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The Mathematical Model of Basin-Type Solar Distillation Systems

Nguyen The Bao

Abstract

This chapter presents a numerical model for calculating basin-type solar water distillation. The model is used to calculate solar distillation for both passive natural convection and forced convection with external condensers. For passive systems, the numerical model allows to simulate and calculate more complex parameters than previous models. For active-forced convection systems, this model allows the simulations of the heat transfer and mass process inside both the distillation unit and the internal heat exchanger. Comparison of numerical simulation results and experimental results shows that the numerical model achieves the acceptable accuracy in calculating the parameters of the fluid flow inside the distillation and the condenser-type heat recovery as well as estimation of the distillate output corresponding to both types of solar distillation.

Keywords: basin-type solar distillation system, passive solar still, active solar still, forced circulation distillation system with external condenser, enhanced heat recovery

1. Introduction

People in the world are increasingly facing the lack of clean water for living nowadays. Every year, millions of people die from lack of clean water and from the diseases relating to drinking and living water. There is a lot of technology in the world to produce fresh water from sea water or brackish water. However, these technologies are mostly expensive, not suitable for the poor and developing countries and communities where most of the water shortages are occurring. In addition, most of industrial-scale distillation technologies and equipment consume a lot of energy, contributing to the depletion of fossil fuel energy sources and increasing environmental pollution. It is therefore necessary to promote cheap, less energy-efficient, and environmentally friendly distillation methods. The methodology and technology of solar distillation almost meet all three criteria: simple equipment with low-cost, no use of fossil fuels, and no contribution to the environmental pollution.

Solar water distillation is a method of using solar energy, a source of clean and endless energy, to produce clean water from impure water. In solar water distillation equipment, evaporation and purification of pure water occur, thereby removing salts and impurities that are harmful to human health from marine and brackish water resources to give out drinking water. In many solar water distillation

technologies and devices, the solar stills are widely used because they are designed and operated in a manner that is consistent with the technological level and economic conditions of the poor and developing countries and communities.

The most popular solar stills are passive type, in which distillation process occurs within the still through evaporation and condensation [1]. They are simple in design and manufacture, easy to operate, usually small, and reasonably cheap. Passive solar stills only use solar energy to remove the salts or impurities in saline or brackish water; thus, it is environmentally friendly and saving energy. Therefore, it is still of value to study in this type of stills to continue improving its efficiencies and designs. This is the main aim of this chapter.

The main drawback of this type of solar distillation system is low energy efficiency and distillate productivities. Hence, many active distillation systems such as solar still coupled with flat plate or evacuated tube collectors, solar still coupled with parabolic concentrator, solar still coupled with heat pipe, solar still coupled with hybrid PV/T system, multistage active solar distillation system, multi-effect active solar distillation system, etc. have been developed theoretically and experimentally [2]. However, a forced circulation solar still with enhanced water recovery has not been researched and presented. Therefore, this type of solar still has been developed and modeled, both theoretically and experimentally, and will be presented in this chapter as well.

In terms of numerical analyses of passive and active solar distillation systems, there are several models presented in literatures [2–8]. Sampathkumar et al. [2] comprehensively reviewed mathematical models applied to predict the performances of active solar distillation systems and concluded that Kumar and Tiwari's model [3] was most suitable for evaluating the internal heat transfer coefficients and hourly yield accurately except in extreme cases. However, Dwivedi and Tiwari [4] observed from their studies in passive solar still that Dunkle's model [5] gave better agreement between theoretical and experimental results. Madhlopa and Johnstone [6] numerically modeled a passive solar still with separate condenser and claimed that the distillation productivity of their still was 62% higher than that of the conventional passive solar still. Ahsan et al. [7] reviewed a few numerical models of a tubular solar still and compared them with Dunkle and Ueda models. Recently, Edalatpour et al. [8] reviewed the latest developments in numerical simulations for solar stills including the use of computational fluid dynamics (CFD) simulations, MATLAB.

Based on the above literature review, it is obvious that although Dunkle's model is one of the oldest thermal model for predicting the internal heat transfers of solar stills, it still can be used to accurately present the performance of heat transfers inside the solar stills. However, there is no research found in the literature review that consistently uses Dunkle's equations to develop the numerical models for both passive and active solar stills. Therefore, this chapter will use this approach to develop the mathematical models for a conventional solar still and a forced circulation solar still with enhanced water recovery.

2. The mathematical model of a passive basin-type solar still

The relationships of heat and mass transfer in a solar still under steady-state conditions were first studied in 1961 by Dunkle [5]. Based on this initial work, this research has developed the transient mode of the solar still in which all heat and mass coefficients and still parameters are calculated using the formulae within the model. The weather data used for simulation will be either input from actual

measured data or data generated from a sub-computer program developed by the author and linked to the main program [9].

The processes of heat and mass transfer in a passive solar still are indicated in **Figure 1**. In order to develop the formulae for the energy and mass balances in the still, the following assumptions are made:

- The lost amount of water through evaporation is small compared to the amount of water in the basin and can be ignored.
- The energy required to heat up the water from outside temperature before adding to the still to the basin temperature is negligible as compared to the latent energy required to evaporate the same amount of water. In other words, $C_{pw}(T_w - T_a) \ll h_w$.
- There is no leakage in a well-designed still.
- The areas of the cover, the water surface, and the still basin are equal.
- The temperature gradients along the cover thickness and the water depth are ignored.

As can be seen in **Figure 1**, the heat and mass transfer inside the solar still occurs as follows: the solar incidence Q_T from the sun reaches the glass, part of it will be reflected Q_r , part will be absorbed by the glass Q_α , and the remaining Q' will transfer through the glass and reach the basin water. Then, Q' absorbed into the basin water will be partially reflected back to the glass under convection q_{cw} , evaporation q_{ew} , and radiation q_{rw} , partially transfer to the basin q_{w-b} , and the remaining will increase the temperature of the basin water $M_w \frac{dT_w}{dt}$. The basin, in its turn, gains the energy partially from the sun (αQ_T), partially from the water (q_{w-b}).

