Advanced exergy analysis for an anode gas recirculation solid oxide fuel cell

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Abstract

Advanced exergy analysis is performed for a solid oxide fuel cell with anode gas recirculation. For this purpose, the unavoidable conditions are determined by specifying the most important electrochemical parameters resulting in the best possible performance. It is observed that, under the unavoidable conditions, the fuel cell exergy efficiency can be 32% higher and the exergy destruction can be 38% lower, compared to the corresponding values under real conditions. The analysis revealed the values of first level splitting of exergy destruction including the avoidable/unavoidable and endogenous/exogenous exergy destructions for all the system components. In addition, the second level splitting of exergy destruction including the unavoidable endogenous, unavoidable exogenous, avoidable endogenous and avoidable exogenous exergy destructions are determined for all the system components. The results show that of the total exergy destruction in the system, 62% is endogenous and 38% is exogenous. Also, 54% of the total exergy destruction is avoidable and the rest, 46%, is unavoidable. In addition, it is observed that the order of component contribution in the total avoidable endogenous exergy destruction of the system is: the inverter, 6.52 kW, the stack, 3.6 kW and the afterburner, 0.62 kW. This result is different from that obtained from conventional exergy analysis suggesting that attention should be paid first on the stack, then on the afterburner and afterward on the inverter.

Furthermore, it is observed that almost half of the avoidable exergy destruction in the stack, 7.56 kW (51%), occurs exogenously. Therefore, for reducing exergy destruction in the stack an enhancement in the stack and the other system component is required.

1. Introduction

Designing innovative energy conversion systems with higher efficiency and lower environmental impact is a major task for an engineer. Fuel cell technology can be helpful in this regard as it converts a gaseous fuel to electrical energy and heat directly by electrochemical oxidization of the fuel. Fuel cells emit lower values of NOx or CO2, even when they are compared with systems using the cleanest combustion process [1,2]. Other advantages such as their capability of producing electricity in a small to a large scale make the fuel cells to be a promising technology for power generation [1].

The well-known solid oxide fuel cells (SOFCs), among the other types, are prominent systems in energy sector, because of their high efficiency and fuel diversity [3,4] as well as high-temperature exhaust gases [5]. The use of high temperature gases exhaust from SOFCs has been suggested by researchers for running such bottoming cycles as gas turbine together with a heater [6], steam or Organic Rankine cycle [7,8], gas turbine [9] and gas turbine and a GAX absorption refrigeration cycles [10].

The mathematical and numerical models for SOFCs has been reported in some studies in literature [4,11]. A good performance for SOFC requires an optimal micro-structural design to have better ion and electron transport and electrochemical reaction in porous electrodes [11].

The physical prototyping and experimental investigation of the SOFC performance in different layers of the cell are complex, expensive and time consuming. The mathematical modeling however, accounts for complex transport processes with chemical and electrochemical reactions in system [11—13]. Depending on the electrodes’ treatment, the mathematical SOFC models can be

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broadly classified into macro and micro models [14]. Introducing the micro-characteristics of electrodes into macro-models not only helps in better understanding of the relevant processes occurring within the electrodes, but also enhances the prediction capability of the overall cell model.

In most of research works electrochemical modeling as well as energy and conventional exergy analysis has been used to estimate the SOFCs’ electrochemical performance, exergy efficiency and exergy destruction rate. The conventional exergy analysis however, is not capable of detecting the interactions among system components and of determining the real contribution of each component in the system’s overall exergy destruction. Identifying and quantifying the real sources of irreversibility and also the extent to which the performance of a component can be enhanced is of a great help in designing thermodynamic systems. In this regard, advanced exergy analysis has been originated from a concept of splitting the exergy destruction into endogenous and exogenous components and also the avoidable and unavoidable parts [15]. The basic formulations and structure of the method was initially introduced by Tsatsaronis et al. [16-18]. There are a lot of research works in literature concerning the application of advanced exergy analysis on energy conversion systems like the Li/Br absorption refrigeration machine [19], boiler used in industrial factory [20], cogeneration and tri-generation systems [21-23], several configuration of geothermal district heating system [24-26], gas engine heat pump for food drying processes [27], aircraft gas turbine engine [28], organic Rankine cycle coupled to an internal combustion engine [29] and geothermal driven dual fluid organic. Rankine cycle [30]. Several methods including thermodynamic cycle method, equivalent component method, structural theory method and engineering method have been proposed in literature and the results obtained from applying these techniques to some energy conversion systems have been compared. It has been reported that among these methods the engineering one is more appropriate to the systems in which a chemical reaction takes place [16]. Soltani et al. [31] applied engineering method for externally fired combined cycle power plant using biofuel. Fallah et al. [32] applied this method for advanced exergy analysis of steam injection gas turbine coupled with an evaporative inlet air cooler (ESTIG). Also Vatani et al. [33] made use of the engineering method for advanced exergy analyses of five different LNG regasification processes. The advanced exergy analysis has also been used to evaluate economic aspects and/or environmental impact of thermal systems such as cogeneration systems [34] and reforming reactor producing hydrogen [35].

A main advantage of advanced exergy analysis over the conventional one is the precise specification of component enhancement priority for improving the performance of a thermodynamic system [36].

As mentioned above, because of some promising features, the advanced exergy analysis have been applied to different energy conversion systems and have provided useful information for thermodynamic system designers. The simple and hybrid SOFC systems have been paid a lot of attention in recent years because of the advantages mentioned above. To the best of our knowledge however, in spite of the excessive research works on SOFC systems, there is no information on the advanced exergy analysis of these systems. The present work is an attempt in this regard by disclosing the real sources of inefficiencies and real potential of performance improvement for the SOFC system.

2. Description of SOFC system

The schematic flow diagram of SOFC module analyzed in the present work is shown in Fig. 1. It includes a SOFC stack with an external pre-reformer and an internal reformer, a mixer, an afterburner, a pre-heater and an inverter. The anode gas is recirculated in the SOFC stack to provide steam and heat required for reforming methane in the pre-reformer. The considered SOFC is basically similar to the 100 kW Siemens-Westinghouse commercial model [37,38]. Methane as a fuel is mixed with the recirculated anode gas in the mixer and flows to the pre-reformer for being reformed before entering the anode side of the SOFC. On the other hand, air is heated by the afterburner exhaust gases in the heat exchanger and then enters the cathode side of the SOFC. Inside the SOFC stack an electrochemical reaction occurs and the resultant non-recirculating gas mixture exits from the anode and the excess air leaves the cathode. These two streams then flow to the afterburner for combustion after which the combustion gas at high temperature and pressure pass to the heat exchanger to heat the incoming air.

