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Simulation-based optimisation of a linear Fresnel collector mirror field and receiver for optical, thermal and economic performance

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ABSTRACT

Increasing the efficiency of concentrating solar power (CSP) technologies by means of optimisation tools is one of the current topics of solar thermal researchers. Of these technologies, Linear Fresnel collectors (LFCs) are the least developed. Therefore, there is plenty of room for the optimisation of this technology. One of the goals of this paper, in addition to the optimisation of an LFC plant, is introducing an applicable optimisation procedure that can be applied for any type of CSP plant. This paper focuses on harvesting maximum solar energy (maximising plant optical efficiency), as well as minimising plant thermal heat loss (maximising plant thermal efficiency), and plant cost (the economic optimisation of the plant), which leads to the generation of cheaper solar electricity from an LFC plant with a fixed power plant cycle (The performance optimisation of this study is based on the plant performance throughout an imaginary summer day). A multi-tube cavity receiver is considered in this study since there is plenty of room for its optimization. For the receiver, optimal cavity shape, tube bundle arrangement, tube numbers, cavity mounting height and insulation thickness are considered, while for the mirror field, the number of mirrors, mirror width, mirror gaps and mirror focal length are considered to achieve the optimisation goals. A multi-stage optimisation process is followed. Firstly, optical (using SolTrace), thermal (using a view area approach) and economic performance are combined in a multi-objective genetic algorithm as incorporated in ANSYS DesignXplorer (DX). This leads to an optimal LFC with a variable focal length for each mirror. After determining a fixed optimal focal length for all the mirrors, a Computational Fluid Dynamics (CFD) approach is used to optimise the thermal insulation of the cavity receiver for minimal heat loss and minimal insulation material. The process is automated through the use of ANSYS Workbench and Excel (coding with Visual Basic for Application (VBA) and LK Scripting in SolTrace). The view area approach provides an inexpensive way of calculating radiation heat loss from the receiver that is shown in the subsequent CFD analysis to be dominating the heat transfer loss mechanisms. The optimised receiver is evaluated at different LFC plant tube temperatures to assess its performance.

1. Introduction

Global crises were the main drivers in moving human energy sources towards renewable sources and solar energy. For example, the oil and energy crisis of 1973–1979 (Ross, 2016) led to grants for scientific work to find a reliable alternative source of energy. Due to the funded scientific works in this period, the successful constructions of Concentration Solar Power (CSP) plants were begun. Examples of such plants are Solar One (Solar One, 2016), constructed in 1982 and operated until 1988, and the nine plants of Solar Energy Generation Systems (SEGS) (SEGS, 2016), constructed from 1984 to 1990 with a combined capacity of 354 MW. The dusk of this period started with the ending of the oil crisis. This period of crisis, however, helped CSP technologies prove themselves to be reliable eco-friendly sources of solar energy. Four main CSP technologies were introduced in this period: the Heliostat Field Collector (HFC), the Parabolic Dish Reflector (PDR), the Parabolic Trough Collector (PTC) and the Linear Fresnel Collector (LFC), although the research and development of these technologies did not take place at the same pace during this period. For instance, by the late 1980s, while great investment had been made into PTC plants, scientific research on LFC developments had only just begun and was halted at the end of the oil crisis and falling oil price. The second golden period of investment into CSP technologies was initiated by global warming in the 1990s and the Kyoto Protocol in 1997 (United Nations, 2016a) and was affected by the worldwide economic

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crises. The development of the LFC took place towards the end of this period. Despite the fact that the first LFC plant commissioned in Spain displayed its competitiveness with the PTC (Abbas et al., 2016), the Spanish government placed a moratorium on the construction of new renewable energy technologies that had not yet been approved (Government of Spain, 2012). This moratorium stopped the development of the LFC and signifies the end of the second period of CSP development. The third period of CSP development started with the help of US loan guarantees for different companies manufacturing CSP plants. This period mainly began because of energy dependence issues of the US government (Abbas et al., 2013). However, due to the achievements of the 21st Conference of the Parties (COP 21) to the United Nations Framework Convention on Climate Change (UNFCCC), which took place in Paris, France, in 2015 (United Nations, 2016b), the commitments and motivations of other countries to subsidise and move towards renewable energy have increased.

