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Dynamic modeling and simulation of a solar-assisted multi-effect distillation plant

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HIGHLIGHTS

- A dynamic model of a solar assisted MED plant is developed and discussed.
- The model is based on a MED unit erected at Plataforma Solar de Almería.
- A modular and hierarchical modeling methodology is used.
- 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 presents a dynamic model of a solar-assisted multi-effect distillation (MED) plant, carrying on with the previous work "Dynamic modeling and performance of the first cell of a multi-effect distillation plant" (de la Calle et al., 2014). The dynamic model has been designed according to the experience with an experimental solar thermal desalination system erected at CIEMAT-Plataforma Solar de Almería (PSA). The mathematical formulation based on physical principles describes the main heat and mass transfer phenomena in this kind of facilities. The model was implemented using the equation-based object-oriented Modelica modeling language. Based on a modular and hierarchical modeling, different specific-phenomenon submodels have been developed. They have been interconnected between them, thus making a three level deep hierarchy. All the submodels have been calibrated and validated with experimental data. The numerical predictions show a good agreement with measured data.

1. Introduction

Water is an essential part of life. The lack of fresh water in areas with high water-stress is one of the most important problems which researchers face. Three-fourths part of The Earth surface is covered by water, but the 97 % is salt water. Seawater desalination is one of the possible solutions for coastal regions, but, it requires significant quantities of energy in order to achieve separation of salt from seawater. Coupling desalination plants with renewable energies is a way to reduce the environmental pollution of this process. Solar energy is one of the most promising alternatives since it is usual to find high insolation levels in high water-stress areas [2].

Reverse osmosis (RO), multi-stage flash (MSF) and MED account for more than 94 % of the global desalination capacity [3]. Among them, MSF and MED technologies can be coupled with solar thermal systems because most of the energy consumption is thermal energy. Both technologies allow to be coupled in two separated devices, the solar collector and the distiller. 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].

The collector is a device which captures the solar radiation and transfers its heat to a fluid. In solar-assisted MED plants, the working fluid is commonly water or synthetic oil and it is usually stored in a thermal storage system [5]. The solar collector or the storage system can be directly connected to the MED unit or indirectly by means of a heat exchanger.

There are many kinds of MED plants, but in all of them, the distillation process is similar. The plant is made up of a series of hermetic elements, called effects, connected between them. At each one, a series of

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Nomenclature

A	Area (m^2)
Ar	Archimedes number (dimensionless)
C_p	Specific heat capacity at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$)
D_i	Internal diameter (m)
F	Apparent wet area fraction (dimensionless)
g	Gravitational acceleration ($m \cdot s^{-2}$)
H	Enthalpy (J)
h	Specific enthalpy ($J \cdot kg^{-1}$)
L	Latent heat of vaporization ($J \cdot kg^{-1}$)
m	Mass (kg)
N	Number (dimensionless)
Nu	Nusselt number (dimensionless)
n	Nusselt correlation coefficient (dimensionless)
K	Mass gas constant ($J \cdot K^{-1} \cdot kg^{-1}$)
k	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
Pr	Prandl number (dimensionless)
p	Pressure (Pa)
Q	Heat (J)
Re	Reynolds number (dimensionless)
r	Radius (m)
S	Salinity, salt mass fraction (dimensionless)
T	Temperature (K)
V	Volume (m^3)
y	Proportional number (dimensionless)

Greek symbols

α	Heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
μ	Dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
ν	Kinematic viscosity ($m^2 \cdot s^{-1}$)
ρ	Density ($kg \cdot m^{-3}$)

Subscripts

av	Average
bc	Horizontal tube bundle condenser
c	Falling film condenser
col	Column
cond	Condensate
e	Falling film evaporator
ev	Evaporated
ff	Falling film evaporator or condenser
fl	Flash
g	Gas volume
in	Inlet
mea	Measured
mix	Mixer
out	Outlet
par	Parallel pipes
pp	Pipe
row	Row
sim	Simulated
sl	Saturated liquid
sv	Saturated vapor
w & w2	Pipe walls
water	Water

Newton's notation is used for time derivatives.
The bold terms depict the continuous time states.

simultaneous evaporation/condensation processes take place in a decreasing sequence of pressures and temperatures. At the first effect, the one with the highest pressure, an external heat source drives the first boiling of the seawater that flows inside. The steam generated within the effect is used as the heat source of the next effect, so, while on the one hand, the incoming steam is condensing, on the other, the seawater is boiling, and thus producing additional steam. This process is repeated in each effect [3].

The process modeling and simulation can provide insight about the physical phenomena and give detailed information about the performance that may be useful in order to improve the efficiency of the plant over a wide range of operating conditions without experimentation in the real plant. Several steady-state models have been published covering a wide variety of plant configurations. Some of the most recent contributions in this area have been done by Kouhikamali who studied the influence of different configurations of feed water preheating [6], Joo and Kwak who increased the mechanical efficiency and economic profit of a MED system [7] or Palenzuela et al. who evaluated different cooling technologies of concentrating solar power plants and their combination with desalination processes (RO and MED) [8]. The contributions made by El-Nashar [9,10] and Palenzuela et al. [11] deserve special attention because they validated their respective models with experimental data.

The literature related to dynamic modeling is scarce. However, the interest for this kind of modeling has grown recently. Kishore et al. [12] presented a work-in-progress 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. [13] developed a dynamic model of a multi-effect distillation plant based on the heat transfer correlations presented in [14]. This model is an improved version of a previous one in which the heat transfer coefficients were considered constants [15]. 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. [16] 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 analysis, includes an evacuated-tube collector, a plate heat exchanger, storage tanks and a MED plant. This model has been used by Thu et al. [17] in the study of a suitable configuration for a hybridization between adsorption desalination (AD) and MED processes.

The present paper carries on the work started in [1] where the focus was on the modeling of the first effect of a solar-assisted MED plant. Using an object-oriented modeling methodology, the model presented was divided into submodels that encapsulated and covered the dynamics of each one of the subprocesses that take place in the system. Reusing part of this work and following with this modeling methodology, a new dynamic model of a MED plant has been developed in order to study its performance in different scenarios and design operating strategies to improve its efficiency. This non-linear first principle model has been implemented with the object-oriented Modelica language. The model uses as inputs the natural inputs of the system, i.e., the inlet heater water flow, the inlet condenser seawater flow and the ambient temperature. The model is based on the AQUASOL experimental solar desalination system [18] and it has been calibrated and validated with experimental data. The model predicts the transient thermal behavior of each effect and its low computational effort allows fast simulation for control purposes.

2. Description of the plant

In 1987, a MED unit manufactured by ENTROPIE was erected at CIEMAT-Plataforma Solar de Almería with the aim of testing and developing the solar thermal MED process. Since then, the original experimental solar desalination system has undergone several changes until becoming a 24-h operation hybrid solar-gas desalination system (v. Fig. 1) that tries to meet at the same time the requirements of low-cost, high efficiency and zero liquid discharge [18]. The current system is flexible regarding the energy supply of the MED plant, it can be