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Modeling and simulation of a solar field based on flat-plate collectors

Gary Ampuño[a], Lidia Roca[b], Manuel Berenguel[c], Juan D. Gil[c], Manuel Pérez[c], Julio E. Normey-Rico[d,*]

[a] Universidad Politécnica Salesiana, Guayaquil, Ecuador
[b] CIEMAT-Plataforma Solar de Almería, Centro Mixto CIESOL, Tabernas, Spain
[c] Universidad de Almería, Centro Mixto CIESOL, ceiA3, Almería, Spain
[d] Federal University of Santa Catarina, Department of Automation and Systems, Florianópolis, Brazil

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ABSTRACT

This paper outlines the development of models of a solar field designed to provide thermal energy to a Multi-Effect Desalination (MED) plant. The dynamic model can be used both for simulation and control purposes. Some of these models have been developed based on static and dynamic energy and mass balances, and some others are based on step response methods (experimental tests). The solar field comprises a flat-plate collector field, an air cooler, a heat exchanger and the corresponding pipelines and interconnections. The main purpose of the solar field is to feed the MED unit with hot water within a specific temperature range using two thermal storage tanks as input buffers to the MED system. The main achievement of this paper is that the developed model provides an adequate tradeoff between complexity and performance.

1. Introduction

Fresh water scarcity and the increasing concentration of greenhouse gases (mainly caused by humans) are an important problem nowadays. Solar desalination has been studied for several years to provide fresh water and minimize CO_2 footprint. The use of solar energy for desalination processes can be done using multi-effect distillation (MED) coupled to a thermal solar energy system, which is known as indirect solar distillation.

During the last years, different solar-powered desalination technologies have been tested at Plataforma Solar de Almeria (PSA), a dependency of the CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas), a public research body assigned to the Spanish Ministry of Economy, Industry and Competitiveness. One of the research lines of the Solar Desalination Unit at PSA is the integration of solar facilities into desalination processes, requiring validated dynamic models to design and test control strategies to improve the operating process. The solar field lumped parameter model presented in Camacho et al. (2012) has been widely used for control purposes not only for parabolic trough collectors (Cirre et al., 2007; Romera Cabrerizo and Santos, 2017), but also for compound parabolic collectors (Roca et al., 2008; Ayala et al., 2011; Torrico et al., 2009, 2010) and flat-plate solar fields (Gil et al., 2018a, 2018b). This kind of simple but accurate models can be used also for optimization studies to maximize economic benefits (González et al., 2014) or to reduce costs (Roca et al., 2016). For the case of the MED unit, a detailed model based on energy and mass balances was developed and validated with real data (de la Calle et al., 2015) and used to determine the optimal operating points taking into account different performance indexes (Carballo et al., 2016). In all of these cases, a fundamental issue is to develop models that account for a performance/accuracy tradeoff to obtain reliable results in a low computational time.

This paper shows the modeling and simulation of the solar field used in the AQUASOL-II solar distillation plant placed at PSA. The model was developed to help analyzing different scenarios in simulation and in order to design, develop and test control algorithms aimed at improving the operation of this kind of plants. This model includes:

- the solar field,
- an air cooler, able to reduce the temperature at the end of the solar field, and,
- a heat exchanger (HX), in charge of transferring thermal energy to the water contained in the storage tanks.

The paper is organized as follows: first, AQUASOL-II plant is explained in Section 2, followed by the implementation of models in Section 3. A comparison between experimental and simulation results is performed in Section 4 and some concluding remarks are finally drawn.

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* Corresponding author.
E-mail address: lidia.roca@psa.es (J.E. Normey-Rico).

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Nomenclature

Symbol	Description Unit
A	cross-sectional area of the loop pipe (m^2)
A_{cs}	collector absorber cross-sectional area (m^2)
A_{hx}	heat exchange surface (m^2)
c_p	specific heat capacity (J·kg^{-1}·°C^{-1})
c_f	conversion factor to account for number of modules, connections and L/min conversion (s·L·min^{-1}·m^{-3})
$d_{j,tout-I}$	irradiance-outlet water temperature related transport delay in loop j (j = 1...5) (s)
$d_{j,tout\text{-}Q}$	Flow rate-outlet water temperature related transport delay in loop j (j = 1...5) (s)
$d_{j,tout-tin}$	inlet water temperature-outlet water temperature related transport delay in loop j (j = 1...5) s
$d_{loopi\text{-}Pj}$	transport delay between the outlet of solar loop i and the point Pj located at the main pipe (i = 1…5, j = 1…4) (s)
$d_{Pi\text{-}Pj+1}$	transport delay between the points Pi and $Pi + 1$ located at the main pipe (i = 1…3) (s)
H	thermal losses coefficient (J·s^{-1}·°C^{-1})
I	solar irradiance (W·m^{-2})
L	loop pipe length (m)
L_{eq}	equivalent length of the flat plate collector tube (m)
L_t	flat plate collector tube length (m)
$\dot{m}_p$	primary circuit mass flow rate (kg·s^1)
$\dot{m}_s$	secondary circuit mass flow rate (kg·s^1)
n_p	number of parallel collectors in each loop-row (–)
n_s	number of collectors in serial connection in each loop (–)
n_t	number of parallel tubes in each collector (–)
Q_{loopj}	volumetric flow rate in loop j (j = 1...5) (L·min^{-1})
Q_p	volumetric flow rate in primary circuit (L·min^{-1})
Q_s	volumetric flow rate in secondary circuit (L·min^{-1})
Speed	air cooler fan velocity (%)
T_a	ambient temperature (°C)
$T_{ac,in}$	air cooler inlet temperature (°C)
$T_{ac,out}$	air cooler outlet temperature (°C)
$T_{hx,p,out}$	outlet temperature of heat exchanger primary circuit (°C)
$T_{hx,s,out}$	outlet temperature of heat exchanger secondary circuit (°C)
$T_{hx,p,in}$	inlet temperature of heat exchanger primary circuit (°C)
$T_{hx,s,in}$	inlet temperature of heat exchanger secondary circuit (°C)
$T_{loopj,in}$	inlet temperature of loop j (j = 1...5) (°C)
$T_{loopj,out}$	outlet temperature of loop j (j = 1...5) (°C)
$\mathrm{T_{Pi}}$	water temperature at point Pi located at the main pipe (i = 1…4) (°C)
t_s	sampling time (s)
$\widetilde{T}$	equivalent flat plate collector tube mean temperature (°C)
v	flow rate (m·s^{-1})

