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Exergy and Energy Analysis of Solid Oxide Fuel Cell Fuelled Using Methanol Propane, and Butane

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Abstract. Exergy and Energy analysis used the principle of conservation of mass and energy, in connection with thermodynamics law in designing and analysing of thermal system This Paper focus on Energy and Exergy analysis of Solid Oxide Fuel Cell (SOFC) system by computer simulation. A comprehensive effect of Energy and Exergy analysis on SOFC using Methanol, Propane, and Butane fuel system with the aid of Thermolib simulation toolbox was investigated. From the configurations simulated for the three different fuel sources, the data produced were used for thermodynamic analysis. The result obtained showed that Butane configuration has the highest energy efficiency of 50.3% .while Methanol and Propane system has an energy efficiency of 46.5% and 47.7% respectively. The total energy produced by Methanol, Propane and Butane Fuel System are 273.66 KW, 234.67 and 263.92 kW respectively. While that required are 69.45 KW, 0.062 KW and 4.972 KW respectively. This shows that the highest energy requiring and producing system is the Methanol Fuelled system. The principle of energy conservation was met in all configurations. The Exergy analysis indicated that around equipment such as Reactor, lambda burner and SOFC stack there is a change between the inlet and outlet chemical Exergy. However the chemical Exergy for Pumps, Heat exchangers, compressor and Mixer remains the same because no chemical reaction occurs in them. In addition, equipment such as pump and compressor gives higher Exergetic efficiency than others. In terms of overall loss work, Methanol, Propane, and Butane system are 422.2 KW, 247.7KW, 195.7 KW respectively. The Overall System Exergetic efficiency of the three fuel systems are 44.2%, 49.3%, and 46.7% respectively. This shows that Propane system has the highest Exergetic efficiency and least irreversibility. While Methanol fuel system has the lowest Exergetic efficiency and most irreversibility. Exergy and energy efficiency favours the choice of propane fuel system. This is because Propane is the most Exergy efficiency system.

Keywords: Solid oxide fuel cell, Exergy analysis, energy analysis, Methanol, Propane, Butane.

1. Introduction

Continued industrial growth as a result of the developments in science and technology has improved comfortability and human standard of living. It has also led to the increase in demand for energy [1]. World stocks of fossil fuels continue to fall, as it is the main source of energy, leading to shortfalls in supply and creating serious environmental degradation as they introduce foreign materials in the atmosphere. This concern has led several countries to review their energy policy and sought radical



measures to remove waste [2]. It has steered the search for other sources of energy that are more effective than the usual heat engine with no or slight emissions of pollutant [3, 4]. According to [5, 6], among several possible fuels, fuel cells (FCs) were recognized as one of the best, and the potential of clean energy technologies to meet all the constraints of energy supply, the economic development and environmental sustainability.

According to [1], fuel cells (FCs) are energy device that converts chemical energy to electrical energy and heat by reduction and oxidation reaction on the anode and the cathode of the cell using hydrogen or hydrogen-rich fuel and oxygen from the air. Merging both the benefits of internal combustion engines in their continuous operation and simplicity of use, and highly efficient and low-noise operation of batteries, fuel cells thus seems to be the perfect energy-alternative.

Hydrogen is the perfect fuel for fuel cell. Fuel cell powered with hydrogen derived from a renewable resource would emit nothing but gaseous water [3, 7, 8]. Despite the fact that hydrogen is the most abundant element on Earth, there are a number of obstacles limiting its direct use [9]. Hydrogen does not occur naturally on Earth, and as such, it is derived from substances notably: natural gas, gasoline, methanol, ammonia and propane [10]. This makes hydrogen expensive. Hydrogen is 14 times as light as air and as a result of this small volumetric density and molecular size, moving even a small amount of hydrogen is very expensive [11]. Hence, the transport and storage of hydrogen is considered as unfeasible. Another major drawback for the direct use of hydrogen is that no hydrogen infrastructure currently exists.

A good analysis should be done to the investigations of the energy and exergy efficiency using various hydrogen fuel sources. The use of energy analysis only to determine the effectiveness of a thermodynamic system can be misleading. Exergy analysis identifies the primary source of loss and offers more accurate information about the effectiveness of a system.

