Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1008049

57 (2016) 6209–6216
March

Correlation for Lewis number for evaluation of mass flow rate for simple/hybrid solar still

Khaoula Hidouri*, Slimane Gabsi

Engineers National of Gabès, Omar Ibn El Khattab Street, Gabès 6029, Tunisia, Tel. +216 97601919; Fax: +216 75392190; emails: hidourik@yahoo.fr (K. Hidouri), slimanegabsi@yahoo.fr (S. Gabsi)

Received 13 February 2013; Accepted 6 January 2015

ABSTRACT

In isolated and arid areas, especially in the almost Maghreb regions, the abundant solar radiation intensity along the year and the available brackish water resources are the two favorable conditions for using solar desalination technology to produce fresh water. In this paper, a theoretical correlation named the "Lewis number" correlation is developed and used for the calculation of a simple and a hybrid solar distiller mass flow rate. Uses of single glass cover for periodically oriented still or double glass cover for fixed still are studied. Calculated results are compared with those obtained experimentally. It was found that the theoretical mass flow rate is in good agreement with that obtained experimentally.

Keywords: Mass transfer; Heat transfer; Simple solar distiller (SSD); Simple solar distiller hybrid with heat pump (SSDHP); Mass flow rate; Solar desalination

1. Introduction

Arid areas constitute about 60% of the earth's area. In many countries, the main resource of water is rainfall, which occurs only during winter and supplies water in shortage reservoirs. The water scarcity becomes a serious problem in many regions of the world, namely, in Maghreb and in the Middle East countries.

In several regions, the increasing demand of potable water can be met only by desalination of brackish or seawater. In developing countries, desalination technologies with large concentration cannot grow fast due to high cost of investment. A solar still needs only low-cost material for water desalination. Enhancement of fresh water productivity obtained by solar stills can be reached via the improvement of the solar desalination technology.

Many parameters influence the production of the solar distiller water, namely, the climatic conditions, the still design, the operating conditions, and the geographical location [1,2,3]. Al-Hinai et al. [4] used a mathematical model to predict the productivity of a simple solar still under different climatic design and operating parameters.

Boukar and Harmim [5] showed that the temperature difference between the glass cover and the water, primarily governs the daily yield of the solar stills and as the difference increases, the daily yield also increases. Kaabi and Smakdji [6] performed a mathematical model to study the impact of temperature difference between water and solar collector on global efficiency of a solar still. Resolution of thermal equations based on finite difference method showed that a better efficiency can be obtained at maximum

*Corresponding author.

temperature difference, for low glass thickness, an inclination angle closer to the latitude area, a low thickness of the solution to be distilled, and a high-velocity wind.

Abu-Arabi et al. [1] studied the modeling and performance analysis of a single-basin solar still with the entering brine flowing between a double glass glazing. The objective of this arrangement is to lower the glass temperature and thus to increase the water-to-glass temperature difference. The results show that the relative performance of the stills depends on the level of the used insulation. The hourly and daily productivities of the stills and the temperatures of the water and the glass covers are also predicted.

Omri [7] performed a numerical simulation of natural convection flows in an asymmetric greenhouse-type solar still, submitted to a uniform heat flux from below when inclined sides are maintained isothermal. He concluded that understanding geometric effects on natural convection allows the prediction of adequate dimensions and covenant location of vapor production and condensation.

Slesarenko [8] found that connecting a heat pump to a thermal desalination plant could significantly increase the economic viability. Tripathi and Tiwari [9] studied the heat- and mass-transfer coefficients for passive and active solar distillation systems. They showed that more yield is obtained for active mode. Hawlader et al. [10] described a new system of solar assisted heat pump desalination. It was found that the coefficient of performance of the system ranges between 5 and 7. Hidouri et al. [11] showed that coupling a solar still with a heat pump is a very efficient way to increase the basin water temperature; it can achieve 82˚C.

Dunkle [12] proposed a group of complete heat and mass correlations based on a modified Grashof number to express the operating process of basin-type solar stills. Water temperature of a greenhouse fish pond was numerically predicted using the energy balance equations, and considering the effects of conduction, convection, radiation, evaporation, and ventilation [13]. Expressions for water and glass temperatures, hourly yield and instantaneous efficiency for double slope solar distillation systems have been analytically determined by Kumar and Kumar [14]. They showed a significant effect of operating temperature ranges on the internal heat transfer coefficient, and then on basin productivity. Mathematical models that can predict hourly distillate productivity are developed by Sadineni et al. [15].

