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Contributing to the improvement of the production of solar still

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ABSTRACT

Solar still can be considered as a promising desalination system to produce distilled water with quality good enough for drinking and irrigation in remote areas due to its simplified design, low maintenance, extended life time, and low capital cost. In addition, among the nonconventional methods to disinfect the polluted water, the solar distillation is considered as one of the most prominent methods. The productivity of the solar still is determined basically by the temperature of water in the basin and the glass temperature. Various active methods have been tested to increase the temperature of the basin, so as to improve the productivity of solar still. In this work, an energy storing material is used in the basin, a flat plate solar collector and a separate condenser are coupled with the solar still to increase the daily productivity by increasing the temperature of the water during the day and to store the hot water excess that would extend water desalination beyond sunset. The models of the different sections of the unit are developed from the governing heat and mass transfer equations. These models will be used for sizing the system. The numeric simulation with the developed models allows the study of the relation among the different control parameters of the unit that would evaluate its performance. An economic analysis was carried out, since it concerns the final cost of produced water, to determine both the cost of fresh water production and the payback period of an experimental setup.

Keywords: Solar still; Water desalination; Modeling; Simulation

1. Introduction

Despite the continual technological progress in desalination methods, the use of solar powered water desalination units continue to be an attractive choice, given the availability of this free energy source in the arid regions, the low cost infrastructure, and the low maintenance. Among the water desalination, installations by solar energy are the conventional solar still. The solar still distillers persist to be an important alternative that can be made, essentially for isolated regions, due to the recognized advantages it has, such as no skilled operators needed, require a simple construction solutions that can be applied locally due to which it can be used anywhere with lesser number of maintenance problems. In addition, among the non-conventional methods to disinfect the polluted water, the solar distillation is considered as the most

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prominent method. However, these distillers cannot compete with the other types of distillers, in particular for the production of large quantities of water. They seem to be useful in providing small communities with fresh water with low efficiency. The low efficiency stems from the fact that only one basin is used in which the brackish water is heated, evaporated, and then condensed. In fact, the brackish water acts as a heat absorber and an evaporator, while the glass cover acts as a condenser [1].

Several investigations have been carried out by researchers to improve performance of the conventional solar still by adopting different techniques. The materials used for the manufacturing of the still and its geometry were intensively studied by many investigators [2–7]. Additional process factors with less or more optimistic consequences on the solar stills production were studied [8–12]. However, developed results confirm that the result is determined generally by the effect of the meteorological conditions, such as the solar radiation, and this state is not easy to adjust since the solar still remains a simple apparatus. In order to progress the performance of the solar still, much more investigation has to be done to optimize its production by improving its design and converting the passive solar still into an active solar still. For an active solar still, an extra thermal energy by external mode is fed into the basin of passive solar still for faster evaporation.

As studied in previous works, the distilled water production rate depends directly on the temperature of the still cover and the temperature of basin water and indirectly on entering solar radiation and ambient temperature. The present work discusses ways to boost fresh water production by performing the design of the conventional solar still. Various solutions investigated are as follows:

- Coupling the solar still to a flat plate solar collector in order to increase the temperature difference between the water surface and the glass cover.
- Using in the basin an energy storing material to store the excess energy and to increase the night time production.
- Incorporating in the solar still a pulverizer and a humidifier to increase the water temperature and the area of water in contact with the air which can accelerate the rate of evaporation.
- Integrating a separate condenser to the still where condensation happens at a temperature lower than of the glass cover.

Thermodynamic models for the different stages based on heat and mass balances are used for simulation to estimate the performance of the whole system under given climatic conditions.

This article is organized as follows: Section 2 shows the principle of design and operation modes of the proposed installation. The formulated mathematical models are presented in Section 3. Simulation results are discussed in Section 4. An economic analysis on the developed unit was presented in Section 5. Recommendations and conclusion are presented in Section 6.

2. Principle of design and operation modes of the proposed installation

Fig. 1 presents the schematic representation of the conventional solar still. It is a simple device which uses part of the collected solar thermal energy for heating water contained in a basin within the still. As a result, vapor of fresh water is formed in the space above the water. The produced vapor condenses on the inside of the glass cover, collected in a side trough and leaded out of the still, being the distilled water production. As discussed in the introduction, this actual design has a low efficiency, therefore a new design is proposed in this paper.