[12-15] describe the technique to carry out Exergy analysis and enhance the understanding of this technique. All the necessary equations to determine exergy analysis, including exergy calculation for heat exchangers, combustion chambers, compressor and gas turbines are explained in their research. In addition, the procedure for the calculation of the second law efficiency of each component and the overall system was illustrated.

[16], in their study centered on an integrated internal-reforming SOFC gas turbine (IRSOFC-GT) power system fed with natural gas. From the simulation results, IRSOFC-GT energy system could reach a net electrical efficiency beyond 59% and system efficiency beyond 79%.

[17] said that the Exergy analysis of a hybrid SOFC show that the SOFC stack was responsible for the largest Exergy loss. This high rate of exergy loss originated in the ineffectiveness of chemical and electrochemical reactions that occur in SOFC stack. In addition, it shows the catalytic burner where anode off-gas flow was burned, has high exergy destruction. They concluded in the end that in designing hybrid energy systems, special emphasis ought to be given to the part with the greatest exergy loss.

[18] in his study gives an understanding from his investigation of operating various fuels on an integrated SOFC reformer system. The simulated results show that significant issues in thermal management may arise from the use of different fuels in the same integrated fuel cell reformer system.

Another study by [1] on the Thermo-economic performance of PEMFC shows that methane-fueled configuration requires less amount of energy compared to methanol configuration. The result of the analysis of the exergy of both configurations revealed greater exergy efficiency around important equipment such as pump and compressor. Based on exergy efficiency, methanol-configuration is better than methane system. Economic analysis revealed that methane system has low capital costs and slightly higher annual costs against methanol system.

[20-22] analyse various integrated system based on Exergy destruction calculation and second law efficiencies. They also show different ways achieved detailed physical and chemical Exergy calculations for both SOFC and PEMFC system.

The results of Thermo-economic study of a hybrid SOFC [7] using Thermolib with Ethanol and methane fuel shows that when the system is powered with ethanol, the solid oxide fuel cell stack

constitute around 29% of the overall exergy loss. For methane configuration, the equipment having the greatest loss of exergy is CO₂ compressor, which constitute around 51 percent of the overall exergy loss. The findings also show that the turbine has the greatest exergy efficiency in the two configurations. The operation of equipment in the two systems reveals that methane has more component with high exergy efficiency, while ethanol configuration has more component with high irreversibility. The simulated results show a total exergy efficiency of the methane and ethanol systems to be 22.3% and 24.6% respectively with a total loss of work of 1066.36 kW and 782.33 kW respectively. This indicate that ethanol fuel configuration yield the greatest exergy efficiency and the highest percentage of irreversibility in relation to methane fueled system.

The use of Thermodynamic analysis in SOFC system with Thermolib using methanol, propane and butane as fuels have not been explored. This study presents a comparative analysis of three different fuels namely: Methanol, propane and Butane on the thermo-economic performance of SOFC. This study provides information essential for the design of profitable conversion systems.

2. Material and Method

2.1. Selection of SOFC Configurations

The configuration proposed by [1] was augmented by the SOFC-DEMO configuration of Thermolib software from which improved configurations for Methanol, Propane, and Butane fuel were derived.

2.2. Description of Process

After the process configurations for the three fuels have been selected, they are modeled and simulated with the aid of trial version 5.30 of Thermolib software. The parameters are set to attain a power yield of 200KW for each of the configurations. After simulation, the results obtained were used for Energy and Exergy analysis for the three systems.

The process description for Methanol fuel as shown in Figure 2.1 is the same with that of Propane and Butane fuel except that in Propane and Butane system there is an additional WGS reactor that converts CO to H₂ and CO₂.

For the Propane and Butane system modeling presented in Figure 2.2 -2.3, the Inlet fuel is mixed with steam and pump through heat exchanger₂ to heat it up to the required temperature for the reaction. At the reformer, the Fuel is converted to H₂ and CO. The reformer outlet is passed to a water-gas shift (WGS) reactor where CO is transformed to additional H₂ and CO₂ [23-25]. The stream from the WGS reactor is sent to the SOFC anode while compressed air is set to the cathode of the SOFC. It is assume that 85% of the hydrogen reacts with oxygen in the fuel cell to generate electricity. The SOFC outlet containing unused hydrogen is sent to the afterburner where it is burnt. So as to reduce the energy requirement of the system, the afterburner outlet is split into two streams: one is sent to heat exchanger 2 and the other to the reforming reactor to provide heat for steam reforming process.

