International Journal of Smart Grid and Clean Energy

Energy and exergy analysis of a micro CCHP system based on SOFC/MGT/ORC and steam ejector refrigeration cycle

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Abstract

This paper proposes a Micro CCHP system for combined production of cooling heating and power. The CCHP system includes a Solid Oxide Fuel Cell(SOFC), a Micro Gas Turbine(MGT), an Organic Rankine Cycle(ORC), a Steam Ejector Refrigeration cycle (SER), heat recovery equipment and other relevant components. The energy-exergy analysis is conducted to thermodynamically investigate on system performances in summer and winter. In addition, a parametric study is presented to observe the effects of some operating parameters such as the fuel flow rate, steam to carbon ratio and the mass flow rate of ORC on the evaluation criteria of the system and its components. Results show that under the design conditions the system exergy efficiency is 64.39% in summer while at the same time the overall energy efficiency can reach 91.21% which is 11.78% higher than that in winter. The mass flow rate of ORC and the entrainment ratio of the ejector both have big impacts on improving the cooling capacity of the Micro CCHP system.

Keywords: micro CCHP, solid oxide fuel cell, micro gas turbine, organic rankine cycle, thermodynamic analysis

1. Introduction

A CCHP system is able to simultaneously produce cooling, heating and power. In recent years, investigations into different kinds of CCHP systems due to their importance in saving energy resources and pollution reduction have been increased [1]. The CCHP systems are very flexible in using different prime movers such as fuel cells, (micro) gas turbine and stirling engine [2]. They can be used in different sectors like residential, official buildings, industrial plants, hospitals and campuses [3].The Solid Oxide Fuel Cell (SOFC) and (Micro) Gas Turbine hybrid system is regarded as the most important technology of DOE'S Vision 21. Researchers have studied the SOFC/MGT hybrid system and made great progress. Cocco et al. analysed the use of alternative fuels with a lower reforming temperature in SOFC/MGT hybrid power plant, and the results showed that using methanol in externally improved efficiency by about 4.0% better than methane [4]. Traverso presented a review of modelling and designed issues for the integration of turbomachinery with the fuel cell system, and the analysis covered three main aspects of performances evaluation: the on-design, the off-design and the control of the hybrid systems [5]. Martin et al. reviewed and analysed the main characteristics of electrical micro-grid and the electrical efficiency of hybrid system based on SOFC/MGT was 66.5 approximately [6]. Although the waste heat from SOFC can be used by (M)GT, the exhaust gas from (M)GT still has relatively high temperature and is affordable to supply enough heat for other cycles such as Kalina Cycle, Organic Rankine Cycle (ORC) which will bring a higher energy efficiency [7]. Fryda studied a CHP system based on SOFC/MGT under two operation pressures which were atmospheric and 4 bar, and results showed that the pressured SOFC configuration obtained a higher efficiency [8]. Maghanki discussed the feasibility of Micro-CHP systems based on internal combustion engines, Micro Gas Turbines, Micro Rankine Cycles, Stirling engines to meet household energy demands [3]. Ebrahimi et al. proposed a combined system of cooling heating and power in micro scale, energy, exergy and pinch analyses were used to evaluate the feasibility of the cycle and the results showed that in the

* Manuscript received June 14, 2018; revised July 7, 2019.
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doi: 10.12720/sgce.8.6.643-654

optimum conditions of summer mode the cycle can save more than 37% fuel while the overall and exergy efficiencies reached 78% and 37% [9]. Sanaye et al. investigated energy, exergy, economic, environment analysis and optimization of a hybrid SOFC and MGT system for use as combined generation of heat and power, the select points from the Pareto distribution of optimization results indicated a total system exergy efficiency of 60.7% and payback period of about 6.3 years for the investment [10].

In the present paper, a novel Micro CCHP system is proposed for combined production of cooling heating and power. This system combines highly new technologies of a MGT and ORC to produce electricity in micro scale while using the waste heat recovery for heating and for cooling with a steam ejector refrigeration cycle. The purpose of this research is to examine the feasibility of the CCHP system based on SOFC/MGT/ORC and steam ejector refrigerator from the thermodynamic point of view. Therefore, a parametric study is presented to observe the effects of some parameters such as fuel flow rate, steam to carbon ratio, the mass flow rate of ORC and the ejector entrainment ratio on the evaluation criteria of the Micro CCHP system and its components. The results may provide useful information for the development of new cycles based on SOFC/ MGT and ORC in different seasons.

2. System Description

The proposed micro CCHP system is depicted in Fig. 1. The system comprises of a Solid Oxide Fuel Cell (SOFC), a Micro Gas Turbine (MGT), an Organic Rankine Cycle (ORC), a steam ejector refrigeration cycle (SER), a waste heat boiler and other related components.