Three compartments constitute the proposed desalination system as shown in Fig. 2 includes: conventional solar still, water solar collector, and condensation chamber. The basin of the conventional solar still is equipped with a sensible heat storage material to store the excess energy and to increase the night time production. A system of water pulverization and a humidifier are fixed inside the solar still to increase the water spray and improve evaporation. A medium temperature solar collector provides hot water to the solar still for faster evaporation. The condenser contains polypropylene plates through which the salty and cold water circulates for preheating. The coupling of the solar still with a condenser increases the condensation rate.

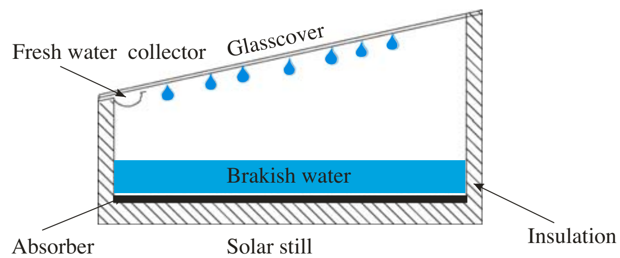

Fig. 1. Schematic representation of the conventional solar still.

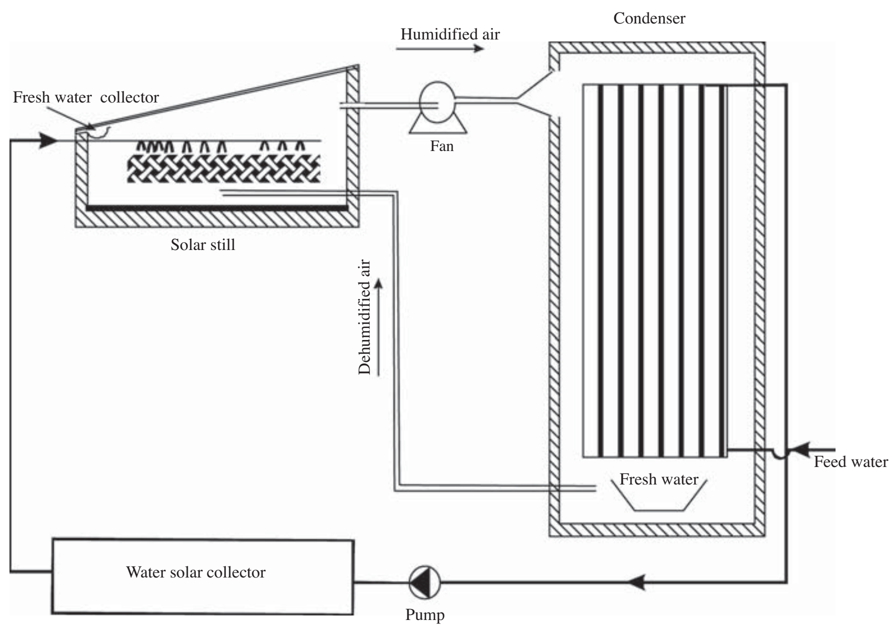

Fig. 2. The proposed desalination system.

Brackish water or seawater is heated by the solar collector. Then, the hot water is injected to the top of solar still. A pulverizer with a special shape is used to assure a uniform pulverization of the hot water in all the sections of the packed bed. The circulation of the hot humid air between the solar still and the condenser is occurred by a fan with a closed air circuit. The hot saturated vapor coming from the solar still is driven toward the condenser where it condenses in contact with the cold plates of the condenser. The brackish water is preheated in the condenser by exchange of heat with the vapor at condensation. It allows the reduction of the consumption of thermal energy necessary for heating the water in the solar collector. The distilled water is collected in a basin at the bottom of the condensation tower.

3. Mathematical models

The proposed installation involved various variables that are space and time dependent, including heating, evaporation, and condensation. The dynamic behavior of the unit would, therefore, be best described through putting the various operational parameters into equations forms. The following section presents the dynamic modeling of the water solar collector, solar still with humidifier and energy storing material modeling, and the condenser. The models developed are a set of partial derivative equations, derivative equations, and algebraic equation. The model is based on a number of assumptions previously described elsewhere [13–15].

