

## **A Study on Performance of Solid Oxide Fuel Cell-Stirling Engine Cycle Combined System - Part I: SOFC Simulation by Programming in Matlab and Modeling in Hysys**

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**Abstract:** In recent years, using new methods in utilization of energy resources has become necessary due to environmental pollution and restriction of energy resources. The hybrid system presented in this article produced power with SOFC and Stirling engine. The purpose is to analyze a 50 kW Solid Oxide Fuel Cell that could produce enough thermal energy for a 10 kW Stirling engine working in the hybrid system. The hybrid system analysis is performed by programming in Matlab and modeling in Hysys. Thermodynamics and electrical parameters of the system are calculated in two ways. The results are close to each other and confirmed the validity of calculations.

**Keywords:** SOFC, Stirling, Hybrid System, Modeling, Internal Reformer, External Reformer.

### **1. Introduction**

Solid oxide fuel cells (SOFCs) are direct energy conversion devices with great potential. They have distinct features which make them suitable for electricity generation in both large central station power plants and distributed generation units (Appleby & Foulkes, 1989). Also, SOFCs are solid state ceramic cells which operate around 1000°C, the highest degree among all types of fuel cells under development. Their high operating temperature not only precludes the need for expensive catalysts but also produces high quality heat which can be used for cogeneration or topping cycles for additional electricity generation (Hussain, Li, & Dincer,

2005). Since the electrolyte phase is solid, many management issues such as electrode flooding, electrolyte migration, and catalyst wetting are not encountered.

In addition, SOFCs cell components can be fabricated into a variety of self-supporting shapes and configurations which may not be feasible with fuel cells employing liquid electrolytes (Dincer, 2002).

Past research has shown that an overall system efficiency of 70% (net ac/LHV) or higher was possible with a more complex thermodynamic cycle (Chan, Ho, & Tian, 2002; Veyo & Lundberg, 1999) which might be due to the feasibility of integration of solid-oxide fuel cell (SOFC) and gas-turbine (GT) technologies

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in power generation. These studies were mainly based on the energy analysis using first law of thermodynamics in conjunction with a techno-economical assessment. However, exergy analysis based on second law of thermodynamics has received tremendous attention from various researchers. Exergy analysis is a useful method for furthering the goal of more efficient energy-resource use as it locates the types and magnitudes of wastes and losses in a system. Generally, more meaningful efficiencies are evaluated using exergy analysis rather than energy analysis since exergy analysis always provides a measure of the approach to the ideal situation. Numerous studies have resulted in system-level discoveries about SOFC power plants; however, the second-law characteristics of the cells still remains understudied (Haynes & Wepfer, 2002). Rosen (1990) performed energy and exergy analyses to compare the cogeneration efficiencies of solid oxide fuel cell systems with other fuel cell systems and electricity generation devices, and found that exergy analysis should be used when analyzing the cogeneration potential of systems for electricity generation.

Bedringas et al. (Bedringås, Ertesvåg, Byggstøyl, & Magnussen, 1997) analyzed two methane fueled SOFC system using the exergy concept and reported that the system should be analyzed as a complete unit rather than separate units. Chan et al. (Chan, Low, & Ding, 2002) examined two solid-oxide fuel cell (SOFC) power systems fed by hydrogen and methane. The hydrogen fed SOFC system analyzed by Chan et al. did not utilize the waste heat produced from SOFC stack rather it was rejected in the environment, which not only created environmental pollution but also decreased the overall system efficiency.

Therefore, in the present study, an integrated power system of SOFC fed with natural gas is analyzed based on thermodynamics concepts. The waste heat produced by SOFC is utilized to pre-heat the air and natural gas. It is also used in a Stirling engine. Moreover, a parametric study is performed to evaluate the effects of various parameters on the performance of fuel by programming (Matlab) and modeling (Hysys).

## 2. System Description

A 10 kW Stirling engine is coupled with a 50 kW Solid Oxide Fuel Cell in a hybrid system. This power level is enough for a residential complex. There are advantages such as low repair and maintenance cost, long life cycle, low noise pollution compared to the common

systems which make it a good choice for distributed generation. Moreover, using natural gas in SOFC instead of solar energy in Stirling engine bring high reliability for this hybrid system. SOFC works in high temperature. Chemical reactions produce thermal energy which is used in Stirling engine. The system output is the total power of SOFC and Stirling engine.

### 2.1. Solid Oxide Fuel Cell

#### 2.1.1. Electrochemical Model of SOFC

The SOFC analyzed in this study is planar fuel cell. Zero dimensional model is considered for it computed power and output stream parameters at SOFC temperature. The maximum voltage (open circuit voltage) is computed by Nernst equation.

$$E_r = \frac{-\Delta G^\circ}{2F} + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} \quad (1)$$

When the electrons are flowed in the circuit, a part of voltage is lost. The most important reasons of these losses are ohmic, activation and concentration resistances. Therefore with consideration of these resistances real voltage of fuel cell is calculated with equation (2).

$$E = E_r - \eta_{ohm} - \eta_{con} - \eta_{act} \quad (2)$$

#### 2.1.2. Ohmic Losses

This loss is because of the electrical resistance of the electrodes in front of the flow of ions and is calculated by equation (3).

$$\eta_{ohm} = I \sum_j R = I \sum_j \frac{\rho_j \delta_j}{A_j} \quad (3)$$

In the equation,  $R_j$  is indicant of resistance,  $\delta_j$  thickness and  $\rho_j$  electrical resistance of anode, cathode, electrolyte and contacts.

#### 2.1.3. Activation Potential Loss

This type of loss is related to reaction mechanism occurring on electrodes, calculated with Butler-Volmer equation.

$$i = i_0 \left\{ \exp \left( \beta \frac{nF\eta_{act}}{RT} \right) - \exp \left[ -(1 - \beta) \frac{nF\eta_{act}}{RT} \right] \right\} \quad (4)$$

$\beta$  is charge transfer coefficient that is about 0.5 normally. The calculation of activation potential loss is done by Newton-Raphson method with trial and error. The exchange current density ( $i_0$ ) is an important parameter, because it is a criterion of electrochemical

kinetics and also it is calculated by equations (5) and (6) for anode and cathode.

$$i_{0,an} = \gamma_{an} \left( \frac{P_{H_2}}{P_{ref}} \right) \left( \frac{P_{H_2O}}{P_{ref}} \right) \exp \left( \frac{-E_{act,an}}{RT} \right) \quad (5)$$

$$i_{0,ca} = \gamma_{ca} \left( \frac{P_{O_2}}{P_{ref}} \right)^{0.25} \exp \left( \frac{-E_{act,ca}}{RT} \right) \quad (6)$$

