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Performance Investigation of a Cascade Type Solar Still for Water Desalination

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ABSTRACT

Solar still is one of the most economical and effective way of desalinating the abundant sea/brackish water into drinking water. Solar desalination system is producing clean water from brackish water in desert regions with limited electricity. The present study concerns experimentally with the performance of cascade type solar still. The literature suggests that the addition of inside and outside reflectors, absorber materials, and outside condensers can improve the basin type solar still's absorption, evaporation, and condensation processes. It has a made a cascade type solar water desalination system. Design device is solar based and more environment friendly. This device is applicable for desalination, purification. The experimental setup for this investigation was successfully finished utilizing PVC tubing, MS sheet, black oxide, transparent glass, and a wooden frame. The output is distilled water, with a maximum volume of 130–135 ml at 12 p.m. for 16-days period from April 3, 2024 to April 18, 2024. According to the plotted graph, the amount of distilled water increased from 11 a.m. to 2 p.m. during the course of these 16 days, ranging from 80–90 ml to 100–110 ml. A few drawbacks include realistic black coating that disrupts absorption and pipe leaks. Cascade type solar water desalination system is more useful but not at the top level. So increasing its performance it has become much more productive, less costly & environmental friendly other conventional solar desalination system.

Keywords: Solar Still, Solar Desalination, Transparent Glass, Brackish Water, Distilled Water

1. Introduction

Food, clean air, and drinkable water are all essentials for human survival. The aforementioned resources are necessary for the survival and advancement of the human species on this planet. The society overuses these limited resources carelessly in the name of economic development and civilization. One of them is the decreasing availability of clean drinking water on a daily basis. Furthermore, as the population grows, the demand for water rapidly increases, expansion of agriculture, and industrialization. It is anticipated that the world's most pressing issue going forward will be a scarcity of clean drinking water. The majority of people get their water from underground water reserves, lakes, ponds, and rivers. But because of the excessive pollution in this water, waterborne illnesses are spreading. Increasing the amount of water available is therefore a pressing social need.

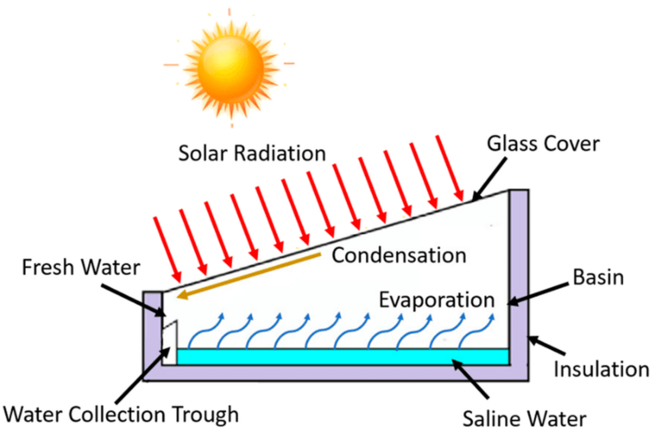

Fig.1: Schematic view of a Basin Type Solar Still. [1]

A.E. Kabeel [1] reported that, improvement of stepped basin which performance of solar still had been done. In this paper, two types like conventional still & stepped still had been investigated & carried out a result that the output distilled water of stepped solar still is higher than conventional solar still.

Badran [2] had been studied that, basin type single slope solar still whose performance depends on reducing water depth is the impact of increasing daily productivity El- Sebaii [3] had been studied that by changing phase the daily productivity should be increased 85.3%.

The current research scenario to preserve the diminishing traditional sources of energy is the harvesting and storage of renewable energy. A device called a solar still uses sun energy to desalinate brackish or seawater. For desalination, seawater or brackish water is placed in an absorber basin within the solar still. The incoming solar radiation heats the water in the absorber basin, causing it to evaporate onto the glass cover. Due to temperature differences, the evaporated vapor on the glass cover condenses, and the condensed vapor is collected as pure water via a collecting channel.