3.1. Water solar collector model

The energy balance equation for the system formed by the absorber and the fluid formed for a slice of the collector having a width of l, a length of dx, and a surface of ds is expressed by the following equation:

$$\frac{\partial T_{\mathrm{w}}}{\partial t} = \frac{1}{\delta}\left(-m_{\mathrm{w}}\xi\frac{\partial T_{\mathrm{w}}}{\partial x} - T_{\mathrm{w}} + f(t)\right) \tag{1}$$

with

$$\xi = \frac{C_{\mathrm{w}}}{U_{\mathrm{w}}l};\ \delta = \frac{(MC)_{\mathrm{g}}}{U_{\mathrm{w}}A};\ (MC)_{\mathrm{g}} = M_{\mathrm{w}}C_{\mathrm{w}} + M_{\mathrm{ab}}C_{\mathrm{ab}};$$

$$f(t) = \frac{\tau_{\mathrm{v}}\alpha_{\mathrm{ab}}I(t)}{U_{\mathrm{w}}} + T_{\mathrm{amb}}(t)$$

3.2. Solar still with humidifier and energy storing material modeling

The dynamic mathematical model of the solar still with humidifier and energy storing material consisted of a set of equations that were developed using thermal and mass balances for the water phase, the air phase, and the air–water interface.

- Heat balance for the glass cover

$$M_vC_vdT_v = IA_vdt + h_{rwv}(T_w - T_v)dt + h_{evp}(T_w - T_v)dt - h_{rc}(T_v - T_{amb})dt \quad (2)$$

- Heat balance for the basin absorber

$$M_bC_bdT_b = IA_bdt - h_{cbw}(T_b - T_w)dt - U_{loss}(T_b - T_{amb})dt \quad (3)$$

- Heat balance for the water basin

$$(M_wC_w + M_{st}C_{st})dT_w = IA_wdt + h_{cbw}(T_b - T_w)dt - h_{rwv}(T_w - T_v)dt - h_{cwv}(T_w - T_v)dt - h_{evp}(T_w - T_v)dt \quad (4)$$

- Heat and mass balances for the packed bed

Water phase

$$M_wC_{pw}dT_wdz = m_wC_{pw}dT_wdt - U_w(T_i - T_w)dzdt \quad (5)$$

Air phase

$$M_aC_{pa}dT_adz = U_a(T_i - T_a)dzdt - m_aC_{pa}dT_adt \quad (6)$$

Air–water interface
The thermal balance can be written under the following shape:

$$U_w(T_i - T_w) = U_a(T_i - T_a) + \lambda_oU_m(W_i - W_a) \quad (7)$$

The mass balance is given by the following equation:

$$M_adW_adz = U_m(W_i - W_a)dzdt - m_adW_adt \quad (8)$$

The curve of saturation of water steam is given by the following equation [14]:

$$W_i = 0.62198\frac{P_i}{1 - P_i} \quad (9)$$

where P_i is the saturation pressure and is given by [14]:

$$\ln(P_i) = -6096.938\frac{1}{T_i} + 21.240964 - 2.7111910^{-2}T_i + 1.6739510^{-5}T_i^2 + 2.43350\ln(T_i)$$

3.3. Condenser modeling

The dynamic mathematical formulation for the condensation tower was developed using thermal and mass balances. This formulation gave the coupling equations that relate temperature, the temperature of the cooling water, and the absolute humidity of the humid air. The balances were applied to an element of volume of the condensation tower having a height dz.

Water phase

$$M_fC_fdT_fdz = U_fA_c(T_{ic} - T_f)dzdt - m_fC_fdT_fdt \quad (10)$$

Air phase

$$M_gC_{pg}dT_gdz = m_gC_{pg}dT_gdt - U_gA_c(T_g - T_{ic})dzdt - \lambda_oU_{mc}A_c(W_g - W_{ic})dzdt \quad (11)$$

Air–condensate interface

The heat balance at air–condensate interface is given by the following equation:

$$U_gA_c(T_g - T_{ic}) + U_fA_c(T_{ic} - T_f) = \lambda_o U_{mc}A_c(W_g - W_{ic}) \quad (12)$$

The mass balance at air–condensate interface is given by the following equation:

$$M_g dW_g dz = m_g dW_g dt + U_{mc}A_c(W_g - W_{ic})dzdt \quad (13)$$

The water condensation rate was determined by using the following algebraic equation that relates the variation of water content to the height of the tower:

$$dm_c = K_{mc}A_c(W_{ic} - W_{gc})dz \quad (14)$$

4. Simulation results and discussion

A number of simulations using the models presented in Section 3 were carried out covering various combinations of operating conditions. The results are presented in this paragraph.

