Exergy and Economic Analyses of a Hybrid Solid Oxide Fuel Cell by Computer Simulation

Abdulkareem A. Saka *Member, IAENG* , Bilyaminu S, Ayo S. Afolabi* *Member, IAENG,* and Yenkwo K.C

***Abstract*— This study is focused on the exergy and economic analysis of hybrid solid oxide fuel cell with zero-CO_2 emission by computer simulation with either methane or ethanol as fuels. Configurations were simulated for ethanol and methane fuelled solid oxide fuel cell system. The results obtained indicate that when the system is fuelled with ethanol, the SOFC stack accounts for about 29 % of the total exergy loss which is the highest exergy loss. In methane system, the component with the highest exergy loss is the CO_2 compressor which accounts for 51 % of the total exergy loss. Results also shown that turbine had the highest exergetic efficiency in both configuration. The performance of equipment in both configurations shows that the methane configuration has more equipment with high exergetic efficiency, while the ethanol configuration has more equipment with high irreversibility. Simulated results also shown that the overall exergetic efficiency of the ethanol and methane systems are 24.63 % and 22.33 % respectively, and overall loss work of 1067.36 kW and 783.33 kW respectively indicating that the ethanol fuelled system has the highest rate of irreversibility but conversely also with the highest exergetic efficiency when compared to the methane fuelled system. Economic evaluation of both configurations showed that the capital cost of ethanol and methane system are 8388.56 $/year and 2666.99 $/year respectively indicating that the methane system is more economically viable. Although the ethanol system is more efficient than the methane system, but trade-off between exergetic and economic efficiency favours the selection of methane fuelled configuration over ethanol fuelled configuration for the hybrid SOFC system because the capital cost of the ethanol is far greater than that of methane system.**

Keywords— *Economic analysis, exergy analysis, ethanol, solid oxide fuel cell and hybrid system..*

I. Introduction

Today the combustion of fossil fuels, such as petroleum, natural gas, and coal, which is a non-renewable energy source, serves as the world's major source of energy production. This process is associated with the release of high amount of greenhouse gases such as carbon dioxide (CO_2), and other substances that pose great danger to the environment [1]. The demand for energy consumption is rapidly increasing leading to the gradual depletion of fossil fuels. This fact, coupled with the fight against environmental pollution due to the emission of greenhouse gases into the atmosphere, has led to considerable interest in the use of alternative source of energy [2]. Fuel cells technologies have been identified as perfect alternative energy with little or no emission. Among the different types of fuel cells currently available, solid oxide fuel cell (SOFC) is a promising means of energy generation due to its high operating temperature, high efficiency, low emission of pollutants into the atmosphere, and fuel management, because it uses solid electrolyte, CO_2 gas can be obtained in the anode exhaust gas, there is no liquid to cause environmental issues and therefore great heat generation can be recovered in order to increase overall thermodynamic efficiency [3-4]. The SOFC hybrid system power plant has a higher system efficiency which even when CO_2 has been captured, the performance of SOFC hybrid system can still be greater than or equal to that of the conventional power systems without CO_2 capture. In order to improve the CO_2 concentration of anode exhaust gas, SOFC can adopt the O_2/CO_2 combustion system in the afterburner [5].

Past works concerning the hybrid power system with CO_2 capture have also been carried out [6]. Studies on two types of carbon dioxide recovering SOFC and gas turbine combined power generation systems in which a gas turbine having a carbon dioxide recycle or water vapour injection is adopted at the bottoming cycle system [6]. The system used two separate technologies for the same base system to attain a low CO_2 emission [6]. Calisea et al [7] presented the integration of a solid oxide fuel cell with high operating temperature in a near-zero emission CO_2/O_2 cycle. Takeshi et al [8] compared and evaluated the techno-economic performance of CO_2 capture from industrial SOFC-combined heat and power plant. Lygre at al. [5] carried out the exergy analysis of a novel hybrid SOFC with zero-CO_2 emission. In this work, the exergy and economic analysis of a hybrid solid oxide fuel cell system with zero-CO_2 emission fed with methane and ethanol will be carried out by computer simulation and the result of this study will provide better understanding of the type and thermo-economic performance of the SOFC with zero-CO_2 emission using different fuel types.

