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Research Article

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Experimental Validation of Optimized Solar Still Using Solar Energy

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Abstract

This paper presents an experimental validation of a new concept of solar distiller with a condenser and coupled with water solar heater and air collector and humidifier to ameliorate the yield of freshwater of this solar still system which is placed at Sfax in Tunisia. An experimental as well as theoretical investigation is carried out. A mathematical model based on heat and mass transfers of the optimized solar system has been presented in dynamic mode. The obtained global model of the solar unit distillation has been converted to a set of algebraic system of equations to render them ordinary equations by the functional approximation method of orthogonal collocation. To compare the numerical and experimental data of the mathematical model of the solar distiller an example of the validation process that has been presented to assess the credibility of the obtained numerical model of solar distiller system, a laptop simulation program based on the model is simulated by C++ software. In this numerical study, the fourth order Runge-Kutta method is programed to solve the model of glass cover, water and basin temperature of the optimised solar still numerically. It was shown that the developed mathematical model is able to predict accurately the trends of the thermal characteristic of the optimized solar still system temperature of the optimized solar still.

Keywords: Solar still; Water; Glass cover; Basin temperature; Experimental; Validation; Simulation

Abbreviations: C_w: Water heat capacity in the solar water collector [J/(kg.K)]; C_b: Basin heat capacity [J/(kg.K)]; C_v: Glass cover heat capacity [J/(kg.K)]; m_w: Water mass flow sprayed onto the solar distiller [kg/s]; M_a: Air mass flow density in the solar still [kg/(m^2.s)]; M_v: Glass cover weight [kg]; M_w: Water weight in the solar still [kg]; M_b: Absorber weight of solar water [kg]; T_b: Temperature of the absorber basin solar still [°C]; T_v: Glass cover température of the solar still [°C]; T_{amb}: Ambient temperature [°C]; T_w: Water température in the solar distiller [°C]; d_w: Water depth [m]; p_w: Vapor pressure at T_w [atm]; p_v: Vapor pressure at T_v [atm]; V_{wind}: Wind speed; ε_{eff}: Effective emissivity; λ_o : Latent heat of water evaporation [J/kg]; ε_1, ε_2: Emissivity of the absorber and the glass cover respectively; ε: The emissivity; σ: STEAFFAN-BOLTZMAN constant; ε_e: Water emissivity; ε_v: Glass cover emissivity

Subscripts: Amb: Ambient; a: Air; w: Water; v: Glass cover; b: Basin

Introduction

The saline water presents the essential elements for human life. Solar still presents a simple method and economical process which use solar energy to produce fresh water. But the yield of the conventional solar distiller unit is very law. Several designs and a lot of study have been presented and developed to ameliorate the yield of freshwater of solar still.

A solar distiller unit was tested with an energy storage media at its base [1]. The performance of the conventional solar distiller unit with different size sponge cubes placed in the blackened basin water [2]. An experimental parametric study of optimized solar still up to a minimum depth of water in the blackened basin and different wick materials like cotton cloth, and sponge sheet arranged in different configurations in the blackened basin water [3]. The solar distiller by incorporating inverted absorber asymmetric line-axis compound parabolic concentrating collector and concluded that the distillate output was increased in comparison to conventional solar distiller because solar still received solar energy both from top and 50 bottom resulting in increased temperature gradient between water surface and glass cover [4]. The various parameters that affecting the yield of solar distiller coupled with a solar collector and the influence of inclination of water collector of conventional solar distiller unit were optimized [5]. An experimental parametric study of an active solar distiller integrated with a water solar heater and found that the maximum increase in the yield was up to 33% [6]. A new mathematical model based of heat and mass transfer of a tubular still system [7]. They found that, the heat balance of the humid air and the mass balance of the water vapour in the humid air were formulized for the first time. An experimental parametric study of a modified solar distiller unit by adding jute cloth in vertical position in the middle of the basin and another row of jute cloth placed in the still wall [8]. A horizontal shaft rotating by a small wind turbine and water solar heater still was integrated to main device of solar distiller unit as a hybrid system of distillation [9]. They founded the inclined water still produced higher output yield than that of the main device of solar distiller by 29.17% approximately. The performance of various designs of active solar distiller experimentally and concluded that the circular box active solar distiller design produced highest overall daily efficiency [10]. Also, a new mathematical model to study the thermal parametric study of the solar distiller system with phase change material [11]. A new concept of a solar distiller coupled to flashing chamber to ameliorate the freshwater yield [12]. A new solar distiller with an energy storing material in the water basin to extend the operation of the distiller at night, a water and air solar collector and a separate condenser that coupled to the solar distiller unit to amoliorate the productivity [13]. A rotating shaft with horizontal axis introduced near to the water surface of the blackened basin of solar distiller unit to