Greek symbol

α_{hx}	heat transfer coefficient (W·m^{-2}·°C^{-1})
β	model parameter that modulates the solar irradiance component (m)
$\eta_{hx,p}$	compensator dimensionless factor for heat exchanger primary circuit (–)
$\eta_{hx,s}$	compensator dimensionless factor for heat exchanger secondary circuit (–)
θ_{hx}	heat exchanger factor (–)
ρ	water density (kg·m^{-3})

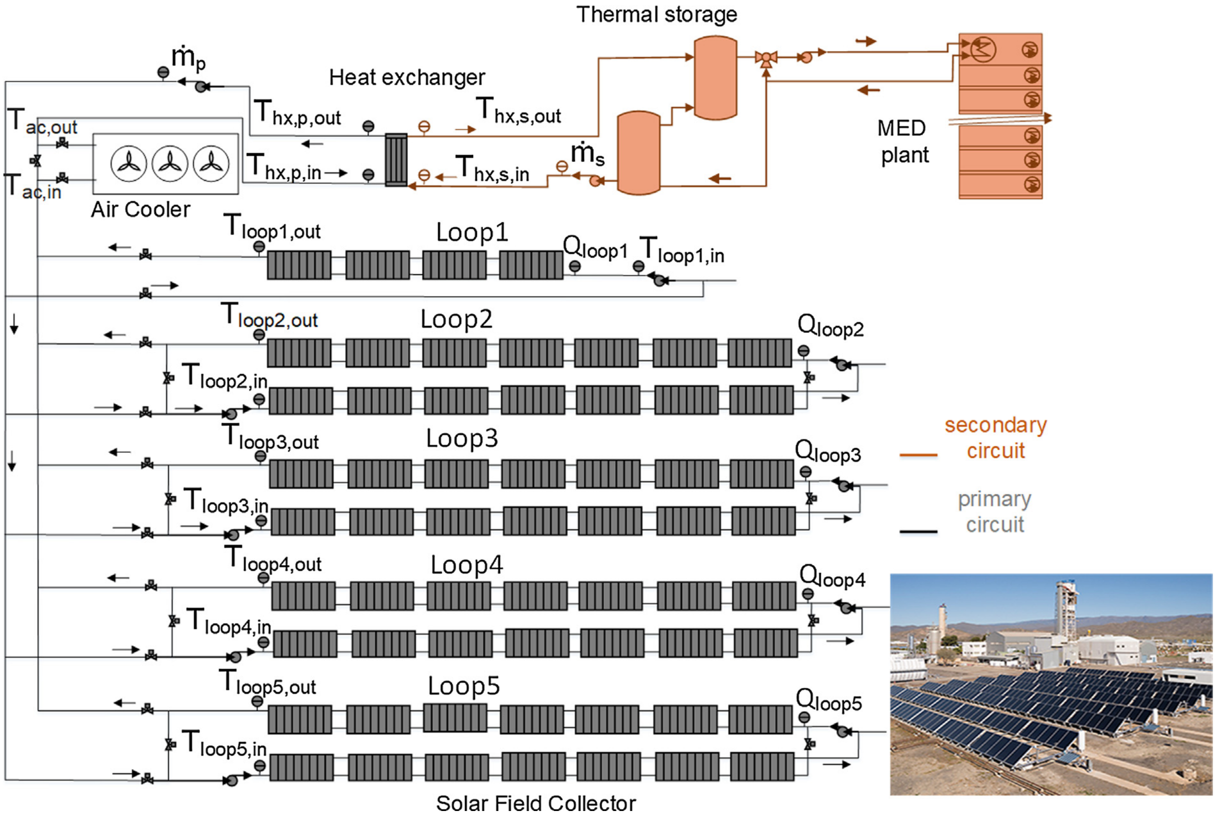

Fig. 1. Schematic diagram of the solar MED facility at PSA and photo of the solar field.