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Thermodynamic analysis of a new hybrid system combined heat and power integrated solid oxide fuel cell, gas turbine, Rankine steam cycle with compressed air energy storage

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ABSTRACT

The combined systems of solid oxide fuel cell-gas turbine (SOFC-GT) can operate with high efficiency and low carbon emissions. However, air compressors power consumption of SOFC-GT is big. In this study, a novel hybrid system integrated SOFC-GT with compressed air energy storage (CAES) is proposed. For the integrated system, the energy efficiency is improved in comparison to traditional SOFC-GT due to no air compressors power consumption in the discharging process. In addition, Rankine steam cycle (RSC) is applied to recover waste heat of SOFC-GT exhaust. The new system is simulated in Aspen plus software. The energy and exergy analysis is investigated. Then, the sensitivity analysis is also studied. The results show the cycle efficiency, electrical cycle efficiency and exergy cycle efficiency of new energy storage can reach 75.98%, 60.49% and 60.79%, respectively. Besides, SOFC has the largest exergy destruction of all components. In conclusion, the new system can provide theoretical guidance for efficient energy utilization.

Keywords: SOFC-GT; CAES; RSC; Energy and exergy analysis; Sensitivity analysis

NONMENCLATURE

Abbreviations	
CAES	Compressed air energy storage
GT	Gas turbine
ST	Steam turbine
SOFC	Solid oxide fuel cell
RSC	Rankine steam cycle
CE	Cycle efficiency
CEE	Cycle electrical efficiency
ECE	Exergy cycle efficiency
AC	Air compressor
FC	Fuel compressor
AB	Afterburner
DC	Direct current
AC	Alternative current
W	Power output(KW)
V_{vessel}	The volume of compressed air vessel(m^3)
E	Energy(kWh)
PRV	Pressure reducing valve
t_{ch}	Charging time(h)
t_{dis}	Discharging time(h)
Subscripts	
Ch	Charging
Dis	Discharging
Out	Outlet
In	Inlet
An	Anode
Cat	Cathode
w	Water

1. INTRODUCTION

The energy consumption and environmental issues are serious due to u excessive utilization of traditional energy resources[1]. Thus, the development of efficient and clean energy conversion technologies is essential and important. Solid oxide fuel cell (SOFC) is regarded as one of high-efficiency and low pollution emissions environmental-friendly power generations [2-4]. The produced high-temperature exhaust of SOFC can be recovered by other power systems. There are many studies on hybrid systems of SOFC-GT and other thermodynamic cycles. Fryda et al. [5] conducted a small combined heat and power system based on atmospheric and pressurized types SOFC. The results indicated that pressurized SOFC has higher electrical efficiency.Chen et al.[6] focused on the feasibility of high efficiency with low SOFC fuel utilization. It was found energy efficiency can reach 70% with 50% SOFC fuel utilization. Emadi et al.[7] investigated thermodynamic and economic performance of combined system SOFC-GT and dual-loop ORC using 20 different organic working fluids. Exergy efficiency can reach 51.6% and total electrical power output is 1040 kW using R601 and Ethane under optimal point. Kumar et al.[8] presented thermoeconomic analysis for the hybrid system on a combination of SOFC-GT, ORC and absorption refrigeration system. They concluded that the efficiency of proposed system increased by 9.91% compared with SOFC-GT system. The electricity cost is 1939.93 $/kW.

However, few studies focus on hybrid system integrated SOFC and energy storage. Compressed air energy storage (CAES) can be one of promising physical energy storage technology due to its peak shaving, long operating life time and low environmental pollution[9-10]. For conventional CAES, the surplus electricity from power grid or renewable energy is consumed to compress air by compressors during low electricity demand period. Then compressed air is stored in cavern or air storage chamber. During peak period of electricity consumption, the high-pressure air is released from cavern or air storage chamber. And then enters the combustion chamber. The high temperature gases produced drive turbine to generate electricity[11-12]. There are some researches about integrated systems of CAES and other cycle subsystems for system performance improvement. Liu et al.[13] evaluated a trigeneration system integrated adiabatic CAES with absorption heat pump. It was concluded that the round-trip efficiency and exergy efficiency can be improved by increasing storage pressure. The trigeneration system consisting of CAES, ORC and refrigeration cycle is investigated by Razmi et al[14]. The conclusion demonstrated the cycle efficiency was increased by 13.15 % in comparision to standalone CAES. Facci et al. [15] conducted a trigeneration system based on A-CAES. The compression heat is to used or stored instead of preheating air turbine inlet temperature. Xu et al. [16] accessed a new system combined compressed air energy storage and an ejector refrigeration system using zeotropic working fluid. The round-trip efficiency and exergy cycle efficiency can reach 52.04% and 58.70%.

