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Object-Oriented Modeling of a Multi-Pass Shell-and-Tube Heat Exchanger and its Application to Performance Evaluation ⋆

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Abstract: Molten salt thermal storage systems are the keystone of the dispatchability of demand in solar thermal power plants and many commercial plants use this technology. Nevertheless, there are still open questions related to long-term durability and reliability of components. During experimental campaigns in the CIEMAT-PSA molten salt testing facility, a performance detriment in a multi-pass shell-and-tube heat exchanger was noticed. For this reason and as a tool for analysis and diagnosis, an object-oriented dynamic model is being developed. This paper describes the testing facility and the thermal oil - molten salt heat exchanger particularly, the design of the Modelica model and compares simulation results against manufacturer calculations and experimental data in steady-state operation conditions and at transients in order to evaluate the heat exchanger performance.

Keywords: object-oriented modeling, dynamic simulation, multi-pass shell-and-tube heat exchanger, thermal energy storage, molten salt, performance evaluation, Modelica.

1. INTRODUCTION

The main problem that renewable energy power plants must tackle is to provide a stable and reliable power supply. The most efficient way of storing heat through solar thermal energy, and thus dispatchability on demand, is one of the most important differences between solar thermal energy and other renewable energies (Romero-Alvarez and Zarza, 2007). This makes it appropriate for large-scale energy production while mitigating solar irradiance variability.

Nevertheless, Thermal Energy Storage (TES) systems may not be able to meet the power plant demand, specially under unfavorable meteorological conditions, due restrictions in their storage sizes because of economic reasons. Presently, this issue is overcome by hybridization with fossil fuels from which mainly emerged two technologies: integrated solar combined cycle power plants, where the solar energy contribution is relatively small (<20%) (Bohtz et al., 2013) and solar thermal power plants with auxiliary fossil fuel heaters as back-up systems, commonly dedicated to avoid the working fluid solidification but not intended to be used for electricity production (Montes et al., 2009).

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Furthermore, rising cost of fossil fuels, environmental issues and concerns about sustainability are currently encouraging investment and research into multiple energy sources hybridization which may provide clean, renewable, sustainable and efficient energy. One of them is the hybridization of concentrating solar power and biomass or biogas. Biogas can be more efficiently transported through a distribution network or liquified in pressurized tanks. With this aim emerges the HYSOL project (Servert et al., 2014).

The goal of the HYSOL project is the study, design, optimization and construction of a pre-industrial demonstrator based on an innovative hybridization configuration of concentrating solar power and biogas for a 100% renewable power plant. The Manchasol parabolic-trough solar thermal power plant, owned by the HYSOL project coordinator, ACS-COBRA, is currently being adapted as a demonstrator of the HYSOL technology.

The HYSOL consortium is composed of research institutions and industrial partners. CIEMAT-PSA is the coordinator of the *dynamic modeling and advanced automatic control* work package. The dynamic model of the pre-industrial demonstrator will be used to evaluate transient responses (i.e, start-ups, shutdowns, etc.) and for the design, testing and validation of advanced control strategies. In order to calibrate and validate some dynamic models of the power plant, before its final tuning in the Manchasol plant, the CIEMAT-PSA molten salt testing facility

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Fig. 1. Aerial view of the molten salt testing facility (Rodríguez-García et al., 2014)

(Rodríguez-García et al., 2014) is being used as a mock-up test bench.

This work presents the development of an object-oriented dynamic model of one of the components of the molten salt testing facility, a multi-pass shell-and-tube thermal oil - molten salt heat exchanger. During experimental campaigns, a performance detriment in this heat exchanger, with respect to design performance, was noticed. For this reason and as a tool for analysis and diagnosis, a model is being developed.

The present paper is organized as follows, section 2 describes the molten salt testing facility and the heat exchanger particularly, section 3 presents the design of the heat exchanger model, section 4 shows simulation results against manufacturer calculations at design conditions, section 5 shows performance evaluation simulations against experimental data and finally, section 6 summarizes the main conclusions and ongoing work.