In this paper, a theoretical correlation named the “Lewis number” correlation is developed for the determination and the calculation of distilled water mass flow rate in a simple/hybrid solar still. Theoretical values are then compared with those obtained experimentally concerning Gabès city (southeast region of Tunisia), which suffers from fresh water scarcity.

2. Theoretical procedure

The convective heat-transfer rate between a hot surface and a cooled fluid in contact within the boundary layer is given by its general equation as:

$$Q = h_{cw} \cdot A \cdot \Delta T \tag{1}$$

where h_{cw} is the convective heat-transfer coefficient, A is the area responsible for heat fluid, and ΔT is the temperature difference between the fluid and the inner surface of condensing cover. The convective heat-transfer coefficient is a function of: the geometry of the surface, the flow characteristics and the physical properties of the fluid at operating temperatures, and the operating temperature ranges. The convective heat-transfer coefficient is related with the three following dimensionless numbers as follows:

$$Nu = \frac{h_{cw} d}{\lambda} = C(Gr \cdot Pr)^n \tag{2}$$

where Nu, Gr, and Pr are Nusselt, Grashof, and Prandtl numbers, respectively. C and n may be constant or variable dimensionless parameters depending on hypothesis established by the authors. Grashof and Prandtl numbers are given by:

$$Gr = \frac{g\beta \Delta T \rho^2 d^3}{\mu^2}, \quad Pr = \frac{\mu C_P}{\lambda} \tag{3}$$

Chen et al. [16] proposed a relation that includes the characteristic length between the evaporation and the condensation surfaces of the solar still. In this case, a free convective heat transfer is given by an empirical relation such that:

$$Nu = 0.2 Ra^{0.26} \tag{4}$$

Ra is the Rayleigh number and it is in the following range: $3.5 \times 10^3 < Ra < 10^6$. By equating Eqs. (2) and (4), the convective heat-transfer coefficient is then given by:

$$h_{cw} = 0.2 Ra^{0.26} \left(\frac{\lambda}{x_1} \right) \tag{5}$$

x_1 is the characteristic length between the evaporation and condensation surfaces. Taking into consideration the characteristic space x_1 of the solar still, is a very interesting parameter for analyzing solar stills of various shapes. By considering the existence of great deal of water vapor, the Rayleigh number should be modified, according to the report of Malik et al. [17], the modified Rayleigh number Ra' is given by:

$$Ra' = \frac{\rho g \beta x_1^3}{\mu \alpha} \Delta T' \tag{6}$$

The temperature difference is therefore given by:

$$\Delta T' = (T_w - T_g) + \left(\frac{(P_w - P_g)(273 + T_w)}{268.9 \times 10^3 - P_w} \right) \tag{7}$$

The Chilton–Colburn analogy can be written as:

$$\frac{Nu}{Pr^n} = \frac{Sh}{Sc^n} \tag{8}$$

In the present case, $n = 0.26$ and Sh is the Sherwood number that expresses the mass transfer flux, it is given by:

$$Sh = \frac{h_m x_1}{D} \tag{9}$$

Substituting the definition equations for Nu and Sh in Eq. (8), we get:

$$\frac{h_{cw}(x_1/\lambda)}{Pr^n} = \frac{h_m(x_1/D)}{Sc^n} \tag{10}$$

Transposing terms, this equation changes into:

$$\frac{h_{cw}}{h_m} = \left(\frac{\lambda}{D}\right)\left(\frac{Pr}{Sc}\right)^n \tag{11}$$

The Lewis number is given by:

$$Le = \frac{Sc}{Pr} = \frac{\alpha}{D} \tag{12}$$

α is the thermal diffusivity, it is given by: $\alpha = \lambda/(\rho C_P)$, then Eq. (11) can be written as:

$$\frac{h_{cw}}{h_m} = \left(\frac{\lambda}{D}\right)\left(\frac{1}{Le^n}\right) = \frac{\alpha \rho C_P}{D} = \rho C_P Le^{1-n} \tag{13}$$

