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Detailed analysis of Integrated Steam Ethanol Reformer and High Temperature Polymer Electrolyte Membrane Fuel Cell

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ABSTRACT

Utilisation of hydrocarbon fuels as a source of hydrogen for Polymer Electrolyte Membrane Fuel Cell (PEMFC) is a possible solution for the demand for hydrogen infrastructure. Ethanol, which is considered to be a domestic and renewable fuel, is a potential source in this regard. Its use as a source of hydrogen production has received appreciations in recent years. For agriculture based countries such as India, China, Brazil, etc., where ethanol can be produced abundantly, this development serves as a boon to meet their future energy demands. This study presents the analysis of high-temperature PEMFC stack integration into a combined system with Steam Ethanol Reformer (SER). One dimensional mathematical model of the integrated system is developed. Performance of the system is studied methodically by varying the operating parameters such as temperature and steam to carbon ratio (S/C) of the SER, temperature of PEMFC and pressure of the system. In addition, the necessity of a Water Gas Shift (WGS) reactor to function as a carbon monoxide removal unit for pre-treating the reformate gas before it is fed to the high temperature PEMFC is also investigated in this study. The S/C ratio and reformer temperature do not affect the performance of the system considerably as long as the fuel processor unit contains WGS reactor along with the reformer. Inclusion of WGS reactor shows a positive influence on the performance of the fuel processor unit. A higher fuel cell temperature and pressure provides a higher voltage more prominently at higher current densities.

Introduction

The exploitation of fossil fuels ever since the beginning of industrial revolution has affected our environment and its diverse ecosystem exorbitantly. Thus, it is a need of the hour to develop and establish alternative energy sources which rely on resources that are clean and plenteous. This ultimately paves a green path towards the globally acclaimed issue of 'sustainable development'. Though the Fuel Cell Technology could not serve the tremendous energy needs to a large extent since its invention, it is realized to have a promising future in the transforming energy sector at hand.

Fuel Cells, fundamentally are open thermodynamic systems [1] which undergo an electrochemical reaction between hydrogen and oxygen to produce water along with electricity

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and heat. Of the many types developed till date, Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are found to be well suited for automotive and Fuel Cell Vehicle (FCV) applications. They are used in both stationary and portable implementations.

PEMFCs essentially consist of a polymer electrolyte membrane sandwiched between anode and cathode electrodes. Based on the working temperature, they are classified into high temperature (HT) and low temperature (LT) PEMFCs respectively. The present work deals with HTPEMFC in view of its advantages over LTPEMFC such as operating without humidity, tolerating impure fuel streams and high temperature waste heat recovery [2]. The increased tolerance of carbon monoxide (CO) in fuels for HTPEMFCs extends an opportunity for many hydrocarbons to replace pure hydrogen, as a source of fuel.

In recent years, a great deal of work has been reported with hydrocarbon fuels such as gasoline, natural gas, diesel, methanol, etc. But the fact that the origin of these fuels is from the non-renewable resources is notable [3]. On the other hand, use of ethanol, which is considered to be a domestic and renewable fuel has received recent appreciations. For agriculture oriented countries such as India, China, Brazil, etc., where ethanol can be produced abundantly, this development definitely helps in meeting their future energy demands.

Ethanol as a fuel similar to other reformate gases such as methane, carbon dioxide, carbon monoxide and water, needs to be primarily reformed using steam to produce hydrogen. A Water Gas Shift (WGS) reactor can be incorporated along with the Steam Ethanol Reformer (SER) in the fuel processor unit to increase the hydrogen production. The hydrogen produced along with traces of CO can then be fed directly as a fuel to the High Temperature PEMFC. The present work deals with the modelling and analysis of such an integrated system of SER – HTPEMFC.

Bernadi and Verbrugge [4] and Li et al. [5] developed a 1D PEMFC model considering various voltage losses and their effect on the overall cell potential. Their models matched reasonably well with the experimental results. Shamardina et al. [6] developed a 1D model explaining the role of crossover in detail. The model concluded that crossover effects were considerable only at low stoichiometric flow of oxygen and the model failed to account for processes at the catalyst layer and initial drop in cell voltage.

Scott et al. [7] developed a steady state, isothermal 1D model of PBI – HTPEMFC in a commercial code COMSOL Multiphysics and validated their results with experimental data. Scott and Mamlouk [8] also studied the effect of electrode parameters on the performance of H_3PO_4 doped PBI – HTPEMFC. In Ref. [9], Mamlouk et al. developed a HTPEMFC model for reformate gas considering mass transport through both the thin film electrolyte and the porous media. The model showed the importance and sensitivity of the electrolyte content on electrode performance, particularly on the cathode.

Steam reforming process for hydrogen production has also been studied with keen interest over the years. Vagia and Lemonidou [10] carried out a thermodynamic analysis of hydrogen production from sources such as acetic acid, acetone and ethylene glycol. Rabenstein et al. [11] investigated the thermodynamics of hydrogen production from ethanol by steam-reforming as a function of steam-to-ethanol ratio (0.00–10.00) and temperatures (200–1000 °C) at atmospheric pressure. Ashutosh et al. [12] presented an extensive literature survey of noble (Pt, Pd, Rh and Ru) as well as non noble metal (Cu, Ni, Ir and Co) catalysts and their role on the productivity and selectivity of generated gas. Basile et al. [13] studied ethanol steam-reforming reaction for the production of synthesis gas theoretically. A mathematical model was developed for a traditional reactor packed with a Co-based catalyst and then applied to a membrane reactor (MR). Authayanum et al. [14–17] conducted an extensive study on the integrated reformer – PEMFC system with glycerol as the fuel. Their study includes – the effect of various fuel processor and fuel cell conditions on the performance of the integrated system [14]; theoretical analysis of hydrogen production and system efficiency [15] and; comparison of LT and HT integrated systems [16]. A comparison on the performance of the system with different fuels such as methanol, methane, glycerol and ethanol [17] was also studied.

Of all the fuels considered for steam reforming, ethanol is found to be the most appropriate fuel as it is renewable and non-conventional. Francesconi et al. [18] estimated the energy efficiency of an ethanol reformer – PEMFC integrated system. The influence of different operating parameters were studied using Hysys. Perna [19] made a theoretical optimisation of a similar system while Pasdag et al. [20] developed a highly integrated system with condensing burner technology for increased electrical efficiency. Jaggi and Jayanti [21] developed a conceptual model of an integrated autothermal reformer-LT-HT fuel cell stack using Aspen Plus. Few studies are available on the ethanol reforming and its integration to PEMFCs as discussed above. However, a detailed analysis of the integrated SER – HTPEMFC considering the effects of various operating parameters on the performance of the system is not found and such a study will be useful for the design of the integrated system with optimized parameters.

In this work, a numerical 1D model of an Integrated SER – HTPEMFC is presented. The performance of the system is analyzed by considering ohmic, kinetic and mass transport losses that impact the overall efficiency of the system. The detailed analysis of the effect of various parameters such as temperature of the reformer, steam to carbon (S/C) ratio, overall pressure of the system, and temperature of the HTPEMFC etc. on the performance of the integrated system is studied and presented. The performance of the system is considered in terms of the output voltage from the HTPEMFC and the overall system efficiency after considering the power generation, energy utilization and waste heat recovery. The developed model of the integrated system will provide a passable optimisation of operating parameters for improving the performance of the overall system.

Integrated Steam Ethanol Reformer (SER) – HTPEMFC system

From various comparative studies, it is recognised that ethanol as a source of hydrogen has a promising future. USA stands first in the global production of ethanol from corn followed by