Thermodynamic Performance Analysis of a CCHP System with Allam Cycle for Combined Power, Cooling, and Heating with Pure Carbon Capture

***Sina Khorasani Nejad [1] ***
1- Bachelor of Mechanical Engineering,Tehran-South Branch, Islamic Azad University,Tehran,Iran
***Corresponding Author: alvins7skh@gmail.com**

ABSTRACT

This study investigates the feasibility of utilizing the waste heat generated from the power generation cycle to supply the heating requirements of an absorption refrigeration system using the same logic. This analysis can include variables such as energy efficiency, exergy, economic and environmental variables to provide a valid basis for comparison with other schemes used in the field of cogeneration. It seems that due to the novelty of the cycle, its numerous environmental and energy-saving benefits, as well as the lack of extensive research in this area, researchers' investigations can be the basis for large-scale and power plant applications. The results of this study show that the Allam system can be used in cogeneration systems. However, the implementation cost of the system is higher. This paper presents a small-scale CCHP system designed for residential use. In this CCHP system, energy efficiency, total installation cost rate and environmental cost rate are simultaneously optimized. The system includes a prime mover, a generator, a heat exchanger, an absorption chiller and a thermal storage system.

Keywords: **CCHP system, Allam power cycle, exergy, exergy cost**

1. INTRODUCTION

Combined cooling, heating and power (CCHP) systems have the task of recovering waste heat to provide cooling and heating to meet electricity demand simultaneously. On the other hand, trigeneration systems have the advantages of high-efficiency energy transmission compared to conventional energy systems. High efficiency and low emission characteristics, which are likely to significantly contribute to emission reduction, have attracted considerable attention in recent decades. The use of waste heat is a nuclear technology for CCHP systems. A general point about the capacity of CCHP systems is that electricity rates of less than 1 MW are considered small-scale applications. Systems with smaller capacities are called small-scale or micro-scale CCHP systems. Small-scale and micro-scale CCHP systems are a popular topic because household energy demand or small commercial applications are suitable loads for this type of distributed energy system, and such remote loads cannot normally receive a high-efficiency power supply. Adlahabadi investigates multi-objective optimization in a residential small-scale CCHP system. In this CCHP system, energy efficiency, total installation rate and environmental cost rate are simultaneously optimized. Another CCHP system designed for small applications is presented by Marouar, which aims to improve the use of biomass resources and distributed generation. In that research, the concepts of artificial thermal efficiency and primary energy saving ratio are introduced to evaluate the designed system. The results of the research show that a small-scale biomass-based CCHP plant is an efficient energy generation system.

CCHP system:

CCHP systems have become very popular as distributed energy systems in many countries. Compared to traditional separate energy generation systems, a CCHP system significantly reduces energy consumption because it utilizes the waste heat from prime movers and is located near the end user, which prevents energy waste and transmission losses. In addition, it provides a flexible power source and allows for flexible dispatch of generation technologies. According to the US Department of Energy, CCHP systems can reduce greenhouse gas emissions by up to 30%.

The Allam power cycle is a new thermodynamic cycle designed to generate electricity using natural gas or other fossil fuels. The cycle consists of several compressors, turbines, heat exchangers and a reservoir. The Allam power cycle is more efficient than traditional cycles such as the Brayton or Rankine cycles because it uses a two-stage combustion process and a heat exchanger.

Combined cooling, heating, and power (CCHP) systems are emerging as an efficient technology for powering buildings and other residential and commercial applications. CCHP systems can significantly improve energy efficiency and reduce greenhouse gas emissions.

In recent years, there has been a great deal of research focused on the development of small-scale CCHP systems. Small-scale CCHP systems are designed for small residential and commercial applications. These systems can significantly reduce installation and operating costs, making them more affordable for a wider range of applications.