The electrochemical reaction of the compressed air and the preheated fuel occurs in the SOFC stack to produce DC current which is converted into AC current by an inverter. The redundant air and fuel combust completely in after burner to produce gas in high temperature and pressure, which will expand amply in MGT to generate electricity. The exhaust gas from MGT is sequentially used to preheat the air, fuel, water in Preheaters (PH1, PH2 and PH3) and enters into a waste heat boiler to reheat the ORC working fluid which will expand in ORC turbine to produce power. The working fluid from ORC turbine has an appropriate pressure so that it is utilized as the power fluid in the SER that can provide district cooling in summer mode. In winter, the fluid enters the condenser directly (Point 36) and the SER is not working because cooling is not required. At last, the exhaust gas from the waste heat boiler still owns heat of high grade and it can be exploited in a heat exchanger to produce domestic hot water. In this system, energy and heat can be used in a cascaded way which has been proved to be of high efficiency and clean.

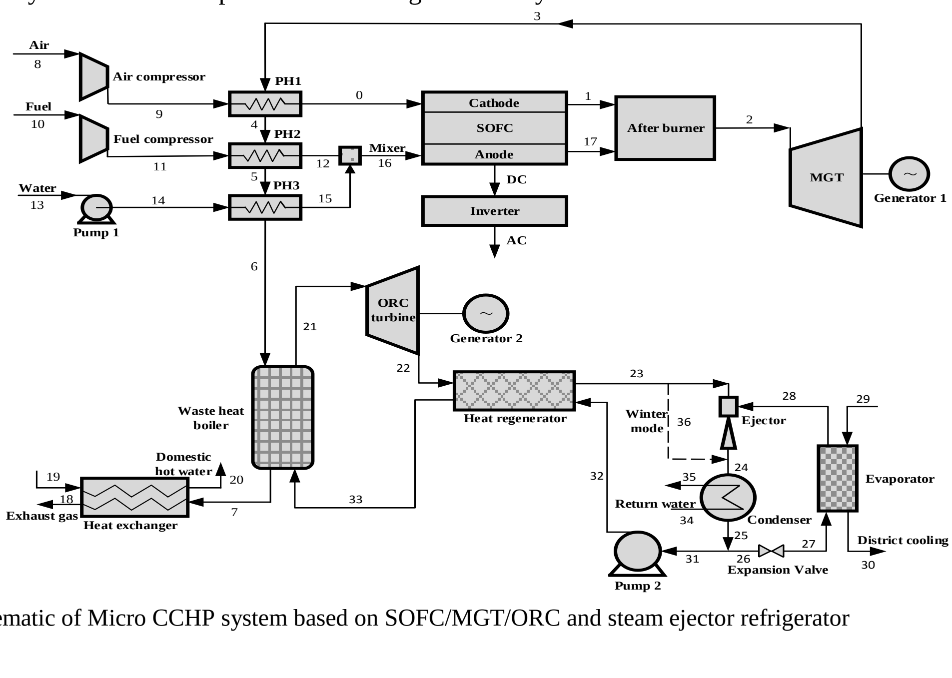


Fig.1. Schematic of Micro CCHP system based on SOFC/MGT/ORC and steam ejector refrigerator

3. Mathematic model

3.1 Assumptions

In order to simplify the modelling of the Micro CCHP system, the assumptions are defined as follows:

- Air is ideal gas consisting of 79% N_2 and 21% O_2 in volume fraction.
- The fuel is CH_4 and can be regarded as ideal gas.
- The temperature of fuel and air at the exit of the SOFC channels are constant and equal to the SOFC operation temperature.
- The pressures of fuel and air at the exit of the SOFC channels are constant and equal to the SOFC operation pressure.
- Heat losses towards the environment are negligible.
- CO only participates in the shifting reaction.
- The working fluid in ORC is R600a, which is environmentally friendly and the latent heat of vaporization is big enough and very appropriate for ORC in this paper.

3.2 SOFC/MGT model

SOFC model

The reaction mechanisms for internal reforming are showed as follows:

Reforming reaction： $CH_4 + H_2O \rightarrow CO + 3H_2$

Shifting reaction： $CO + H_2O \rightarrow CO_2 + H_2$

Electrochemical reaction： $H_2 + 0.5O_2 \rightarrow H_2O$

The equilibrium constants of reforming K_{pr} and shifting equilibrium K_{ps} are defined as：

$$K_{pr} = \frac{n_{CO} n_{H_2}^3}{n_{H_2O} n_{CH_4} n_{total}^2} \left(\frac{P}{P_0} \right)^2 \tag{1}$$

$$K_{ps} = \frac{n_{CO_2} n_{H_2}}{n_{CO} n_{H_2O}} \tag{2}$$

where, P is the total pressure, P_0 is the standard pressure, and n is the mole number of corresponding substance.

When the working temperature of SOFC is given, the equilibrium constants can be expressed by:

$$\log K_p = AT_{SOFC}^4 + BT_{SOFC}^3 + CT_{SOFC}^2 + DT_{SOFC} + E \tag{3}$$

where, constants A, B, C, D and E can be determined according to literature [11].