II. Materials and Methods

The simulated configuration for the solid oxide fuel cell fuelled with ethanol and methane are presented in Fig. 1 and 2 respectively. In order to realize a Zero-CO_2 emission and lower energy consumption of CO_2 capture, the configuration mainly adopts the following measures: The cathode outlet

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Abdulkareem A.S is with the Department of Chemical Engineering, Federal University of Technology, PMB 65 Gidan Kwano Minna, Niger State Nigeria and Civil and Chemical Engineering Department, College of Science, Engineering and Technology, University of South Africa, Johannesburg South Africa. E-mail: kasaka2003@futminna.edu.ng

Ayo S Afolabi* is with the Department of Civil and Chemical Engineering, University of South Africa, Florida Campus, Johannesburg, South Africa. (*Corresponding author: phone: +27 114713617; e-mail: afolaas@unisa.ac.za).

Bilyaminu S Yenkwo is with the Department of Chemical Engineering, Federal University of Technology, PMB 65 Gidan Kwano Minna, Niger State Nigeria. E-mail: bilyaminusuleiman@yahoo.com

Yenkwo K.C is with the Department of Chemical Engineering, Federal University of Technology, PMB 65 Gidan Kwano Minna, Niger State Nigeria.

gas of the SOFC stack is channelled into a turbine to expand and the product gas is channelled into the afterburner. The system uses a multi-stage compression mode.

A. Energy and Exergy Analysis of Hybrid

The parameters determined were streams' physical and chemical exergy, lost work and exergy efficiency. The physical exergy (kJ/sec) of a stream of matter with flow in enthalpy (kJ/sec) and entropy (kJ/K. sec) at T and P, relative to the surroundings (dead state) at T_o and P_o was determined using equation (i).

$$\dot{B}_{phy} = [h(T,P) - h(T_o - h_o)] - T_o[s(T,P) - s(T_o,P_o)]$$
(i)

The chemical exergy $\dot{B}_{chm}$ (kJ/sec) of each stream of matter with component mole fraction x_i (y_i for vapour) and standard chemical exergy (kJ/sec) of each component in a stream using equation (ii)

$$\dot{B}_{chm} = \sum x_i e_i^o \qquad \text{(ii)}$$

The total stream exergy in equation (iii) was evaluated as the sum of its physical and chemical exergy.

$$\dot{B}_{total} = \dot{B}_{phy} + \dot{B}_{chm} \qquad \text{(iii)}$$

The lost work LW, around each piece of equipment or for overall configuration with streams flows $\dot{m}$ (kg/s), streams exergy B (kJ/kg), work flows $\dot{W}$ (kJ/s), utility heat duties Q (kJ/s) at actual temperature T_o (K) and reference state temperature (K) was evaluated using equation (iv).