The first set of simulation was performed for the temperature variation of different parts of the solar still. Fig. 3 shows the temperature profiles of the glass cover, the saline water, and the basin absorber as a function of time. As can be seen from the figure, the different temperatures profiles show the same trend.

Also shown in Fig. 4 are the theoretical simulation results of fresh water production for conventional solar still, solar still with energy storing material, and solar still with humidifier and condenser. Theoretical simulation showed that this new concept would give as much as seven times the output of a conventional solar still and three times the output of a solar still with energy storing material for the same input.

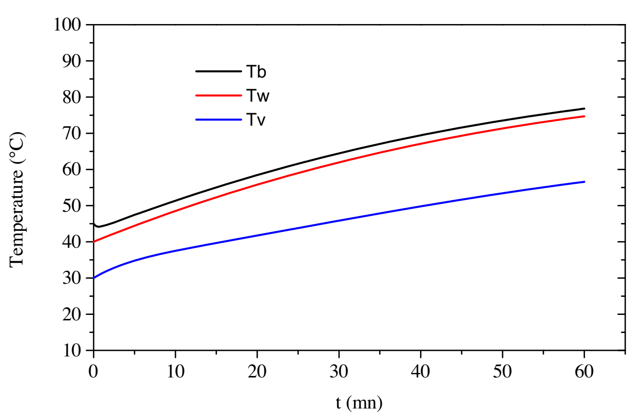

Fig. 3. Temperature variation of different elements of the solar still only.

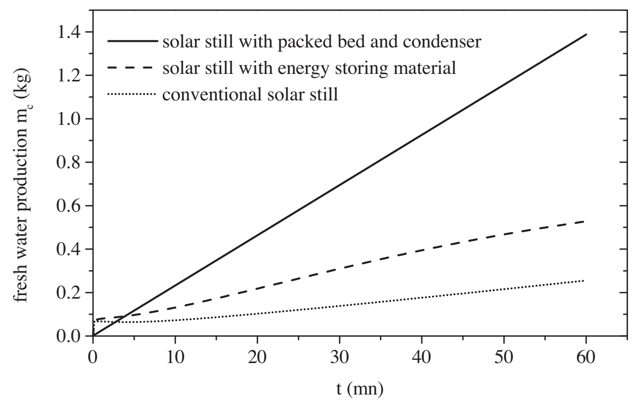

Fig. 4. Comparison of fresh water production.

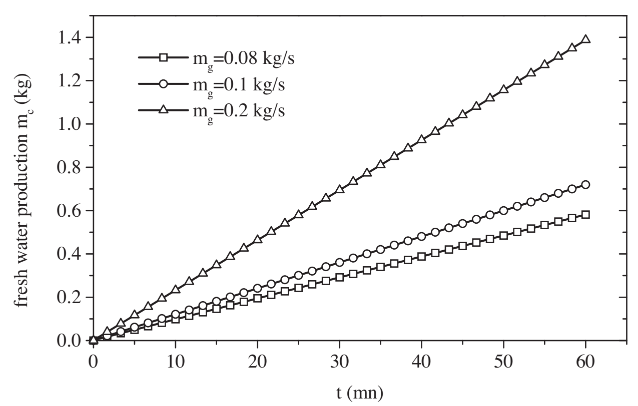

Fig. 5. Effect of moist air flow rate on fresh water production $m_f = 0.1$ kg/s, $T_{f1} = 20$ ℃, $T_{g2} = 50$ ℃, and $W_{g2} = 87.537$ g/kg.

The effect of moist air flow rate on fresh water production is shown in Fig. 5. Three different flow rates were considered: 0.08, 0.1, and 0.2 kg/s. For these simulations, the effect of rising the moist air flow rate was found to be very motivating. With the increase in the flow rate from 0.08 to 0.2 kg/s, the fresh water production augmented considerably from 0.55 to 1.4 kg.

