International Journal of Scientific & Engineering Research, Volume 8, Issue 10, October-2017 1648
ISSN:2229-5518

Experimental and Analytical Investigation of a Cascade Type Passive Solar Desalination System

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Abstract – Solar distillation is a process by which desalination of water is achieved in a solar still that absorbs irradiated solar energy and produces potable water by continuous evaporation and condensation process. In this research, experiments were conducted on a cascade type passive solar still, and collected field data have been used to compare system performance with a mathematical model of solar desalination process. The objective of this research is to study the physics behind solar desalination process for cascade type solar stills, compare the theoretical and experimental performance, and investigate the effect of salt deposition in the still bed. Primary investigation shows that cascade type still performs better compared to conventional stills. Findings show that the temperature profiles obtained from the mathematical model are in good agreement with data obtained during experiments. However, the hourly yield and performance predicted by the model is higher than that off experiments due to the imposed assumptions. The deposition of salts also reduces fresh water production when the still is in operation for consecutive days.

Index Terms – Mathematical model of desalination, Solar desalination, Cascade solar still, Solar still thermal performance.

1. Introduction

AVAILABILITY of fresh water has become a scarcity in the coastal regions of Bangladesh due to rising sea level, cyclones, and storm surges in the recent decades. This situation is worsening year to year as world climate is changing due to global warming. One solution to this challenge is solar desalination where potable water is produced and collected from a solar still which uses irradiated solar energy to evaporate brackish water.

Different designs of solar stills have emerged from researchers all over the world with the goal of improving the performance. The various factors affecting the performance of a solar still are solar intensity, wind velocity, ambient air temperature, free surface area of water, absorber plate area, water-glass temperature difference, temperature of inlet water, glass inclination, and water depth [1]. Among these factors solar intensity, ambient water temperature, and wind velocity cannot be controlled as they are metrological parameters. The effect of water depth and cascade design can be found in [2 – 6].

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In this research work, a cascade type passive solar still was used to experimentally evaluate solar desalination performance. A transient model [6] was used to simulate the behavior of the desalination system disregarding the spatial variation of temperatures, and comparison was carried out with the data found in the experiments. The performance of the system is also carried out using experimental data.

2. Experimental Investigation

2.1 Experimental Setup

A cascade type solar still whose absorber is made of cement concrete was used with a glass cover on the top of the still to

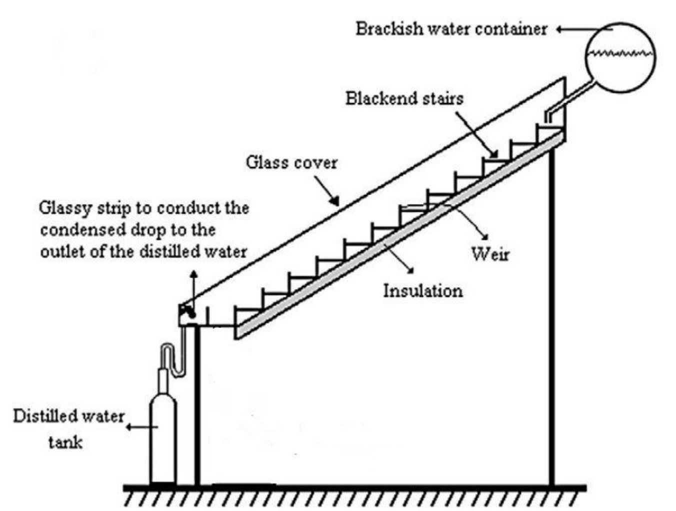

Fig.1 Schematic of the experimental setup.

construct the desalination chamber. The chamber consists of thirty steps with each step making 10° depression angle with horizontal to create water holding area. Fig. 1 shows the schematics of the experimental setup. The basin surface was painted black with a mixture of synthetic paint and black oxide so that it can absorb greater amount of radiated energy from the sun. A reservoir holding brackish water was kept above the still, and water was fed into the chamber through the inlet port situated at the middle of the top edge. To collect condensed water from the still there was an outlet at the bottom right corner together with a small window with removable glass cover to clean the dissipated salts in the still. Saw dust and cock sheet were used to insulate the still at the bottom of the device.

2.2 EXPERIMENTAL PROCEDURE

Experiments were conducted on the roof ($10\ m$ above the ground level) of Mechanical Engineering Building, Khulna University of Engineering & Technology, Bangladesh and carried out from $9:00\ am$ to $5:30\ pm$ on 13th April and from 15th April to 20th April 2017. Solar radiation, ambient temperature, and temperature of basin surface, saline water, glass cover and condensed water were measured every $30\ min$. The depth of the water in the still was kept constant during the experiments.