Esfahani et al. [4] used a solar collector, black wool wall, water sprinkling system, and thermoelectric cooling device to create a portable still with increased evaporation and water condensation. The study found that while ambient temperature and solar radiation directly impact still performance, increasing wind speed led to decreasing water productivity. The study found a maximum efficiency of 13% and an average daily productivity of 1.2 L/m2 during winter. A theoretical framework was used to evaluate the

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effectiveness of three thermal management strategies: a spectrally selective absorber, a convection cover, and a conduction barrier. The analysis showed that inadequate thermal insulation leads to over a 75% decrease in solar-vapor conversion efficiency [5].

Advanced, non-conventional water treatment methods are deemed crucial for addressing the escalating water scarcity challenge. The IDA Water Security Handbook, released in January 2019, provides the latest market insights into global desalination and water reuse trends. According to this report, jointly published by the International Desalination Association (IDA) and Global Water Intelligence (GWI), the seawater desalination market is projected to witness its most dynamic growth since the late 2000s [6].

In Chile, the purpose is to examine the country's current and prospective desalination capacity, as well as key technical challenges, environmental difficulties, and economic aspects of the desalination industry. The present position is determined by doing an inventory of the industrial scale and reviewing scientific publications on the subject published through 2018. Chile has eleven industrial-scale desalination units that produce a total of 5,868 liters per second of desalinated water. Furthermore, eleven desalination projects are in various stages of study, with the potential to increase desalination capacity by 116.5% to 12,706 l/s over the next few years [7].

The global market for water desalination equipment is predicted to develop at a 7.1% CAGR from 2020 to 2028.Increased urbanization, population expansion, and developing water shortages in many regions of the world are likely to drive up demand for water desalination technology throughout the forecast period. The COVID-19 epidemic forced the closure of numerous construction and manufacturing facilities in 2020, lowering demand for water desalination equipment. However, as the world returns to normalcy in the first half of 2021, the need for water desalination technology is predicted to soar as governments throughout the globe look to invest in water treatment technologies [8].

According to the 2018 Water Statistics Report in GCC Countries, Saudi Arabia's average municipal water use per capita is 270 l/day. It means that for 1 million citizens, we need to establish a water desalination plant with a capacity of 270,000 m3/day [9].

The literature analysis suggests that the stepped solar still is a viable structure, but requires more changes to improve productivity and efficiency. Despite the steps solar stills can be modified with internal and exterior reflectors, copper fins, and clear step trays to efficiently reach all saline water levels. However, no experiments have been conducted on this combination. This study investigated that successfully finished utilizing PVC tubing, MS sheet, black oxide, transparent glass, and a wooden frame.

2. Methodology

2.1 Design of Solar Distillation device

Various equations and parameters for the experiment had been determined here. Area calculations for the solar still, energy balance for the water mass within the solar still, and the heat balance equation for the basin water can be formulated as follows:

$$I_1 + Q_b + C_w \frac{dT_w}{dt} = Q_{cw} + Q_{rw} + Q_{ew} + I_2$$

Where,

Q_b= Heat transfer through convection between the basin and the water

C_w= The thermal capacity of the basin water.

T_w= The basin water temperature

Q_{ew} = Heat transfer through evaporation through the water to the glass

Q_{rw}= Heat transfer of thermal radiation through water to glass

Q_{cw}= Heat transfer of convection through water to glass

I_1= The solar radiance reaching the water surface after passing through the glass

I_2 = The solar radiance reaching the basin liner after passing through the surface

I_1 & I_2 ,it can be expressed as,

$$I_1 = (1 - \alpha_g)I$$
$$I_2 = (1 - \alpha_g)(1 - \alpha_w)I$$

Where,

α_g= The glass radiation absorptivity

α_w=The water radiation absorptivity

I= The solar intensity available

Radiation heat transmission happens through the water surface towards the glass cover. From Stefan Boltzmann's law,

$$Q_{rw} = h_{rw} A_w (T_w - T_g) = \varepsilon_{\text{eff}} A_w \sigma (T_w^4 - T_g^4)$$
$$h_{rw} = \varepsilon_{\text{eff}} \sigma \left((T_w^2 - T_g^2)(T_w^2 + T_g^2) \right)$$