2.3. Modelling and Simulation of Selected Configurations

After the process configurations for the three fuels have been selected, they are modelled using Thermolib, which is a MATLAB/Simulink's toolbox. Thermolib is developed for modelling and simulation of thermodynamic systems. A detailed description on using Thermolib to model the selected configuration is given by [1]. The parameters are set to reach a power productivity of 200KW for each of the configurations. After simulation, the results obtained were used for Exergy and economic analysis for the four systems. The simulated configurations for the three fuels are show in figure 2.1-2.3.

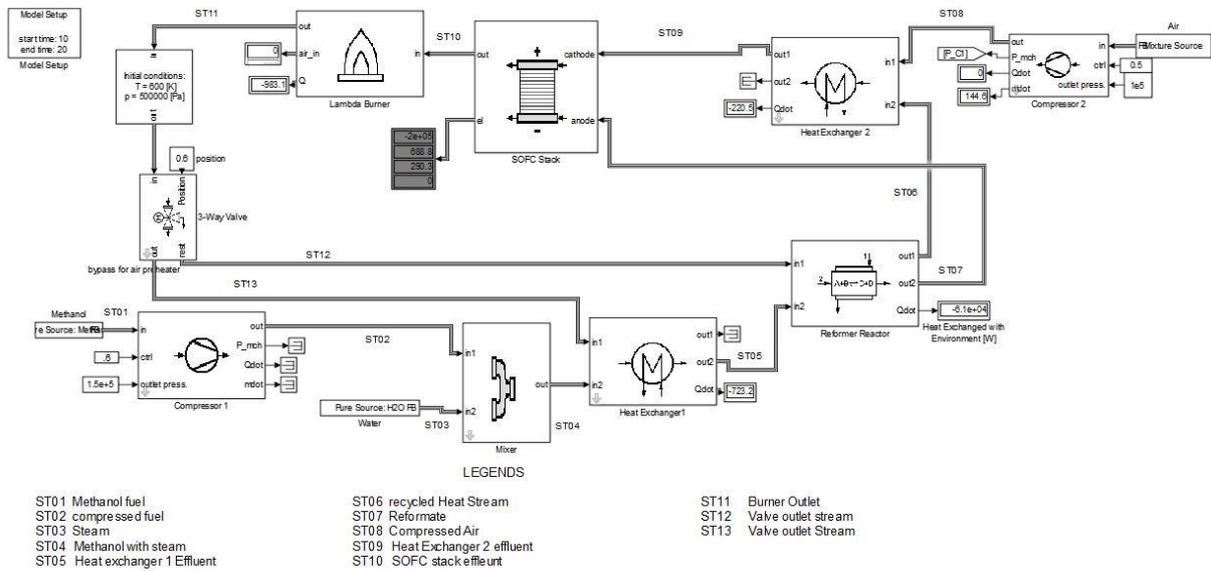


Figure 2.1 Methanol SOFC System

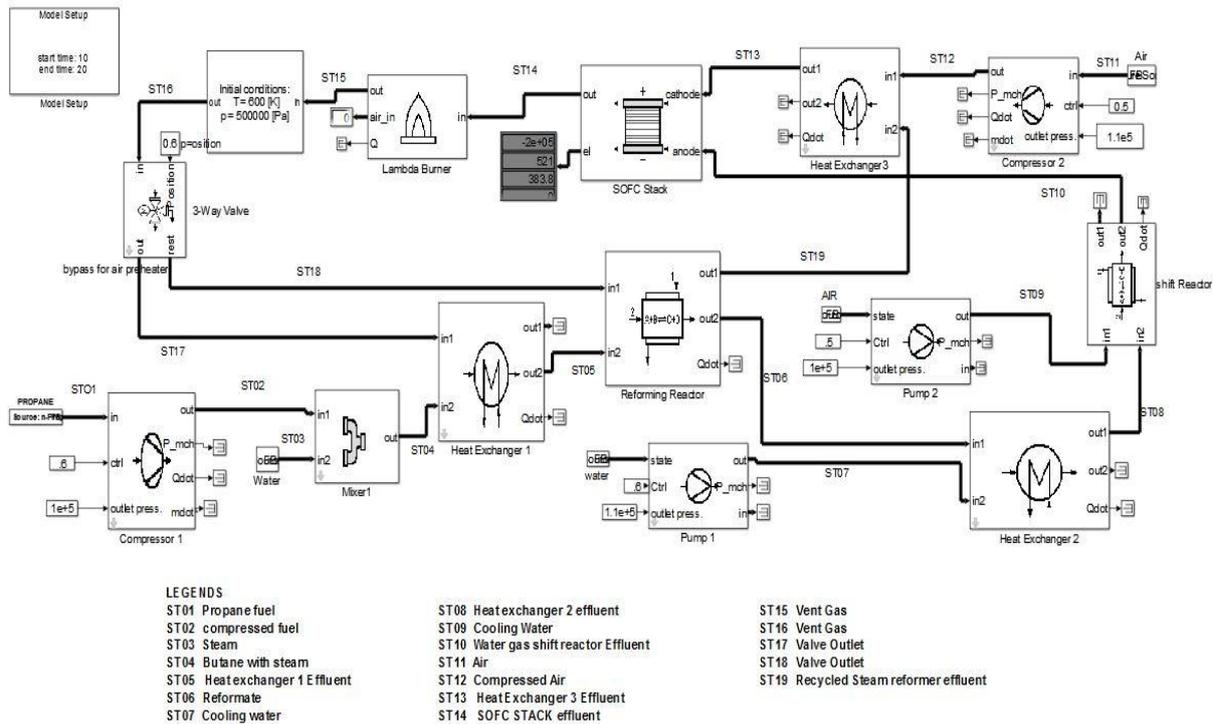


Figure 2.2 Propane SOFC system

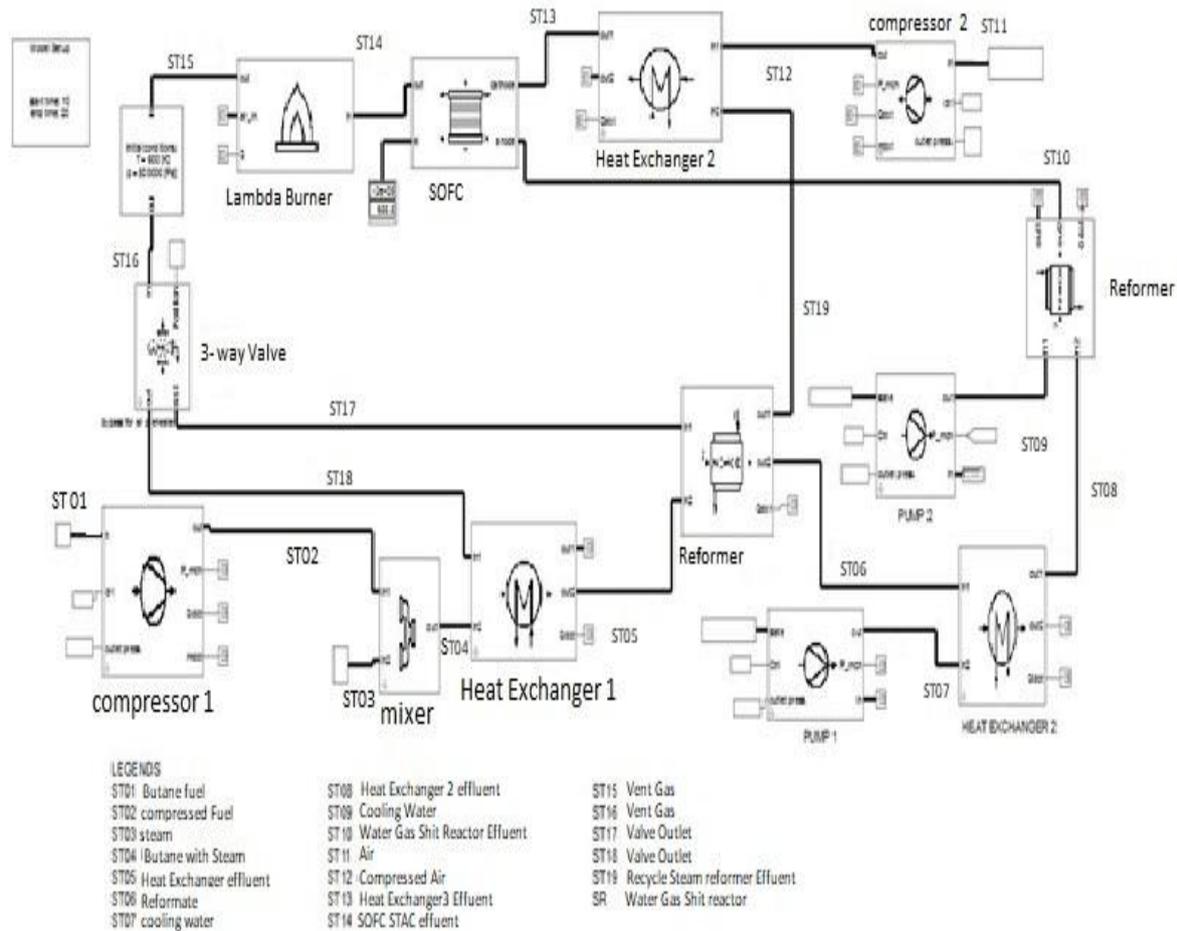


Figure 2.3 Butane SOFC system

2.4. Selection of SOFC Configurations

The configuration Exergy analysis is a technique of using the principle of conservation of mass and energy, in connection with thermodynamics second law in designing and analyzing of thermal system [24]. Exergy is the highest quantity of work that can be achieved when a system is taken to equilibrium (mechanical, thermal and chemical) with the environment [5]. The parameters determine in the exergy analysis are physical exergy and chemical exergy, loss of work and exergetic efficiency.

