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A Computational Model for Performance Optimization of a Stepped Solar Still

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ABSTRACT
In modern times, several coastal and remote regions still face a scarcity of safe drinking water sources. Theconventional fossil fuels used for boiling the water are also running short day by day, so using renewable energy sources to purify the water is a dire need. In the present research, a computational model has been developed using appropriate equations and data, thus optimizing the solar still performs. The daily drinking water production rate still depends on several factors such as solar insolation, ambient temperature, wind velocity, etc. The production rate also depends on still size, shape, inclination angle, wick material properties, insulation system, water depth, heat-storing mediums, etc. The main challenge is the low production rate that depends on the natural conditions and still parameters. Besides, installation and maintenance costs are also the great concerns. So, the primary goal of this research is to increase the production rate and design the still as a cost-effective one. The study was conducted by using meteorological data of specific locations in Bangladesh. At first, a preliminary design of the stepped solar still was prepared by using a design software then its performance was optimized by using the computational model. Finally, it results in the final design of the solar still. Maximum distillate water achieved on a typical day of March for Dhaka city was around 4 liters by using polystyrene foam as the wick material, copper wire mesh and external reflectors. A cost estimation shows the price per liter of desalinated water is around 1.422 BDT.

Keywords: *Insolation, Stepped solar still, Reflector, Wire mesh, Heat transfer.*

1. INTRODUCTION

The worldwide growth of industries, cities, and population has led to high demand for drinking water. Solar still in many respect, is an alternative for producing drinking water for a community. However, the main challenge is the low productivity of still, ranging from 2-5 L/m^2/day and making it less economical [1]. For such reasons, various research works have been done to increase the freshwater production rate of solar stills.

According to Velmurugan et al. [2], "stepped solar stills have 98% more output over conventional stills". It has been stated in [3] that the maximum yield of 53.7% can be obtained by using a 5mm water depth tray. According to [4], "using proper cover increases productivity by 22.3 %". The analysis in [5] with cover material, found that using glass cover increases the productivity by 53% more than PVC cover. According to the analysis in [6], performance can be increased by 48% more while using reflectors.

Analysis performed in [7] using wick materials was able to yield water of around 4.28 litres/day by using coral fleece. According to the analysis in [8], the amount of freshwater production can be increased up to 85.3% by using PCM in the solar still basin.

The computational model is an alternative way to investigate the performance of a solar still without the need for any experimental models [9]. The present research aims to develop a computational model that helps in designing solar stills having a better performance compared to other stills of the same type. At first, the computational model was validated with the experimental model in reference [9]. After validation, the sensitivity analysis was done with several parameters. The still's basin is made of wood having an internal surface area of 0.6 m^2. It has 5 steps and each step has a tray made of galvanized steel. Copper wire mesh is used as a heat-storing medium with the dimensions shown in Table 1. The analysis was done for the location of Ahsanullah University of Science and Technology situated in Dhaka city. Insolation Data were obtained from PVGIS [10]. Figure 1 shows the dimension of the solar still. For a more clear understanding, an exploded view of the solar still with all important parameters is shown in Figure 4. The copper wire mesh is used as a heat-storing medium. It has high thermal conductivity and high corrosion resistance. There are in total 5 sets of copper wire mesh which every step contains a single wire mesh. The dimensions of the wire mesh are set according to the reference [11] and are given in Table 1. The dimensions of wire mesh are set in such a way that they perfectly fit inside each tray of the still. A labelled diagram of the wire mesh is shown in Figure 3. Figures 1 and 4 are the final design of the still.

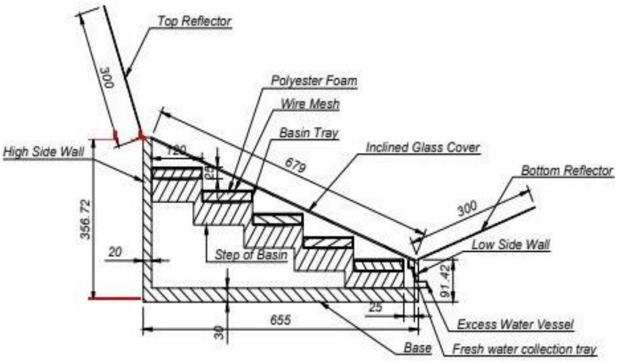

Figure 1 The Side View of Designed Solar Still (Unit in mm).

