Exergetic sustainability indicators of a polymer electrolyte membrane fuel cell at variable operating conditions

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Abstract Based on the exergetic sustainability indicators of polymer electrolyte membrane (PEM) fuel cell, this paper studied the effects of ir-reversibility of thermodynamics on some exergetic sustainability indicators of PEM fuel cell under changing operating temperature, operating pressure and current density. Some conclusions are drawn by analyzing the curves. As the operating temperature increases, the negative impact of PEM fuel cell on various parameters due to irreversibility decreases; As the operating pressure increases, the negative impact of PEM fuel cell on various param-eters due to irreversibility decreases; On the other hand, with the increase of current density, the negative impact of the PEM fuel cell on various pa-rameters due to irreversibility increases.

Keywords: PEM fuel cell; Exergy balance; Exergy analysis; Exergetic sustainability indicators

Nomenclature

C_{ed}	–	environmental destruction coefficient
C_p	–	specific heat

Ex – total exergy
ESI – exergetic sustainability index
e^- – electrons
ex – exergy
ex_n^{ch} – chemical exergy of *n*th component
f_{est} – exergy stability factor
f_{exd} – exergy destruction factor
H^+ – hydrogen ions
h – enthalpy
i – current density
k – specific heat rate
n – molar flow rate
P – partial pressure
R – gas constant
r – waste exergy ratio
r_{hl} – heat loss rate
s – entropy
T – temperature
T_{fc} – working temperature of fuel cell
t_{mem} – thickness of the proton membrane
W_{fc} – output work of fuel cell
V_{act} – activation overpotential
V_{ohm} – ohmic overpotential
V_{conc} – concentration overpotential
$V(i)$ – net voltage output at *i* current density

Greek symbols

λ_A, λ_B – positive and negative charge transfer coefficients
η – exergy efficiency
θ_{edi} – environmental destruction index (EDI)
θ – environmental benign index

Subscripts and superscripts

0 – dead (standard) state
ch – chemical
d – destruction
fc – fuel cell
H_2 – hydrogen
H_2O – water
in – input
O_2 – oxygen
out – output
ph – physical
rw – reusable waste
uw – unusable waste
w – waste exergy
we – waste exergy
x_n – mole fraction of the *n*th component

1 Introduction

With the continuous use of fossil energy, energy reserves are excessively consumed, and environmental problems are becoming more and more seri-ous. New energy utilization technologies will be continuously developed and utilized. Fuel cell is a new energy with great potential. The efficiency of ther-moelectric connection can reach more than 95%. At the same time, it has the advantages of noiseless, environmental protection, high reliability and easy maintenance. It is considered to be the most promising new generation technology in modern times. The polymer electrolyte membrane (PEM) fuel cell is hydrogen fuel cell that directly converts hydrogen and oxygen into electrical energy, water, and waste heat, without generating harmful gases emitted by conventional internal combustion engines. In general, PEM fuel cells have the advantages of compact structure, low operating temperature, fast startup speed, long working life and zero pollution.

However, the thermodynamic irreversibility that occurs during operation of the battery affects the performance of the PEM fuel cell. Reducing the thermodynamic irreversibility is crucial to improve the operating efficiency of the battery and optimize the performance of PEM fuel cell, so it is necessary to study the thermodynamic irreversibility in PEM fuel cell system. The exergy analysis by the second law of thermodynamics is an important method to study the irreversible exergetic performance of the PEM fuel cell. By reading some related papers, some research has been done on the exergy analysis in PEM fuel cell system. Among them, Cengel and Bole proposed that exergy is the potential to convert a given energy into useful work under certain conditions, so the exergy analysis based on the second law of thermodynamics and the energy analysis based on the first law of thermodynamics are equally important [1]; Dincer studied the technology, environmental protection, and exergy aspects of hydrogen en-ergy systems, emphasizing the importance of exergy analysis [2]; Kazim studied the exergy analysis of PEM fuel cell units under varying operating conditions [3]; Dincer *et al.* [4] studied the economic analysis of PEM fuel cell system for vehicles, and proposed that the operating temperature and pressure have an impact on the efficiency of the system; Barelli *et al.* [5] studied the energy and exergy analysis of PEM fuel cell based on combined heat and power system.

Before Midilli proposed the exergetic sustainability index (ESI) of PEM fuel cells [6], most of the evaluation indexes of PEM fuel cells based on exergy analysis are exergy efficiency. In recent years, there have been some studies on exergy efficiency. For example, Ay *et al.* [7] studied the change in exergy efficiency under varying operating conditions; Hanapi *et al.* [8] studied the change in exergy efficiency of a 1 kW open cathode fuel cell under varying operating pressures and temperatures. This is because improving efficiency can reduce environmental impacts and resource consumption, and exergy analysis can improve efficiency, thereby improving sustainability [9]. Taking into account the exergy and sustainability aspects of PEM fuel cell, a parameter for evaluating PEM fuel cell emerges, *i.e.* ESI [6]. In terms of the second law of thermodynamics, ESI is an important parameter for PEM fuel cell based on the sustainability of exergy. Defining the ESI for PEM fuel cell should take into account the environmental benign index and the exergetic stability factor. In mathematical expression, ESI of the PEM fuel cell is the product of the environmental benign index and the exergetic stability factor. In terms of publicly published researches, there are not many studies on the exergetic sustainability indicators in PEM fuel cells, but there are many studies in other fields. Among them Midilli *et al*. [10] studied some of the exergetic sustainability indicators of PEM fuel cell's high-pressure hydrogen production and storage system. In other areas, Tayfun *et al.* [11] analyzed the quantum irreversible Otto cycle through the ESI. Balli *et al.* [12] studied the ESI for irreversible Carnot refrigerators. These studies point out that due to increasing attention to environmental and sustainability issues, ESI should be used as a basic thermodynamic parameter.

