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# Thermodynamic investigation of a SOFC- Steam turbine hybrid system powered by Synthetic gas from Municipal Solid Waste

**Venkitesh K S[1], Joseph Daniel[2], Manavalla Sreekanth[3]**

[1] Research scholar, School of Mechanical Engineering, VIT University, Chennai.

[2,3] Associate Professors (Sr.), School of Mechanical Engineering, VIT University, Chennai-600127, T.N

Corresponding author email: venkiteshks@gmail.com

**Abstract:** This study presents the performance evaluation of a system consisting of a Solid oxide fuel cell (SOFC) and steam turbine where the fuel cell is powered by synthetic gas from municipal solid waste (MSW). Analysis is performed based on first and second laws of thermodynamics. The modelling of the system is done in a flow sheeting software Cycle Tempo®. This work mainly focusses on the effective utilization of solid waste by producing the Syngas from gasification. Syngas after cleaning is supplied to the SOFC along with air. The syngas undergoes internal reforming at the fuel cell producing hydrogen which acts as fuel for SOFC. The influence of various operating parameters such as compressor pressure ratio, turbine inlet temperature (TIT), upon thermal efficiency and specific power output are studied. Exergy destruction of various components of the system are also evaluated. The evaluation results are helpful for making suitable modification of the parameters for obtaining optimum configuration of the system.

## 1. Introduction

The everyday life of a human being is directly or indirectly connected to the energy available in different forms in nature. The average demand for energy rises every day which in the near future may result in a heavy energy crisis. The key focus of the energy sector is on steps to obtain and transform energy from different forms. The key energy sources are those derived from fossil fuels, and they are used in all energy systems. The biggest drawback is that day after day their reserve is depleting and cannot be renewed or reused in any way. As such, we must think about transitioning to non-conventional or renewable energy sources entirely or partially.

Hybridization is a technique which combines conventional sources of energy with renewable sources of energy which results in reduced fuel consumption, decreased emissions of fossil fuels, and improved productivity and output. Fuel cells are devices, where the chemical energy of supplied fuel is converted in to heat and electricity by electrochemical reactions. Because of the direct conversion of power, they ensure constant electricity supply. the anode of the system is fed with fuel and cathode is fed with the oxidant. Fuel undergoes electrochemical oxidation at the anode and the oxidant undergoes reduction at the cathode. Due to its reactivity, which minimizes costly catalysts, the preferred fuel for fuel cells is hydrogen. Hydrocarbon fuels may also be used in fuel cells, but must eventually be converted into hydrogen. This includes a "reformer" or fuel processing system to turn HC fuel into hydrogen [1]. The fuel reformer transforms hydrocarbon fuel into hydrogen-rich gases that are further refined to create pure hydrogen.

Steam turbine combined with SOFC is considered here for hybridization. Syngas derived from municipal solid waste is fed as input to the SOFC where it undergoes internal reforming releasing hydrogen which is the fuel for the fuel cell. SOFC has the ability to withstand higher operating temperatures.

Gaseous fuels have the advantage that they are pure and have high thermal resilience, making burning process ash and soot free. The majority of natural gases have a high content of heat, while those produced from different processes range from moderate to low [2]. High-calorific-value fuels contain less nitrogen, while low-calorific-value fuels contain up to 55% nitrogen [3,4].

Syngas is a blend of fuel mainly composed of carbon monoxide and hydrogen, and most commonly, a little carbon dioxide. It is used as an intermediate in the manufacture of ammonia, hence the name [5]. Syngas is primarily used for the generation of electricity when used with energy conversion systems and is generated by the gasification process. The energy density of syngas is just half of that of natural gas, and can be derived from wood, coal and natural gas. Syngas is an intermediate source for the manufacture of ammonia, hydrogen, methanol and hydrocarbon fuels. Natural gas or liquid hydrocarbons undergoes steam reforming reaction to generate syngas. Syngas is an intermediate source to produce hydrogen during coal gasification and biomass gasification [6].