According to [24], the pressure $P = 1.01$ bar, temperature $T_o = 298.15$ K, and environment composition of 0.92% argon, 3.03 % water, 0.03 % carbon dioxide, 20.35 % oxygen, and 75.67 % Nitrogen are assumed as reference. Unlike energy, Exergy is not generally conserve but destroyed by irreversibility within a system. Without magnetism, electricity, nuclear and surface tension effects, [9] defines specific molar Exergy (KJ/mol) as the summation of kinetic Exergy

$$(1)$$

The kinetic and potential Exergy is assume negligible in this study. Hence the Exergy equation is reduced to only physical and chemical Exergy as given by [15] in equation (2)

$$(2)$$

Thermal Exergy, which is also known as physical Exergy, is the maximum amount of work, which can be obtained from a stream of material brought to the environmental state from its initial state but exchanging heat only with the environments thermal reservoir [24, 25]. The chemical Exergy according to [25] is the total amount of work, which can be acquired from a stream of material brought from the environment (restricted dead) state to the total dead (unrestricted) state while exchanging only materials and heat with the environment. The equation for the chemical and thermal Exergy is specified by [21, 24, 26] in equation 3 as

(3)

The lost work (LW) around each piece of equipment with stream inlet Exergy flow ($n_{(i)} \text{ [[ex]]}_i$), outlet exergy flow ($n_{(o)} \text{ [[ex]]}_o$), work flow \dot{W} (kJ/s), and utility heat duties Q (kJ/s), was evaluated with equation (4) given by [26].

(4)

Also Exergetic efficiency is calculated as follow [1, 26]

(5)

Table 2.2 shows the simulated parameters for the selected configurations.

Table 2.2 Simulation Parameters for the Selected Configurations

Parameter	Methanol Configurations	Propane Configurations	Butane Configurations
Fuel utilization	0.85	0.85	0.85
Compressor 1 power required (Watt)	0.2	0.2	0.2
Compressor 2 power required (Watt)	24100	33.9	1060
Pump 1 power (Kw)	-	0.1923	0.193
SOFC Temperature ($^{\circ}\text{C}$)	850	850	850
SOFC Pressure (bar)	1	1	1
SOFC Area (cm^2)	323	323	323
Number of SOFC cell	800	800	800
Reformer Pressure	20	1	1.2
Reformer Temperature	650	603	612
Water gas Shift Reactor Pressure	-	1	1
Water gas Shift Reactor Pressure	-	302	411