During the experiments J-type thermocouples were used for temperature measurement. Four thermocouples were used at the inner surface of the glass where each was placed at $20\ cm$ apart from the adjacent. Another four were used to measure saline water temperature inside the chamber, and two were used to measure the base temperature. A glass thermometer was used to measure the ambient temperature. The incoming solar radiation was measured using a pyranometer.

Table 1: Accuracies and range for various measuring instruments.

SI.no.	Instrument	Accuracy	Range
1	Pyranometer	$\pm 1\ Wm^{-2}$	$0-3000\ Wm^{-2}$
2	Thermocouple	$\pm 1\ °C$	$0-110\ °C$
3	Collection tank	$\pm 10\ ml$	$0-1000\ ml$

3. MATHEMATICAL MODEL AND ANALYSIS

The basic heat transfer process in a solar distillation unit can be classified as external and internal modes [7,8]. For a solar still, external heat transfer include heat transfer from the outer glass cover to the ambient air. The mutually independent mechanisms are conduction, convection and radiation. The heat transfer processes that take place between the water's top surface and the glass cover are categorized as internal heat transfer modes, and they include convection, evaporation, and radiation. Though evaporation depends on convection, radiation is independent of both convection and evaporation [7,8].

The analytical results are obtained by solving the simultaneous differential energy equations for the concrete absorber base, saline water, and glass cover of the solar still. Using these equations with measured solar radiation the saline water temperature, basin temperature, and glass cover temperature can be evaluated at every instant of time. The following assumptions were taken into consideration:

1. Steady state condition throughout the cascade solar still.
2. The solar still is vapor leakage proof.
3. Make up water is at atmospheric temperature and takes heat from the basin.

Energy balance for the basin [1,6],

$$I(t)A_b\alpha_b = m_bC_b\frac{dT_b}{dt} + Q_{c,b-w} + Q_{loss} \tag{1}$$

Energy balance for saline water [6],

$$I(t)A_w\alpha_w + Q_{c,b-w} = m_wC_w\frac{dT_w}{dt} + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} + Q_{fw} \tag{2}$$

Energy balance for the glass cover [6],

$$I(t)A_g\alpha_g + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} = m_gC_g\frac{dT_g}{dt} + Q_{r,g-sky} + Q_{c,g-sky} \tag{3}$$

The convective heat transfer between basin and water [6],

$$Q_{c,b-w} = h_{c,b-w}A_b(T_b - T_w) \tag{4}$$

The convective heat transfer coefficient between basin and water $h_{c,b-w}$ is taken as $95\ W/m^2K$, [7].

The heat loss by convection through the basin base to ambient is given by [6],

$$Q_{loss} = U_b(A_b + A_s) \times (T_b - T_a) \tag{5}$$

The convection heat transfer between water and glass is given by [6],

$$Q_{c,w-g} = h_{c,w-g}A_w(T_w - T_g) \tag{6}$$

where the convection heat transfer coefficient between water and glass is given by [6,7],

$$h_{c,w-g} = 0.884\left\{(T_w - T_g) + \frac{(p_w - p_g)(T_w + 273.15)}{(268900 - p_w)}\right\}^{1/3} \tag{7}$$

The values of p_w and p_g for operating temperature range of $10-90°C$ can be expressed as follows [6,7]:

$$p(T) = exp\left(25.317 - \frac{5144}{T + 273.15}\right) \tag{8}$$

The radiation heat transfer from the basin to glass cover is predicted from [6],

$$Q_{r,w-g} = \sigma\varepsilon_{wg}A_w\left[(T_w + 273.15)^4 - (T_g + 273.15)^4\right] \tag{9}$$

where

$$\varepsilon_{wg} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right)^{-1} \quad (10)$$

The evaporative heat transfer between water and glass is given by [6],

$$Q_{e,w-g} = h_{e,w-g} A_w (T_w - T_g) \quad (11)$$

The evaporative heat transfer coefficient between water and glass is given by [1,6,7],

$$h_{e,w-g} = \frac{(16.273 \times 10^{-3}) h_{c,w-g} (p_w - p_g)}{(T_w - T_g)} \quad (12)$$