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ameliorate the yield productivity [14]. They coupled this solar still to an electrical motor to rotate the shaft. They founded that this new concept of the solar distiller was improved by 5.5% in July, 5% in June, and 2.5% in May. Solar still adding mirrors at interior walls and coupled with FPC experimentally [14]. This work presents a mathematical modeling and an experimental validation of the optimised solar distiller unit with a condenser and coupled with water and air solar heater and humidifier which are placed at Sfax in Tunisia. To develop a general dynamic model able to predict the performance of the optimized solar still system to ameliorate the freshwater yield of this new concept of a solar distiller unit [15]. To compare the numerical and experimental data of the mathematical model of the solar distiller an example of the validation process that has been presented to assess the credibility of the obtained numerical model of solar distiller system, a laptop simulation program based on the model is simulated by C++ software [16].

Materials and Methods

System description

Figure 1 demonstrated the new concept of solar distiller unit with a condenser and coupled with water and air solar heater and humidifier to ameliorate the freshwater production. First of all, water will be heated by a solar water collector then the humidified air exiting will be conveyed to the condensation tower where it condenses when it comes in contact with the outer walls of the tubes of the condenser chamber that circulate cold water to ensure the dehumidification of the humid air obtained. The yield of the condensed water obtained will be collected in a tray placed below the condensation tower. The humidifier used in this solar still unit to ameliorate the exchange surface of water and water in the optimized solar still to ameliorate the heat and mass transfer, and thereafter ameliorate the yield of freshwater. Figure 2 shows a three-dimensional simplified schematization of the water desalination unit by using solar energy which explains different components of the optimized solar still system. Figure 3 shows the experimental setup of the still system.

Thermal modeling of solar still

The general mathematical model of the optimized solar distiller with a condenser and coupled with water and air solar heater and humidifier consisted of a set of equations that were obtained using thermal and mass balances.

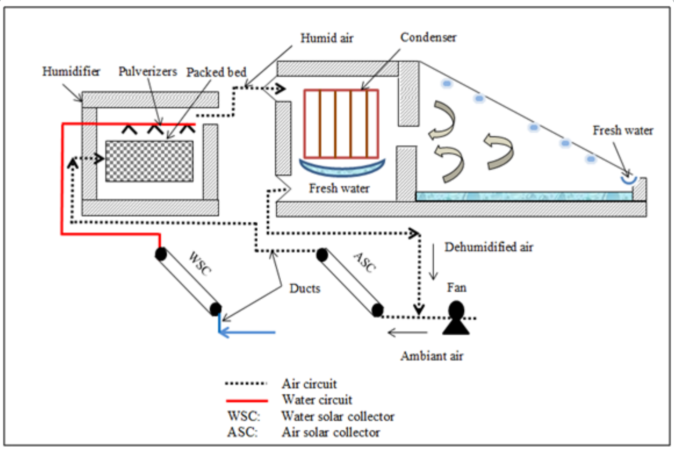

Figure 1: Schematic view of new solar distillation system the new design of solar still with an internal condenser and coupled with solar water and air heater and humidifier.

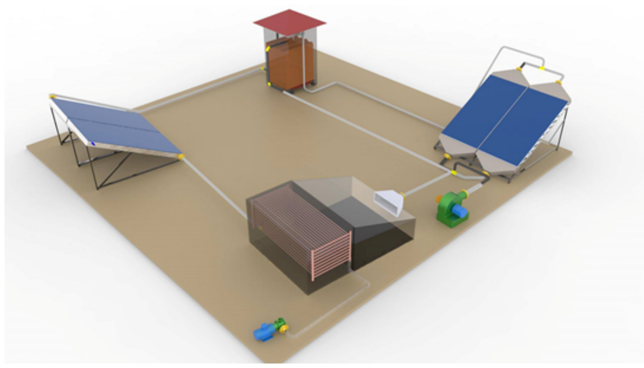

Figure 2: Three-dimensional simplified schematization of new solar distillation system by solar energy.