## 2. Gasification Municipal solid waste

The globe is looking for solutions for successful solid waste disposal and greenhouse gas reduction. The amount of urban solid waste is rising day by day and can cause significant environmental problems and health risks unless handled properly. Laws and legislation have improved significantly the recycling and reuse of solid waste products in the U.S and European countries. Only 1/4$^{th}$ of the overall MSW is recovered in these regions, despite substantial improvements in recycling and energy recovery, leaving the remaining 3/4$^{th}$ to be scrapped off in landfills or incinerated.

Energy research personnel concentrate on the integration of alternative energy resources with conventional power systems that can effectively reduce fuel consumption and emissions. Gasification process converts solid wastes in to useful source of energy. Before gasification, the raw solid waste will be processed. Due to the advantage of gas over solid fuels, a part of the heating value of the solid fuel is transferred to a gaseous energy carrier through the process of gasification. [7].

Gases are easy to clean, transport and burn efficiently with less excess air and contains lower levels of some types of contaminants [8]. Numerous studies have been conducted on the gasification process of different biomass feed stocks [9, 10] and coal [8, 11-16]. Gasification appears to be an interesting option for plastic and rubber waste utilization based on high polymer consumption [17]. Although energy recovery and recycling have increased significantly in some zones, only about a quarter of the total solid waste is recovered, and the remaining three-fourths are incinerated or disposed off in landfills [18].

The process of incineration involves burning the wastes with high volume of air which produces carbon monoxide and thus gasification is preferable over incineration. The hot gases which exit from the system are used to produce electricity in energy systems. Gasification transforms MSW into synthetic gas or syngas, which is very much useful. The ash that falls right from the gasifier in the high-temperature gasification process is in a liquid state, which is cooled by quenching. A glassy, non-leachable slag is produced that can be used for producing roofing shingles, cement, and as an asphalt filler.

In this work, effective management of solid waste to produce power is discussed by considering a hybrid energy system consisting of an SOFC integrated with a steam turbine. The fuel is the synthetic gas derived from the gasification of solid waste and is fed directly to the anode side of the solid oxide fuel cell (SOFC) and the air is fed to the cathode side of the SOFC. The air and fuel streams are preheated by the exhaust gases from the combustor or after burner, before entry in to the fuel cell. The fuel undergoes internal reforming reaction at the fuel cell producing hydrogen which acts a fuel for the fuel cell. Heat and electricity are produced within the fuel cell.

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The unburned fuel and the gases are further burned in an after burner increasing the temperature further. These hot gases are used in a boiler to produce high temperature steam which runs a steam turbine producing additional power.

**Nomenclature**

| | | |
|---|---|---|
| P | Pressure | bar |
| T | Temperature | K |
| W | Work | kJ |
| $\dot{m}$ | Mass flow rate | kg/s |
| h | Enthalpy | kJ/kg |
| E | Reversible cell voltage | Volt |
| $E^0$ | Ideal cell voltage at standard conditions | |
| $\bar{R}$ | Universal gas constant | (8.314 kJ/kg. K) |
| $n_e$ | Number of electrons | - |
| N | No of cell in SOFC stack | |
| F | Faraday's constant | 96485 (C/mole) |
| I | Current | Ampere |
| i | Current density | $A/m^2$ |
| A | Area | $m^2$ |
| V | Voltage | Volt |
| $\dot{Q}$ | Heat transfer rate | kJ |
| ex | Exergy | kJ |
| y | Mole fraction | - |
| LHV | Lower heating value of fuel | kJ/kg |

**Greek symbols**

| | |
|---|---|
| $\eta$ | Efficiency |
| $\gamma$ | Ratio of specific heats (kJ/kg. K) |
| $\phi_w$ | Exergy associated with work |
| $\epsilon$ | Effectiveness of heat exchanger |