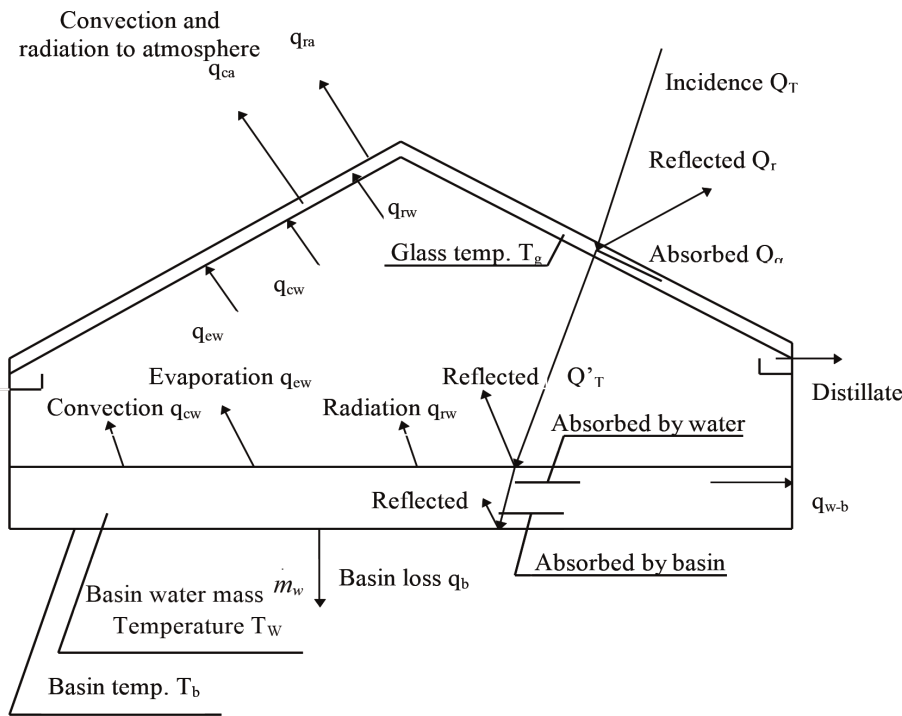


Figure 1.
The heat and mass transfer processes in a conventional solar still.

This gained energy will be partially lost from surroundings q_b , and the remaining will increase the temperature of the basin $M_b \frac{dT_b}{dt}$. Similarly, the energy going in the glass includes the reflected energy from the basin water through convection q_{cw} , evaporation q_{ew} , radiation q_{rw} , and the energy absorbed from the sun $\alpha_g Q_T$. This gained energy of the glass will partially transfer to the ambient through convection q_{ca} and radiation q_{ra} and partially increase the temperature of the glass $M_g \frac{dT_g}{dt}$.

Based on these assumptions and the heat and mass transfer explained above, the energy balances for the glass, for the basin water and for the basin, are

$$q_{cw} + q_{ew} + q_{rw} + \alpha_g Q_T = (q_{ra} + q_{ca}) + M_g \frac{dT_g}{dt} \quad (1)$$

$$\alpha_w Q'_T = q_{cw} + q_{ew} + q_{rw} + q_{w-b} + M_w \frac{dT_w}{dt} \quad (2)$$

$$\alpha_b Q''_T + q_{w-b} = q_b + M_b \frac{dT_b}{dt} \quad (3)$$

where

q_{cw} : heat transfer by convection from the still water to the glass (W/m^2), which is calculated by using Dunkle's equation:

$$q_{cw} = 0.884 \left[(T_w - T_g) + \frac{(p_w - p_g)(T_w + 273)}{(268.9 \times 10^3 - p_w)} \right]^{1/3} (T_w - T_g) \quad (4)$$

with p_w and p_g being the partial pressure of water vapor at the temperatures of the basin water and the glass, respectively (in Pa).

q_{ew} : heat transfer by evaporation from the still water to the glass (W/m^2):

$$q_{ew} = 16.276 \times 10^{-3} q_{cw} \frac{(p_w - p_g)}{(T_w - T_g)} \quad (5)$$

q_{rw} : heat transfer by radiation from the basin water to the glass cover (W/m^2), given by

$$q_{rw} = \epsilon_w \sigma [(T_w + 273)^4 - (T_g + 273)^4] \quad (6)$$

where ϵ_w is the emission of water

$$\sigma = 5.67 \times 10^{-8} W/m^2.K^4$$

q_{ca} : heat transfer by convection from the glass to the ambient around the still (W/m^2), calculated as [10]

$$q_{ca} = (5.7_w + 3.8)(T_g - T_a) \quad (7)$$

with W being the velocity of wind (m/s) and T_a the temperature of the atmosphere ($^{\circ}C$).

q_{ra} : heat transfer by radiation from the glass to the ambient around the still (W/m²):

$$q_{ra} = \varepsilon_g \sigma \left[(T_g + 273)^4 - (T_a + 273)^4 \right] \quad (8)$$

where ε_g is the emission of the glass.

q_{w-b} : heat transfer by convection from the still water to the absorbing surface of the basin (W/m²):

$$q_{w-b} = h_{w-b} (T_w - T_b) \quad (9)$$

where h_{w-b} is the coefficient of convection from the water to the basin (W/m².°C).

q_b : heat transfer by convection from the basin to the surroundings of the still (W/m²):

$$q_b = h_b (T_b - T_a) \quad (10)$$

where h_b is the coefficient of convection from the basin to the ambient around the still (W/m².°C):

$$\frac{1}{h_b} = \frac{\delta_{insul}}{k_{insul}} + \frac{1}{h_i} \quad (11)$$

k_{insul} (W/m.°C) and δ_{insul} (m) are the basin thermal conductivity and the thickness of the basin insulation, respectively.

h_i : the combination of heat transfer coefficients by convection and radiation from the basin insulation to the ambient surroundings, which can be derived from formulae (6) and (7).