The cell voltage produced by the solid oxide fuel cell is given by:

$$V_{SOFC} = V_{re} - \eta_{act} - \eta_{conc} - \eta_{ohm} \tag{4}$$

where, V_{SOFC} is the fuel cell voltage, V_{re} is the reversible cell voltage, η_{act} is the activation over voltage, η_{conc} is the concentration over voltage, and η_{ohm} is the ohmic over voltage.

V_{re} can be obtained from the well-known Nernst equation [12]:

$$V_{re} = -\frac{\Delta G^0}{2F} + \frac{RT}{2F} \ln \left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right) \tag{5}$$

where, ΔG^o is the Gibbs free energy at the standard pressure and temperature, T is the reactant temperature at the exit of the fuel cell, R is the universal gas constant, F is Faraday constant, and p is the pressure of corresponding substance.

The activation overvoltage can be expressed by:

$$\eta_{act} = \frac{2RT}{n_e F}\sinh^{-1}\left(\frac{i}{2i_0}\right) \tag{6}$$

where, i and i_0 are the current, exchange current densities of SOFC.

The concentration over voltage can be obtained by:

$$\eta_{conc} = -\frac{RT}{2F}\ln\left(1-\frac{i}{i_{an}}\right)+\frac{RT}{2F}\ln\left(1+\frac{P_{H_2}^{an} i}{P_{H_2O}^{an} i_{an}}\right)-\frac{RT}{4F}\ln\left(1-\frac{i}{i_{ca}}\right) \tag{7}$$

where, i_{an} and i_{ca} are the anodic, cathodic limited currents.

The ohmic over voltage can be expressed by ohm's law:

$$\eta_{ohm} = i\sum_k \partial_k A_k e^{\left(\frac{B_k}{T}\right)} \tag{8}$$

where, δk is the thickness, A_k and B_k represent the constants of the anode, cathode, electrolyte and interconnect, respectively [13].

The current density is defined as:

$$i = \frac{Zn_e F}{NA} \tag{9}$$

where, N is the cell number, A is the active surface area, and Z is the quantity of hydrogen participating in the electrochemical reaction of SOFC.

The power output of SOFC can be obtained by:

$$W_{SOFC} = Zn_e F V_{SOFC}\eta_{DA} \tag{10}$$

where, W_{SOFC} is the electricity generation of SOFC, and η_{DA} is the inverter efficiency.

MGT model

The redundant air and fuel from SOFC combust completely in after-burner to produce gas in high temperature and pressure for the micro gas turbine. The after-burner model can be defined as:

$$m_1 h_1 + m_{17} h_{17} + \left(m_{H_2,17} Q_{H_2,LHV} + m_{CO,17} Q_{CO,LHV}\right)\eta_{ab} = m_2 h_2 \tag{11}$$

where, m_1, m_{17} and m_2 are the inlet, outlet mass flux of the after burner, h_1, h_{17} and h_2 are the enthalpy values at points 1, 17and 2, $m_{H2,17}$ and $m_{CO,17}$ denote the mass flux for hydrogen and carbon monoxide inlet of the after burner, η_{ab} is the after burner thermal efficiency, and Q_{LHV} denotes lower heating value of fuel.

MGT turbine model can be expressed as:

$$W_{MGT} = \left(m_2 h_2 - m_3 h_3\right)\eta_{MGT}\eta_{gen1} \tag{12}$$

where, W_{MGT} denotes the net power generated by the MGT, m_3 is the outlet mass flux of MGT, h_3 is the enthalpy value at point 3, η_{MGT} is isentropic efficiency of MGT, and η_{Gen1} is the efficiency of generator 1.

In addition, the MGT components including preheater, compressor are simulated as below.

$$m_{high}\left(h_{in,high} - h_{out,high}\right) = m_{low}\left(h_{out,low} - h_{in,low}\right) \tag{13}$$

$$W_{COM} = m_{COM}\left(h_{out} - h_{in}\right)/\eta_{COM} \tag{14}$$

where, $h_{in,high}$, $h_{in,low}$, $h_{out,high}$, $h_{out,low}$ are the enthalpy values, in and out denote the inlet and outlet of the preheater, high and low denote the sides of high temperature and low temperature respectively. W_{COM} is the consumption of power in compressor or pump, η_{COM} is the isentropic efficiency.

Waste heat boiler model

Pinch technology is a powerful tool to determine the conditions in waste heat boiler to improve efficiency. A sample of the pinch technology curve is shown in Fig.2.The pinch temperature and pinch point temperature difference can be calculated as below [9].

$$T_{pp} = T_{ORC} + \Delta T \tag{15}$$

$$T_{pp} = \frac{m_{21}\left(h_{21} - h_{33}\right)}{m_6\left(h_6 - h_7\right)}\left(T_6 - T_7\right) + T_7 \tag{16}$$

where, T_{pp} is the pinch temperature, ΔT is called pinch point temperature difference, m denotes the flow rate, h is enthalpy, and T represents temperature.