Exergy analysis can help to improve efficiency and reduce heat losses. Increased exergy efficiency can reduce the impact on the environment [13]. The sustainability of PEM fuel cell based on exergy requires not only the sustainable use of hydrogen, but also the efficient use of hydrogen [14]. Therefore, the exergy analysis method of improving efficiency is crucial. The high utilization of hydrogen is beneficial to the sustainability of ex-ergy. Even if hydrogen energy eventually becomes cheap and widely used, improving efficiency is likely to remain one of the key aspects. Based on the above-mentioned related literature, it can be seen that Midilli et al.

[6] only proposing the ESI conception of PEM fuel cell, but did not study it in depth. Therefore, this paper will study some exergetic sustainability indicators of PEM fuel cell under changing operating parameters, and explore the effects of different operating temperatures, pressures and current densities on the exergetic sustainability indicators. Based on the second law of thermodynamics, the exergy analysis of the PEM fuel cell operation process is carried out to study the effect of operating parameters on the

ESI, in order to improve the efficiency, sustainability and environmental impact of the PEM fuel cell.

2 Mathematical and physical models

2.1 Polymer electrolyte membrane fuel cell model

A PEM fuel cell is a type of fuel cell and is essentially an inverse device for water electrolysis. In the process of electrolyzing water, water is electrolyzed by an external power source to generate hydrogen and oxygen; in a fuel cell, hydrogen and oxygen should generate electricity by electrochemistry and release electrical energy. The PEM fuel cell consists mainly of four parts, namely anode, cathode, electrolyte, and the external circuit. The anode is a hydrogen electrode and the cathode is an oxygen electrode. Between the two poles is the electrolyte, and the electrolyte is the proton exchange membrane. The reaction principle is as follows:

The anode and the cathode supply hydrogen and oxygen, and the hydrogen atoms entering the porous anode are ionized into hydrogen ions (H^+) and electrons (e^-) under the action of the catalyst; the hydrogen ions are transferred to the cathode *via* the electrolyte, and the electrons are flowed to the cathode through the external circuit; the hydrogen ions com-bine with the oxygen atoms to form water molecule. The electrochemical reaction formula is:

anode reaction: $$H_2 \rightarrow 2H^+ + 2e^- , \tag{1}$$

cathodic reaction: $$2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow H_2O + \text{heat} , \tag{2}$$

total response: $$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{heat} + \text{electricity} . \tag{3}$$

It can be seen from the total reaction formula that the PEM fuel cell generates only water while generating electricity and no pollutant gas is discharged. Since the proton exchange membrane can only conduct protons, hydrogen protons can pass directly through the proton exchange membrane to the cathode, and electrons can only reach the cathode through an external circuit. Direct current is generated when electrons flow through the external circuit to the cathode. The theoretical upper limit of the power generation voltage per fuel cell unit is 1.22 V [15]. The output voltage is dependent on the output current density when connected to a load typically from 0.5 to 1 V. Combining multiple cells can form a battery stack with an output voltage that meets the actual load requirements [16].

In order to perform exergy analysis and to study changes in exergetic sustainability indicators under different operating conditions, the following assumptions for PEM fuel cell should be considered:

1. PEM fuel cell is in a stable state, hydrogen and oxygen are reactants, all gases are ideal gases.
2. The flow of reactants is stable, incompressible, and laminar.
3. The reaction product water is in the liquid phase.
4. Kinetic exergy and potential exergy are neglected.
5. The mass flow of water to humidify the oxygen and hydrogen streams is negligible, the effect of this simplification on the results of the exergy analysis is negligible because the flow rate of the humidified water is small, and its state is close to environmental conditions [17].
6. The heat loss rate (r_{hl}) is 20%. According to the literature, 20% of the total heat generated by the fuel cell is lost by convection and radiation [18].
7. Hydrogen and oxygen utilization rates are 80% and 50%, respectively [19].
8. Activation polarization, concentration polarization and ohmic polarization are all considered.

2.2 Exergy balance model

Taking into account the above assumptions, the exergy balance model of PEM fuel cell is shown in Fig. 1. Based on Fig. 1, the exergy balance of the PEM fuel cell can be written as:

Total Exergy Input = Total Exergy of Desired Output + Total Waste Exergy Output + Total Exergy Destruction,

$$Ex_{in}^{fc} = Ex_{out}^{fc} + Ex_{w,out}^{fc} + Ex_{d}^{fc}. \quad (4)$$

The total exergy input and output is

$$Ex_{in}^{fc} = Ex_{H_2,in} + Ex_{O_2,in}\,, \quad (5)$$

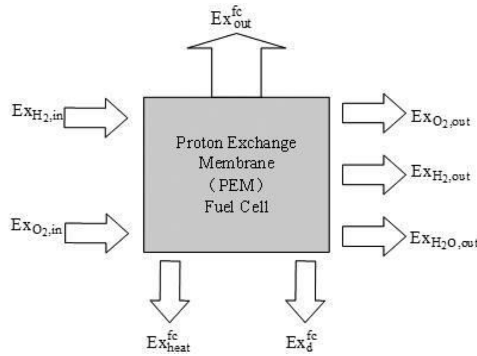

Figure 1: Exergy balance diagram of PEM fuel cell.

$$Ex^{fc}_{w,out} = Ex^{fc}_{rw} + Ex^{fc}_{uw} . \tag{6}$$

Chemical exergy of the exhaust gases of PEM fuel cell

$$Ex^{fc}_{rw} = n_{H_2,out} ex^{ch}_{H_2,out} + n_{O_2,out} ex^{ch}_{O_2,out} . \tag{7}$$

Unusable waste exergy of PEM fuel cell

$$Ex^{fc}_{uw} = n_{H_2,out} ex^{ph}_{H_2,out} + n_{O_2,out} ex^{ph}_{O_2,out} + n_{H_2O,out} ex^{ph}_{H_2O} + Q^{fc}_{w,out} \times \left(1 - \frac{T_0}{T_{fc}}\right) r_{hl} . \tag{8}$$

