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Thermo-economic analysis of proton exchange membrane fuel cell fuelled with methanol and methane

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ABSTRACT

Exergy and economic analysis is often used to find and identify the most efficient process configuration for proton exchange membrane fuel cell from the thermo-economic point of view. This work gives an explicit account of the synergetic effect of exergetic and economic analysis of proton exchange membrane fuel cell (PEMFC) using methanol and methane as fuel sources. This was carried out through computer simulation using Thermolib simulation toolbox. Data generated from the simulated model were subsequently used for the thermodynamic and economic analysis. Analysis of energy requirement for the two selected processes revealed that the methane fuelled system requires the lower amount of energy (4.578 kJ/s) in comparison to the methanol fuelled configuration which requires 180.719 J/s. Energy analysis of both configurations showed that the principle of energy conservation was satisfied while the result of the exergy analysis showed high exergetic efficiency around major equipment (heat exchangers, compressors and pumps) of methane fuelled configuration. Higher irreversibility rate were observed around the burner, stack, and steam reformer. These trends of exergetic efficiency and irreversibility rate were observed around equipment in the methanol fuelled system but with lower performance when compared with the methane fuelled process configuration. On the basis of overall exergetic efficiency and lost work, the methanol system was more efficient with lower irreversibility rate of 547.27 kJ/s and exergetic efficiency of 34.44% in comparison with the methane fuelled system which has the highest irreversibility rate of 624.03 kJ/s and highest exergetic efficiency of 36.51%. Economic analysis showed that methane system had a lower capital cost of $ 476 396.2 and slightly higher annual utility cost of $ 10 334.2 as against the methanol system whose capital and annual total utility cost were $ 683 919 and $ 10 073 respectively. The methane system configuration is favoured based on the assumed economic parameters by the least cost per kilowatt of electricity produced ($3 804.99/kW). The result of various analysis conducted shows that trade-off between economic, energy and exergetic performance of methane and methanol system favoured selection of methane system configuration as the best preferred choice of PEMC configuration.

1. Introduction

Fuel cell power systems for automobile applications are presently receiving considerable attention because of the need for efficient and zero-emission vehicles. The relative importance of zero emission vehicles cannot be under estimated as it eliminate the possibilities of release of toxic gases to the atmosphere thereby promoting sustainable development of the entire eco-system [1]. In recent time fuel cell systems are being developed and used in different part of the world [2]. Fuel cells are electrochemical devices that convert the chemical energy directly into electrical power. It consists of an anode, cathode electrodes and a proton-conducting membrane (electrolyte) sandwiched in between the electrodes [3–5]. These cells are characterized with high efficiencies, flexibility in size, quiet operation and lower emissions [3]. High operating temperature is not necessary for achieving high efficiency when compared to fossil fuelled systems since electrochemical processes are not governed by Carnot's law [5]. There are several types of fuel cell among which include: Solid oxide fuel cell (SOFC), Molten carbonate fuel cell (MCFC), Direct methanol fuel cell (DMFC), Phosphoric acid fuel cell (PAFC), Alkaline fuel cell (AFC) and Proton exchange membrane fuel cell (PEMFC). Irrespective of the types of fuel cell, it is made up of two electrodes (negative anode and positive cathode) separated by a solid or liquid

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electrolyte. Catalysts, such as platinum are often used to speed up the reactions at these electrodes [4].

PEMFC is one of the most promising and attractive source of clean energy for various applications due to the low cost of construction materials, environmental friendliness, high efficiency; simplicity in design and operation [6]. PEMFC can be used as an alternative source of energy for automobile, laptop computers, cell phones, and other electronic devices that requires low operating temperature, east to start, possesses high power density and are usually light in weight [6].

Hydrogen remains the main fuel for fuel cell operation. It can be derived from hydrocarbon sources via three major thermo-chemical reforming techniques such as steam reforming (SR), partial oxidation reforming (POR) and auto-thermal reforming (ATR), (combination of steam and partial oxidation) [7]. However, in each of these thermo-chemical reforming techniques for hydrogen generation, water gas shift (WGS) is required convert carbon monoxide and water vapour into carbon dioxide and hydrogen. [8]. Steam reforming process have shown a greater advantages over all other techniques for the production of hydrogen but this technique is limited as it requires the use of a complex reactor fuelled by an external combustion system [7,8]. To date steam reforming as a traditional method remains the most economical, common and traditional method for the production of hydrogen on industrial scale [7]. This process is capable of yielding a high concentration of hydrogen (up to 70% on a dry basis) [7,9]. The application of partial oxidation and auto-thermal reforming methods are limited by the production of low hydrogen concentration, especially if when air is used as the oxidant [10]. Heat Partial oxidation is exothermic, but it produces a high carbon monoxide concentration which has negative consequences on the polymer electrolyte membrane fuel cells [7]. There is the need for proper understanding of the PEMFC process design, performance and areas that requires improvement.