2. CIEMAT-PSA MOLTEN SALT TESTING FACILITY

With the aim of studying TES systems, a multipurpose molten salt testing facility was set up at Plataforma Solar de Almería (PSA), division of CIEMAT, the public research center for Energy, Environmental and Technological Research, which is owned by the Spanish government. The main purpose of this facility is to evaluate and control the heat exchange between molten salt and different kinds of heat transfer fluids that can be used in solar thermal power plants, i.e. thermal oil and pressurized gases. For this reason the molten salt testing facility is coupled to the innovative fluids test loop facility (Rodríguez-García, 2009) by means of a CO_2 - molten salt heat exchanger. This last facility comprises two parabolic-trough collectors and allows studying pressurized gases as heat transfer fluids.

The principal components of the molten salt testing facility are listed as follows. See figure 1 to match numbers with components. For further details consult Rodríguez-García and Zarza (2011) and Rodríguez-García et al. (2014).

- *Two molten salt tanks.* Hot (1) and cold (2) molten salt tanks are in the facility in order to reproduce the sensible-heat thermal storage systems of commercial solar power plants. The cold tank is under ground level.
- *CO_2 - molten salt heat exchanger* (3). This heat exchanger can work with any other gas from the innovative fluids test loop facility.
- *Thermal oil loop.* To store and release thermal energy to/from the molten salt. The loop includes a thermal oil expansion tank, a centrifugal pump, an oil heater (8), a thermal oil - molten salt heat exchanger (5), molten salt (4) and oil (6) air coolers, an expansion tank (7) and nitrogen bottles (10) to render both fluids inert. The oil heater emulates parabolic-trough collectors by providing the same amount of heat, and also allows the plant to replicate transients such as, clouds, start-ups and shutdowns.
- *Two flanged pipe sections* (9). In these pipe sections, components can be installed and tested in the molten salt circuit under real working conditions.
- *Electrical heat-tracing system.* It was installed in order to prevent salt freezing.

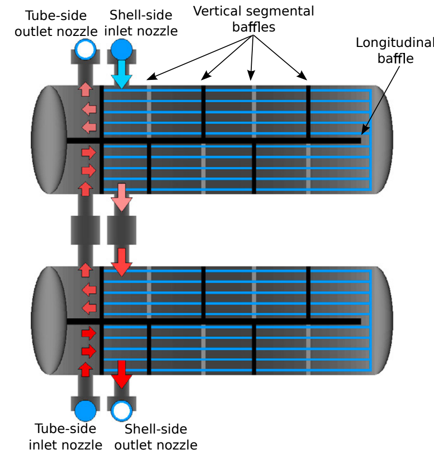

Fig. 2. Two-unit heat exchanger representation

There are four different operating modes in the facility. In mode 1, the molten salt TES system is charged from thermal energy coming from the innovative fluids test loop facility. Mode 2 cools down the molten salt using the air cooler system. Mode 3 charges the TES system from thermal energy coming from the thermal oil loop by means of the thermal oil - molten salt heat exchanger. Finally, mode 4 discharges the TES system by means of the same heat exchanger thus heating thermal oil.

2.1 Multi-Pass Shell-and-Tube Heat Exchanger

The thermal oil - molten salt heat exchanger is composed of two counter-flow multi-pass shell-and-tube units, see figure 2, having the molten salt in the shell side and the thermal oil in the tube side due to its high pressure.

Each unit has a TEMA-NFU (Tubular Exchanger Manufacturers Association - N-type front end stationary head, F-type shell and U-type rear end stationary head) design. The F-type shell is the most common and economical heat exchanger design used at commercial parabolic-trough solar thermal power plants (Herrmann et al., 2004). The units are tilted 2° in order to facilitate their drainage. Each one has two shell passes defined by a longitudinal