**Subscripts/Superscripts**

| | |
|---|---|
| C | Compressor |
| Act | Activation |
| Ohm | Ohmic |
| Conc | Concentration |
| DC | Direct current |
| AC | Alternating current |
| SOFC | Soli Oxide Fuel Cell |
| Inv | Inverter |
| In | Inlet |
| Out | Outlet |
| AB | After Burner |
| ST | Steam turbine |
| CW | Cooling water |
| P | Pump |
| k | $k^{th}$ component |
| D | Destruction |
| Ph | Physical |
| Ch | Chemical |
| $T^0$ | Ambient Temperature |

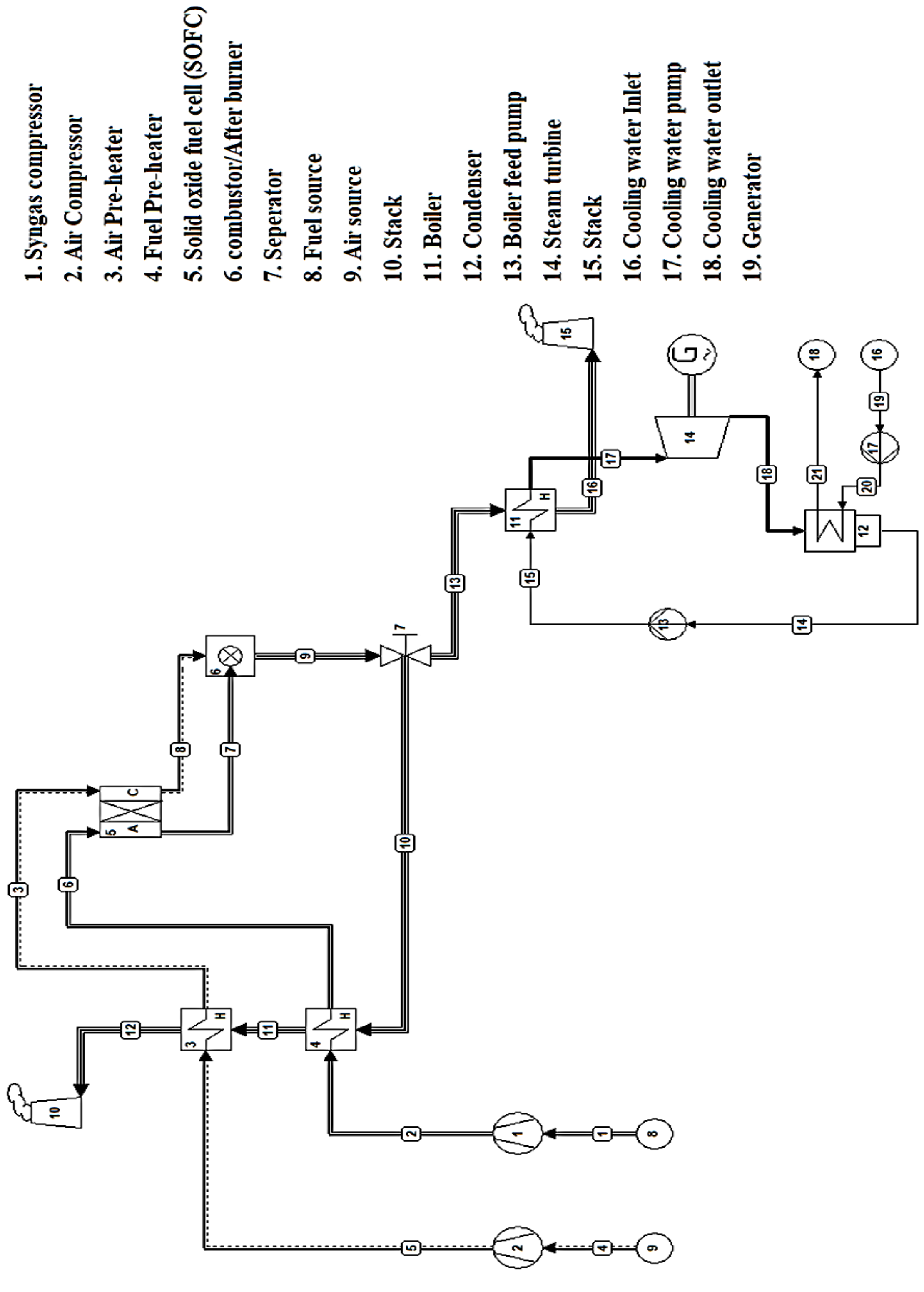


**Figure. 1** Layout of Hybrid-SOFC- Steam turbine system powered by syngas from MSW.

## 3. Description of the system.

The system consists of 2 compressors one for compressing inlet air and other compressing the syngas fuel. They are preheated using the exhaust gases from the combustor before entry in to the solid oxide fuel cell. Preheated air enters the cathode and syngas fuel enters the anode side of the SOFC. Hydrogen is produced as a result of electrochemical reaction inside the fuel cell. The unburned gas and residual fuel are further burned in an after burner which further increases the temperature. The hot gases are used to produce high temperature steam in a boiler and the steam expands in a steam turbine producing additional power.

## 4. Modelling of the system

Modelling of the proposed hybrid system is done with the flow sheeting software Cycle Tempo® developed by the Delft university of Technology. The program has got inbuilt models of all the components used in energy systems and it calculated the performance parameter based on the inputs given. The analysis of the system is based on laws of thermodynamics and it calculated the energy and exergy efficiency of the entire system, destruction of exergy in individual components of the system. By changing the parameters, the performance of the system can be assessed thermodynamically.