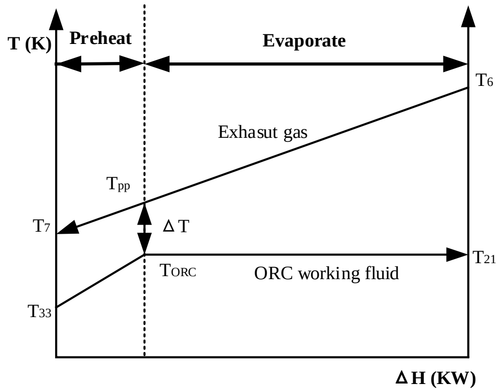


Fig.2 The pinch technology illustration for waste heat boiler

Heat exchanger model

In heat exchanger, the waste heat from the waste heat boiler is further used to produce domestic heat water, which can be defined as:

$$Q_{heating} = m_7\left(h_7 - h_{18}\right) = m_{19}\left(h_{20} - h_{19}\right) \tag{17}$$

where, $Q_{heating}$ is the heating capacity, m, h denotes the flow rate and the enthalpy respectively.

3.3 ORC/SER model

ORC model

ORC turbine model can be expressed as:

$$W_{ORC} = m_{21}\left(h_{22} - h_{21}\right)\eta_{ORC}\eta_{gen2} \tag{18}$$

where, W_{ORC} is the net power generated by the ORC, m_{21} is mass flow rate of working fluid in ORC, h_{21} and h_{22} are the enthalpy values at points of 21 and 22, η_{ORC} denotes the isentropic efficiency of ORC turbine,and η_{Gen2} is the efficiency of electricity generator 2.

Regenerator and Condenser model

$$m_{22}\left(h_{22} - h_{23}\right) = m_{32}\left(h_{33} - h_{32}\right) \tag{19}$$

$$m_{24}\left(h_{24} - h_{25}\right) = m_{35}\left(h_{35} - h_{34}\right) \tag{20}$$

where, m is the flow rate, and h is the enthalpy.

Steam Ejector Refrigerator model

A steam ejector refrigerator (SER) is installed at the outlet of the ORC turbine to make use of the steam outlet pressure as the primary motive flow in the steam ejector system. The SER cycle comprises of four components which are ejector, condenser, expansion valve and evaporator.

According to the mass and energy conservation laws, the mathematical model of these components are presented as below [14].

$$m_{23} + m_{28} = m_{24} \quad (21)$$

$$m_{23}h_{23} + m_{28}h_{28} = m_{24}h_{24} \quad (22)$$

$$\lambda_{SER} = m_{28} / m_{23} \quad (23)$$

$$h_{26} \approx h_{27} \quad (24)$$

where, m is the mass flow rate of working fluid in ORC, h is the enthalpy, λ_{SER} is called the entrainment ratio of the ejector and plays an important role in the SER cycle.

The cooling capacity of the SER cycle can be evaluated as:

$$Q_{cooling} = m_{27}\left(h_{28} - h_{27}\right) = m_{29}\left(h_{29} - h_{30}\right) \quad (25)$$

3.4 System performance criteria

The performance of the Micro CCHP system can be evaluated by SOFC electrical efficiency, the overall system electricity generation, the overall electrical efficiency, the overall system primary energy and the exergy efficiencies, which can be defined as blow:

SOFC electrical efficiency:

$$\eta_{SOFC} = \frac{W_{SOFC}}{m_{CH_4} Q_{CH_4,LHV}} \quad (26)$$

Overall system electricity generation:

$$W_{system,ele} = W_{SOFC} + W_{MGT} + W_{ORC} - \sum W_{pump,COM} \quad (27)$$

Overall system electrical efficiency:

$$\eta_{system,ele} = \frac{W_{system,ele}}{m_{CH_4} Q_{CH_4,LHV}} \quad (28)$$

Overall system primary energy efficiency:

$$\eta_{system,\text{energy}} = \frac{W_{system,ele} + Q_{heating} + Q_{cooling}}{m_{CH_4} Q_{CH_4,LHV}} \quad (29)$$

Overall system exergy efficiency:

$$\eta_{system,exergy} = \frac{Exergy_{in} - I_{total}}{Exergy_{in}} \quad (30)$$

where, $Exergy_{in}$ is the input exergy of overall system, and I_{total} denotes the exergy loss of overall system.