Exergy analysis identified as a potential tool for system design analysis, process evaluation and improvement. It is employed for the identification of primary sources of loss and also provides more accurate information about the performance of an energy system relative to the theoretical ideal [11]. The cost of an integrated PEMFC powered automobile can be reduced by improving the performance of the PEMFC [12]. Exergy analysis (or second law analysis) has proven to be a powerful tool in the simulation thermodynamic analyses of energy systems [13].

The use of normative discipline like economics analysis alone for the measure of the performance of energy might be misleading [14]. Doubt has been raised on the use of exergo-economic analysis to determine the performance of thermodynamic systems. It is regarded as an attempt to merge the two qualitatively different approaches; one descriptive and the other normative [15]. It was argued that they may be in large measure incompatible; nevertheless, this approach may yield practical benefits in terms of the optimisation of power and process plant; even when the theoretical basis is open to question [15]. Methods integrating exergy and economics have been developed over the last several decades; Georgescu-Roegen is often cited as a pioneer in the field of the thermodynamics of economics [16]. In thermo-economics, the uses of exergy based economic methods have evolved over several decades for the evaluation of the actual efficiency of a thermodynamic system [17].

There are few reported studies that attempt to investigate separately the exergetic and economic performance of hydrogen fuelled low temperature PEMFC for transportation applications [5,18]. The exergetic performances of other PEMFC fuel cells for various applications have been studied using exergy method of analysis [19–23]. In other related study, the PEM fuel processor efficiency and start up energy were investigated for different fuels with a view of establishing minimum fuel processor start up energy with maximum efficiency [24]. The impacts of fuels a type on energy efficiency was also studied [25]. Steam reforming (SR), auto-thermal reforming (ATR), and ATR membrane reactor based fuel processors using a commercial $CuO/ZnO/Al_2O_3$ catalyst based and methanol as fuel were compared in order to determine the system with a better overall energy efficiency [10]. Second-law analysis of an integrated fuel processor and fuel cell system, using methanol, ethanol, octane, ammonia, and methane as fuels was also reported [26]. The theoretical performance of HT-PEMFCs fuelled using reformate gas derived from methane, methanol, ethanol, and glycerol were investigated [27]. The review of the conversion of hydrocarbon fuels to hydrogen with a degree of purity suitable for PEMFC operation was also carried out [28]. The current technologies used for hydrogen production from both fossil and renewable biomass resources; includes steam, partial oxidation, auto thermal, plasma, aqueous phase reforming and pyrolysis were also extensively reviewed [9].

Critical review of steam reformation of methane, partial oxidation of hydrocarbon and gasification of biomass coal and waste was carried out [29]. Analysis of the energy efficiency of fuel processors of PEMFC systems with detailed description of conventional and membrane based fuel processors was documented [30]. The total fuel infrastructure cost comparison of on board fuel processors using hydrogen, methanol and gasoline has been documented [31]. Local air pollution and greenhouse gas advantages of hydrogen fuel cell vehicle compared to those powered by methanol and gasoline were identified [31]. The effect of operating parameters of an irreversible proton exchange membrane fuel cell/absorption refrigerator hybrid system on its performance was investigated [32]. Exergo-economic analysis of PEM vehicular fuel cell system was carried out for the two alternative configurations (with and without expander) using two alternative design concepts (Begin of life and End of life) and concluded that system with expander and end of life concept is most cost effective [33]. The exergo-economics based analysis of thermodynamic processes considers the cost of exergy only not the entire cost of its elements (utility, equipment cost, labour cost, raw materials) for detailed economic analysis. The later approach has been reported to be used in the thermo-economic analysis of some thermodynamic systems which gives more realistic measure of performance such as in oil shale retorting processes with gas or solid heat carrier [34], low-grade waste heat recovery in Yazd combined-cycle power plant by a CO_2 trans critical Rankine cycle [35], distillation based hybrid configurations for bioethanol refining [36], Organic Rankine cycle for exhaust waste heat recovery of a diesel engine [37], pressure swing adsorption process for bioethanol refining [38], combined supercritical CO_2 (carbon dioxide) recompression Brayton/organic Rankine cycle [39], ORCs (organic Rankine cycles) for low temperature waste heat recovery [40], milk spray dryer exhaust to inlet air heat recovery [41], Dual-purpose Power and Desalination Plants [42] and air energy storage (CAES) system integrated with a wind power plant in the framework of the IPEX market [43]. In addition, significant progress has been made in the design of hybrid system to convert the waste heat in PEMFC to electricity [44,45]. The PEMFC system has been diagnosed to improve its stability and reliability using ANN [46]. Significant effort was made to improve the performance of PEMFC using different approach. Mathematical models [47,48], catalyst [49] and porous material [50] has been used to investigate and improve PEMFC performance. The effect of operating conditions on the performance of PEMFC had received considerable attention in recent time. The performance of PEMFC under various conditions of its operation has been investigated [32,51–54]. Meanwhile, optimisation techniques used to optimize