Table 1. The Copper Wire Mesh Parameters.

Parameter	Value
Material of Wire Mesh	Copper
Wire Diameter, mm	0.56
Wire to Wire Gap, mm	2.5
Length X Width, mm	996 x 118.5
Number of Wire Mesh	5

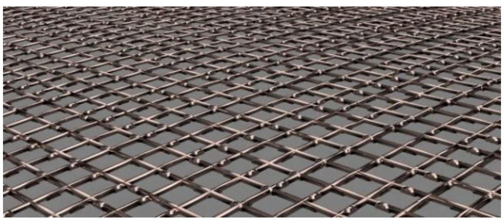

Figure 2 The Copper Wire Mesh.

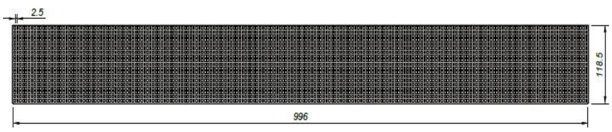

Figure 3 The Copper Wire Mesh Dimensions (Unit in mm).

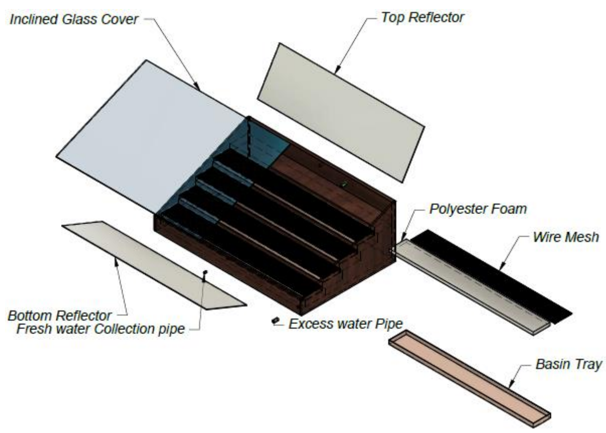

Figure 4 The Exploded View of the Solar Still.

The design was prepared according to the performance optimization result obtained from the computational analysis. The details about the computational model and final solar still design are discussed in the upcoming sections. In comparison to previously available researches, this research includes the use of wire mesh as a heat-storing medium and two external reflectors for increasing the amount of solar insolation falling on the still basin. As a result, the main objective is to increase freshwater productivity. The maximum water production of the designed solar still is around 4 litres/day during March.

2. METHODOLOGY

The present research aims to develop a computational model by using appropriate equations and data. The model will be used to design efficient solar still depending on the required output of fresh drinking water. The main steps of the research work are shown below:

- Develop the computational model using appropriate equations and data.
- Validate the developed computational model with the experimental model in reference [9].
- Do performance optimization of the solar still by using the computational model and prepare a final design.
- Do performance analysis of the final design for a specific location.

The above steps were followed in the research. The details about the whole process have been explained below.

2.1. The Computational Model

In this research, the computational model was developed by using the appropriate equations by Dunkle [12-14]. The analysis was done using the Excel spreadsheet and some important assumptions were made:

- The solar still has vaporous leakage.
- The heat capacity of the insulation system was negligible compared to the heat capacity of water [9].
- The physical qualities of water were kept constant even with temperature variation and water quality was not brought into consideration.

2.1.1. Internal Heat Transfer

The basin water in solar still evaporates due to internal heat transfer [9]. Three types of heat transfer processes taking place are convection, radiation, and evaporation. The initial basin water temperature is expressed as T_{wi}, internal glass temperature as T_{gi}, and initial basin temperature as T_{bi} [9] . All the temperatures are in (°C) and the partial pressure of water, P_w, and glass, P_g, in (Pascal) is calculated using the following equations:

$$P_w = exp(25.137 - \frac{5144}{T_{wi}-273}) \quad (1)$$

$$P_g = exp(25.137 - \frac{5144}{T_{gi}-273}) \quad (2)$$

The convective heat transfer coefficient, h_{Cwgi}, radiation heat transfer coefficient, h_{Rwgi}, and evaporative heat transfer coefficient, h_{Ewgi}, from the water surface to the glass in the unit (W/m^{2}K) are expressed as:

$$h_{Cwgi} = 0.884\left[(T_w - T_{gi}) + \frac{(P_w - P_g)(T_w + 273)}{(268,900 - P_w)}\right]^{1/3} \quad (3)$$

$$h_{Rwgi} = E_{ff}\sigma\left[\frac{(T_w + 273)^4 - (T_g + 273)^4}{(T_w + T_{gi})}\right] \quad (4)$$

$$h_{Ewgi} = 16.28 \times 10^{-3} \times h_{Cwgi}\left[\frac{(P_w - P_g)}{(T_w + T_{gi})}\right] \quad (5)$$