The heat taken by the replaced water is estimated from [6],

$$Q_{fw} = m_e C_w (T_a - T_w) \quad (13)$$

The radiative heat transfer between glass and sky is given by [6],

$$Q_{r,g-sky} = h_{r,g-sky} A_g (T_g - T_{sky}) \quad (14)$$

The radiative heat transfer coefficient between glass and sky is given by [6],

$$h_{r,g-sky} = \frac{\sigma\varepsilon\left[(T_g + 273.15)^4 - (T_{sky} + 273.15)^4\right]}{(T_g - T_{sky})} \quad (15)$$

The sky temperature is taken as [1,6,7],

$$T_{sky} = T_a - 6 \quad (16)$$

The convective heat transfer between glass and sky, $Q_{c,g-sky}$ is given by [6],

$$Q_{c,g-sky} = h_{c,g-sky} A_g (T_g - T_{sky}) \quad (17)$$

where $h_{c,g-sky}$ is taken from [6,7],

$$h_{c,g-sky} = 2.8 + 3.0V \quad (18)$$

The hourly yield is given by the following equation,

$$\dot{m}_{ew} = h_{e,w-g}(T_w - T_g) \times \frac{3600}{h_{fg}} \quad (19)$$

The hourly efficiency of the still is given by the following equation [8],

$$\eta_d = \frac{h_{e,w-g} \times (T_w - T_g)}{I(t)} \quad (20)$$

The daily efficiency, η_d, is obtained by the summation of the hourly condensate production $\dot{m}_{ew}$, multiplied by the latent heat h_{fg}, hence the result is divide by the daily average solar radiation $I(t)$ over the whole area A of the device [1, 6 – 8]:

$$\eta_d = \frac{\sum \dot{m}_{ew} \times h_{fg}}{\sum A \times I(t)} \quad (21)$$

4. Results and Discussion

The differential equations appearing in the model were solved using ordinary differential equation solver $ode45$ available in Octave. Simulation was carried out for time $9:00\ am$ to $5:30\ pm$ with temperature initialization using the experimental data collected on 15th April, 2017. The value of the parameters used in the modeling are listed in Table 2. For evaluation of basin temperature T_b, water temperature T_w, and glass temperature T_g, the experimental measured value of solar radiation, ambient temperature, and average wind velocity of corresponding day and hour were used

Table 2: Parameter values used in theoretical calculation

Item	Mass $[kg]$	Area $[m^2]$	Specific heat $[J/kg\ K]$	Absorptivity $[-]$	Emissivity $[-]$
Basin	15.0	1.2	450	0.50	-
Water	8.0	1.4	4190	0.05	0.95
Glass	10	1.0	800	0.05	0.85

4.1 Temperature Profile and Solar Radiation

The temperature changes over time of still basin, water, and glass cover in case of both simulation and experiment are shown in Fig. 2. It is observed that the temperature profiles obtained from the mathematical model are in good agreement with data obtained during experiments. Among the three temperature profiles, the temperature of basin water T_w, predicted by the theoretical model is slightly higher than the experimental values. It is also observed that the temperatures at all points increase as the time increases

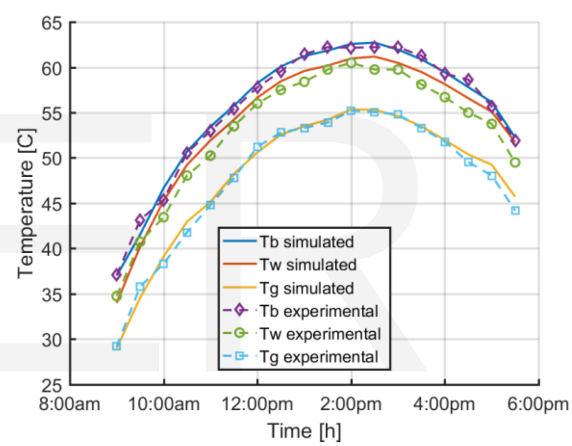

Fig.2: The experimental and simulated hourly temperature variation of cascade type passive solar still.