Fig. 6 represents the effect of inlet cooling water temperature in the condenser on fresh water production. Four different temperatures were considered which includes 20, 30, 40, and 45 ℃. The fresh water production increased with the decreasing of the inlet cooling water temperature as shown in the figure. For these simulations, the inlet cooling water temperature was decreased from 45 to 20 ℃, whereas the fresh water production increased significantly from 0.2 to 1.3 kg.

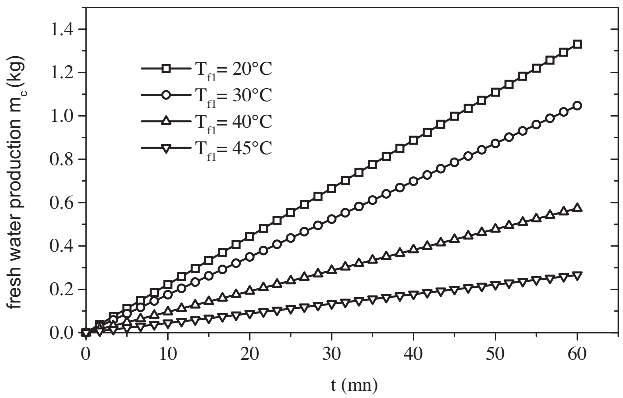

Fig. 6. Effect of inlet cooling water temperature on fresh water production $m_f = 0.1$ kg/s, $m_g = 0.2$ kg/s, $T_{g2} = 50$ ℃, and $W_{g2} = 87.537$ g/kg.

5. Cost analysis

The present cost analysis was performed to determine both the production cost of freshwater and the payback period of the experimental setup. In fact, several factors are important to consider when estimating the cost of freshwater production. Some of the most determining factors include the fixed charges (mainly equipments) and operating costs (mainly energy costs). Other parameters that have relatively less effects on the production cost of the unit include the cost of the chemicals and manpower. The total cost of the solar desalination unit is given by the following relation:

$$C_{Tc} = C_{fc} + C_{oc} \tag{15}$$

The fixed charges cost, C_{fc}, defines the annual payments that cover the total direct and indirect cost. This cost is obtained by multiplying the total direct and indirect cost by the amortization factor, a, which is defined by the following relation:

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{16}$$

where i is the annual interest rate and n is the plant life.

The operating cost, C_{oc}, covers all expenditures incurred after the implementation of the plant and during the actual functioning, such as chemicals, maintenance, and manpower costs. Tables 1 and 2 show the investment cost of each component constituting the desalination unit and a summary of the cost evaluation results of the desalination process, respectively.

Table 1
Investment cost of each component involved in the desalination unit

Unit components	Quantity	Cost
Water solar collector	2 m^2	416 €
Condenser	1	800 €
Solar still	1	400 €
Ducts	–	200 €
Packed bed	1	50 €
Immersed pump	1	50 €
Fan	1	50 €
Total		1,966 €

Table 2
Summary of the cost evaluation results of the desalination unit

Economic parameters and cost types	Values
Direct cost	1,966 €
Operating cost	0.64 € d^{-1}
Lifetime	20 year
Interest rate	5%
Amortization factor	0.08 $year^{-1}$
Fixed charges	157.28 € $year^{-1}$
Total unit cost	757.28 € $year^{-1}$
Unit availability	80%
Unit capacity	0.0112 $m^3 d^{-1}$
Cost of water produced	231.55 € m^{-3}
Net earning	1 €
Payback period	1,006 d

The value provided for the freshwater production cost of the proposed solar desalination unit should not be considered as a reference value since the system is only in its initial study phase. In fact, cost reduction requires simple conception, ease of use, and optimized distillate water production. Taking these considerations into account, the authors are currently working on the increase of the daily production yields of distillate water through elevating the daily operation time of the unit to reach 24 h/d using an energy storage device that would help to extend the operation ability of the unit beyond daylight hours and cloudy days.

Water desalination systems combined with solar energy provide one of the most attractive sustainable sources of freshwater. The solar desalination system presented in this work showed a number of attractive properties and attributes that are highly valued in the freshwater production industry, which make it a promising potential candidate for future industrial application. The proposed model showed good flexibility, simplified design, user friendly functioning, low maintenance, extended lifetime (of more than 20 years), and quasi-null values of energy consumption, construction, and adaptation for use in rural areas.

