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Computational analysis and performance optimization of a solar thermoelectric generator

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ABSTRACT

Solar energy has been considered for many years one of the most reliable and predictable renewable energy resources for the production of both electricity and heat. At the moment, renewable energy market is mainly focused on photovoltaics and solar thermal systems. Quite recently, the implementation of thermoelectric generators in solar energy conversion systems, as an alternative method for exploiting the potential of this huge resource, has attracted increasing attention. In this paper, the performance of a thermoelectric-based solar conversion unit is investigated computationally, using ANSYS Workbench v. 14.0 CAE Software. The electrical output of the system under consideration has been evaluated and performance prediction has been conducted under various operating conditions, demonstrating maximum power output of 33.7 W. Moreover, different techniques are discussed in order to enhance power output and optimize system operation according to the incoming solar irradiation levels, which can differ significantly throughout the year.

1. Introduction

During the last decades, the integration of renewable energy power plants into the global energy infrastructure has seen significant growth due to the worldwide effort to reduce the global emissions of greenhouse gasses and address the issue of environmental pollution. Within this framework, the enormous potential of solar energy has been clearly recognized, which is depicted by the decisive contribution of solar energy conversion systems in the global renewable energy portfolio [1]. For the moment, solar energy market is primarily focused on photovoltaics as well as solar thermal type installations. Photovoltaic (PV) technology, directly converting sunlight into electricity, has been considered for many years one of the most reliable renewable energy technologies. PV systems can cover a wide range of applications, from a few Watts to hundreds of Megawatts and can be met either as stand-alone or grid-connected configurations [2–5]. On the other hand, solar thermal systems are more commonly met in large scale installations when considering power generation or combined-heat-and-power (CHP) applications. In that case, optical concentrators (mirrors or lenses) and different types of heat engines have to be used [6–8]. Examining domestic scale applications, solar thermal systems have been widely utilized for many years as hot water production units, where flat panel or evacuated tube collectors are more frequently employed [9,10].

Thermoelectric generators (TEGs) have recently emerged as a promising alternative amongst other renewable energy technologies, due to the particular advantages they present. Their solid state nature and silent operation, the absence of moving parts and the low maintenance requirements gave rise to a growing interest considering the exploitation of thermoelectric technology for power generation purposes [11,12]. However, the relatively small conversion efficiency of TEGs has limited for many years their utilization to applications where reliability and lifetime are the main considerations. Nevertheless, when waste-heat is available there is no concern regarding the cost of thermal energy input, which makes thermoelectric devices excellent candidates for waste-heat recovery applications [13]. In this respect, the incorporation of TEGs in solar energy conversion systems has attracted a lot of attention during the last years. Since the incoming ambient solar flux would be too low to create substantial temperature gradients and ensure the effective operation of thermoelectric

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generators, in most cases thermal or optical concentration is necessary in order to obtain satisfactory power output levels.

Early attempts to evaluate the feasibility of solar thermoelectric power generation systems indicated significantly low conversion efficiency for flat plate configurations, although considerably improved performance was observed when optical concentration was employed [14,15]. Numerical analysis of a solar TEG using large optical concentration and higher temperature thermoelectric materials (SiGe alloys) provided more encouraging results, obtaining efficiency of more than 12% [16]. Later, a more detailed theoretical analysis of solar TEGs pointed out the importance of optimizing thermoelement geometry for maximum power, rather than maximum efficiency, conditions [17]. More recently, computational and experimental examination of concentrated thermoelectric solar systems indicated efficiencies above 10% for non-conventional thermoelectric materials, underlying also the importance of adjusting the concentration ratio according to the thermoelectric materials employed [18,19]. Furthermore, numerical analysis of a concentrated thermoelectric-based CHP system led to overall efficiency in the order of 80%, stressing out the need for thermoelectric materials of higher efficiency in order to increase the ratio of electrical vs. thermal efficiency [20]. In addition, performance investigation of solar TEGs utilizing thermal and/or optical concentration mechanisms, indicated the necessity for evacuated operation, especially in the case that only thermal concentration is used, achieving efficiencies near 5% for flat panel configurations which is considerably higher than previously reported values [21,22]. Optimization analysis of solar TEGs highlighted also the overall performance enhancement achieved when integrating thermoelectric generators in solar hot water systems [23]. Quite recently, computational tools have also been employed towards the evaluation and optimization of the performance of solar thermoelectric systems [24,25].

