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Modeling an active solar still for sea water desalination process optimization

Osman Ali Hamadou, Khamlichi Abdellatif *

Department of Physics, Faculty of Sciences at Tetouan, Tetouan 93030, Morocco

HIGHLIGHTS

- Comprehensive numerical modeling of an active solar still was performed.
- All the design parameters with those of the heat transfer fluid were included in the model.
- Validation of the modeling was assessed by comparison to an exact 2-D model of a humid-air cavity.
- Adequacy of the correlations used for the heat transfer coefficients was verified.
- Extensive parametric studies enabled to determine the relative influence of the key factors.

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ABSTRACT

Active solar stills can provide enhanced distillate productivity, as saline water is circulated and put in contact with an additional heat source which supplies extra heat to the system. In this work, a single slope solar still having a transparent glass cover is considered to be heated at its bottom by a circulating heat transfer fluid. The rate of this flow and the temperature at the inlet of the still are assumed to be controlled such that they are adjusted to the desired values. A modeling based on relevant correlations giving the heat transfer coefficients and the vaporization heat flux as function of Rayleigh number was derived. This takes the form of a set of highly coupled nonlinear ordinary differential equations in terms of time-dependent temperatures of the still components. The obtained model enabled to take into account the effects of heat transfer fluid rate, inlet temperature, sea water rate, basin depth, ambient temperature, wind speed and relative humidity of ambient air. Extensive parametric studies were performed and optimization of the rate and yield of distilled water was discussed.

1. Introduction

Water is scarce in many areas across the world. As demand on water is increasing, supply of water constitutes a critical problem to deal with by using innovative concepts.

Literature review indicates that approximately 99% of available water on Earth is salty, brackish or frozen and that only 1% is fresh and set to consumption as potable water. Sea water desalination can help addressing the water-shortage problem. The separation of salts from sea water requires however a large amount of energy. Therefore, it is beneficial to employ renewable energy sources for desalination. Solar energy which is in abundance, particularly in dry areas, can be utilized for this purpose in order to produce potable water with reduced energy cost [1].

Solar thermal desalination comprises direct and indirect processes [2]. Direct processes are such that all parts are integrated into one system whereas indirect processes are those for which heat is coming from a separate solar collecting system such as solar collectors or solar ponds. The most common solar thermal arrangements that are used in practice for desalination are solar stills and solar ponds. Solar stills were recognized to be more efficient for small production scale where the freshwater demand does not exceed 100 m^3 per day [3].

Natural convection takes place in solar stills because of the buoyant force caused by density variation due to the temperature and concentration gradients. Various numerical approaches were considered in order to study evaporation and condensation in a humid air-filled cavity, which constitutes the physical representation of solar stills.

The first family of approaches use coupled heat and mass transfer equations for natural convection taking place in the cavity with wall surface condensation and evaporation. Talukdar et al. [4] have performed 3-D computational fluid dynamics simulations for convective heat and mass transfer between water surface and humid air in a horizontal rectangular duct. They have concluded that the numerical results compare well for most of the observed experimental data. Sun et al. [5] have analyzed the case where the cavity walls are subjected to uniform

* Corresponding author. Tel.: +212 600769960.
E-mail address: khamlichi7@yahoo.es (K. Abdellatif).

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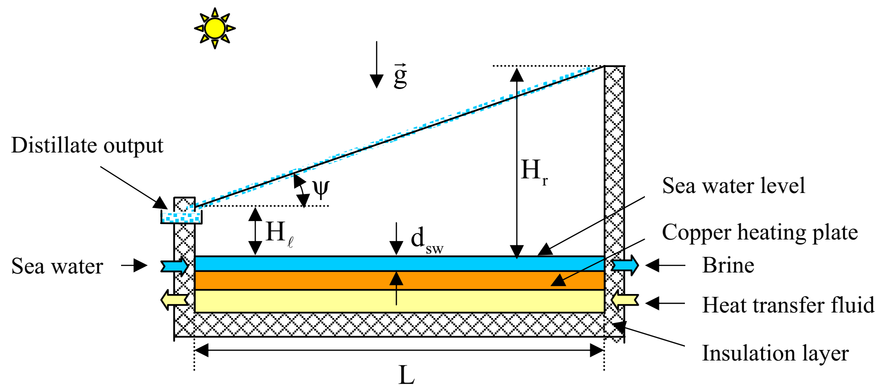

Fig. 1. Schematic diagram of an active single-slope solar still.

time-dependent temperatures. The authors noted that various transient flow structures occur during condensation and evaporation processes. The thickness distributions of the water films condensed at the wall were discussed as function of the aspect ratio. By using a control volume based finite element method, Chouikh et al. [6] have analyzed the two-dimensional natural convection flow resulting from the combined buoyancy effects of thermal and mass diffusion in an inclined cavity. They showed that the performance of the solar distiller can be enhanced while a single cell develops and rotates in a sense that allows enough time for the vapor to cool down.

