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Fuel Composition Influences on Exergetic Performance of a Standalone Internal Reforming Solid Oxide Fuel Cell

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Abstract. An approach to resolve global warming and fuel resource depletion, is maintaining biofuels like biogas and syngas from biomass gasification in internal reforming solid oxide fuel cells. In this research effects of fuel composition on exergetic performance of standalone SOFC are investigated. Biogas, syngas and pure methane are compared in terms of efficiency and exergy destruction. Results show that pure methane has the highest efficiency in atmospheric and pressurized applications. Syngas efficiency is the least among three cases specially in high pressure conditions due to higher rate of air and compressor work required.

INTRODUCTION

With fuel resources depletion and global warming already affecting the whole planet, energy efficiency and emission reduction is more crucial than ever. Renewable resources like bioenergy are attracting more attentions worldwide. Biogas from anaerobic digestors and syngas from biomass gasification are among renewable resources which provide two benefits simultaneously: the first, a green source of renewable energy and the second, waste and natural emission control[1].

From many technologies adopted to work with biogas and syngas, only few including internal reforming solid oxide fuel cells (SOFC) can operate with large variations in fuel compositions[2&3] . In SOFCs which operates at high temperature and can resist high pressures as well, hydrogen reacts with oxygen. Since only hydrogen provides electrical useful power, all materials with hydrogens like methane can be fed to an internal reforming SOFC. Syngas is normally rich in hydrogen and biogas and natural gas (nearest case to pure methane) are rich in methane which is a source of hydrogen.

Due to this flexibility of operation, internal reforming solid oxide fuel cells are considered recently for biogas and syngas applications [4]. In internal reforming SOFCs, methane is converted to carbon dioxide and hydrogen along the SOFC length and the latter is utilized in fuel cell to generate electricity. SOFCs with internal reforming have been subjected for many researches specifically in flow and reaction modeling [5], dynamic performance [6] and system thermodynamic modeling [7]. However, effects of fuel composition variation on the exergetic performance has not been investigated. Composition of biogas and syngas and even natural gas varies drastically for miscellaneous resources and because of this fact it is important to understand the effect of such variations on the SOFCs'

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performance. Exergy analysis is selected for assessment since it is capable of evaluating the quality of resources and flows as well as their quantity which is a requirement in a variable fuel analysis [8].

SYSTEM DESCRIPTION

In the present study, a standalone SOFC equipped with an air compressor and an air preheater (AP) is investigated. Schematic of the process under study is shown in FIGURE 1.

SOFC Modeling

SOFC modeling includes reforming, shifting and Hydrogen oxidization phenomena. Equations of reactions and their corresponding equilibrium equations are provided here.

Reforming:

$$CH_4 + H_2O \leftrightarrow H_2 + CO \tag{1}$$

Shifting:

$$CO + H_2O \leftrightarrow H_2 + CO_2 \tag{2}$$

Electrochemical reaction which produces heat and Work is defined as:

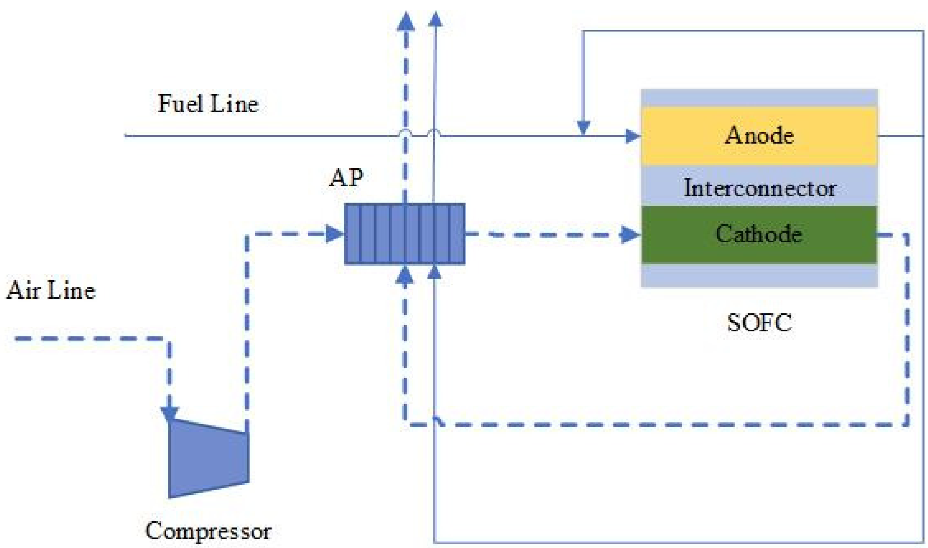


FIGURE 1. Schematic diagram of the system under study.

$$H_2 + O_2 \leftrightarrow H_2O \tag{3}$$

Chemical reactions are considered in equilibrium and equilibrium constants expressed by following equations[6],[8]:

$$K_{\text{reforming}} = \frac{x_{H_2}^3 x_{CO}}{x_{CH_4} x_{H_2O}} P^2 \tag{4}$$

$$K_{\text{shifting}} = \frac{x_{H_2} x_{CO_2}}{x_{CO} x_{H_2O}} \tag{5}$$

$$\ln(K) = AT^4 + BT^3 + CT^2 + DT + E \tag{6}$$

For air preheater and compressor modeling, mass balance and first law of thermodynamics are implemented. For compressor modeling, isentropic efficiency definition is implied.