Previous researches mainly focus on integrated CAES system for system performance improvement. However, few studies focus on CAES, SOFC-GT and Rankine steam cycle. To fill the gap, a new combined system of CAES, SOFC-GT and RSC is presented. The main novelty of this study is the combination of energy storage and SOFC-GT-RSC. There is no air compressor power consumption of SOFC-GT at the peak-time since the compressed air in air tank is used as the anode gas of SOFC. In this study, the main objectives are given: firstly, round-trip efficiency and exergy round-trip efficiency of new system can be calculated. Then, the effect of main parameters (air tank volume, ratio of inlet pressure to outlet pressure ratio, steam turbine inlet pressure) on system performance is studied. In addition, the exergy destruction is also studied.

2. METHODOLOGY

2.1 Basic assumption

The new system is developed and simulated through process simulation. The system simulation is based on Aspen plus software.The design value of parameters is seen in table 1. The basic assumption for system modeling is as follows:

(1) The air composition is composed of N_2 and O_2.

(2) The integrated system is simulated under steady conditions.

(3) The pressure and temperature are evenly distributed in SOFC.

(4) The SOFC outlet gas temperature is the same as the operating temperature.

Table 1. Design parameters of the integrated system

Parameter	Value
Fuel composition [17]/%	CH_4(81.3),C_2H_6(2.9), C_3H_8(0.4),C_4H_{10}(0.2), N_2(14.3),CO(0.9)
Air composition (%)	N_2(79%), O_2(21%)
Ambient pressure/bar	1.013
Ambient temperature/℃	25
Mass flow of fuel (kg/h)	29.73
Mass flow of air (kg/h)	488.73
AC isentropic efficiency [18]/%	85
Compression ratio of air compressors	4.5
FC isentropic efficiency[18] /%	85
SOFC operating pressure/MPa	0.6
SOFC operating temperature [17]/ ℃	910
GT isentropic efficiency[19] /%	85
Fuel utilization factor [17]/%	85
Activated area [17] /m^2	96.1
Number of cells [17]	1152
Steam to carbon ratio of SOFC	2.5
SOFC operating pressurea/bar	6
DC-AC conversion efficiency /%	95
Pump isentropic efficiency[20] /%	90
RSC isentropic efficiency /%	85
RSC inlet pressure/bar	20
Air vessel volume/m^3	250

2.2 SYSTEM DESCRIPTION

The system process of the new cogeneration system is shown in figure 1. During low electricity demand period, the air is compressed by two compressors with same ratio. The compression heat from air is recovered by cooling water. The high-pressure air flowing out of the aftercooler is stored in compressed air tank. The storage air pressure of compressed air is at 2 MPa. The stored air temperature is at 353.15K. During electricity demand peak period, the stored air is released at 0.8 MPa. Then the preheated stored air enters anode of SOFC. After natural gas undergoes reforming reaction, the reformed gas enters cathode of SOFC. The reformed gas and compressed air undergo electrochemical reaction in the SOFC stack. Then unreacted fuel and air react further in the combustion chamber. The function of reflux is to prevent carbon deposition in SOFC. The high temperature gas produced drives gas turbine to generate electricity. The exhaust waste heat of gas turbine can be recovered by applying a Rankine steam cycle. The temperature of exhaust waste heat is at 722.67K (stream 21). In the Rankine steam cycle, the water is heated into superheated vapor. The superheated vapor drives steam turbine to generate electricity. The temperature of superheated vapor is at 673.15K (stream 22). Then vapor is condensed into water by cooling water. The exhaust of outlet hot stream from evaporator is recovered by heating water. The exhaust temperature of outlet hot stream is at 427.90K (stream 26). The temperature of domestic hot water is at 325.41K (stream g).