Where,

h_{rw} = the radiation heat transfer co-efficient through water to glass

A_w= Basin water Cross sectional Area

T_g= Stefan Boltzmanns Constant=5.67*10^{-8} K

ε_{eff} = Effective emittance between water surface and glass cover

The heat transfer rate towards the water surface to the glass via convection through the humid air in an upward direction,

$$Q_{cw} = h_{cw} A_w (T_w - T_g)$$

The Rate of heat loss reason behind to evaporation can be expressed as,

$$Q_{ew} = h_{ew} A_w (T_w - T_g)$$

Where,

h_{cw}=The heat transfer co-efficient of Convection

h_{ew}=The heat transfer co-efficient of Evaporation

The glass cover Energy Balance

Equations on heat balance of the glass cover,

$$Q_{rg} + Q_{cg} + I_1 = I + Q_{ew} + Q_{rw} + Q_{cw}$$

Where,

Q_{cg} = The heat transfer of convection from glass to atmosphere

I= Solar radiation reaching on the still

Q_{rg} =The Radiation heat transfer from glass to atmosphere

Here, Q_{rg} can be defined as,

$$Q_{rg} = \varepsilon_g A_g \sigma(T_g^4 - T_s^4) = h_{rg} A_g (T_g - T_a)$$

Where,

A_g=The glass exposed surface area towards atmosphere

h_{rg}= Heat transfer co-efficient of radiation towards glass to atmosphere

T_a = Atmospheric Temperature

T_s= Sky Temperature

Through the glass to ambient, the convective heat transfer is,

$$Q_{cg} = h_{cg} A_g (T_g - T_a)$$

Heat balance equation on basin liner

$$I = Q_b + Q_{bot}$$

Where,'

Q_{bot} = Heat transfer towards the basin liner to the atmosphere through bottom surface

Then,

$$Q_{bot} = U_{bot} A_b (T_b - T_a)$$

Whereas,

U_{bot}= Overall heat transfer co-efficient through water basin liner to the atmosphere

Through the basin liner to the water the convection heat transfer is,

$$Q_b = h_b A_b (T_b - T_w)$$

Where,

h_b= Convection heat transfer coefficient through basin liner to water

So the equation of the water of input,

$$m_w = \frac{A_w Q_{ew} \times 3600}{h_{fg}}$$

By using this equation and assume factor of safety 1.4

tanα= Perpendicular/Base

= 64/149 Cm

So, α=24.73 °

The top surface of a basin type solar desalination plant is inclined at 25 degrees in a tapered form box arrangement. The slanted glass surface is 148 cm × 54 cm in size. The surface facing the sun is 10 cm in height, and the backside of the arrangement is 74 cm in height.

2.2 Theoretical Calculation

Here, numerous equations had been derived for the theoretical design of the experiment. Then it proceeds through,

Total Energy= Solar Intensity × Surface Area

Where,

Solar Intensity= 800 w/m^2

Surface Area= Length × width

= 150×60 cm^2

= 0.9 m^2

Total Energy= 720 W

The solar still efficiency is expressed as, [10]

$n_e = \frac{Qevp}{I} \times 100\%$............................(1)

Where,

h_{ew}= Radiation heat transfer co-efficient through water to glass cover

I = Solar intensity at an average time

Δt =Glass cover & basin water temperature difference

The distilled water can be expressed as, [11]

$M_w = \frac{h_{ew}(T\omega - T_g) \times 1900}{L_{eV}}$……………………….(2)

Where,

h_{ew}= Radiative heat transfer co-efficient through water to glass cover

T_ω= Basin water temperature

T_g = Glass cover temperature

The evaporative heat transfer co-efficient as expressed as,[12]

$h_{ew} = \frac{16.28 * 10^{-3} \times h_{cw}(p_\omega - p_g)}{(T_\omega - T_g)}$ ……………………….(3)

Where,

h_{cw}= Convective heat transfer co-efficient

p_ω = Partial saturated vapor pressure at basin water temperature

p_g = Partial Saturated vapor pressure at glass cover temperature

Equations of convective heat transfer co-efficient, [12,13]