The equations for convective heat transfer, Q_{Cwgi}, radiation heat transfer, Q_{Rwgi}, and evaporative heat transfer, Q_{Ewgi}, in the unit (W/m^{2}K) are shown below:

$$Q_{Cwgi} = h_{Cwgi} \times (T_w - T_{gi}) \quad (6)$$

$$Q_{Rwgi} = h_{Rwgi} \times (T_w - T_{gi}) \quad (7)$$

$$Q_{Ewgi} = h_{Ewgi} \times (T_w - T_{gi}) \quad (8)$$

Stefan Boltzmann's constant, σ is 5.68 × 10^{-8} W/m^2/K^4 [9]. Effective emissivity, E_{eff}, depends on the emissivity of water, (E_w), and emissivity of glass, (E_g):

$$E_{eff} = \left(\frac{1}{E_w} + \frac{1}{E_g} - 1\right)^{-1} \quad (9)$$

Q_{Twgi}, is the total heat transfer rate. The total internal heat transfer coefficient, h_{Twgi}, [9] is shown below:

$$Q_{Twgi} = Q_{Cwgi} + Q_{Ewgi} + Q_{Rwgi} \quad (10)$$

$$h_{Twgi} = h_{Cwgi} + h_{Ewgi} + h_{Rwgi} \quad (11)$$

2.1.2. External Heat Transfer

External heat transfer takes place between the solar still and the surrounding atmosphere [9]. The convective heat transfer from glass to the atmosphere, Q_{Cgoa}, in (W/m^{2}K) is shown below and the convective heat transfer coefficient is expressed by h_{Cgoa}:

$$Q_{Cgoa} = h_{Cgoa} \times (T_g - T_a) \quad (12)$$

$$h_{Cgoa} = 2.8 + 3.0 \times V_w \quad (if\ V_w \leq 5\ m/s) \quad (13)$$

$$h_{Cgoa} = 2.8 + 3.8 \times V_w \quad (if\ V_w > 5\ m/s) \quad (14)$$

T_a, is the ambient temperature in (°C). The equation of h_{Cgoa} is used depending on the variation of wind velocity. The radiation heat transfer coefficient is defined by h_{Rgoa}, which is the radiation heat loss from glass cover to the surrounding [9]:

$$h_{Rgoa} = E_{eff}\sigma\left[\frac{(T_{go} + 273)^4 - (T_{sky} + 273)^4}{(T_{go} + T_{sky})}\right] \quad (15)$$

T_{go}, is the outer temperature of glass and T_{sky}, is the sky temperature in (°C):

$$T_{sky} = 0.0552 \times T_a^{1.5} \quad (16)$$

According to [9, 12], the total thermal loss from glass to the surrounding is calculated as shown below:

$$h_{Tgoa} = h_{Cgoa} + h_{Rgoa} \quad (17)$$

The total heat loss coefficient, U_{Tgia} in (W/m^{2}K), takes place from the glass cover to the atmosphere. The overall heat transfer between water and surrounding is expressed by, U_T:

$$U_{Tgia} = \frac{\frac{k_g}{L_g} \times h_{Tgoa}}{\frac{K_g}{L_g} + h_{Tgoa}} \quad (18)$$

$$U_T = \frac{h_{Twgi} \times U_{Tgia}}{h_{Twgi} + U_{Tgia}} \quad (19)$$

The conduction heat transfer between the basin and the surrounding atmosphere is expressed by h_b, in (W/m^{2}K) [9]:

$$h_b = \left(\frac{L_i}{K_i} + \frac{1}{h_{Tba}}\right)^{-1} \quad (20)$$

$$h_{Tba} = 5.7 + (3.8 \times V_w) \quad (21)$$

L_i, is the thickness of glass and K_i, is the insulation thermal conductivity. The overall bottom heat transfer coefficient between water and surrounding is expressed by, U_b [9, 12]. The total side heat transfer, U_{ss}, between water and surrounding is:

$$U_b = \frac{h_w \times h_b}{h_w + h_b} \quad (22)$$

$$U_{ss} = \left(\frac{A_{ss}}{A_b}\right) U_b \quad (23)$$

h_w, is the heat transfer between basin and water. A_{ss}, is the total area of sidewalls and A_b, is the internal surface area in (m^2) [9]. U_{bs}, is the bottom and side heat loss coefficient and U_{LS}, is the overall heat loss coefficient between water mass and surrounding. U_t, is the total top heat transfer coefficient between water and atmosphere [9]:

$$U_{bs} = U_b + U_s \quad (24)$$

$$U_{LS} = U_t + U_{bs} \quad (25)$$

2.1.3. Productivity, Temperature, and Insolation

The hourly water production in (litres/hour) is expressed by m_w, and the total water production amount in 24 hours is expressed as M_w. Here, L_{ev} is the latent heat of vaporization of water:

$$m_w = \frac{Q_{Ewgi}}{L_{ev}} \quad (26)$$

$$M_w = \sum_{i=1}^{24} m_w \quad (27)$$

The final temperature of the water is expressed by, T_w [9]. Due to the energy balance, the water temperature changes with time. $T_w(i)$, is the initial temperature of water:

$$T_w = \frac{f(t)}{a}(1 - e^{-at}) + T_w(i)e^{-at} \quad (28)$$

$$a = \frac{U_{LS}}{m_w \times C_w} \quad (29)$$

$$f(t) = \frac{\alpha_{eff} \times I_{eff}(t) \times U_{LS} \times T_a}{m_w \times C_w} \quad (30)$$

Effective solar absorptivity of the basin, water, and glass are α'_b, α'_w, and α'_g respectively:

$$\alpha_{eff} = \alpha'_b \times \frac{h_w}{h_w + h_b} + \alpha'_w + \alpha'_g \times \frac{h_{Twgi}}{h_{Twgi} + h_{Tgoa}} \quad (31)$$

$$\alpha'_b = \alpha_b(1 - \alpha_g)(1 - R_g)(1 - R_w) \times \left[\sum \mu_j EXP(\eta_j d_w)\right] \quad (32)$$

$$\alpha'_w = \alpha_w(1 - \alpha_g)(1 - R_g)(1 - R_w) \times \left[\sum \mu_j EXP(\eta_j d_w)\right] \quad (33)$$

$$\alpha'_g = (1 - R_g)\alpha_g \quad (34)$$

Sm_j EXP $(h_j d_w)$ is the attenuation factor that depends on the depth of the trays [9]. The final temperature of the basin, T_b, and final temperature of glass inner surface, T_g in (°C) are:

$$T_b = \frac{\alpha_b I_{eff}(t) + h_w \times T_w + h_b \times T_{bi}}{h_w + h_b} \quad (35)$$

$$T_g = \frac{\alpha_g I_{eff}(t) + h_{Twgi} \times T_w + U_{Tgia} \times T_a}{h_{Twgi} + U_{Tgia}} \quad (36)$$

In the above equations, h_w will be replaced by h_{cw}, if copper wire mesh is used [9]. $I_{eff}(t)$, is the effective solar insolation for a while. The effective solar insolation is the sum of incident insolation, $I(t)$, and the reflected insolation due to the top and bottom reflectors [15]. The effective solar insolation $I_{eff}(t)$ is expressed as:

$$I_{eff}(t) = I(t) + I_{ref_{r1}} + I_{ref_{r2}} \quad (37)$$

$$I_{ref_{r1}} = R_{Al} \times I(t) \times Sinx_1 \times Sin(\alpha - \alpha_1) \quad (38)$$

$$I_{ref_{r2}} = R_{Al} \times I(t) \times Sinx_2 \times Sin(\alpha - \alpha_2) \quad (39)$$

$$x_1 = \alpha_c + 2\alpha_1 - \alpha \quad (40)$$

$$x_2 = \alpha + 2\alpha_2 - \alpha_c \quad (41)$$

I_{refr1} and I_{refr2}, are the reflected solar insolation reaching the solar still basin from the bottom and top reflectors respectively [15]. x_1 and x_2, are the incident angles from the bottom and top reflectors respectively. α is the solar altitude angle. α_1 is the angle of the bottom reflector to the horizontal plane, and α_2 is the angle of the top reflector to the vertical plane in degrees [15].