4. Results and Discussion

Some representative researches of CCHP system based on SOFC have been presented and discussed [15-17]. The Micro CCHP system in this paper is simulated under the conditions listed in Table 1 and the results are validated using available data in the literature [4]. Table 2 shows the simulation results of different points in the Micro CCHP system in summer and winter. The simulation results in Table 3 are calculated under the design conditions. According to Table 3, it can be recognized that the SOFC electrical efficiency, the system electrical efficiency, the system exergy efficiency, the primary energy efficiency in summer mode are 44.79%, 66.84%, 64.39% and 91.21% respectively. In winter mode, the primary energy efficiency is 79.43% which is 11.78% lower than that in summer nevertheless the system electrical efficiency and the system exergy efficiency are 0.13% and 1.49% higher respectively.

Table 1. Parameters for simulating the micro CCHP system

Parameter	Value
Ambient temperature/K	298.15
Ambient pressure/Kpa	101.3
SOFC active surface area/cm^2	270
Number of cell	4000
Fuel utilization factor/%	85
SOFC inlet temperature/K	700
SOFC working pressure/ Kpa	810.6
Steam to Carbon Ratio	2
Air compressor efficiency/%	75
Fuel compressor efficiency/%	80
Pump efficiency/%	80
MGT efficiency/%	85
DC-AC inverter efficiency /%	98
Generator efficiency/%	95
ORC turbine efficiency/%	85
ORC turbine inlet pressure/Kpa	1600
Condensing temperature /K	303
Ejector entrainment ratio	0.27

Table 2. Simulation results of different points of the Micro CCHP system in summer (winter)

Point	T/K	P/Kpa	Flow/ mol/s	Point	T/K	P/Kpa	Flow/ mol/s
0	700	810.6	7.0	19	298.15	101.3	13.91
1	1138	810.6	6.184	20	338.15	101.3	13.91
2	1430	810.6	8.50	21	555.7	1600	10.00
3	982	101.3	8.50	22	536.7	800	10.00
4	919.4	101.3	8.50	23	311.4	800	10.00
5	901.6	101.3	8.50	24	303(311.4)	402.5(800)	12.70(10.00)
6	703.7	101.3	8.50	25	298.15	402.5(800)	12.70(10.00)
7	548.7	101.3	8.50	26	298.15 (—)	402.5(—)	2.70(—)
8	298.15	101.3	7.00	27	278(—)	186.6(—)	2.70(—)
9	612.4	810.6	7.00	28	283(—)	186.6(—)	2.70(—)
10	298.15	101.3	0.50	29	285.15(—)	101.3(—)	126.4(—)
11	496.2	810.6	0.50	30	280.15(—)	101.3(—)	126.4(—)
12	700	810.6	0.50	31	298.15	402.5(800)	10.00
13	298.15	101.3	1.00	32	299.57	1600	10.00
14	298.21	810.6	1.00	33	528.7	1600	10.00
15	700	810.6	1.00	34	293.15	101.3	180.00(52.04)
16	700	810.6	1.50	35	298.15	101.3	180.00(52.04)
17	1138	810.6	2.5	36	—(311.4)	—(800)	—(10.00)
18	393.15	101.3	8.50				

Table 3. Simulation results of the Micro CCHP system in summer (winter)

Parameter	Value
SOFC operating temperature/K	1138
SOFC current density/ A/m^2	2916
SOFC voltage/V	0.5813
SOFC electrical power/KW	179.4
MGT electrical power/KW	142.6
ORC electrical power/KW	23.28 (23.81)
Air compressor power/KW	65.524
Fuel compressor power/KW	4.068
Water pump power/KW	0.016
Pump power of ORC/KW	2.049 (1.524)
Net electrical power of system/KW	275.7 (276.3)
Domestic hot water capacity/KW	41.93
District Cooling capacity/KW	47.68(—)
SOFC electrical efficiency/%	44.79
SOFC/MGT electrical efficiency/%	63.02
Electrical efficiency of system/%	68.84 (68.97)
Exergy efficiency of system/%	64.39 (65.88)
Primary energy efficiency/%	91.21(79.43)

The exergy destruction ratios of the Micro CCHP system components in summer mode are presented in Fig.3.The results show that the mainly exergy destructions are in SOFC, after burner and Preheater 3 (PH3) which count for 29%, 17%, 12% of the total exergy destruction respectively. In SOFC, the reforming, shifting, electrochemical reactions of fuel and air are irreversible which leads to the biggest exergy destruction. The combustion process happened in after burner also has a large irreversibility and it brings a bigger exergy destruction than other components except SOFC. In PH3, the water needs a large amount of heat to be transformed from liquid to vapour, so the temperature difference of heat transfer between point 5 and 6 is nearly 200 K which is big enough to cause an exergy destruction of 12%. By exergy analysis, it's obvious to find which are the main components to improve the efficiency of the Micro CCHP system and how to select the most proper operating parameters is also feasible.