Total exergy of desired output is

$$Ex^{fc}_{out} = W_{fc} , \tag{9}$$

where

$$\begin{aligned} W_{fc} &= V(i)\, i = (V_{rev} - V_{act} - V_{ohm} - V_{conc})\, i \\ &= i\left[1.229 - 8.47 \times 10^{-4}(T_{fc} - 298.15) + 4.308 \times 10^{-5}\left(\ln P_{H_2} + \frac{1}{2}\ln P_{O_2}\right)\right] \\ &\quad - i\, \frac{\lambda_A + \lambda_C}{\lambda_A \lambda_C}\, 4.31 \times 10^{-5}\, T_{fc} (\ln i + 9.9) \\ &\quad - i\, t_{mem}\left[0.028 \exp\left(1268\left(\frac{1}{303} - \frac{1}{T_{fc}}\right)\right)\right]^{-1} \\ &\quad + i\, 0.085 \ln\left(1 - \frac{i}{1.4}\right) , \end{aligned} \tag{10}$$

where $V(i)$ is the net voltage output of the PEM fuel cell at i current density, V_{act} is the activation overpotential, V_{ohm} is the ohmic overpotential, and V_{conc} is the concentration overpotential, T_{fc} is the temperature at which the battery reacts, t_{mem} is the thickness of the proton membrane. P_{H_2} and P_{O_2} are the partial pressures of hydrogen and oxygen. λ_A and λ_C are the positive and negative charge transfer coefficients, which are 0.5 and 1, respectively.

According to Eq. (4), the total exergy destruction can be obtained as

$$Ex_d^{fc} = Ex_{in}^{fc} - Ex_{out}^{fc} - Ex_{w,out}^{fc} . \tag{11}$$

The exergy value of the system is equal to the product of the molar flow rate and the exergy value of the considered substance [13]

$$Ex = n \times ex . \tag{12}$$

The exergy transfer for any thermodynamic process can be seen as the sum of specific physical exergy, chemical exergy, dynamic exergy and po-tential exergy, whereas for PEM fuel cell, energy calculations only consider physical exergy and chemical exergy, whereas kinetic exergy and potential exergy can be ignored. Therefore, the total exergy of the entire electrochem-ical reaction process consists of physical exergy and chemical exergy [16]

$$ex = ex^{ph} + ex^{ch} . \tag{13}$$

The calculation of physical exergy involves different temperatures, pres-sures, and enthalpy and entropy differences at T_0 = 298 K and P_0 = 1.013×10^5 Pa. The physical exergy is expressed as follows:

$$ex^{ph} = (h - h_0) - T_0(s - s_0) , \tag{14}$$

where h_0 and s_0 are the enthalpy and entropy values at the standard state of T_0 = 298 K and P_0 = 1.013×10^5 Pa, respectively, h and s are the enthalpy and entropy values under different temperature and pressure op-erating conditions, respectively [18].

The physical exergy of an ideal gas having a constant specific heat C_p and a specific heat rate k can be expressed as

$$ex^{ph} = C_p T_0 \left(\frac{T}{T_0} - 1 - \ln\frac{T}{T_0} + \ln\left(\frac{P}{P_0}\right)^{\frac{k-1}{k}} \right) . \tag{15}$$

Chemical exergy is the maximum amount of work that can be obtained based on the substance under consideration at ambient temperature T_0 = 298 K, P_0 = 1.013 × 10^5 Pa, which can be expressed as

$$ex^{ch} = \sum x_n e^{ch}_n + RT_0 \sum x_n \ln x_n \,, \tag{16}$$

where, x_n is the mole fraction of the component under consideration, e^{ch}_n is the chemical exergy of each component, and R is the gas constant [20].

2.3 Exergetic sustainability index derivation process

In the published literature, the specific definition of exergy efficiency is not uniform. In this paper, from the definition of Midili, exergy efficiency depends on the input of effective work output and total exergy energy [10]

$$\eta_{ex}^{fc} = \frac{Ex_{out}^{fc}}{Ex_{in}^{fc}} \,. \tag{17}$$

In order to develop novel exergetic sustainability indicators, Midili defined the waste exergy including two parts, *i.e.* reusable waste exergy and unusable waste exergy which represented chemical exergy and physical ex-ergy of the exhaust gases respectively [10]. In this paper, the waste exergy ratio can be expressed as

$$r_{we}^{fc} = r_{rw}^{fc} + r_{uw}^{fc} \,, \tag{18}$$

where

$$r_{rw}^{fc} = \frac{Ex_{rw}^{fc}}{Ex_{in}^{fc}} \,, \tag{19}$$

$$r_{uw}^{fc} = \frac{Ex_{uw}^{fc}}{Ex_{in}^{fc}} \,. \tag{20}$$

For PEM fuel cells, the exergy destruction is an important parameter. The decrease in this parameter indicates an increase in the positive impact of PEM fuel cell on exergy-based sustainability. In this paper, the exergy destruction factor can be expressed as

$$f_{exd}^{fc} = \frac{Ex_{d}^{fc}}{Ex_{in}^{fc}} \,. \tag{21}$$

The reciprocal of exergy efficiency in this paper is defined as the environmental destruction coefficient, and the expression is as follows:

$$C_{ed}^{fc} = \frac{1}{\eta_{ex}^{fc}}. \tag{22}$$

The environmental destruction index (EDI) is used to evaluate the extent to which unusable waste exergy and exergy destruction affect the environ-ment. The expressions are as follows:

$$\theta_{edi}^{fc} = (r_{uw}^{fc} + f_{exd}^{fc})C_{ed}^{fc}. \tag{23}$$

From the perspective of the PEM fuel cell reaction equation, the product consists of only water, heat and electricity under the premise of reversible operation. However, in practical applications, it is observed that there is also unused hydrogen and oxygen due to irreversibility, which is the main cause of exergy destruction. Due to the above-mentioned unused hydrogen and oxygen, and the destruction of exergy, the operational stability of the PEM fuel cell is degraded. On the other hand, the main output that affects discharge stability is the power output. Therefore, the unused hydrogen and oxygen, as well as the exergy destruction are important parameters to describe the stability of PEM fuel cell, so the stability factor of PEM fuel cell is expressed as follows:

$$f_{est}^{fc} = \frac{Ex_{out}^{fc}}{Ex_{out}^{fc} + Ex_{w,out}^{H_2} + Ex_{w,out}^{O_2} + Ex_{d}^{fc}}. \tag{24}$$