System Performance Measures

Exergetic analysis is carried out, to understand performance of the system and contributions of different processes and components to irreversibility of the system. For each component, exergetic destruction and efficiencies are defined as follows:

$$Ex_D = \sum Ex_{in} - \sum Ex_{out} \tag{7}$$

$$\eta_{ex} = \frac{Ex_p}{Ex_F} \tag{8}$$

Total exergy efficiency is:

$$\eta_{ex} = \frac{W_{Net}}{Ex_{Fuel}} \tag{9}$$

Results and discussion

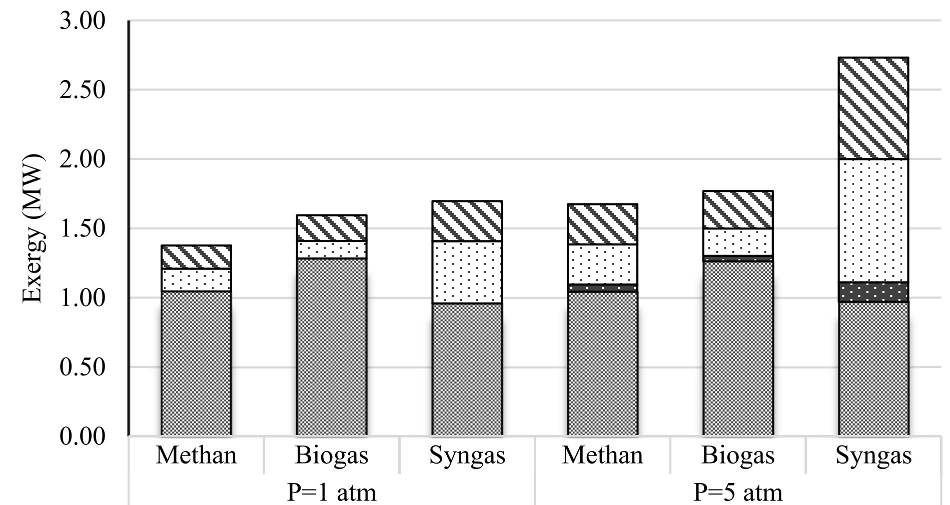
Three basic cases of fuel are considered here: pure methane, biogas and syngas. Composition of different fuels are presented in TABLE 1.

TABLE 1. Fuel compositions for methane, biogas and syngas.

	Pure Methane	**Biogas** [9]	**Syngas** [8]
Methane	100%	65	21
Hydrogen	0	0	40
Carbon Dioxide	0	35	18
Carbon Monoxide	0	0	20
Nitrogen	0	0	1

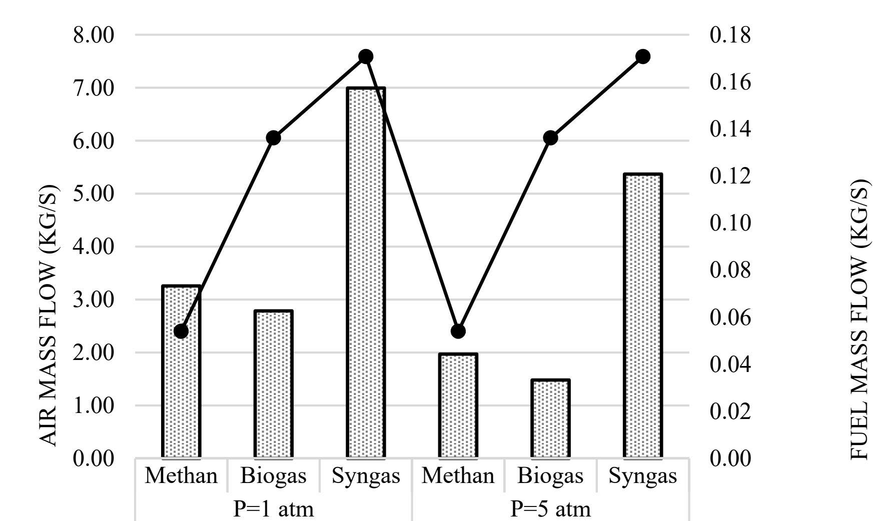
In addition to above composition changes, operating pressure of the SOFC is important as well. Since all mentioned fuels may come from sources with different pressure levels, analyzing the effects of the pressure on the performance is important. Due to SOFC mechanical structure limitations, fuel and air supply to the SOFC should have similar pressure for a safe and durable operation. For the mentioned reason, an air compressor is required. To assure accuracy of results, Fuel physical exergy is considered in total fuel exergy calculations.