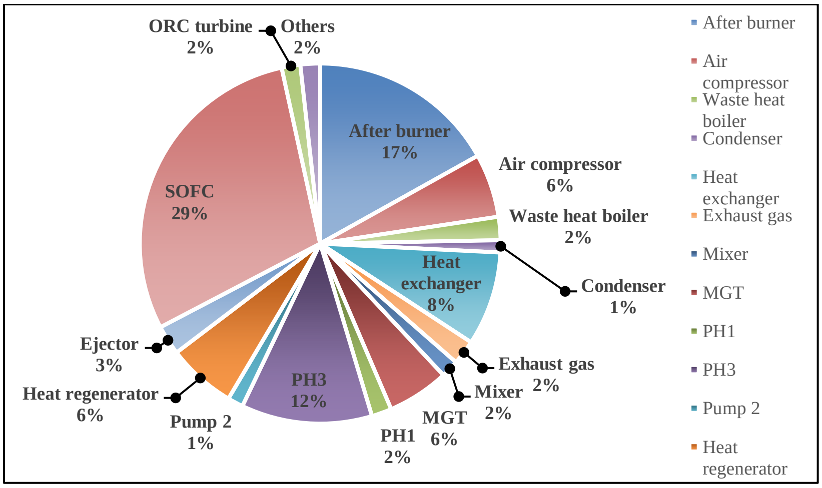


Fig. 3. The exergy destruction ratio for each component of the Micro CCHP system in summer

When one parameter is changed, the other parameters remain constant under the off-design conditions in this paper.

Fig.4 depicts the impacts of fuel flow rate on the system performances. It can be observed from Fig.4 (a), the electricity outputs of SOFC, SOFC/MGT and overall CCHP system increase simultaneously when the fuel flow rate increases. In Fig.4 (b) and (c) , the electrical efficiencies of the SOFC/MGT, CCHP system increase firstly and have a slight decrease next along with increase in the fuel flow rate. When the fuel flow rate is 0.63 mol/s , the efficiency of SOFC can reach a maximal value of 45.22%. The exergy efficiency of system increases with increase in the fuel flow rate while the overall system primary energy efficiency reduces. It can be explained as that: when the fuel flow rate increases, the energy input of the Micro CCHP system increases, and the electricity efficiencies increase as well as the increase in electricity generation. Nevertheless the electricity generation's increasing can't keep up with the increasing of energy input, as a result, the overall system primary energy efficiency decreases. As shown in Fig.4 (d), the heating capacity and ORC electricity generation both increase with increase in the fuel flow rate owing to the adding of the waste heat in the exhaust gas from MGT and the waste heat boiler can obtain more heat of higher grade. The cooling capacity remains the same because the designed parameters of ORC have not been changed.