The main assumptions in analyzing the SOFC system are as follows:

1. The system operates under steady state conditions.
2. Changes in kinetic and potential energies and exergies are neglected.
3. Some pressure losses are considered for the streams passing through the heat exchangers and pipelines.
4. The environmental air is composed of 79% N2 and 21% O2 on a volumetric basis.
5. The gas mixtures are considered to be as ideal gas mixtures.
6. The gas mixture at the exit of the anode reaches a chemical equilibrium.
7. The system components are insulated perfectly and there is no heat interaction with the environment.
8. There is no gas leakage in the components.

3. Modeling and thermodynamic analysis

A zero-dimensional mathematical model is developed to present the chemical and electrochemical characteristics of the SOFC module. The details of chemical, electrochemical, energy and exergy relations for analyzing the SOFC module are presented in this section.

3.1. SOFC modeling

An external pre-reformer and a direct internal reformer is used in the system. The high temperature circulating anode gas containing steam is used for reforming methane in the pre-reformer. The amount of circulating gas is determined by steam to carbon ratio. The steam to carbon ratio, $r_{sc}$, is defined as the ratio between the number of H2O molecules and the number of the C-atoms of combustible components [39], can be expressed as [40]:

$$r_{sc} = \frac{n_{6,H_2O}}{n_{2,CH_4} + n_{2,CO}}$$

The steam reforming reaction for methane and the water-gas shifting reaction taking place in the pre-reformer are as follows [40,41]:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (\text{reforming, } x_r)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (\text{shifting, } y_r)$$

The composition of exhaust gases leaving the pre-reformer is obtained from the molar balance for the reactions. The equilibrium constants $(K)$ for the reforming and shifting reactions, as a function
of the partial pressures of reactants and products, are defined as [40–42]:

\[
K_{pr} = e^{\left(-\frac{\Delta G}{R T}\right)} = \left(\frac{n_{2,H_2} + 3x_r + y_r}{n_{2,CH_4} - x_r} \times \frac{n_{2,CO} + x_r - y_r}{n_{2,CH_4} - x_r} \times \frac{P_3}{n_{2,CO} + 2x_r}\right)^2
\]

(3a)

\[
K_{ps} = e^{\left(-\frac{\Delta G}{R T}\right)} = \left(\frac{n_{2,H_2} + 3x_r + y_r}{n_{2,CO} + x_r - y_r} \times \frac{n_{2,CO} + x_r - y_r}{n_{2,CH_4} - x_r} \times \frac{P_3}{n_{2,CO} + 2x_r}\right)^2
\]

(3b)

In these equations, \(\Delta G\) and \(R\) are the molar Gibbs free energy change for the chemical reaction and the universal gas constant, respectively. Also, \(x_r\) and \(y_r\) are the molar flow rates of consumed methane and carbon monoxide, as obtained from the equilibrium reaction.

The partially reformed gas mixture exiting the pre-reformer is reformed completely to hydrogen and carbon dioxide in the anode part, in the internal reformer. The reforming and shifting reactions as well as the overall electrochemical reaction occur simultaneously in the fuel cell. The overall electrochemical reaction is as follows [40,41]:

\[
H_2 + 1/2O_2 \rightarrow H_2O \quad \text{(overall electrochemical, } \dot{z} \text{)}
\]

(4)

Considering \(\dot{z}\) for the molar flow rate of the consumed hydrogen, the molar flow rates of consumed methane and carbon monoxide (\(x\) and \(y\)) are obtained from the equilibrium reaction. The equilibrium constants for the reforming and shifting reactions are expressed as [40,42]:

\[
K_r = e^{\left(-\frac{\Delta G_r}{R T}\right)} = \left(\frac{n_{3,H_2} + 3x + y - z}{n_{3,CO} + x - y + z} \times \frac{P_4}{n_{3,H_2} + 2x}\right)^2
\]

(5a)

\[
K_s = e^{\left(-\frac{\Delta G_s}{R T}\right)} = \left(\frac{n_{3,H_2} + 3x + y - z}{n_{3,CO} + x - y} \times \frac{n_{3,CO} + y)}{n_{3,H_2} + 3x + y - z}\right)^2
\]

(5b)

The molar flow rate of hydrogen utilized in the overall electrochemical reaction, \(\dot{z}\), is obtained by using the fuel consumption factor as follows [38–40]:

\[
\dot{z} = U_f \times (4n_{3,CH_4} + n_{3,H_2} + n_{3,CO})
\]

(6)

The fuel cell output power, \(W_{FC}\), is defined as:

\[
W_{FC} = N_c \times V_c \times i \times A_a
\]

(7)

where \(N_c\) is the number of cells, \(A_a\) is the active surface area, \(i\) is the current density and \(V_c\) is the produced cell voltage. The current density and cell voltage are calculated as [40,41]:

\[
i = \frac{2 \times F \times \dot{z}}{N_c A_a}
\]

(8)

\[
V_c = V_R - V_{loss}
\]

(9)

here \(V_R\) is the reversible cell voltage given by Nernst equation and \(V_{loss}\) is the voltage loss which is the sum of ohmic loss \(V_{ohm}\), activation and concentration overvoltages \(V_{act}\) and \(V_{conc}\) [40,43]:
The concentration overvoltage is the sum of two values concerned with the anode and cathode sections as follows [43,48]:

\[ V_{\text{conc}} = V_{\text{conc,a}} + V_{\text{conc,c}} \]  

(18)

\[ V_{\text{conc,a}} = \frac{RT}{2F} \ln \left( \frac{1 - \frac{1}{\kappa_{\text{i,a}}} \exp \left( \frac{i_{\text{act,a}}}{RT} \right)}{\frac{1}{\kappa_{\text{i,a}}} \exp \left( \frac{i_{\text{act,a}}}{RT} \right)} \right) \]  

(19)

\[ V_{\text{conc,c}} = \frac{RT}{2F} \ln \left( \frac{1 - \frac{1}{\kappa_{\text{i,c}}} \exp \left( \frac{i_{\text{act,c}}}{RT} \right)}{\frac{1}{\kappa_{\text{i,c}}} \exp \left( \frac{i_{\text{act,c}}}{RT} \right)} \right) \]  

(20)

The relations used to evaluate the limiting or maximum possible current density for diffusion of gas species \( j \) (\( i_{j} \)), can be found in the literature [43,49].