Admittedly, the integration of additional subsystems (thermal or optical concentrators, heat extractors etc.) increases the complexity of thermoelectric-based solar conversion systems. In this respect, computational methods can be of great value both for evaluating the performance and optimizing the operation of solar thermoelectric generators. However, until now, little effort has been put on the computational modelling of large scale solar TEGs. Most relevant studies examine the operation of single thermocouples, which can lead to underestimation of heat losses, especially for configurations employing high levels of thermal concentration. Moreover, a lack of information is observed when considering the direct performance comparison between thermal and optical concentrated solar thermoelectric systems. In addition, the several aspects of operating solar TEGs under different conditions of ambient temperature and solar irradiation have not been discussed in detail.

In this work, the performance of a solar thermoelectric generation unit has been computationally investigated using ANSYS Workbench v. 14.0 CAE Software. Two main configurations were examined, with the first one employing thermal concentration while the second one optical concentration. Furthermore, two commercial TEG modules, consisting of 127 and 31 thermocouples respectively, were used for the analysis conducted in order to evaluate the behaviour of both high and low power thermoelectric devices. Computational results indicated significantly improved performance for the set-up utilizing optical concentration, especially when high power TEG modules and high levels of concentration are employed. For the maximum concentration ratio examined, electrical output of 33.7 W was obtained. Finally, different approaches are discussed in order to enhance power output and optimize system performance according to the incoming solar irradiation levels.

2. Performance analysis of solar TEGs

A comprehensive overview of the coupled-field thermal-electric analysis available through ANSYS software, that has been used for the construction of the computational models in this work, can be found in the relevant literature [26]. In this Section, the fundamental analytical equations, describing the operation of a solar thermoelectric generator from an energy balance point of view, are provided. The analysis conducted below refers to systems employing thermal (Fig. 1a) or optical (Fig. 1b) concentration. Moreover, the following assumptions have been made:

a) The configuration of Fig. 1a (thermal concentration) operates under vacuum environment. The importance of evacuated operation in order to eliminate convection heat losses has been underlined by relevant studies investigating the operation of thermal concentrated solar TEGs [21–23]. For this reason, convection heat transfer has been neglected during the examination of the configuration employing thermal concentration.
b) Considering the set-up utilizing optical concentration (Fig. 1b), an additional heat spreader of high thermal conductivity (aluminium plate) has been regarded on top of the hot alumina

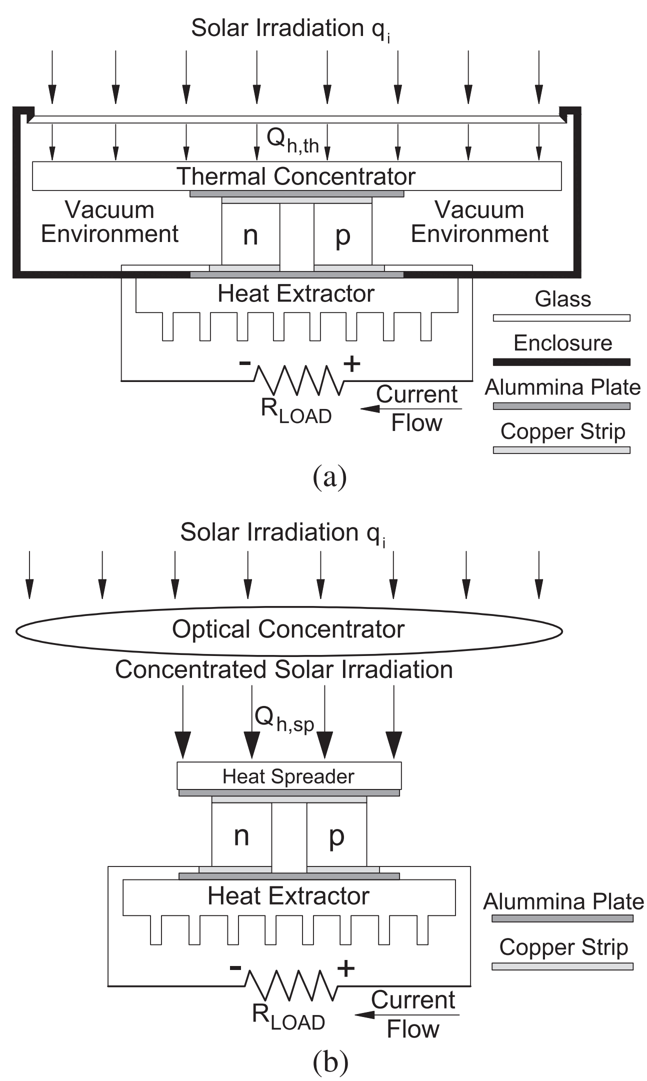

Fig. 1. Schematic diagram illustrating the basic setup of a unicouple solar TEG employing thermal (a) and optical (b) concentration.