The evaporation rate per unit area of evaporation surface in the still is given by:

$$m_e = h_m(\rho_w - \rho_g) = \frac{h_{cw}}{\rho C_P Le^{1-n}}(\rho_w - \rho_g) \tag{14}$$

ρ_w and ρ_g can be calculated by the perfect gas equation given by:

$$\rho = \frac{M}{R}\left(\frac{P}{T}\right) \tag{15}$$

The mass flow rate of the distilled water is therefore given by:

$$m_e = \frac{h_{cw}}{\rho C_P Le^{1-n}} \left(\frac{M_w}{R}\right) \left(\frac{P_w}{T_w} - \frac{P_g}{T_g}\right) \tag{16}$$

Eq. (16) is called the “Lewis number” correlation, and used for the mass flow rate calculation of the solar still. The calculations of physical properties of humid air such as, isobaric specific heat C_P, thermal conductivity λ, mass density ρ, dynamic viscosity μ, and vapor partial pressures P_w and P_g are based on the correlations given by Jain and Tiwari [18]. All the above-mentioned properties are given in Table 1.

3. Experimental setup

3.1. Simple solar distiller

In simple solar distiller (SSD) model, distilled water is simply obtained by purely solar energy. Fig. 1 shows the schematic diagram. This model works only on day.

It consists of a basin fabricated from fiber-forced plastic material (Fig. 2) that accommodates the brackish water, and is covered by a slopping glass cover. The height of the lower vertical side of the still is equal to 60 cm and the basin area is 1 m^2. Water depth considered in this work is fixed in all experiments at 30 cm, the choice of this value aims simply to see the water productivity of the still. The operation of the still is very simple; the incident solar radiation is transmitted through the transparent glass cover to the water. As a result, water is evaporated and reached the glass cover, then collected at the distilled water gutter at condensed phase. The heated, then the evaporated water due to solar radiation is done automatically by natural convection [19].

Temperature is measured at different points of the system. Glass, water, and ambient temperatures are

Table 1
Physical properties of humid air

Physical property	Formulae
L (J/kg)	$2.569 \times 10^5(647.3 - T_w)^{0.38}$
C_P (J/mol K)	$999.2 + 0.1434T_w + 1.01 \times 10^{-4}{T_w}^2 - 6.7581 \times 10^{-8}{T_w}^3$
λ (W/m K)	$0.0244 + 0.6773 \times 10^{-4}T_w$
μ (Pa s)	$1.718 \times 10^{-5} + 4.62 \times 10^{-8}T_w$
ρ_g (kg/m^3)	$\frac{353.44}{273.15 + T_g}$
ρ_w (kg/m^3)	$\frac{353.44}{273.15 + T_w}$
P_g (N/m^2)	$\exp\left(25.317 - \frac{5,144}{273.15 + T_g}\right)$
P_w (N/m^2)	$\exp\left(25.317 - \frac{5,144}{273.15 + T_w}\right)$
β (K^{-1})	$\frac{1}{\frac{T_w + T_g}{2}}$

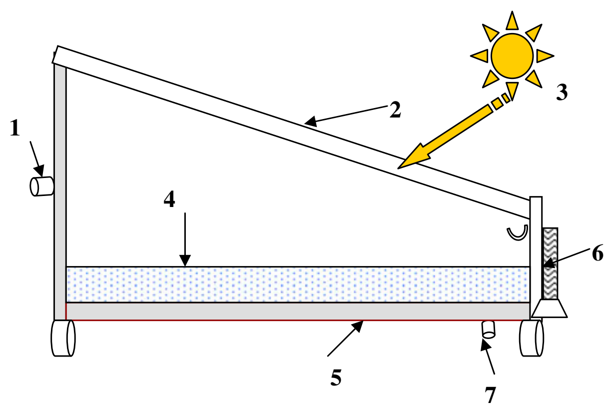

Fig. 1. Schematic diagram of a simple solar still: 1—impure water in, 2—glass cover, 3—sun, 4—brackish water, 5—insulation, 6—pure water out, and 7—output impure water.

measured by thermometers giving 0.1˚C precision, the reading scale ranges between −50 and 300˚C. The mass flow rate (distiller output) is measured by a graduated test tube (error 1–3 mL).

