Applied Thermal Engineering 133 (2018) 622–632

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental investigation and numerical model validation of a 2.5 kWt concentrated solar thermal plant

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HIGHLIGHTS

- A 2.5 kWt Concentrated Solar Thermal Power system has been designed and tested.
- The tests campaign has shown high performance and efficiency of the prototype plant.
- A numerical model has been developed to support the CSP plant design.
- The simulated and experimental data were in good agreement even with varying DNI.
- The validation of the model makes it a potential useful tool for CSP plants design.

ARTICLE INFO

Keywords:
Small scale CSP system
Non-imaging small-sized heliostats
Experimental tests
Simulation analysis
Domestic hot water production
Household applications

ABSTRACT

In this paper the design of a 2.5 kWt Concentrated Solar Thermal Power system is reported. The prototype plant uses 25 heliostats for a total active area of 4.4 m^2. Each mirror is moved by a two-axis tracking mechanisms to reflect the sun's rays onto a fixed target having an area of 0.5332 m^2.

Tests have been carried out in order to obtain a complete comprehension of the system's performance under different operating conditions. The prototype plant was installed in a town of central Italy and the experimental analysis allowed to assess the overall plant performance in terms of thermal power and efficiency. In particular, the daily energy production and the plant efficiency reached a peak value of about 22.5 kWh and 71.71% while the mean values were 13.75 kWh and 60.50% respectively.

The plant output has also been investigated using an analytical model previously developed to support the prototype design. The analytical model takes into account the main losses related to the heliostat systems. In general, the simulation results were in good agreement with the experimental data.

The validation of the proposed numerical model makes it an efficient tool to support the design of other small scale concentrated solar thermal plants.

1. Introduction

The global growing utilization of energy has led to a better quality of life but it also generated harmful effects on the environment. A sustainable development is certainly a great challenge for the future generations and a more widespread use of renewables will play a key role in achieving such an important target. Concentrated Solar Power (CSP) is one of the viable options among renewable energy technologies [1], because it is considered a valuable alternative to substitute thermal and electric power generation from fossil-fueled plants thanks to its lower environmental impact, lower carbon dioxide and pollution emissions [2]. In the short term, hybridization of traditional plants is foreseen as the most viable solution [3].

The CSP technology aims at concentrating sunlight from a large area onto a small area using optical devices like lenses or mirrors. The concentrated light is collected using a solar receiver and converted into electrical or thermal power depending on the applications. Considering that about half of total world final energy consumption in 2014 went to providing heat for buildings and industries [4], solar thermal power has a huge potential in curbing fossil fuel energy consumptions for heating purposes.

CSP systems can employ different methods of capturing solar thermal energy depending on temperature level and plant scale. At present, there are four main available CSP technologies: Parabolic

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https://doi.org/10.1016/j.applthermaleng.2018.01.095
Received 8 June 2017; Received in revised form 28 December 2017; Accepted 25 January 2018
Available online 20 February 2018
1359-4311/

Trough Collector (PTC), Solar Power Tower (SPT), Linear Fresnel Reflector (LFR) and Parabolic Dish System (PDS) [5]. Parabolic trough is by far the most mature technology and more than 95% of the installed CSP plants are built upon this technology [6]. Solar tower technology is the second most mature technology and represents the alternative to PTC when higher operating temperatures are required [7]. Fresnel reflectors prove to be a promising alternative solution as solar concentrator in medium and high temperature thermal applications due to its potential to overcome techno-commercial constraints associated with conventional reflector based CSP [8,9].