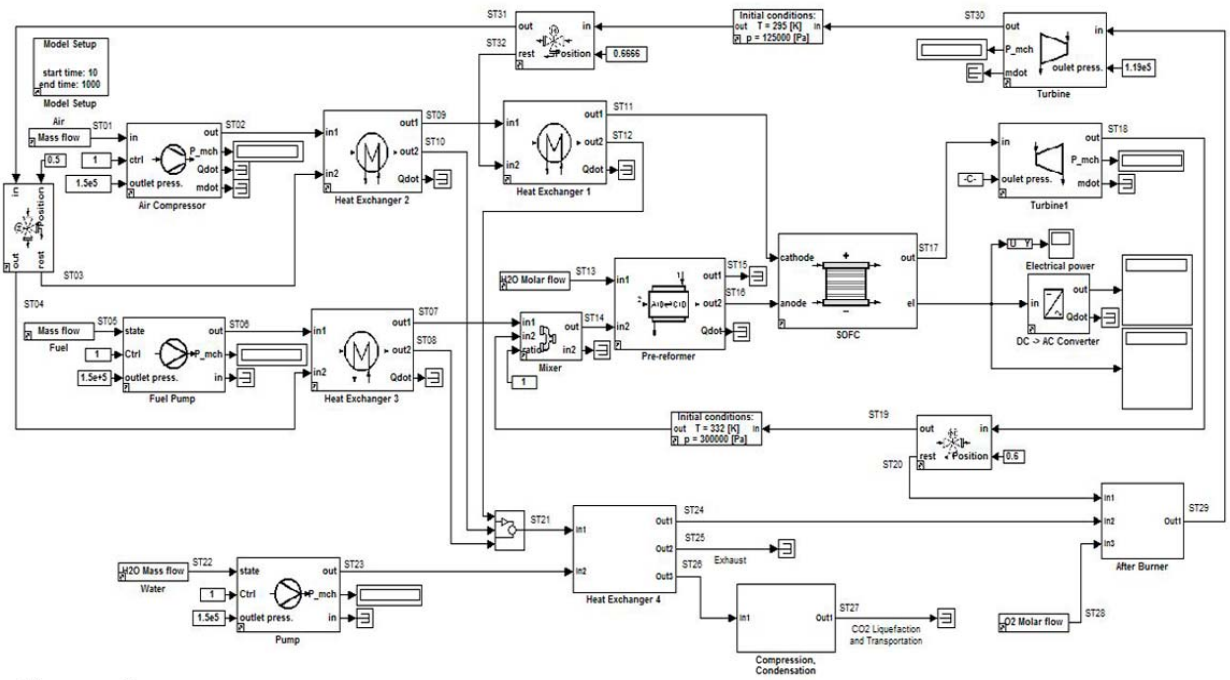
$$L\dot{W} = \Sigma(\dot{m}B)_{in} - \Sigma(\dot{m}B)_{out} + \Sigma\dot{W}_{in} - \Sigma\dot{W}_{out} + \Sigma[Q(1-\frac{T_o}{T})]_{in} - \Sigma[Q(1-\frac{T_o}{T})]_{out} \qquad \text{(iv)}$$

In addition, exergetic efficiency (η_{Exergy}) was evaluated around equipment and for each hybrid configuration. The exergetic efficiency is the ratio of the exergy recovered $\Sigma\dot{B}_{out}$ (total output exergy) to the total input exergy $\Sigma\dot{B}_{in}$ as given in equation (v).

$$\eta_{exergetic} = \frac{\Sigma(exergy\ out)}{\Sigma(exergy\ in)} \qquad \text{(v)}$$

B. Economic Analysis

The economic analyses of both configurations were carried out in stages. The first stage was the evaluation of cost of all equipment used, then the evaluation of cost of utility. The values obtained were used to calculate the direct costs and indirect costs.



Legend

ST01 Air
ST02 Compressed Air
ST03 Cathode exhust gas
ST04 Cathode exhust gas
ST05 Ethanol
ST06 Compressed ethanol
ST07 Pre heated ethanol
ST08 Heated ethanol
ST09 Air
ST10 Cathode exhust
ST11 Oxygen
ST12 Oxygen
ST13 Water
ST14 Hydrogen
ST15 Water
ST16 Hydrogen
ST17 Cathode product gas
ST18 Steam
ST19 Steam
ST20 CO2 & steam
ST21 Cathode exhust gas
ST22 Water
ST23 Steam
ST24 Water
ST25 Exhust
ST26 CO2 gas
ST27 Condensed and compresed CO2
ST28 Pure oxygen
ST29 Comburtion gas
ST30 Cathode exhust gas
ST31 Cathode exhust gas
ST32 Cathode exhust gas