3. Result and Discussion

3.1. Energy Analysis

Table 3.1 - 3.3 shows the flow of energy in each equipment of Methanol, Propane, and Butane configuration respectively. The results presented in the Tables shows that the equipments requiring energy are the compressors and pumps with Compressors having the highest energy requirement. The results show that the energy available in the outlet stream is higher than in the inlet stream with exception to pumps and compressors because they are energy requiring equipment. The Tables also reveal that the SOFC stack is the highest energy producing equipment. Methanol Fuel System has the highest energy requirement which can be attributed to the High energy required by the Methanol compressor. Note that despite the fact that Propane and Butane has an extra unit (WGS Reactor), the Energy required by the two system which is 0.062 KW and 4.972 KW respectively is less than 69.45KW required by Methanol system. This is also validated by [1]. The energy produced by Propane Fuel system is 234.67 KW which is the least while that produce by Methanol is 273.66 KW being the highest energy produced among the four system. The first law of Thermodynamic was satisfied in all system.

Table 3.1. Energy Flow for Methanol System

Equipment	Energy of inlet stream (Kw)	Energy of Outlet Stream (Kw)	Required Energy (Kw)	Energy Produced (Kw)
Compressor 1	105.1	69.45	69.45	-
Mixer	665.2	665.2	-	-
Heater 1	1051.6	1052.5	-	0.92
Reforming Reactor	687.07	758.5	-	71.43
Compressor 2	0.1	0.1	-	-
Heater 2	342.27	342.5	-	0.24
SOFC Stack	428.7	628.7	-	200
Lambda Burner	627.6	628.7	-	1.07
3 Way Valve	628.7	628.7	-	-

Table 3.2 Energy Flow for Propane System

Equipment	Energy of inlet stream (Kw)	Energy of Outlet Stream (Kw)	Required Energy (Kw)	Energy Produced (Kw)
Compressor 1	19.600	19.550	0.060	-
Mixer	362.500	362.500	-	-
Heater 1	405.500	406.400	-	0.870
Reforming Reactor	403.210	429.600	-	26.390
Compressor 2	0.100	0.100	-	-
Heater 2	586.400	586.400	-	0.260
Heater 3	190.230	190.400	-	0.170
Shift	246.800	246.800	-	-

Reactor				
Pump 1	3.100	3.100	-	-
Pump 2	164.800	164.780	0.002	-
SOFC Stack	156.300	356.300	-	200.000
Lambda Burner	356.300	363.280	-	6.980
3 Way Valve	363.280	363.280	-	-

Table 3.3. Energy Flow For Butane System

Equipment	Energy of inlet stream (Kw)	Energy of Outlet Stream (Kw)	Required Energy (Kw)	Energy Produced (Kw)
Compressor 1	21.170	16.200	4.970	-
Mixer	1191.800	1191.800	-	-
Heater 1	1914.500	1915.330		.830
Reforming Reactor	1553.300	1609.340		56.040
Compressor 2	.100	.100	-	-
Heater 2	1237.900	1238.240		.340
Heater 3	536.500	536.710		.210
Shift Reactor	1078.300	1078.300	-	-
Pump 1	3.100	3.100	-	-
Pump 2	164.802	164.800	0.002	-
SOFC Stack	989.800	1189.800		200.000
Lambda Burner	1189.800	1196.300	-	6.500
3 Way Valve	1196.300	1196.300	-	-

Table 3.4 shows the overall energy efficiency of the four Fuel SOFC system. From the result presented in Table 3.4, Butane fuel System is the most energy efficient system having an efficiency of 50.3%. However, the quality and direction of energy flow is not considered. Though Butane Fuel system has the most energy efficiency, it does not mean that it has the least energy degradation. Since no information is available on the degradation of energy occurring in each process.