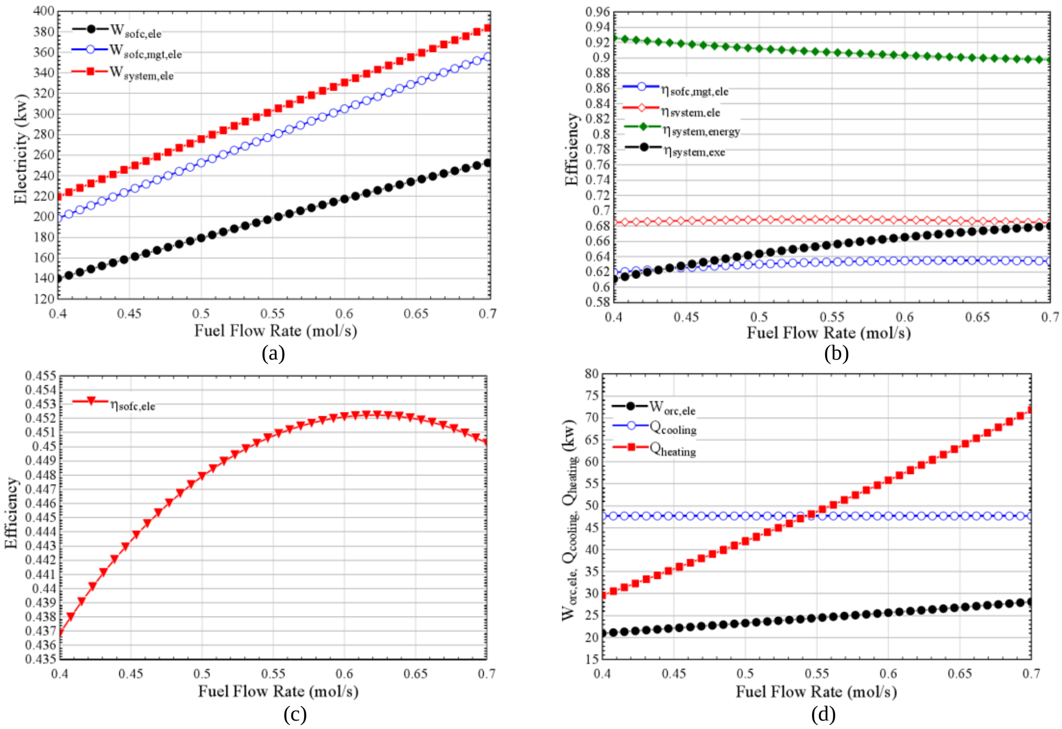


Fig.4 Effects of fuel flow rate on the system performances

Fig.5 reveals the influences of steam to carbon ratio on the system performances. As shown in Fig.5 (a),the electricity outputs of SOFC reduces with increase in the steam to carbon ratio, at the same time the electricity output of MGT has a slight raise smaller than the decrease of SOFC, leading to a decrease in electricity output of the overall CCHP system. In Fig.5 (b) and (c), the electrical efficiencies of the SOFC and overall system, the primary energy efficiency, the system exergy efficiency all decrease with increase in the steam to carbon ratio, whereas the electrical efficiency of SOFC/MGT increases. It can be explained that when the steam to carbon ratio increases, the pressure of water vapour increases, leading to the reduction of the temperature and voltage in SOFC. Although there are more water vapour entering the MGT turbine and making contributions to the electricity generation of MGT, the output of SOFC reduces more. At the same time, the water vapour cools the exhaust gas from SOFC/MGT, as a result, the heat capacity in waste heat boiler decreases which leads to the reductions of the heating capacity and ORC electricity generation shown in Fig.5 (d).

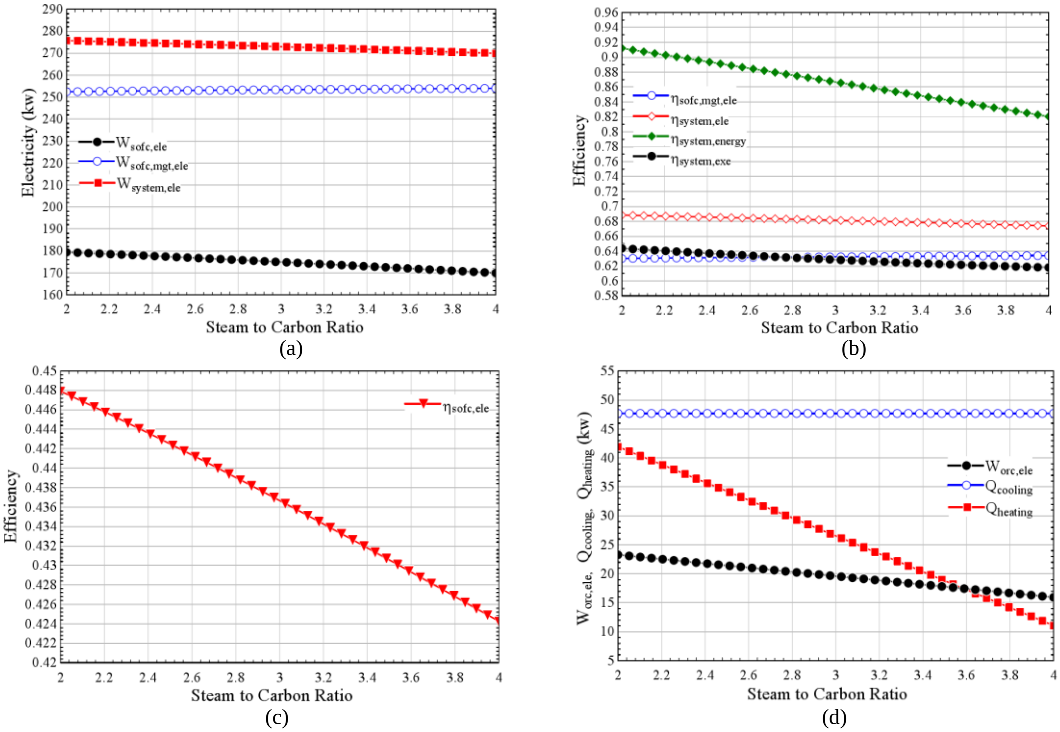


Fig.5 Effects of steam to carbon ratio on the system performances

Fig.6 represents the impacts of the mass flow rate of ORC on the system performances. In Fig.6(a), the electricity output of ORC and the cooling capacity of SER both increase obviously along with increase in the mass flow rate of ORC, whereas the heating capacity of system has a reduction. When the mass flow rate increases, more heat is exchanged in the waste heat boiler and less heat is remained to supply domestic heating. In Fig.6(b), the exergy efficiency of system decreases with adding the mass flow rate while the system electricity and the primary energy efficiency increase. The results indicate that changing the mass flow rate of ORC is an effective way to regulate the capacity of cooling, heating and power simultaneously.