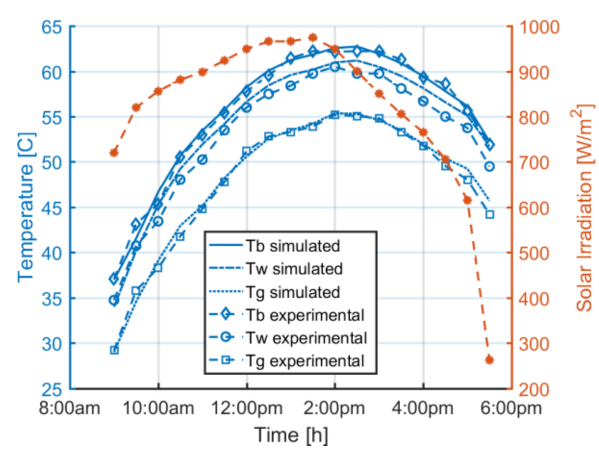

Fig.3: Hourly solar radiation with temperature profiles of cascade type passive solar still.

till a maximum value after midday and start to decrease after that. This is due to the increase of solar radiation intensity in the morning and its decrease in the afternoon.

Figure 3 shows temperature profiles with solar irradiation of that particular date. It is important to notice that though the maximum value of radiation occurred between $1:00\,pm$ to $2:00\,pm$, the maximum values of the temperature histories over time appear around $2:30\,pm$. This indicates that the material used for construction of the still, namely cement concrete, takes time to respond to the incoming solar radiation as it has higher thermal mass compared to other construction material that are commonly used for solar stills.

4.2 Water Productivity

In Fig.4, hourly fresh water production is plotted against time. The red and blue lines represent the theoretical and experimental hourly yields respectively. The results obtained from the mathematical model show somewhat smooth pattern with increase in production as the day progresses and decreases during afternoon. On the other hand, though experimental results show same pattern, the production rate does not increase or decrees monotonously.

The principal reason for this phenomena is that during the condensation process at the inner surface of the glass plate droplets tend to coagulate together and finally drop into the basin again. The condensed liquid that fail to reach

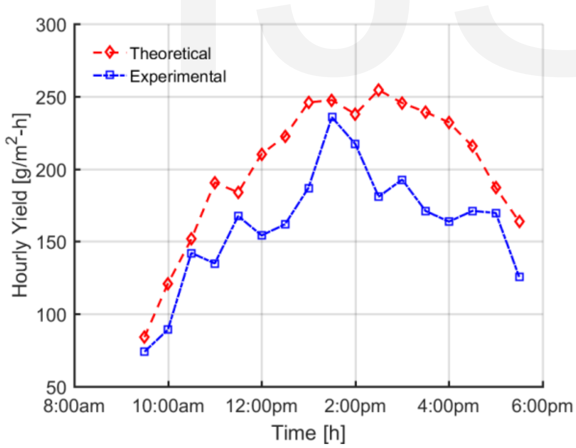

Fig.4: The theoretical and experimental variation of fresh water production of cascade type passive solar still.

the lower portion of the glass plate is not collected into the distilled water tank and further require energy to evaporate. Thus, the production of fresh water is less than the value predicted by the mathematical model.

4.3 Hourly Efficiency

The maximum theoretical hourly efficiency of the cascade solar still is found to be around 20% where experimentally it is about 18%. Figure 5 shows that as the day progresses the hourly efficiency also increases. The fluctuation in the experimental date attributes to the fact mentioned in the earlier paragraph i.e. coagulation of condensed water and falling back into the basin.

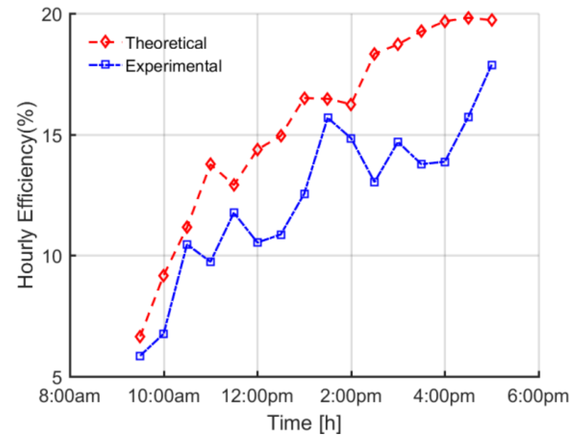

Fig.5: The theoretical and experimental hourly efficiency of cascade type passive solar still

4.4 Daily Water Production and Solar Radiation

Daily production of fresh water by the solar still is fundamentally dependent on the incoming solar radiation i.e. the weather condition of a particular day. In Fig.6 the irradiated solar energy is plotted against time for the days when experiments were conducted. As shown in the Fig.6 during the last two days of experiment availability of solar radiation was erratic for cloudy weather. Consequently, fresh water production was less as can be seen from Fig.7.

