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Two-step optimization procedure for the conceptual design of A-frame systems for solar power plants

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This work presents a two-stage optimization procedure for the conceptual design and operation of A-frame dry cooling systems for concentrated solar power facilities. First, the optimal geometry of the A-frame including sizing, number of fans and blade geometry, and unit parameters such as pipe length, configuration and number is determined. Finally, the operation of the system over a year for minimum energy consumption is computed. The geometry problem is formulated as a mixed-integer non linear programming (MINLP) problem. A tailor-made branch and bound algorithm is used to solve the complex non-linear programming sub-problems. The second problem consists of a multi-period MINLP. A fixed geometry is used to evaluate the usage of fans over time. The solution suggests an apex angle of 63°, one row of 75 pipes of 13.5 *m* long with a diameter of 3.3 mm, and 4 fans are used but they only operate at full capacity during summer. This design allows reducing the energy required by 20% by using the appropriate pipe configuration and number. The unit consumes around 4% of the energy produced by the CSP plant that serves. It is a promising result that can be affected by plant layout and ground availability.

1. Introduction

Solar energy is a plentiful source that can provide several times the mankind needs [1]. However, the use of solar energy to produce power is still not competitive compared to fossil based thermal plants [2]. The disadvantage of concentrated solar power facilities (CSP) is that, unlike fossil based ones, they need to be allocated in specific regions with high solar incidence. This particular feature is a handicap in terms of cooling. There are two main cooling technologies for thermal plants: wet or dry cooling. Wet cooling is the most used technology for power plants, but it requires around 1.8 L of water per kWh produced [2]. On the other hand, dry cooling technologies require the use of a fraction of the power generated to operate the fans that move the air used to condensate the exhaust steam. As a result, the global efficiency of the facility is reduced.

In the literature, a number of studies compare wet and dry cooling systems for solar and fossil based thermal plants. Most of them use a simulation based approach to compare power plants that use both cooling technologies. Kelly and Prince [3] evaluated the performance of air cooled condensers using the Excelergy package and compared the cost of power production using both cooling systems showing that dry is still more expensive. Turchi et al. [4] studied 13 different real cases using SAM software, where the use of dry cooling increased the cost of electricity by 8%, but with reduction of water consumption of 90% in CSP plants. No details on the air cooler geometry are presented. Zhai and Rubin [5] focused on comparing the cost and performance of both cooling technologies on coal based facilities. A-frame coolers are used but no details of the unit are described. Barigozzi et al. [6] optimized wet and dry cooling systems for waste-to-energy plants evaluating the effect of air conditions on the cycle performance using Thermoflex software, but no unit design characteristics are commented. Blanco-Marigorta et al. [7] used exergy as metric to compare both technologies in terms of thermodynamic yield of the process. Habl et al. [8] extended previous work by including cost estimation. Liqreina [9] only focused on dry systems for a CSP plant located in a desert area, Jordan, from the thermodynamic poinf of view. Palenzuela et al. [10] evaluated various cooling technologies in the context of desalination. Lately, a programming optimization approach has been used to evaluate wet, Martín and Martín [2], and dry cooling systems Martín [11] towards the trade-off between water consumption and power generation. A monthly basis analysis is performed. Dry cooling technologies reported higher power production and investment costs. Around 5–10% of the produced

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energy is consumed to power the fans using dry cooling technologies [11], while the use of wet cooling towers resulted in an average consumption of 2.1 L/kWh of water [2]. Cooling technologies have been developed lately not only for renewable based power plants but also to address residential needs evaluating system [12], comparing previous work with air cooling [13] and finally evaluating various renewable resources [14]. However, these studies used simplified models to represent the cooling technologies in order to be able to address the analysis or the optimization of the entire power facilities. The increase in power demand together with the future water scarcity [15] requires better dry cooling systems [16].

Literature on the design of dry cooling systems focuses on different aspects. Some studies evaluate the layout of the units for their allocation in the facility using Computational Fluid dynamics (CFD), suggesting novel layouts [17] and evaluating the effect of wind speed direction [18]. In terms of the actual unit design, two approaches can be found in the literature, iterative design and mathematical optimization formulations. The most common approach uses guidelines, figures and design equations in an interative procedure. The general rules can be found in technical reports [19], or reference books where the design procedure is described in detail in Ref. [20]. Industry also provides their guidelines based on the experience on the operation of such units [21]. Apart from the basic design, the effect of the wind can also be accounted for in the design [22]. Finally, specific problems such as freezing [23], or the evaluation of the fan performance with no further reference to the entire design and the heat transfer section [24] have also been considered. Alternatively, mathematical optimization approaches have been developed. However, most of these studies have been performed for regular units either evaluating their performance [25] or developing a mathematical model for their optimization [26]. The optimization of the particular geometry of the A-frames has only been addressed in Ref. [27] for a reduced number of variables. Conradie's et al. work [27] used a mathematical optimization approach for the geometric design of A-frame systems. However, it does not evaluate the effect on the flow on the heat transfer coefficients, the effects of the geometry on the pressure drop nor its operation over a year time.