$h_{cw} = 0.884 \sqrt[3]{[(T_\omega - T_g) + \frac{(p_\omega - p_g)(T_\omega + 273)}{(268.9 * 10^3 - p_\omega)}]}$………(4)

p_ω=EXP [25.317-$\frac{5144}{(T_\omega + 273)}$] ……………………….(5)

p_g=EXP [25.317-$\frac{5144}{(T_g + 273)}$] ……………………...(6)

Assume that,

T_ω= 60 °Celsius

T_g= 49 °Celsius

So, Putting this value of equations (5) & (6) respectively,

p_ω= 19332.687 N/m^2

p_g= 11405.429 N/m^2

Putting the value of $T_\omega, T_g, p_\omega, p_g$ in Equations (4),

h_{cw} =2.461 W//m^2C

Then Putting value of $h_{cw}, T_\omega, T_g, p_\omega, p_g$ In Equations (3),

h_{ew}=28.874 W/m^2C

At, basin water temperature=60 degree Celsius

We Know, water heat of vaporization=2357.7 kJ/kg

From Equations (2),

M_w=0.25596 kg/$\frac{m^2}{h}$

3.Experimental setup

3.1 Cascade Type solar desalination device

The top surface of a basin type solar desalination plant is inclined at 25 degrees in a tapered form box arrangement. The entire box is composed of glass, including the slanted upper surface, with a thickness of 5mm.The slanted glass surface is 148 cm × 54 cm in size. The surface facing the sun is 10 cm in height, and the backside of the arrangement is 74 cm in height. A water collection pipe was placed on the bottom side of the upper surface, and an input pipe was positioned on the upper edge of the backside.

3.2 CAD Model

In this CAD Model in the inlet pipe water goes in and then water flows through staircase and then expected distilled water had been found.

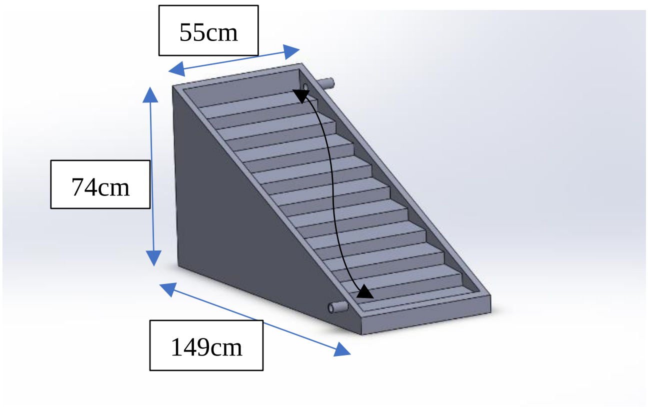

Fig.2: Schematic view of the Cascade type solar water desalination device.

3.3 Construction Materials and Quantity:

For the construction purpose, numerous equipment had been gathered for the fulfillment of the construction. Here one piece of collector (Transparent glass) is needed to construct this device. As absorber needed MS sheet and black oxide (200gm) to absorb heat. As insulation system the cotton is needed with 3000gm.To supply water two pieces PVC pipe and five pieces M seal needed.

3.4 Experimental setup:

A clear glass had been put between a wooden frame on a basin type plant. The diagram depicts the project's entire setup. The basin type plant's outflow pipe is on the right side.

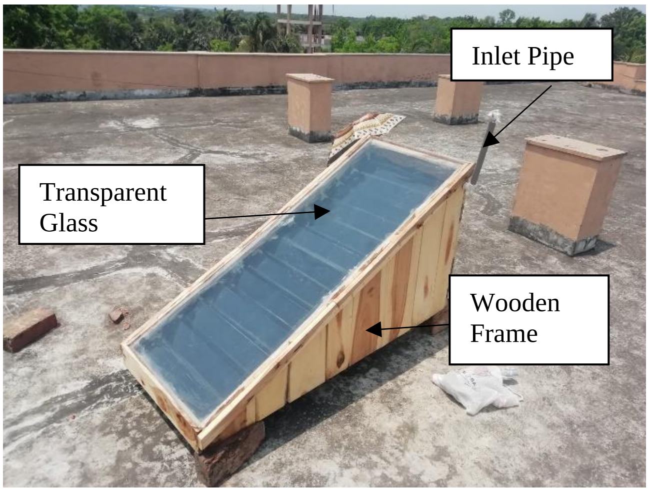

Fig.3: Photographic diagram of complete setup of the Cascade type solar desalination device