### 2.1.4. Concentration Potential Loss

Equation (7) resulted from Nernst equation.

$$V_{con} = \frac{RT}{n_e F} \ln \left( \frac{P_2}{P_1} \right) \quad (7)$$

Moreover studies have indicated that there is a linear relation between pressure and limit current density. As such, equation (8) can be derived from such an assumption. ( $P_1$  is the pressure when  $i=0$  and  $P_2$  is the pressure when  $i=i_L$ )

$$P_2 = P_1 \ln \left( 1 - \frac{i}{i_L} \right) \quad (8)$$

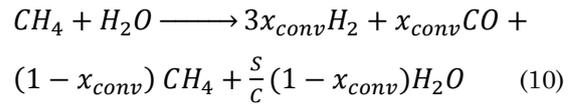
Equation 9 is resulted from equation (8).

$$\eta_{con} = \frac{RT}{2F} \left( 1 - \frac{i}{i_L} \right) \quad (9)$$

Input parameters of SOFC are presented in table 1.

## 3. Internal Reforming Model of Solid Oxide Fuel Cell

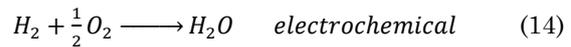
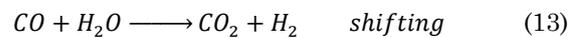
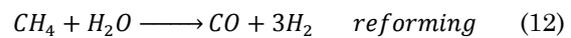
Reforming of methane conversion to hydrogen is required for a system with natural gas as fuel. The water steam needed is obtained from the water of electrochemical reaction products. Because the steam reforming reaction is very endothermic, complete internal reforming could lead to problems such as carbon formation on anode and input temperature difference. Reforming reaction is presented in equation (10).



$$x_{conv} = \left( 1 - \frac{n_{out}}{n_{in}} \right) CH_4 \quad (11)$$

In equation (11)  $x_{conv}$  is part of methane that convert and S/C is molar fraction of steam to carbon. The concentration of parts after reforming is calculated by continuous solving of mass balance equations.

As regards the reforming is internal, the researchers assumed that the following reactions were done in the fuel cell.



Equilibrium constants of reforming and shifting are calculated by equations (15) and (16).

$$K_{pr} = \frac{P_{H_2}^3 P_{CO}}{P_{CH_4} P_{H_2O}} \quad (15)$$

$$K_{ps} = \frac{P_{H_2} P_{CO_2}}{P_{CO} P_{H_2O}} \quad (16)$$

Equilibrium constants are functions of temperature as it is shown in equation (17).

$$\ln(K_p) = AT^4 + BT^3 + CT^2 + DT + E \quad (17)$$

The constant values of equation (17) are presented in table 2.

**Table 1.** Input Parameters of SOFC

Parameters	Values
Ohmic Potential Losses	
Specific resistance of anode	$\left(95 \times \frac{10^6}{T}\right)^{-1} \exp\left(-\frac{1150}{T}\right)$
Specific resistance of cathode	$\left(42 \cdot \frac{10^6}{T}\right)^{-1} \exp\left(-\frac{1200}{T}\right)$
Specific resistance of connector	$\left(9.3 \times \frac{10^6}{T}\right)^{-1} \exp\left(-\frac{1100}{T}\right)$
Anode thickness	150 $\mu\text{m}$
Electrolyte thickness	50 $\mu\text{m}$
Cathode thickness	50 $\mu\text{m}$
Connector thickness	2.5 $\mu\text{m}$
Cell area	0.1 $\times$ 0.1 $\text{m}^2$
Activation Potential Losses	
Coefficient of prior to power phrase of cathode	5.5 $\times 10^8 \text{ A/m}^2$
Coefficient of prior to power phrase of anode	7 $\times 10^8 \text{ A/m}^2$
Activation energy of anode	100 $\text{kJ/mol}$
Activation energy of cathode	120 $\text{kJ/mol}$

**Table 2.** Constant Values for Calculation of Balance Constant of Reforming and Shifting Reactions

Constant	Reforming reaction	Shifting reaction
A	$-2.63121 \times 10^{-11}$	5.47301 $\times 10^{-12}$
B	$1.24065 \times 10^{-7}$	-2.57479 $\times 10^{-8}$
C	$-2.25232 \times 10^{-4}$	4.63742 $\times 10^{-5}$
D	$1.95028 \times 10^{-1}$	-3.91500 $\times 10^{-2}$
E	$-6.61395 \times 10$	1.32097 $\times 10$

Total flow and operational temperature are defined based on internal reforming of SOFC with recursive parts of anode around output gases.

Three equations are obtained after differentiation and simplification.

$$K_r = \frac{x_{\text{eq}}^{\text{CO}} (x_{\text{eq}}^{\text{H}_2})^3}{x_{\text{eq}}^{\text{H}_2\text{O}} x_{\text{eq}}^{\text{CH}_4}} \left(\frac{P}{P_0}\right)^2 \quad (18)$$

$$K_s = \frac{x_{\text{eq}}^{\text{CO}_2} (x_{\text{eq}}^{\text{H}_2})}{x_{\text{eq}}^{\text{H}_2\text{O}} x_{\text{eq}}^{\text{CO}}} \quad (19)$$

$$I = 2F \frac{(3a+b)U_f}{1-r+rU_f} \quad (20)$$

$K_r$  and  $K_s$  are equilibrium constants of reforming and shifting reactions that can be calculated by a simple relation and coefficient of equilibrium constant.  $U_f$  is fuel utilization factor and  $r$  presents recursive ratio.  $a$  and  $b$  are molar rates of reaction (11) and (12).  $x_{\text{eq}}^i$  for a mixture of gases in equilibrium condition is a function of  $a$ ,  $b$ ,  $r$ ,  $U_f$  and  $N_i$  and can be calculated by equations (21) to (27).

$$x_{eq}^{CH_4} = \frac{0.97N_t - a}{N_t + 2a} \quad (21)$$

$$x_{eq}^{H_2} = \frac{3a+b}{N_t+2a} \frac{(1-r)(1-U_f)}{1-r+rU_f} \quad (22)$$

$$x_{eq}^{CO} = \frac{a-b}{N_t+2a} \quad (23)$$

$$x_{eq}^{CO_2} = \frac{0.015N_t+b}{N_t+2a} \quad (24)$$

$$x_{eq}^{CO_2} = \frac{0.015N_t+b}{N_t+2a} \quad (25)$$

$$x_{eq}^{H_2O} = \frac{-a-b+(3a+b)\frac{U_f}{1-r+rU_f}}{N_t+2a} \quad (26)$$

$$x_{eq}^{N_2} = \frac{0.015N_t}{N_t+2a} \quad (27)$$

$N_i$  is the molar rate of total gases in anode input. The next step is to calculate of temperature of output gases from SOFC. The produced thermal energy from electrochemical reaction is used for SOFC products heating and the other remained reactions. Therefore, the thermal energy of hot output gases could be used for the other purposes.