Fig. 1: Process flow sheet of simulated configuration for ethanol system

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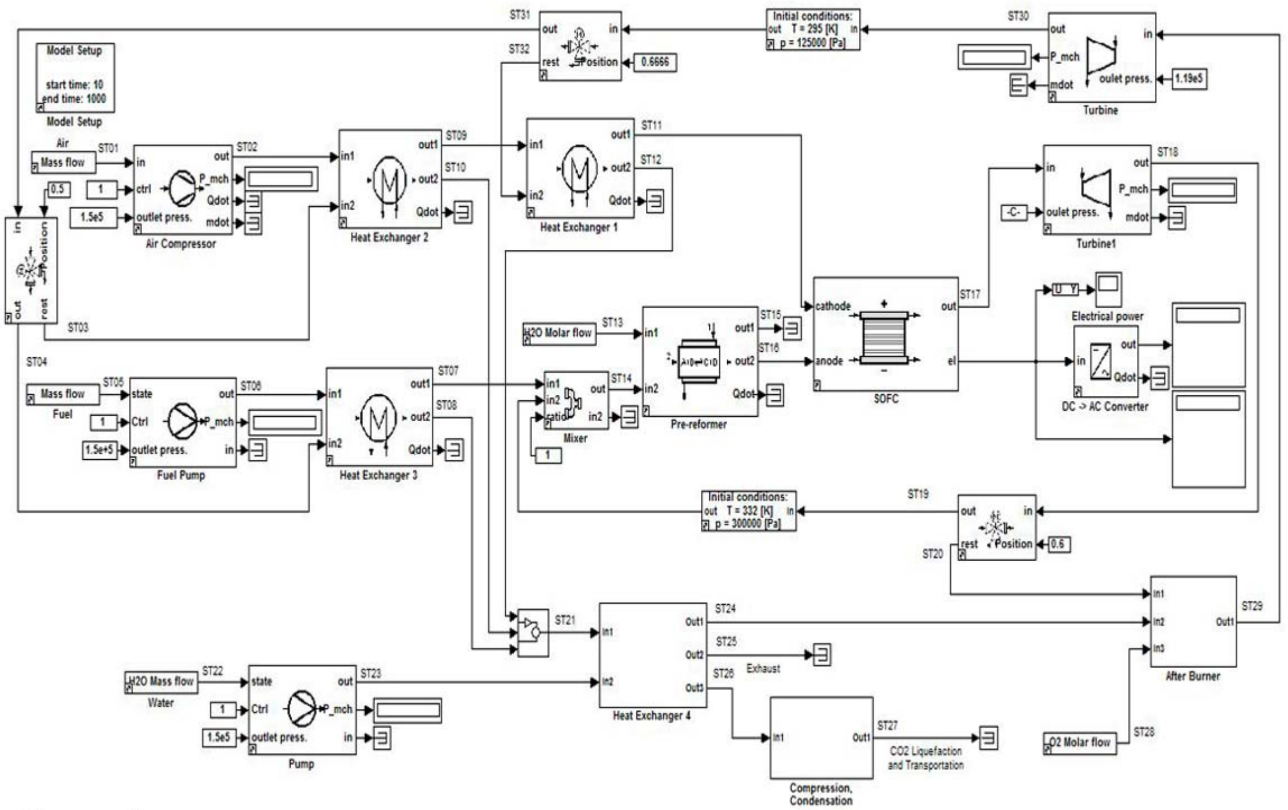

Legend

ST01 Air
ST02 Compressed Air
ST03 Stack exhust gas
ST04 Stack exhust gas
ST05 Methane
ST06 Compressed methane
ST07 Pre heated methane
ST08 Heated methane
ST09 Air
ST10 Stack exhust gas
ST11 Oxygen
ST12 Oxygen
ST13 Water
ST14 Hydrogen
ST15 Water
ST16 Hydrogen
ST17 Cathode product gas
ST18 Steam
ST19 Steam
ST20 CO2 & steam
ST21 Stack exhust gas
ST22 Water
ST23 Steam
ST24 Water
ST25 Exhust
ST26 CO2 gas
ST27 Condensed and compresed CO2
ST28 Pure oxygen
ST29 Comburtion gas
ST30 Stack exhust gas
ST31 Stack exhust gas
ST32 Stack exhust gas

Fig. 2: Process flow sheet of simulated configuration for methane system.

III. RESULTS AND DISCUSSION

Table I shows flow of exergy, the behaviour of physical and chemical exergy separately and the extent of physical and chemical exergy destruction in equipment in ethanol configuration. Simulated results presented in Table I indicate that heat exchanger 4 has the highest physical exergy input of 517794965.2 W, and highest physical exergy output of 514794991.1 W. This is because the equipment has a high temperature change of 412.393K and high pressure change of 118973Pa between its inflowing streams of 21 and 23 and out flowing streams of 24, 25 and 26.