4. Results and Discussions

It had been found that several factors, such as solar radiation, ambient temperature, basin water temperature, and glass surface temperature, affect the efficiency of basin-type solar water desalination. It was found that in order to maximize the intensity of the sun, more distilled water produced.

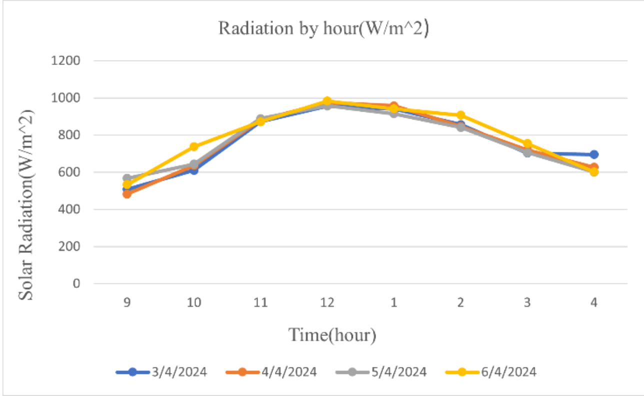

Fig.4: Variation of hourly radiation in 3,4,5,6/04/2024

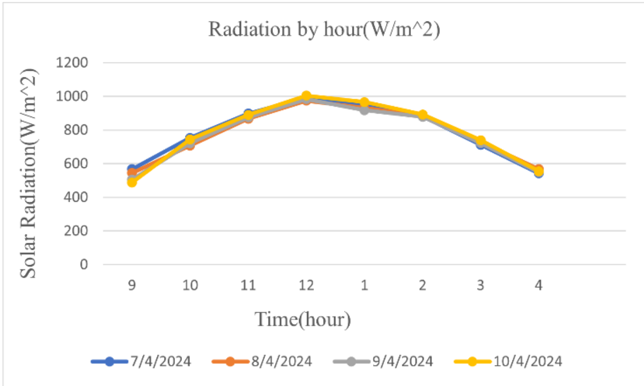

Fig.5: Variation of hourly radiation in 7,8,9,10/04/2024

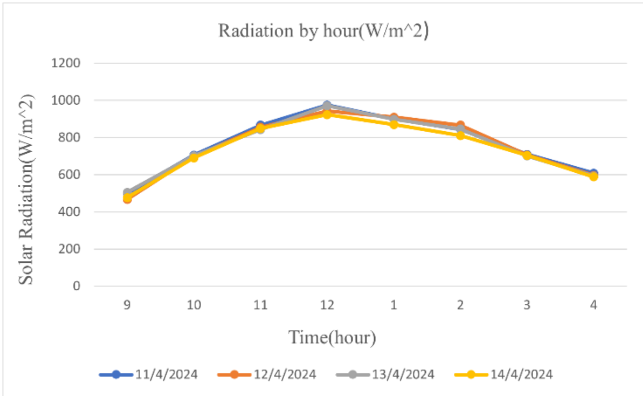

Fig.6: Variation of hourly radiation in 11,12,13,14/04/2024

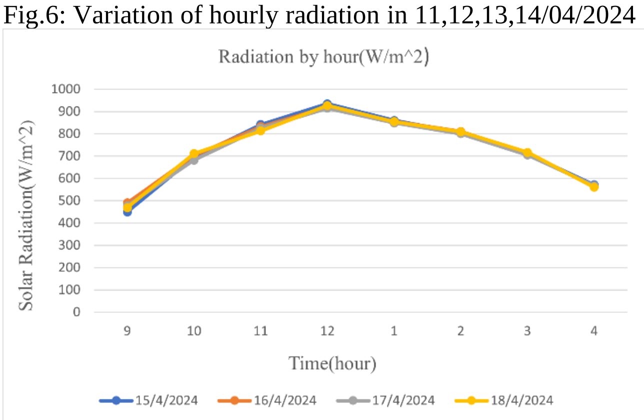

Fig.7: Variation of hourly radiation in 15,16,17,18/04/2024

Table 1: Data table for distilled water per hour

Date	Distilled water per hour(ml/hr)							
	9.0	10.0	11.0	12.0	1.0	2.0	3.0	4.0
3/4/2024	0	75	103	130	117	90	50	25
4/4/2024	0	83	110	135	110	95	55	15
5/4/2024	0	77	117	150	100	87	45	10
6/4/2024	0	89	106	122	105	97	40	10
7/4/2024	0	71	115	130	108	80	40	12
8/4/2024	0	73	117	125	104	85	45	14
9/4/2024	0	80	104	115	105	85	48	12
10/4/2024	0	78	108	125	100	90	45	15
11/4/2024	0	75	105	110	95	84	45	10
12/4/2024	0	70	103	107	90	80	38	10
13/4/2024	0	80	107	115	98	85	40	15
14/4/2024	0	65	95	105	85	75	35	10
15/4/2024	0	70	100	110	95	85	40	15
16/4/2024	0	65	90	100	90	75	30	10
17/4/2024	0	60	85	95	80	65	25	15
18/4/2024	0	55	80	100	85	60	30	10