The produced hydrogen in reforming in anode and oxygen in cathode performed the electrochemical reaction according to equation 14, after passing through the electrolyte. This reaction is very exothermic ( $\Delta h_f = -242000$  kJ/kmol). The energy provide required heating for reforming process. Reforming reaction is endothermic and it need 206830 kJ/kmol thermal energy. Moreover, produced thermal energy in shifting reaction is 41150 kJ/kmol. The thermal energy of reforming, shifting, and electrochemical reaction is calculated from equations (28) to (30).

$$Q_r = a(h_{CO} + 3h_{H_2} - h_{H_2O} - h_{CH_4}) \quad (28)$$

$$Q_s = b(h_{CO_2} + h_{H_2} - h_{H_2O} - h_{CO}) \quad (29)$$

$$Q_e = U_f(b + 3a)(h_{H_2O} - h_{H_2} - 0.5h_{O_2}) \quad (30)$$

Given that produced thermal energy in electrochemical reaction is used just for heating the input flows and required thermal

energy for reforming reaction. The balance energy equation is shown in equation (31).

$$\sum_{in} n_i h_i = \sum_{out} n_e h_e + W_{FC} \quad (31)$$

### 3.1. Compressor Modeling

If the compression process be considered as an ideal one in compressor, the mixture of gas and air compress in an isentropic process when passing through it. So, pressure and entropy of the mixture after compression is known. In real compressors isentropic efficiency is defined as equation (32).

$$\eta_s = \frac{h_2^s - h_1}{h_2 - h_1} \quad (32)$$

In equation (32) subscripts 1 and 2 are indicants of compressor input and output and the superscript s is indicant of isentropic compression process. Calculation of output parameter of compressor is done according to the algorithm shown in figure 1.

### 3.2. Throttle Valve Modeling

Throttle valve reduces the pressure of air and natural gas mixture and as a result decreases temperature reduction. Based on the first law of thermodynamics, throttle valve process is a constant enthalpy one. Output parameter of throttle valve is computed according to the algorithm shown in figure 2. (Ghorbani et al., 2014).

### 3.3. Heat Exchanger Modeling

The algorithm of calculation of thermodynamic parameters of output mixture of heat exchanger is very similar to presented algorithm for throttle valve. Pressure, temperature, flow rate and the percent compound of the mixture are clear in entrance. Also, thermal load and pressure drop are known. The output mixture enthalpy is calculated by energy balance equation. The output pressure is calculated by considering the pressure drop. In the next step, knowing pressure and enthalpy, the other thermodynamic parameters of the mixture are calculated according to the algorithm presented for throttle valve. The only difference between these two algorithms is the output enthalpy calculation method. (Ghorbani et al., 2014)

