An Experimental Investigation on an Inclined Solar Distiller with a Stepped-Corrugated Absorber and Evacuated Tubes

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Abstract- Everyone should have access to water since it is one of the necessities for survival. Renewable energy-based desalination is gaining popularity over other methods because it seems to be a viable technology for low-cost desalination that can support long-term expansion. It is necessary since alternative water purifying procedures use much more energy. This paper discusses how testing on two different adjusted circumstances in solar still resulted in increased production and competency. The experiments were carried out to assess the cumulative yield and competence in Case: 1, which was the slanted solar still with corrugated fins and stepped absorber. The same design was paired with vacuum tubes in Case: 2. Experimental results show that the cumulative yield for Case: 2 was 4.7 kg/m^2/day, more significant than the cumulative yield for Case:1, which was 3.82 kg/m^2/day. The energy efficiency in Case: 2 was 46.72%, and 39.98% in Case-1. The combined arrangement of solar still and vacuum tubes generated 23.0% more fresh output than the version without vacuum tubes. According to experimental data, the functioning of the solar still had a long way to go in Case: 2. The findings showed that vacuum tubes with slanted solar panels with stepped absorbers and corrugated fins might significantly boost productivity and efficiency.

Keywords Evacuated Tube; Inclined Solar Still; Solar Distillation; Solar Energy; Stepped Absorber; Water Productivity.

Nomenclature

A	Accuracy of the measurement devices
A (m^2)	Size of surface
A (Rs)	Total annual cost
AMC (Rs)	Annually operating and maintenance cost
ASV (Rs)	Annual salvage value
C (J/kg^{0}C)	Heat Capacity
CF	Cash flow
CPL (Rs)	Cost of freshwater per litre
CRF	Capital recovery factor
CS (Rs)	The total cost of still
FAC (Rs)	First annual cost
g (m/s^2)	Gravity
Gr	Grashoff number
h (W/m^{2o}C)	Overall heat transfer coefficient
h_1 (W/m^{2o}C)	Basin raw water-absorber plate convective heat transfer coefficient
h_2 (W/m^{2o}C)	Heat transfer coefficient between raw water and glass cover interior.
h_{fg} (J/kg)	Latent heat of evaporation of brackish water
İ	Interest rate

I(t) (W/m^2)	The intensity of solar radiation
I_{on} (W/m^2)	Solar radiation on a surface perpendicular to Earth's atmosphere
Ir (W)	Irreversibility
k (W/m^oC)	Thermal conductivity
L	Yearly freshwater output
m (kg)	Mass
m (kg/min)	Mass flow rate
m_{ew} (kg/m^2h)	Freshwater output per hour
N	Working days per year
n (year)	Solar still life
P (Pa)	Vapour partial pressure
Pr	Prandtl number
S	Salvage value
SFF	Sinking fund factor
T (^oC)	Temperature
U	Unreliability in measurement devices
U ($W/m^{2o}C$)	The overall coefficient of heat loss
UNO	United Nations Organisation
V (m/s)	Wind velocity
WHO	World Health Organisation

Subscripts

A	Ambient
B	Black
C	Convection
Des	Destruction
E	Evaporation
g	Glass
I	Liquid
In	Inlet
Ins	Insulation
loss	Loss
out	Out
P	Absorber plate
R	Radiation
S	Solid, sky
Sun	Sun
T	Top
Th	Thermal
V	Humid air
W	Raw water

Greeks

α	Coefficient of absorption
ρ	Coefficient of reflection
σ (W/m^2K^4)	Stefan-Boltzmann constant
η (%)	Efficiency
θ (Degree)	Zenith angle
β (Degree)	The inclination of the condenser glass cover
β (K^{-1})	Coefficient of cubical expansion
ρ (kg/m^3)	Density
τ_b	Beam radiation transmittance
τ_d	The transmission coefficient of diffuse radiation
ε_{eff}	Water surface and glass cover effective emissivity
ΔT (^oC)	Temperature difference
θz (Degree)	The inclination angle amongst condenser glass cover and solar irradiation
μ ($N\text{-}s/m^2$)	Fluid viscosity

1. Introduction

Every person should be able to access water since it is one of the most fundamental needs for maintaining life. Governments around the globe have initiated several initiatives to guarantee that every person can obtain harmless and fresh drinking water. The effectiveness of the water system is contingent on factors such as the availability of groundwater, consumption and distribution levels, water quality, patterns of usage, and institutional structures governing maintenance and operation [1] [2]. There have been instances in which pertinent policies have been created, and various programs have been implemented to solve the difficulty of providing clean drinking water to families dwelling in rural and urban regions. This challenge has been addressed in several different ways. These examples can be found in many parts of the world [3] [4]. In an area experiencing a water shortage, ensuring an adequate potable water supply is frequently complicated by its unfavourable geographic character and climatic circumstances, making it a difficult challenge.