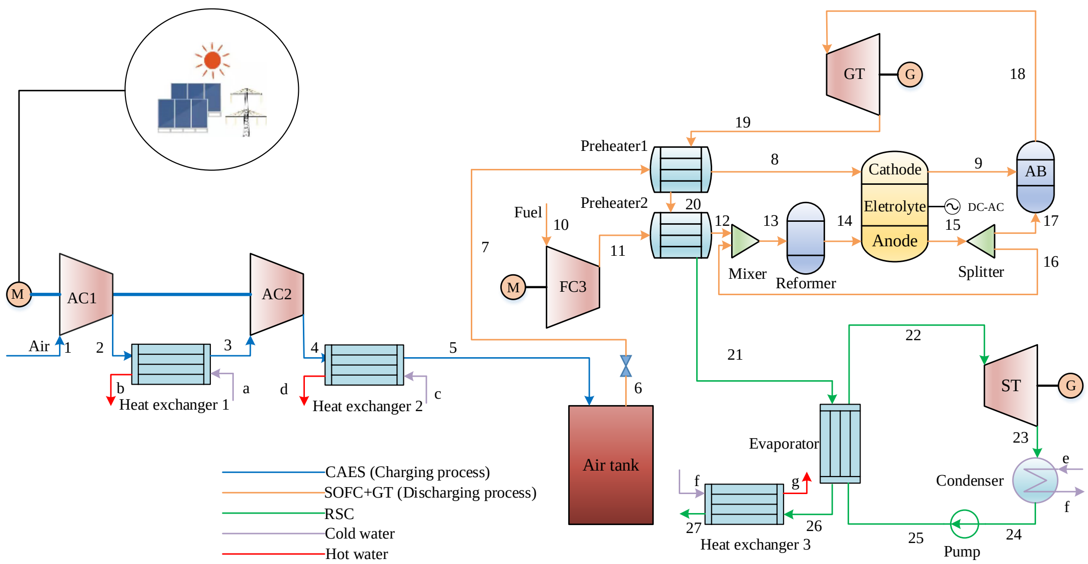

Figure 1 The flowchart of the new system

2.3 MATHEMATICAL MODEL

2.3.1 SOFC model

The SOFC model chosen is based on Westinghouse's tubular model. The fuel used is natural gas. The reforming reaction and electrochemical reaction in reformer and SOFC are as follows [17]:

$$CH_4 + H_2O \Leftrightarrow 3H_2 + CO \qquad (1)$$

$$C_2H_6 + 2H_2O \Leftrightarrow 5H_2 + 2CO \qquad (2)$$

$$C_3H_8 + 3H_2O \Leftrightarrow 7H_2 + 3CO \qquad (3)$$

$$C_4H_{10} + 4H_2O \Leftrightarrow 9H_2 + 4CO \qquad (4)$$

$$CO + H_2O \Leftrightarrow H_2 + CO_2 \qquad (5)$$

$$H_2 + \frac{1}{2}O_2 \to H_2O \qquad (6)$$

The current formula is described as[17]:

$$I = 2\times\left[n_{H_2} + n_{CO} + 4n_{CH_4} + 7n_{C_2H_6} + 10n_{C_3H_8} + 13n_{C_4H_{10}}\right]\times F \times U_{fuel} \qquad (7)$$

Where *F* is Faraday constant, 96485.33 C/mol. U_{fuel} is the fuel utilization factor. *n* is the molar flow, mol/s.

The equation for calculating current density is as follows [17]:

$$i = \frac{I}{m_c \cdot A_c} \qquad (8)$$

Where i is current density, mA/cm^2. m_c is cells number and A_c is active surface area, cm^2. i is current density, mA/cm^2.