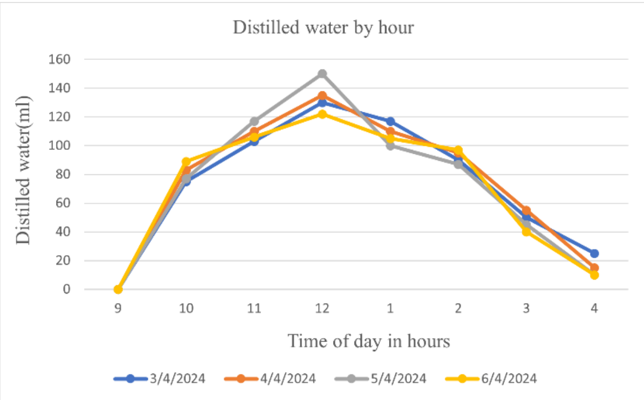

Fig.8: Variation of hourly distilled water in 03/04/2024 to 06/04/2024

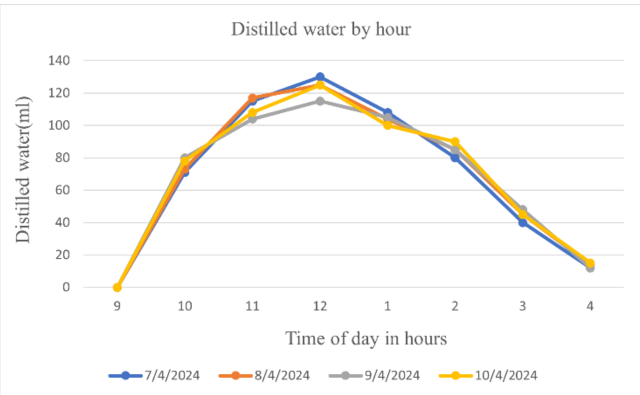

Fig.9: Variation of hourly distilled water in 07/04/2024 to 10/04/2024

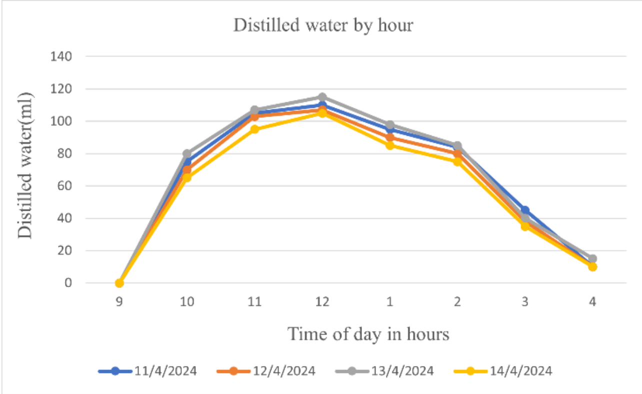

Fig.10: Variation of hourly distilled water in 11/04/2024 to 14/04/2024

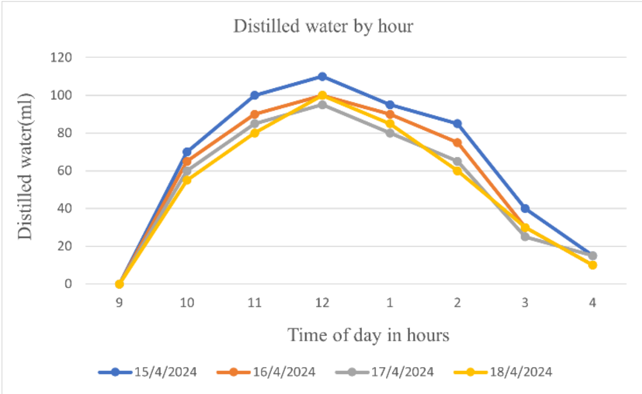

Fig.11: Variation of hourly distilled water in 15/04/2024 to 18/04/2024

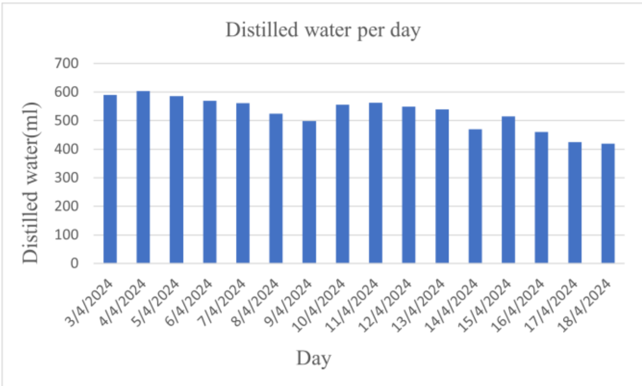

Fig.12: Variation of total distilled water per day

The temperature rises during the day from its lowest to its maximum point. The daily distilled water variation per hour in Khulna was calculated between April 3 and April 18 of 2024. Here various graph had been plotted between distilled water per hour vs time of day in hour. In these graphs, from 10 A.M to 2 P.M more distilled water had been found. The change of distilled water per hour over numerous days in Khulna had been depicted in Figures 8 to 11 The temperature differential between the glass surface and the basin water had been determined to be 10-15 degrees Celsius on average. Because of the solar intensity, both temperatures climbed and fell in a similar fashion. The evaporative and convective heat transfer coefficients had been discovered in this study. From 3rd April 2024 to 18th April 2024 between 16 days the highest distilled water had been collected as 150 ml at 12 p.m. Between these 16 days the average highest distilled water had been collected as 130-135 ml. It had been seen that between 8 to 11 graphs distilled water had been decreased from 2.30 P.M because the solar intensity had been lowered, so ultimately impact for the distilled water. The evaporative and convective heat transfer coefficient had been discovered in this study. Among these 16 days the average highest distilled water had been collected as 130-135 ml per hour. Pipe leakage had been one of the drawbacks that's why calculated distilled water had not been gathered in the experiment. Another drawbacks had been the black coating had not been accurate black surface that absorbed solar radiation properly.

5. Conclusion

This project's major goal had been designed a system for enhancing the performance of current basin-type solar desalination plants. It had been a few days since the performance review began. Eventually, the sun was available for long enough to gather data, despite the fact that the availability of solar radiation had been a major issue. According to the data table, graphical representations, and tabular findings, the absorber plate was formed in a stepped shape to demonstrate the effectiveness of a basin type solar desalination plant. Due to the substantially reduced solar intensity throughout the winter, distilled water was not found as anticipated. Due to the projected solar intensity, distilled water was discovered throughout the summer. For the further research & development this project, the following recommendation can be considered

a) Some External heat source like parabolic solar collector can be used for better performance.
b) Transparent glass can be poured with cold water where more condensing can be occurred, so better output can be found.

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