### 3.2. Exergy analyses

In conventional exergy analysis the exergy balance for component \( k \) and the overall system, in terms of fuel and product exergies, are expressed as follows [50]:

\[ \dot{E}_{\text{D,k}} = \dot{E}_{F,k} - \dot{E}_{P,k} \]  

(21)

\[ \dot{E}_{F,\text{tot}} = \dot{E}_{F,\text{tot}} + \sum_{k} \dot{E}_{D,k} + \dot{E}_{L,\text{tot}} \]  

(22)

In addition, the exergy efficiency and exergy destruction ratio for component \( k \) is expressed as [32,36]:

\[ \varepsilon_{k} = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \]  

(23)

\[ y_{k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,\text{tot}}} \times 100 \]  

(24)

\[ y'_{k} = \frac{\dot{E}_{D,k}}{\dot{E}_{L,\text{tot}}} \times 100 \]  

(25)

In Eqs. (21)–(25), \( \dot{E}_{D,k} \) is the exergy destruction rate, \( \dot{E}_{F,k} \) is the fuel exergy rate and \( \dot{E}_{P,k} \) is the product exergy rate for the \( k \)th component. In these equations, \( \varepsilon_{k} \), \( y_{k} \) and \( y'_{k} \) are the exergy efficiency and exergy destruction ratio for this component, respectively.

Neglecting the exergies associated with kinetic and potential energies the exergy rate (\( \dot{E} \)) can be considered as the sum of physical and chemical exergies as follows [50,51]:

\[ \dot{E} = \dot{E}_{\text{ph}} + \dot{E}_{\text{ch}} \]  

(26)

where the physical and chemical exergies is determined as follows [50]:

\[ \dot{E}_{\text{ph}} = \sum_{i} n_{i} \left[ \left( \bar{c}_{i} - \bar{c}_{0,i} \right) - T_{0} \left( \bar{s}_{i} - \bar{s}_{0,i} \right) \right] \]  

(27)

\[ \dot{E}_{\text{ch}} = \dot{n} \left( \sum x_{i} \bar{c}_{i}^{ch} + RT_{0} \sum x_{i} \ln x_{i} \right) \]  

(28)

The energy and exergy balance equations for different components of the SOFC system, as shown in Fig. 1, are outlined in Table 1.
3.3. Advanced exergy analysis

Advanced exergy analysis accounts for the influence of components on one another and also considers the extent to which a component performance can be enhanced. This is done by splitting the exergy destruction in each component into endogenous/exogenous and avoidable/unavoidable exergy destruction parts as [15]:

\[
\dot{E}_{D,k} = \dot{E}^{\text{EN}}_{D,k} + \dot{E}^{\text{EX}}_{D,k}
\]

(29)

\[
\dot{E}_{D,k} = \dot{E}^{\text{AV}}_{D,k} + \dot{E}^{\text{UN}}_{D,k}
\]

(30)

The endogenous exergy destruction in the kth component, \( \dot{E}^{\text{EN}}_{D,k} \), is associated with the irreversibility occurring only inside this component. The exogenous exergy destruction for the kth component, \( \dot{E}^{\text{EX}}_{D,k} \), is caused by the irreversibilities taking place in the other system components. The \( \dot{E}^{\text{EN}}_{D,k} \) is obtained when the kth component works under the real condition and all the other system components operate under their ideal conditions. Different methods have been proposed for calculating the endogenous exergy destruction. Among these methods, an acceptable accuracy level has been reported for the thermodynamic cycle (hybrid cycles) and engineering methods [16,36].

Referring to Eq. (30), the splitting of exergy destruction in the kth component into avoidable exergy destruction, \( \dot{E}^{\text{AV}}_{D,k} \), and unavoidable exergy destruction, \( \dot{E}^{\text{UN}}_{D,k} \), highlights the real potential for improving its thermodynamic performance. The unavoidable exergy destruction part cannot be reduced because of such technical restrictions as manufacturing methods, availability and material cost. The avoidable exergy destruction, however, can be reduced using technological enhancement in material and manufacturing method and/or layout improvement process [15,36].

The unavoidable part of exergy destruction rate for the kth component is determined as follows [32]:

\[
\dot{E}^{\text{UN}}_{D,k} = \dot{E}_{p,k} \left( \frac{\dot{E}_{D,k}^{\text{UN}}}{\dot{E}_{p,k}} \right) = \dot{E}_{p,k} \left( \frac{1}{\dot{E}_{p,k}} - 1 \right)
\]

(31)

Combining the above-mentioned parts of exergy destruction for the kth component (Eqs. (29) and (30)) leads to some new concepts such as unavoidable endogenous \( (\dot{E}^{\text{UN}}_{D,k}) \), avoidable endogenous \( (\dot{E}^{\text{EN}}_{D,k}) \), unavoidable exogenous \( (\dot{E}^{\text{EX}}_{D,k}) \), avoidable exogenous \( (\dot{E}^{\text{AV}}_{D,k}) \), and avoidable exogenous \( (\dot{E}^{\text{UN}}_{D,k}) \) parts of exergy destruction for the component. The \( \dot{E}^{\text{UN}}_{D,k} \) is the exergy destruction occurring within the kth component when it operates with highest achievable exergy efficiency, \( \epsilon^{\text{UN}}_{k} \), and the other components work under their ideal conditions. The \( \dot{E}^{\text{UN}}_{D,k} \) can be calculated as follows [32]:

\[
\dot{E}^{\text{UN}}_{D,k} = \dot{E}^{\text{EN}}_{D,k} \left( \frac{\dot{E}_{D,k}^{\text{UN}}}{\dot{E}_{p,k}} \right)
\]

(32)

The remaining combinations of exergy destruction rate for the kth component are obtained using Eqs. (33)–(35) [15,36]:

\[
\dot{E}^{\text{UN,EX}}_{D,k} = \dot{E}^{\text{EN}}_{D,k} - \dot{E}^{\text{UN,EN}}_{D,k}
\]

(33)

\[
\dot{E}^{\text{UN,EN,AV}}_{D,k} = \dot{E}^{\text{EN}}_{D,k} - \dot{E}^{\text{UN,EN}}_{D,k}
\]

(34)

\[
\dot{E}^{\text{UN,EX,AV}}_{D,k} = \dot{E}^{\text{EN}}_{D,k} - \dot{E}^{\text{UN,EX,AV}}_{D,k}
\]

(35)

3.3.1. Engineering method

In literature, several approaches have been proposed for determining the endogenous part of exergy destruction rate in a component. In the present work the well-known engineering or graph method, described in detail by Kelly et al. [16], is used. The engineering approach can be used for different types of the energy conversion systems and is a convenient method for the systems in which chemical reactions take place.

