Heat Transfer Intern Coefficient Determination in the Process of Solar Still

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Abstract. In this work, a study of internal heat transfer coefficients is performed in a solar still of a slope is presented, when it operated with brine. The estimate is based on the experimental observation of the solar still for 4 different initial volumes (2, 4, 6 y 8 L), under the climatic conditions of the city of Mexico. The internal coefficients to evaluate are: convection, evaporation and radiation through the use of the thermal model proposed by Kumar and Tiwari. As a result it was found that the internal coefficient more representative in the process of solar distillation is the evaporation ($h_e$), reaching a maximum of 30 W/m$^2$K, the coefficients of convection ($h_c$), and radiation ($h_r$), attained values of 2.5 W/m$^2$K and 4 W/m$^2$K respectively. It was also noted that as the initial volume of brine increases, the internal heat transfer coefficients decrease.

1. Introduction
Solar distillation is one of the oldest methods to obtain drinking water from saline water by the use of solar energy. The performance of a solar still is characterized by the different heat and mass transfers that happen inside it, the solar radiation absorption frees water steam, that rises up to the glass surface helped by the internal heat convection transfer that flows to the top.

The heat transfer in the inside of the solar still, from the water surface to the glass cover where the condensation is produced, is performed by convection, evaporation and radiation, where the heat transfer by convection and evaporation flow simultaneously and independently from the heat transfer by radiation. To analyze the performance of the solar still is essential to know the value of these coefficients more precisely. Some contributions of papers performed about heat transfer events that happen in the inside of these devices are now exposed. Anil and Tiwari [1], studied the effect that the water depth has with the mass transfer coefficients by evaporation in a passive solar still system of a slope for the summer weather conditions. They realized experiments for different water depths for 0.04 m, 0.08 m, 0.12 m, 0.16 m and 0.18 m, with the glass cover tilted 30° and found that the heat transfer intern coefficients depend significantly in the water depth. Finally they found that the higher productivity and efficiency is found in the lowest depth.

Tripathi and Tiwari [2], studied the effects of the heat and mass transfer coefficients for an active solar still for different water depths in the absorber container, founding that the performance decreases significantly with the rise of the water depth in the absorber container of the solar still. They performed experiments 24 hours during months of winter for the different water depths of the absorber container (0.05, 0.1 and 0.15 m), and found that the heat transfer coefficient by convection between
water and the inside depends largely on the water depth. Kumar and Tiwari [3], made a survey to estimate the heat transfer internal coefficients of a hybrid active solar still (PV/T). They assess the solar for the weather conditions of New Delhi (28°35'N 77°12'E). As a result they obtained the average values per year from the heat transfer coefficient by convection for the hybrid active solar distiller (PV/T) which are of 0.78 and 2.41 W/m² K, respectively, for a 0.05 m depth. Aminul and Teruyuki [4], propose a new model of heat and mass transfer for a tubular solar still (TSS), in which they incorporate heat and mass coefficients keeping in mind the properties of humid air inside the solar still. With the proposed model they calculated different variations such as water temperature, cover and gutter, water steam density, relative humidity of humid air and also predict the condensation and evaporation flow per hour. The validity of the proposed model was verified by using the experimental results field performed in Fukui, Japan and Muscat, Oman in 2008, theoretical and experimental results show that the proposed model is acceptable to predict the production flow daily and hourly in an accurate way. Zheng et al. [5], establish an empiric correlation based on the analogy of the heat and mass transfer in the basin of a solar still. To perform the validation of the correlation, they build a multi-phase solar still made out of aluminum with a basin area of 0.665x0.650 m as a result they obtained that the group of developed correlations can provide better predictions for the evaporation rate in solar stills, for the wide range of the Rayleigh number (3.5x10³< Ra<2.26x10⁷), so as the temperature (35<T fluid<86°C).

The objective of this paper is intended to find the relation of the thermal behave of a solar still regarding the heat transfer inner coefficients when this is operated with brine and varying the thickness that the fluid occupies, for that purpose energy balances are established to observe the thermal behavior of the device.

2. Experimental procedure

Basically, the solar distiller used for this investigation has only one slope, it has an absorber container painted in matte black with an area of 0.36 m², the transparent cover that works as a condenser is made out of glass with a tilt angle of 40°, also the solar distiller has 4 glass gutters with a tilt angle of 5° approximately, in which condensate from the walls of the cover is collected. In figure 1 the solar still is shown.

