Computación y Sistemas Número Especial pp. 035 - 041
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New Models for Computer Assisted Solar Distillation Research

Nuevos Modelos para el Estudio Asistido por Computadora de la Destilación Solar

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Article received on June 18, 2001; accepted on March 03, 2002

Abstract

Modeling of solar distillation is reported in this work.
The development of two new models, empirical and numerical, are presented. Experimental work was accomplished with a specially designed computer-controlled still with which various conditions for basin water temperature and water-to-cover temperature differences were established. The numerical model was derived from a lumped parameter analysis of solar stills and implemented in a computer program. The novelty of this model is its sensitivity to orientation, that results in a different performance for each condensing cover, showing therefore thermal asymmetries not reported before in the literature.
Keywords: Solar still; Experimental; Mathematical model; Automation.

Resumen

Se reporta un trabajo de desarrollo de nuevos modelos de simulación de la destilación solar, de tipo empírico y numérico, obtenidos con la ayuda de un sistema de control automático por computadora, mediante el cual se establecieron diferentes condiciones térmicas en el agua y las cubiertas de un equipo experimental de destilación.
El modelo numérico se basa en un análisis de parámetros concentrados de un destilador solar y se implantó en un programa de cómputo. La novedad de este modelo es su sensibilidad a la orientación, que reproduce las diferencias en el comportamiento de las cubiertas condensadoras, así como asimetrías térmicas que no han sido reportadas en la literatura.
Palabras clave: Destilador solar; Experimental; Modelo matemático; Automatización.

1 Introduction

Performance of single and double slope solar stills have been extensively studied. It has been found that the main heat transfer mechanisms are convection and radiation for the outside of the still, and additionally, evaporation for the inside due to the simultaneous heat and mass transfer during the evaporation-condensation process.
Experimental work has been carried out and some empirical models have been proposed to predict production and temperatures in solar stills. For example, it has been found that over a limited range of operation, the mass transfer rate can be expressed as a linear function of water and cover temperatures as proposed by Cooper (1973).

Another semi-empirical model to estimate cover temperature as a function of ambient, sky and water temperatures was reported by Sharma and Mullick (1991).

Different authors have also carried out numerical work in this area. The problem is tackled by means of a lumped parameter analysis. An energy balance, which considers the input, output and stored energy, is applied to each component of the system deriving its corresponding expressions. In the case of a single slope still it results in three differential equations to model the performance of the cover, water and absorber bottom.

This approach has been used to study several aspects of single cover solar stills, as shown by Kumar and Tiwari (1988), with the report of the temperature dependence of internal heat transfer coefficients on its performance; the thermal analysis to optimize the inclination of the glass cover for maximum yield by Tiwari *et al.* (1994); the effects of water depth, wind speed and glass cover thickness in production, by Toure and Meukam (1997) and the effect of a solar still with a baffled suspended absorber to study the preheating time of the basin water by El-Sebaii *et al.* (2000).

For experimental and numerical work in double slope solar stills, some details have been ignored in the past, as it is the case of the performance differences of each cover. This is shown in the experimental work by Akash *et al.* (2000), where measured productions for each cover show a similar fashion. Various authors have published numerical results with this attic shape geometry by using a single equation for the thermal analysis of the two covers forcing the results to a single cover case (Morse and Read, 1968; Sharma and Mullick, 1992; Sing *et al.*, 1995; Srivastava *et al.*, 2000).

2 Proposed Numerical Model

A numerical model for a double slope solar still that takes into account the performance differences between the two condensers, should consider the heat and mass transfer interactions resulting from a lumped parameter analysis applied to four components: water, absorber bottom, and the two covers.

Based on the first law of thermodynamics, the energy balance for the evaporating water that includes the interaction with the covers and the basin is:

$$m_w c_w \frac{dT_w}{dt} = \alpha_w E + h_{bw}(T_b - T_w) - h_{wg1}(T_w - T_{g1}) - h_{wg2}(T_w - T_{g2})$$

While for the blackened bottom that absorbs the most of the sun energy and interacts with the environment and the water:

$$m_b c_b \frac{dT_b}{dT} = \alpha_b E - h_{bw}(T_b - T_w) - h_{be}(T_b - T_e)$$

For one glass cover, named east cover, the terms relating the heat exchange with water and the environment result as:

$$m_{g1} c_{g1} \frac{dT_{g1}}{dt} = \alpha_{g1} E + h_{wg1}(T_w - T_{g1}) - h_{g1g2}(T_{g1} - T_{g2}) - h_{g1e}(T_{g1} - T_e)$$

Similarly, for the second cover, named west cover:

$$m_{g2} c_{g2} \frac{dT_{g2}}{dt} = \alpha_{g2} E + h_{wg2}(T_w - T_{g2}) - h_{g2g1}(T_{g2} - T_{g1}) - h_{g2e}(T_{g2} - T_e)$$

The left most term in these equations represents the variation in the stored energy, meanwhile the right terms describe the energy losses and gains.