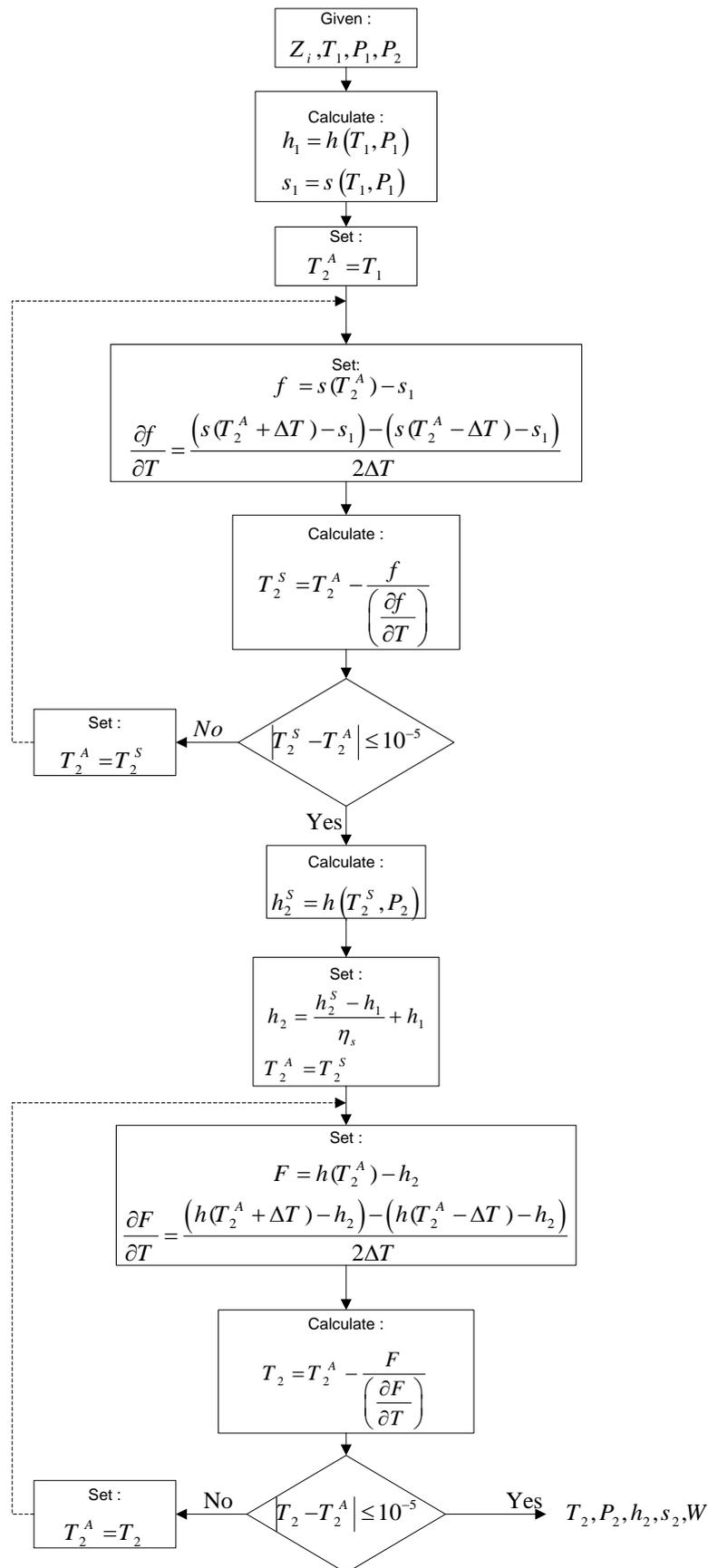


Figure 1. Algorithm of Calculation of Output Parameters of Compressor

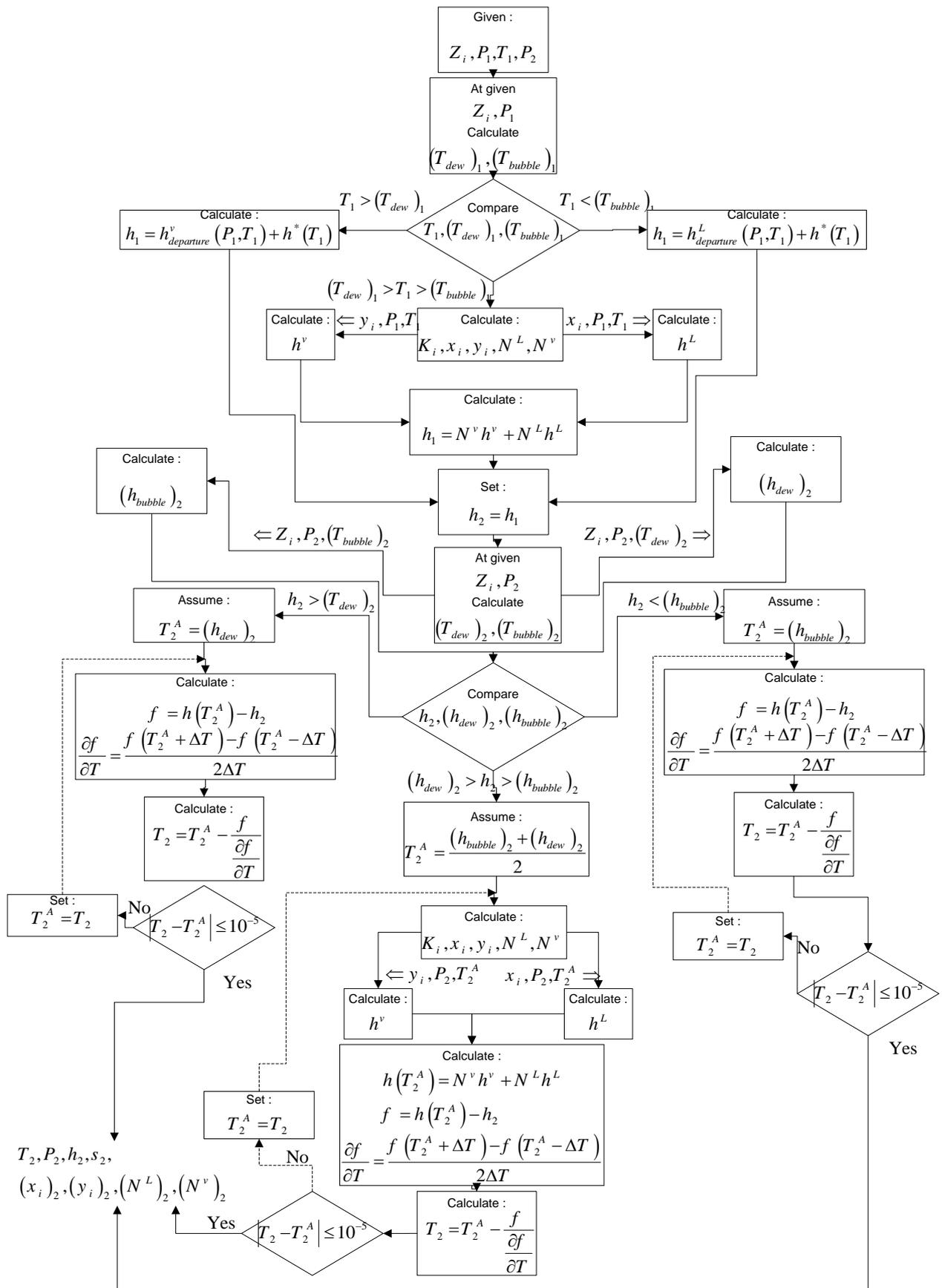


Figure 2. Algorithm of Calculation of Output Parameters of throttle Valve

### 3.4. Mixer Modeling

Mixer is an instrument that is used for mixing two flows with different temperature and percent composition but with the same pressure. Based on balance mass equation for mixer, the percent composition of output flow can be calculated by equation (33).

$$(Z_i)_3 = \frac{(N_i)_3}{(N_{total})_3} = \frac{(N_i)_1 + (N_i)_2}{(N_{total})_1 + (N_{total})_2} \quad (33)$$

In equation (33), subscripts 1 and 2 are for input flows and subscript 3 is for output flow.  $(N_i)_1$  and  $(N_i)_2$  are molar rates of the  $i$ th compound that can be written as:

$$\begin{aligned} (N_i)_1 &= \dot{m}_1 (Z_i)_1 \\ (N_{total})_1 &= \sum_i (N_i)_1 \end{aligned} \quad (34)$$

$$\begin{aligned} (N_i)_2 &= \dot{m}_2 (Z_i)_2 \\ (N_{total})_2 &= \sum_i (N_i)_2 \end{aligned} \quad (35)$$

Moreover, based on energy balance and mass balance in mixer, equations (36) and (37) are:

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (36)$$

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \quad (37)$$

The mixture enthalpy is obtained from equation 38.

$$h_3 = \frac{\dot{m}_1 h_1 + \dot{m}_2 h_2}{\dot{m}_1 + \dot{m}_2} \quad (38)$$

Assuming a pressure drop for mixer, the output mixture pressure can be calculated. So, percent composition, pressure, and enthalpy are known and in the next step one can calculate the other parameters by using the throttle valve algorithm. The only difference is the enthalpy calculation method that should consider it (Ghorbani et al., 2014).

### 4. The System Efficiency Calculation by Using the Algorithms and Developed Codes

In this section the parameters and applicable efficiencies for energy production systems are discussed. Calculations for Internal reformer with capacity of 1 kW is described and the

results of the other systems are presented in the following table 3.