Q_T : global solar irradiation to the cover, in W/m².

Q'_T : global solar irradiation dropping on the still water, after transmitting through the glass, in W/m².

Q''_T : global solar irradiation dropping on the basin, after transmitting through the still water, in W/m².

α_b , α_w , and α_g : solar radiation absorption coefficients of the basin, water, and glass, respectively.

M_b , M_w , and M_g : solar radiation heat capacities per unit area of the basin, water, and glass, in J/m².°C.

T_b , T_w , and T_g : transient temperatures of the basin, of the water, and of the glass, respectively, in °C.

Formulae (1), (2), and (3) can be derived as follows:

$$M_g \frac{dT_g}{dt} = \alpha_g Q_T + q_{cw} + q_{ew} + q_{rw} - (q_{ra} + q_{ca}) \quad (12)$$

$$M_w \frac{dT_w}{dt} = \alpha_w Q'_T - (q_{cw} + q_{ew} + q_{rw} + q_{w-b}) \quad (13)$$

$$M_b \frac{dT_b}{dt} = \alpha_b Q''_T + q_{w-b} - q_b \quad (14)$$

It is often to present all solar components Q_T , Q'_T , and Q''_T in the above formulae by the global solar incidence of the sloped cover, Q_T , which is well-known computed [9]. If τ_b , τ_w , and τ_g are, respectively, defined as the proportions of solar radiation incident absorbed by the basin, water, and glass liner, formulae (12), (13), and (14) can be written as

$$M_g \frac{dT_g}{dt} = \tau_b Q_T + q_{cw} + q_{ew} + q_{rw} - (q_{ra} + q_{ca}) \quad (15)$$

$$M_w \frac{dT_w}{dt} = \tau_w Q_T - (q_{cw} + q_{ew} + q_{rw} + q_{w-b}) \quad (16)$$

$$M_b \frac{dT_b}{dt} = \tau_b Q_T + q_{w-b} - q_b \quad (17)$$

3. The mathematical model of an active basin-type solar distillation system with enhanced water recovery condenser

This section will focus in developing the relationships of heat and mass transfer in an active solar distillation system with enhanced water recovery condenser. Then, this mathematical model will be validated by comparing its results with those from the experimental model.

An active solar distillation system with enhanced water recovery condenser has been chosen in this study for several reasons. Compared with other types of active solar stills such as solar stills coupled with flat plate or evacuated tube collectors, solar stills coupled with parabolic concentrator, solar stills coupled with heat pipe, solar stills coupled with hybrid PV/T system, multistage active solar distillation systems, multi-effect active solar distillation systems, etc., solar stills represent simple yet mature technology. This is suitable for poor and developing countries and communities like Vietnam.

The main disadvantage of a conventional passive solar still as low productivity and efficiency can be overcome by changing the principle of operation as follows:

- Using air as an intermediate fluid and using forced convection to increase the heat transfer in the still, leading to increase the evaporation of water.
- Replacing saturated air in the passive solar still by “drier” air to increase the potential for mass transfer in the still, resulting in increasing the distillate outputs.
- Circulating the air-vapor mixture from the passive still to an external condenser to increase efficiency from a lower condensing temperature. If the water with low temperatures such as well water or wastewater from refrigeration process is available, then this condensing process will be more effective.
- Recovering heat extracted in the condensing process and using it to preheat the air-vapor mixture entering the still.
- Replacing the limited condensing area of the hot glass covers in the standard still by the external condenser with much larger heat exchange areas and much lower temperature to increase condensing process.

3.1 Developing of the relationships of heat and mass transfer in an active solar distillation system

Figure 2 presents a schematic diagram of an active solar distillation system with enhanced water recovery condenser. The airflow entering the solar still with a temperature of T_{fin} and moisture content w_{in} is heated up. After absorbing the vapor from the basin water, the airflow exits the solar still at a temperature of T_{fout} and moisture content w_{out} . Then the hot air-vapor mixture passes through the dehumidifying coil, acting as a condenser. The dehumidifying coil with cooling water running inside will cool the hot air-vapor mixture down and condense the vapor from the mixture to produce the distillate. The air after passing the condenser has T_{c-out} and w_{c-out} . The airflow continues passing through the preheater before going back to the still; hence, part of its heat will be extracted to recover in the preheater.

The heat and mass transfer relationships in this still can be seen in **Figure 3**. The heat and mass transfer is mainly similar to that of the conventional solar still, except the energy reflecting from the basin water through convection q_{cw} and evaporation q_{ew} will go into the flowing air first (defined as q_{cwf} and q_{ew}) instead of going directly to glass as in the conventional case. Then, the flowing air (the flow) will release part of its energy to the glass through convection q_{cfg} . The gained energy of the flow, mainly from the basin water, will increase both latent heat ($h_{out} - h_{in}$) and sensible heat $M_f \frac{dT_f}{dt}$ of the flow.