![Figure 1. Solar still](image)

In the device, 4 experimental tests were made each one with a different initial volume, which are: 2, 4, 6 and 8 L, the working fluid was brine and it was operated in the city of Mexico, where the weather conditions are very positive. Brine is used by the lack of fresh water what has motivated the development of desalination projects marina. Instrumentation was implemented which allowed to obtain temperature and incident solar radiation data with the use of a Compact FieldPoint equipment, K thermocouples and a pyranometer, all together added to a LabVIEW interface obtaining data in the lapse of time from 10:00 am to 18:00 pm in 10 minutes gaps, considering that in this period of time more sunstroke is received. To perform the corresponding survey, 7 thermocouples were placed, mostly in the intern walls of the glass cover, fluid, absorber container and environment.
3. Internal heat transfer coefficients

The solar still behavior is characterized by the different heat and mass transfers that happen inside it, in figure 2, heat transfer phenomena involved in the evaporation-condensation process are shown. Usually the heat transfer in solar still systems can be classified in terms of internal and external. The external heat transfer is mainly controlled by the process of conduction, convection and radiation, and these are independent of each other. This heat transfer happens outside the solar distiller, in other words, from the glass cover to the environment. On the other hand the heat transfer inside the distiller is mostly radiation, convection and evaporation, in this case the heat transfer by convection happens simultaneously with the heat transfer by evaporation, these two processes in turn are independent from the heat transfer by radiation.

The total energy received by the glass cover is equal to the incident solar radiation and evaporative, convective and radiative heat transfer from the brine minus the sum of the energy loss between the glass cover and the sky by radiative and convective heat transfers and the energy accumulation within the glass cover. The equation for the glass cover is given by:

$$Q_{t,g} = (\alpha_g I(t)A_g + Q_{r,w-g} + Q_{ev,w-g} + Q_{c,w-g}) - (Q_{c,g-w} + Q_{r,g-w} + (m_w C_{p,w} \frac{dT_g}{dt}))$$  \(1\)

Based on abovementioned and on figure 2, it has been observed that the most acceptable surveys in heat transfer by convection and evaporation in a confined space have been made by Kumar and Tiwari [6], due to the model can be used in a more realistic way for a wide range of water temperature. In the inside of the solar distiller a movement from the saturated water steam is produced, due to the temperature difference that is generated, this steam is conducted by natural convection, which is caused by the buoyancy effect and mainly because of the density variation generated between the humid fluid and the glass cover. The rate of heat transfer by convection, $Q_{C,w-g}$ [W], between the cover glass and water is given by the following expression, [7]:

$$Q_{C,w-g} = h_{C,w-g} A_w (T_w - T_g)$$  \(2\)

So the convection heat transfer rate between the water and the glass cover, is given by the following expression, equation (1). The convection heat transfer coefficient from the water to the glass cover, $h_{C,w-g}$ [W/m² K], can be determined by the following expressions:
\[ h_{c,w-g} = \frac{k}{d} x C (Gr \Pr)^n \]  

(3)

Where:

\[ Gr = \frac{d^3 \rho^2 g \beta}{\mu^2} \Delta T' \]  

(4)

\[ \Pr = \frac{\mu C_p}{k} \]  

(5)

\[ \Delta T' = \left[ \Delta T + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right] \]  

(6)

The values of \( P_w \) and \( P_g \), can be elicited from the expression obtained by Fernández and Chargoy [8], which are applied for the temperature range 10\(^\circ\)C–90\(^\circ\)C.

The rate of heat transfer by evaporation \( Q_{E,w-g} \) [W], between the cover glass, and water is given by the following expression, [7]:

\[ Q_{E,w-g} = h_{E,w-g} A_w (T_w - T_g) \]  

(7)

The evaporation heat transfer coefficient from water to the glass cover, \( h_{E,w-g} \) [W/m\(^2\) K], can be determined as:

\[ h_{E,w-g} = 0.01623 \frac{k}{d} C (Gr \Pr)^n \left[ \frac{P_w - P_g}{T_w - T_g} \right] \]  

(8)

The rate of heat transfer by radiation \( Q_{R,w-g} \) [W], between the cover glass, and water is given by the following expression, [7]:

\[ Q_{R,w-g} = h_{R,w-g} (T_w - T_g) \]  

(9)

The radiation heat transfer coefficient between water and glass cover, \( h_{R,w-g} \) [W/m\(^2\) K] is given by:

\[ h_{R,w-g} = \left( \frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} \right)^{-1} \sigma \left[ (T_w + 273)^2 + (T_g + 273)^2 \right] (T_w + T_g + 546) \]  

(10)

4. Result

Through experimentation in the solar distiller using brine, obtained data from temperature and radiation figures 3 to 6, were processed for the corresponding calculation of the internal heat transfer coefficients.
In figures 7 to 9, the distribution of the convection, evaporation and radiation heat transfer are shown for each test.