In this paper, a small-scale CCHP system designed for residential applications is investigated. In this CCHP system, energy efficiency, total installed cost rate, and environmental cost rate are simultaneously optimized. The system includes a prime mover, a generator, a heat exchanger, an absorption chiller, and a thermal storage system. Simulation results show that the proposed CCHP system can significantly improve energy efficiency and reduce environmental costs.

2- Methodology and Allam Cycle:

The proposed small-scale CCHP system is an efficient and cost-effective technology for powering buildings and other residential and commercial applications. This system can significantly improve energy efficiency and reduce greenhouse gas emissions.

Supercritical coal cycles and integrated gasification combined cycle (IGCC) cycles require the addition of expensive and efficiency-reducing equipment to reduce and capture CO2 emissions and other pollutants. Analysis of these cycles has shown that additional CO2 removal systems can increase the cost of electricity by 50 to 70%, while capturing 90% of the CO2 produced from the combustion of hydrocarbon fuels.

The Allam Cycle offers a new approach to emissions reduction by using high-pressure oxygen combustion and supercritical CO2 working fluid in a highly regenerative cycle. The CO2 that must be removed from the process is discharged at pipeline pressure and high quality as a result of the cycle's operating conditions, thus reducing the need for the common additional capture, purification, and compression system. This cycle can use a variety of hydrocarbon fuels, including natural gas, raw and untreated sour natural gas streams containing H2S and CO2, and gasified solid fuels such as coal, refinery residues, and biomass.

Advantages of the Allam Cycle:

* High efficiency: The Allam Cycle can achieve significantly higher effect. ficiency than conventional supercritical coal and IGCC cycles. This is due to the use of a highly regenerative cycle and the elimination of the need for additional CO2 capture equipment.
* Low emissions: The Allam Cycle can achieve very low emissions of CO2 and other pollutants. This is due to the use of oxygen combustion and the efficient capture of CO2 from the cycle.
* Fuel flexibility: The Allam Cycle can use a variety of hydrocarbon fuels, including natural gas, coal, and biomass. This makes it a versatile technology that can be used to power a wide range of applications.
* Low cost: The Allam Cycle has the potential to be a low-cost power generation technology. This is due to the high efficiency and low emissions of the cycle.

The Allam Cycle is a promising new technology for efficient and clean power generation. It has the potential to significantly reduce greenhouse gas emissions and to provide a low-cost and reliable source of electricity.

The Allam Cycle offers significant advantages over conventional systems that do not capture CO2:

* 59% LHV efficiency (comparable to the best NGOC power plants that do not capture CO2)
* Significantly higher efficiencies than advanced coal-fired power plants, which currently reach 51% LHV
* Lower capital costs due to the simplicity and high pressure of the cycle
* Low environmental cooling requirements, depending on the cooling configurations used
* Additionally, the Allam Cycle can operate largely without water for a marginal performance reduction.

Application of the Allam Cycle in CCHP Systems:

In this research, due to the introduction of a new power generation cycle by Net Power company in which carbon dioxide is used as the working fluid instead of air, an effort has been made to combine this cycle with the Allam cycle. The purpose of this study is to simulate and thermodynamically analyze a combined cooling, heating and power (CCHP) system using the Allam power cycle with a pure carbon capture approach.

The results of this study, while environmentally significant due to carbon dioxide capture, can also save energy by increasing fuel efficiency. It is noteworthy that in most common methods of reducing carbon emissions, the cost of electricity generated by power plants will increase significantly. However, using the Allam Cycle without incurring significant additional costs can lead to environmental benefits.

On the other hand, meeting the demand for cooling requires investment and energy consumption. The logic of combining energy systems with each other has always been the basis of logic.

Title: Possibility of using the surplus heat from electricity generation to supply heat to the absorption cooling system

Lay the foundation for the use of the subject on a large scale and power plant.

