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Dynamic modeling and performance of the first cell of a multi-effect distillation plant

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HIGHLIGHTS

- A dynamic model of the first cell of a solar assisted MED plant is developed and discussed.
- The model is based on a MED unit erected at Plataforma Solar de Almería.
- The cell is made up by an effect and a preheater, both have been modeled.
- The model was calibrated and validated with real experiments.
- The dynamic model shows a good agreement with measured data.

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ABSTRACT

This paper describes a model to simulate the thermal transient behavior of the first cell of a solar-assisted multi-effect distillation (MED) plant. It has been designed according to the experience with an experimental solar thermal desalination system erected at CIEMAT-Plataforma Solar de Almería (PSA). The non-linear first principles model has been developed using the object-oriented Modelica language. It includes two submodels corresponding to the effect and the preheater of the first cell of the MED plant. Both submodels have been calibrated and validated with experimental data. The numerical predictions show a good agreement with measured data.

1. Introduction

The alleviation of the lack of potable water in areas with high water-stress is a challenge nowadays. Seawater desalination is one of the possible solutions for regions close to sea, but, the high energy consumption and environmental pollution of this process are some of the disadvantages that researchers try to face. Coupling desalination plants with renewable energies is a way to avoid these disadvantages. It is usual to find high insolation levels in high water-stress areas, which makes solar thermal energy one of the most promising alternatives [1].

Solar thermal desalination consists of a solar thermal system coupled with a conventional thermal desalination process. Although this technology can be found in an integrated system (direct solar desalination), the majority of the large scale applications have two separated devices, the solar collector and the distiller (indirect solar desalination). In spite of recent studies that show the feasibility of several non-conventional options, e.g. the adsorption desalination (AD) due to its low temperature waste heat [2] or the membrane distillation (MD) which combines the advantages of membrane processes (low footprint) with those of thermal processes (robust operation) [3], MED technology carries on being preferred in most of the large scale solar thermal plants due to its low top-brine-temperature (TBT), typically less than 80 °C, and its low specific energy consumption requirements [4].

Different types of solar collectors can be coupled with MED plants. In most of them, the device captures the solar radiation and transfers this heat to a fluid. The fluid can be either water or synthetic oil which is usually stored in an insulated thermal tank or other kind of thermal storage system [5]. The solar collector or the storage system can be connected to the MED unit directly or to a heat exchanger indirectly.

Although there are many variations of MED plants, the distillate process is similar in all of them. The plant is composed of a number of elements called effects which are connected between them. The steam produced in one effect is used as the heat source of the next effect, so, while in one hand, the incoming steam is condensing, on

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the other, the seawater is boiling producing more steam. This is possible because each effect has lower pressure than the previous one [1].

To improve the efficiency of the process, mathematical models and computer simulations can provide detailed information of the performance of the plant over a wide range of operating conditions. Several steady-state models have been published covering a wide variety of them. El-Dessouky and Ettouney [6,7] published several contributions in steady-state modeling and simulation of MED processes. Recently, some authors have applied their respective models to study and/or improve the process, e.g., Kouhikamali who studied the influence of different configurations of feed water preheating [8], Joo and Kwak who increased the mechanical efficiency and economical profit of a MED system [9] or Palenzuela et al. who evaluated different cooling technologies of concentrated solar power plants and their combination with desalination processes [10]. El-Nashar [11,12] and Palenzuela et al. [13,14] validated their respective models with experimental data.

Regarding dynamic modeling, the literature is scarce. El-Nashar and Qamhiyeh [15] developed a model for the study of the transient behavior of a multi-effect stack-type distillation plant. The results were compared with real data obtaining a reasonable agreement. Aly and Marwan [16] developed a dynamic model for a multi-effect process which has been the basis for other dynamic models, such as the six-effect evaporator model of paper industry developed by Kumar et al. [17]. Kishore et al. [18] presented the work-in-progress of a simulator for the steady state and the dynamics of a multi-effect distillation mechanical vapor compression (MED-VC) desalination system, showing a dynamic simulation of a single effect. Roca et al. [19] developed a dynamic model of a multi-effect distillation plant based on the heat transfer correlations obtained in Ref. [13]. This model is an improved version of a previous one in which the heat transfer coefficients were treated as constants [20]. It was developed with the object-oriented Modelica language and its main purpose was the prediction of the thermal dynamics of the heater and the distillate production rate. Kim et al. [21] presented a simulation model for predicting transient behavior of a solar-assisted MED plant. The model, which was focused on the long-term thermal and performance analyses, includes an evacuated-tube collector, a plate heat exchanger, storage tanks and a MED plant. Thu et al. developed a simulation model based on the actual sorption characteristics of the adsorbent–adsorbate pair, energy and mass balances applied to the components of an AD cycle [22]. A similar model of an AD cycle was coupled with the transient MED model developed by Kim et al. for the study of a suitable hybrid configuration of AD and MED processes in Ref. [23].