The system routine considers the real state of various components without any assumption of steady state.

### *4.1. Air and Fuel Compressors*

The compression process is assumed to be adiabatic. From the knowledge of isentropic efficiency and pressure ratio of the compressor, the outlet temperature and work done can be determined.

$$\left(\frac{T_{5s}}{T_4}\right)=\left(\frac{P_5}{P_4}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} \quad (1)$$

$$\eta_C=\frac{W_{isentropic}}{W_{actual}}=\frac{h_{5s}-h_4}{h_5-h_4} \quad (2)$$

$$W_C=\overset{g}{m_4}\times\left(h_5-h_4\right) \quad (3)$$

Similar equations can be written for the fuel compressor.

### *4.2. SOFC*

The fuel cell considered here is the direct internal reforming type where the heat released by the electrochemical reactions is used for the reforming reaction which is endothermic in nature. The fuel is the syngas derived from the gasification of municipal solid waste. The reforming, shifting and electrochemical reactions occurring within the SOFC are given below [19-21].

Reforming reaction:

$$CH_4+H_2O\rightarrow CO+3H_2---------(4)$$

Water gas Shifting reaction:

$$CO+H_2O\rightarrow H_2+CO_2----------(5)$$

Electrochemical Reaction:

$$H_2+0.5O_2\rightarrow H_2O------------(6)$$

The amount products of reforming and shifting reactions which are equilibrium reactions, depends on the final temperature and initial composition of the reaction.

The reversible cell voltage produced by the SOFC stack is given by Nernst equation given below [22]

$$E = E^0 = \frac{\overline{R}T}{n_e F} \ln\left( \frac{\left(P_{H_2O}\right)}{P_{H_2}\left(P_{O_2}\right)^{0.5}} \right) ------(7)$$

Where $E^0$ is the ideal cell voltage at standard conditions (298K and 1 bar) and R is the universal gas constant, F represents the Faraday's constant (96485 C/mole), n is the number of electrons and T is the temperature of the stack.