From **Figure 3**, the energy and mass balances for the glass, for the flow in the still, for the basin water, and for the basin are

$$q_{cfg} + q_{rw} + \alpha_g Q_T = (q_{ra} + q_{ca}) + M_g \frac{dT_g}{dt} \quad (18)$$

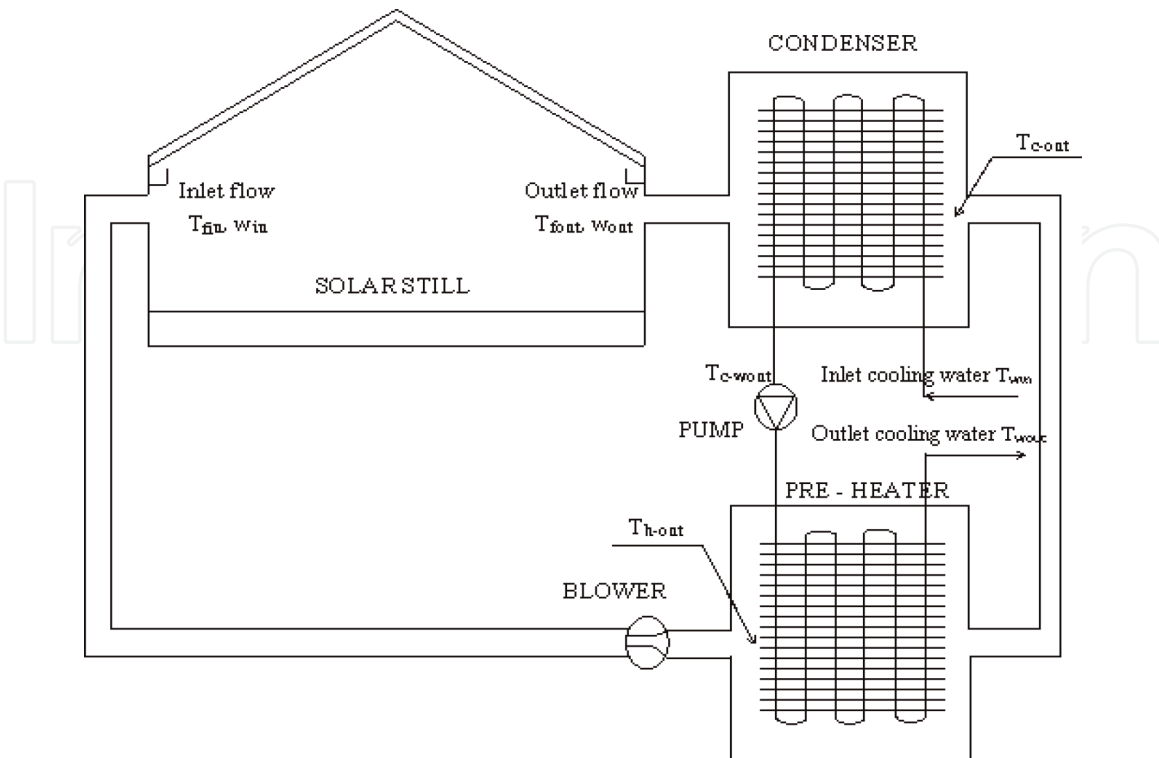


Figure 2.
 Schematic diagram of a forced circulation solar still with enhanced water recovery.

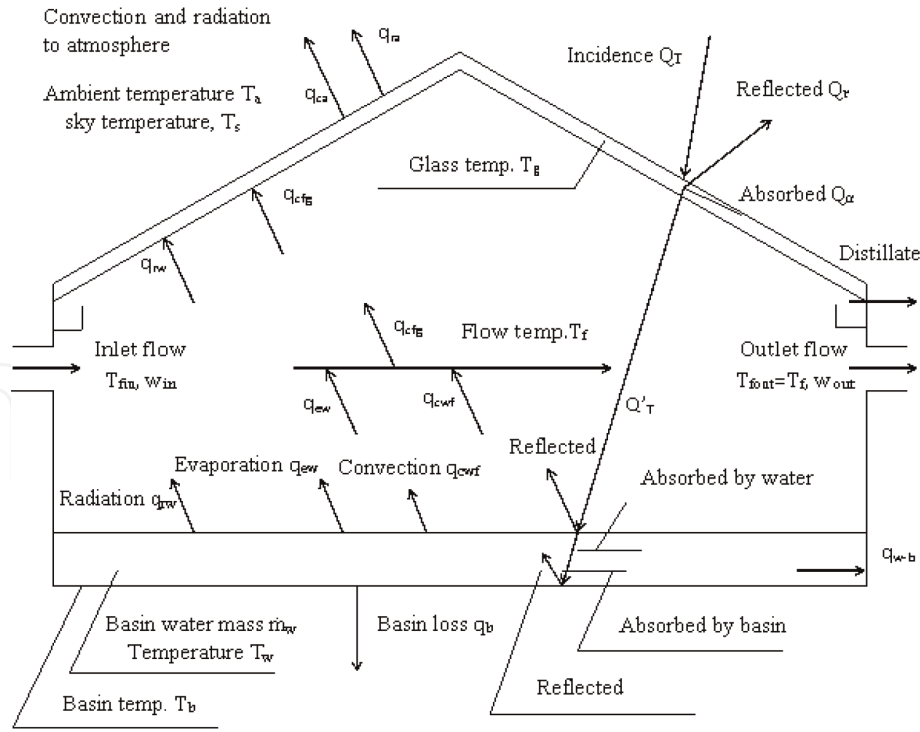


Figure 3.
The heat and mass transfer process in a forced circulation solar still.

$$q_{ew} + q_{cwf} = q_{cfg} + m_f(h_{out} - h) + M_f \frac{dT_f}{dt} \quad (19)$$

$$m_{ew} = \frac{q_{ew}}{h_{fg}} = m_f(w_{out} - w) + m_{ew-g} \quad (20)$$

$$\alpha_w Q'_T = q_{cwf} + q_{ew} + q_{rw} + q_{w-b} + M_w \frac{dT_w}{dt} \quad (21)$$

$$\alpha_b Q_T'' + q_{w-b} = q_b + M_b \frac{dT_b}{dt} \quad (22)$$

q_{cwf} : heat transfer by convection from the still water to the air (W/m^2). In theory, the blower flowing the air must use energy as low as possible, or it should be powered by solar PV system. Depending on the flow velocity, the process of heat transfer in the still may be in natural or forced mode. Therefore, in this mathematical model, the coefficient of heat transfer in the still is computed by using both Reynolds and Grashof numbers for the forced and natural convection relations separately; then the larger one is chosen [10]:

$$Gr = \frac{g\beta' \Delta T L^3}{\nu^2} \quad (23)$$

$$Re = \frac{VD_h}{\nu} \quad (24)$$

where L is the distance between the water surface and the glass, in m; $g = 9.81 \text{ m/s}^2$ is the gravity constant; β' is the volumetric expansion coefficient, in K^{-1} ; for air $\beta' = 1/T$; ΔT is the difference between the water and the glass temperatures, in $^{\circ}\text{C}$; ν is the kinematic viscosity, in m^2/s ; V is the airflow velocity, in m/s ; $D_h = \frac{4(\text{flow area})}{\text{wetted perimeter}}$ is the hydraulic diameter of the solar still.