4. Result and discussion

4.1. Input data

The input data and real operating conditions used for energy and exergy analysis for anode recirculation SOFC system are outlined in Table 2.

4.2. Model validation

The developed model for fuel cell system is validated using the

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Table 1

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy balance equations</th>
<th>Exergy balance equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture</td>
<td>( \sum_{j} (n_{1j}T_{1j} + n_{2j}T_{2j}) \lambda_{j} = \sum_{j} (n_{1j}T_{1j}) \lambda_{j} )</td>
<td>( \dot{E}<em>{D,k} = \dot{E}^{\text{EN}}</em>{D,k} + \dot{E}^{\text{EX}}_{D,k} )</td>
</tr>
<tr>
<td>Pre-reformer</td>
<td>( \sum_{j} (n_{2j}T_{2j}) \lambda_{j} = \sum_{j} (n_{2j}T_{2j}) \lambda_{j} )</td>
<td>( \dot{E}<em>{D,k} = \dot{E}^{\text{EN}}</em>{D,k} + \dot{E}^{\text{EX}}_{D,k} )</td>
</tr>
<tr>
<td>Stack</td>
<td>( Q_{L} - W_{IC} + \sum_{j} (n_{1j}T_{1j} + n_{2j}T_{2j}) \lambda_{j} = \sum_{j} (n_{1j}T_{1j} + n_{2j}T_{2j}) \lambda_{j} = 0 )</td>
<td>( \dot{E}<em>{D,k} = \dot{E}^{\text{EN}}</em>{D,k} + \dot{E}^{\text{EX}}_{D,k} )</td>
</tr>
<tr>
<td>Inverter</td>
<td>( \eta_{in} - \frac{W_{IC}}{W_{in}} )</td>
<td>( \dot{E}<em>{D,k} = \dot{E}^{\text{EN}}</em>{D,k} + \dot{E}^{\text{EX}}_{D,k} )</td>
</tr>
<tr>
<td>After Burner</td>
<td>( \sum_{j} (n_{2j}T_{2j} + n_{3j}T_{3j}) \lambda_{j} = \sum_{j} (n_{2j}T_{2j} + n_{3j}T_{3j}) \lambda_{j} )</td>
<td>( \dot{E}<em>{D,k} = \dot{E}^{\text{EN}}</em>{D,k} + \dot{E}^{\text{EX}}_{D,k} )</td>
</tr>
<tr>
<td>H.E.</td>
<td>( \sum_{j} (n_{2j}T_{3j} + n_{3j}T_{3j}) \lambda_{j} = \sum_{j} (n_{2j}T_{3j} + n_{3j}T_{3j}) \lambda_{j} )</td>
<td>( \dot{E}<em>{D,k} = \dot{E}^{\text{EN}}</em>{D,k} + \dot{E}^{\text{EX}}_{D,k} )</td>
</tr>
<tr>
<td>Overall</td>
<td>( \eta_{out} = \frac{W_{IC}}{W_{out}} )</td>
<td>( \dot{E}<em>{D,k} = \dot{E}^{\text{EN}}</em>{D,k} + \dot{E}^{\text{EX}}_{D,k} )</td>
</tr>
</tbody>
</table>

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The fuel composition was 89% H2, 11% H2O and the fuel and air utilization factors of 85% and 16.7%, respectively. The obtained results are consistent with those reported in the literature [38,40,54].

### 4.3. Result obtained by energy and conventional exergy analyses

Thermodynamic properties and the obtained results associated with exergy destructions for each system component are observed in Tables 4 and 5, respectively. As indicated in Table 5, the first law efficiency is 51.37% and the net output power is 108.6 kW. Also, the order of components for highest exergy destruction rate is: the fuel cell stack, 14.83 kW (32.7%); the afterburner, 13.59 kW (29.96%); the inverter, 8.82 kW (19.45%); the heat exchanger, 4.437 kW (9.78%); the mixer, 2.212 kW (4.878%) and the pre reformer, 1.465 kW (3.23%). The obtained results are consistent with those reported in the literature [38,40,54].

### 4.4. Results of advanced exergy analysis

To perform advanced exergy analysis and also to calculate the first and second level splittings of exergy destruction, the specification of unavoidable exergy destruction rates in system components is a fundamental issue.

#### 4.4.1. Unavoidable conditions

There is a lack of information in literature for the best possible conditions achievable for solid oxide fuel cells. This conditions, referred to as “unavoidable conditions” is determined in the present work by means of a parametric study. Through the parameter study the optimal values of such parameters as TPB length, porosity, tortuosity, electrodes and electrolyte thickness and activation energy resulted in the highest exergy efficiency (unavoidable conditions) are determined.

Fig. 3a and b shows the effects of current density on the fuel cell performance i.e., the cell voltage, output power, energy and exergy efficiencies as well as the exergy destruction of stack and total system for different values of TPB length. As seen from Fig. 3, an increase in the TPB length, enhances the net produced power, energy and exergy efficiencies and reduces the exergy destruction and the maximum power density occurs at a current density of about 5000 A/m². However, the voltage values less than 0.6 V is not very meaningful for the SOFCs, because of incipient degradation issues.

The variations in LTPB is in fact occur because of the changes in grain size, electronic and ionic volumetric ratio (φel and φion) as well as the porosity. Fig. 4a depicts the effects of LTPB of the grain size for φel = 0.5 and different ion to electron diameter ratios (B). A reduction in grain size leads to an increase in the LTPB and a reduction in the mass transfer rate. This brings about a reduced value of activation overvoltage (Fig. 3c). It is observed that the maximum power density occurs at a current density of about 5000 Am⁻². However, the voltage values less than 0.6 V is not very meaningful for the SOFCs, because of incipient degradation issues.

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smaller compared to electron conductivity; thus an increase in the volumetric ionic ratio i.e. a decrease in $\phi_\epsilon$ leads to a reduced value of ohmic polarization and consequently, a better fuel cell performance.

The $L_{TPB}$ is also, influenced by the electrode porosity so that a decrease in porosity brings about a higher solid volume in a given electrode and this results in a higher $L_{TPB}$. The reduction in porosity however, leads to a decrease in the mass transfer rate by a smaller compared to electron conductivity; thus an increase in the volumetric ionic ratio i.e. a decrease in $\phi_\epsilon$ leads to a reduced value of ohmic polarization and consequently, a better fuel cell performance.