The environmental benign index indicates the environmental suitability of the PEM fuel cell. To improve the environmental adaptability of the PEM fuel cell, it is necessary to reduce the environmental damage index. So in mathematical expressions, these two parameters are reciprocal

$$\theta_{ebi}^{fc} = \frac{1}{\theta_{edi}^{fc}}. \tag{25}$$

According to previous studies, ESI for PEM fuel cells is the product of the environmental benign index and the exergy stability factor in mathematical expression

$$\theta_{esi}^{fc} = \theta_{ebi}^{fc} \times f_{est}^{fc}. \tag{26}$$

3 Results and analysis

The effects of thermodynamic irreversibility on the exergetic sustainability indicators of PEM fuel cells under different operating parameters have been investigated. In the calculation, the operating temperature of PEM fuel cell is 323, 333, 343, and 353 K, the thickness of the proton exchange membrane is 1.6×10^{-4} m, the current density is $0.05–2.0\times10^{4}$ A/m^2, and the interval is 0.05×10^{-4} A/m^2. Dead state pressure is 1.013×10^{5} Pa and standard state temperature is 298.15 K. The exergetic sustainability indicators for PEM fuel cells may be affected by operating parameters including temperature, pressure, current density, reactant utilization, and gas composition. The relationships for exergy efficiency, waste exergy ratio, exergy destruction ratio, environmental destruction index and exergetic sustainability index of the PEM fuel cell with current density under variable operating temper-ature and pressure with fixed membrane thickness are presented. Finally, some exergetic sustainability indicators of PEM fuel cell are compared.

3.1 Exergy efficiency

Figures 2 and 3 are graphs showing the relationship between current density and exergy efficiency at varying battery operating pressures, temperatures, and constant membrane thickness (1.6×10^{-4} m). From a theoretical anal-ysis, the exergy efficiency of a PEM fuel cell depends on the total exergy input, cell voltage, heat loss and thermodynamic irreversibility of the PEM fuel cell. As shown in graphs, it can be clearly seen that at a constant membrane thickness, the exergy efficiency decreases as the current density increases. For example, when the operating pressure is 3.039×10^{5} Pa and the operating temperature is 323 K, the exergy efficiency drops from 0.55 to 0.275 at a change in current density from 0.05 to 2.0×10^{4} A/m^2. It is well known that under certain operating conditions, the overpotential increases with increasing current density. An increase in overpotential reduces the desired output and the net output voltage of the cell. Therefore, it leads to a decline in exergy efficiency. In addition, it is noted that the exergy efficiency increases as the cell operating temperature and pressure increase. As shown in Fig. 2, when the current density is 1×10^{4} A/m^2 and the op-erating pressure is 3.039×10^{5} Pa, the exergy efficiency rises from 0.398 to 0.423 when the operating temperature varies from 323 to 353 K. As shown in Fig. 3, the exergy efficiency rises from 0.378 to 0.397 when the operating pressure is varied from $1.013–3.039 \times 10^{5}$ Pa with a fixed current density

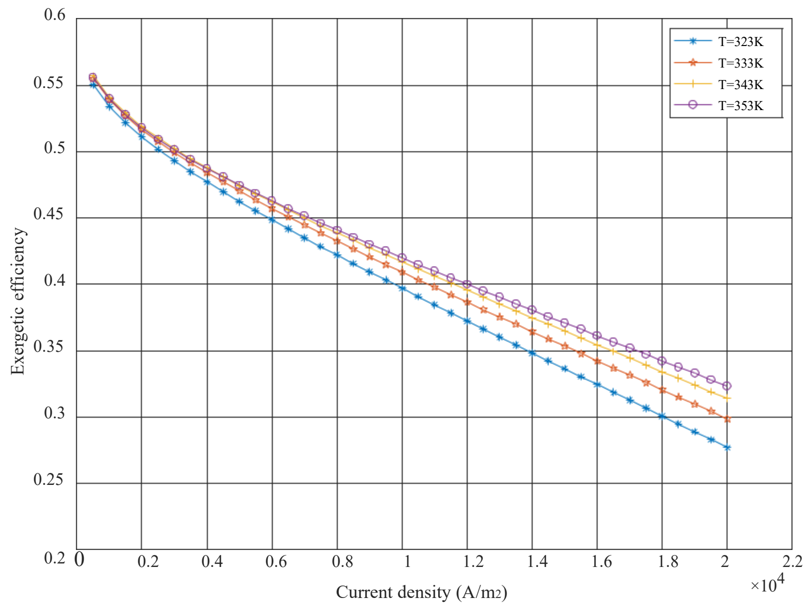

Figure 2: Variation of exergetic efficiency as a function of current density, under varying operating temperatures when the operating pressure is fixed to 3.039 × 10^5 Pa.