If it fulfils the numerous parameters suggested by WHO for the quality of drinking water, it can be declared appropriate for consumption. The TDS level is the most crucial factor in determining water quality worldwide. Total dissolved solids (TDS) concentration pertains to the quantity of cations and anions in a dissolved state within the water. TDS in water can arise from various sources such as natural occurrences, sewage, urban runoff, industrial wastewater, or chemicals introduced during water treatment. All these are plausible origins of the substance. According to the Indian Standard (IS) for drinking water quality, the maximum amount of TDS that should exist in water is 500 mg/l. If the presence of TDS in the water is above 1000 mg/l, it is unsafe for human consumption and is not recommended for any consumption. Long-term water use with high TDS can cause various chronic health issues, including cancer, renal failure, nervous system disorder, liver difficulties, and loss of immunity [5].

Numerous studies have concluded that there are needs to be run active programs at the national level to ensure that all of the residents in water-stressed states must have access to safe drinking water [6] [7]. In many locations, efforts are made at both the centralised and the decentralised levels to purify the water and supply it to citizens. It is done to provide people with clean water for daily consumption. Despite the efforts of several different agencies, it has not yet been made feasible to solve the problem of providing clean drinking water to every individual in part of the country due to vast and different geographical conditions [8] [9].

1.1 Renewable Energy

The term "renewable energy" (RE) refers to a category of natural energy resources that can be readily converted into other forms of usable energy. There are many different types of natural energy resources. Solar, wind, biological, and hydrological activities, as well as geothermal and hydrothermal activities, all fall under this energy category. The rapid introduction of renewable energy sources may be attributed to the fact that fossil fuel resources are being exhausted at an alarming rate, which in turn is contributing to weather variation and distributing the atmosphere. The fact that unconventional energy sources may be implemented extensively and extended by utilising various technologies is another significant element growing the deployment of RE sources [10] [11].

The amount of water available on the planet is vast, including surface water like reservoirs, lakes and rivers, and groundwater stored beneath the earth’s surface. However, such water is unfit for human consumption without treatment or purification [12]. Therefore, we must use green energy sources to disinfect this water. Solar desalination systems are a technology that uses renewable solar energy widely available to extract salt and impurities from seawater or brackish water, thereby generating clean and fresh water. This technology is particularly advantageous for communities residing in arid areas with a shortage of freshwater resources. Solar desalination systems that use renewable energy are suitable for the environment since these systems drastically cut back on emissions of greenhouse gases and contribute to the fight against climate change [13]. Additionally, solar desalination systems offer an economical solution since they do not require fuel or electricity input, reducing the expenses incurred in running and maintaining them thoroughly [14].

Solar distillers like this one provide a number of benefits, some of which include an uncomplicated design, low initial expenses for installation, and the capacity to produce water on their own [15] [16] [17]. Additionally, they are quite simple to maintain. However, they also have a variety of drawbacks, some of which include limited efficiency as well as the accumulation of salt, scale, and rust. In a properly constructed system, the water should not be heated in any way. It is important to minimize the amount of heat that escapes from the panels and the tank in order to prevent inadequate heating. On the other hand, when the sun's strength is low, it produces an unsatisfactory outcome for the system [18] [19].