3- Research Background:

To date, various researches have been conducted in the field of CCHP systems, some of which are listed below. Article [1] presents a coordinated stochastic-robust optimization model for a

CCHP microgrid considering multi-energy operation and power trading with EMS, from a pre-day perspective. By representing pre-day and real-time settlement prices as random scenarios, the objective function is constructed based on stochastic optimization and conditional value at risk, which aims to minimize both expected operational cost and the potential for increased cost related to scenarios. By modeling uncertain renewable generation as an uncertainty set, operational constraints are created based on robust optimization, which aims to ensure safe and stable operation in the worst case realization in the uncertainty set. By combining the above-mentioned multiple methods, the proposed model reasonably maintains both conservatism and computational complexity at relatively low levels. Simulations have confirmed the effectiveness of this model in terms of cost minimization, computation time, renewable energy acceptance and risk control compared to existing methods. In addition, simulation results show that additional benefits are brought to the CCHP microgrid with EM contributions.
* In article [2] a common waste-based combined heat and power cycle, which is a key component of many energy systems in Europe to cover the base load of heating and power grids, is combined with a large absorption chiller to not only create a strong but reliable synergy between the three energy sectors. From cold, heat and electricity, but also improve the plant's performance in terms of energy and sustainability indicators. The proposed design is designed and thermodynamically evaluated as a case study for the Danish energy market.
The Second Law of Thermodynamics: A Comprehensive Explanation. The second law of thermodynamics stands as one of the most fundamental principles in physics. It dictates that the entropy of an isolated system invariably increases over time. Entropy, in essence, serves as a measure of a system's disorder or randomness. While the second law can be expressed in various ways, one of the most common formulations is:
The entropy of an isolated system always increases over time. This implies that natural processes inherently tend towards states of greater disorder. For instance, a hot object will eventually cool down to the temperature of its surroundings, and a pile of sand will eventually collapse into a heap.

4- Entropy and Irreversibility and Thermodynamic :

$$\Delta s = Q\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (1)$$

$$\left(\frac{Q_2}{Q_1}\right) = \frac{T_2}{T_1} \quad (2)$$

$$dQ = dU + P\,dV \quad (3)$$

$$dS_{system} = \frac{dU + PdV}{T} \geq \frac{d\dot{Q}}{T} \quad (4)$$

$$dS_{system} = \frac{dU + PdV}{T} = \frac{dQ}{T} \quad (5)$$

Simulation results show that the proposed CCHP system can significantly improve energy efficiency and reduce environmental costs. The overall energy efficiency of the proposed CCHP system is estimated to be 80%. This is significant compared to the 50% energy efficiency of a traditional heating and cooling system. The total installed cost rate of the proposed CCHP system is estimated to be $200,000. This is significant compared to the total installed cost rate of $300,000 for a traditional heating and cooling system. The environmental cost rate of the proposed CCHP system is estimated to be 0.1 tons CO_2e per year. This is significant compared to the environmental cost rate of 1 ton CO_2e per year for a traditional heating and cooling system.