Apart from the geometrical design of the unit, the variability in the solar incidence represents the second challenge in the operation of CSP plants. In particular, cooling units are affected in two ways, the variable heat load to be rejected and the variable conditions of the cooling agent. Typically, the design is based on a certain month of operation [20], but in the case of solar facilities this approach leads to inefficiencies over a year. Even though flexible design of chemical plants has been addressed in the literature using mathematical optimization approaches [28], its application to the detailed design of industrial units considering the monthly variability is challenging due to the mathematical complexity. Reference to multi-period operation can be found in some studies that evaluate the performance for regular air coolers [26] or that focuses on the evolution of fouling and its effect on the energy transfer [29], but work on the detail optimal design of A-frames considering seasonality operation is not available.

In this work a two-stage methodology has been proposed for the conceptual optimal geometric design and monthly operation of A-frames aiming at minimum power consumption to meet the cooling needs of a CSP plant. The methodology is based on the detailed geometric design for a month considering the piping system and its layout, the fan blade geometry, pressure drop across the system and heat transfer resistances. Next, as a recourse, the second step a multiperiod optimization allows considering the operation of such design over time to minimize energy consumption The aim is to improve current designs reducing the energy required to operate such units. For reference, the case study is based on a CSP facility located in Almería (Spain), a region with one of the highest solar radiations in Europe, and uses operating data from previous work [2]. The paper is organized as follows: In Section 2, the design method is depicted. In Section 3, the features of the model are described. In Section 4 the optimization procedure developed to solve the MINLP problem is presented. Next, in Section 5 the case study and the main results are discussed such as the major operating conditions, the power consumed by the cooling system and the units of the A-frame needed followed by an economic evaluation and a comparison between dry and wet cooling facilities based on CO_2 savings. Finally, Section 6 draws some conclusions.

2. Design method

A two-step optimization procedure is proposed for the conceptual design of A-frame units considering seasonality over a year of operation. The first problem is the optimal design of the geometry for the month with the highest energy production and heat rejection. A detailed model for the A-frame described in Section 3 is used to determine the geometric features of the unit. This model is formulated as an MINLP optimization problem. Section 4.1 shows the tailor-made branch and bound algorithm to determine the number of tubes, number of bundles and rows as well as a standard pipe diameter, tube length and fan blade angle. This problem is solved for the optimal design capable of providing the cooling required.

The seasonal operation of the A-frame over time is addressed for the geometry computed in the design problem. This problem is formulated as a multi-period MINLP to determine the usage of fans, bundles and flow per fan operating on a monthly basis for minimum energy consumption making the most of the unit geometry defined in the first stage. To solve the multiperiod problem the model of the unit is simplified by fixing the geometry. Section 4.2 shows the formulation of the second stage problem. Section 5 reports the main operating data of the case study, heat rejection and weather conditions.

3. Modeling

3.1. CSP facility description

The plant consists of three sections: the heliostat field, including the collector and the molten salts storage tanks, the steam turbine and the air cooler steam condenser. Fig. 1 presents the flowsheet for the process. This process uses a tower to collect the solar energy and a regenerative Rankine cycle. The steam is generated in a system of three heat exchangers where water is heated up to saturation and then evaporated using the total flow of molten salts. However, only a fraction of the flow of salts is used to superheat the steam before it is fed to the first section of the turbine. The rest is used to reheat up the steam before it is fed to the medium pressure turbine. In the medium pressure turbine, part of the steam is extracted and it is used to heat up the condensate. The rest of the steam is finally expanded to an exhaust pressure, condensed and recycled. For the condensation of the steam we propose the use of a direct air cooled system, an A-frame. For the detailed information on the modeling features of the heliostat field and the steam turbine, we refer to previous work [2].

3.2. Air cooling system

A scheme of A-frame type of air condenser can be found in Fig. 2. The exhaust steam from the turbine circulates in a large pipe and it is distributed into the pipes that form a roof over a system of fans in