Calculation of the actual cell voltage involves determination of various losses such as activation loss ($V_{act}$), ohmic loss ($V_{ohm}$) and concentration loss ($V_{conc}$) associated with the fuel cell. The actual cell voltage is given by the following equation.

$$V_{cell} = E - \left(V_{act} + V_{ohm} + V_{conc}\right) = \text{E-}\left(\Delta V_{loss}\right) -------(8)$$

The amount of current and power generated by the fuel cell can be calculated from the following set of equations from (9) through (12).

$$I_{cell} = i \times A_{cell} ------------------------(9)$$

$$I_{total} = N \times I_{cell} ------------------------(10)$$

$$(\overset{g}{W})_{DC_{SOFC}} = V_{cell} \times I_{total} ----------(11)$$

$$\left(\overset{g}{W}\right)_{AC_{SOFC}} = (\overset{g}{W})_{DC_{SOFC}} \times \eta_{inv_{SOFC}} ----------(12)$$

Where $\eta_{inv_{SOFC}}$ is the efficiency of DC-AC inverter.

### *4.3. Afterburner*

The unreacted fuel and gases from the SOFC stack are further burned in an afterburner for further increasing the temperature. The reaction at the afterburner is completely exothermic and no external fuel is supplied. The energy balance can be written as follows

$$\sum m_{in} h_{in} - m_{out} h_{out} - (\overset{g}{Q})_{loss.AB} = 0 ------------(13)$$

$$Q_{loss.AB} = (\overset{g}{m})_{fuel} \times \left(1 - U_f\right) \times \left(1 - \eta_{AB}\right) \times LHV ----------(14)$$

### *4.4. Air and fuel preheaters and steam generator*

The exhaust gases from the afterburner is split in to two sections, one going to preheat the air and fuel streams from respective compressors and the other one going directly in to the steam generator. The outlet temperatures of the preheaters and the steam generator are calculated by the following energy balance equations.

$$\varepsilon = \frac{h_6 - h_2}{h_{10} - h_2} --------------(15)$$

$$\overset{g}{m}_2 \left(h_6 - h_2\right) = \overset{g}{m}_{10} \left(h_{10} - h_{11}\right) -------(16)$$

The equations for fuel preheater and steam generator are similar to the above ones.

### *4.5. Steam turbine*

The hot steam generated at the steam generator is expanded in the steam turbine producing power and is discharged to the condenser.

$$\frac{T_{18s}}{T_{17}} = \left(\frac{P_{18}}{P_{17}}\right)^{\frac{(\gamma-1)}{\gamma}} ------------(17)$$

$$\eta_{ST} = \frac{W_{ST.actual}}{W_{ST.isentropic}} = \frac{h_{17} - h_{18}}{h_{17} - h_{18s}} ------(18)$$

$$W_{ST} = \dot{m}_{17}\left(h_{17} - h_{18}\right) ---------(19)$$

### 4.6. Condenser

The exit steam from the turbine is entering the condenser to which cooling water is supplied externally. The following energy balance equation can be written for the condenser.

$$\dot{m}_{18} h_{18} + \dot{m}_{20} h_{20} = \dot{m}_{14} h_{14} + \dot{m}_{21} h_{21} ---(20)$$

### 4.7. Feedwater and cooling water pumps

The energy balance equations for the pumps used in this system are as follows

$$W_{CW.pump(isentropic)} = \dot{m}_{19} v_{19}\left(P_{20} - P_{19}\right) ----(21)$$

$$\eta_{pump} = \frac{W_{isentropic}}{W_{actual}} --------(22)$$

### 4.8. Hybrid system

The efficiency of the entire hybrid system is obtained from the following equation

$$\eta = \frac{\dot{W}_{net}}{m_{fuel} \times LHV_{fuel}} ---------(23)$$

$$W_{net} = W_{SOFC} + W_{ST} - \Sigma W_P - \Sigma W_C ---(24)$$

### 4.9. Exergy equations

The performance of the system is assessed based second law of thermodynamics through exergetic analysis. In helps in identifying the processes which are thermodynamically undesirable. The irreversibility associated with the entire system are computed from exergy loss and exergy destruction associated with various components. The mass, energy and exergy balance equations are considered in the exergetic assessment of the system. Each part of the system is considered as a control volume. The exergy balance equation is written in general as follows.