Nowadays CSP plants are in most cases large scale solar farms having a total thermal power ranging from few MWs to over 250 MW [10]. However, an increasing interest exists in medium- and small-scale plants due to their higher flexibility and lower capital cost. For example, Rawlins and Ashcroft [11] investigated the potential of small CSP systems in emerging countries with a focus on industrial heat and rural on/off-grid applications while Coccia et al. [12] designed and tested a small scale PTC for industrial process heat. At lower temperature ranges, Compound Parabolic Collector (CPC) is also another suitable option due to its low cost and good thermal performance for low and medium temperature ranges [13]. CPC indeed is able to collect both direct and diffuse solar radiation without a tracking system. For example, Nkwetta et al. [14] compared the performance of an evacuated tube heat pipe solar collector with those of a concentrated evacuated tube single-sided coated heat pipe absorber of the same receiver area. Although the significantly lower optical efficiency with a solar radiation perpendicular to the collector aperture, the CPC evacuated tube was able to achieve a daily total collected energy higher than the traditional evacuated tube because of a 46.22% lower heat loss coefficient. As regards the CPC technology, Nwketta and Smyth [15] designed and compared the profile of two different truncated CPC collectors finding that the double sided absorber CPC is able to realise an overall 42.4% improvement in average outlet and inlet fluid temperature differential compared to the single sided absorber CPC. Therefore, such kind of CPC absorber tube is foreseen to be usefully integrated into buildings for heating and cooling demands. At present, indeed, the adoption of medium temperature concentrated solar thermal technologies in civil and industrial applications is very limited and the integration of such systems in buildings is usually restricted to simulation analysis. For example, Tsoutsou et al. [16] investigated the integration of LFR on the façade of a building for heating applications but evacuated tubes are by far the most adopted solution in households. Thanks to the low production cost, the ease of installation and the absence of a tracking mechanism the installed capacity of evacuated tube collectors has increased significantly during the last 10 years especially in China [17]. Nevertheless, concentrated solar thermal technologies are likely to be preferred to meet the energy demand of most of the industry processes and of the medium temperature heat in buildings [18]. However, scaling down concentrated solar thermal technologies has little economic appeal due, for example, to the high cost of the tracking system but, if low cost and reliable tracking devices can be adopted in miniature CSP systems, it is possible to overcome this limitation [19]. In addition, the optical efficiency of a compact concentrator can be kept high thanks to the small ratio of the focal point's height to the distance of the heliostat. This issue was studied also by Danielli et al. [20], who described a tower plant having several heliostats' micro-fields with an independent tower receiver each. Authors demonstrated that the ratio of the focal point's height to the distance of the heliostat is one of the most important parameters to optimize the optical efficiency of a central receiver concentration plant. This solution improves the ground usage and reduces the inefficiency of the widely spaced remote heliostats of a large tower system. In addition, the reduced distance of the heliostats from the focal point ensures the minimization of astigmatism and aberrations. Another study by Daabo et al. [21] proved that a proper design of the receiver is crucial to grant high performance also in small scale CSP systems.

At present, for medium and low temperature applications, evacuated tubes are by far the most adopted solution in households due to their ease of installation and the absence of a tracking mechanism. However, the daily thermal energy production can be increased to a large extent by adopting CSP systems such as the ones that use small movable mirrors.

In literature, there are few works describing the operation and performance of small-sized central tower CSP systems, while there are some examples of small-scale solar furnaces [22,23]. For instance, N'Tsoukpoe et al. [24] described the design and the construction of a micro-tower CSP system used to feed an Organic Rankine Cycle. The authors reported the construction of the plant consisting of 20 heliostats and they estimated the performance of the optical and thermal performance of the whole system. In a work by Abu-Hamed et al. [25] the authors described the construction and the design considerations of 10-heliostats central tower system. The collected thermal power was measured and the results were in accordance with the design parameters. Nevertheless, no data on the optical efficiency and the overall efficiency are available.

In this paper a small concentrated solar thermal central tower prototype, for residential and civil applications, consisting of 25 non-imaging small-sized heliostats is presented and its performance is analyzed both experimentally and using an "in-house" ray-tracing simulation tool.

The main objectives of this work are: (i) to define the actual performance of the designed concentrated solar thermal prototype plant and (ii) to validate the analytical model in order prove its potential to support the design of different size small scale concentrated solar thermal plants.

The paper is organized as follows: after the introduction, Section 2 describes the methodology of the work; Sections 3 and 4 report the experimental investigation and the numerical model validation of the prototype unit; Section 5 presents and discusses the main results of the work while conclusions are reported in Section 6.

2. Methodology

A complete understanding of the performance of a system can certainly be achieved through an extended field test phase of the prototype unit. Nevertheless, comprehensive experimental investigations to elucidate all the optical effects and the heat transfer phenomena are time and cost consuming, especially for large scale CSP plants. As an alternative, a numerical tool offers the opportunity to expand on the limits of the experimental analysis supporting the design of the system through a more cost-effective manner. Considering the high modularity and flexibility of a small scale CSP plant, an analytical model can be considered a powerful tool to evaluate the performance of such systems whose dimensions can be varied to suit the user's needs.

A first heliostat concentrator prototype consisting of 90 flat mirrors for a total area of 7.5 m^2 was previously designed by some of the authors [26]. After the test campaign and the analysis of the results, a re-engineering of the prototype has been carried out in order to both improve the plant performance and reduce the overall cost of the apparatus for a subsequent industrialization phase. In this paper, authors present the relevant activities and their main results obtained with the design and test of this second prototype.

In a first design stage, a numerical analysis has been carried out in order to define the size of the plant and its optimal configuration prior to the prototype realisation. A 2.5 kWt concentrated solar thermal plant consisting of 25 hexagonal flat mirrors proved to be the most interesting configuration to obtain a uniform intensity and a medium concentration ratio of about 8.25. After the prototype construction, a test campaign has been carried out in order to evaluate the plant performance under different operating conditions. Finally, the numerical model has been validated according to the experimental results in order to assess its potential as useful and effective method to support the design of