Results of analysis for destruction and losses are presented in FIGURE 2. For atmospheric pressure cases, most of destruction occurs in the SOFC. As chemical reactions are responsible for large destructions, syngas shows the least amount, destruction in SOFC, due to reduction in methane reforming and shifting reactions rates. When pressure rises, destruction and losses increase considerably, but SOFC share of total loss and destruction reduces which means higher pressure provides higher efficiencies for the SOFC. Unusual behavior of syngas in high pressure is due to high air mass flow rate. As FIGURE 3 shows, air mass flow rate in a case with syngas is much higher than other cases. The reason is for syngas, methane reforming and shifting decreases considerably since there is low amount of methane and high pure hydrogen concentration. Because overall reforming and shifting reactions of methane is endothermic, a considerable amount of released heat in SOFC is absorbed by these reactions and lesser amount of air is required to cool down the SOFC to its acceptable temperature limit. However, when pure hydrogen is introduced, amount of air required to cooldown SOFC increases drastically. This causes a major efficiency reduction due to high compressor work in syngas case.



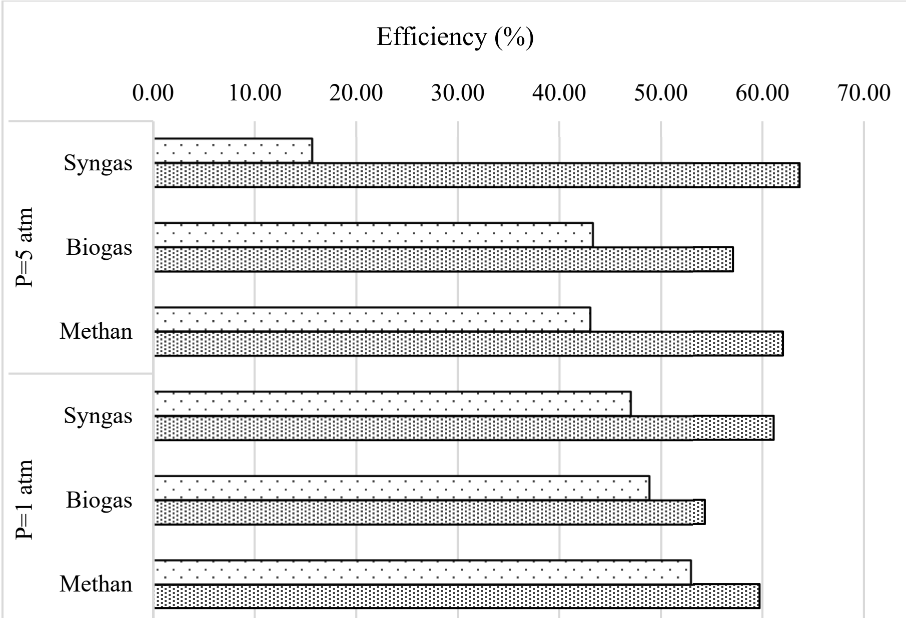
	P=1 atm Methan	P=1 atm Biogas	P=1 atm Syngas	P=5 atm Methan	P=5 atm Biogas	P=5 atm Syngas
Loss	167.29	186.57	288.35	289.19	269.53	731.29
AP	163.11	125.92	448.35	290.20	197.78	889.10
Comp	0.00	0.00	0.00	51.62	38.80	140.65
SOFC	1045.24	1281.97	958.46	1042.49	1261.96	969.97

FIGURE 2. Exergy loss and destruction in the plant



	P=1 atm Methan	P=1 atm Biogas	P=1 atm Syngas	P=5 atm Methan	P=5 atm Biogas	P=5 atm Syngas
Air	3.26	2.79	6.99	1.97	1.48	5.37
Fuel	0.05	0.14	0.17	0.05	0.14	0.17

FIGURE 3. Air and Fuel mass flow rates for different pressure and fuels.



	P=1 atm			P=5 atm		
	Methan	Biogas	Syngas	Methan	Biogas	Syngas
Total	52.97	48.88	47.04	43.05	43.32	15.69
SOFC	59.71	54.32	61.11	62.02	57.10	63.66

FIGURE 4. SOFC and total Efficiencies for different fuels and pressure.