In this study, we focus on the first effect of a solar-assisted MED plant. This effect, also called heater, is the key to predict the thermal consumption of the MED unit due to its condition as heat exchanger between the solar field/storage system and the MED plant. In order to study its performance in different scenarios and design operating strategies to improve its efficiency, a new dynamic model of a first cell has been developed. This non-linear first principles model has been implemented with the object-oriented Modelica language. It uses as inputs the hot water flow, the feed seawater flow and the outlet pressure. The model is based on the AQUASOL experimental solar desalination system [24] and it has been calibrated and validated with experimental data. It predicts the thermal behavior of the first cell and its low computational effort allows fast simulation for control purposes.

2. Description of the plant

With the aim of testing and developing the solar thermal MED process, an experimental solar thermal desalination system was built at CIEMAT-Plataforma Solar de Almería at the early nineties [25]. Some modifications of the original plant were carried out within the AQUASOL project whose main objective was the development of a hybrid solar-gas desalination system that meets at the same time the requirements of low-cost, high efficiency and zero discharge [24].

The current configuration of the experimental solar thermal desalination plant permits a 24-h MED plant operation (cf. Fig. 1). The system is flexible regarding the energy supply of the plant and three operating mode are possible:

- Solar-only mode: A compound parabolic collector (CPC) solar field provides all the thermal energy required.
- Fossil-only mode: A propane gas boiler by means of a double effect absorption heat pump (DEAHP) supplies the heat required by the MED plant. The DEAHP is coupled with the last effect of the MED plant recovering part of the energy. In this mode, the DEAHP can be connected to the MED plant directly or through the tanks indirectly.
- Hybrid mode: The energy comes from both the DEAHP and the solar field. The DEAHP permits a part-load operation from 30% to 100% strangling the steam flow between the boiler and the DEAHP.

Recently, a new operating mode has been tested at PSA [26]. With the aim of reducing the gas consumption, the gas boiler was replaced by a steam generator which was supplied by a small parabolic trough collector (PTC) solar field.

The desalination plant consists of a forward-feed MED unit with preheaters (Fig. 2). The plant has 14 effects in a vertical arrangement (Fig. 3) in which the seawater descends by gravity from the 1st to 14th effects achieving a 3 m^3/h nominal distillate production. It was manufactured and delivered by ENTROPIE in 1987. Within the framework of the AQUASOL project in 2005, the original first effect, that worked with low-pressure saturated steam (70 °C, 0.31 bar), was replaced [27]. The new effect allows to work directly with hot water.

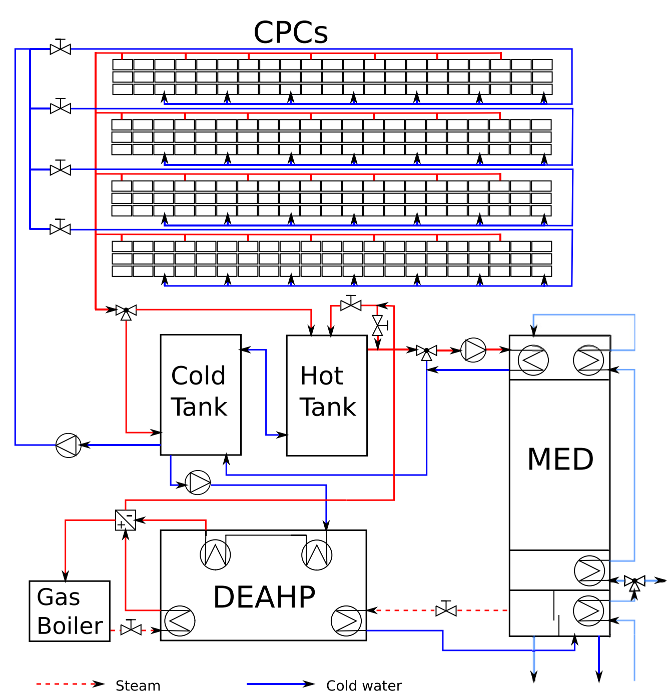

Fig. 1. AQUASOL project plant flow sheet.