The increase of concentration overvoltage brings about an adverse effect on the cell performance. Referring to Fig. 7b, the limiting exchange current density is reduced because of a reduction in the reactant concentration at the $L_{TPB}$ with an increase in the tortuosity.

Table 3
Validation for the model developed in the present work using the experimental and theoretical data reported in literature.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental data [37,54]</th>
<th>Thermodynamics model [38]</th>
<th>Data obtained in present work</th>
<th>Relative difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell voltage (V)</td>
<td>0.682</td>
<td>0.678</td>
<td>0.6785</td>
<td>0.07</td>
</tr>
<tr>
<td>Gross DC power (kW)</td>
<td>118</td>
<td>117.2</td>
<td>117.3</td>
<td>0.09</td>
</tr>
<tr>
<td>Pre-reformer outlet temperature (°C)</td>
<td>550</td>
<td>550.5</td>
<td>551</td>
<td>0.09</td>
</tr>
<tr>
<td>Module exhaust gas temperature (°C)</td>
<td>847</td>
<td>846.5</td>
<td>847</td>
<td>0.06</td>
</tr>
<tr>
<td>Gross DC electrical efficiency (%)</td>
<td>53.25</td>
<td>55.4</td>
<td>55.5</td>
<td>0.18</td>
</tr>
<tr>
<td>Gross AC electrical efficiency (%)</td>
<td>50</td>
<td>51.3</td>
<td>51.37</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 4
Thermodynamic properties and mass flow rates at different state points of the SOFC system, under real conditions.

<table>
<thead>
<tr>
<th>$P$ (bar)</th>
<th>$T$ (°C)</th>
<th>$m$ (kg/s)</th>
<th>$n$ (k mole)</th>
<th>$\dot{V}$ (kg/kmole)</th>
<th>$E_{\phi k}$ (kJ/s)</th>
<th>$E_{\phi e}$ (kJ/s)</th>
<th>$E$ (kJ/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1</td>
<td>400.2</td>
<td>0.004247</td>
<td>0.000265</td>
<td>–7520</td>
<td>1.759</td>
<td>220.2</td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
<td>804</td>
<td>0.03448</td>
<td>0.001557</td>
<td>–78865</td>
<td>27.08</td>
<td>294.5</td>
</tr>
<tr>
<td>3</td>
<td>1.089</td>
<td>550.8</td>
<td>0.03448</td>
<td>0.00175</td>
<td>–159079</td>
<td>15.19</td>
<td>304.9</td>
</tr>
<tr>
<td>4</td>
<td>1.067</td>
<td>930</td>
<td>0.04882</td>
<td>0.002086</td>
<td>–203770</td>
<td>41.66</td>
<td>122.8</td>
</tr>
<tr>
<td>5</td>
<td>1.067</td>
<td>930</td>
<td>0.01859</td>
<td>0.000794</td>
<td>–203770</td>
<td>15.86</td>
<td>46.76</td>
</tr>
<tr>
<td>6</td>
<td>1.056</td>
<td>780</td>
<td>0.03024</td>
<td>0.001292</td>
<td>–23497</td>
<td>25.77</td>
<td>76.07</td>
</tr>
<tr>
<td>7</td>
<td>1.078</td>
<td>780</td>
<td>0.03724</td>
<td>0.001686</td>
<td>23978</td>
<td>128.7</td>
<td>130.1</td>
</tr>
<tr>
<td>8</td>
<td>1.056</td>
<td>898</td>
<td>0.2948</td>
<td>0.01018</td>
<td>27387</td>
<td>151.8</td>
<td>141.6</td>
</tr>
<tr>
<td>9</td>
<td>1.025</td>
<td>1012</td>
<td>0.3134</td>
<td>0.01089</td>
<td>10735</td>
<td>198.9</td>
<td>343.5</td>
</tr>
<tr>
<td>10</td>
<td>1.025</td>
<td>847</td>
<td>0.3134</td>
<td>0.01089</td>
<td>4959</td>
<td>151.6</td>
<td>343.5</td>
</tr>
<tr>
<td>11</td>
<td>1.1</td>
<td>600.2</td>
<td>0.3078</td>
<td>0.01063</td>
<td>17577</td>
<td>85.87</td>
<td>1365</td>
</tr>
</tbody>
</table>

Table 5
Results obtained from conventional exergy analyses for the SOFC system, under real conditions.

<table>
<thead>
<tr>
<th>Component</th>
<th>$E_{\phi k}$ (kJ/W)</th>
<th>$E_{\phi e}$ (kJ/W)</th>
<th>$E_{\phi k}$ (kJ/W)</th>
<th>$E_{\phi e}$ (%)</th>
<th>$E_{\phi k}$ (%)</th>
<th>$E_{\phi e}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture</td>
<td>323.8</td>
<td>321.6</td>
<td>2.212</td>
<td>4.878</td>
<td>0.7156</td>
<td>99.32</td>
</tr>
<tr>
<td>Pre-reformer</td>
<td>321.6</td>
<td>320.1</td>
<td>1.465</td>
<td>3.229</td>
<td>0.4737</td>
<td>99.54</td>
</tr>
<tr>
<td>Stack</td>
<td>132.4</td>
<td>117.6</td>
<td>14.83</td>
<td>3.149</td>
<td>8.88</td>
<td>100</td>
</tr>
<tr>
<td>Inverter</td>
<td>171.6</td>
<td>108.8</td>
<td>8.82</td>
<td>19.45</td>
<td>2.853</td>
<td>92.5</td>
</tr>
<tr>
<td>AFTERBURNER</td>
<td>215.9</td>
<td>202.3</td>
<td>13.59</td>
<td>29.96</td>
<td>4.396</td>
<td>93.7</td>
</tr>
<tr>
<td>H.E.</td>
<td>47.3</td>
<td>42.86</td>
<td>4.437</td>
<td>9.783</td>
<td>1.435</td>
<td>90.62</td>
</tr>
<tr>
<td>Overall</td>
<td>309.13</td>
<td>108.6</td>
<td>45.354</td>
<td>100</td>
<td>14.67</td>
<td>35.13</td>
</tr>
</tbody>
</table>

$\eta_{fl} = 51.37\%$, $W_{net} = 108.6$ kW
temperatures [11,59].

Fig. 11 shows the variations of cell voltage and output power with current density for several values of anode and cathode activation energies and pre-exponential factors. These values are selected from Refs. [60–63]. Referring to Fig. 11 the results obtained for $E_{act,an} = 140$ (kJ mol$^{-1}$), $E_{act,ca} = 137$ (kJ mol$^{-1}$), $\gamma_{an} = 6.54 \times 10^{11}$ (A/m$^2$) and $\gamma_{ca} = 2.35 \times 10^{11}$ (A/m$^2$) show the best performance for SOFC.