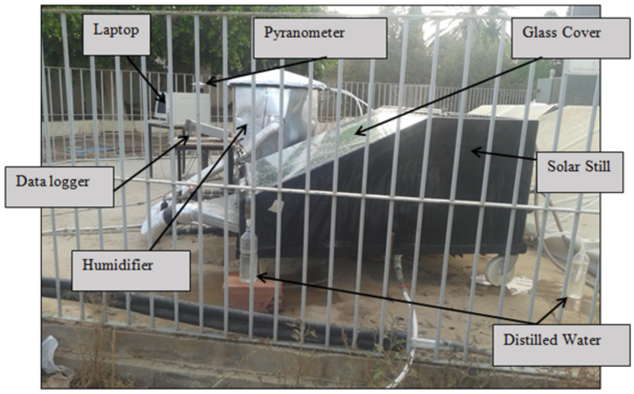

Figure 3: Photograph of the new design of solar still with an internal condenser and coupled with solar water and air heater and humidifier.

- Thermal modeling for the glass cover

$$M_v C_v dT_g = IA_v dt + h_{rwv}\left(T_w - T_g\right)dt + h_{evp}\left(T_w - T_g\right)dt - h_{rc}\left(T_g - T_{amb}\right)dt \quad \text{Eq. (1)}$$

- Thermal modeling for the basin absorber

$$M_b C_b dT_b = IA_b dt - h_{cbw}\left(T_b - T_w\right)dt - U_{loss}\left(T_b - T_{amb}\right)dt \quad \text{Eq. (2)}$$

- Thermal modeling for the water basin

$$\left(M_w C_w\right)dT_w = IA_w dt + h_{cbw}\left(T_b - T_w\right)dt - h_{rwv}\left(T_w - T_g\right)dt - h_{cwv}\left(T_w - T_g\right)dt - h_{evp}\left(T_w - T_g\right)dt \quad \text{Eq. (3)}$$

- The water condensation rate in the solar still system

$$d\dot{m} = \frac{hevp\left(T_w - T_g\right)3600}{L} \quad \text{Eq. (4)}$$

Where,

The evaporation coefficient:

$$h_{evp} = 16 \cdot 273\left(10^{-3}\right)h_{cwv}\frac{\left(P_w - P_v\right)}{T_w - T_g} \quad \text{Eq. (5)}$$

The convection coefficient:

$$h_{cwv} = 0.884\left[T_w - T_g + \frac{\left(P_w - P_v\right)\left(T_w + 273\right)}{268.9\,10^3 - P_w}\right]^{\frac{1}{3}} \quad \text{Eq. (6)}$$

The coefficient of heat transfer by convection: Eq. (7)

$$h_{cbw} = 135\ W / m^2 K \quad \text{Eq. (7)}$$

The radiation coefficient from the water to the glass cover:

$$h_{rwv} = \varepsilon_{eff}\sigma \frac{\left[(T_w + 273)^4 - (T_g + 273)^4\right]}{T_w - T_g} \quad \text{Eq. (8)}$$

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_v} - 1\right]^{-1} \quad \text{Eq. (9)}$$

The coefficient of convective radiative heat transfer in the solar still system from glass cover to the ambient air:

$$h_{cr} = h_{cva} + h_{rva} \quad \text{Eq. (10)}$$

$$h_{rva} = \varepsilon_v\sigma \frac{\left[(T_g + 273)^4 - (T_{amb} + 273)^4\right]}{T_g - T_{amb}} \quad \text{Eq. (11)}$$

$$h_{cva} = 5.7 + 3.8V_{wind} \quad \text{Eq. (12)}$$

Approximation of mathematical models of solar distiller unit

The analytical solution of equations of mathematical model of solar distiller unit is impossible. So the obtained global model of the solar unit distillation has been converted to a set of algebraic system of equations to render them ordinary equations by the functional approximation method of orthogonal collocation (OCM).