$$\Sigma\left[1 - \left(\frac{T_0}{T}\right)\right]Q_k + \Sigma ex_{in} = \Sigma \varphi_w + \Sigma ex_{out} + Ex_D ---(25)$$

The first term in the above equation represents the exergy rate due to heat transfer, $\phi_w$ is the exergy rate due to work transfer, $Ex_{in}$ and $Ex_{out}$ are the exergy input and output of the control volume and $Ex_D$ is the exergy destruction. The exergy rate of entire system is obtained by summing up the physical and components of exergies as follows

$$\dot{E}_x = \dot{E}_{x\,ph} + \dot{E}_{x\,ch} \qquad (26)$$

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$$E_{xph} = \overset{g}{m}\left[\left(h - h_0\right) - T_0\left(s - s_0\right)\right] \tag{27}$$

$$E_{xch} = \overset{g}{m}\left[\sum y_i \times ex_{ch.in} + \bar{R} \times T_0 \sum_i y_i \ln y_i\right] \tag{28}$$

The exergy efficiency is given by the following expression

$$\eta_{ex}^{cycle} = \frac{W_{net}}{\sum E_{x.in}} \tag{29}$$

**Table 1.** Input parameters for the Hybrid System

| Parameter | Value Input |
|---|---|
| Ambient temperature | $25^0$C |
| Ambient Pressure | 1 bar |
| Syngas Temperature | $800^0$C |
| Calorific value of Syngas | 5 MJ/kg |
| SOFC Temperature | $900^0$C |
| Fuel utilization factor | 0.85 |
| Cathode and anode pressure drop | 4% |
| Current density | 3000 A/m$^2$ |
| Resistance of the cell | $5\times10^{-5}$ ohm m$^2$ |
| DC-AC Inverter efficiency | 89% |
| Compressor isentropic efficiency | 0.81 |
| Turbine isentropic efficiency | 0.85 |
| Generator isentropic efficiency | 0.95 |

## 5. Results and discussions

The proposed system is modelled and simulated by varying the parameters and the system performance was determined. The main parameters that affect the performance of the plant are the fuel cell current density, Cell pressure etc. The influence of these parameters on energy and exergy efficiencies, cell voltage is determined. The exergy destruction for various components is determined. This will help in finding ways for minimizing exergy loss and improving the performance of the entire system.

### *5.1. Influence of current density*

Figure 2 shows the impact of current density on energy efficiency at fuel utilization factor of 0.85, cell temperature of 1173K and cell pressure of 3 bar. The energy efficiency has a decreasing trend with respect to the current density. As the current density increases, the power developed from the SOFC stack decreases and thus the efficiency.