As Figs. 3 and 7 - 11 suggest, for having the best possible performance, the $L_{TPB}$ should have the highest practical value, $L_{TPB} = 2.4$ (μm/μm$^3$) for $B = 2$; the tortuosity and the thickness of anode, cathode as well as electrolyte should have minimum practical value, $\varepsilon = 2$, $d_{an} = 400$ (μm), $d_{ca} = 100$ (μm), $d_{el} = 35$ (μm). However, referring to Fig. 6, there is an optimum value for porosity, $\varepsilon = 0.3$, at which the produced power and consequently...
the exergy efficiency are maximized. Therefore, the optimum value of porosity together with the practical maximum and minimum values of mentioned parameters bring about the unavoidable conditions.

By determining the best possible values of electrochemical parameters, the unavoidable conditions for system performance is specified. Table 6 shows some thermodynamic properties and mass flow rates at all the state points of the system under the unavoidable conditions. Under these conditions the results of exergy analysis are outlined in Table 7. Referring to Table 7, the energy and exergy efficiencies and also the output power are increased by about 25%, 32% and 25%, respectively compared to the real conditions. Table 7 also indicates that the exergy destruction under the unavoidable conditions is 38% less than that under the real conditions.

To accomplish the advanced exergy analysis, the output power (the product of the overall system) should be kept constant, as it is achieved under the real conditions. Table 8 indicate the unavoidable exergy destruction rates when the product of the overall system remains constant, $E_{PT} = 108.6 \, \text{kW}$. 

4.4.2. First and second level splittings of exergy destruction

The first level splitting of exergy destruction in a component including the unavoidable/avoidable and endogenous/exogenous and also the second level splitting including the unavoidable endogenous, unavoidable exogenous, avoidable endogenous and avoidable exogenous parts are shown in Table 9. For all the system components, the exergy destruction and the first as well as the second level splitting parts are presented in Figs. 12 and 13, for more clarification.

Considering the data in Table 8, the inverter with $E_D^{EN} = 8.82 \, \text{kW}$, the afterburner with $E_D^{EN} = 8.01 \, \text{kW}$ and the stack with $E_D^{EN} = 7.27 \, \text{kW}$ have the first, second and third highest contribution on the total endogenous exergy destruction rate in the

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**Fig. 6.** The effects of porosity on (a) the activation and concentration overvoltages and (b) the cell voltage.

**Fig. 7.** The effects of tortuosity on (a) the cell performance, (b) the overvoltages and (c) the exergy destruction of system.
Referring to Table 8, the $E_D^{EX}$ for heat exchanger is 2.84 kW which is 63.8% of the total exergy destruction in this component. This indicates that the major part of exergy destruction in this component is originated from the irreversibilities occurring in the other components.

The value of exogenous exergy destruction in the stack is $E_{EN}^{EN}$ = 7.56 kW, which is 51% of the total value in this component. Therefore, in order to improve the stack performance enhancements in both the stack and other components are necessary.

The $E_D^{EN}$ in mixer, inverter, pre-reformer and afterburner is however, more than the $E_D^{EX}$. For all the components except the stack and inverter, the $E_D^{EN}$ is higher than the $E_D^{EX}$ i.e. not much improvement can be made for these components. All the avoidable part in exergy destruction for mixer is associated with external sources.

For all the components, the unavoidable endogenous part of exergy destruction, $E_D^{UN, EN}$, is higher than the avoidable...
endogenous part, $E_{AV, EN}$. One of the important parameters for optimizing the system performance is the avoidable endogenous exergy destruction in the components. Considering the values of this parameter for the inverter, $E_{AV, EN} = 6.52$ kW, for the stack, $3.6$ kW and for the afterburner, $E_{AV, EN} = 0.62$ kW, these components have the highest improvement potentials, respectively (see Table 8). As shown in Table 8, the avoidable endogenous exergy destruction, $E_{AV, EN}$ for heat exchanger is negative. This indicates that the exergy destruction is decreased with a reduction in the heat exchanger effectiveness. This occurs as an increase in the effectiveness causes both the fuel and product exergies of heat exchanger increase in a way that the difference between the two i.e., the exergy destruction in this component increase. Also, the highest and second highest avoidable exogenous exergy destruction rates occur in the stack and the afterburner, respectively. From 10.34 kW avoidable exergy destruction of the stack, 6.74 kW (65.2%) is exogenous and also, from 5.1 kW avoidable exergy destruction in the afterburner, 4.48 kW (87.8%) is exogenous. This means that the stack and the afterburner performances are highly influenced by the performance of other system components. The avoidable and unavoidable exergy destructions for the major components of the SOFC system are represented in Fig. 14 for more clarification.

Fig. 15 shows the first and second level splittings of exergy destruction rate for the overall system. Referring to Fig. 15, from the total exergy destruction, 38% occurs exogenously and 62% takes place endogenously. Also 54% of the total exergy destruction is avoidable from which 31% of the total happens exogenously and 23% of the total occurs endogenously. This means that only 54% of total exergy destruction can be reduced. Similarly, 46% of the total exergy destruction is unavoidable from which 39% of the total is endogenous part and 7% of the total is exogenous part.

Fig. 15 also indicates that the total avoidable exergy destruction rate in the overall system is greater than the total unavoidable part. Therefore, the cycle has a good potential for efficiency improvement.

5. Conclusion

Advanced and conventional exergy analysis are performed for an SOFC system with anode gas recirculation. To accomplish the former, the impacts of electrochemical parameters on the system performance is studied so that the best possible operating conditions (unavoidable conditions) are obtained. The real improvement potential are determined by advanced exergy analysis and different orders of component enhancement are found from the advanced and conventional exergy analysis. The following conclusions can be made from the obtained results:

- It is observed that, the energy and exergy efficiencies as well as the output power could be higher than the corresponding values obtained under the real conditions, by up to 25%, 32% and 25%, respectively.
- It is also revealed that the exergy destruction under the unavoidable conditions could be 38% lower than the corresponding value under real conditions.
- Based on the results of advanced exergy analysis, the order of components for higher avoidable endogenous exergy destruction is: the inverter, the stack and the afterburner. This order becomes: the stack, the afterburner and the inverter when the results of conventional exergy analysis is considered.
- Relying on the conventional exergy analysis can be misleading.
- The highest exogenous exergy destruction rate is calculated for the stack. This indicates that the stack performance is strongly dependent on the other system components.
Table 6
Thermodynamic properties and mass flow rates at different state points of the SOFC system under unavoidable conditions.