As can be seen, these differential equations should be solved by numerical methods and depend on the energy received from the sun through a factor αE that is the absorbed fraction of energy and the heat transfer coefficient h defined according to the involved transfer mechanism.

The relations concerning the coefficients that consider simultaneous heat and mass transfer are reported by Dunkle (1961), where the expressions for the convective and evaporative fraction of the energy are as follows:

$$h_c = 0.884[T_w - T_g + (\frac{P_w - P_g}{268.9x10^3 - P_w}) \cdot T_w]^{1/3}$$

$$q_e = 16.273x10^{-3} h_c (P_w - P_g)$$

and for the external coefficient for losses to the environment due to the wind according to Watmuff *et al.* (1977) is:

$$h = 5.7 + 3.8 \bullet V$$

3 Experimental Set-up

To develop an empirical model to predict the mass flow rate for solar stills it was necessary to design an experimental laboratory still with an automatic control system to establish the desired steady state conditions.

The geometry of the still used in this work was triangular with dimensions shown in Fig. 1.

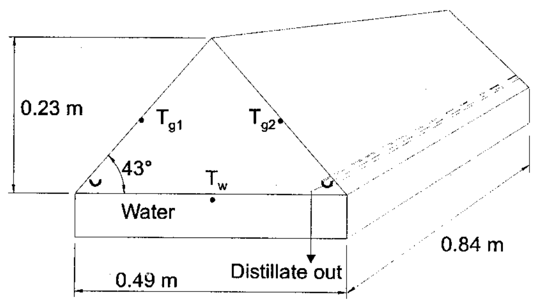

Figure 1. Sketch of the laboratory still

This is a double slope still with glass covers and stainless steel basin. Distillate collection channels were incorporated on each condenser plate.

To simulate the sun energy that heats the bottom of the still, an electric heater was installed beneath the basin. To establish the desired temperatures on the covers, a controlled sheet of cold air was forced to flow into a thin metallic channel incorporated over each cover. A general sketch of the control system is shown in Fig. 2.

An air-conditioner equipment was used to supply the air to cool the covers and an electronic interface was designed to implement the air flow by means of the electromechanical system shown in Fig. 3. This interface controlled two motors that move the plates to let the air flow into the channels and lower the temperatures of the covers when necessary.

Measuring system and heating control was implemented with a personal computer as shown in Fig. 4. The CPU parallel port was used to control the solid state power interface of the electric heater. The serial port was used to acquire temperature data from thermocouples bonded to the still. A multichannel scanning thermocouple thermometer was used as the measurement interface.

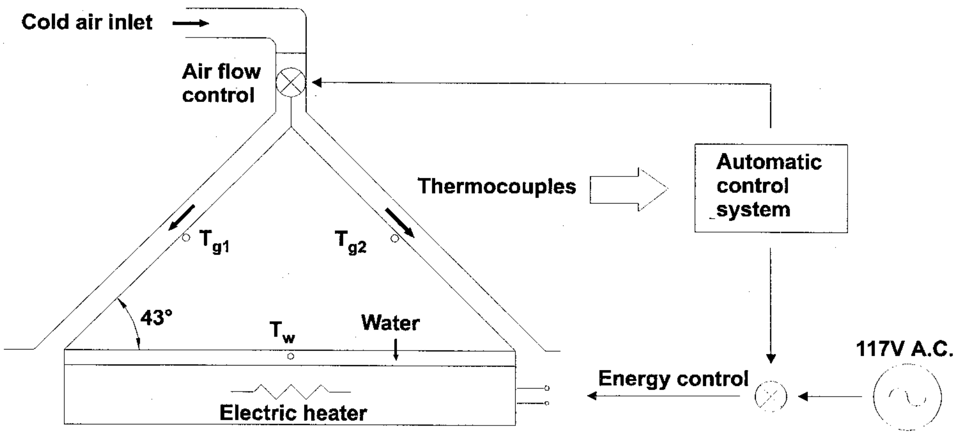

Figure 2. Control elements for heating and cooling

An object oriented program was developed in order to automate this thermometer and be able to read and send serial data to the computer to be used in control functions. A picture of the graphical interface is shown in Fig. 5.