It is worth noting that the high cost of freshwater production is associated with solar desalination techniques when compared to conventional desalination strategies remains one of the major limitations hampering their applications in large-scale systems. The higher cost of freshwater is in part caused by the small scale of the tested units. At any rate, when compared to water prices charged by local water authorities, the increase in the cost of freshwater per cubic meter can be justified not only in terms of the autonomy of such a desalination unit, but also in terms of the difficulties associated with its setup in harsh and remote regions where other procedures for water desalination are difficult or even impossible to implement.

Taking into account the factors involved in the maximization of water connection maps and the minimization of water production costs, the following recommendations could help contribute to control of water production cost associated with solar desalination systems:

- The use of geothermal water can significantly reduce the price of distillate water by 20–30% since it becomes unnecessary to have solar collectors to preheat the water.
- The extension of the unit operation time to beyond daylight hours and cloudy days would also be constructive. This would be possible when insulated storage tanks and solar ponds are used. The possibility of operating at night could double the cost-effectiveness of solar desalination plants as compared to conventional ones.
- The optimization of the unit's functioning by integrating a regulation algorithm using mathematical models such as the ones developed here into it.
- The use of local and less expensive construction materials.
- The perfect thermal insulation of each component in the unit and the ducts would also help decrease the heat losses by conduction to the surroundings; this could be achieved through the use of low-cost and long-life insulating materials.
- The optimization of the geometry and orientation of the collectors can also maximize solar heat collection with variable solar irradiation.

5. Conclusion

In this paper, an investigation and an economic analysis on an innovative solar powered water desalination unit were presented. The unit consists of a conventional solar still with energy storing materials and coupled with an external heat source and condenser device. The effects of incorporating the different modules on the system performance were studied. For all configurations, modeling of the system and simulating its behavior have been successfully done on the base of thermal and mass balances approach. Based on theoretical simulations, the proposed unit would perform much better than a conventional solar still. This design allows the use of any available thermal source nearby, such as heat from condenser of chillers, conventional sources, hot industrial waste heat, geothermal sources, etc.

In order for the based solar desalination units to gain more acceptance for application on large-scale systems worldwide, further work is needed to consider the question of increasing the productivity and decreasing the water production cost associated with this promising system. The newly designed system presented in the current work exhibited a number of attractive attributes that might open new promising opportunities for the advent of freshwater to environments with limited water resources and high solar radiation rates.

Appendices

- For the solar still

$$h_{\mathrm{evp}} = 16.273 \times 10^{-3} h_{\mathrm{cwv}} \frac{P_{\mathrm{w}} - P_{\mathrm{v}}}{T_{\mathrm{w}} - T_{\mathrm{v}}}$$

$$h_{\mathrm{cwv}} = 0.884 \left[T_{\mathrm{w}} - T_{\mathrm{g}} + \frac{(P_{\mathrm{w}} - P_{\mathrm{v}})(T_{\mathrm{w}} + 273)}{268.9 \times 10^{3} - P_{\mathrm{w}}} \right]^{\frac{1}{3}}$$

$$h_{\mathrm{cbw}} = 135\ \mathrm{W/m^2\ K}$$

$$h_{\mathrm{rwv}} = \varepsilon_{\mathrm{eff}} \sigma \frac{[(T_{\mathrm{w}} + 273)^4 - (T_{\mathrm{v}} + 273)^4]}{T_{\mathrm{w}} - T_{\mathrm{v}}}$$

$$\varepsilon_{\mathrm{eff}} = \left[\frac{1}{\varepsilon_{\mathrm{w}}} + \frac{1}{\varepsilon_{\mathrm{v}}} - 1 \right]^{-1}$$

$$h_{cr} = h_{cva} + h_{rva}$$

$$h_{rva} = \varepsilon_v \sigma \frac{[(T_v + 273)^4 - (T_{amb} + 273)^4]}{T_v - T_{amb}}$$