The mixer has the highest chemical exergy in of 711721.58 W; this is because streams 7 and 19 which are streams entering into the mixer are each made up of 0.5 mole fraction of H_2O and C_2H_5OH with respective standard chemical exergy of 11710 J/mol and 1370800 J/mol. The results obtained for the methane fuelled configuration are presented in Table II. The results obtained indicate that mixer had the highest physical exergy input of 459920.81 W and highest physical exergy output of 459920.81 W. This pattern of results could be attributed to the fact that the difference in temperature and pressure between its inflowing streams 7 and 19 and its out flowing stream 14 are 1846.93 K and 134999 Pa respectively, and a corresponding increase in flow rate from 0.965925 mol/sec to 1.93185 mol/sec. Like the ethanol fuelled system mixer also has the highest chemical exergy input of 845272.98 W. This is because streams 7 and 21 which are entering streams into the mixer are made up of components with high standard chemical exergies.

The general overview of Table II shows that physical exergy across equipment might increase or can be destroyed depending on whether it is a work requiring or work producing equipment. The extent of physical or chemical

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exergy degradation depends on the equipment type energy quality and components composition. Table III shows the rate of exergetic performance evaluated around equipment for the selected process using ethanol and the exergy in and out of a unit.

The result reveals that there are pieces of equipment with exergetic efficiency around 100%. Though, this does not mean there was no loss of exergy, but it was very small and insignificant in comparison to the equipment in the process. However, the highest exergetic efficiency and low irreversibility in the pump shows clearly and reaffirms what is in principle that equipment such as pumps and compressors that use electricity as source of energy may have low irreversibility and high efficiency because it is of high grade energy. However, high irreversibility was observed around mixer, after burner and the SOFC stack which has the highest irreversibility of 220.09 kW, 229.98 kW and 315 kW respectively. This extent of irreversibility and low efficiency around the equipment could be attributed to the changes in component most especially in mixers and SOFC stack. However, one might expect that heat exchanger that uses thermal energy from steam to have highest loses around them, but the case was different.

This is probably because of the appropriate choice of temperature specified in the heat exchangers which has strong effect on their exergetic performances.

Therefore, in addition to the choice of proper operating conditions, there is the need to also look at the possibility of mixing appropriate stream composition in the mixer to reduce the extent of irreversibility. Lower exergetic efficiency was observed around air compressor with 1.56 % efficiency. This indicates that despite the fact that compressor uses electrical energy, there was high exergy losses which can be attributed to high temperature change from 288.15 to 323.542 K thereby leading to a corresponding increase in entropy from 1027.93 to 1027.97 W/K. Also the result shows that it is possible for equipment to have high irreversibility with low or high efficiency or vice versa.

This can be observed in the case of mixer and turbine 1, where the mixer has higher irreversibility than turbine 1 but yet it has highest efficiency than turbine 1. Therefore, it is not possible to draw a general conclusion on the performance efficiency of equipment on the basis of their irreversibility rate. However, both exergetic efficiency and irreversibility have to be taken into consideration to be able to identify the most efficient unit. Also, it is evident that the result in this work corresponds to a conclusion made by Suleiman *et al.* [9] that equipment may have high lost work with low or high exergetic efficiency.

A general observation around all equipment in this process shows that the potentials of these pieces of equipment to produce work is decreasing as indicated by the extent of their respective lost work. Same principle applies to the methane fuelled system as shown in Table IV. Stack is the component having both the highest exergy in and highest exergy out with exergies of 2271250.20 W and 2036722.18 W respectively, this is because the inlet streams 11 and 16 respectively contain oxygen and hydrogen both of which have high flow rates and chemical exergy, while the outlet stream 17 contains exhaust which has high temperature and high mole fractions of compositions and high chemical exergy. Pump is the component having both the lowest exergy in and lowest exergy out with exergies of 2.56 W and 2.06 W respectively, this is due to the fact that the pump which performs only physical work contains only streams of feed water, therefore the mole fraction of other chemical components are absent thereby reducing its chemical exergy and consequently total exergy