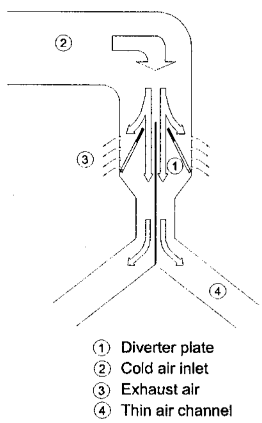

Figure 3. Cold air flow control

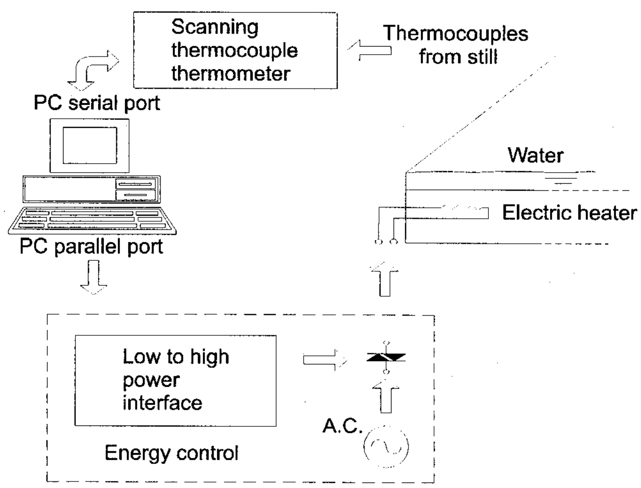

Figure 4. Automatic measurement and control system

4 Experimental Results

Various thermal conditions for water temperature and water-to-cover temperature differences were established with the aid of the automated computer system in the normal range of operation of a solar still. Temperatures and distillate yield data were correlated and a mathematical model for the prediction of the mass flow rate was derived. The terms in the final expression were taken dimensionless and the model resulted as follows:

$$m_E = 0.11 \Delta T^* \; (14.4)^{Tw^*} + 0.0052 (28.16)^{Tw^*}$$

where m_E is production expressed in [kg m^{-2} h^{-1}],

$$Tw^* = \frac{T_W - 293.15}{55}, \qquad \Delta T^* = \frac{T_W - T_g}{17}$$

$293 < T_W < 348$, and $1.5 < T_W - T_g < 17$.

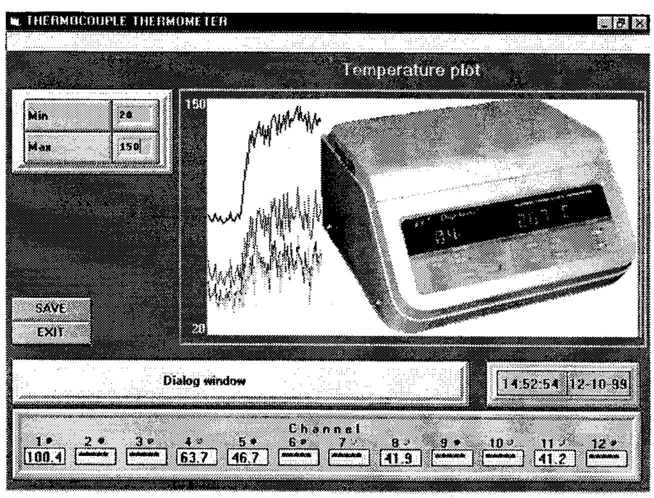

Figure 5. Data acquisition graphical interface

A graph of production for constant water temperatures resulting from this model is shown in Fig. 6.

The widely used Dunkle's relations for estimating mass flow rate (Dunkle, 1961) and those from another author (Clark, 1990) were used to make a comparison with the model. A graph for different temperatures is shown in Fig. 7.