If the natural mode dominates, the heat transfer by convection from the still water to the airflow can be calculated from

$$Nu = \frac{h_{cwf}L}{k} = 0.075(Gr.Pr)^{1/3} \quad (25)$$

with $Pr = \frac{\mu}{\alpha}$ being the Prandtl number.

In order to have the same format with Dunkle's expression [11], T_f is replaced for T_g :

$$q_{cwf} = 0.884 \left[(T_w - T_f) + \frac{(T_w - T_f)(T_w + 273.15)}{(268 \times 10^3 - p_w)} \right]^{1/3} (T_w - T_f) \quad (26)$$

where p_f and p_w are, respectively, the partial water vapor pressures at the temperatures of the flow and the basin water, in Pa.

If the forced convection dominates, the relation between Nu and Re is given by [10]

$$Nu = \frac{h_{cwf}D_h}{k} = 0.664 \times Re^{1/2} \times Pr^{1/3} \quad (27)$$

Considering $T_w = 50^\circ\text{C}$ and $T_f = 40^\circ\text{C}$ and introducing the corresponding air properties into Eq. (27), the convective heat transfer rate between the basin water and the flow can be computed by

$$q_{cwf} = 3.91 \left(\frac{V}{D_h} \right)^{1/2} (T_w - T_f) \quad (28)$$

q_{ew} : heat transfer by evaporation (W/m^2) from the still water to the flow, which is calculated using formula (5) with p_f and T_f are replaced for p_g and T_g .

q_{rw} : heat transfer by radiation (W/m^2) from the still water to the glass, which is computed by using formula (6).

q_{cfg} : heat transfer by convection (W/m^2) from the air to the glass, which is computed as

$$q_{cfg} = 2.8 \left(\frac{V^{4/5}}{L_s^{1/5}} \right) (T_f - T_g) \quad (29)$$

with V the airflow velocity (m/s) and L_s are the still length (m).

q_{ca} and q_{ra} are, respectively, the heat transfer rates by convection and radiation (W/m^2) from the glass and the ambient around the still, calculated from formulae (7) and (8) correspondently.

q_{w-b} and q_b are the heat transfer (W/m^2) from the still water to the basin and from the basin to the ambient around the still and computed from formulae (9) and (10) correspondently.

Q_T : the global solar irradiation dropping on the still (W/m^2).

Q'_T : the global solar irradiation dropping on the water, after transmitting through the glass, (W/m^2).

Q''_T : global solar irradiation dropping on the basin, after transmitting through the still water, (W/m^2).

m_f : the airflow mass rate, in kg/s .

m_{ew} : the mass rate evaporating from the basin water to the airflow, in kg/s .

α_b , α_w , and α_g : solar absorption ratios of the basin, of the water and of the glass correspondently.

M_b, M_f, M_w , and M_g : heat mass are unit area of the basin, the air, the water in the still, and the glass ($J/m^2 \cdot ^\circ C$).

T_b, T_f, T_w , and T_g : respectively, the basin, the airflow, the still water, and the glass temperatures ($^\circ C$).

h_{fg} : latent heat of vaporization of water at T_f (J/kg).

w_{out} and w_{in} : the air-vapor mixture's moisture contents exit and enter the still (kg/kg).

h_{out} and h_{in} : respectively, the enthalpies of air exiting and entering the still (J/kg). The air enthalpy exiting the still h_{out} can be computed as the temperature T_f function as follows:

$$h_{out} = (T_f + w_{out} \times (2500 + 1.81 T_f)) \times 10^3 \quad (30)$$

The yield of the distillate in the solar still depends on the air and the glass temperatures. Water will condense on the glass surface only when the airflow dew point temperature T_{fd} is higher than the glass temperature T_g . In this case, the amount of the distillate produced from the glass m_{ew-g} can be computed from ($kg/s \ m^2$):

$$\dot{m}_{ew-g} = \frac{q_{con-g}}{h_{fg}} \quad (31)$$

h_{fg} : latent heat of vaporization of water at T_f , (J/kg).

$q_{con-g} = h_{con-g}(T_f - T_g)$: heat transfer by condensation from the airflow to the glass. Using the Nusselt to calculate

$$Nu = \frac{h_{con-g} L_c}{k} = 0.943 \left(\frac{g^2 \sin \beta h_{fg} L_c^3}{\mu k \Delta T} \right)^{1/4} \quad (32)$$

where L_c is the length of the glass, in m; $L_c = L_s$; k is the thermal conductivity, in $W/m \ K$; $g = 9.81 \ m/s^2$ gravity constant; β is the slope of the glass, in degree; ρ is the air density, in kg/m^3 ; ΔT is the dew point temperature difference between the airflow and the glass, in $^\circ K$; μ is absolute viscosity, in $Pa \ s$.

Using the properties of the air at $T_f = 40^\circ C$, one can achieve

$$q_{con-g} = 70.93 \left(\frac{\sin \beta}{\Delta T L_c} \right)^{0.25} \quad (33)$$

Hence, with five formulae from (18) to (19), five parameters T_g, T_w, T_f, w_{out} , and T_b , can be found.