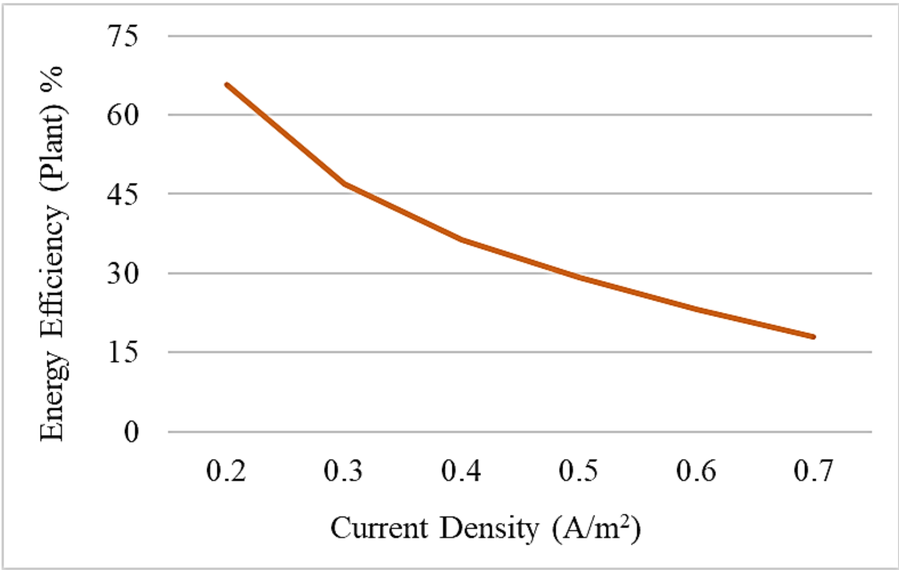


**Figure. 2** Influence of current density on energy efficiency

Exergy efficiency as shown in figure 3 also has a similar trend as that with energy efficiency with current density. The exergy destruction at cell temperature of 1173K and 3 bar pressure is shown in figure 4. The exergy efficiency decreases while exergy loss increases with increasing SOFC current density. At higher current densities, there is a decrease in the cell voltage and the requirement for average number of cells is high which leads to low output power from the fuel cell.

*5.2. Influence of Cell pressure*

Figure 5 shows the impact of cell pressure on the cell voltage. Pressure of the cell is varied from 1 to 6 bar. The cell voltage increases as the Nernst voltage increases. As a result of this, cell voltage increases. When cell pressure increases, the overpotentials decreases (Akkaya et al. 2007) which also result in increased cell voltage.