The formula for calculating SOFC voltage is defined as:

$$V_{SOFC} = E - V_{ohm} - V_{act} - V_{conc} \quad (9)$$

V_{ohm}, V_{act} and V_{conc} is ohmic polarization, activation polarization and concentration polarization, V, respectively. V_{conc} is ignored in this study.

$$V_{ohm} = I\sum_k r_k \quad (10)$$

$$r_k = \sum_k \frac{\rho_k \delta_k}{A} \quad (11)$$

$$\rho_k = a_k \exp\left(\frac{b_k}{T}\right) \quad (12)$$

r_k denotes the ohmic resistance of SOFC, Ω. δ_k denotes the thickness, cm. ρ_k is the resistivity, Ω•m.

The calculation for of the anode and the cathode activation polarization is as follows[21]:

$$i_0^{an} = Y_{an}\left(\frac{p_{H_2}}{P_{an}^0}\right)\left(\frac{p_{H_2O}}{P_{an}^0}\right)\exp\left(-\frac{E_{act,an}}{RT}\right) \quad (13)$$

$$i_0^{cat} = Y_{cat}\left(\frac{p_{O_2}}{P_{cat}^0}\right)^{0.25}\exp\left(-\frac{E_{act,cat}}{RT}\right) \quad (14)$$

$$V_{act}^{an} = \frac{RT}{F}\ln\left(\frac{i}{2i_0^{an}} + \sqrt{\left(\frac{i}{2i_0^{an}}\right)^2 + 1}\right) \quad (15)$$

$$V_{act}^{cat} = \frac{RT}{F}\ln\left(\frac{i}{2i_0^{cat}} + \sqrt{\left(\frac{i}{2i_0^{cat}}\right)^2 + 1}\right) \quad (16)$$

The Y_{an} and Y_{cat} denotes the diffusion coefficient anode and cathode, A/m^2; E_{act} is the cathode and anode activation energy, kJ/kmol. i_0 represents the exchange current density, A/m^2. p^0 is electrode surface gas partial pressure, bar.

2.3.2 CAES model

The air is compressed by compressors consuming excess electricity. The electricity is from renewable energies or grid power. After compressing air, the compressed air is stored in the compressed air tank. During peak periods of power demand, the released air enters SOFC cathode.

The equation for isentropic efficiency of compressors can be expressed below:

$$\eta_{AC} = \frac{h_{e,s} - h_i}{h_e - h_i} \quad (17)$$

The power consumption of air compressors is obtained by using following equation:

$$W_{AC} = m_i(h_e - h_i) \quad (18)$$

h_e and h_i denotes outlet and inlet enthalpy, respectively.

The charging time and discharging time of the combined system are denoted as follows [22]:

$$t_{ch} = \frac{(\rho_i - \rho_e)V_{vessel}}{3600 m_i} \quad (19)$$

$$t_{dis} = \frac{(\rho_i - \rho_e)V_{vessel}}{3600 m_e} \quad (20)$$

ρ_i and ρ_e are inlet and outlet air densities,kg/m^3. m_e and m_i are inlet and outlet air mass flow rate,kg/s. V_{vessel} is stored air vessel volume,m^3.

2.3.3 RSC model

The heat power absorption of the heat exchanger can be calculated as follows [23]:

$$Q_C = m_w c_p (T_{in} - T_{out}) \quad (21)$$

The pump power consumption using following equation

$$W_{pump} = m_w\left(h_{out,i} - h_{in,i}\right) \quad (22)$$

The heat power of the condenser can be calculated as follows:

$$Q_C = m_w c_p (T_{in} - T_{out}) \quad (23)$$

The calculating power produced by turbine using following equation:

$$W_{OT} = m_w\left(h_{in,i} - h_{out,i}\right) \quad (24)$$

2.3 Performance crietria

The cycle efficiency is used to evaluate the system efficiency due to separate two operating times (charing time and discharging time). The calculation equation for cycle efficiency is as follows:

$$CE = \frac{(W_{SOFC} + W_{GT} + W_{ST})t_{dis} + E_{heat,ch}t_{ch} + E_{heat,dis}t_{dis}}{E_{fuel}t_{dis} + W_{AC}t_{ch} + (W_{FC} + W_{pump})t_{dis}} \quad (25)$$

Where W_{SOFC}, W_{GT}, W_{ST} are power output of SOFC,GT and ST, kW. $E_{heat,ch}$ and $E_{heat,dis}$ are thermal energy absorbed by cold water during charging hours and discharging time,kW, respectively.