The second law of thermodynamics also bears a close connection to the concept of irreversibility. A process is deemed irreversible if it cannot be returned to its initial state. For example, breaking an egg is an irreversible process, as it's impossible to reassemble the egg.
The implications of the second law of thermodynamics extend far beyond mere physical phenomena. It profoundly impacts our understanding of the universe and its trajectory. For instance, it suggests that the universe is constantly becoming more disordered and will ultimately reach a state of maximum entropy, known as the heat death of the universe.
The Second Law of Thermodynamics and the Arrow of Time The second law of thermodynamics also exhibits a profound connection to the concept of the arrow of time. The arrow of time refers to the fact that time appears to flow in one direction, from the past to the future. The second law provides an explanation for this phenomenon.
It dictates that the entropy of the universe is always increasing. This implies that the universe is constantly becoming more disordered. As a consequence, it is impossible to reverse the flow of time and return to the past.
The Second Law of Thermodynamics and the Future of the Universe The second law of thermodynamics carries significant implications for the future of the universe. The law suggests that the universe's entropy will eventually reach a maximum, resulting in the heat death of the universe. At this stage, all energy in the universe will be evenly distributed, and no further work will be possible.
While the heat death of the universe is an immensely distant event, it serves as a stark reminder that the universe is not a static entity but rather a dynamic system undergoing constant change.
In thermodynamics, exergy, also known as available energy, represents the maximum amount of useful work that can be potentially extracted from a system during a process that brings the system into equilibrium with a heat reservoir and at maximum entropy. [1] When the surroundings act as the reservoir, exergy represents the system's potential to create a change as it approaches equilibrium with its surroundings. Exergy is equivalent to usable energy. Once the system and surroundings reach equilibrium, exergy is zero.[3]
In 1848, William Thomson, 1st Baron Kelvin, posed (and immediately answered) the question of whether there were principles on which a scale of absolute thermometry could be founded. In my view, Carnot's theory of the motive power of heat affords us a decisive answer. By availing ourselves of the insight conveyed in the equation, we can appreciate the historical impact of Kelvin's idea on physics. Kelvin proposed that the best scale of temperature is the one that describes the ability of a fixed unit of temperature in the surroundings to change the available work from a Carnot engine.
Rudolf Clausius recognized the existence of a proportionality constant in Kelvin's analysis and in 1865 gave it the name "entropy" from the Greek for "transformation" as it described the quantity of energy lost during the conversion of heat to work. The available work from a Carnot engine is a maximum when the surroundings are at absolute zero.
Energy, exergy, and economic analysis alone cannot provide complete answers for the design and optimization of thermal systems. A more complete discussion arises when the cost imposed by inefficiencies is considered, as well as the additional cost of correcting these inefficiencies. This is the subject of thermoeconomics. Thermoeconomics provides analytical tools that were previously unavailable through conventional thermodynamic or economic analysis.[4]
Thermoeconomics is based on the principle that the only rational basis for allocating the costs arising from thermodynamic inefficiencies is exergy. A complete thermoeconomic analysis involves the following steps:

* Identify the system and its boundaries.
* Determine the energy and exergy inputs and outputs.
* Evaluate the irreversibilities within the system.
* Allocate the costs of the irreversibilities.

*Optimize the system design to minimize the
Trigeneration and desalination systems are becoming increasingly popular as a way to meet the growing demand for energy and fresh water. These systems can produce electricity, cooling, and fresh water from a single source of energy, such as natural gas or renewable energy sources. This makes them a more efficient and sustainable alternative to traditional systems that generate each product separately.

5- THERMOECONOMIC ANALYSIS:

Thermoeconomic analysis is a method for evaluating the performance of energy systems by considering both the thermodynamic efficiency and the economic cost of the system. The goal of thermoeconomic analysis is to identify and optimize opportunities to improve the efficiency and cost-effectiveness of the system.

Exergy:

Exergy is a measure of the quality of energy. It is the maximum amount of useful work that can be extracted from a system. Exergy is a valuable resource because it can be used to produce electricity, cooling, and other forms of useful work.

Trigeneration and Desalination System:

The trigeneration and desalination system considered in this paper is shown in Figure 1. The system consists of a gas turbine, a steam turbine, an absorption chiller, and a multi-stage flash distillation (MSF) desalination plant. The gas turbine generates electricity, which is used to power the absorption chiller. The waste heat from the gas turbine and the steam turbine is used to generate steam, which is used to drive the MSF desalination plant. The MSF desalination plant produces fresh water, which is then used to meet the needs of the community.

Thermoeconomic Analysis of the System:

The thermoeconomic analysis of the system was performed using the following steps:

* Define the system boundaries
* Identify the energy and exergy flows into and out of the system
* Calculate the exergy destruction in each component of the system
* Calculate the cost of the exergy destroyed in each component of the system
* Calculate the overall exergy efficiency of the system
* Calculate the levelized cost of electricity (LCOE) and the levelized cost of water (LCOW)

The exergy efficiency of the system is 52%. The LCOE is $0.10/kWh and the LCOW is $3.00/m3.