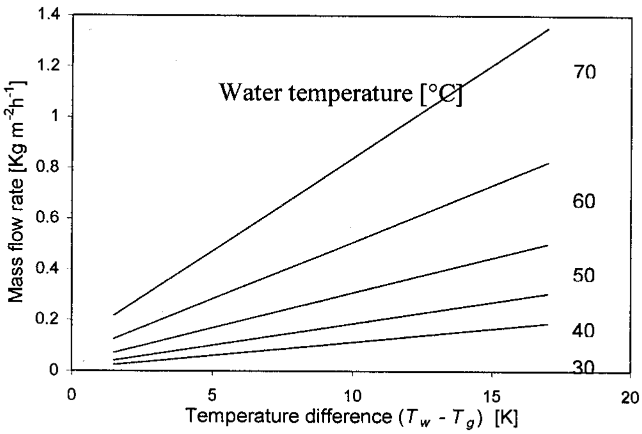

Figure 6. Empirical model results

The least production corresponds to Clark's work because his heat transfer coefficient is defined as half of the others. The proposed model and Dunkle's equations show a good correlation. The former has a tendency to slightly predict higher rate of distillate yield because of the combined final effect of heat exchange by convection, radiation and evaporation.

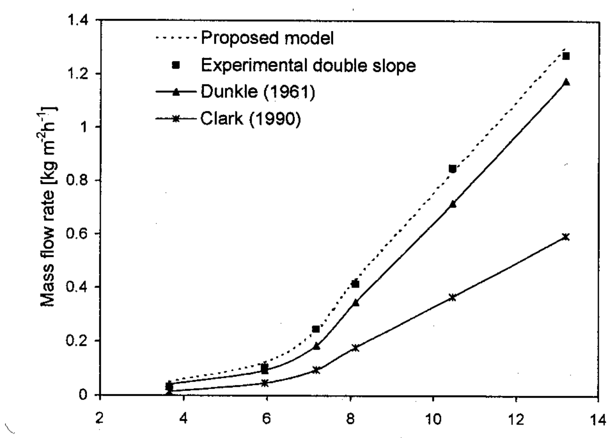

Figure 7. Mass flow rate models comparison

5 Numerical Results

As solar radiation is the source of energy for distilled water production, optical properties of the covers should be considered through the transmitted absorbed and reflected fractions of energy in the four equations.

The numerical solution of the differential equations was achieved by the Runge-Kutta methods and a new model resulted that is sensible to orientation of the solar still reflecting different temperatures and productions for each cover. Results of this numerical model were compared with experimental measurements of a solar still to check its validity. As solar radiation is the main factor that produces differences in temperatures of the covers, only selected graphs for this parameters are presented in figs. 8-10.

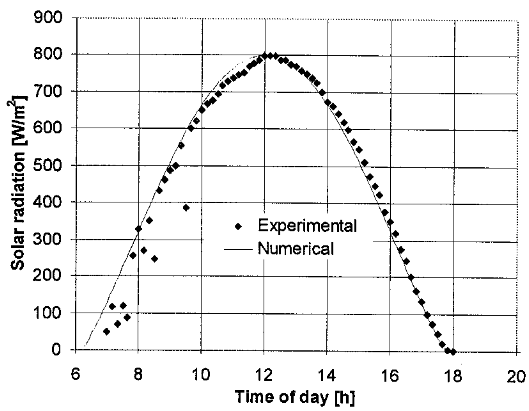

Figure 8. Predicted and measured solar radiation

This new model was implemented in C language with a graphical user interface (GUI) to respond to user commands. In this implementation, the user has the option to set specific parameters for physical properties of the materials, site of the simulation and initial conditions. Results for covers, water and bottom temperatures as well as solar radiation and distillate yield are presented in selectable graphics to check their evolution. An option has been incorporated to create a file of data when these meet the user criteria.

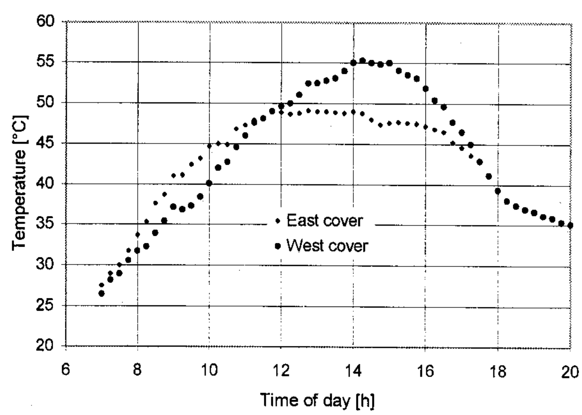

Figure 9. Covers temperature measured data

A picture of the graphical user interface of the model is shown in Fig. 11. As it can be seen, predictions reproduce the expected asymmetries in temperatures and values correlate in good agreement with the measured data.