Solar radiation is measured by a pyranometer mounted near the glass. The glass cover inclination angle with respect to horizontal plane is equal to 33˚ which corresponds to the latitude of Gabès city. Mean values of experimental data are collected for the month of June 2010.

3.2. Hybrid solar still

A hybrid solar distiller still with a heat pump (SSDHP) configuration is used to enhance the water temperature of basin to increase the evaporation and enhance the condensation of distillate. Area of the basin is equal to 0.4 m^2. Water depth is fixed at 30 cm as in the previous case.

Fig. 2. Photo SSD.

Fig. 3 shows this configuration. It corresponds to a vapor compression cycle of refrigeration. In fact, a condenser is immersed in the basin water to increase the water temperature and then the evaporated quantity of water will increase. The evaporator which is located near the upper region of the glass cover (Fig. 4) enhances the condensation of the water vapor, and the refrigerant (R12) leaving the condenser is introduced into a recuperator filled with fresh water in order to maintain the temperature of the refrigerant. After that the refrigerant enters the evaporator at low

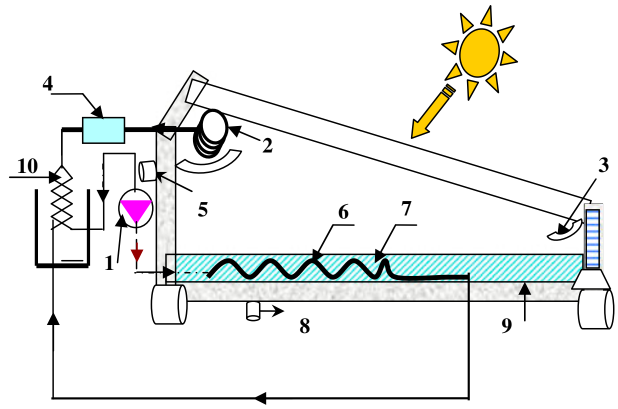

Fig. 3. Schematic diagram of a SSDHP: 1—compressor, 2—evaporator, 3—pure water out, 4—expansion valve, 5—impure water in, 6—condenser, 7—impure water, 8—output impure water, 9—insulator, and 10—regulator.

Fig. 4. Photo SSDHP.

pressure inducing the condensation of water vapor. As a consequence, a more quantity of condensed water will be recuperated at the distilled water gutter. The consuming power as compressor works for pumping heat is equal to 0.2 kW. This process has the advantage that it is done naturally [20].

As in the case of the simple solar still, temperatures, distiller output, and solar radiation are measured. Then, mean values of experimental data concerning the June month are calculated.

3.3. Experimental parameters

For the installation, we assigned the value (0) for which the SSD and the SSDHP plants are oriented toward the south and the value (1) for which the distiller is periodically oriented toward the sun (azimuth consideration).

For the glass cover, the value (0) is given when a single glass cover is used and the value (1) for double glass cover. Similarly, the value (0) is given in absence of heat pump and the value (1) is given when the heat pump is used. Table 2 illustrates the different studied models.

4. Results and discussion

Theoretical calculations are carried out by a Matlab program; calculation of convective heat-transfer coefficient provides the determination of the mass flow rate of the still using Eq. (16), and mean values of the solar still mass flow rate are then compared with those obtained experimentally.

Experimental determination of the solar distiller still productivities (SSD or SSDHP) and their corresponding theoretical values based on "Lewis number" correlation are studied for two cases: (a) utilization of a single glass cover with periodically oriented still (azimuth consideration), and (b) use of double glass cover with variation orientation of the still toward the south.

4.1. Simple solar still

Figs. 5 and 6 show that the maximum experimental mass flow rate for the SSD model is about 300 g/m^2 h, obtained at 14h25. Maximum theoretical value is equal to 320 g/m^2 h and it is obtained at 14h25. As time proceeds, experimental mass flow rate decreases from its maximum value to reach 40 g/m^2 h at 16h25 (0 0 0) configuration. The decrease of both values can be explained by the fact that, on the one hand, the quantity of evaporated and then condensed water decreases due to the decrease of natural convection process, since, solar radiation intensity decreases, and on the other hand, in theoretical considerations, the loosed condensed water is neglected, which is in reality not the case [21]. Further, fluctuations of temperature difference between glass cover and water surface are observed when time exceeds that corresponding to the maximum value. As a consequence, convective heat transfer will fluctuate and a slight difference between experimental and theoretical mass flow rate is obtained.