3.2 The dehumidifying coil and preheating coil calculation

The calculation of dehumidifying and preheating coils has been studied and is shown in [11, 12]. However, a clear and detailed procedure for simulating the performance of dehumidifying coils was not available in these references. Hence, a numerical model of the performance of the dehumidifying and the preheater coils in this research was developed from the handbook and the standard. The calculation procedures for the psychometric properties of humid air were given in [11]. A detailed procedure for simulating the coils of preheating and dehumidifying of an active distillation system is presented in [9].

The simulation of the preheater includes (i) computing the heat transfer coefficient for the coil, (ii) computing the coil effectiveness, and then (iii) calculating the air and cooling water temperatures leaving the coil.

The simulation of the dehumidifying includes finding consistent values of temperature and humidity by using an iterative process.

4. The comparison of results from numerical modeling and experimental results

4.1 The passive solar still

Figures 4 and 5 show the computed distillate yields and still water temperatures from the mathematical model compared to those from the experiments. As shown in these figures, the simulation model developed in this study gave very accurate calculated results. Hence, one can confidently use this program to simulate solar passive stills.

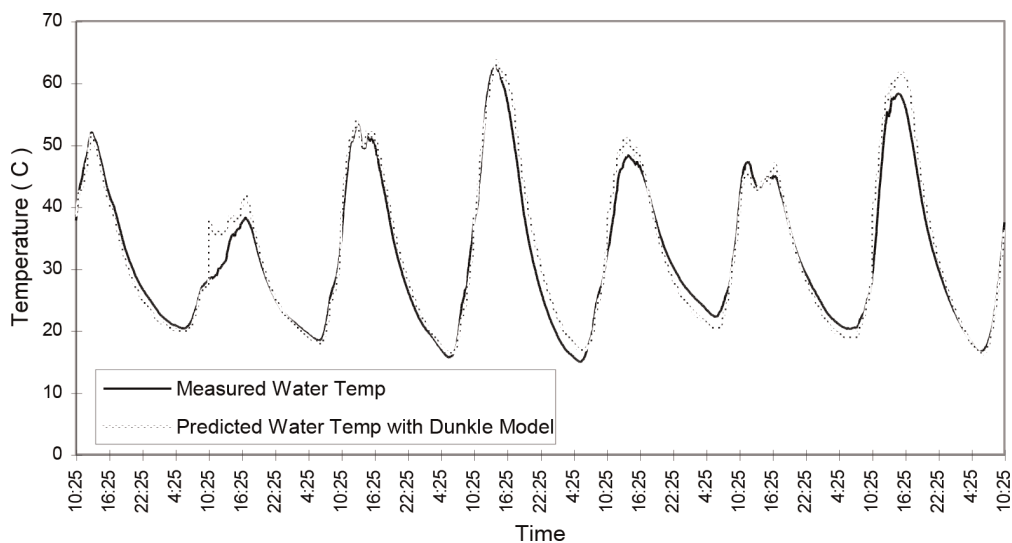


Figure 4.
The water calculated and measured temperatures in a passive solar still.

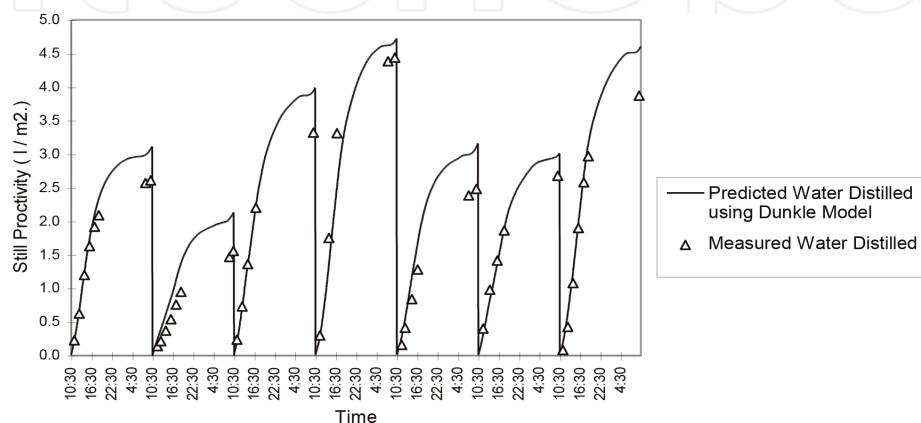


Figure 5.
The measured and predicted distillate outputs of a conventional solar still.

4.2 The active solar distillation system with external condenser and enhanced water recovery

To simulate the performance of the active distillation system, the computer program is first input with the measured weather parameters of the site and the measured values of the air entering the still's relative humidity and temperature. The results of the simulation program include still water temperature, glass temperature, basin temperature, air leaving the still temperature and relative humidity, air leaving the condenser temperature, and air leaving heat recovery's temperature and relative humidity, as well as the distillate production from the glass and from the condenser. **Figure 6** shows the measured and predicted temperatures and relative humidity of the air leaving the still, while **Figure 7** shows those of the air leaving the preheater. **Figure 8** shows the air leaving the still calculated and measured moisture content, and **Figure 9** shows the basin water calculated and measured temperatures. **Figures 10 and 11** correspondingly show the calculated and measured distillate yields from the glass and the condenser.

