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Exergy analysis and optimization of an integrated micro gas turbine, compressed air energy storage and solar dish collector process

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ABSTRACT

An integrated micro gas turbine, compressed air energy storage and solar dish collector system is proposed and analyzed. The required equations for modeling different components of the system are presented. Performance of the system is analyzed by changing effective parameters including maximum and minimum pressure of the cavern, inlet temperature of the gas turbine and outlet mass flow rate of the cavern. Performance of the system is investigated by energy and exergy analyses methods. The results show that in design condition, the plants charging and discharging times are six and 5 h, respectively. During the operating time, the system consumes 152 kW h and produces 228 kW h. It is also capable of producing four tons of hot water. The highest exergy destruction occurs in dish collector. Optimization results indicate that round trip efficiency increases with the difference between the minimum and maximum pressure of the air cavern. In the optimum operating point, round trip efficiency of the system increases by 4.2% compared to the situation before optimization.

1. Introduction

Population growth and industrial development have increased energy demand in the last decades. Since the main source of world energy is fossil fuels, this increment in energy supply increased depletion of resources and raised environmental issues. Renewable energies are the promising solution to overcome the encountered problems (Mehrpooya et al., 2015). Solar energy as one of the most available renewable energy sources has been investigated for using in the hybrid energy systems. A novel power cycle which uses low-temperature solar energy is introduced (Mehrpooya et al., 2016). Performance of a hybrid solar photovoltaic-fuel cell system is investigated by dynamic modeling (Mehrpooya and Daviran, 2013). Concentrating solar power (CSP) systems are one of the most effective technologies which can be used to generate heat and power. Al-Soud and Hrayshat (2009) performed a feasibility study on utilization of CSP systems for generating electricity. Zhai et al. (2009) coupled a parabolic trough collector, a Rankine cycle and a refrigeration system to produce combined heat, power and cooling. Mokheimer et al. (2015) integrated parabolic trough collectors with steam production section of a combined cycle power plant and performed a feasibility study on the system. Many authors have studied heat transfer processes in solar dish receivers. Şener et al. (2015) studied the effects of solar irradiation and collector and receiver material in total heat loss from the receiver. Convective heat transfer in three different types of receivers at different inclination angles was investigated by (Sendhil Kumar and Reddy, 2008). Natural convection loss in three solar dish collector receivers with low aspect ratios was studied by (Paitoonsurikarn et al., 2004). They also considered the effect of wind speed and direction in combined heat loss of the receiver. Reddy and Kumar (2008) considered a two-dimensional simulation model of a modified cavity receiver and performed a numerical study. A 3-D numerical study on the same receiver was also done (Reddy et al., 2015). Madadi et al. (2015) investigated heat losses from an isotherm cylindrical cavity receiver. They considered the effect of wind speed and its direction, heat transfer fluid (HTF) mass flow rate, receiver geometry and inclination angle as effective parameters. Prakash et al. (2009) carried out numerical and experimental analysis on convective heat loss from a cylindrical cavity receiver at different inclination angles and different fluid inlet temperature. The results showed that increasing the fluid inlet temperature leads to an increase in the rate of convective heat loss. (Dehghan et al. (2015) studied combined heat transfer process in a heat

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exchanger filled with porous medium. Kumar and Reddy (2007) analyzed natural convection heat loss from a modified cavity receiver of fuzzy focal solar dish concentrator. Taumoefolau et al. (2004) used an electrically heated simulated solar cavity receiver for estimating heat losses at different inclination angles, from −90° to 90°, in different temperature ranges (450°C-650 °C) and in different ratios of the aperture diameter to cavity diameter of 0.5, 0.6, 0.75, 0.85 and 1.0. Paitoonsurikarn and Lovegrove (2006) performed a numerical simulation on three different cavity receivers. Based on the obtained results, an empirical model to predict the free convection heat loss of open cavity receivers was proposed.