Rahbar and Esfahani [7] have investigated the natural convection effect in a 2-D single slope solar still. A numerical model based on SIMPLEC (Semi Implicit Method for Pressure Linked Equations Corrected) was used for the solution of mass, momentum, energy and concentration equations. A new correlation for estimating the convective heat transfer coefficient has been derived as function of the aspect ratio and Rayleigh number. Alvarado-Juárez et al. [8] have performed a numerical study of conjugate heat and mass transfer in a solar still device having the form of an inclined cavity. Double-diffusive natural convection and surface thermal radiation were considered through a steady state 2-D approximation of the equations which were solved by the finite volume method. The authors noted strong effect on the Nusselt number which results from the surface thermal radiation as it increases the velocity near the walls.

The previous models based on rigorous mathematical formulation of the problem provide thorough understanding of the complex physical phenomena occurring in the humid air filled cavity. These models show for instance the existence of multiple cells depending on the intervening parameters. They can thus be used to enhance the design of solar stills in terms of aspect ratio, inclination angle and Rayleigh number [8]. Their use in practice is effective however only within the framework of steady-state approximation to the problem where time variations are neglected. The possibility of employing them for transient regimes in a step-by-step analysis type is highly time consuming. Besides, this requires using the same precision level models for the heat transfer fluid, ambient air and heat transfer occurring in the absorption plate and glass cover domains. Even with a 2-D approximation of the problem, huge numerical difficulties arise then.

Table 1
Thermo-physical properties of the system.

	Density ($kg\ m^{-3}$)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Heat capacity ($J\ kg^{-1}\ K^{-1}$)	Volume (m^3)
Sear water	1027	0.6038	3976	Variable
Glass	2500	1.2	720	0.025
Copper	8933	420	385	0.005
Heat transfer fluid	768.6	0.1663	2515.6	0.5

In the second family of approaches to modeling of solar stills, use is made directly of proper correlations between the Nusselt number and Rayleigh number. This enables to obtain the convective heat transfer coefficient as a function of fluid properties, still geometry, flow characteristics and operating temperature. Various experimental models have been proposed to evaluate the internal heat transfer coefficients. These include for instance Jacob's model [9], Dunkle's model [10], Corcione's model [11] and Chilton–Colburn model [12]. Enhanced correlations giving the evaporation/condensation heat transfer coefficient can also be obtained by means of the first family of approaches [11]. Conservation equations of mass, momentum, energy, and concentration can be solved enabling to perform extensive parametric simulations. Using the simulation data and the least square method through a logarithmic multiple regression procedure, Rahbar and Esfahani [7] have fitted a dimensionless equation that gives the Nusselt number as function of the aspect ratio and Rayleigh number. The authors have shown that in the investigated range of parameters, the obtained results are close to those given by the Chilton–Colburn model or by Dunkle's model.

Using such correlations for the heat transfer coefficient enables effective computation of the temperatures during the transient regime while avoiding solution of bulky coupled time-dependent nonlinear partial differential equations.

Considering passive solar stills which use directly solar radiation to produce distillate water, various parametric studies and optimization methods have been considered by using the heat transfer correlation based modeling [13–16]. The objective is to increase the performance of solar stills. But, these systems have yet low productivity which explains their rather limited commercial utility. Currently available state-of-the-art single-effect solar stills have an efficiency not exceeding 40% [3]. The main reason is the heat loss which is quite large for these installations [17–19]. As a main step toward improving solar still productivity, optimizing the system input and geometric configuration is of crucial importance. Design problems encountered with passive solar stills deal with brine depth, vapor tightness of the enclosure, distillate leakage, materials for thermal insulation, and cover slope and shape [20]. One can add to this list of design parameters, the aspect ratio and the work Rayleigh number in the solar still cavity [7,8].

Productivity in terms of distillate yield can be increased by providing extra supply of heat to the sea water through an exchange with a heat transfer fluid heated previously in a solar collector system. It is then of interest modeling and optimizing the active solar still having this configuration. This is really important in practice in order to achieve control of the heat transfer fluid rate and the input temperature as in practice the ambient temperature and solar intensity are continuously changing.

In this work, modeling of an active solar still with a circulating heat transfer fluid that supplies heat to the still bottom is performed. Three correlations giving explicitly the intervening heat transfer coefficients