The (OCM) approximates the solution of the obtained model by a polynomial trial function, render them ordinary equations.

Formulation of the approximation method of solar distiller unit

By substituting the approximations method of the global model of the solar distiller unit presented earlier in the initial system formed by partial derivatives equations to render them ordinary equations according to the time localized in every solar still system reduced dynamic model.

$$\frac{dT_{vi}}{dt} = \frac{1}{M_vC_v}\left(IA_v + h_{rwv}(T_{wi} - T_{vi}) + h_{evp}(T_{wi} - T_{vi}) - h_{rc}(T_{vi} - T_{amb})\right) \quad \text{Eq. (13)}$$

$$\frac{dT_{bi}}{dt} = \frac{1}{M_bC_b}\left(IA_b - h_{cbw}(T_{bi} - T_{wi}) - U_{loss}(T_{bi} - T_{amb})\right) \quad \text{Eq. (14)}$$

$$\frac{dT_{wi}}{dt} = \frac{1}{(M_wC_w)}\begin{pmatrix} IA_w + h_{cbw}(T_{bi} - T_{wi}) - h_{rwv}(T_{wi} - T_{vi}) - \\ h_{cwv}(T_{wi} - T_{vi}) - h_{evp}(T_{wi} - T_{vi}) \end{pmatrix} \quad \text{Eq. (15)}$$

Results and Discussion

As presented in Figure 4 the measured climatic conditions; solar irradiation and ambient temperature for a typical day of July at in Sfax city, Tunisia. This day is characterized by clear sky conditions. It is made clear from this figure that the highest value of solar radiation thereabouts 1000 W/m^2 occurred at noon in July and the highest air ambient temperature thereabouts 45°C. It is seen that during this day that these climatic conditions increases gradually and reaches a maximum value at the midday and then it decreases. To experimentally validate the developed general models of water, basin and glass cover temperature, the values of global solar irradiation, ambient temperature, were inserted to the simulation program as input data (Figure 4).

Experimental validation of solar distiller with a condenser and coupled with water and air solar heater and humidifier

Figures 5-7 shows that the comparison between experimental and numerical temperature measurements, respectively, water, glass cover and basin temperature. It is seen that both the experimental and theoretical temperatures have the same trends. The law difference between the experimental and theoretical temperature of respectively, water, glass cover and basin values is because that the thermocouples are in contact with the exterior wall of the surface not emerged in the solar distiller unit with a condenser and coupled with water and air solar heater and humidifier. So, theoretical given by simulation is less than the measured temperature given by the sensor is that of the water temperature and basin temperature. That is why the theoretical temperature ones is less than the experimental temperature values.

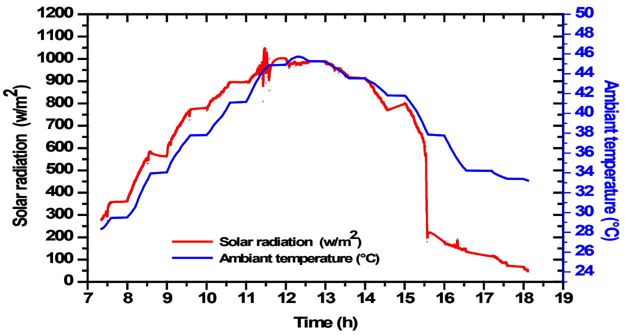

Figure 4: Solar radiation and ambient temperature measured during typical day in August.

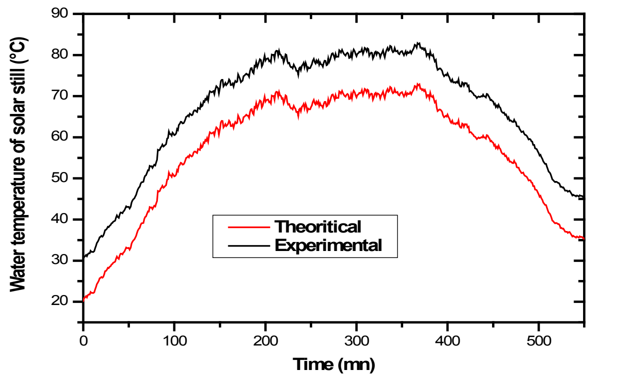

Figure 5: Comparison between numerical and experimental water temperature of solar still.

