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Virtual Solar Field - Validation of a detailed transient simulation tool for line focus STE fields with single phase heat transfer fluid

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ABSTRACT

Simulation models enable designers and operators to test different settings of the real systems while avoiding the large costs associated with experimental or practical systems. However, creating models that resemble the real physical system with acceptable accuracy and computational time remains a challenge for developers of such tools. With this motivation, a new simulation tool, the Virtual Solar Field (VSF), has been developed for line-focus power plants with single-phase heat transfer fluid (HTF) to assist in plant control during transient processes. VSF is a whole-field model based on an efficient coupling of hydraulic and thermal solvers that take into account the flow distribution in the parallel loops, as well as the transient conditions in the field.

In this paper, some validation cases for VSF using data from Andasol-3 power plant are shown. Five test cases are examined, which include normal operation, start-up and evening operation during clear-sky and strong transients. The results show very good agreement with the real plant and some discrepancies are discussed and studied. The main sources of discrepancies are associated with difficulties in modelling all fine details of reality using the current technologies in some commercial power plants. For example, small cloud passage are not detected by the few weather stations in the power plant, as well as knowing the exact loop valve settings is not possible in Andasol-3. In addition, an overview of the potential applications of VSF are mentioned and briefly discussed. VSF offers a suitable platform for testing novel control strategies and assessing the performance of the solar fields.

1. Introduction

Simulation software have helped engineers and scientists to develop, optimize and control concentrated solar power (CSP) plants. In addition, reliable simulation tools reduce the costs and time during designing and testing phases when compared to preparing experimental test benches and building prototypes. Numerous simulation tools for line-focus solar thermal power plants are used throughout all the designing, financing, building, and commissioning phases of the plant. In principle, line-focus CSP plants concentrate the incident solar irradiation on linear receiver tubes laying in the focus line of linear Fresnel collectors (LFC) or parabolic trough collectors (PTC). A heat transfer fluid (HTF) is heated as it flows through the receiver tubes in the solar field to collect thermal energy from the sun. The HTF could be a single-phase fluid that retains its physical state or could evaporate, like in direct steam generation (DSG) systems. Examples for single-phase HTFs are thermal oils or molten salt (MS). The heated liquid flows through heat exchangers to boil water and the generated steam is used to operate a steam turbine connected to an electric generator. For DSG systems, the steam generated at the solar field is directly used to operate the turbine. Some power plants also include thermal energy storage (TES) systems to be able to economically supply electricity when there is no solar irradiation for some time. In most of those systems, MS is used as the storage medium in one or two tanks.

The majority of commercially-operated line-focus CSP plants are based on PTC technology using thermal oil as an HTF. Despite the high cost of electricity production of CSP as compared to some other solar energy technologies, CSP remains interesting and economically feasible for various reasons. For example, CSP offers cost-effective energy storage in the form of thermal energy, and is able to produce dispatchable electric power during different periods of the day (Platzer, 2016). This adds a significant value of

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the technology as the share of intermittent renewable energy sources is increased in the electricity generation mix (ESTELA, 2016). Nevertheless, further optimizations are needed to improve the competitiveness of the technology and reduce the levellized cost of electricity (LCoE). The optimization processes involve not only improving component efficiencies, but also maximizing the collected solar energy through optimizing the power plant operation where solar field simulation tools could play an important role. This could increase the competitiveness of the technology and render it more economically feasible.

On the other hand, the use of MS as HTF in the solar field has been intensively investigated, researched, and also implemented in some pilot plants due to its advantages over thermal oils (Wagner and Wittmann, 2013). Firstly, MS could be heated to higher temperatures than thermal oils, thus higher thermodynamic efficiencies of the work cycle of the steam turbine could be achieved. Secondly, MS could be used as the storage media directly without the need for heat exchangers at the storage tanks. Nevertheless, MS as an HTF imposes a lot of challenges in terms of solar field control. The combination of critical temperature limitations (upper and lower operating temperatures) and the large size of MS fields requires a detailed understanding of the solar field behaviour (Wagner and Wittmann, 2013). Particularly challenging is control during transient processes, such as start-up, cool down, and passing clouds (García et al., 2011). To keep the field operation controllable and stable under all conditions, the operator has to find the best trajectory for field mass flow, temperature set-points, and defocusing of collectors (Wagner and Wittmann, 2013).