- Input heating based on HHV

HHV thermal input

$$\begin{aligned} &= \left(0.4972 \frac{\text{lb}}{\text{h}} \text{ fuel}\right) \\ &\times \left(\frac{18127.03 \text{ Btu, HHV}}{1 \text{ lb fuel}}\right) \\ &\times \left(\frac{1 \text{ MBtu}}{10^6 \text{ Btu}}\right) = 0.009 \frac{\text{MBtu}}{\text{h}} \end{aligned}$$

HHV thermal input

$$\begin{aligned} &= \left(0.009 \frac{\text{MBtu}}{\text{h}}\right) \times \left(\frac{1 \text{ MW}}{3.412 \text{ MBtu}}\right) \\ &= 0.0026 \text{ MW} \end{aligned}$$

- Input heating based on LHV

LHV thermal input

$$\begin{aligned} &= \left(0.4972 \frac{\text{lb}}{\text{h}} \text{ fuel}\right) \\ &\times \left(\frac{16362.6 \text{ Btu, LHV}}{1 \text{ lb fuel}}\right) \\ &\times \left(\frac{1 \text{ MBtu}}{10^6 \text{ Btu}}\right) = 0.008 \frac{\text{MBtu}}{\text{h}} \end{aligned}$$

LHV thermal input

$$\begin{aligned} &= \left(0.008 \frac{\text{MBtu}}{\text{h}}\right) \times \left(\frac{1 \text{ MW}}{3.412 \text{ MBtu}}\right) \\ &= 0.0024 \text{ MW} \end{aligned}$$

- Electrical efficiency based on HHV

$$\begin{aligned} \text{Electrical Efficiency (HHV)} &= \left[\frac{\text{output AC}}{\text{Input, HHV}}\right] \\ &= \left[\frac{1000 \times 10^{-6} \text{ MW} \times 0.95}{0.0026 \text{ MW, HHV}}\right] \\ &\times 100 = 35.96 \% \text{ HHV} \end{aligned}$$

- Electrical efficiency based on LHV

$$\begin{aligned} \text{Electrical Efficiency (LHV)} &= \left[\frac{\text{output AC}}{\text{Input, LHV}}\right] \\ &= \left[\frac{1000 \times 10^{-6} \text{ MW} \times 0.95}{0.0024 \text{ MW, LHV}}\right] \\ &\times 100 = 39.84 \% \text{ LHV} \end{aligned}$$

It should be noted that due to the smaller amount of fuel LHV in comparison with HHV amount, efficiency based on LHV was always greater than HHV.

**Table 3.** Input Heating and Electrical Efficiency Based on LHV and HHV

<b>Input Heating Based on HHV</b>						
		Internal reformer		External reformer		
Power (W)	fuel (lb/h)	thermal input (Mbtu/h)	thermal input (MW)	fuel (lb/h)	thermal input (Mbtu/h)	thermal input (MW)
500	0.2527	0.0045807	0.001342527	0.2282	0.004136588	0.001212365
1000	0.4972	0.009012759	0.002641489	0.4483	0.008126348	0.002381696
2500	1.247	0.022604406	0.006624973	1.109	0.020102876	0.005891816
50000	24.85	0.44981898	0.131834402	22.15	0.40094529	0.11751034

<b>Input Heating Based on LHV</b>						
		Internal reformer		External reformer		
Power (W)	fuel (lb/h)	thermal input (Mbtu/h)	thermal input (MW)	fuel (lb/h)	thermal input (Mbtu/h)	thermal input (MW)
500	0.2527	0.004134829	0.001211849	0.2282	0.003733945	0.001094357
1000	0.4972	0.008135485	0.002384374	0.4483	0.007335354	0.002149869
2500	1.247	0.020404162	0.005980118	1.109	0.018146123	0.005318325
5000	24.85	0.399839098	0.117186136	22.15	0.35639587	0.104453639

<b>Electrical Efficiency Based on HHV</b>						
		Internal reformer		External reformer		
Power (W)	fuel (lb/h)	Electrical Efficiency (%)		fuel (lb/h)	Electrical Efficiency (%)	
500	0.2527	35.38105158		0.2282	39.17963074	
1000	0.4972	35.96456852		0.4483	39.88753841	
2500	1.247	35.84920503		1.109	40.3101521	
5000	24.85	36.03004927		22.15	40.4219747	

<b>Electrical Efficiency Based on LHV</b>						
		Internal Reformer		External Reformer		
Power (W)	fuel (lb/h)	Electrical Efficiency (%)		fuel (lb/h)	Electrical Efficiency (%)	
500	0.2527	39.19630031		0.2282	43.40449206	
1000	0.4972	39.8427397		0.4483	44.18873562	
2500	1.247	39.7149362		1.109	44.65692105	
50000	24.85	40.5338051		22.15	45.4747201	

## 5. Results

The hybrid system modeled in Hysys software and thermodynamic characteristics of system are obtained. The results are shown in Figure 3.

The input data for analysis are presented in Table 4. Natural gas composition, operating temperature and operating pressure of SOFC, Required fuel and some other parameters are listed in the table.