Table V shows the overall exergy analysis for the hybrid configuration using ethanol and methane as fuels. The result shows that the ethanol fuelled system has the highest rate of irreversibility but also conversely with the highest exergetic efficiency when compared to the methane fuelled system. This also shows that the claim made in the case of equipment that irreversibility of the process cannot be based on exergetic efficiency. However, it is apparent that the efficiency values of the two processes are close but the irreversibility rate difference is much higher and therefore favours methane system because less energy is lost to the environment.

This is the reason why the useful work generated by the fuel led to the reduction in chemical energy and increment in the exergy loss. For the methane system, the component with the highest exergy loss is the CO_2 compressor which accounts for 51 % of the total exergy loss. This is due to the fact that the CO_2 compressor in the configuration serves as a multi stage compressor mode which captures, compresses and condenses the CO_2 for easy transportation.

The results also shown that for both configurations, turbine has higher efficiency than turbine 1; this is as a result of disparity in the work carried out by both turbines in which the loss of work in turbine 1 is far greater than that of turbine. It can also be seen that the overall efficiency of the ethanol and methane systems are 24.63 % and 22.33% respectively.

The results obtained for the component cost analysis for both configurations are presented in Table VI. From the economic analysis carried out, the annual cost of ethanol and the price of utility used in the ethanol configuration were 8,388.56 $/kW and $547,155.46 respectively, while the annual cost of methane and the price of utility used in the methane configuration were 2,666.99 $/kW and $218,717.64 respectively. These Figs made the ethanol system to have a higher capital cost of 8,388.56 $/kW, while the methane configuration had a capital cost of 2,666.99 $/kW.

IV. CONCLUSIONS

This study is focused on the exergy and economic analysis of a hybrid solid oxide fuel cell with zero CO_2 emission by computer simulation. Mathematical model was developed and simulated with the aim of finding efficient fuel for the hybrid solid oxide fuel cell with the same configuration. The result obtained shown that the hybrid solid oxide fuel cell system fuelled with either methane or ethanol is possible. Exergy and economic analyses were carried out on the data generated. Though, from the results obtained ethanol system is more efficient than the methane system. However, trade-off between exergetic and economic efficiency favours the choice of methane fuelled configuration for the hybrid solid oxide fuel cell because the capital cost of ethanol is greater than that of the methane.

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TABLE I
EQUIPMENT EXERGY FLOW FOR ETHANOL SYSTEM

Equipment	Physical Exergy In (kW)	Physical Exergy Out (kW)	Chemical Exergy In (kW)	Chemical Exergy Out (kW)
Air compressor	244.26	269.97	128.49	128.49
Heat ex-1	11.59	27528.02	7682.79	7682.79
Heat ex-2	26.99	11598.37	9825.9	9825.9
Heat ex-3	36.65	79667.49	699234.22	699234.22
Heat ex-4	514.96×10^3	514794991.1	12817.41	20371.71
Fuel pump	9.93	9927.55	682121.81	682121.8
Pre reformer	42.17	53513.41	357837.02	125444.62
SOFC stack	53.51	5147232206	125444.62	3120
Pump	514×10^4	5147232206	3120	3120
After burner	727.77	50500.62	3970	9697.41
Turbine	50.50	50476.3	9697.41	9697.41
Turbine 1	65.97	35825.02	22184.77	22184.77
CO_2 compressor	71.79	61738.05	9697.41	3970
Splitter	38.82	102653.26	22184.77	44369.44
Mixer	106.28	42170.01	711721.58	357837.02