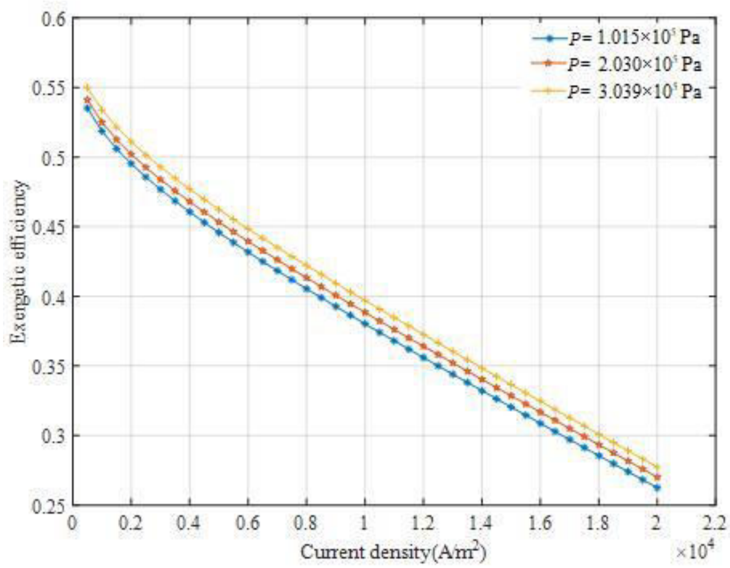

Figure 3: Variation of exergetic efficiency as a function of current density, under varying operating pressure when the operating temperature is fixed to 323 K.

1×10^4 A/m^2 and operating temperature 323 K. From the electrochemical kinetic analysis, increasing the operating temperature of the battery can increase the conductivity of the proton exchange membrane and reduce the electrochemical polarization of PEM fuel cell. As the operating pressure increases, the exergy efficiency will also increase. This can be explained in two ways. On the one hand, the increase of pressure increases the diffusion rate of the two-pole gas, thereby increasing the partial pressure of the reaction gas, improving the mass transfer of the reaction gas, and improving the reversible electromotive force of PEM fuel cell; on the other hand, the pressure is increased. It increases the concentration of the two-pole gas, reduces the degree of polarization polarization, and reduces the activation overpotential, thereby increasing the net output voltage.

3.2 Waste exergy ratio

Figures 4 and 5 show the relationship of the waste exergy ratio as a function of current density at varying temperatures, pressures, and fixed proton film thicknesses (1.6×10^{-4} m) for the operating pressure 3.039×10^5 Pa and the operating temperature 323 K, respectively. The waste exergy ratio increases from 0.428 to 0.577 at a current density of 0.05–2.0 $\times 10^4$ A/m^2.

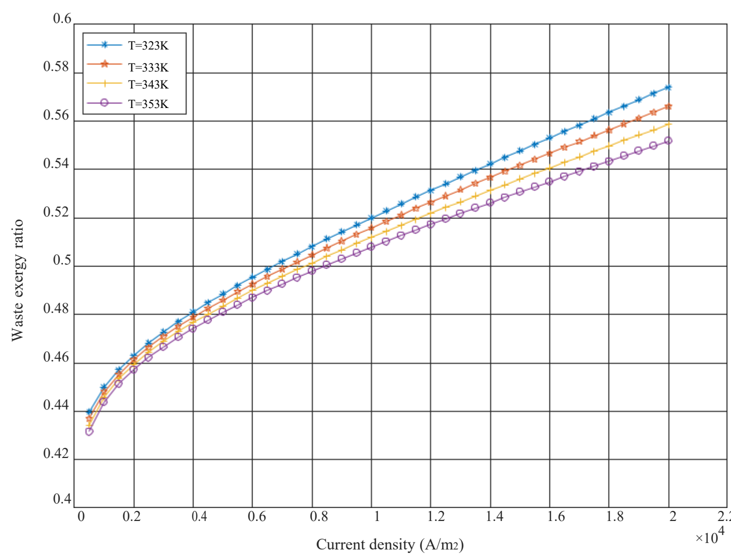

Figure 4: Variation of waste exergy ratio as a function of current density, under varying operating temperatures when the operating pressure is fixed to 3.039×10^5 Pa.

This is because the charge flow increases as the current density increases. The impedance increases, so more exergy is dissipated as heat in fric-tion; in addition, as the temperature and pressure increase, the waste ex-ergy ratio decreases. As shown in Fig. 4, when the operating pressure is 3.039 × 10^5 Pa and the current density is 1 ×10^4 A/m^2, the operating tem-perature changes from 323 to 353 K, and the exergy loss rate decreases from 0.52 to 0.508. As is shown in Fig. 5, for fixed operating temperature 323 K and current density 1 ×10^4 A/m^2, when the operating pressure varied from 1.013–3.039 × 10^5 Pa the waste exergy ratio decreased from 0.532 to 0.518. As the temperature rises, the gas transport capacity is improved, so the internal resistance is reduced, the corresponding heat loss is reduced, and the waste exergy ratio is decreased. From the pressure point of view, as the pressure rises, the fuel mix is somewhat improvement; the friction of the gas in the airway will also be reduced, so the loss will also decrease.

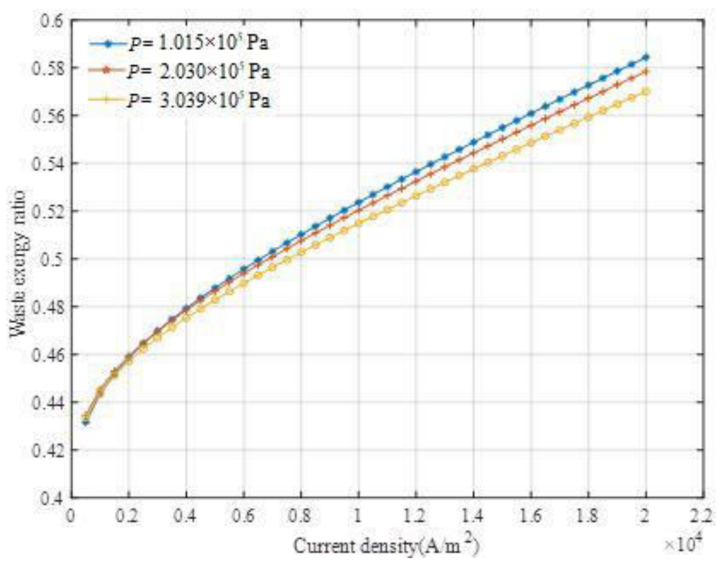

Figure 5: Variation of waste exergy ratio as a function of current density, under varying operating pressure when the operating temperature is fixed to 323 K.