6 Conclusions

Two new models applied to solar energy distillation were presented. An automated data acquisition system to establish the desired experimental conditions was developed to get an empirical model that can be used in the energetic analysis for predicting the mass flow rates from temperatures at the interior of the cavity of the still.

At the same time, a lumped parameter analysis was used in a double slope solar still to get a numerical model that reproduces in good agreement its performance.

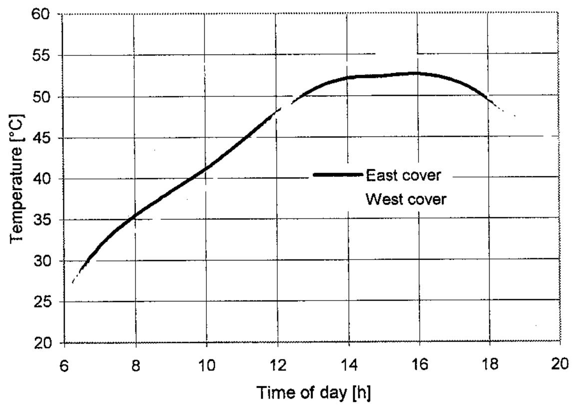

Figure 10. Covers predicted temperature results

The numerical model reflected thermal asymmetries on the condenser plates resulting from a different orientation of each cover with respect to the sun. Finally, a solar still simulator was implemented and can be used for engineering analysis.

It represents also a helpful and valuable didactic tool for solar energy topics. Further research is under way to evaluate surface heat transfer and variable wind conditions.

7 Acknowledgments

Mexican National Council for Science and Technology (CONACyT) funded this work through grant 28932A. The authors thank Dr. Rodrigo Salgado for his cooperation with experimental data.

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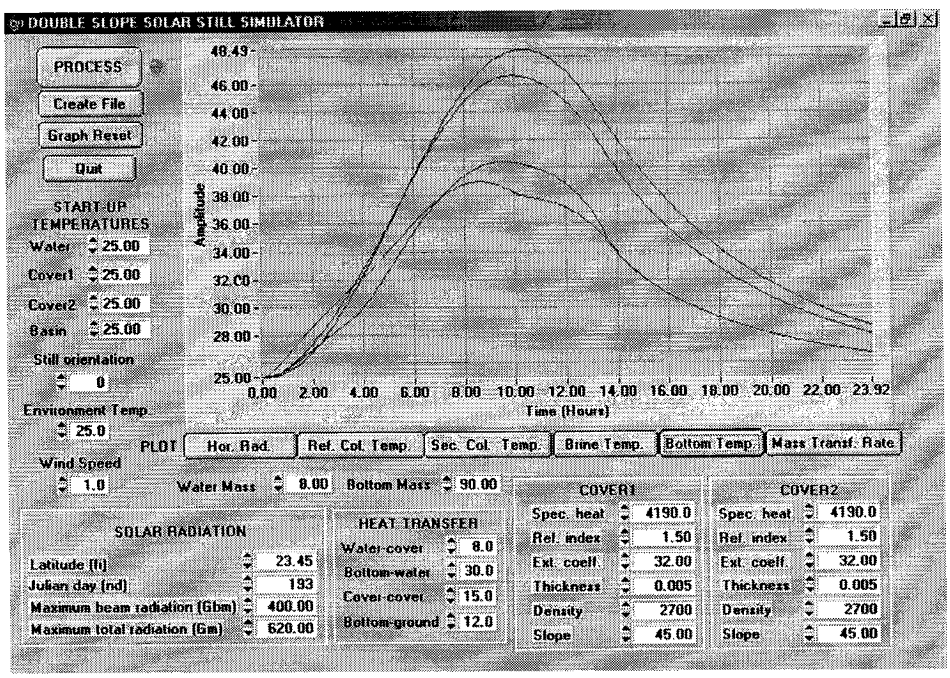

Figure 11. Solar still numerical model GUI

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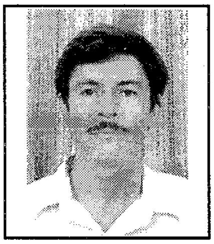

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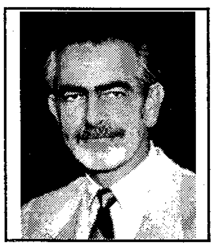

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