α_c is the tilt angle of the glass cover that is equal to the latitude of this place and taken as 23 degrees with the horizon [15]. R_{Al}, is the reflectivity of aluminum sheet reflectors. The solar still efficiency can be expressed using the given equation:

$$\eta = \frac{M_w \times L_{ev}}{A_b \times I_{eff}(t) \times \Delta t} \quad (42)$$

3. RESULTS AND DISCUSSION

3.1. Validation of the Computational Model

The developed computational model was validated with the experimental model in [9]. The comparison of basin water temperature from the day time, 9:00 to 17:00 hours is shown in Figure 5:

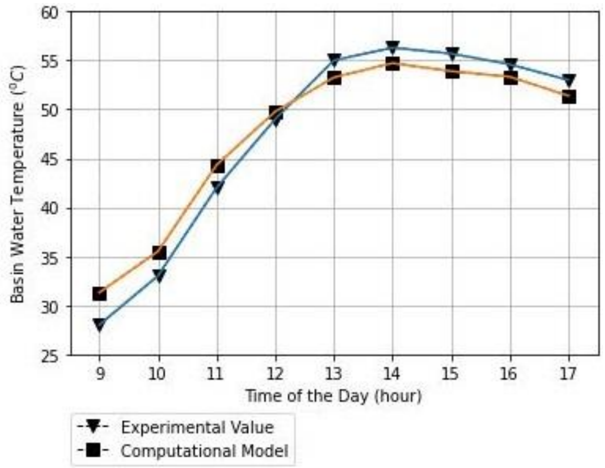

Figure 5 The Validation of the Computational Model.

The computational model gives almost similar output as the experimental model in [9]. On average, there is around a 4% difference between outputs of the experimental model and computational model.

3.2. Performance Optimization of the Solar Still

After validation, a preliminary model of the still was prepared in design software. The sensitivity analysis was done with parameters such as surface area of tray, selecting the wick material, selecting material for trays, and analysis with insulation thickness, etc. In the final design, there are 5 steps in the still basin and each contains a single tray made of galvanized steel sheet.

Galvanized steel is used as it is highly resistant to corrosion and is available in local markets. The dimensions are in Table 2. Each tray is kept in separate steps and if the solar still is fabricated then it will be easy to dismount the trays for maintenance.

The basin frame is made of wood which is a good insulating material and wall thickness is 0.05m on all sides. The internal length of the basin is 1000 mm, which is not visible in Figure 1 and the internal width is 600mm. The surface area of the basin is 0.6m^2. The internal walls of the still are painted with black spray paint to maintain a high temperature inside the still.

One of the primary goals of this research is to design a still that can last for a longer period without the replacement of any parts. For this reason, polystyrene foam is used as a wicking material. It does not have much heat-storing capacity and porosity compared to coral fleece.

Although having a low heat-storing capacity, 52.06% porosity, and 0 mm/h capillary rise, polystyrene foam takes a longer time to degrade [7]. Table 3 shows the wick material properties. Two external reflectors made of aluminium sheet are used as shown in Figures 1 and 4. The reflectors are used to enhance the amount of production by concentrating more solar insolation into the basin. Copper wire mesh is also used in the basin as it can store more heat.

Details about the copper wire mesh are shown in Table 1 and Figure 3. The copper wire mesh is placed above the polystyrene foam, to receive direct solar insolation. PVC (Polyvinyl chloride) pipe is used in the inlet and outlet of the solar still.

Table 2. The Tray Parameters.

Parameter	Value
Tray Material	Galvanized Steel Sheet
Sheet thickness, mm	1
Length X Width X Depth, mm	1000 X 120 X 25
Number of Trays	5

Table 3. The Wick Material Parameters.

Parameter	Value
Wick Material	Polystyrene Foam
Porosity, %	52.06
Capillary Rise, mm/h	0
Length X Width X Height, mm	996 X 118.5 X 20
Number of Foams	5

3.3. Performance Analysis of the Final Design

The performance analysis of the final design was done, for the location, Ahsanullah University of Science and Technology (23.7634° N, 90.4072° E) situated in Dhaka city. According to PVGIS [10] data, this location receives the most solar insolation during March and the least during June. The meteorological data sets of insolation and ambient temperature, T_a, for day time hours (7:00 to 18:00), are shown in Table 4 and 5 [10]:

Table 4. Insolation and Ambient Temperature (March).