3.3 Exergy destruction factor

Figures 6 and 7 are graphs of the exergy destruction factor as a function of current density at varying operating temperatures, pressures, and fixed proton membrane thicknesses (1.6×10^{-4} m). From the theoretical analysis,

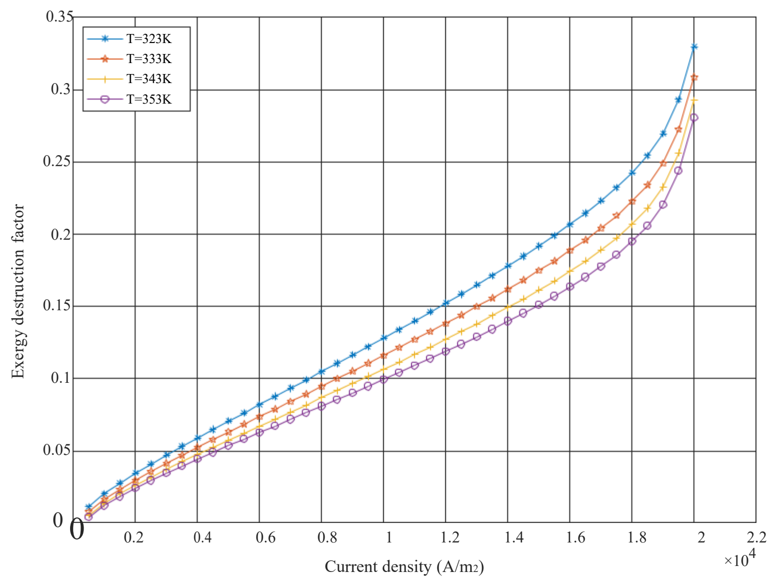

Figure 6: Variation of exergy destruction factor as a function of current density, under varying operating temperatures when the operating pressure is fixed to 3.039×10^5 Pa.

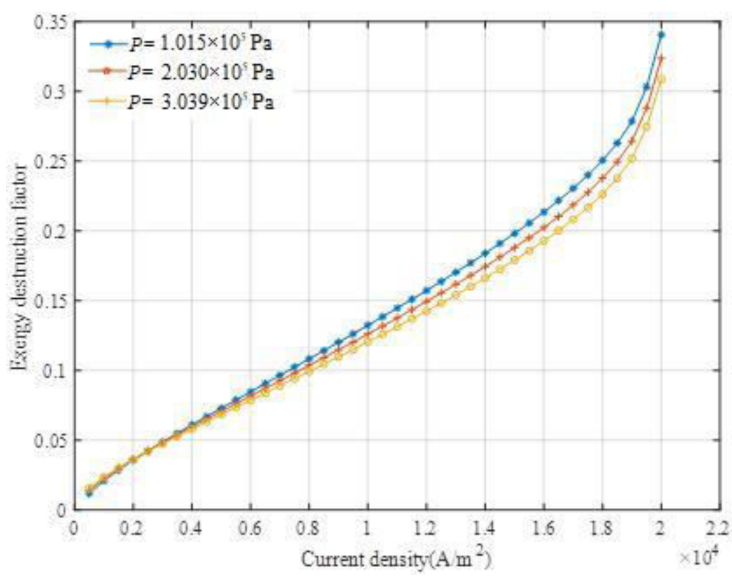

Figure 7: Variation of exergy destruction factor as a function of current density, under varying operating pressure when the operating temperature is fixed to 323 K.

exergy destruction is the exergy of the input system minus the exergy of the output system, minus the waste exergy. The exergy destruction of the large current density changes greatly (Fig. 6). This is because when the fuel cell is at a high current, the reaction gas reaches the electrochemical reaction surface more slowly or the product leaves the electrochemical surface more slowly, so that the concentration overpotential is higher. The figures also show that the exergy destruction factor decreases with increasing temperature and pressure. As shown in Fig. 6, when the operating pressure and the current density is fixed to 3.039×10^5 Pa and 1×10^4 A/m^2, respectively, when the operating temperature is changed from 323 to 353 K, the exergy dissipation rate is decreased from 0.128 to 0.102. As shown in Fig. 7, for the operating temperature 323 K and current density 1×10^4 A/m^2, when the operating pressure varied from 1.013–3.039×10^5 Pa, the exergy destruction factor decreased from 0.142 to 0.129. This is because processes such as diffusion of reactant molecules to the electrode, proton conduction, and discharge of cathode product water are highly advantageous as the temperature and pressure increase.

3.4 Exergy destruction index

Figures 8 and 9 are plots of exergy destruction index as a function of current density for varying operating temperatures, pressures, and fixed pro-ton membrane thicknesses (1.6×10^{-4} m). The EDI is the extent to which unusable waste exergy and exergy destruction are harmful to the environment, so unusable waste exergy and exergy destruction are particularly important for the index; from figures, we can see two aspects of informa-tion. On one hand, EDI increases with the increase of current density. As shown in Fig. 8, for the operating pressure 3.039×10^5 Pa and the oper-ating temperature 323 K, with the change of current density from 0.05 to 2.0×10^4 A/m^2, EDI decreases from 2.09 to 0.52. This is because the value of EDI after the partial derivative of the current density is greater than zero; on the other hand, as the operating temperature and pressure increase, EDI will also decrease accordingly. As shown in Fig. 8, when the operating pressure is 3.039×10^5 Pa and the current density is 1×10^4 A/m^2, the operating temperature changes from 323 to 353 K, EDI decreases from 1.03 to 0.98. As shown in Fig. 9, for the operating temperature 323 K and the current density 1×10^4 A/m^2, when the operating pressure varied from 1.013 − 3.039×10^5 Pa, EDI decreased from 1.19 to 1.02. The increase of temperature and pressure will make the gas transportation smoother and