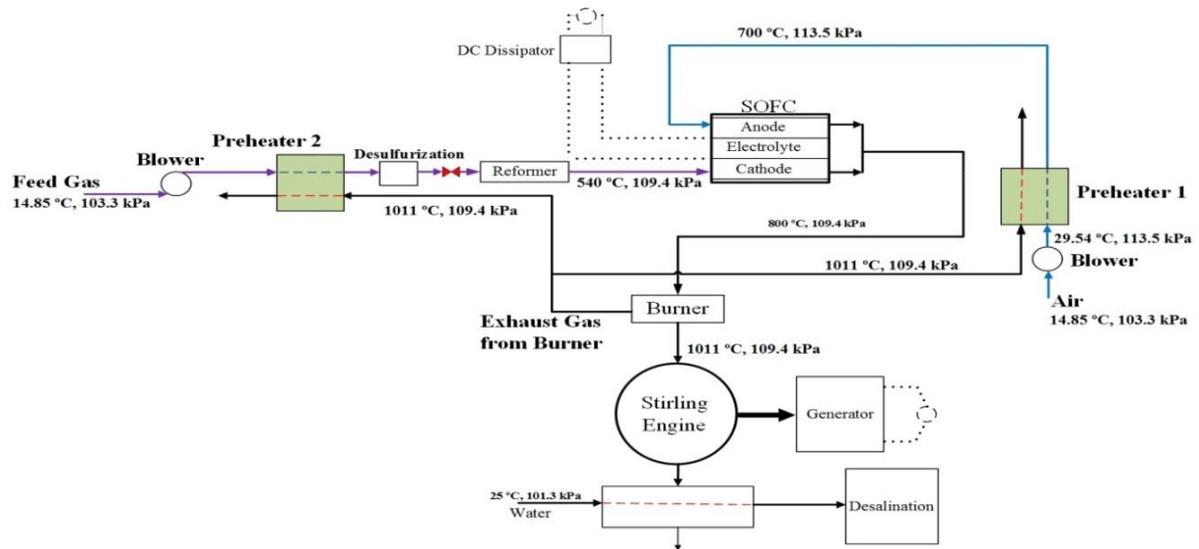


Figure 3. SOFC and Stirling Hybrid System Modeling in HYSYS

Table 4. Common Input Data for Analysis

Parameter	Characteristics
Input natural gas composition (%)	Methane: 81.3 , Ethane: 2.9 , Propane: 0.4 , Butane: 0.2 , CO2: 0.9 , N2: 14.3
Operating temperature of SOFC (°C)	800
Operating pressure of SOFC (atm)	≅1
Fuel utilization factor ( $U_f$ )(%)	80
Air use efficiency ( $U_a$ )(%)	30
Current density ( $A/cm^2$ )	0.3
Density of produced electricity with internal reformer ( $W/cm^2$ )	0.164
Density of produced electricity with external reformer ( $W/cm^2$ )	0.184
Effective area of each cell( $cm^2$ )	100
Carbone to steam ratio for reformer	2
Input water, fuel and air temperature (°C)	15
Temperature of input air to stack (°C)	700
Temperature of output flow from stack (°C)	800
Temperature of input fuel to desulfurizer (°C)	400
Temperature drop of desulfurizer (°C)	20
Pressure drop of desulfurizer (atm)	0.02
Temperature of output flow from furnace (°C)	≅1010
Furnace heat dissipation (%)	5
SOFC heat dissipation (%)	5
Pressure drop of SOFC (atm)	0.02
Pressure drop of gas side of heat exchanger (atm)	0.02
Pressure drop of liquid side of heat exchanger (atm)	0.08
Water pump efficiency (%)	50
Air and fuel compressor efficiency (%)	65
DC to AC inverter (%)	95
Process fuel pressure (atm)	1
Process air pressure (atm)	1
Process water pressure (atm)	3
Gas temperature of process output (°C)	70
Produced water temperature (°C)	70

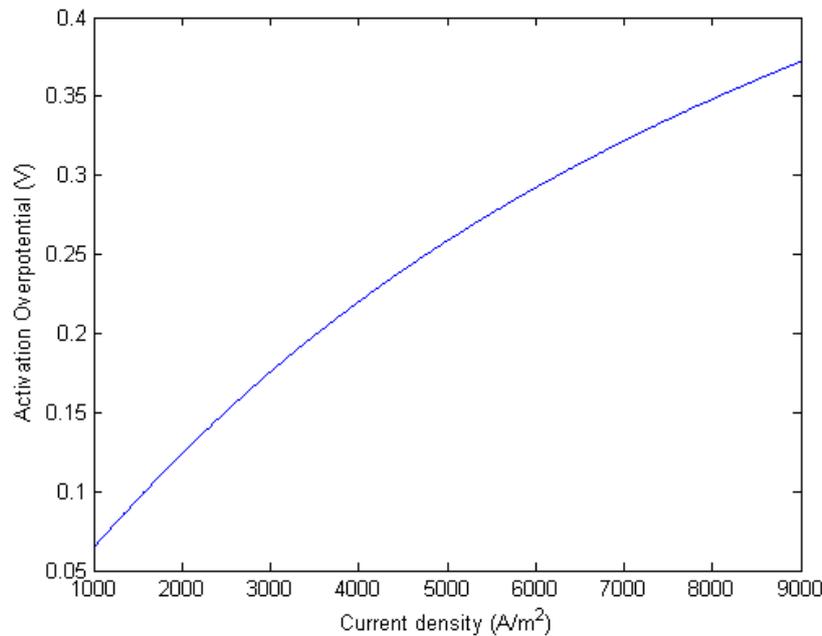
The results of SOFC analysis are shown in Table 5. Cell voltage, cell numbers, total current of stack, required O<sub>2</sub>, air, H<sub>2</sub>, and fuel are illustrated in the table.

After analysis of SOFC with programming in Matlab voltage loss diagrams are obtained. The findings are presented in Figure 4 to Figure 7. All 3 types of voltage losses had direct

relationship with current density but the most increase in loss together with the increase in current density occurred in concentration loss (Figure 6) and the least increase is in activation loss (Figure 4). In Figure 5, the linear relationship of ohmic loss with current density is presented.

**Table 5.** SOFC Analysis Results

Parameter	Calculations
Cell voltage (V)	$V = \frac{Pc}{Ic} = \frac{0.1840}{0.3} = 0.6133$
Cell numbers	$N = \frac{P}{(effective\ area) \times (power\ per\ area)} = \frac{50000}{100 \times 0.1840} \cong 2717$
Total current of stack (A)	$I = effective\ area \times current\ density \times cell\ number = 100 \times 0.3 \times 2717 = 81520$
Required O <sub>2</sub> (kg/h)	$O2\ usage = 8.29 \times 10^{-8} \times \frac{P}{Vc} \times 3600 = 24.33$
Required air (kg/h)	$air\ required = 3.57 \times 10^{-7} \times \frac{P}{(Vc \times Ua)} \times 3600 = 349.2$
Required H <sub>2</sub> (kgmol/h)	$H2\ required = \frac{0.018664 \times I}{Uf} = \frac{0.018665 \times 81520}{0.80} = 1901$
Required fuel (kgmol/h)	$Fuel = \frac{n\ H2}{C\ H2 + C\ CO + (4 \times C\ CH4) + (7 \times C\ C2H6) + \dots} = \frac{1.901}{3.521} = 0.5399$



