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Performance comparison of different supercritical carbon dioxide Brayton cycles integrated with a solar power tower

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ABSTRACT

In this study, a thermodynamic comparison of five supercritical carbon dioxide Brayton cycles integrated with a solar power tower was conducted. The Brayton cycles analyzed were simple Brayton cycle, regenerative Brayton cycle, recompression Brayton cycle, pre-compression Brayton cycle, and split expansion Brayton cycle. A complete mathematical code was developed to carry out the analysis. A heliostat field layout was generated and then optimized on an annual basis using the differential evolution method, which is an evolutionary algorithm. The heliostat field was optimized for optical performance and then integrated with the supercritical CO_2 Brayton cycles. Using the results of the optimization, a comparison of net power outputs and thermal efficiencies for these cycles was performed. The findings demonstrated that the highest thermal efficiency was achieved using the recompression Brayton cycle, at June noontime. The maximum integrated system thermal efficiency using this cycle was 40% while the maximum thermal efficiency of this cycle alone was 52%. The regenerative Brayton cycle, although simpler in configuration, shows comparable performance to the recompression Brayton cycle. This analysis was carried out for Dhahran, Saudi Arabia.

1. Introduction

The demand for energy is continually increasing while conventional fossil fuel energy resources are being consumed at an alarming rate. This predicament needs to be addressed. Reliable and more sustainable energy resources are required to compensate for the uncertainty surrounding the supply of fossil fuels. Renewable energy sources, such as solar, biomass, geothermal, wind, and hydro, can be good alternatives to conventional fuel sources. These sustainable energy sources are available in sufficient quantities and have minimal impact on the environment. Recently, there has been increasing interest in deploying solar central receivers (solar power towers). These receivers operate at a high temperature using a heat transfer fluid, usually molten salt. A power plant integrated with a solar system usually incorporates a storage medium to leverage the potential of prolonged energy storage opportunities. Such a plant is based on its high capacity factor achievable, low energy storage cost, higher efficiency of the integrated thermodynamic cycle and its firm output capability [1,2]. Cost assessments of different renewable power generation systems were discussed in Ref. [1]. It was presented that concentrated solar power is one of the most promising renewable energy technology in the future and its cost will be reduced significantly. On the other hand, central receiver thermal power plants were reviewed by Behar et al. [2]. They discussed the research and development in the central receiver thermal power plants.

On the other hand, supercritical CO_2 Brayton cycles are another emerging efficient technology, with thermal efficiencies reaching around 50%. These cycles, when integrated with solar power tower systems, can achieve high thermal efficiencies due to the high solar concentration ratio associated with solar central receiver systems [3]. When CO_2 is operated beyond its critical point ($T = 304.1$ K, $P = 7.37$ MPa), it is called supercritical CO_2.

Yann Le Moullec [4] performed a study on a coal fired power plant with a supercritical CO_2 Brayton cycle and a post combustion CO_2 capture mechanism. The study was intended to explore the potential of this concept. A techno-economic evaluation of the designed power plant was performed as well. The results indicated that the reduction in the LCOE (levelized cost of electricity) was

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15%, and the reduction of cost of avoided CO_2 was 45%, without transport and storage, when compared to a reference supercritical coal fired power plant equipped with a standard carbon capture process.

The characteristics of solar supercritical and transcritical CO_2 Rankine cycles using a low temperature heat source were studied experimentally by Yamaguchi and his research group [5–10]. Heat transfer characteristics of CO_2 in a solar Rankine cycle was investigated experimentally at different flow conditions by Niu et al. [5]. On the other hand, in a different research solar energy powered Rankine cycle was studied theoretically [6]. Furthermore, their system was also investigated for heat cogeneration. Later on, this study was carried out experimentally [7]. In their studies, evacuated tube solar collectors were employed. Numerous aspects of the Rankine cycle were studied, including the effect of mass flow rate, pressure ratio, and temperature. On the other hand, Zhang and Yamaguchi [8] studied performance of evacuated tube solar collector using CO_2 as the working fluid experimentally and theoretically. Their study showed the potential of CO_2 based solar collectors in solar thermal energy utilization. Optimal arrangement of the solar collectors incorporating CO_2 as a working fluid for a Rankine cycle was studied in detail [9]. In addition, an evacuated tube solar collector was used to operate a CO_2 Rankine cycle and the performance was evaluated experimentally on daily, monthly, and yearly data [10].

Researchers at Sandia National Laboratories [11] investigated the application of Brayton cycles with sCO_2 as a working fluid. They tested a variety of heat sources, including solar, fossil, nuclear, and geothermal energy. Additionally, they focused on improving the cycle efficiency and extending the applicability of the sCO_2 power generation systems by developing, testing, and upgrading the sCO_2 components.