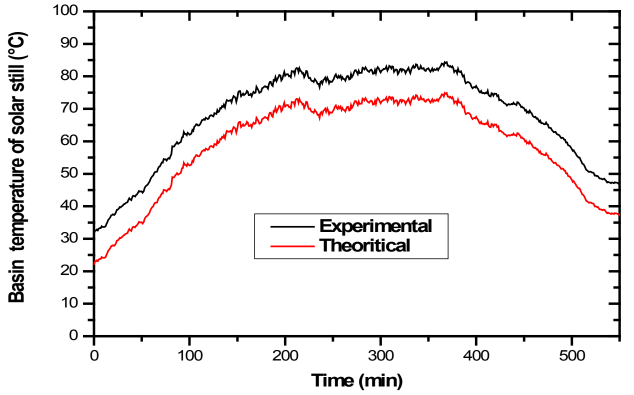

Figure 6: Comparison between numerical and experimental basin temperature of solar still.

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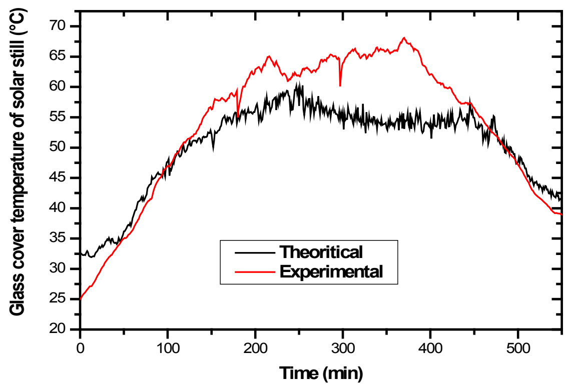

Figure 7: Comparison between numerical and experimental glass cover temperature of solar still.

Parameter	Average Relative ε_{ar} (%)	Maximum Absolute Error ε_{max} (°C)	Minimum Absolute error ε_{min} (°C)
T_w	7.321	7.834	8.87×10^{-2}
T_b	6.851	7.242	2.07×10^{-2}
T_g	3.871	6.385	5.16×10^{-2}

** $\varepsilon_{\min} = \min\left|T_{\exp}(i) - T_{sim}(i)\right|$, $\varepsilon_{\min} = \min\left|T_{\exp}(i) - T_{sim}(i)\right|$, i=1, 2,….k

Table 1: The precision of the experimental results.

This would explain the difference between the experimental results and theoretical simulations measurements.

Experimental error

Simple statistical calculus of the relative error between simulation and experimental measurements is included in Table 1. The precision of the experimental results may be calculated in Table 1 using the following definition:

$$\varepsilon_{ar}(\%) = \frac{100}{k}\sum_{i=1}^{k}\frac{\left|T_{\exp}(i) - T_{sim}(i)\right|}{T_{sim}(i)}$$

Where, T_{exp} presents the experimental data values of T, while, k and T_{sim} present respectively the number of experimental measurements and the theoretical prediction of T. The error analysis of respectively, water temperature, basin temperature and glass cover temperature (Figures 6 and 7). It is seen in Table 1 that the agreement between the results simulated and experiment data from the global model of the respectively, water, glass cover and basin temperature of the new concept of solar distiller with a condenser and coupled with water and air solar heater and humidifier device is fairly good.

Conclusion

In this work, the mathematical model of solar still coupled to a condenser, solar air and water collector and packed bed stepped with humidification- dehumidification system was presented. To numerically simulate the optimized solar still system, we have developed dynamic mathematical models describing the behaviour of the solar still coupled to a condenser, solar air and water collector and packed bed. The proposed mathematical models can be used to predict the thermal performances of solar still unit with good accuracy under the meteorological conditions for a typical day of July at the city of Sfax, Tunisia which is characterized by clear sky conditions and the variations of the entrance parameters. The experimental validation revealed that the numerical prediction of the respectively, water temperature, basin temperature and glass cover temperature of the new design of solar still with an internal condenser and coupled with solar water and air heater and humidifier was in good agreement with the experimental values measured by sensors installed on board the solar still system. This proves the validity of the mathematical models established for the optimised solar still and the effectiveness of the OCM used to solve them.

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