**Figure 4.** Activation Voltage Loss Graph

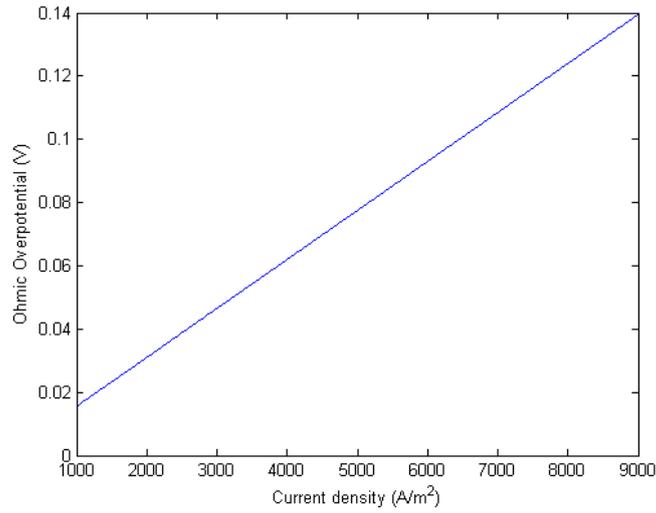


Figure 5. Ohmic Voltage Loss Graph

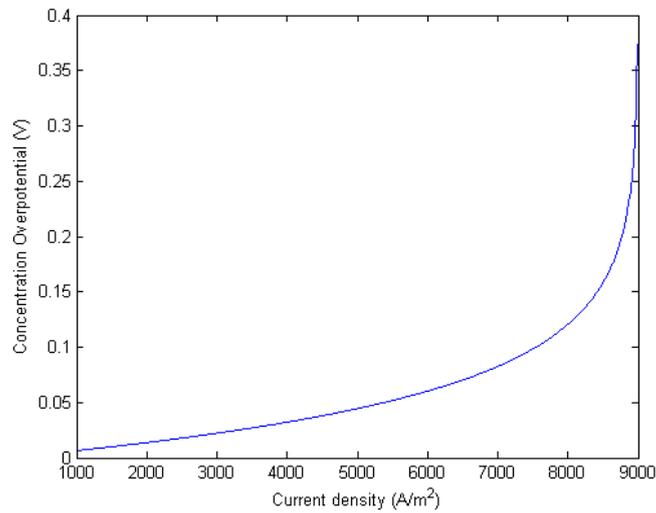


Figure 6. Concentration Voltage Loss Graph

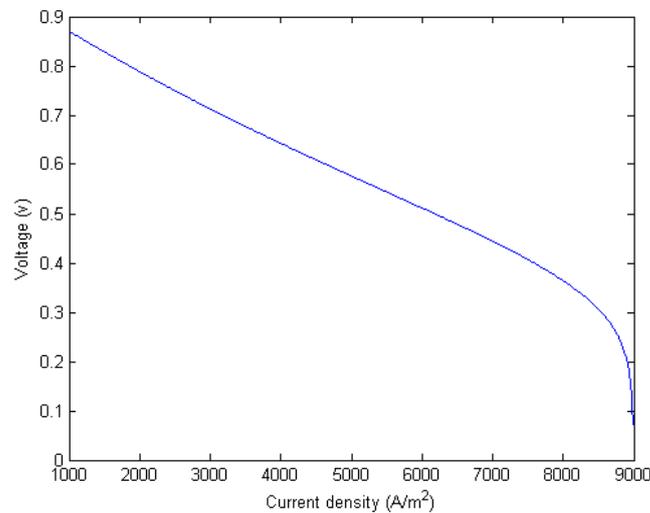


Figure 7. Cell Voltage versus the Current Density Graph

The system simulation in Hysys is shown in Figure 8 and Figure 9. In Figure 8 the system with internal reforming is modeled, and Figure 9 shows the system external reforming components.

This section is developed to verify the accuracy of the algorithms and codes are designed to predict thermodynamic properties of multi-component process and phase equilibrium calculation. The results are compared with the predicted results of Hysys software.

