pumping devices and external process for blowing air into the cell are eliminated. Hence, oxygen of ambient air is defused into the cathode via air-breathing feature of the cell. Similarly, methanol is defused into the anode from an integrated feed reservoir driven by a concentration gradient between the anode and the reservoir. Passive systems are cheap, simple and capable of substantial reduction in parasitic power loss and system volume.

Methanol is utilized in DMFCs in form of vapour or liquid. Vapour feed is preferable to liquid feed in term of cell voltage and power density. Methanol does not perform perfectly for mass transfer and requires high localized cooling at anode. Furthermore, the extent of methanol crossover from anode to cathode and gas release at the electro catalyst surface leads to the lower performance of liquid feed cells [42]. On the other hand, vapour feed cells have some drawbacks as well, such as dehydrating the membrane, less lifetime and high temperature required for fuel vaporization. Consequently, more complex and costly reformer is needed. In addition, they are not suitable for portable applications.

Proton Exchange Membrane (PEM) is considered as the main part in DMFCs to provide low penetrability and high proton conductivity. In addition, it provides high thermal and chemical stability for proper performing of DMFC. Flemion from Asahi Chemical and Nafion from Dupont are the most common perfluorinated ion-exchange polymers used for DMFC. They have both mechanical strength and high hydrophobicity of the sulphuric acids which is more prominent due to the presence of the water. As a consequence, water and methanol travel across perfluorosulfonic acid membrane which is a form of methanol crossover that has negative impact on its performance [43,44]. The PEM can be modified to overcome this problem in 2 ways: sulfonation and preparing composite membrane by the incorporation of inorganic-ceramic materials [45,46].

6. Comparison of different fuel cell technologies

Applications of fuel cells depend on the type of fuel cell to be used. With various types of fuel cell technologies available, it is necessary to clarify which technology is best suited to a specific application. Fuel cells can produce a wide range of power from 1 to 10 MW; hence they can be employed in almost any application that needs power. They can be used in small range power devices and personal electronic equipment such as mobile phones and personal computers (PCs). Medium scale power applications include fuel cell vehicles, domestic appliances, military applications and public transportation. Finally, in the large range power applications (1–10 MW), fuel cells are used in distributed power systems and grid quality AC. Table 2 is a summary of operational specifications of fuel cell technologies, while Table 3 presents the applications, main advantages and key features of fuel cells.

Fig. 8 compares the maximum operating temperature of fuel cells vs. output power. Generally, higher output power can be achieved at higher operating temperature. Fig. 9 demonstrates the electric efficiencies and combined heat and power (CHP) efficiencies of various fuel cells.

Efficiency and specific costs of conventional CHP (co-generation heat power) plants for different fuel–cell systems are tabulated in Table 4. The electrical power capacity ranges between 100 and 300 kW [15,47–50].

Table 2
Summary of operational specifications of fuel cell technologies [8].

Fuel cell type	AFC	PAFC	SOFC	MCFC	PEMFC	DMFC
Common Electrolyte	Aqueous solution of potassium hydroxide soaked in a matrix	Liquid phosphoric acid soaked in a matrix	Yttria stabilized zirconie	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	Solid organic polymer poly-perfluorosulfonic acid	Solid polymer membrane
Anode reaction	$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$	$2H_2 \rightarrow 4\,H^+ + 4e^-$	$O^{2-}\,(S) + H_2\,(g) \rightarrow H_2O\,(g) + 2e^-$	$H_2O + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$H_2\,(g) \rightarrow 2H^+ + 2e^-$	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$
Cathode reaction	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	$O_2 + 4\,H^+ + 4e^- \rightarrow H_2O$	$1/2\,O_2\,(g) + 2e^- \rightarrow O^{2-}(s)$	$1/2\,O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$1/2O_2\,(g) + 2H^+ + 2e^- \rightarrow H_2O$	$3/2O_2 + 6e^- + 6H^+ \rightarrow 3H_2O$
Charge carrier	OH^-	H^+	O^-	$CO_3{}^-$	H^+	H^+
Fuel	Pure H_2	Pure H_2	H_2, CO, CH_4, other	H_2, CO, CH_4, other	Pure H_2	CH_3OH
Oxidant	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air
Cogeneration	No	Yes	Yes	Yes	No	No
Reformer is required	Yes	Yes	–	–	Yes	–
Cell voltage	1.0	1.1	0.8–1.0	0.7–1.0	1.1	0.2–0.4

Table 3
Comparison of technical characteristics of fuel cell technologies [39].