The transient effect of a solar heat input on a supercritical CO_2 split flow recompression Brayton cycle was studied by Iverson et al. [12]. They studied the behavior of the turbomachinery of the Brayton cycle in response to a fluctuating solar heat source. In particular, the thermal input was cut by 50% and 100% for short durations to check the effect of these variations on power conditions. It was observed that the thermal mass in the system effectively enables the Brayton cycle to continue to run for short periods until the thermal input can recover. A comparison of short and long-term thermal storage options was also presented, where the thermal storage can alleviate the thermal fluctuations.

In different studies, parabolic trough concentrators with supercritical CO_2 as a heat transfer fluid for Brayton cycles were examined [13–16]. Singh et al. [13] developed a control oriented model for the sCO_2 dynamic behavior. They highlighted the need for utilizing sCO_2 charge manipulations during summer and winter to sustain fully supercritical operation of the cycle. In addition, the effects of relative volume ratios on dynamic characteristics of a direct heated sCO_2 closed loop Brayton cycle was investigated in another study by Singh et al. [14]. It was established that increasing the hot to cold size volume ratio in the closed loop Brayton cycle results in a slower and more gradual response when there are variations in the solar irradiation. Furthermore, an extremum-seeking controller was proposed by Singh et al. [15] to maximize the power output of a direct heated supercritical CO_2 closed loop Brayton cycle as the solar heat input and the ambient temperature fluctuate. This was achieved by manipulating CO_2 mass inventory in a closed loop Brayton cycle. It was concluded that this control method compared favorably to the operation while the retuning was not required between summer and winter seasons. Chapman and Arias [16] examined the use of sCO_2 in a thermocline storage system and stated that sCO_2 thermal storage was not practical due to the high cost of pressure vessels. Furthermore, it was concluded that the use of sCO_2 has greater benefits than the use of steam cycles, as the former requires smaller and simpler turbomachinery when integrated with parabolic trough solar concentrators.

A closed loop sCO_2 recompression Brayton cycle was analyzed by Turchi [17]. From the analysis, it was concluded that using sCO_2 as a working fluid has the potential for higher thermal efficiency as compared to other cycles, such as the helium Brayton cycle, the supercritical steam cycle, and the superheated steam cycle. Furthermore, some uncertainties associated with the use of such technology were reported, such as the lack of experience with closed loop Brayton cycles and the high pressure required. Ma and Turchi [18] recommended a small solar tower design for simplicity in the power block.

Comparative analysis was carried out between supercritical, transcritical, and subcritical CO_2 operating in a closed loop regenerative Brayton cycle by Garg et al. [19]. It was concluded that supercritical CO_2 is the most promising among the three cases. Chacartegui et al. [20] studied supercritical and transcritical CO_2 for solar thermal power plants. Three cycles were taken into account: a regenerative closed loop CO_2 Brayton cycle, a partial cooling closed loop CO_2 Brayton cycle, and a combined cycle comprising of a topping CO_2 Brayton cycle and a bottoming Rankine cycle using an organic fluid. From the preliminary results, it was concluded that, in terms of efficiency and cost, CO_2 Brayton cycles have the potential to compete with conventional cycles. Different parameters were taken into account to examine the comparative performance of the two Brayton cycles, and it was concluded that the partial cooling Brayton cycle exhibits higher thermal efficiency as compared to the simple regenerative Brayton cycle.

In another study by Akbari and Mahmoudi [21], an exergoeconomic analysis was performed on a combined cycle comprising of a topping sCO_2 recompression Brayton cycle and a bottoming organic Rankine cycle using different organic fluids. The performance of the combined cycle was optimized both thermodynamically and economically. It was observed that the exergy efficiency of a combined cycle was higher than the sCO_2 recompression Brayton cycle. And the total product unit cost of the combined cycle was lower than that of the sCO_2 recompression Brayton cycle.

From the literature review, it can be observed that a few studies have been conducted using supercritical CO_2 Brayton cycles integrated with solar power tower systems. However, those studies have not considered modeling the solar tower power and using the results of the modeling to assess the performance of the sCO_2 Brayton cycles. They rather assumed a heat source that has heat outputs that are similar to those of the solar power tower. In the current study, we have modeled and optimized the solar power tower system. We then used the result of the optimization to study the sCO_2 Brayton cycle to demonstrate the relation between the solar power tower and the Brayton cycles. Therefore, this research is original. The current study demonstrates the relation between the heat produced from the solar power tower system and the power produced from each of the five sCO_2 Brayton cycles considered. The cycles considered are simple, regenerative, recompression, pre-compression, and split expansion sCO_2 Brayton cycles. The study considers the solar radiation variation throughout the day for three selected days of the year. These days are the average day of radiation for March, June, and December, which represent, spring, summer, and winter. The reference location for this study was taken as Dhahran, Saudi Arabia. A comparative detailed thermal analysis was carried out between the closed loop sCO_2 Brayton cycles. The performance of each cycle versus the solar radiation variation was examined.