Integrating energy systems with renewable energies has gained many attentions recently (Nastasi and Basso, 2016). Since, operating temperature of dish collectors is usually higher than 600 °C; they have the capability of coupling with other thermal cycles. Combination of Stirling engines with solar dish collectors are a common hybrid system for dish collectors (Mancini et al., 2003). Moghadam et al. (2013) used dish-Stirling as a micro combined heat and power (CHP) system for residential application and analyzed it in terms of energy, economic and environment. Ahmadi et al. (2013) carried out energy analysis on a solar powered Stirling engine and optimized power output and efficiency of the system. Wu et al. (2010) coupled a solar dish collector with an alkali metal thermal to electric converter (AMTEC). They showed that parabolic dish/AMTEC solar power system has some advantages over the dish-Stirling system. An alternative for Stirling engines to couple with solar dish collectors is the Brayton cycle. A method to design a cavity receiver especially for coupling dish collector and Brayton cycle was developed by (Wang et al., 2014). Aichmayer et al. (2015) designed a special solar dish collector receiver to integrate with a micro gas turbine (MGT). Le Roux et al. (2014) evaluated energy and exergy efficiencies of a solar receiver in a solar thermal Brayton cycle. By using the obtained results, an optimum receiver to concentrator area ratio was calculated. Exergy analyses of a hybrid power plant using low-temperature solar energy is investigated (Mehrpooya et al., 2016). Wang et al. (2014) designed a 25 kWe hybrid gas turbine-receiver unit and found the optimal dimensions of the receiver and impinging cooling system. (Jansen et al. (2015) performed a comparison between two different configurations of a hybrid dish collector and Brayton cycle. Aichmayer et al. (2014a,b) compared performance of a solar MGT cycle with a conventional diesel generator in terms of thermodynamic, economic and CO_2 production. A dish micro gas turbine system with a steam turbine were integrated (Aichmayer et al., 2014a,b) and performance of the system was compared with both conventional combined-cycle power plant and a hybrid solar-tower combined-cycle. Ragnolo et al. (2014) designed a small scale hybrid solar micro gas turbine. Efficiency of the designed system was 29.6%. The results showed that the MGT-Dish system could provide a more reliable electricity generation than the Dish-Stirling. The proposed system also had a better economic performance. Lanchi et al. (2015) studied OMSoP (Optimized Microturbine Solar Power System) project in which a dish collector coupled to a micro gas turbine. They analyzed the model to investigate its performance at different DNI (direct normal insolation) values.

The biggest problem with renewable energies is that they are intermittent. Solar energy technology is also suffering from this issue as it is not available during the nights. To overcome this, usually a thermal storage added to the cycle to store the surplus energy and use it during the nights. Owrak et al. (2015) placed a porous bed beneath the room to store the heat received from the sun. Then, this stored heat was used to heat a room. Unfortunately, thermal storage systems increase capital cost of the plant considerably. Therefore, some simpler energy storage systems are introduced. Compressed air energy storage (CAES) systems are one of these technologies which use electrical energy to drive a compressor to produce compressed air. Whenever needed, this compressed air could be used in a gas turbine to generate power. Currently, there are two operating CAES systems. The first one was built in 1978 in Germany which could produce 290 MW electricity for 3 h (Raju and Khaitan, 2012). The second one was built in Alabama in 1991. It has a 110 MW capacity and could supply the electricity for 26 h (Cavallo, 2007).

In recent years, many studies about the CAES have been published. Ibrahim et al. (2015) reviewed different topologies of CAES and wind turbines hybrid system. de Boer et al. (2014) compared three different types of energy storage systems, including power to gas, pumped hydro storage and compressed air energy storage at different wind power penetration levels. Zhao et al. (2015a) proposed a new system to recover the waste heat of charge and discharge modes of compressed air energy storage systems. To do so, they coupled the CAES with humid air turbine in a combined heat and power system. The results showed that the proposed system could improve the power output by 26% compared with the conventional CAES system. In another study (Zhao et al., 2015b), used a Kalina system as a bottoming cycle for a gas turbine which uses CAES system to recover the waste heat during discharge mode. Kantharaj et al. (2015) investigated an energy storage system which constitutes of compressed air and liquid air storages and perform energy analysis on air to liquid and liquid to air conversions. Zhao et al. (2016) studied charge and discharge processes of an axial turbine which uses a constant volume CAES under constant and variable turbine inlet pressure modes. They showed that in design condition, variable inlet pressure mode of the turbine results in higher exergy efficiency.

As mentioned above, many researchers used exergy analysis to evaluate the system performance. A new index based on the exergy concept is introduced to evaluate integrated cryogenic energy systems (Mehrpooya et al., 2011). Novel integrated liquefied natural gas and fuel cell electrochemical power plant processes are considered by exergy analysis method (Mehrpooya, 2016). Liquefied natural gas processes are evaluated by exergy analyses method (Vatani et al., 2014). Exergoeconomic evaluation of the single mixed refrigerant natural gas liquefaction processes is investigated (Mehrpooya and Ansarinasab, 2015a,b,c). (Said et al. (2016a,b) performed an experimental study on the effect of Aluminum oxide water Nano fluid as working fluid in a flat plate solar collector and calculated its exergy efficiency. Koroneos and Tsarouhis (2012) utilized exergy analysis and life cycle assessment to investigate performance of a solar heating and cooling system. Xydis (2013); Petrakopoulou et al. (2016) analyzed a solar-wind power system exergetically.

In this study, a new system is designed for domestic application in which a micro gas turbine, a CAES system and a solar dish collector are integrated for the first time. The proposed system could provide hot water as well as the electricity. Using micro gas turbines is a common way to produce electricity in residential scale. Utilizing the CAES system also allows us to produce electricity during the peak hours. Fortunately, peak hours of electricity usage coincide with the highest radiation of the sun. The proposed system has the capability of using this opportunity by introducing the solar dish collector to the system, which decreases the fossil fuel usage and as a result, alleviates the environmental problems. To investigate the performance of the proposed system, both energy and exergy analyses could be used. Exergy analysis is a better criterion than energy analysis, because energy transfer to the environment is the only source of inefficiency that is considered in the energy analysis, whereas exergy analysis takes into account the irreversibility of the system as well. A parametric study is also carried out to study the effect of different key parameters on the system