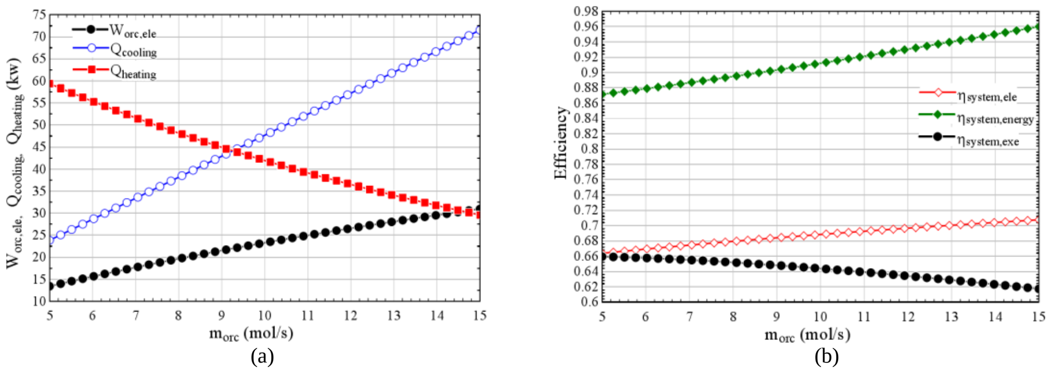
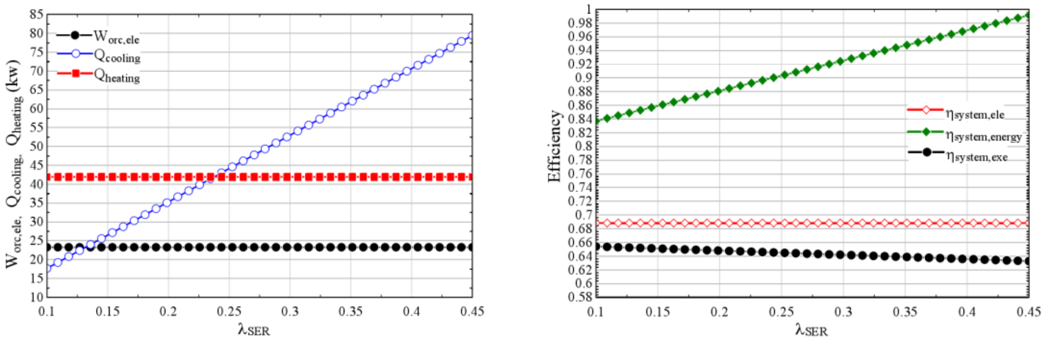


Fig.6 Effects of ORC mass flow rate on the system performances

Fig.7 illustrates the effects of the ejector entrainment ratio on the system performances. As indicated in Fig.7 (a), the ejector entrainment ratio almost has no effects on the electricity output of ORC and heating capacity of CCHP system. When the ejector entrainment ratio increases, the cooling capacity of SER has an obvious raise. From Fig.7 (b), the electricity efficiency of system remains at a value of 68.84% and the primary energy efficiency increases with increase in the ejector entrainment ratio, however, the exergy efficiency of CCHP system decreases. The results show that altering the ejector entrainment ratio can adjust the capacity of cooling on the premise of offering stable heating and power.



(a) (b)

Fig.7 Effects of ejector entrainment ratio on the system performances

5. Conclusions

This paper proposed a Micro CCHP cycle comprising of a SOFC/MGT hybrid system as the main prime mover, an ORC Cycle as the prime mover, and a SER Cycle as the heart of the cooling cycle and some heat recovery components such as regenerator, waste heat boiler and heat exchangers. The system can simultaneously supply domestic hot water, district cooling and electricity of small scale in hot climates. Based on the developed mathematical model and energy-exergy analysis on the effects of some key parameters on the Micro CCHP system performances, the main conclusions can be summarized as follows:

- The SOFC and overall system electrical efficiencies are 44.79% and 68.84% under the given conditions in summer, and the Micro CCHP system has more advantages on the electricity generation than the simple SOFC, MGT or their hybrid system. When the fuel flow rate is 0.63 mol/s, the electricity efficiency of SOFC can reach a maximal value of 45.22%.
- The primary energy efficiency of the whole CCHP system decreases with increase in the fuel flow rate and the steam to carbon ratio. In summer mode, the primary energy efficiency and system exergy efficiency can reach 91.21% and 64.39% respectively. The primary energy efficiency in summer is 11.78% higher than that in winter.
- The SOFC, after burner and PH3 count for 58% of the total exergy destruction in Micro CCHP system, which are the key components to be improved to increase the whole CCHP system efficiencies.
- The mass flow rate of ORC and the ejector entrainment ratio have positive effects on improving the cooling capacity of SER cycle. The results shows that the mass flow rate of ORC is a key parameter in ORC system and can be changed to adjust the capacity of cooling and heating to cater to the domestic demands. When the heating and power requirements is invariant, changing the ejector entrainment ratio might be better.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 51376110) and supported by the Fund for International Cooperation and Exchange of the National Natural Science Foundation of China (Grant No. 41761144067).

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