SOFC and total exergy efficiencies are presented in FIGURE 4. Syngas, due to lower chemical reactions rates has highest SOFC efficiencies in both pressure levels. However, due to higher air mass flow rate both cases present lowest total efficiencies since higher losses, AP exergy destruction and compressor work (in high pressure) occur as a direct consequence of higher mass flow rates of air. Total efficiency in case of pure methane is the highest value among different fuels and pressure levels.

Composition variations and system performance

Effects of carbon dioxide and hydrogen concentration on the plant performance are investigated here to have more insightful view of composition effects on the SOFC performance. Hydrogen composition variations considered to be in range of 0-20 % and carbon dioxide in range of 0-40%.

Contours of efficiencies are shown in FIGURE 5 for atmospheric pressure condition. Higher hydrogen mole fraction results in higher air mass flow rate as discussed earlier. Carbon dioxide increment has negative effects on all efficiencies as shown here except air preheater efficiency which improves less than 1% by Carbon dioxides' concentration. Hydrogen enrichment increases the SOFC performance but because of higher airflow rate total efficiency reduces significantly.

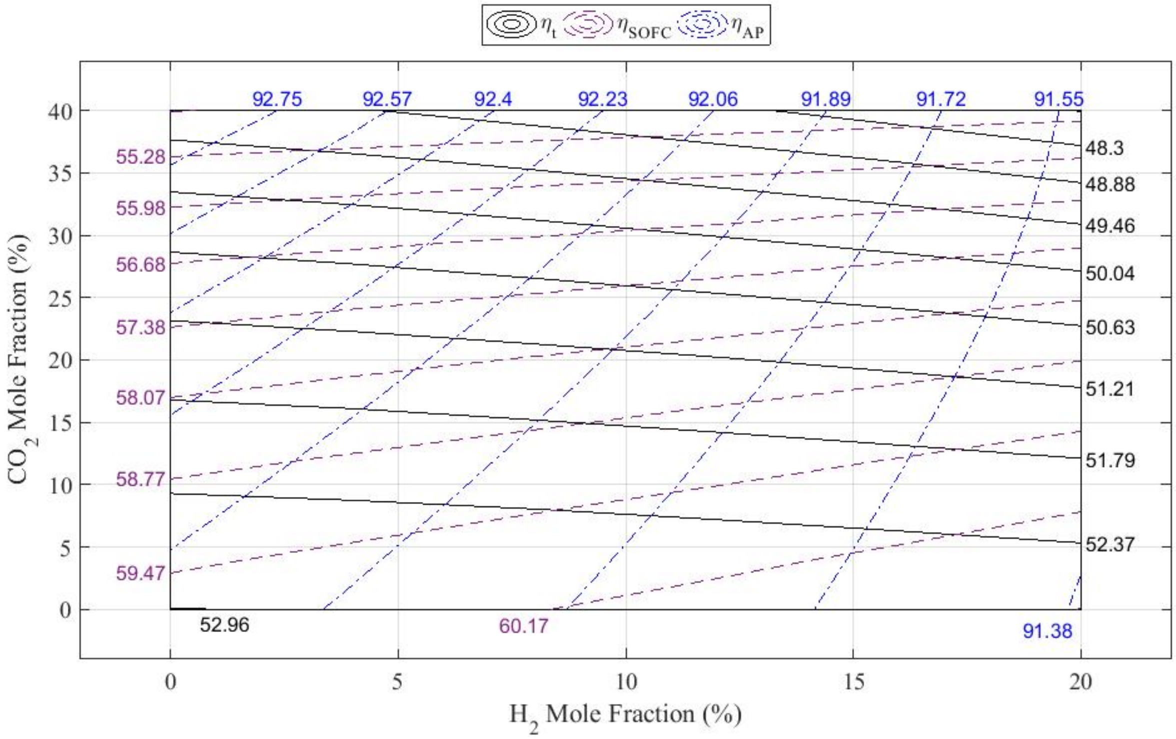


FIGURE 5. contours of efficiencies for different fuel hydrogen and carbon dioxide compositions.

CONCLUSION

SOFC exergetic performance comparison for different fuels called: pure methane, biogas, and syngas is carried out here. The first is rich in methane, the second in carbon dioxide and last in hydrogen respectively. Effect of pressure is analyzed as well, and results lead to following highlighted conclusions:

- High concentration of hydrogen and low methane leads to higher required air flow rates.
- Generally, carbon dioxide causes the performances of the system to reduce.
- Syngas is not a reasonable choice for high pressure standalone SOFC applications.

Since the output of the SOFC is a source of exergy itself (high temperature and possibly pressure), SOFCs are normally coupled with bottoming cycles. Fuel comparison on the SOFC based multigeneration systems may provide different results and most be carried out separately which can be a subject of further studies.

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