Fuel cell type	Operating Temperature (°C)	System Output (kW)	Electrical Efficiency (%)	Combines Heat and Power (CHP) Efficiency	Applications	Advantages
Alkaline (AFC)	90–100	10–100	60	>80	Military Space	Cathode reaction faster in alkaline electrolyte, leads to higher performance Can use a variety of catalysts
Phosphoric Acid (PAFC)	150–200	50–1000	>40	>85	Distributed generation	Higher overall efficiency with CHP Increased tolerance to impurities in hydrogen
Solid Oxide (SOFC)	600–1000	<1–3000	35–43	<90	Auxiliary power Electric utility Large distributed generation	High efficiency Fuel flexibility Can use a variety of catalysts Solid electrolyte reduces electrolye management problems Suitable for CHP Hybrid/GT cycle
Molten Carbonate (MCFC)	600–700	<1–1000	45–47	>80	Electric utility Large distributed generation	High efficiency Fuel flexibility Can use a variety of catalysts Suitable for CHP
Polymer Electrolyte Membrane (PEM)	50–100	<1–250	53–58	70–90	Backup power Portable power Small distributed generation Specialty vehicle Transportation	Solid electrolyte reduces corrosion & electrolyte management problems Low temperature Quick start-up
Direct methanol fuel cell (DMFC)	60–200	0.001–100	40	80	Replace batteries in mobiles; computers and other portable devices	Reduced cost due to absence of fuel reformer

Table 4
Specific cost for CHP plants with commercial fuel cells [15].

	PEMFC (BPS)[a]	PAFC (ONSI)[b]	MCFC (MTU)[c]	SOFC (SWPC)[d]
Electrical power (kWe)	250	200	280	100
Efficiency (%)	34	38	48	47
Specific cost (€/kWe)	~10,000	~5000	~8000	~20,000

[a] BPS: Ballard Power System, e.g., BEWAG Berlin 250 kWe PEMFC, natural gas, co-generation.
[b] ONSI: 200 kWe PAFC, natural gas, co-generation.
[c] MTU: Hot Module, e.g., Stardwerke Bielefeld, RWE, 250 kWe MCFC, natural gas, co-generation.
[d] SWPC: Siemens WestingHouse Power Corporation, 100 kWe SOFC, co-generation.

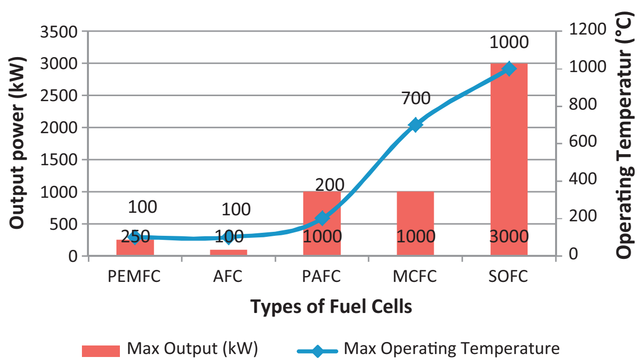

Fig. 8. Comparison of maximum operating temperature of fuel cell vs. output power.

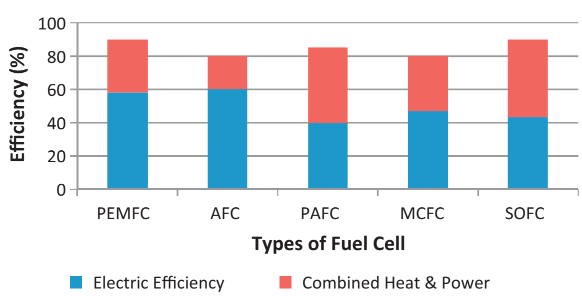

Fig. 9. Efficiency of different fuel cell types.

7. Fuel cell electric vehicle (FCEV)

There are numerous applications for fuel cells. Each application demands its own requirements as well. The majority of fuel cell applications can be classified as:

- Applications with high power reliability: telecommunication, high technology manufacturing facilities, data processing and call centers.
- Applications with emission minimization or elimination: urban areas, industrial facilities, airports, cars, buses and regions with strict emission standards.
- Applications for areas with limited access to utility grid: portable applications and remote areas.
- Applications for biological waste gases management: waste treatment plants.