Day Time (hour)	Solar Insolation (W/m^2)	T_a (°C)
7:00	89.32	22.85
8:00	273.42	24.89
9:00	433.5	26.94
10:00	553.56	28.49
11:00	624.27	30.04
12:00	643.42	31.59
13:00	636.91	31.85
14:00	603.31	32.11
15:00	546.42	32.37
16:00	457.02	31.09
17:00	313.05	29.82
18:00	47.37	28.54

Table 5. Insolation and Ambient Temperature (June).

Day Time (hour)	Solar Insolation (W/m^2)	T_a (°C)
7:00	35.49	26.48
8:00	58.64	27.41
9:00	120.68	28.34
10:00	195.81	29.27
11:00	261.33	29.84
12:00	274.96	30.4
13:00	284.78	30.96
14:00	273.11	30.96
15:00	227.91	30.96
16:00	226.65	30.95
17:00	194.31	30.45
18:00	129.12	29.95

Several parameters are kept fixed during the computational analysis. The fixed parameter values related to the heat transfer, glass, and insulation are given in Table 6. The performance of a still heavily depend on the amount of insolation, $I(t)$, and ambient temperature, T_a. Performance analysis only for March and June is shown for estimating the best and worst performance of the still during a year respectively.

Table 6. Fixed Parameters of the Computational Model.

Parameter	Value
Basin absorptivity, α_b	0.9
Glass absorptivity, α_g	0.05
Water reflectivity, R_w	0.05
Glass reflectivity, R_g	0.05
Aluminum reflectivity, R_{Al}	0.85
Water heat capacity, C_w	4180 J/kg K
Time, t	3600 s
Glass thermal conductivity, K_g	1.03 W/m K
Glass cover thickness, L_g	0.003 m
Insulation thermal conductivity, K_i	0.036W/m K
Insulation thickness, L_i	0.05 m
Wind velocity	2.2 m/s
h_w	250 W/m^{2}K
h_{cw}	340 W/m^{2}K

The comparison of basin water temperature during March and June from 6:00 to 18:00 hours is shown in Figure 6. The maximum temperature during March is around 45°C and the maximum temperature during June is around 38°C at around noon daily. The hourly water production from 6:00 to 18:00 is shown in Figure 7. The maximum distillate produced at around noon is 0.48 litres/hour.

Figure 8 shows the accumulated production from 6:00 to 24:00 hours. During March it is around 4 litres/day and during June it is around 1.6 litres/day. Solar stills are site-specific and Dhaka city is located in the central part of the country, receives one of the least amounts of solar insolation. So, for best performance, the still must be installed in a place that receives the highest solar insolation.

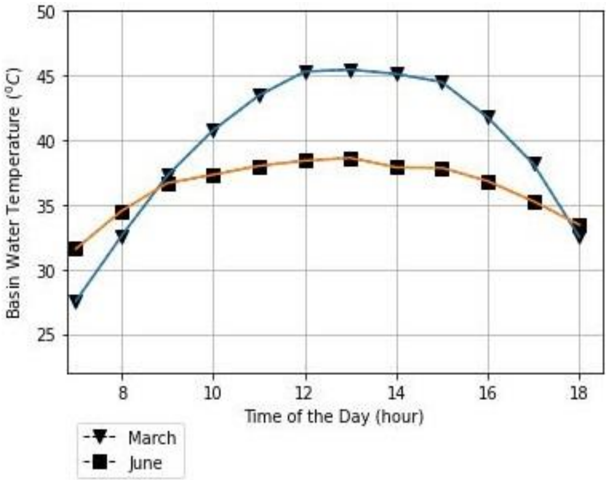

Figure 6 Basin Water Temperature, T_w, from 6:00 to 18:00 hours for this location during March and June.

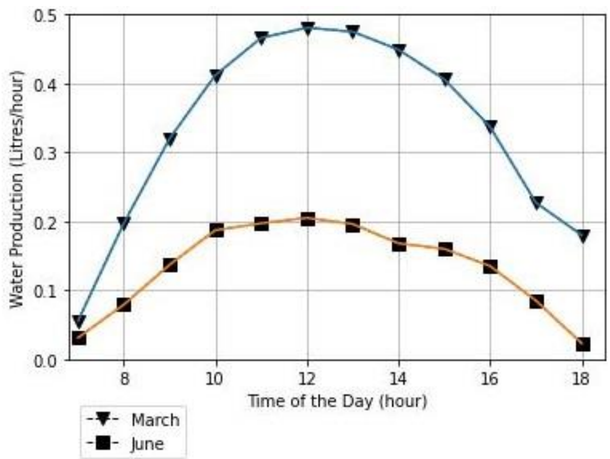

Figure 7 Hourly water production, m_w, for this location during March and June.