Table 3.4 Energy Efficiency

Parameter	Energy Efficiency
Methanol	46.5
Propane	47.7
Butane	50.3

3.2. Energy Analysis

Table 3.1 - 3.3 shows Table 3.5 - 3.7 shows the behavior of physical, chemical Exergy, and the total Exergy flow for Methanol, Propane, and Butane fuel system respectively. The result presented indicate that around equipment such as Reactor, lambda burner, and SOFC stack there is a change between the inlet and outlet chemical Exergy. This is as a result of chemical reaction occurring in them, which

alters the chemical composition of the outlet stream. From the Propane and Butane fuel results shown in table 3.6 - 3.7 the SOFC inlet has the highest chemical Exergy flow of about 14.7% and 14.4% respectively of the total chemical Exergy flow. This is because of the high standard chemical Exergy of hydrogen in the streams. Lambda burner outlet has the highest physical Exergy owing to the combustion reaction, which gives off heat energy. From the results, pumps and compressor have very low physical Exergy because the streams conditions are or almost same with the reference temperature and pressure and the flow rate were very low. Also note that the Physical Exergy for Propane increase by 10.2% and Butane Fuel system increased by 24.7%. The increase in Physical Exergy in propane and Butane system is due to the high increase in Physical Exergy at the SOFC stack component. Although there is a rise in the Physical Exergy of the two systems, the overall Exergy of the system decrease by 19.6% and that of Butane by 2.9% respectively.

Table 3.5 Equipment Exergy Flow for Methanol System

Equipm ent	Physical Exergy In (KW)	Chemic al Exergy In (KW)	Total Exergy In (KW)	Physi cal Exergy Out (KW)	Chemica l Exergy Out (KW)	Total Exergy Out (KW)
Compre ssor 1	0	424.8	424.8	10.7	424.8	435.5
Mixer	26.8	427.4	454.2	26.5	425.9	452.4
Heater 1	182.2	437.4	619.6	98.8	437.4	536.2
Reactor	234.4	433.6	668	43.9	434.7	478.6
Compre ssor 2	0	16.1	16.1	0	16.1	16.1
Heater 2	12.7	25.9	38.6	7.3	20.9	28.2
SOFC	41.5	447.9	489.4	312.9	81.8	249.1
Lambda Burner	249.1	81.8	330.9	155.3	19.2	174.5
3 Way Valve	155.3	19.8	174.5	154.7	19.2	173.9

Table 3.6 Equipment Exergy Flow for Propane System

Equipm ent	Physical Exergy In (KW)	Chemical Exergy In (KW)	Total Exergy In (KW)	Physical Exergy Out (KW)	Chemical Exergy Out (KW)	Tota l Exergy Out (KW)
Compre ssor 1	0	402	402	0	402	402
Mixer	0	403.6	403.6	0	403.6	403.6
Heater 1	120.3	414.6	534.9	46.4	414.6	461

Reactor	156	413.9	569.9	51.6	431.8	483.4
Pump 1	0	30.1	30.1	0	30.1	30.1
Heater 2	16.9	433.9	450.8	12.5	433.9	446.4
Pump 2	0	0.75	0.75	0	0.75	0.75
Shift Reactor	12.5	433.2	445.7	14.6	434	445.6
Compressor 2	0	0	0	0	0	0
Heater 3	34.7	39	73.7	9.1	39	48.1
SOFC	17.2	464.2	481.4	162	88	250
Lambda Burner	162	88	250	169	22.6	191.6
3-Way Valve	169.2	22.6	191.8	167	22.6	189.6

Table 3.7 Equipment Exergy Flow or Butane System

Equip ment	Phy sical Exergy In (KW)	Che mical Exergy In (KW)	Total Exergy In (KW)	Phy sical Exergy Out (KW)	Che mical Exergy Out (KW)	Total Exergy Out (KW)
Compr essor 1	0	380.8	380.8	1.9	380.8	382.7
Mixer	10.4	387.3	397.7	10.4	387.3	397.7
Heater 1	148.4	410.7	559.1	133.8	410.7	544.5
Reactor	178.4	405.5	583.9	83.3	443.3	526.6
Pump 1	0	26.9	26.9	0.0	26.9	26.9
Heater 2	36.3	433.6	469.9	34.8	433.6	468.4
Pump 2	0	0.75	0.75	0.0	0.8	0.8
Shift Reactor	36	432.9	468.9	31.0	431.7	462.7
Compr essor 2	0	0.013	0.013	0.0	0.0	0.0
Heater 3	47	37.3	84.3	32.1	37.3	69.4
SOFC	61.6	458.6	520.2	181.0	88.1	269.1
Lambd a Burner	181	185.1	366.1	228.6	26.0	254.6

