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Simulation of the performance of a solar concentrating photovoltaic-thermal collector, applied in a combined cooling heating and power generation system

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ABSTRACT

The aim of this study is evaluating the performance of a combined cooling, heating, and power generation system (a trigeneration), composed of a concentrating photovoltaic-thermal unit, coupled with a water-ammonia absorption chiller. In the presented design, an ammonia-water absorption refrigeration cycle with 5 kW of cooling capacity is considered as a part of the trigeneration system. Also, a concentrating photovoltaic-thermal device, equipped with a linear Fresnel collector, is employed as the heat source. The performance of the system is modeled and simulated using TRNSYS. Furthermore, in case of replacing the concentrating collector by a conventional one, the performance of the cycle is investigated. It is revealed that, with the conventional collector type, the system could not provide enough thermal energy for the refrigeration cycle. The annual average of the electrical efficiency of the designed collector and trigeneration system are 12.8% and 58.01%, respectively. By investigating the produced energy from the presented unit, it is concluded that this system could be employed as the heating and cooling source of a typical residential building. However, the electrical energy demand of the building cannot be fully supplied with the presented design, and 6030 kWh of the electrical energy must be provided from the grid.

1. Introduction

By considering the destructive environmental effects of fossil fuels, renewable energies are getting popular throughout the world [1]. Solar energy is an ideal source of energy because of its worldwide availability [2]. Both the thermal and electrical energies can be produced from the sunlight. Different applications have been developed by employing a variety of technologies. In the recent decades, the use of combined solar heat and power systems is rising more and more all over the world [3]. This technology can play an effective role in the industry by converting the solar energy into the electricity and heat, without greenhouse emissions [4]. The photovoltaic thermal system (PVT) directly converts the radiant energy into electrical energy. Also, that part of the radiant energy which is converted to heat can be used for thermal purposes. For the cases in which high temperatures are required for the thermal application, concentrators can be utilized. Moreover, using the concentrators can reduce the required surface area of the PVT panels. There are lots of studies reported in the literature on different aspects of the CCHP and CPVT systems. Therefore, the literature is reviewed in four main sections.

1.1. Photovoltaic-thermal systems

The thermal solar energy systems have drawn lots of attention during the past decades. Many scientists have designed energy systems for practical applications, such as water and space heating for residential buildings [5]. Kern and Russel [6] were the first researchers who introduced the concept of PVT systems, experimentally, in 1978. They tested water and air as the working fluids. Later, Hegazy [7] compared the thermal and electrical performance of four different types

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of PVTs in 2000. They studied the effects of different parameters of the system on its electrical and thermal performance. By estimating the heat transfer coefficients, he reported that there was a linear relationship between the electrical efficiency and the temperature of the cell. This study has provided valuable information on the design and operation of different PVT systems. Del Amo et al. [8] studied a PVT theoretically and experimentally to predict the technical performance of the system, which has a significant application in the industry.

In 2004, Krauter [9] investigated the effect of water film cooling on the power generation of a PV module. In 2006, Kalogirou and Tripanagnostopoulos [10] investigated the advantages of PVT systems over the typical PV modules, analytically. They studied these systems in aspects of energy and economy. The enhancement of the electrical efficiency can be noted as one of the main advantages of PVTs. Moreover, Moharram et al. [11] calculated the optimized value of the required water flow and electricity for cooling of solar panels. It was found that the highest efficiency could occur in the panel temperature of 45 °C.

1.2. Concentrating photovoltaic thermal systems and the Fresnel collectors

By development of the PVT systems, with the aim of reducing the capital costs, the CPVT collectors were introduced and investigated profoundly. Many studies have been conducted on the CPVT collectors as operating solely, and the ones integrated with other technologies. Tian et al. [12] have recently measured and simulated the annual thermal performance of a hybrid solar collector field with 5960 m^2 of flat plate, and 4039 m^2 of parabolic trough collectors. The studied field is located in Denmark and generates both thermal and electrical energies with an emphasis on the application of district heating.

One of the most practicable CPVT technologies, especially for the high operating temperatures, is the combination of the Fresnel collectors with PVT systems [13]. The Fresnel collectors include two main types of linear Fresnel and Fresnel lens. The small volume and low cost of the Fresnel collectors, make them useful as a concentrator in the industry [14]. In 2010, Zhai et al. [15] compared the thermal efficiency of three solar collector types as a flat-plate collector, a non-concentrated evacuated tube collector and a concentrated collector constructed with a linear Fresnel collector. The results showed that the flat-plate collector had the lowest efficiency. Moreover, the non-concentrated evacuated tube collector, in comparison to the concentrated solar collector, resulted in more rate of energy loss.