**Figure 3.** Distribution of temperature and solar radiation for 2 L of brine

**Figure 4.** Distribution of temperature and solar radiation for 4 L of brine

**Figure 5.** Distribution of temperature and solar radiation for 6 L of brine.

**Figure 6.** Distribution of temperature and solar radiation for 4 L of brine.

**Figure 7.** Convection heat transfer coefficients for 2, 4, 6 and 8 L of brine in relation to time.

**Figure 8.** Evaporation heat transfer coefficients for 2, 4, 6 and 8 L of brine in relation to time.
5. Discussion
The temperature distribution and solar radiation increases as time passes, reaching its maximum values since 12:30 p.m. to 15:30 p.m., after this period the value of temperature and radiation decreases. In the absorber container, the highest temperature data were registered being between 63.4°C and 65 °C, subsequently the fluid with maximum values between 63.4 °C and 64.7 °C and finally the glass cover inner Surface got values from 53.6 °C to 56.4 °C. As can be seen in each figure, the temperatures behavior is very similar to the solar radiation, because this was altered due to cloudiness, dust, etc., so that the temperatures got affected by this fact. On the other side, using the equations shown earlier and the temperature register, the convection, evaporation and radiation heat transfer inner coefficients were calculated for each test, in figure 3 we can see the behavior of the convection heat transfer inner coefficient, obtaining that for 2 L, 4 L, 6 L and 8 L of brine minimum values of 0.6, 0.9, 0.7 and 0.5 W/m² K and maximum values of 2.2, 2.2, 2.3 and 2.4 W/m² K were obtained respectively, subsequently, evaporation heat transfer coefficient is shown on figure 4, obtaining the highest values of 29.4, 27.5, 29.3 and 27.5 W/m² K, for 2 L, 4 L, 6 L and 8 L respectively, however for the radiation heat transfer coefficients, maximum values of 3.6 W/m² K were reached for every test. It is shown an increase of the 3 heat transfer coefficients as time goes by, after 3 p.m., it decreases, as the solar radiation, the coefficients are affected as time goes by due to this ones depend on the temperature of the fluid and the glass cover inner surface, which depend on the solar radiation and the weather parameters that appear every day of experimentation.

6. Conclusion
The study of the variation in the heat transfer inner coefficients in a solar distiller, using the Kumar and Tiwari model, for different initial volumes of brine, allows to establish that the inner coefficient that predominates is the one from evaporation \( h_{E,w,g} \), reaching values from 1.5 to 30 W/m² K, followed by the radiation coefficients \( h_{R,w,g} \), and finally convection coefficients \( h_{C,w,g} \), which reach values of 0.5 to 4 W/m² K being this ones less relevant.

According to the results, the coefficients depend significantly in the water depth, it means, as the initial volume increases the coefficients decrease and as a consequence the performance of the solar distiller is affected. The highest values in coefficients are obtained for the test with 2L of brine since energy is required to be able to evaporate it, from 15:40 hours, the coefficients decrease by solar radiation lower in intensity. It is concluded that if the temperature difference between the fluid and the glass inner surface increases, the coefficient by evaporation will increase playing an important role in the performance optimization, as well as in the coefficient by convection and finally in the mass transfer, which are the most important parameters in the distillation process.
Nomenclature

Subscript

\( \text{Nu} \) Nusselt dimensionless numbers

\( \text{Gr} \) Grashof dimensionless numbers

\( \text{Pr} \) Prandtl dimensionless numbers

\( \text{E} \) Evaporation

\( \text{C} \) Specific heat, J/kg K

\( \text{g} \) Glass

\( \text{H} \) Heat Transfer coefficient, W/m² K

\( \text{d} \) Distance between the water surface and the glass cover, m

\( \text{P} \) Pressure

\( T \) Temperature, ºC

\( g \) gravity acceleration, m/s²

\( k \) Thermal conductivity W/m°C

\( \rho \) Density

Greek letters

\( \varepsilon \) Emissivity

\( \mu \) Viscosity

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