3-Way Valve	228.3	26	254.3	228.2	26.0	254.2
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The result of the exergetic performance (Exergy loss and Exergy efficiency) is presented in Table 3.8-3.10. Table 3.8 - 3.10 show the Exergetic efficiency and loss work for Methanol, Propane, and Butane. The calculations for Exergy loss takes into account the work required or Produced and the heat supply or loss. The results show that there are components with 100% Exergetic efficiency such as pumps, mixers and compressors. This high efficiency and low exergetic irreversibility in compressors and pumps clearly show that the equipment such as compressors and pumps that use electricity as a source of energy have high efficiency because it has good energy. This is validated by [1, 24]. It is observe that the Lambda Burner in all systems has the highest degradation of energy (Exergy loss). This could be ascribed to high temperature change of the equipment, therefore having the lowest Exergy efficiency of 53%, 79.4% and 71.3% for Methanol, Propane and Butane Fuel System respectively. This agrees with the findings of previous work by [1].

Table 3.8 Exergetic Performance Analysis Result for Methanol System

Equipment	Loss Work(Kw)	Exergetic Efficiency (%)
Compressor 1	13.4	96.8
Mixer	1.8	99.6
Heater 1	82.5	86.7
Reactor	118.0	82.3
Heater 2	0.0	100.0
Compressor 2	10.2	73.6
SOFC Stack	40.3	91.8
Lambda Burner	155.4	53.0
3 Way Valve	0.6	99.7

Table 3.9 Equipment Exergetic Performance Analysis Results for Propane System

Equipment	Loss Work(Kw)	Exergetic Efficiency (%)
Compressor 1	0.0	100.0
Mixer	0.0	100.0
Heater 1	73.0	86.4
Reactor	60.1	89.5
Pump 1	0.0	100.0
Heater 2	4.1	99.1
Pump 2	0	100.0
Shift Reactor	0.1	100.0
Compressor 2	0.0	100.0
Heater 3	25.4	65.5
SOFC	31.4	93.5

Lambda Burner	51.4	79.4
3-Way Valve	2.2	98.9

Table 3.10 Equipment Exergetic Performance Analysis Results for Butane System

Equipment	Loss Work(Kw)	Exergetic Efficiency (%)
Compressor 2	2.0	99.5
Mixer	0.0	100.0
Heater 2	13.8	97.5
Reforming Reactor	1.4	99.8
Heater 1	0.0	100.0
Heater 3	1.2	99.8
Shift Reactor	0.0	100.0
Compressor 1	6.2	98.7
Pump 1	0.0	100.0
Pump 2	14.7	82.6
SOFC Stack	51.1	90.2
Lambda Burner	105.2	71.3
3 Way Valve	0.1	100.0

Table 3.11 shows the overall loss work, energy and Exergy efficiency of Methanol, Propane, and Butane system. Among the three fuels, Methanol has the highest loss work of 422.2 KW while Butane has the least loss work of 162.7 KW. From the table methanol has the least Exergetic efficiency of 44.2% while Butane has the highest Energy efficiency. The result also reveals that propane which has the second highest Energy efficiency after Butane Fuel has the highest Exergy efficiency. Hence, from the result propane fuel is most favourable. Hence energy analysis alone is not sufficient to give the best possible process part, instead a combination of both energy and Exergy analysis will give a better and actual performance of a system.

Table 3.11 Overall Loss work, Energy Efficiency, and Exergy Efficiency

System	Overall Loss Work (Kw)	Overall Energy Efficiency	Overall Exergetic Efficiency
Methanol	422.2	46.5	44.2
Propane	247.7	47.7	49.3
Butane	195.7	50.3	46.7

4. Conclusion

The exergy and energy analysis on SOFC system using different fuels was successfully carried out. SOFC system configurations for Methanol, Propane and Butane fuel system was design using Thermolib. The configuration was successfully simulated to give power output of 200KW using Thermolib. From the results obtained, Exergy analysis was done on the different fuel SOFC system. From the result obtained, Butane Fuel system gave the highest Energy efficiency; Propane Fuel system has the highest Exergy efficiency. Although Butane system is the most Energy effective system when compared with the other three, Nevertheless a compromise between Exergy and energy efficiency favours the choice of propane fuel system. This is because Propane is the most Exergy efficiency system.

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