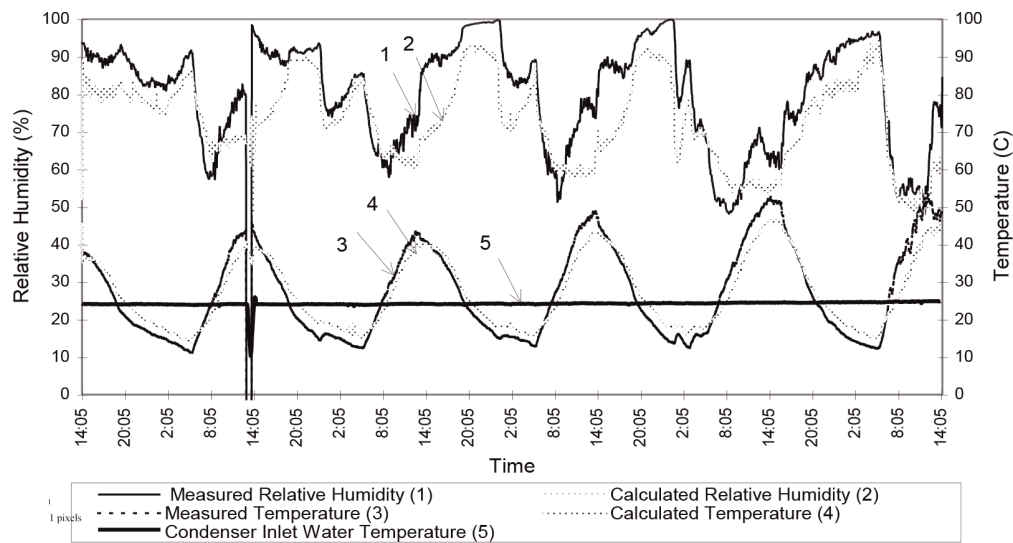


Figure 6.
The predicted and measured temperature and relative humidity of the air leaving the forced convection still.

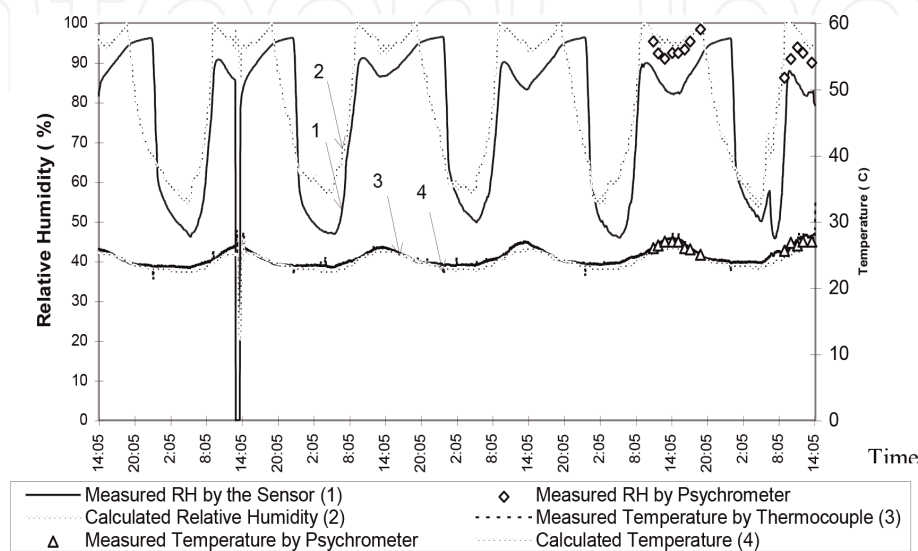


Figure 7.
The predicted and measured temperature and relative humidity of the air leaving the preheater.

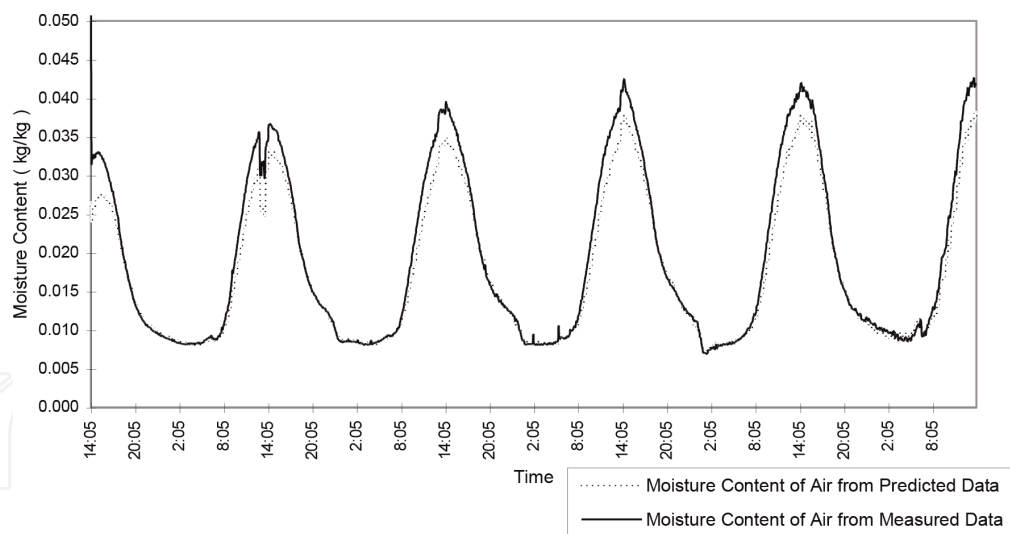


Figure 8.
The predicted and measured moisture content of the air leaving the still.