$$h_{cva} = 5.7 + 3.8 V_{wind}$$

$$U_w = 5,900 \left(m_w^{0.169}\right) m_a^{0.5894}$$

$$U_m = 2.09 \left(m_w^{0.45}\right) m_a^{0.11515}$$

$$U_a = C_{pa} U_m$$

- For the condenser

$$\frac{1}{U_f} = \frac{1}{h_e\left(\frac{d_e}{d_i}\right)} + \frac{1}{h_c} + R_{ee}\left(\frac{d_e}{d_i}\right) + R_{ec} + \frac{d_e}{2\lambda_p}\mathrm{Log}\left(\frac{d_e}{d_i}\right)$$

$$h_e = \frac{\lambda_e}{d_i} 0.023 R_e^{0.8} \mathrm{Pr}^{0.4}$$

$$h_c = 0.943 \left(\frac{g \rho_c^2 \lambda_c^3 \lambda_o}{L \mu_c (T_i - T_p)}\right)^{\frac{1}{4}}$$

$$U_g = \frac{\lambda_g}{d_e} 1.04 \mathrm{Re}^{0.4} \mathrm{Pr}^{0.36}$$

$$U_{mc} = \frac{U_g}{C_{pg}}$$

$$W_{ic} = 0.62198 \frac{P_{ic}}{1 - P_{ic}}$$

Symbols

A	surface (m^2)
C	specific heat (J/(kg K))
C_p	specific heat (J/(kg K))
d_e	outer diameter of the condensation tower tube (m)
d_i	inner diameter of the condensation tower tube (m)
g	gravitational acceleration (m/s^2)
h_{evp}	evaporative heat transfer coefficient from water to cover ($W/(m^2\ ^\circ C)$)
h_{cbw}	convective heat transfer coefficient from basin absorber to water ($W/(m^2\ ^\circ C)$)
h_{cwv}	convective heat transfer coefficient from water to cover ($W/(m^2\ ^\circ C)$)
h_{cva}	convective heat transfer coefficient from cover to ambient ($W/(m^2\ ^\circ C)$)
h_{rva}	radiative heat transfer coefficient from cover to ambient ($W/(m^2\ ^\circ C)$)
h_{rwv}	radiative heat transfer coefficient from water to cover ($W/(m^2\ ^\circ C)$)
U	overall heat transfer coefficient in the condenser ($W/(m^2 K)$)
U_g	air film voluminal heat transfer coefficient in the condenser ($W/(m^3 K)$)
U_{mc}	water vapor voluminal mass transfer coefficient at the vapor–condensate interface in the condensation tower ($kg/(m^3 s)$)
U_a	air voluminal heat transfer coefficient at the air–water interface in solar still ($W/(m^3 K)$)
U_w	water voluminal heat transfer coefficient at the air–water interface in solar still ($W/(m^3 K)$)
U_m	water vapor voluminal mass transfer coefficient at the air–water interface in solar still ($kg/(m^3 s)$)
K_m	water vapor mass transfer coefficient at the air–water interface ($kg/(m^2 s)$)
L	tube length of the condensation tower (m)
I	solar flux (W/m^2)
m	mass flow rate (kg/s)
M	mass (kg)
Pr	Prandtl number
Re	Reynolds number
P	pressure (Pa)
P_l	longitudinal pitch (m)
P_t	transverse pitch (m)
T	temperature (K)
T_i	temperature at the air–water interface (K)
W	air humidity (kg water/kg dry air)
W_i	saturation humidity (kg water/kg dry air)
V_{wind}	wind velocity (m/s)
z	coordinate in the flow direction (m)

Greek

λ_o	latent heat of water evaporation (J/kg)
λ_p	wall thermal conductivity (W/m K)
λ_e	water thermal conductivity (W/m K)
λ_c	condensed water thermal conductivity (W/m K)
λ_{gc}	humid air thermal conductivity in the condenser (W/m K)
ρ_c	water density (kg/m^3)
μ_c	dynamic viscosity of condensed water (Ns/m^2)
μ_p	dynamic viscosity at the wall temperature (Ns/m^2)
σ	Stefan–Boltzman constant
ε_{eff}	effective emissivity
ε_v	glass cover emissivity
ε_w	water emissivity

Subscripts

a	moist air in solar still
amb	ambient

b basin absorber
c condenser
f feed water
v glass cover
w water
g moist air in condenser
loss loss to ambient

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