TABLE II
EQUIPMENT EXERGY FLOW FOR METHANE SYSTEM

Equipment	Physical Exergy In (W)	Physical Exergy Out (W)	Chemical Exergy In (W)	Chemical Exergy Out (W)
Air compressor	26.66	1002.6	128.49	128.49
Heat ex-1	48950.93	128427.7	3077.88	3077.88
Heat ex-2	144184.34	48950.93	3077.88	3077.88
Heat ex-3	158973.24	379925	839459.39	839459.39
Heat ex-4	70593.66	409556.7	6069.39	16052.62
Fuel pump	14704.12	15791.5	836510	836510
Pre reformer	446996.81	434697.63	50965.08	50965.08
SOFC stack	434697.63	131517.78	50965.08	8762.97
Pump	33970.11	33974.33	3120	3120
After burner	972.06	144661.29	3970	2949.39
Turbine	144661.29	143181.66	2949.39	2949.39
Turbine 1	131517.78	129508.61	8762.97	8762.97
CO_2 compressor	225823.9	9433.38	2949.39	1393.26
Splitter	129508.61	259017.22	8762.97	17525.95
Mixer	459920.81	446996.81	845272.97	58388.9

TABLE III
EQUIPMENT EXERGETIC PERFORMANCE ANALYSIS RESULTS FOR ETHANOL SYSTEM

Equipment	Exergy In (W)	Exergy Out (W)	Loss work (KW)	Exergetic Efficiency (%)
Air compressor	133222	2071.73	131.15	1.56
Heat ex-1	89075	94859.31	5.78	93.90
Heat ex-2	40459	60940.27	20.48	66.39
Heat ex-3	706855	753592.51	46.74	93.80
Heat ex-4	543324	543406.08	0.08	99.98
Fuel pump	668473	668467.78	0.01	100.00
Pre reformer	766726	564953.52	201.77	73.68
SOFC stack	634540	120000.00	514.54	18.91
Pump	285715	285715.312	1.34168E-07	100.00
After burner	420356	19.372.66	229.98	45.29
Turbine	190373	190295.73	0.08	99.96
Turbine 1	686344	475019.23	211.32	69.21
CO_2 compressor	348091	225910.35	122.18	64.90
Splitter	475019	382366.62	92.65	80.49
Mixer	986808	766726.22	220.08	77.70

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TABLE IV
EXERGETIC PERFORMANCE ANALYSIS FOR METHANE FUELLED SYSTEM

Equipment	Exergy In (W)	Exergy Out (W)	Loss work (KW)	Exergetic Efficiency (%)
Air compressor	6170.68	5880.89	0.29	95.30
Heat ex-1	501230.75	491074.41	10.16	97.97
Heat ex-2	291080.64	236428.26	54.65	81.22
Heat ex-3	732627.36	714981.03	17.65	97.59
Heat ex-4	231701.08	1339609.7	1107.91	17.30
Fuel pump	447428.77	447427.61	0.00	100.00
Pre reformer	1806578.27	1776012.86	30.57	98.31
SOFC stack	2271250.25	2036722.18	234.53	89.67
Pump	2.56	2.06	0.00	80.34
After burner	803258.86	864350.62	61.09	92.93
Turbine	864350.62	864210.49	0.14	97.20
Turbine 1	2065422.18	2007551.29	57.87	97.20
CO_2 compressor	1716507.20	63396.42	1653.11	3.69
Splitter	2007551.29	2007548.48	0.00	100.00
Mixer	1817121.51	1806578.27	10.54	99.42

TABLE V
OVERALL LOSS WORK AND EXERGETIC EFFICIENCY

Parameter	Methane	Ethanol
Overall Loss Work (kW)	783.33	1067.36
Overall exegetic efficiency (%)	22.33	24.63

TABLE VI
SUMMARY OF COST ESTIMATION FOR ETHANOL SYSTEM

	Ethanol	Methane
Cost of fuel ($/yr)	442821.47	84671.42
Total cost of production ($)	457243.70	99090.73
Total direct cost ($)	50782.77	50782.77
Total indirect cost ($)	22852.25	22852.25
Working capital ($)	4062.62	4062.62
Fixed cost ($)	20313.11	20313.11
Total capital ($)	24375.73	24375.73
Utility ($)	547155.46	218717.64
Total cost of equipment ($)	16650.09	16650.09
Overall expenditure ($)	1006627.20	320038.80
Power output (kW)	120	120
Capital cost ($/yr)	8388.56	2666.99

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