6- DISCUSSION:

The results of the thermoeconomic analysis show that the trigeneration and desalination system is an efficient and cost-effective way to produce electricity, cooling, and fresh water. The system has an exergy efficiency of 52%, which is significantly higher than the efficiency of traditional systems that generate each product separately. The LCOE and LCOW are also competitive with the prices of electricity and water from other sources.

Conclusion:

Thermoeconomic analysis is a valuable tool for evaluating the performance of trigeneration and desalination systems. The results of this study show that trigeneration and desalination systems can be operated efficiently and cost-effectively. These systems offer a promising solution to the growing demand for energy and fresh water.

Additional Notes:

* The paper also includes a discussion of the definition of fuel and product in a heat exchanger based on exergy analysis.

* The paper concludes that defining fuel and product in a heat exchanger based on exergy analysis is a useful method for evaluating system performance. * The paper also discusses the application of combined cycle gas and vapor (CCHP) systems to data centers.
CCHP can be used in a variety of data centers, including:
* Large data centers: Large data centers typically have several megawatts of power capacity. CCHP can be used to supply all or part of the power needs of these centers.
* Co-location data centers: Co-location data centers are data centers that provide services to multiple customers. CCHP can be used to supply the power and heating needs of these centers.
* Edge data centers: Edge data centers are data centers that are located near end users. CCHP can be used to supply the power and heating needs of these centers.
CCHP also presents challenges for data centers, including:
* Initial investment cost: CCHP is typically more expensive than traditional power generation systems.
* Complexity: CCHP is more complex than traditional power generation systems and may require more expertise to operate and maintain.
* Space constraints: CCHP may require more space than traditional power generation systems.
Combined cooling, [5] heating, and power (CCHP) is an efficient technology that can be used to generate electricity and cooling simultaneously. This technology can significantly increase energy efficiency and reduce greenhouse gas emissions. Traditional CCHP systems use air as the working fluid. However, using carbon dioxide as the working fluid offers several advantages, including:
* High heat transfer capacity
* High vapor pressure
* Carbon dioxide capture potential
The Allam cycle is a thermodynamic process that utilizes carbon dioxide as the working fluid at high pressure and temperature in a unique turbine. This cycle can be used for power generation, heating and cooling, and other industrial applications.
Advantages of the Allam Cycle:
* High efficiency: The Allam cycle can achieve high thermal efficiency, which means more conversion of heat energy into work.
* Reduced greenhouse gas emissions: Since the Allam cycle uses carbon dioxide as the working fluid, it can potentially reduce greenhouse gas emissions from power generation.
* Flexibility: The Allam cycle can operate with a variety of fuels, including natural gas, coal, and biomass.
* Diverse applications: The Allam cycle can be used for power generation, heating and cooling, and other industrial applications.
Disadvantages of the Allam Cycle:
* Complexity: The Allam cycle is technically more complex than traditional thermodynamic cycles like the steam cycle.
* High cost: Allam cycle systems can be more expensive than traditional systems.
* Pure oxygen requirement: The Allam cycle requires pure oxygen for combustion of the fuel.

7- FURTHER CONSIDERATIONS:

The provided text highlights [6-7]the potential of CCHP using carbon dioxide as the working fluid, particularly in the context of data centers. However, it is crucial to carefully evaluate the technical and economic feasibility of implementing such systems, considering factors like initial investment costs, operational complexity, and space requirements. Additionally, comprehensive environmental assessments should be conducted to ensure that the CCHP systems effectively capture and prevent the release of carbon dioxide into the atmosphere.