Therefore, the Fresnel collectors can be used for the concentrating photovoltaic-thermal technology. CPVT is one of the effective solar collectors, because of its compactness and multi-output nature [16]. In a CPVT system, the simultaneous production of electricity and heat from the solar energy could lead to a high efficiency, and a low-cost energy generation. The thermal component of the CPVT systems, not only produces a hot fluid for side applications but also reduces the loss of the electrical efficiency of the panels [17]. In 2013, Kong et al. [18] designed a CPVT using a Fresnel lens and flat mirrors. They tested the system under different weather conditions. In the same year, Xie et al. [19] studied a CPVT with a Fresnel lens, as the collector, theoretically and experimentally. They applied a distinct analysis to obtain the efficiency and heat removal factors of the system. Recently, some promising research works on the development of CPVT systems reveal that, by using spectral beam filters, higher outlet temperatures of heat transfer fluid would be achieved without any change of electrical efficiency of the designed CPVT [20]. Also, Calise et al. [21] employed CPVT collectors to fulfill the power demand of an electrolyzer in a polygeneration process.

1.3. Combined cooling, heating, and power generation systems

As it can be found in the literature, PVTs and CPVTs can produce power and heat simultaneously. Also, the CCHPs have been increasingly developed in recent years, and many activities have been carried out in the field of solar energy conversion. Zhai et al. [22] conducted an energy analysis on using CCHP for simultaneous power production, heating, and cooling, for off-grid applications, in 2009. Moreover, in 2013, Buonomano et al. [23] analyzed a combined cooling, heating and power supply unit, using the evacuated tube technology. Najafi et al. [24] applied a cooling method on photovoltaic panels using the thermoelectric cooling modules (TECs). In this design, a small part of the sunlight energy was converted to electricity by photovoltaic panels, and the remaining part was used for thermal purposes. Also, a portion of the generated electricity was used to provide cooling conditions for the PV cell. Soheily et al. [25] proposed a system in which the renewable energy resources were considered as the main energy supply. Wind turbines, PV modules, and solid oxide fuel cells were used as the prime movers, which could provide the power demand of the device.

1.4. Integration of the trigeneration system and concentrating collectors

There are a few works, reported in the literature, on the investigation of the CCHP cycles coupled with CPVT. In 2007, Mittelman et al. [26] evaluated a solar CCHP for cooling and power supply, by using a single-effect absorption refrigeration cycle. The thermal energy source of their work was a CPVT unit. They have claimed that this system could be economically more efficient than the conventional refrigerating cycles. In 2014, Garcia-Heller et al. [27] performed an energetic analysis of a high concentration photovoltaic thermal (HCPVT) for a specific power plant, to determine whether solar energy could be used efficiently in a CCHP. In this study, the multi-dish concentrators allowed using the coolant fluid temperatures up to 80 °C. Imtiaz et al. [14] studied a concentrated photovoltaic co-generation (CPVC) system to investigate all parameters such as the collector area, inlet temperature, mass flow rate, and solar radiation, which affected the cooling and heating performance. Xu et al. [28] presented a novel CCHP system, coupled with a parabolic trough collector. In their design, the thermal energy of the sun was collected by the collector, and utilized in the methanol decomposition process. Then, the released chemical energy went into a combustion chamber of a micro gas turbine, which caused this design to be counted as a CCHP unit. Later, Wang and Fu [29] combined a chemical-looping combustion with a solar heliostat collector. They reported a significant energy efficiency of 67% for the designed solar CCHP unit. Also, Zhang et al. [30] have combined a trough collector to produce the required thermal energy of a biogas gasification process. The designed process has achieved the overall and electrical efficiencies of 77.4% and 17.8%, respectively.

In this paper, a novel CPVT design is presented containing a linear Fresnel collector as the concentrator component and a triangular prism-shaped configuration of the PVT system. Moreover, the combination of the designed CPVT with a water-ammonia absorption refrigeration cycle is investigated for the first time. Also, the effects of variations in the key parameters on the performance of the system have been studied. The system, proposed by Boudéhenn et al. [31], has been considered as the absorption refrigeration cycle, and the whole unit has been simulated and analyzed by the TRNSYS software.

2. Design of the concentrating photovoltaic-thermal unit

For modeling the system, firstly it is needed to determine the local weather conditions and the specifications of the CPVT device. Table 1 provides some information on the project site location.

Moreover, the designed CPVT in this paper is composed of a Fresnel collector, PV cells, insulator, conductive casing, and heat transfer fluid. All of these items are briefly described below.

2.1. Fresnel collector

In the designed device, the CPVT acts as the generator of the absorption refrigeration cycle. Generally, the water-ammonia absorption