Among all the applications for fuel cells, FCEV has attracted more attention in the last years. Almost all the vehicle manufacturers are presently performing the Research and Development (R&D) on FCEVs. They are special type of electric vehicles constructed in different structure of common internal combustion engine. In conventional diesel or gasoline-fuelled vehicles, energy from the fuel is transmitted from the engine to the wheels by a mechanical power train; however, in FCEVs the power train is electrical.

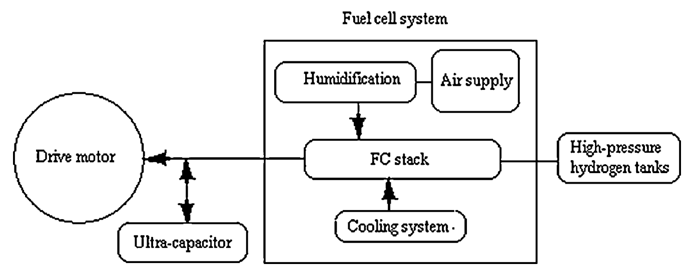

Fig. 10. Hybrid FCV power train [52].

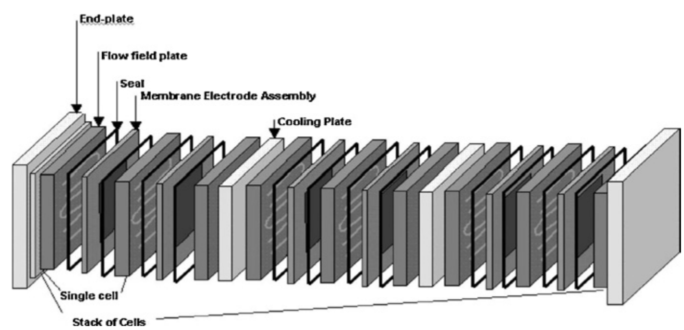

Fig. 11. Stack of PEMFC [53].

A study conducted by Bitsche et al. [51] indicates that a hybrid FCV with combination of fuel cell and battery system provides higher overall efficiency than a pure FCEV. Hence, more important concern is to design and develop hybrid FCVs. To enhance vehicle efficiency through the use of a storage device, using a battery or an ultra-capacitor for 'load leveling' is suggested. Another suggestion is to regenerate the braking power used for acceleration and hill-climbing. A typical hybrid FCV power train is shown in Fig. 10.

Commonly, PEMFC stack is used as power source for FCEV due to its low operating temperature (about 80 °C), high power and current density, compactness, light weight, quick start up system and fast output power adjustment. Table 5 shows the car manufacturers involved in the Research and Development (R&D) of FCEVs. The table indicates that most of the manufacturers are using PEMFC. A fuel cell stack is shown in Fig. 11.

8. Hydrogen fuel cell vs. internal combustion engine vehicles

Fuel cells generate electricity as a result of electrochemical reactions. The main difference compared to a normal battery is that fuel cells are power generation systems while batteries are generally storage devices. In fuel cells the reversed reaction is happening in which oxygen and hydrogen molecules react to form water and electricity, however, in electrolysis process, oxygen and hydrogen are expelled due to passing electricity through the water.

The external electrical load (electric motor) in a car causes an electrical gradient and makes the electrons to flow through it.

Table 5
Car manufacturers undertaking the development of FCEV [41].

Company	System type	Fuel cell	Fuel
DaimlerChrysler	Straight fuel cellFuel-cell–battery hybrid	Direct Indirect	Hydrogen Methanol
Ford	Straight fuel cell	Direct/indirect	Hydrogen/methanol
General Motors	Fuel-cell–battery hybrid	Direct/indirect	Hydrogen/methanol
Honda	Fuel-cell–ultra capacitor hybrid	Direct/indirect	Hydrogen/methanol
Mazda	Fuel-cell–ultra capacitor hybrid	Direct	Hydrogen
Nissan	Fuel-cell–battery hybrid	Indirect	Methanol
Renault	Fuel-cell–battery hybrid	Direct	Hydrogen
Toyota	Fuel-cell–battery hybrid	Direct/indirect	Methanol
Volkswagen	Straight fuel cellFuel-cell–battery hybrid	Direct Indirect	Hydrogen Methanol
ZeTech	Fuel-cell–battery hybrid	Direct	Hydrogen

BMW, General Motors, Nissan, Daimler-Chrysler, Honda, Toyota and Hyundai have concentrated their researches on more efficient hydrogen-powered vehicles. Hydrogen FCVs are promising substitutes for ICEVs because they are more efficient, simple, fuel abundant and safe with no environmental impacts. In addition, for the same amount of fuel they generate more output power compared with conventional ICEs. Fuel cells output power ranges between 50 and 250 kW; however, a single fuel cell cannot provide essential energy to run a car. Hence, "fuel cell stack" is used as a combination of several fuel cells attached together to generate sufficient power to run a car.