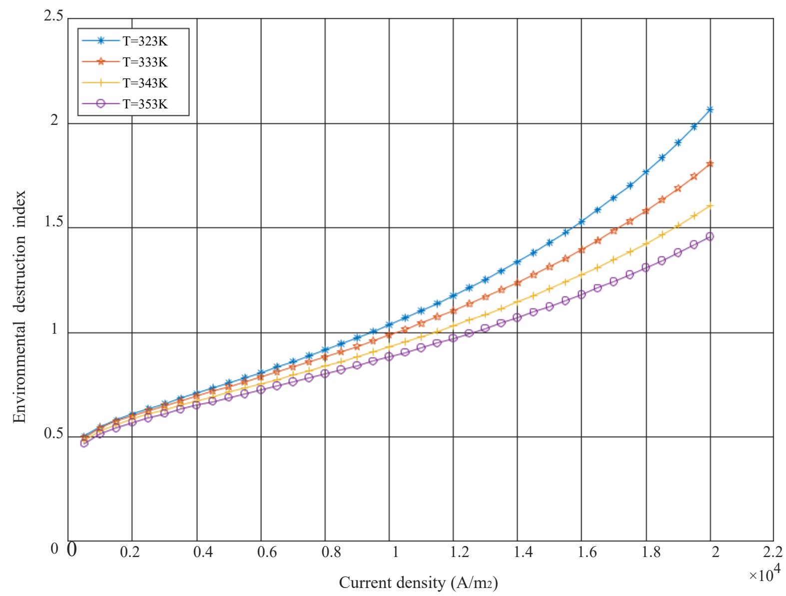

Figure 8: Variation of EDI as a function of current density, under varying operating temperatures when the operating pressure is fixed to 3.039×10^5 Pa.

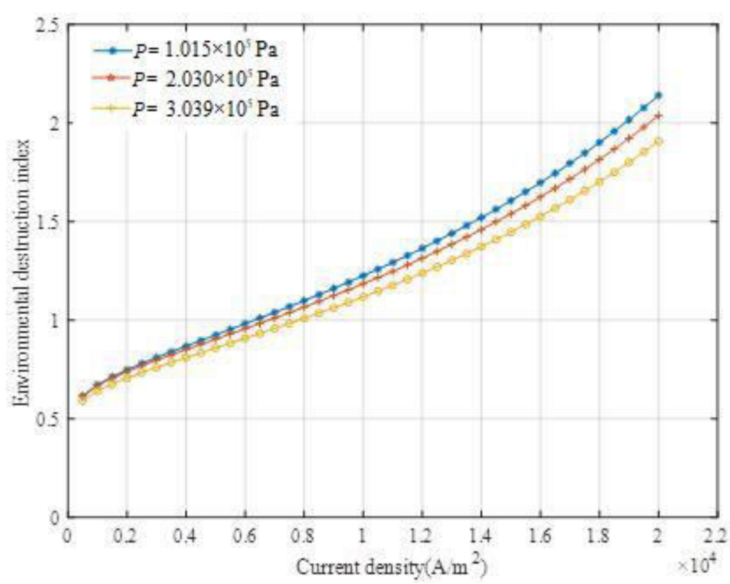

Figure 9: Variation of EDI as a function of current density, under varying operating pressure when the operating temperature is fixed to 323 K.

the mixing of fuel will be improved. Therefore, the hydrogen and oxygen discharged will also decrease, and the internal resistance will also decrease. The end result is a reduction in the waste exergy of the exhaust gas and destruction of heat.

3.5 Exergetic sustainability index

Figures 10 and 11 are plot of exergetic sustainability index as a function of current density for varying temperature, pressure, and fixed proton mem-brane thickness (1.6×10^{-4} m). It can be clearly seen that ESI decreases with increasing current density, and the rate of change at low current density is higher than that at high current density; in addition, when the operat-ing temperature and pressure increase, ESI has risen. As shown in Fig. 10, when the operating pressure is 3.039×10^5 Pa and the current density is 1×10^4 A/m^2, then the operating temperature changes from 323 to 353 K, ESI decreases from 0.58 to 0.64. As shown in Fig. 11, for the operating temperature 323K and the current density 1×10^4 A/m^2, when the operat-ing pressure varies from 1.013–3.039×10^5 Pa, ESI decreases from 0.48 to

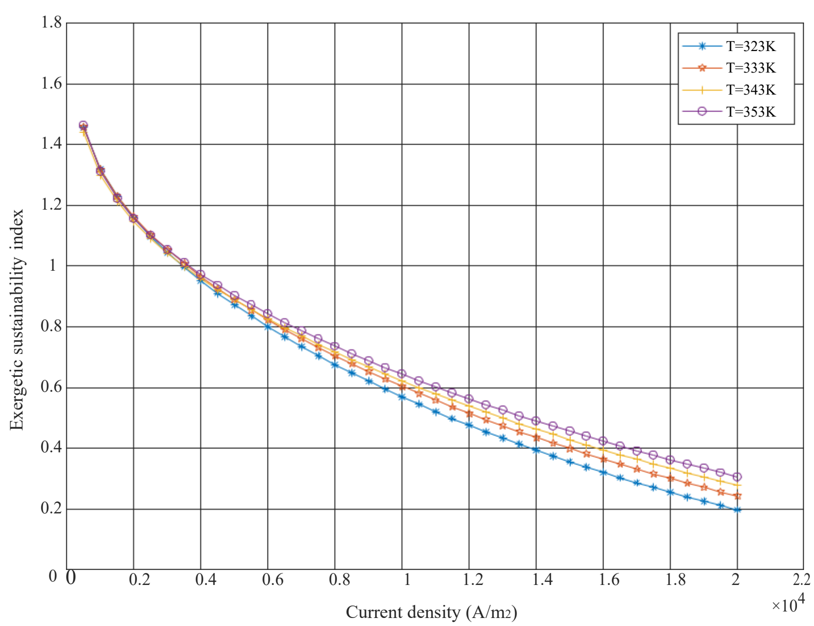

Figure 10: Variation of ESI as a function of current density, under varying operating temperatures when the operating pressure is fixed to 3.039×10^5 Pa.