<table>
<thead>
<tr>
<th>P (bar)</th>
<th>T (°C)</th>
<th>m (kg/s)</th>
<th>n (kmole/s)</th>
<th>$E_{DP}$ (kJ/s)</th>
<th>$E_{EP}$ (kJ/s)</th>
<th>$E_{EN}$ (kJ/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1</td>
<td>400</td>
<td>0.004247</td>
<td>0.000265</td>
<td>57308</td>
<td>1759</td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
<td>804</td>
<td>0.03444</td>
<td>0.001557</td>
<td>178865</td>
<td>270.8</td>
</tr>
<tr>
<td>3</td>
<td>1.095</td>
<td>551</td>
<td>0.03448</td>
<td>0.00175</td>
<td>159093</td>
<td>15.22</td>
</tr>
<tr>
<td>4</td>
<td>1.084</td>
<td>930</td>
<td>0.04882</td>
<td>0.002086</td>
<td>203770</td>
<td>41.74</td>
</tr>
<tr>
<td>5</td>
<td>1.084</td>
<td>930</td>
<td>0.01835</td>
<td>0.000794</td>
<td>203770</td>
<td>15.89</td>
</tr>
<tr>
<td>6</td>
<td>1.084</td>
<td>930</td>
<td>0.03024</td>
<td>0.001292</td>
<td>203770</td>
<td>25.85</td>
</tr>
<tr>
<td>7</td>
<td>1.089</td>
<td>920</td>
<td>0.2014</td>
<td>0.006953</td>
<td>28190</td>
<td>108.4</td>
</tr>
<tr>
<td>8</td>
<td>1.078</td>
<td>975</td>
<td>0.1884</td>
<td>0.006505</td>
<td>29996</td>
<td>110.2</td>
</tr>
<tr>
<td>9</td>
<td>1.067</td>
<td>1133</td>
<td>0.207</td>
<td>0.007217</td>
<td>4611</td>
<td>158.6</td>
</tr>
<tr>
<td>10</td>
<td>1.067</td>
<td>847</td>
<td>0.207</td>
<td>0.007217</td>
<td>5612</td>
<td>102.3</td>
</tr>
<tr>
<td>11</td>
<td>1.1</td>
<td>600</td>
<td>0.2014</td>
<td>0.006953</td>
<td>17577</td>
<td>56.18</td>
</tr>
</tbody>
</table>

Table 7
Results of exergy analyses of the system under unavoidable conditions.

<table>
<thead>
<tr>
<th>Component</th>
<th>$E_{DP}$ (kW)</th>
<th>$E_{EP}$ (kW)</th>
<th>$E_{EN}$ (kW)</th>
<th>$y_1$ (%)</th>
<th>$y_2$ (%)</th>
<th>$e_1$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture</td>
<td>323.8</td>
<td>321.6</td>
<td>2.29</td>
<td>8.13</td>
<td>0.82</td>
<td>99.29</td>
</tr>
<tr>
<td>Pre-reformer</td>
<td>321.6</td>
<td>320.1</td>
<td>1.44</td>
<td>5.11</td>
<td>0.52</td>
<td>99.55</td>
</tr>
<tr>
<td>Stack</td>
<td>153.6</td>
<td>147.5</td>
<td>6.06</td>
<td>21.47</td>
<td>2.17</td>
<td>96.09</td>
</tr>
<tr>
<td>inverter</td>
<td>147.5</td>
<td>144.6</td>
<td>2.95</td>
<td>10.46</td>
<td>1.06</td>
<td>98</td>
</tr>
<tr>
<td>After Burner</td>
<td>173.8</td>
<td>162.5</td>
<td>11.34</td>
<td>40.18</td>
<td>4.06</td>
<td>93.48</td>
</tr>
<tr>
<td>H.E.</td>
<td>56.31</td>
<td>52.18</td>
<td>4.14</td>
<td>14.66</td>
<td>1.48</td>
<td>92.66</td>
</tr>
<tr>
<td>Overall</td>
<td>278.98</td>
<td>244.6</td>
<td>28.22</td>
<td>100</td>
<td>10.12</td>
<td>51.82</td>
</tr>
</tbody>
</table>

-$\Delta{P}_{\text{min}} = 1\%$ $\eta_{\text{m}, \text{max}} = 99\%$ $T_{\text{C}} = 920$ °C $\eta_{\text{m}} = 68.1\%$ $\eta_{\text{energy}} = 51.98\%$ $W_{\text{net}} = 144.6$ kW

Table 8
Results of exergy analyses under unavoidable conditions, for $W_{\text{net}} = 108.6$ kW obtained under real conditions.

<table>
<thead>
<tr>
<th>Component</th>
<th>$E_{DP}$ (kW)</th>
<th>$E_{EP}$ (kW)</th>
<th>$E_{EN}$ (kW)</th>
<th>$y_1$ (%)</th>
<th>$y_2$ (%)</th>
<th>$e_1$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture</td>
<td>242.77</td>
<td>241.05</td>
<td>1.72</td>
<td>8.16</td>
<td>0.82</td>
<td>99.29</td>
</tr>
<tr>
<td>Pre-reformer</td>
<td>241.05</td>
<td>239.97</td>
<td>1.082</td>
<td>5.13</td>
<td>0.52</td>
<td>99.55</td>
</tr>
<tr>
<td>Stack</td>
<td>115.31</td>
<td>110.82</td>
<td>4.49</td>
<td>21.30</td>
<td>2.15</td>
<td>96.11</td>
</tr>
<tr>
<td>inverter</td>
<td>110.82</td>
<td>108.6</td>
<td>2.216</td>
<td>10.51</td>
<td>1.06</td>
<td>98</td>
</tr>
<tr>
<td>After Burner</td>
<td>129.74</td>
<td>121.24</td>
<td>8.492</td>
<td>40.28</td>
<td>4.06</td>
<td>93.45</td>
</tr>
<tr>
<td>H.E.</td>
<td>41.99</td>
<td>38.9</td>
<td>3.084</td>
<td>14.63</td>
<td>1.48</td>
<td>92.66</td>
</tr>
<tr>
<td>Overall</td>
<td>208.94</td>
<td>198.6</td>
<td>21.084</td>
<td>100</td>
<td>10.10</td>
<td>51.98</td>
</tr>
</tbody>
</table>

-$\Delta{P}_{\text{min}} = 1\%$ $\eta_{\text{m}, \text{max}} = 99\%$ $T_{\text{C}} = 920$ °C $\eta_{\text{m}} = 68.2\%$ $\eta_{\text{energy}} = 51.98\%$ $W_{\text{net}} = 108.6$ kW

- The avoidable part of the exergy destruction in the stack is significantly more than the unavoidable part. Therefore, more attention should be paid on the other system components to reduce the exergy destruction in this component.