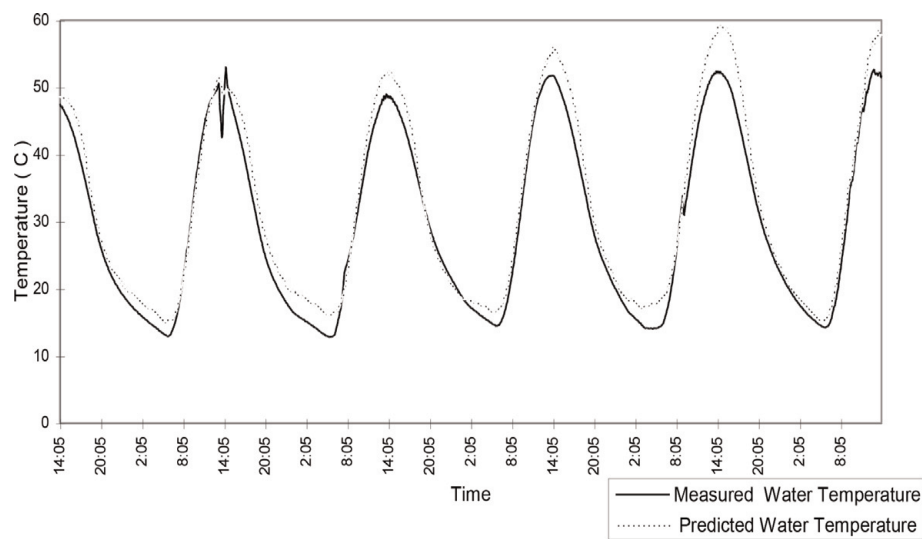


Figure 9.
The predicted and measured temperature of the water in the still.

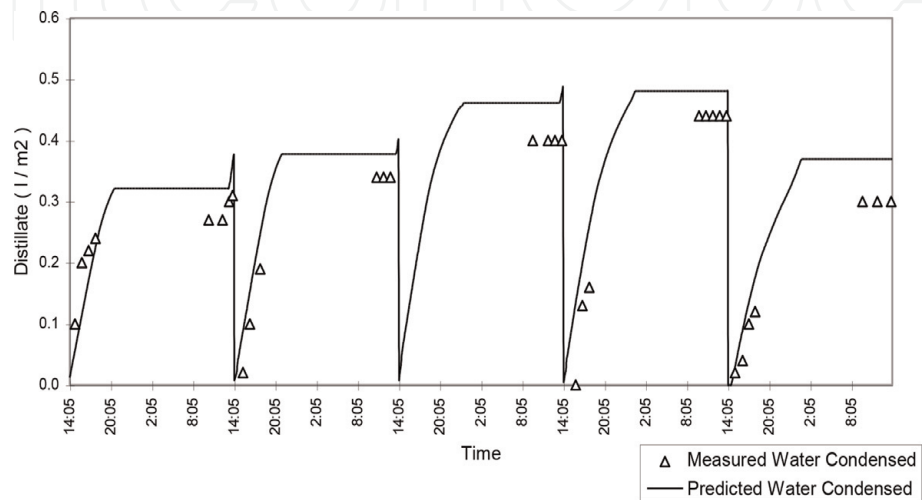


Figure 10.
The predicted and measured distillate condensed on the glass of the still.

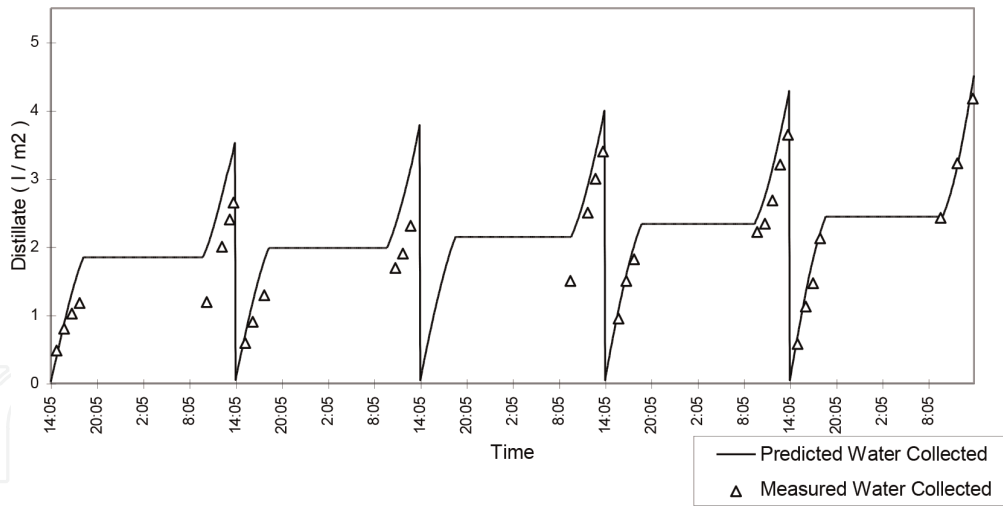


Figure 11.
The predicted and measured distillate collected from the condenser of the still.

As shown in **Figure 6**, the mathematical model can predict reasonably well both the actual values and the trend of the temperature of the air leaving the still. The maximum error of the calculated temperatures compared to measured values is 5°C and occurs in the early afternoon. The average errors in the relative humidity calculation are around 10% with maximum error values up to 20%. In most cases, the computed values are lower than the measured ones. **Figure 8** once again confirms that the mathematical model underestimates the moisture in the air leaving the still in the middle of the day. At other times, the predicted and measured computed moisture contents of the outlet air are similar, which shows the observed variations in relative humidity at these times are due to difference between the predicted and measured air temperatures.

5. Conclusion

In this chapter, a numerical model for calculating basin-type solar water distillation was presented. The model can be used to calculate solar distillation for both passive natural convection and forced convection with external condensers. For passive systems, the numerical model allows to simulate and calculate more complex parameters than previous models. For active-forced convection systems, this model allows the simulations of the heat transfer and mass process inside both the distillation unit and the internal heat exchanger. Comparison of numerical simulation results and experimental results showed that the numerical model achieves the acceptable accuracy in calculating the parameters of the fluid flow inside the distillation and the condenser-type heat recovery as well as estimation of the distillate output corresponding to both types of solar distillation.

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Author details

Nguyen The Bao
Department of Heat and Refrigeration Engineering, Faculty of Mechanical
Engineering, University of Technology, Vietnam National University of
Ho Chi Minh City, Ho Chi Minh City, Vietnam

*Address all correspondence to: drthebao@gmail.com

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