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Parabolic-trough solar thermal power plant simulation scheme, multi-objective genetic algorithm calibration and validation

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Abstract

The dynamic simulator design and development of a direct steam generation parabolic-trough solar thermal power plant is detailed in this paper. The dynamic simulator is not only the equation-based object-oriented model but also includes features to facilitate the simulation process. A whole simulator scheme has been developed for that purpose. This simulator scheme considers the issues of fetching and converting sensors data to model inputs and obtaining suitable initial values for the boundary condition problem in the numerical integration. The calibration and validation processes have been tackled, using Matlab as the primary tool. However, several tools were studied and tested. A multi-objective genetic algorithm approach has been chosen for calibrating the dynamic model.

Keywords: Dynamic simulation; Calibration and validation; Direct steam generation; Parabolic-trough solar thermal power plant; Multi-objective genetic algorithm calibration

1. Introduction

The focus of this paper is the development of a simulator scheme for a direct steam generation parabolic-trough solar thermal power plant. It is important to note that the simulator scheme, apart from the Equation-based Object-Oriented (EOO) dynamic model, includes several features to facilitate the simulation, calibration and validation processes. The simulator scheme also considers important numerical aspects, such as boundary conditions fulfillment. Fetching, converting and comparing real data to simulated results has been taken into account. Several tools to perform the calibration and validation process have been studied and a appropriate framework has been defined for this task. A multi-objective genetic algorithm approach was eventually used to calibrate the dynamic model.

The real system, under study in this work, is the CIEMAT-PSA (Centro de Investigaciones Energéticas Medioambientales y Tecnológicas – Plataforma Solar de Almería, a Spanish government research and test center) DISS (DIrect Solar Steam) test facility, a parabolic-trough solar thermal power plant.

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Abbreviations: DISS, DIrect Solar Steam; PTC, Parabolic-Trough Collector; EOO, Equation-based Object-Oriented; HTF, Heat Transfer Fluid; DSG, Direct Steam Generation; BOP, Balance Of Plant; IDE, Integrated Development Environment; CSV, Comma-Separated Value; PRE, Percentage Relative Error; IAM, Incidence Angle Modifier; HEM, Homogeneous Equilibrium Model; FVM, Finite Volume Method; HTC, Heat Transfer Coefficient; DSI, Direct Solar Irradiance; DNI, Direct Normal Irradiance.

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This paper presents in detail the latest improvements made in a dynamic equation-based object-oriented simulator to study the DISS test facility behavior, this dynamic simulator is primarily intended to be used for the development of advanced control systems. A fair amount of research has been devoted to study this thermal power plant, first of all the study of its feasibility, erection and safe operation in the DISS project (Zarza et al., 2004; Eck et al., 2003). Considering modelling and simulation of the DISS solar thermal power plant are worth mentioning (Eck and Hirsch, 2007; Yebra, 2006).

2. The DISS parabolic-trough solar thermal power plant

The DISS (DIrect Solar Steam) test facility is a parabolic-trough solar thermal power plant owned by CIEMAT-PSA (see Fig. 1). The parabolic-trough technology is one of the several different solar thermal concentrating technologies available. The aim of the DISS facility is to develop a new generation of solar power plants using Parabolic-Trough Collectors (PTCs) to produce high pressure steam in the absorber tubes. Their high working temperature makes PTCs suitable for supplying heat to industrial processes, replacing traditional fossil fuels (Kutshcer et al., 1982; Zarza, 2000). The Heat Transfer Fluid (HTF) used in the DISS test facility is the two-phase-flow steam–water, which circulates in three different states, subcooled liquid, steam–water mixture and superheated steam. This technology, known as direct steam generation (DSG), increases overall system efficiency while reducing investment costs, by eliminating the oil previously used as a heat-transfer medium between the solar field and the Balance Of Plant (BOP), and thereby also eliminating the need for a heat exchanger.

2.1. Main features of the DISS facility

The DISS plant consists of two subsystems, the solar field of PTCs and the BOP. In the solar field, feed water is preheated, evaporated and converted into superheated steam as it circulates through the absorber tubes of a 665-m-long row of PTCs with a total solar collecting surface of 3838 m^2. Superheated steam generated in the solar field is condensed, processed and reused again as feed water for the solar field (closed-circuit operation) in the BOP. The BOP consists of water/steam separators, condensers, chemical dosing system, preheaters, deaerators and water pumps. Fig. 2 shows a simplified diagram of the DISS loop.

Fig. 1. General view of the DISS test facility, a parabolic-trough solar thermal power plant owned by Plataforma Solar de Almería (CIEMAT).

3. DISS facility model

A DISS solar thermal power plant EOO model (Yebra, 2006; Yebra et al., 2006) was developed to study the behavior of the real plant, the DISS model only considers the once-trough operation mode.

An EOO methodology allows to describe the system as a set of equations which are acausal, maintaining its mathematical meaning. Moreover, a object-oriented methodology allows to define basic models of components which can be reused to develop new complex models without additional effort. This methodology allows to develop reusable and easy to maintain components. The modelling language chosen was Modelica 2.2.1 (Modelica Association, 2007) which is a equation-based object-oriented modelling language. Modelica is developed and maintained by the Modelica Association. The Integrated Development Environment (IDE) chosen, which supports the Modelica language, has been Dymola 6.0b (Dynasim, 2006).

Fig. 3 shows the DISS test facility Modelica component diagram which has 11 PTC components. The model inputs are the following, the ambient temperature (*Tamb*), the Direct Solar Irradiance (DSI) (*Rad*), with regards to the HTF, the inlet temperature (*inletTemp*), the inlet pressure (*inletPres*) and the mass flow rate (*mdot_ws*), the three last inputs are also provided for the last collector injector, since this model only supports the once-through operation mode. From the DSI, the Direct Normal Irradiance (DNI) is computed using the incidence angle. The PSA algorithm (Blanco-Muriel et al., 2001) is used to calculate the solar vector, the PTCs are considered to properly follow the sun trajectory.

The PTC thermal potency is computed using the DNI, the PTC area and the thermal, geometrical and optical losses. A experimental global thermal losses model for this kind of PTC, proposed by Ajona (1999) is considered. The geometrical losses are included in the experimental Incidence Angle Modifier (IAM) model, also for this kind of PTC, proposed by González et al. (2001). The optical losses model is described in this manuscript, in Section 5. The absorber tube, located in the geometrical focal line of the parabolic-trough receiver, is composed of a steel pipe and a glass cover. Conduction in the steel pipe has been neglected in the model.

The two-phase flow is modelled as a discretized or distributed-parameter model, using a Homogeneous Equilibrium Model (HEM), which contains mixture equations for the mass, momentum and energy balances, described in (Bonilla et al., 2011a). The Finite Volume Method (FVM) (Patankar,