In order to develop appropriate control schemes to optimize plant operation, a better understanding of the behaviour of the solar field under transient conditions will help to reduce defocusing instances, improve field control, and hence, increase the energy yield and confidence in the technology. Therefore, comprehensive numerical models are required to study the hydraulic and thermal interactions in the field. These models could also help with predicting the behaviour of solar fields at specific conditions especially using MS as HTF where there is less experience with plant operation.

Most transient models for line-focus power plants either investigate a single loop, like the model in Zaversky et al. (2013), or consider a single representative loop to model the whole field as in Hirsch and Schenk (2010). On the other hand, performance and annual yield models, like the model in García et al. (2011), assume equal mass flow distribution among the loops. Consequently, realistic mass flow distributions in the collector loops arranged in parallel cannot be modelled. A model developed in Giostri (2012) calculates the flow distribution; however, it is not fully coupled with the thermal condition of the field. Commercial simulation software, like Dynamic process modelling (2016), can simulate multiple loops under transient conditions. However, there are limitations regarding computational time rendering it not possible to model whole scale commercial CSP power plants (Dynamic process modelling, 2016). For these reasons, a new transient simulation tool for a whole solar field was developed at the Institute of Solar Research at the German Aerospace Centre (DLR). The tool is named Virtual Solar Field (VSF) and is meant to provide a virtual replica of the complete field (Noureldin et al., 2016).

VSF is able to represent the whole solar field in detail and enables the analysis of transient effects in the field. The main aim is to achieve acceptable accuracy and high computational efficiency to study the field behaviour during transient conditions, like passing clouds and start-up. In addition, VSF is able to compute flow maldistribution due to thermal transients and inhomogeneity of the solar irradiance on the large fields as reported in Abutayeh et al. (2014). Together with control algorithms linked to the field model, comprehensive control strategies can also be studied in detail. The model can also be used to compute the field response to spatially discretized weather forecasts which allows the controller to be proactive to the changes rather than reactive. VSF has been introduced in Noureldin et al. (2016) where the main governing equations and modelling assumptions have been described. In addition, preliminary model verification cases against other simulation tools have been shown for the different parts of the tool separately. In this paper, we introduce a new implementation of the tool that allowed us to efficiently compute a full-sized solar field, as well as validation cases using operational power plant data from Andasol-3 power plant in southern Spain.

The next section describes the 2 parts of the model, namely, the hydraulic and thermal parts. The governing equations, as well as the numerical methods, are outlined. Section 3 shows 5 different validation test cases where the model results were compared to the plant data provided from Andasol-3 power plant. Finally, possible tool applications are briefly explained and a future outlook is discussed.

2. Tool description

The Virtual Solar Field (VSF) is an in-house developed simulation tool that models the HTF flowing from the power block (PB) through the main header pipes to the subfields through the solar collector loops and back through the header pipes to the PB. VSF is based on coupling a hydraulic network solver to compute the flow distribution among the pipes in the field with a thermal solver to compute the temperatures with respect to the solar condition and the thermal losses in the pipes. The output is the fluid and wall temperatures, and the fluid flow rate at all locations in the solar field depending on temporally- and spatially-varying input data. VSF is fully developed in the object-oriented C++ programming language and the linear equation systems are solved using Armadillo linear algebra library (Sanderson and Curtin, 2016). Input and output are in the form of ASCII- or MATLAB® (`*.mat`) files. Moreover, output to regular binary files is also possible.

The main governing equations, assumptions and limitations are explained in Noureldin et al. (2016) where a prototype of the tool has been described and some preliminary validation test cases against other simulation tool tools have been shown. In this section, the main functionality of the hydraulic and thermal parts is outlined, in addition to added features as compared to the model version as described in Noureldin et al. (2016).

2.1. Hydraulic part

The tool in its current form can model H-layout solar fields with 1–4 subfields and arbitrary number of loops per subfield, however, it could be expanded for more layouts and subfield numbers. The user can input the orientation of the loops with respect to the north direction. The solar field is modelled as a closed hydraulic network with a central pump driving the HTF in the main header pipes. The flow is then split among the parallel subfields and then further split among the parallel loops. Fig. 1 shows a simplified schematic for the hydraulic network in the solar field with the main pump at the power block, the subfields and the loops illustrated.

The flow splitting between 2 branches depends on the pressure drop in each branch. The splitting has to satisfy the fluid continuity and energy conservation equations as illustrated in Swamee and Sharma (2008). The equations are solved iteratively due to the non-linear nature of the problem. The resulting mass flow rates in each pipe are then used as a boundary conditions at the entrance of each pipe for the flow equations in the thermal part described in the next section.