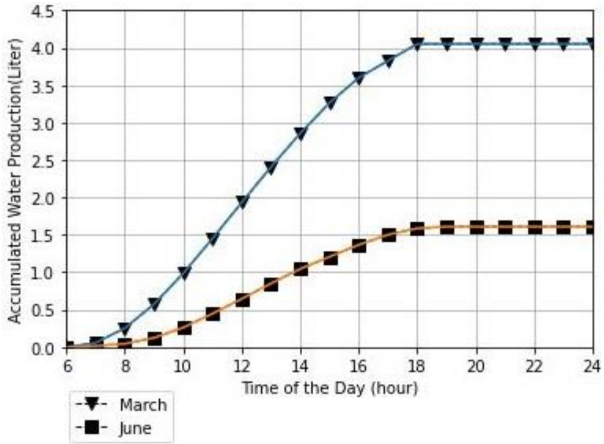

Figure 8 Accumulated water production from 6:00 to 24:00 hours, M_w, for this location during March and June.

4. CONCLUSION

The work presents the developed computational model for performance optimization of a solar still. The main goal was to increase the performance of the solar still. At first, the model was developed in an Excel spreadsheet by using the appropriate equations and data. The model was validated, and sensitivity analysis was done with several parameters, then the final design of the still was prepared. The final design consists of copper wire mesh as a heat-storing medium and two external reflectors. A performance analysis was done for a location in Dhaka city as mentioned earlier.

The performance analysis was done in March when solar insolation is the highest and in June when solar insolation is the lowest in this location. During March, the maximum yield of desalinated water production can be reached up to 4 liters/day and during June, the production rate drops down to 1.6 liters/day. The calculated average efficiency of the still is around 30%. However, a limitation of this research is that the water quality and brine desalination were not brought into consideration. A cost estimation shows the price per liter of desalinated water is around 1.422 BDT.

4.1. Future Works

In the upcoming future, the solar still can be fabricated according to the final design. The materials required for the fabrication process are available in the local markets of Bangladesh. The fabricated model can be used for the experimental analysis and the experimental results can be further compared with the computational model presented in this paper. If the experimental model performs efficiently then it will be implemented in small villages for providing fresh drinking water for the people. However, the quality of the drinking water is still a big issue that may need further analysis.

NOMENCLATURE

A_b	Basin water area (m^2)
A_{ss}	Area of side walls (m^2)
C_w	Water specific heat (kJ/kgK)
E	Emissivity
h_b	Heat transfer coefficient, basin and ambient (W/m^{2}K)
h_C	Convective heat transfer coefficient (W/m^{2}K)
h_E	Evaporative heat transfer coefficient (W/m^{2}K)
h_R	Radiation heat transfer coefficient (W/m^{2}K)
h_{Twgi}	Total heat transfer coefficient water to glass (W/m^{2}K)
h_w	Heat transfer between basin and water (W/m^{2}K)
h_{cw}	Heat transfer between wire mesh and water (W/m^{2}K)
$I(t)$	Solar Insolation (W/m^2)
K	Thermal conductivity (W/mK)
L	Thickness (m)
m_w	Hourly water production in (litres/hour)
M_w	Total water production in 24 hours (litres/day)
P_w	The partial pressure of water (Pascal)
P_g	The partial pressure of air (Pascal)
Q_{Cwgi}	Convective heat transfer rate water to glass (W/m^{2}K)
Q_{Ewgi}	Evaporative heat transfer rate water to glass (W/m^{2}K)
Q_{Rwgi}	Radiative heat transfer rate water to glass (W/m^{2}K)
Q_{Twgi}	The total heat transfer rate from water to glass (W/m^{2}K)
R	Reflectivity
T	Temperature (°C)
t	Time(s)
U_b	Heat transfer coefficient water and ambient (W/m^{2}K)
U_{bs}	Bottom and side heat loss coefficient(W/m^{2}K)
V_w	Wind velocity (m/s)
x	The incident angle from the reflectors
α	Solar absorptivity

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