0.58. Therefore, it can be said that if one wants to improve ESI, you need to reduce the current density and increase the operating temperature and pressure when the proton membrane thickness is constant.

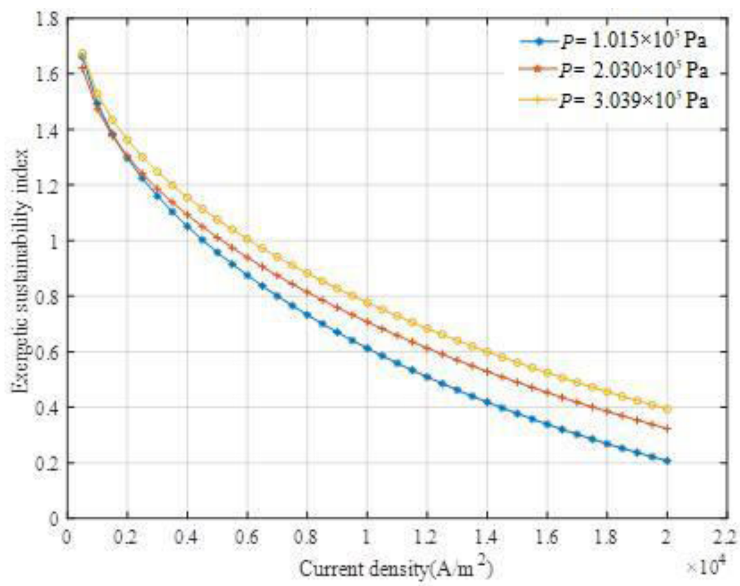

Figure 11: Variation of ESI as a function of current density, under varying operating pressure when the operating temperature is fixed to 323 K.

3.6 Exergetic sustainability indicators

Figure 12 presents the exergetic sustainability indicators and the desired output versus the exergetic efficiency curve at a fixed membrane thickness (1.6×10^{-4} m), a fixed operating pressure (3.039×10^{5} Pa), a fixed operating temperature (323 K), and a varying current density ($0.05–2 \times 10^{4}$ A/m^2). From the figure it can be seen that with the increase of exergy efficiency EDI decreases while ESI increases. This proves that with the increase in exergy efficiency, the environmental impact of PEM fuel cell operation is reduced and the sustainability of PEM fuel cell is increasing. But we cannot just pursue the improvement of some indicators, but ignore other equally important indicators. It can be seen that the desired output decreases with the increase of exergy efficiency, so we need to balance the various indicators, which will be our next research direction.

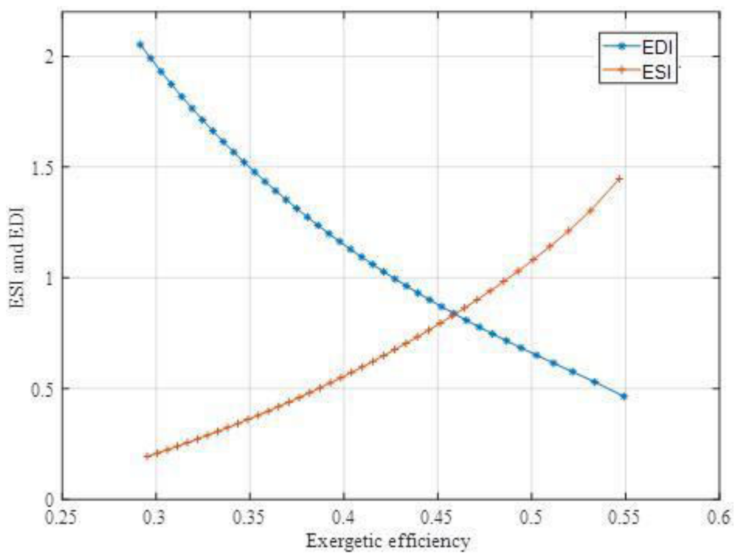

Figure 12: Relationship of ESI and EDI for the varying exergy efficiency.

4 Conclusions

In order to reduce the environmental impact of PEM fuel cell operation process and improve the sustainability of PEM fuel cell, some exergetic sus-tainability indicators of fuel cell were studied. Based on the image change and theoretical basis, some conclusions are drawn. As the operating tem-perature and operating pressure increase, the exergy efficiency will increase, but as the current density increases, the exergy efficiency decreases signifi-cantly, so also under reasonable current density conditions. Increasing the operating temperature and pressure of the PEM fuel cell will improve the exergy efficiency; as the temperature and pressure increase, the waste ex-ergy ratio, the exergy destruction factor and EDI will decrease, but as the current density increases, the irreversibility of PEM fuel cell operation pro-cess is improved, and the waste exergy ratio, exergy destruction factor and EDI increase significantly. Therefore, increasing the operating temperature and pressure of PEM fuel cell under reasonable current density will reduce the irreversibility of PEM fuel cell operation; ESI increases with increasing temperature and pressure. Similarly, the irreversibility of the operational process due to the increase in current density has a significant impact on ESI. Increasing exergy efficiency will greatly reduce the environmental im-pact of the PEM fuel cell operation process and improve its sustainability, but the desired output of the fuel cell decreases as the exergy efficiency increases, so how to properly control the current density to balance output and sustainability are something needed in future to study in depth.

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