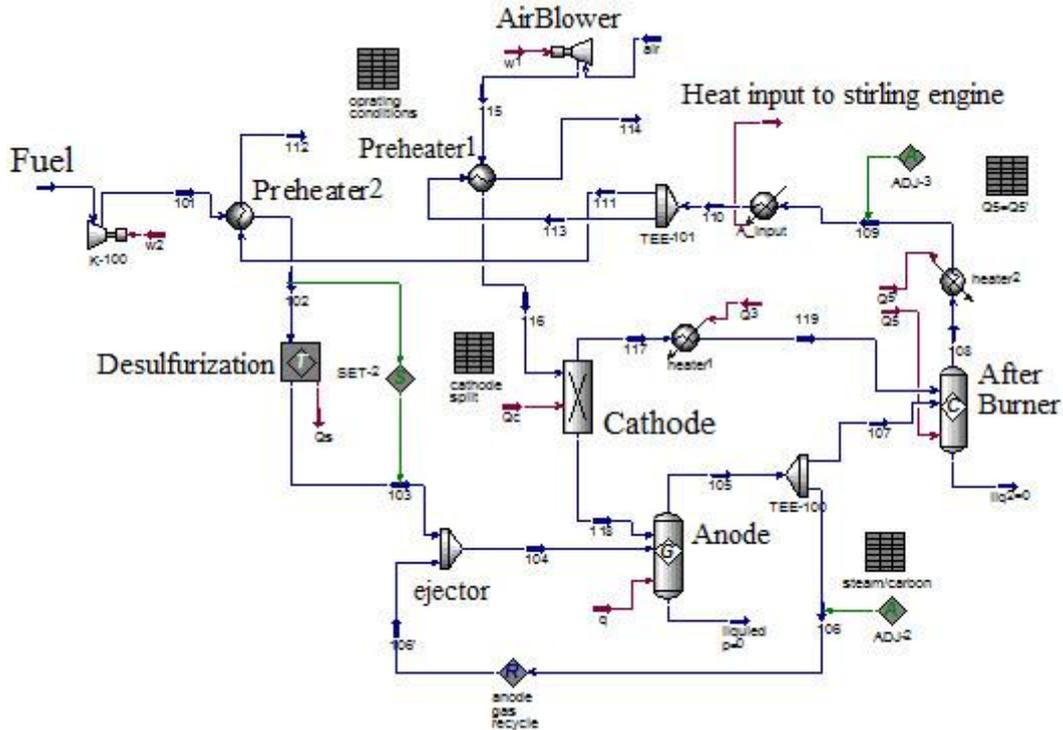


Figure 8. The Diagram of Simulated Units with Internal Reformer in Hysys

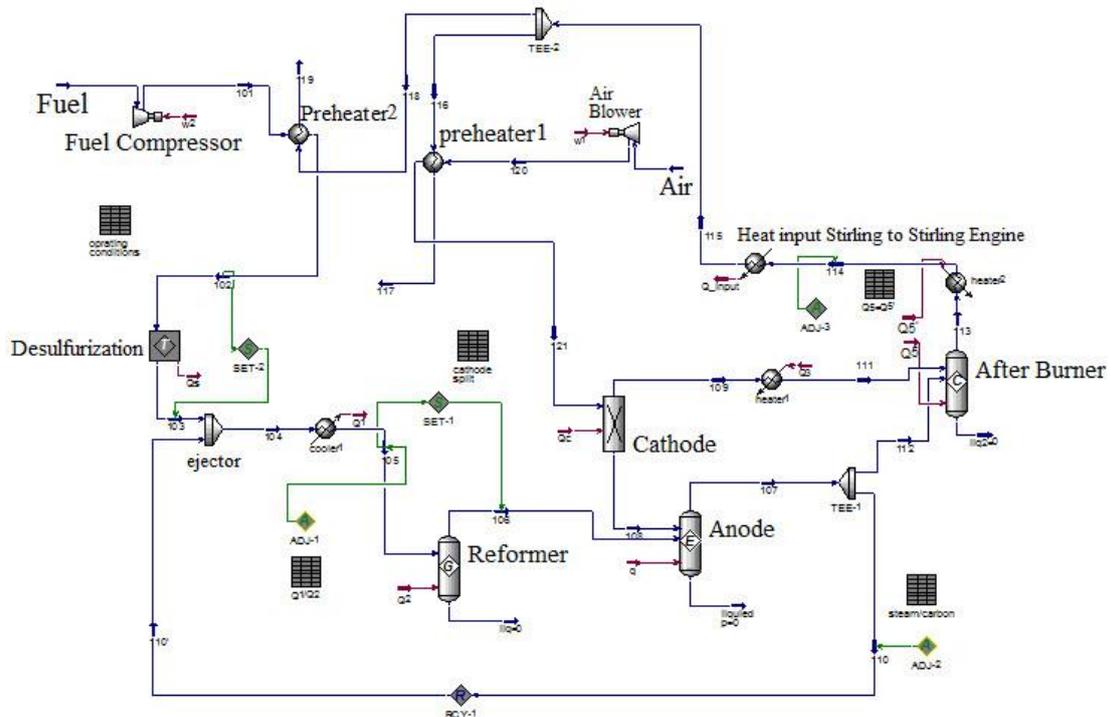


Figure 9. The Diagram of Simulated Unit with External Reformer in Hysys

**Table 6.** Accuracy Validation and Developed Codes

Parameter	Using Developed Codes	Simulation in Hysys for External Reformer	Simulation in Hysys for Internal Reformer
Cell voltage (V)	0.6133	0.6391	0.5467
Cell numbers	2717	2812	2749
Total current of stack (A)	81520	81516	81460
Required O <sub>2</sub> (kg/h)	24.33	24.37	25.30
Required air (kg/h)	349.2	348.1	341.8
Required H <sub>2</sub> (kgmol/h)	1901	1906	2033
Required fuel (kgmol/h)	0.5399	0.5267	0.5469

Comparing the results presented in Tables, the accuracy of the developed codes is confirmed. The minimal differences between amounts that presented in tables is due to the differences between the coefficients and parameters used in the equation of state coefficients of Hysys software and available resources and references. The coefficients and parameters of different equations of state in Hysys software, compared to available resources and references, are modified to predict more accurately physical and thermodynamic properties.

## 6. Conclusion

Solid oxide fuel cell is a good choice for hybrid systems. Because of its prominent features, it can be used in a hybrid system to obtain higher efficiency and lower pollution. Solid oxide fuel cell works in high temperature, and the thermal energy in its stack can be used in another power generation component or in a heating or cooling one to make a CHP or CCHP system. Thermodynamic and electrical parameters of the system are calculated both in Matlab and Hysys to achieve more exact and reliable results.

## References

- Appleby A.J & Foulkes F.R, Fuel Cell Handbook (1989). van Nostrand Reinhold. New York, 18.
- Bedringås, K. W., Ertesvåg, I. S., Byggstøyl, S., & Magnussen, B. F. (1997). Exergy analysis of solid-oxide fuel-cell (SOFC) systems. *Energy*, 22(4), 403-412.
- Chan, S., Ho, H., & Tian, Y. (2002). Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant. *Journal of Power Sources*, 109(1), 111-120.
- Chan, S., Low, C., & Ding, O. (2002). Energy and exergy analysis of simple solid-oxide fuel-cell power systems. *Journal of Power Sources*, 103(2), 188-200.
- Dincer, I. (2002). Technical, environmental and exergetic aspects of hydrogen energy systems. *International Journal of Hydrogen Energy*, 27(3), 265-285.
- Ghorbani, B., Mafi, M., Shirmohammadi, R., Hamed, M.-H., & Amidpour, M. (2014). Optimization of operation parameters of refrigeration cycle using particle swarm and NLP techniques. *Journal of Natural Gas Science and Engineering*, 21, 779-790.
- Haynes, C., & Wepfer, W. J. (2002). Enhancing the performance evaluation and process design of a commercial-grade solid oxide fuel cell via exergy concepts. *Journal of energy resources technology*, 124(2), 95-104.
- Hussain, M., Li, X., & Dincer, I. (2005). Multi-component mathematical model of solid oxide fuel cell anode. *International Journal of Energy Research*, 29(12), 1083-1101.
- Rosen, M. (1990). Comparison based on energy and exergy analyses of the potential cogeneration efficiencies for fuel cells and other electricity generation devices. *International Journal of Hydrogen Energy*, 15 (4), 267-274.
- Sheikhi, S., Ghorbani, B., Shirmohammadi, R., & Hamed, M.-H. (2014). Thermodynamic and Economic Optimization of a Refrigeration Cycle for Separation Units in the Petrochemical Plants Using Pinch Technology and Exergy Syntheses

- Analysis. *Gas Processing Journal*, 2(2), 39-52. Retrieved from [http://uijs.ui.ac.ir/gpj/browse.php?a\\_code=A-10-350-1 & slc\\_lang = en & sid = 1](http://uijs.ui.ac.ir/gpj/browse.php?a_code=A-10-350-1&slc_lang=en&sid=1)
- Shirmohammadi, R., Ghorbani, B., Hamed, M., Hamed, M.-H., & Romeo, L. M. (2015). Optimization of mixed refrigerant systems in low temperature applications by means of group method of data handling (GMDH). *Journal of Natural Gas Science and Engineering*, 26, 303-312.
- Veyo, S. E., & Lundberg, W. L. (1999). Solid oxide fuel cell power system cycles. *ASME paper*, 99.