Table 9
First and second level splittings of exergy destruction (kW) obtained from the advanced exergy analyses for SOFC system with anode recirculation.

<table>
<thead>
<tr>
<th>Component</th>
<th>$E_{DP}$</th>
<th>$E_{EN}$</th>
<th>$E_{EX}$</th>
<th>$E_{AV}$</th>
<th>$E_{EN}$</th>
<th>$E_{AV}$</th>
<th>$E_{DP}$</th>
<th>$E_{EN}$</th>
<th>$E_{AV}$</th>
<th>$E_{DP}$</th>
<th>$E_{EN}$</th>
<th>$E_{AV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixer</td>
<td>2.21</td>
<td>1.53</td>
<td>0.68</td>
<td>0.49</td>
<td>1.72</td>
<td>1.35</td>
<td>0.09</td>
<td>0.00</td>
<td>0.49</td>
<td>2.21</td>
<td>1.53</td>
<td>0.09</td>
</tr>
<tr>
<td>Pre-reformer</td>
<td>1.47</td>
<td>0.88</td>
<td>0.59</td>
<td>0.38</td>
<td>1.082</td>
<td>0.88</td>
<td>0.20</td>
<td>0.00</td>
<td>0.4</td>
<td>1.47</td>
<td>0.88</td>
<td>0.59</td>
</tr>
<tr>
<td>Stack</td>
<td>14.83</td>
<td>7.27</td>
<td>7.56</td>
<td>10.34</td>
<td>4.49</td>
<td>3.67</td>
<td>0.82</td>
<td>3.60</td>
<td>6.74</td>
<td>14.83</td>
<td>7.27</td>
<td>7.56</td>
</tr>
<tr>
<td>inverter</td>
<td>8.82</td>
<td>8.82</td>
<td>6.00</td>
<td>6.60</td>
<td>2.216</td>
<td>2.30</td>
<td>0.00</td>
<td>6.52</td>
<td>0.06</td>
<td>8.82</td>
<td>8.82</td>
<td>6.00</td>
</tr>
<tr>
<td>After Burner</td>
<td>13.59</td>
<td>8.01</td>
<td>5.58</td>
<td>5.10</td>
<td>8.492</td>
<td>7.39</td>
<td>1.10</td>
<td>0.62</td>
<td>4.48</td>
<td>13.59</td>
<td>8.01</td>
<td>5.58</td>
</tr>
<tr>
<td>H.E.</td>
<td>4.45</td>
<td>1.61</td>
<td>2.84</td>
<td>1.36</td>
<td>3.084</td>
<td>2.14</td>
<td>0.94</td>
<td>-0.53</td>
<td>1.89</td>
<td>4.45</td>
<td>1.61</td>
<td>2.84</td>
</tr>
<tr>
<td>Overall</td>
<td>45.37</td>
<td>28.12</td>
<td>17.25</td>
<td>24.28</td>
<td>21.08</td>
<td>17.91</td>
<td>3.26</td>
<td>10.21</td>
<td>13.99</td>
<td>45.37</td>
<td>28.12</td>
<td>17.25</td>
</tr>
</tbody>
</table>
Fig. 14. The system components with highest avoidable exergy destruction.
Appendix A

The parameters involved in calculating $L_{TPB}$ are defined as follows [11,44]:

$$d_c = \sin(\theta/2) \cdot \min(d_{io}, d_{el})$$

$$Z_{el} = 3 + \frac{(Z - 3)}{n_{el} + (1 - n_{el})B^2}$$

$$Z_{io} = 3 + \frac{(Z - 3)B^2}{n_{el} + (1 - n_{el})B^2}$$

$$n_{el} = \frac{\beta^3 \phi_{el}}{1 - \phi_{el} + \beta^3 \phi_{el}}$$

$$n_{io} = 1 - n_{el}$$

$$P_1 = \left[ 1 - \left( \frac{4.236 - Z_{io}}{2.472} \right)^{2.5} \right]^{0.4}$$

$$N_i = \frac{1 - e}{(\pi/6)d_{el}^3(n_{el} + (1 - n_{el})B^3)}$$

### Nomenclature

- $A_a$ active surface area
- $B$ diameter ratio of ions to electrons
- $d_c$ neck diameter of the TPB
- $e$ specific exergy
- $E_{act}$ activation energy
- $E$ exergy
- $F$ Faraday’s constant
- $G$ Gibbs free energy
- $H$ specific enthalpy
- $i$ current density
- $K$ equilibrium constant
- $L_{TPB}$ three phase boundary length
- $n$ number fraction
- $N_c$ number of cells
- $N_t$ number density of all particles
- $n_i$ molar flow rate
- $P$ pressure/percolation probability
- $P_{ref}$ ambient pressure
- $\phi_{el}$ the volumetric ratio of electrons
- $R$ universal gas constant
- $U_a$ air utilization factor
- $U_f$ fuel utilization factor
- $V_{act}$ activation overvoltage
- $V_c$ produced cell voltage
- $V_{cons}$ concentration overvoltage
- $V_{loss}$ voltage loss
- $V_{N}$ Nernst cell voltage
- $V_{Ohm}$ ohmic overvoltage
- $W_{FC}$ fuel cell output power
- $W_{net}$ net output power
- $x$ molar fraction
- $x_{ch}$ molar flow rates of consumed methane
- $y, y^*$ exergy destruction ratio
- $y_{ch}$ molar flow rates of consumed carbon monoxide
- $Z$ coordination number
- $\dot{z}$ molar flow rate of reacted hydrogen
- $\gamma$ pre-exponential coefficient
- $\epsilon$ porosity
- $\epsilon_k$ kth exergy efficiency
- $\eta_{ex}$ exergy efficiency
- $\eta_{eh}$ energy efficiency
- $\theta$ contact angle,
- $\tau$ tortuosity

### Subscript

- $a$ anode
- $c$ cathode
- $ch$ chemical
- $D$ destruction

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Fig. 15. First and second level splittings of exergy destruction rate of the overall system.