The calculation equation for cycle electricity efficiency is as follows:

$$CEE = \frac{(W_{SOFC} + W_{GT} + W_{ST})t_{dis}}{E_{fuel}t_{dis} + W_{AC}t_{ch} + (W_{FC} + W_{pump})t_{dis}} \quad (26)$$

The calculation equation for exergetic cycle efficiency is as follows:

$$ECE = \frac{E_{t,e,dis}t_{dis} + E_{heat,ch}\left(1-\frac{T_0}{T}\right)t_{ch} + E_{heat,dis}\left(1-\frac{T_0}{T}\right)t_{dis}}{Ex_{fuel,dis}t_{dis} + W_{AC}t_{ch} + (W_{FC} + W_{pump})t_{dis}} \quad (27)$$

3 RESULTS AND DISCUSSION

The new system can produce total power output of 250.93 kW in discharging process. The cycle efficiency, electrical cycle efficiency and exergetic cycle efficiency of new energy storage are 75.98%, 60.49% and 60.79%, respectively. The simulation results are given in table 1. The simulation results for every stream of new system are presented in table 2.

Table 1 The simulation results of the new system

Parameter	Value
Charge time/h	7.0
Discharge time/h	7.0
W_{SOFC}/kW	155.24
W_{GT}/ kW	83.58
W_{RST}/kW	12.11
CE/%	75.98
CEE/%	60.49
ECE/%	60.79

Table 2 The simulation results for each stream of the integrated system

Stream	Flow (kg/h)	Pressure (bar)	Temperature(K)	h (kJ/kg)	S (kJ/(kg·K))	Exe (kJ/kg)
1	488.73	1.01	298.15	0.00	0.14	0.00
2	488.73	45.60	484.22	190.243	0.20	172.13
3	488.73	45.60	338.15	40.60	-0.17	132.10
4	488.73	20.20	547.50	256.14	-0.1	329.51
5	488.73	20.20	351.15	53.82	-0.56	263.50
a	504.00	1.01	298.15	-15864.30	-8.60	0.00
b	504.00	1.01	332.76	-15719.20	0.59	8.48
c	684.00	1.01	298.15	-15719.80	-9.06	0.00
d	684.00	1.01	332.63	-9534.920	-8.60	8.42
6	488.73	20.2	351.15	53.82	-0.56	261.31
7	488.73	6.00	351.15	52.51	-0.20	156.91
8	488.73	6.00	745.60	467.51	-9.32	687.40
9	413.55	6.00	1183.15	977.04	1.05	118.36
10	29.73	1.00	298.15	-0.03	-3.60	0.00
11	29.73	6.00	454.50	-3175.81	-3.52	306.04
12	29.73	6.00	712.67	-2478	-2.31	190.36
13	198.27	6.00	1065.45	-7296.54	1.03	1010.21
14	198.27	6.00	873.15	-7340.33	1.08	743.83
15	274.88	6.00	1183.15	-8140.31	1.39	1089.20
16	168.72	6.00	1183.15	-8140.31	1.39	1100.55
17	106.16	6.00	1183.15	-8140.31	1.39	1100.55
18	519.71	6.00	1502.59	1087.67	1.45	0.00
19	519.73	1.01	1067.47	-1470.12	1.51	484.27
20	519.73	1.01	755.60	-1861.53	1.08	221.90
21	519.73	1.01	722.67	-1901.20	1.02	198.23
22	57.60	20.00	673.15	-12722.60	-2.30	1154.28
23	57.60	0.20	1231.77	-13487.30	-1.89	269.83
24	57.60	0.20	336.00	-15801.10	-8.78	9.88
25	57.60	20.00	336.00	-15798.80	-8.78	12.26
26	519.73	1.01	427.90	-2242.14	0.42	37.46
27	519.73	1.01	335.41	-2344.67	0.15	15.39
f	432.00	1.01	298.15	-15971.90	-9.32	0.00
g	432.00	1.01	325.41	-15848.50	-8.92	5.32

found that cycle efficiency, electrical cycle efficiency and exergetic cycle efficiency has slight change with rise of air inlet mole flow of air compressors.