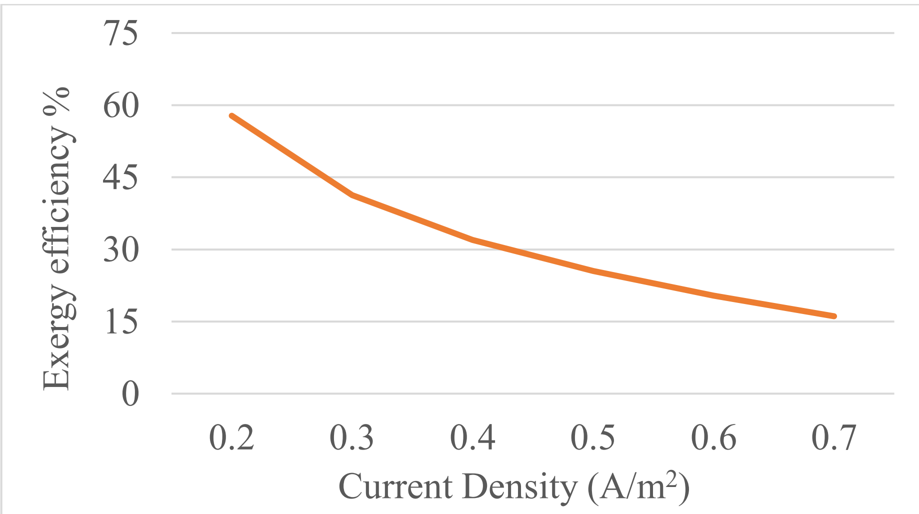


**Figure. 3** Influence of current density on exergy efficiency

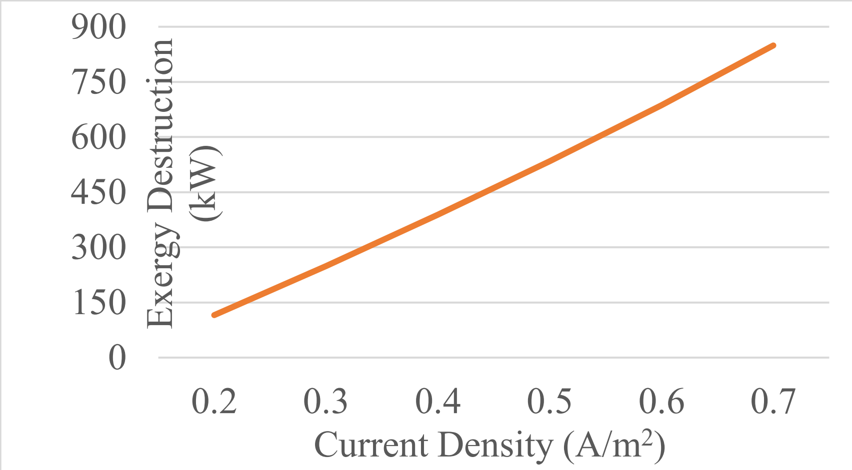


**Figure. 4** Influence of current density on exergy destruction

Figure 6 shows the destruction of exergy in different components of the system. Exergy destruction is maximum at the combustor followed by the heat exchanger and fuel cell. This is because of the highest irreversibility associated with the heat transfer occurring in these components.

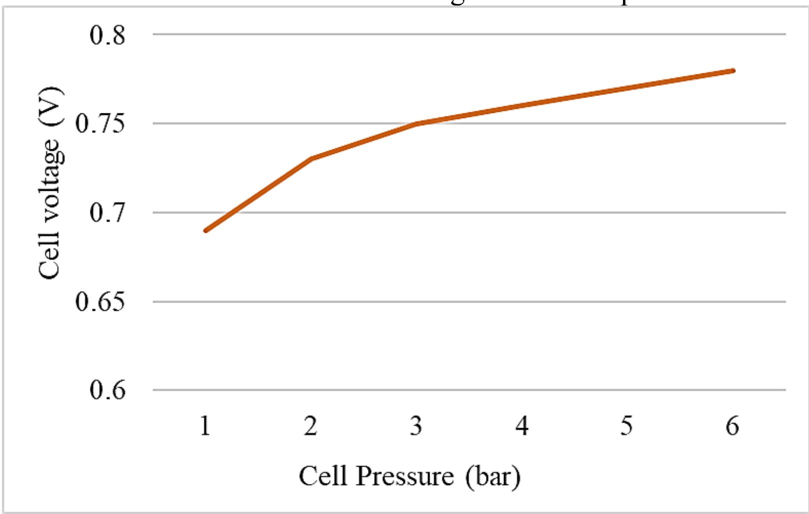


**Figure. 5** Effect SOFC pressure on Cell voltage

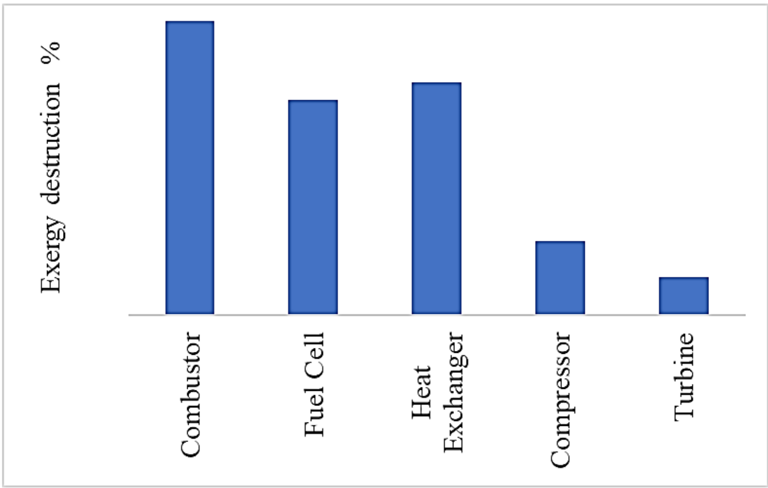


**Figure. 6** Exergy destruction in the system

## 6. Conclusion

The proposed hybrid system was modelled and analyzed thermodynamically. The exergy analysis gives the destruction of exergy in various components. The exergy destruction is maximum in the combustor due to the higher heat transfer rate. Maximum efficiency of the entire system is 46% and the exergy efficiency is 41%. The net output power of the system is 180kW. The system can be used as a domestic CHP (combined heat and power) to power up restaurants, small offices and shopping centres.

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