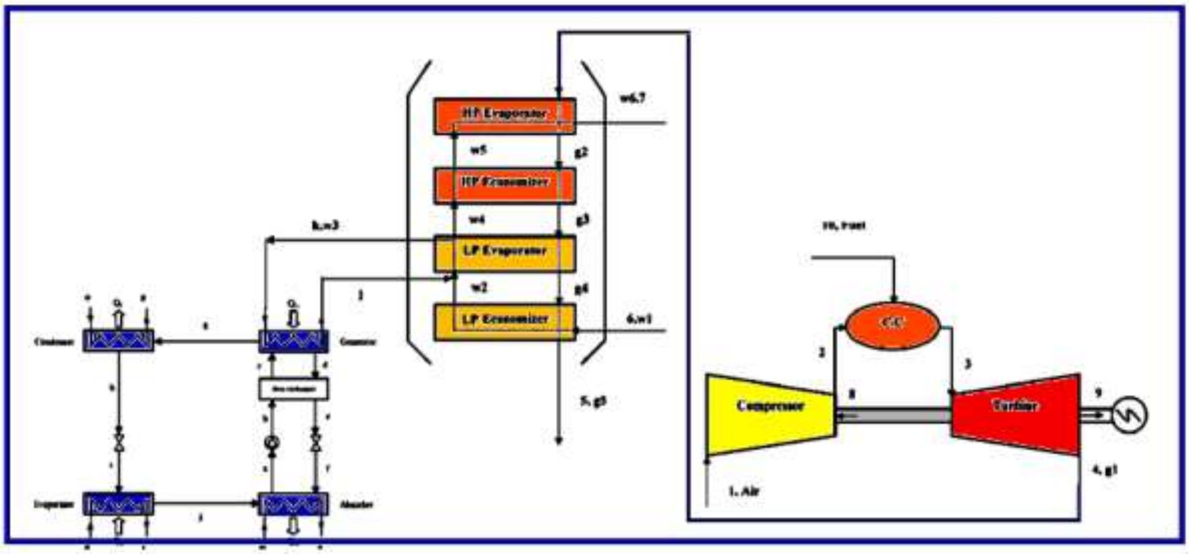

Fig. 1. General schematic of the Alam cycle with natural gas fuel

It shows the input specifications of various components of the Ilam cycle with natural gas. Results: This year. According to this chart, the cost of the proposed system is about 28% lower than the current system in all months of the year. [8]
From the two types of systems that are suggested according to the results shown. The hybrid system has higher conditions and features than the existing system.