Fuel cells' efficiency is 30–90% greater than a regular gasoline ICE. The most significant and obvious advantage of hydrogen FCVs is that they have zero polluting emissions. In other words, vehicles with fuel cell energy system have no or minor environmental impacts since they only produce heat, water and electricity. For a conventional ICEV that use gasoline as fuel, there are by-products of sulphur-oxide (SO_2), nitrogen-oxides (NO_x), carbon-monoxide (CO) and carbon dioxide (CO_2) [6,54,55].

FCEVs have extremely simple structure compare to ICEVs. They are solid state devices with no moving parts and therefore, they are inherently low vibration and noiseless devices. The need to have lubrication oil in FC systems is eliminated by removing mechanical parts; hence, maintenance expenses are reduced. The vehicle's power train is embedded in the wheel's area so the engine compartment in front side of the vehicle is eliminated as well. Consequently, hydrogen FCVs are simple in design, highly reliable with silent operation which can lead to a long-life system. When comparing FCEV and ICEV, economic analysis and price differences should be take into consideration as well [55–57]. Hydrogen FCV poses an expensive distribution infrastructure. A hydrogen fuel cell reformer costs around $5000 (RM 16,000) while manufacturing a conventional car engine costs about $3000 (RM 9600). Hydrogen FC costs between $1500 and $3000 (RM 4800–9600)/kW while an ICE costs about $50 (RM 160)/kW.

Pure hydrogen refuelling stations need high capital cost of around $470,000 (RM 1,504,000) to be constructed. Modifying a medium-size gas station to deliver fuels require $70,000 (RM 224,000). The price of the hydrogen FCVs should be decreased and further economical improvements should make it practical for commercial stage. The first FCEV was introduced by Ford Company. It was quite expensive; however, mass production helped remarkably to decrease the costs [6].

Zamel [56] has calculated the costs of a fuel cell car to be around RM 90,400 and compared it with RM 69,496 for internal combustion vehicle in Canada. The results show 30% higher initial costs for FCEV. Table 6 compares the current ICEV costs with a future FCEV. It shows that the fuel cell power unit and exhaust gas cleaning are more costly in FCEVs. The fuel cell power unit contribute a huge cost to the total cost of the system. Although FCEV is much expensive than ICEV, the operational costs during the vehicle's lifetime are more convincing.

Table 6
Price evaluation of an ICEV and a future FCEV.

Propulsion system	SI ICE	FC hybrid
Fuel	Gasoline	Hydrogen
Vehicle type	Passenger	Passenger
Baseline vehicle	US $21,717.65	US $21,717.65
Engine		
Credit for downsizing		−US $6000.00
Fuel cell system		
Fuel cell		US $5195.04
Fuel tank		US $975.00
Electric motor		US $1558.51
Single stage red. transm.		US $226.50
Battery		US $2597.52
Exhaust gas cleaning		−US $645.00
Vehicle		
Weight reduction		US $2400.00
Aerodynamics		US $225.00
Total vehicle price	US $21,717.65	US $28,250.22

9. Conclusion

Different types of fuel cells are studied in order to clarify the best application for each type. It was discussed that although all types of fuel cells operate on similar basis; Alkaline is the most efficient (60%), followed by Polymer electrolyte membrane (58%) and Molten carbonate (47%) in terms of power efficiency. While AFCs are the most efficient, the PEMFC is ideal for transportation applications like automotives and buses. DMFC and PAFC are economically efficient; however, they suffer from low efficiency. SOFC and MCFC perfom high CHP efficiency. Comparison of the estimated capital costs between ICEV and FCEVs shows that although the latter is more expensive due to costs involved with hydrogen system modifications and distribution infrastructure, the operational costs during the vehicle's lifetime are more convincing. Current innovative and modern fuel cell technologies need to meet the economical features and exceeds the advantages of the existing technologies to be acceptable for mass production. In order to improve the feasibility and to increase the efficiency of FCEVs, more R&D should be conducted by research institutes and industries. Fuel cells offer a number of important advantages over internal combustion engine (ICE) and other current power generator systems.

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