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Dynamic performance assessment of the efficiency of fuel cell-powered bicycle: An experimental approach

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ABSTRACT

Zero-emission fuel cell driven systems are regarded as promising technological advances in the future of the transportation industry that have the potential to replace internal combustion engines. The design, performance, and efficiency properties of a vehicle are often stated to be some of the key challenges in its commercialization. This paper highlights a polymer electrolyte membrane fuel cell (PEMFC)-powered system of an electric bicycle. The system consists of a 250-W fuel cell, ECU, battery pack, DC/DC converter, electric motor, and other supporting equipment. After introducing the different parts of the bicycle, its overall efficiency will be discussed in great detail. The efficiency of fuel cells is not specific; it is a subordinate to the power density where the system operates. Experimental work has been conducted to measure the values of the efficiency and energy flow. The results indicated a maximum fuel cell efficiency of 63% and an overall system efficiency of 35.4%. The latter value is expressed with regards to the Lower Heating Value (LHV) of hydrogen. All measurements were taken for the cruising conditions of the vehicle and its corresponding to power consumption. The results are superior to those of a standard internal ignition engine. The fuel cell performance is least efficient when functioning under maximum output power conditions.

Introduction

Due to the increasing adverse effects of global warming, the depletion of energy resources, and the environmental impact of conventional energy sources such as fossil fuel, the development of alternative energy sources has become a considerable subject of interest, especially in the fields of portable and stationary power generation [1]. In the context of these problems and purposes, commercial hydrogen fuel cells have shown remarkable promise. In addition, a high efficiency, near zero emissions in producing electricity, and recyclability are other unique futures of these devices [2]. While hydrogen and oxygen atoms undergo an electrochemical reaction in a fuel cell, they release a considerable amount of power in the form of electrical currents. The by-product of these reactions are water molecules [3]. Currently, fuel cells are categorized into six different types, including the [4] Direct Methanol fuel cell (DMFC), which consumes methanol for functionality. The utilization of these fuel cells is limited to applications in which

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the efficiency is superseded by the power density in terms of importance. To act as a fuel, methanol should be diluted in water at low concentrations. Hence, the utilization of DMFCs is not as common as that of other fuel cells [5]. Solid Oxide fuel cells (SOFC) are another type of fuel cell; they contain a solid oxide or ceramic electrolyte. A high temperature threshold between 600 and 1000 °C constitutes the main concern for the utilization of SOFC in vehicles [6,7]. Molten carbonate fuel cells (MCFCs) are based on a mixture of molten salts that act as an electrolyte. These fuel cells can perform only at temperatures that are higher than 650 °C [8]. MCFCs also require gasified coal and natural gas, which is another disadvantage of this system, because global warming remains a major concern [9]. Alkaline fuel cells (AFC) are currently popular; they contain an alkaline solution derived from an alkaline electrolyte. They can operate over a wide range of temperatures that depend on the fuel cell application, which constitutes the main advantage of these fuel cells over other types. However, the significant technical disadvantage of this type of fuel cell is the carbon dioxide poisoning of the electrolyte [10]. Phosphoric acid fuel cells (PAFCs) use liquid phosphoric acid as an electrolyte. The operating temperature of these devices is approximately 150–200 °C [11]. PAFCs are used in both stationary power and mobile applications, such as large vehicles. The pre-heating requirement, and its open-ended structure, which requires the careful control of hydrogen flow, are some of its drawbacks [12]. Finally, proton exchange membrane fuel cells (PEMFC), or solid polymer fuel cells (SPFC), are one of the most promising systems, especially regarding automotive and vehicular transport [4]. In recent years, the high efficiency of PEMFCs has provided impressive capabilities for the transportation sectors. For example, the maximum theoretical efficiency of these fuel cells is 83% at standard conditions, although the experimental efficiency is considerably lower due to internal resistance issues [13].

Detailed theoretical efficiency calculation methods have been presented in many available publications. Low efficiency and high production cost are some of the most serious challenges for previous fuel cell technologies. Therefore, many research groups have focused on this area as key challenges for the commercialization stage. Z Qi (2009) [14] demonstrated various vehicular applications, such as bicycles, wheelchairs, forklifts, and scooters, that utilize PEM fuel cells instead of batteries. Fuel cells are expected to generate power for longer periods and at higher efficiencies compared to batteries. Meiyappan Siva Pandian (2010) [15] stipulated that enhancing the power output of PEM would reduce the efficiency, which would be detrimental to the economical aspect of the system. Furthermore, Barbir and Gomez (2007) [16] surmised that the economics and operating efficiency of a fuel cell are interrelated. Yongping Hou et al. (2007) [13] proposed models that detail the efficiency of fuel cells and investigated their theoretical and experimental efficiency while evaluating several influencing parameters that are related to the efficiency of a fuel cell.

Furthermore, the reduction of hydrogen production costs renders the cost of hydrogen comparable or even cheaper than the cost of fossil fuels in the near future. Although such big-picture studies showed that the hydrogen economy and fuel cells can the future of the transportation system, this work is more interested in the ability of a light vehicle that is powered by a hydrogen fuel cell to meet daily transportation requirements. Numerical and theoretical models regarding the efficiency of fuel cell applications in light vehicles vastly outnumber experimental reports. To study the behavior and the efficiency of such a system, we decided to study, test, and analyze the features of an electric-assisted bicycle that is powered by a PEM fuel cell as a common and suitable type of power source for transportation systems.

PEM fuel cell principles

Similar to other types of fuel cells, PEMs also consist of three significant parts: a cathode and an anode that act as electrolytes formed by platinum-catalysis and the membrane [2]. In a PEM fuel cell reflex, the hydrogen oxidation and oxygen reduction reactions occur simultaneously at the anode and cathode [17]. Fig. 1 shows the single cell of a fuel cell.

At the anode, the stream of hydrogen molecules is disarticulated into protons and electrons as follows:

$$H_2 \rightarrow 2H^+ + 2e^- \text{ Anode reaction}$$

Electrons are released from hydrogen, and move along the external load circuit to the cathode; therefore, the flow of electrons creates the electrical output current.

The electron arriving at the cathode from the external circuit concurrently reacts with oxygen molecules that are joined with a platinum catalyst of electrode and two protons (which have moved through the membrane) to create water molecules; this reduction is represented by the following:

$$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O \text{ Cathode reaction}$$

$$H_2 + 1/2O_2 \rightarrow H_2O \text{ Overall reaction}$$

The chemical reaction is now complete. Despite the reaction, a portion of the energy is expended in the form of heat released from the respective redox reaction as a byproduct. PEM fuel cells are used in many applications without

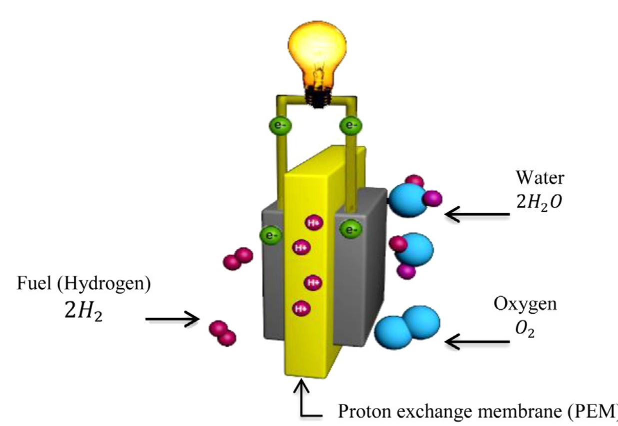

Fig. 1 – Schematic of fuel cell's single cell.