The advantage of cascade solar stills made of cement concrete is that they have higher thermal mass than other conventional materials together with durability. Due to this

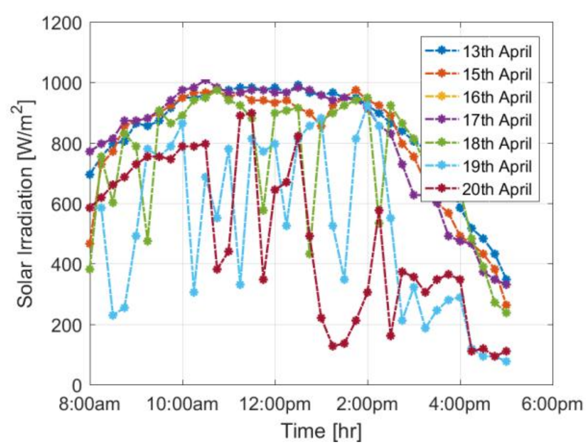

Fig.6: Recorded solar radiation of seven days of experiment.

higher thermal mass the still retains heat even after sunset, and that can produce fresh water during twilight and all through night up to dawn. The total fresh water collected each day of experiment and the corresponding available solar energy on respective day are shown in Fig.7. The total yield on a particular date consists of three parts, namely yield collected from $8:00\ am$ to $5:30\ pm$ (in grey color), from $5:30\ pm$ to $6:30\ pm$ (in blue color), and from $6:30\ pm$ to $8:00\ am$ (in yellow color).

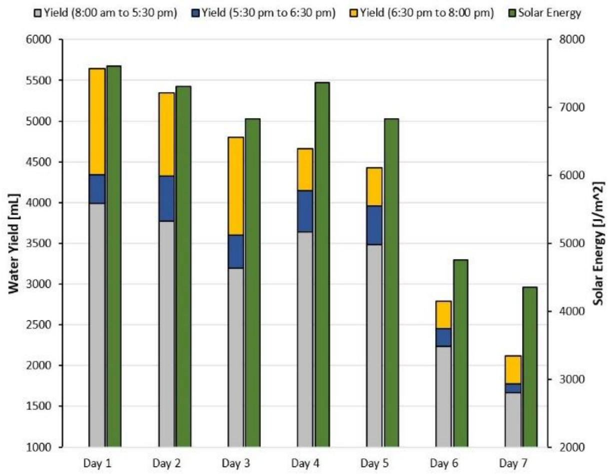

Fig.7: Total fresh water production each day of experiment and corresponding available solar energy.

One important point to notice that for the first five days the production of fresh water decreased though fluctuation in available solar energy is about $500\ J/m^2$. This decreasing trend is due to the salt deposited on the still bed, hence decreased yield performance.

5. Conclusion

The following conclusions can be drawn from the presented theoretical and experimental results:

1. Mathematical model of solar desalination process can closely predict the temperature profiles of the cascade still.
2. Though the hourly production rate and hourly efficiency of the still predicted by the theoretical model give smooth curves, experimental data shown fluctuation of these quantities as the model does not take into account the fact that some condensed water may fall back into the basin without reaching the bottom of the glass plate and into the fresh water collector tank. Another reason may be the assumptions imposed on the mathematical modelling, namely the still is vapor leakage proof where in reality it is not the case.
3. Solar stills made of cement concrete shows delayed response toward the incoming solar radiation due to its thermal mass.
4. The advantage of cascade solar stills made of cement concrete is that these are durable and can produce fresh water during night hours as they dissipate heat slowly to the ambient.
5. Salt accumulation occurs rapidly in cascade type solar still, and this affect the fresh water production.
6. In order to correctly predict the heat transfer processes inside the still a computational heat transfer model is necessary.

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NOMENCLATURE

Symbol	Meaning	Unit
A	Area	m^2
C	Specific heat	$J/kg\ K$
h	Heat transfer coefficient	W/m^2K
h_{fg}	Enthalpy of evaporation at T_w	J/kg
$I(t)$	Solar radiation on inclined surface	W/m^2
m	Mass	kg
P	Pressure	N/m^2
T	Temperature	$°C$
U	Heat loss coefficient from basin to ambient	W/m^2K
V	Wind velocity	m/s

Greeks

ε	Emissivity
α	Absorptivity
ρ	Density, kg/m^3

ISSN:2229-5518

η_d	The daily efficiency of the still
V	Wind velocity

Subscripts

a	Ambient
b	Basin
c	Convection
e	Evaporative
fw	Feed water
g	Glass
r	Radiation
w	Water