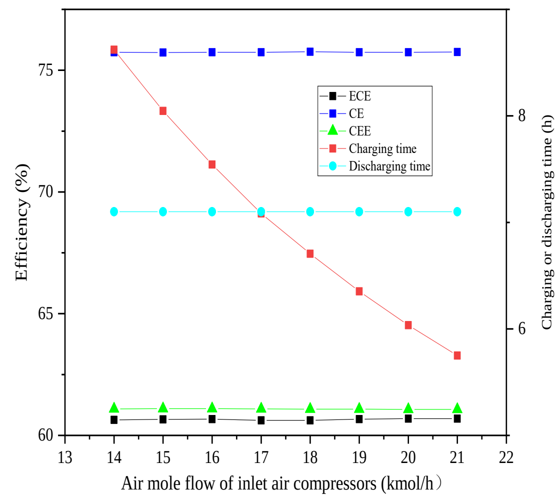

Figure 3. The effect of inlet air mole flow of air compressors on system performance

3.1 Sensitivity analysis

3.1.1 The effect of compressed air tank volume on system performance

Figure 2. demonstrates the effect of compressed air tank volume on cycle efficiency, cycle electrical efficiency and exergetic cycle efficiency. It is seen that charging time and discharging time both increase with increase of compressed air tank volume. However, the cycle efficiency, cycle electrical efficiency and exergetic cycle efficiency are constant. The reason may be that the charging time and discharging time are same. It is concluded compressed air tank volume has a great effect on charging time and discharging time, but has no effect on efficiencies when charging time and discharging time are same. According to equations of efficiencies, the efficiencies are not changed. The cycle efficiency, cycle electrical efficiency and exergetic cycle efficiency are 75.98%, 60.49% and 60.79%, respectively.

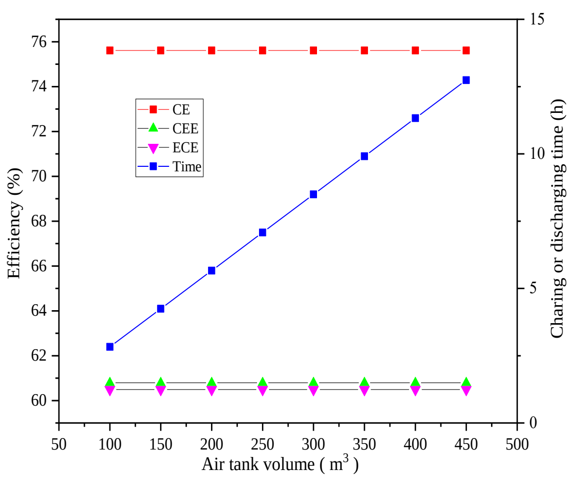

Figure 2. The effect of compressed air tank volume on system performance

3.1.2 The effect of inlet air mole flow of air compressors on system performance

The effect of air mole flow of inlet air compressors on cycle efficiency, cycle electrical efficiency, exegetic cycle efficiency, discharging time and charging time is shown in figure 3. From figure 3, it is observed that the charging time decreases as air inlet mole flow of air compressors increases. But discharging time is unchanged due to no change of outlet air flow. It is also

3.1.3 The effect of inlet air mole flow of air compressors on system performance

Figure 4 shows the effect of inlet pressure of steam turbine power on efficiencies and steam turbine power output. The inlet pressure of steam turbine ranges from 12 bar to 26 bar. It can be seen that with rise of inlet pressure of steam turbine, cycle efficiency, electrical cycle efficiency and exegetic cycle efficiency increases very slightly. In addition, the power output increases from 11.16 kW to 12.7 kW as inlet pressure of steam turbine increases from 12 bar to 26 bar.