Although the LFC technology was developed late in the aforementioned periods, it proved its advantages in comparison with the most mature CSP plant technology (PTC) to name a few: easy maintenance, no requirement for high pressure joints, lower height of mirrors and lower wind loads, inexpensive mirror field and simple tracking system due to lightweight reflectors, and so on (consult Moghimi et al. (2015c) for a more detailed discussion). However, the disadvantages of LFC compared to PTC are higher optical losses (lower efficiency) and lower technology maturity (less reliability) which may lead to some difficulties in the financing conditions of such projects (Günther, 2017). Interesting investigations have taken place in the research and development of LFCs. Zhu et al. (2014) conducted a comprehensive study on the history of LFCs and presented promising LFC technologies. Among these technologies, two commercialised technologies received more attention by researchers. These are the LFC with a multi-tube cavity receiver (Singh et al., 1999; Sahoo et al., 2012; Abbas et al., 2013; Pye et al., 2003; Moghimi et al., 2014; Hongn et al., 2015) (see Fig. 1b) and the LFC with a mono-tube cavity receiver with a compound parabolic-shaped secondary reflector (Haberle et al., 2002; Heimsath et al., 2014; Sharma et al., 2015; Qiu et al., 2015; Moghimi et al., 2015a) (see Fig. 1a). The first technology was commercialised by Areva Solar (Areva Solar, 2016) and the second by Novatech Solar (Novatech Solar, 2016) and Solarmundo (Zhu et al., 2014).

The late development of LFC technologies left plenty of room for their optimisation and made them an interesting topic among researchers. However, due to the definition of a variety of optimisation objective goals, the results of those studies vary and hence do not provide a fixed utopian design. This issue will be addressed later when the results of a thermal and optical optimisation study are compared with an economic optimisation study on the same LFC configuration. Traditionally, researchers perform the economic optimisation of a CSP plant via the definition of Levelised Electricity Cost (LEC), also known as Levelised Cost of Electricity (LCOE) (LCOE, 2016) and its minimisation. The results of LEC minimisation may not predicate the same utopian design as a pure optical or thermal optimisation. For instance, Bernhard et al. (2008) reported on the results of an optimisation study of the FRESDEMO project which concerns an LFC plant with a mono-tube cavity receiver and secondary reflector. In that study, firstly, the receiver height, the tube diameter and the mirror width were determined based on practical restrictions. Then, the optimisation was performed on the set of independent parameters, consisting of the following: the number of mirrors, the mirror gaps, the mirror curvature, mirror aiming points and the shape of the secondary reflector. They reported that, for a constant field width, thermal efficiency reached its maximum value with 22 mirror rows, while the LEC optimisation of a similar problem showed that the minimum cost of the field occurred with 30 mirrors (Fig. 2). Indeed, adding more than 22 mirrors decreases the thermal efficiency because of the mirror shading and blocking effects in the constant field width, while mirror field cost decreases by increasing rows up to 30. In another study, Montes et al. (2012) conducted an optimisation study on the optical and thermal losses of the mirror field of the FRESDEMO plant disregarding economic factors of the plant and thermal and optical losses of cavity receiver. Their study's focus was on minimisation of shading and blocking, end and lateral losses, and mirror reflection losses of the FRESDEMO plant by changing the receiver height and mirror field total width parameters of the plant. These researchers showed that, for a constant receiver height, by

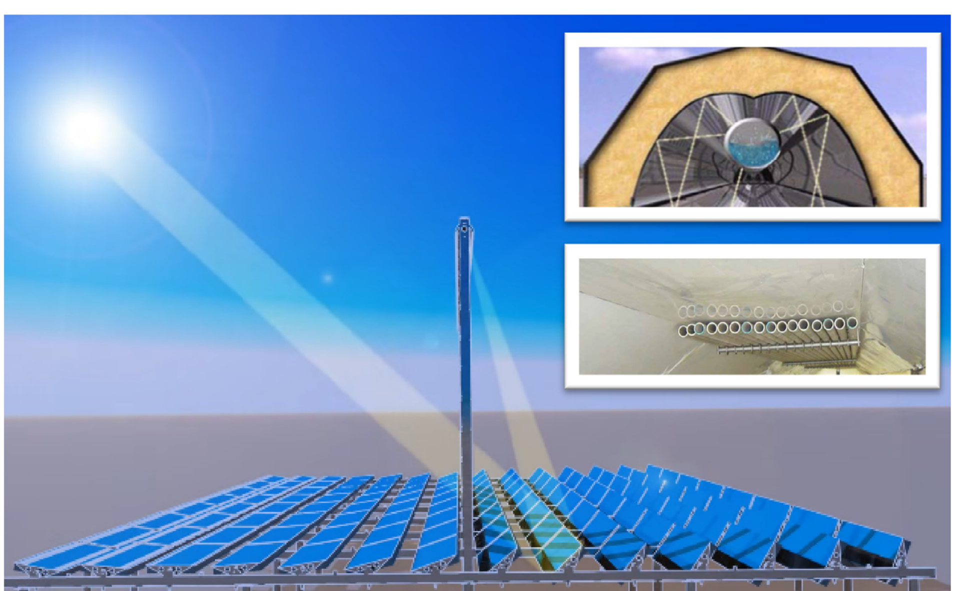

Fig. 1. Layout of LFC technology with the inserted images of cavity receiver configuration. Top right corner, mono-tube secondary reflector cavity receiver used in the Nova-1 project (Novatech Solar technology – reprinted from Selig and Mertins, 2010). Middle right side, multi-tube arrangement in a trapezoidal cavity during construction (reprinted from Pye, 2008).