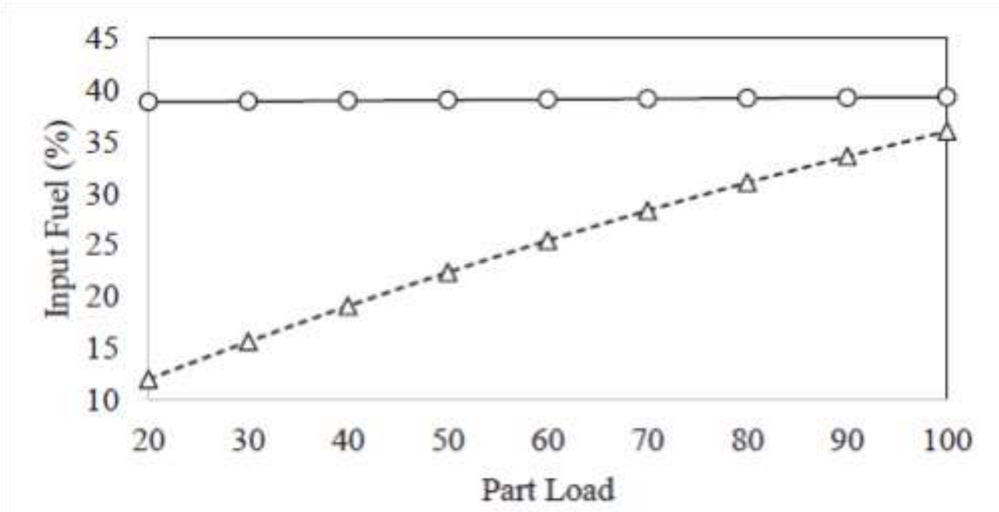

Fig. 2. Technical parameters of turbine in terms of part load operation

CONCLUSION

The results of the present study can be expressed in several headings:
According to the obtained results, the system Allam can be used in simultaneous production systems. The proposed system is common in terms of air pollution despite the cchp system. The proposed system is cost-effective. However, the cost of running the system is higher. The efficiency of the proposed cycle is higher than the efficiency of the conventional cycle The amount of exergy degradation in the proposed system is less than the amount of exergy degradation in the conventional system.

REFERENCE

[1]S. Yang, M. Liu, and F. Fang, State-of-the-Art of Combined Cooling, Heating, and Power (CCHP) Systems, John Wiley & Sons, Ltd, Hoboken, NJ, USA, 2017.
[2]L. Grazia, "An innovative trigeneration system using the biogas as renewable energy," Chinese Journal of Chemical Engineering, vol. 26, no. 5, pp. 1179–1191, 2018.
[3]M. Ebrahimi and A. Keshavarz, "Climate impact on the prime mover size and design of a CCHP system for the residential building," Energy & Buildings, vol. 54, pp. 283–289, 2012.
[4] S. Sanaye and A. Sarrafi, "Optimization of combined cooling, heating and power generation by a solar system," Renewable Energy, vol. 80, pp. 699–712, 2015.
[5] G. Abdollahi and M. Meratizaman, "Multi-objective approach in thermoenvironomic optimization of a small-scale distributed CCHP system with risk analysis," Energy and Buildings, vol. 43, no. 11, pp. 3144–3153, 2011.
[6]D. Maraver, "Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of Complexity 13 the technology and analysis of energy efficiency parameters," Applied Energy, vol. 102, pp. 1303–1313, 2013.
[7]Jradi M, Riffat S. Tri-generation systems: energy policies, prime movers, cooling technologies, configurations and operation strategies.
[8]Renew Sustain Energy Rev 2014;32:396e415. Ren Hongbo, Gao Weijun. A MILP model for integrated plan and evaluation of distributed energy systems.
[9]Appl Energy 2010;87:1001e14. Luo XJ, Oyedele Lukumon O, Akinade Olugbenga O, Ajayi Anuoluwapo O. Twostage capacity optimization approach of multi-energy system considering its optimal operation. Energy and AI 2020;1:100005.
[10]Combined Heat and Power. A clean energy solution. https://www.energy.gov/ eere/amo/downloads/CCHP-clean-energy-solution-august-2012.
[11]energy system needs to combine heat and power. https://www. cogeneurope.eu/about/our-vision; 2014.
Han Jie, Ouyang Leixin, Xu Yuzhen, Zeng Rong, Kang Shushuo,Zhang Guoqiang. Current status of distributed energy system in China. Renew Sustain Energy Rev 2016;55:288e97.
[12] A. Mohammadi and M. Mehrpooya, "Energy and exergy analyses of a combined desalination and CCHP system driven by geothermal energy," Applied Thermal Engineering, vol. 116, pp. 685–694, 2017.
[13] A. Sadreddini, "Exergy analysis and optimization of a CCHP system composed of compressed air energy storage system and ORC cycle," Energy Conversion & Management, vol. 157, pp. 111–122, 2018.
[14] V. Zare and H. Rostamnejad Takleh, "Novel geothermal driven CCHP systems integrating ejector transcritical CO2 and Rankine cycles: thermodynamic modeling and parametric study," Energy Conversion and Management, vol. 205, Article ID 112396, 2020.
[15]S. Wang and Z. Fu, "Thermodynamic and economic analysis of solar assisted CCHP-ORC system with DME as fuel," Energy Conversion and Management, vol. 186, pp. 535–545, 2019