The analysis difference between experimental and theoretical mass flow rate is obtained for calculated statistics tools for the (000) configuration the error is 3.3% and for (110) the error is 8.2%.

Table 2
Operating parameters for different studied plants

Position	Glass cover	Heat pump compression	Configurations
0	0	0	(0 0 0)
0	0	1	(0 0 1)
1	1	0	(1 1 0)
1	1	1	(1 1 1)

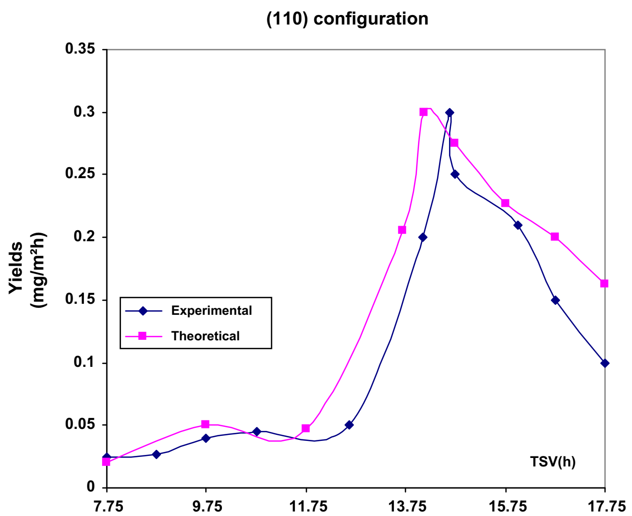

Fig. 5. Experimental- and theoretical-based "Lewis number" correlation productivities vs. true solar time. Configuration (1 1 0).

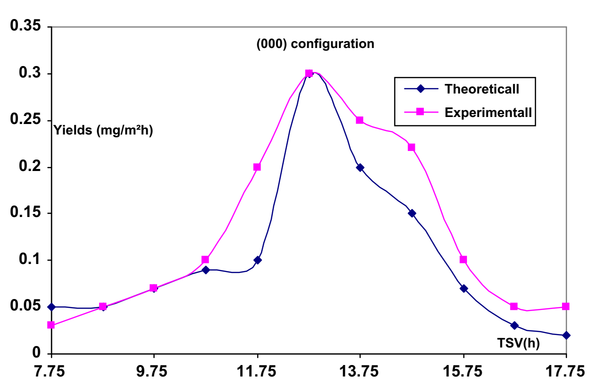

Fig. 6. Experimental- and theoretical-based "Lewis number" correlation productivities vs. true solar time. Configuration (0 0 0).

4.2. Hybrid solar still

Experimental determination of the configuration of SSDHP productivities and their theoretical values based on the "Lewis number" correlation are illustrated in Figs. 7 and 8.

As it can be seen from these figures, both experimental and calculated mass flow rate of distilled water increases with time from morning, reaches a maximum value, and then gradually decreases. For a single glass cover, Fig. 7 shows that the maximum mass flow rate is about 1,400 g/m^2 h, obtained at 11h25. Maximum theoretical value is 1,380 g/m^2 h and it is obtained at 11TSV. It is important to note that while theoretical value of productivity still increases in the time interval 10h30–12h25, the corresponding experimental value decreases and then increases [22]. This is due to the fact that in theoretical considerations, the loosed condensed water is neglected, which is in reality not the case. As time proceeds, both theoretical and experimental productivity have the same trend, they gradually decrease and then increase in the time interval 15h25–16h00.