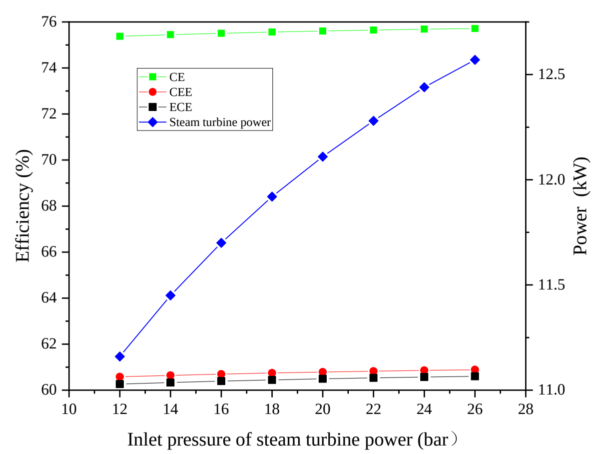

Figure 4. The effect of inlet pressure of steam turbine on system performance

3.2 Exergy analysis

Figure 5 and Figure 6 demonstrates exergy destruction and exergy destruction ratio of all components, respectively. It is seen from figure 6, SOFC and afterburner have high exergy destructions, which accounts for 20.82% and 19%, respectively. SOFC and afterburner have high exergy destructions due to large irreversible chemical exergy. The exergy destruction of pressure reducing valve (PRV) ranked third, which accounts for 11.60% of all components. The reason is caused by large pressure drop. Preheater 1 also has high exergy destruction (11.04%).Others includes preheater 2 and The reason may be caused by large temperature difference between hot and cold streams.

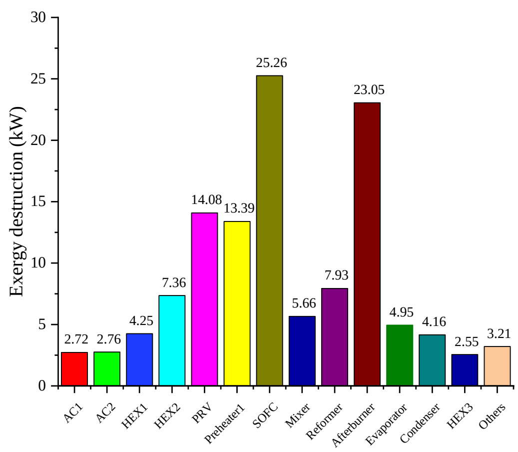

Figure 5. The exergy destruction of all components

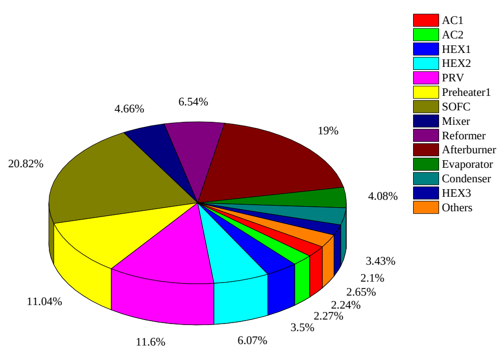

Figure 6. The exergy destruction ratio of all components of the new system

4.CONCLUSIONS

The new cogeneration system combined SOFC-GT-RST with energy storage is proposed and developed based on energy cascade utilization. Compared with traditional SOFC-GT system, the new system can improve system performance. During high power demand period, SOFC-GT-RST can produce power with high efficiency. In addition, domestic hot water is produced. The energy and exergy are studied in this study. Besides, the effect of main parameters (compressed air storage vessel volume, Air mole flow of inlet air compressor and inlet pressure of steam turbine power) on system performance is investigated. The main conclusions are as follows:

(1) The cycle efficiency, cycle electrical efficiency and exergetic cycle efficiency of new energy storage can reach 75.98%, 60.49% and 60.79%, respectively. The discharging time and charging time are both 7 h. The efficiencies are improved in comparison to conventional CAES.

(2) Compressed air storage vessel volume has an obvious effect on charging time and discharging time. Air mole flow of inlet air compressors affects charging time directly. But air mole flow has little effect on efficiencies. In addition, with increase of inlet pressure of steam turbine power, the efficiencies increase very slightly.

(3) SOFC has largest exergy destructions, which accounts for 20.82% of all components. Followed by afterburner (19%). Exergy destructions of PRV and preheater 1 ranked the third (11.60%) and fourth (11.04%), respectively.

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