The use of double glass cover at variation position of the still (south orientation) coupled with heat pump (1 1 1) configuration (Fig. 8) shows that the experimental outputs are better when compared with all models 1,800 g/m^{2}h at 13h25 and theoretical have always the same behavior 1,800 g/m^2 h. The statistical analysis

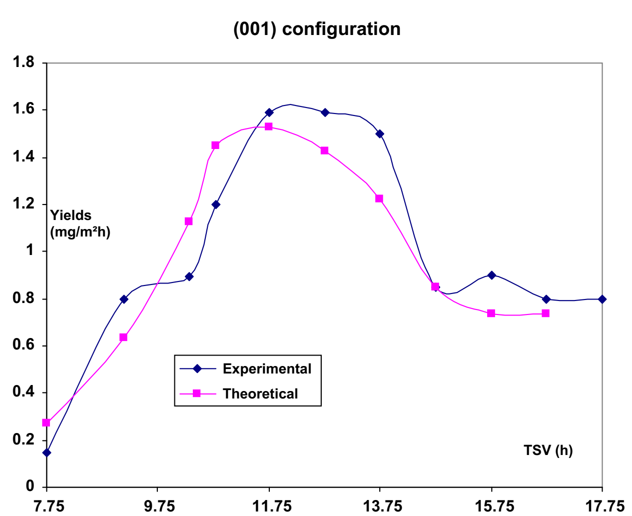

Fig. 7. Experimental- and theoretical-based "Lewis number" correlation productivities vs. true solar time. Configuration (0 0 1).

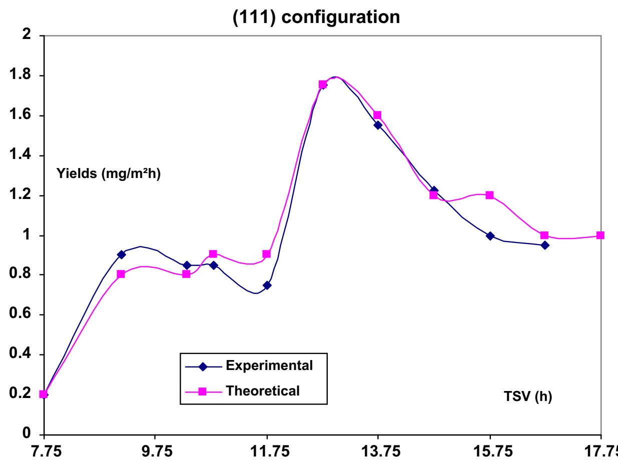

Fig. 8. Experimental- and theoretical-based "Lewis number" correlation productivities vs. true solar time. Configuration (1 1 1).

shows that the error for (1 1 1) configuration is 19%, then for the (0 0 1) configuration is equal to 3.7%.

5. Conclusion

Theoretical mass flow rate based on a developed correlation named as "Lewis number" correlation is developed. Calculated results concerning SSD and SSDHP are compared with those obtained experimentally. Results show that both theoretical and experimental productivities are in good agreement.

For the case of a SSD, the use of double glass cover gives less hourly yield as compared to that obtained with single cover. In this case, both maximum experimental and theoretical mass.

For the hybrid solar still, the (1 1 1) configuration gives better productivity in compared with (0 0 1) configuration.

The SSDHP mass flow rate is considerably higher than that obtained with the SSD, since the condensation process is enhanced by the presence of the condenser near the glass cover.

Nomenclature

C_p — isobaric specific heat (J/mol K)
D — diffusivity coefficient of water vapor (m^2/s)
e — square root of mean percent deviation
Gr — Grashof number
g — gravitational acceleration (m/s^2)
h_{cw} — convective heat transfer coefficient (W/m^2 ℃)
h_m — convective mass transfer coefficient (m/s)
L — latent heat of evaporation (J/kg)
Le — Lewis number
M — molecular weight of water vapor (g/mol)
m_e — mass flow rate (g/m h)
Nu — Nusselt number
P_g — partial pressure of saturated vapor at glass cover temperature (N/m^2)
P_w — partial pressure of saturated vapor at water temperature (N/m^2)
Pr — Prandtl number
Q — convective heat transfer rate (W)
R — universal gas constant (J/mol K)
r — coefficient of linear correlation
Ra — Rayleigh number
Ra' — modified Rayleigh number
Sh — Sherwood number
T_g — glass cover temperature (℃)
T_w — water temperature (℃)
TST — true solar time (h)
x_1 — characteristic length between the evaporation and the condensation surfaces (m)

Greek symbols

α — thermal diffusivity (m^2/s)
β — thermal expansion coefficient (K^{-1})
ΔT — temperature difference (℃)
μ — dynamic viscosity (Pa s)
ρ_g — mass density of vapor at glass surface (kg/m^3)
ρ_w — mass density of vapor at water surface (kg/m^3)
σ_{xy} — standard deviation of xy

References

[1] M. Abu-Arabi, Y. Zurigat, H. Al-Hinai, S. Al-Hiddabi, Modeling and performance analysis of a solar desalination unit with double-glass cover cooling, Desalination 143 (2002) 173–182.
[2] B.L. Akash, M.S. Mohsen, W. Nayfeh, Experimental study of the basin type solar still under local climate conditions, Energy Convers. Manage. 41 (2000) 883–890.
[3] H. Al-Hinai, M.S. Al-Nassri, B.A. Jubran, Parametric investigation of a double effect solar still in comparison with a single-effect solar still, Desalination 150 (2002) 75–83.
[4] H. Al-Hinai, M.S. Al-Nassri, B.A. Jubran, Effect of climatic, design and operational parameters on the yield of a simple solar still, Energy Convers. Manage. 43 (2002b) 1639–1650.
[5] M. Boukar, A. Harmim, Performance evaluation of a one-sided vertical solar still tested in the desert of Algeria, Desalination 183 (2005) 113–126.
[6] A. Kaabi, N. Smakdji, Impact of temperature difference (water-solar collector) on solar-still global efficiency, Desalination 209 (2007) 298–305.
[7] A. Omri, Numerical investigation on optimization of a solar distiller dimensions, Desalination 206 (2007) 373–379.
[8] V.V. Slesarenko, Heat pumps as a source of heat energy for desalination of seawater, Desalination 139 (2001) 405–410.

[9] R. Tripathi, G.N. Tiwari, Thermal modeling of passive and active solar stills for different depths of water by using the concept of solar fraction, Sol. Energy 80 (2006) 956–967.
[10] M.N.A. Hawlader, P.K. Dey, S. Diab, C.Y. Chung, Solar assisted heat pump desalination system, Desalination 168 (2004) 49–54.
[11] K. Hidouri, A. Benhmiden, R. Ben Slama, S. Gabsi, Effects of SSD and SSDHP on convective heat transfer coefficient and yields, Desalination 249 (2009) 1259–1264.
[12] R.V. Dunkle, Solar water distillation: The root of type still and multiple effect diffusion still, International Development in Heat transfer, ASME Proceeding International Heat Transfer 1961, Part V, University of Colorado, 5 (1961) 895–902.
[13] B. Sarkar, G.N. Tiwari, Thermal modeling and parametric studies of a greenhouse fish pond in the Central Himalayan Region, Energy Convers. Manage. 47 (2006) 3174–3184.
[14] S.S. Kumar, A. Kumar, Analytical thermal modelling of double slope solar still by using inner glass cover temperature, Therm. Sci. 12 (2008) 139–152.
[15] S.B. Sadineni, R. Hurt, C.K. Halford, R.F. Boehm, Theory and experimental investigation of a weir-type inclined solar still, Energy 33 (2008) 71–80.
[16] Z. Chen, X. Ge, X. Sun, L. Bar, Y.X. Miao, Natural convection heat transfer across air layers at various angles of inclination, Eng. Thermophys. 4 (1984) 211–220.
[17] M.A.S. Malik, G.N. Tiwari, S. Kumar, M.S. Sodha, Solar Distillation, Pergamon Press, Oxford, 1982.
[18] D. Jain, G.N. Tiwari, Thermal aspects of open sun drying of various crops, Energy 28 (2003) 37–54.
[19] K. Hidouri, R. Ben Slama, S. Gabsi, Hybrid solar still by heat pump compression, Desalination 250 (2010) 444–449.
[20] K. Hidouri, R. Ben Slama, S. Gabsi, Desalination by simple solar distiller assisted by a heat pump, J. Environ. Sci. Eng. 5 (2011) 1183–1188.
[21] K. Hidouri, N. Hidouri, R.B. Slama, S. Gabsi, A.B. Brahim, Experimental validation of theoretical correlation for calculation of mass transfer in simple and hybrid solar stills, Desalin. Water Treat. 26 (2011) 287–296.
[22] N. Hidouri, K. Hidouri, R.B. Slama, S. Gabsi, Effects of the simple/double glass cover use and the orientation of a simple solar still on operating parameters, Desalin. Water Treat. 36 (2011) 1–9.