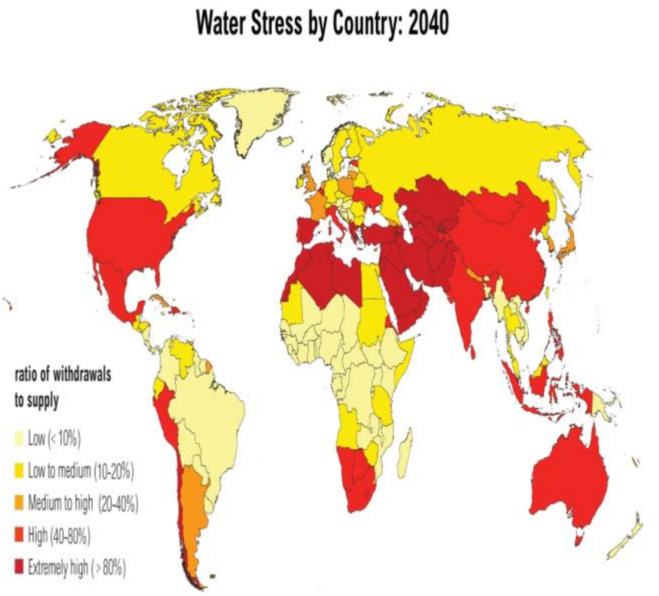

Fig. 1: Projected water stress in 2040

1.2 Literature Review

1.2.1 Study Related to Stepped Absorber in Solar Still

Many researchers have modified the solar geometry to improve its performance and get an enhanced yield. Researchers have spent much time looking at stepped absorbers for solar stills. Samadony et al. [20] showed a theoretical analysis of a stepped solar distiller and found that cooling the upper glass cover with cold water increases daily distillate yield by 8.2%. Mehdiabadi et al. [21] accomplished a mathematical study on stepped cascade PV/T collectors of unified solar still. When connected with the PV/T collector, they still generated 5.71 kg/m^2/day and provided 20% more fresh water. Saadi et al. [22] have researched stepped solar stills linked with a multi-tray evaporator mounted on the back wall's interior. They discovered that using a multi-tray evaporator instead of conventional solar still could generate between 47.18% and 104.73% more pure water than with the standard solar still. In research undertaken by A. Shyora et al. [23], they compared the effectiveness of traditional stills to that of stepped solar stills. The results indicated that using stepped solar stills led to a 23.88% rise in potable water production compared to old solar still. Kabeel et al. [24] did experimental research on PCM in stepped solar stills and linked it with using vacuum tubes and reflectors. They discovered daily fresh water up to 13.6 to 13.62 Lit. Per meter square using phase change material graphite in an integrated stepped solar still with an internal reflector and vacuum tube. They also found 51.7% to 51.82% daily competence. Sharshir et al. [25] completed the experimental research on a double slope stepped solar distillation system utilising nanoparticles and lien wi. They obtained around 80.57% more fresh water than conventional stills. Katekar et al. [26] conducted a thermo-economic examination of a solar distillation unit with a corrugated stepped absorber plate. They obtained 147.93% more yield than the standard still since the stepped solar distiller utilised a corrugated absorber. Amiri [27] experimented on stepped solar still to enhance performance using a condenser. Stepped solar stills with in-built condensers generated 30% to 150% higher fresh yields than traditional ones. Mosahebi et al. [28] tested a cascade solar distillation system through an interior mirror and concave steps. The employment of concave stepped cascade solar desalination yielded a production rate of 621cc/m^2. Atteya et al. [29] tested solar with stepped absorbers with different sand beds and reflectors. A 136% increase in fresh yield production was reported compared to traditional still when reflectors and sand beds are used in stepped solar still. Mohamed E. Zayed et al. [30] use a kernel-based machine learning model to predict the performance of stepped solar still. They found that 255% and 239% fresh water yield and efficiency of still is increased for stepped solar still compared to conventional solar still. Aasawari Bhaisare et al. [31] experimented on modified solar still having stepped corrugated absorber plates. The 2.50 Kg/m^2/day of productivity and 33.33% efficiency were still found for modified solar.

1.2.2 Study Related to Evacuated Tube

Similarly, because an evacuated tube has a cylinder shape, its performance is better when there is a low intensity of sunlight or fog outside. Therefore ShivKumar et al. [32] performed the study on the forced vacuum tube; they obtained around 3.9 litres of fresh water per day during the experimentation with vacuum tubes. Regarding energy and exergy competency, they discovered 33.8% and 2.6% of enhancement, respectively. While Panchal et al. [33] used a single basin to conduct their experiments with passive solar energy, i.e., vacuum tubes were us. Consequently, their production was around 97.6% more as associated with old-style still. In another work, Panchal et al. [34] involved phase change material and investigated using vacuum tubes and calcium stones in the still is done. According to the experimentation results, there was about a 104.68% improvement in the yield in traditional still. Panchal et al. [35] used a vacuum tube to investigate the black granite gravel. Throughout the inquiry, they were able to acquire increased competence of 65% with black granite gravel and as well as 56% with the vacuum tube. Panchal et al. [36] investigated solar distillers with double basins and solid fins on evacuated tubes wearing solid fins. They obtained a 25% improvement in fresh output due to these endeavours. A roof-mounted still was utilised, equipped with both a vacuum tube and a flat plate collector, Badran et al. [37]. The vacuum tubes augmented fresh yield by 13.25%.

Shehata et al. [38] examined solar still with a single slop with an evacuated solar collector and humidifier. They employed this arrangement and studied it daily by altering the water's height and recording their findings' results. For each new level of altitude, they achieve even greater levels of productivity. In the experimental research, M. Bhargva and A. Yadav [39] utilised a vacuum tube still and a heat exchanger. They experimented with different amounts of water depth and found that it might affect the effectiveness of the typical still between 30.5% to 138.9%. Patel et al. [40] investigate solar still equipped with a triple basin, absorber repurposed as corrugated material, vacuum heat pipe, granite, and heat-saving material with a moderate temperature. Compared to conventional stills, it has been discovered that they distilled water daily at a rate ranging from 19 to 17.5 kg/m^2.

Saw et al. [41] experimented with a vacuum tube-operated solar still in natural mode. 18.2% of freshwater was generated from 40 litres of hotel effluent; the average competency was 60.5%. Shoeibi et al. [42] researched the solar desalination system using an exterior condenser, a wind ventilator, and a cooling water system. Compared to conventional solar still, the production of the modified solar still, which was 213% fresh distillate, was much higher. Moghadam et al. [43] did experimental work on solar still, and its performance was evaluated considering the condenser effect when integrated with vacuum tubes. The 7.231 kg/m^2/day maximum daily yield was produced from modified solar still. Liu et al. [44]experimented with a solar desalination system with a vacuum tube, nanofluid, and ultrasonic atomisers. The 83.87% fresh water production was increased when the solar still was combined with an evacuated tube, ultrasonic atomisers, and painted with nanoparticles. The upper surface of the glass was cooled. M.A. Alghoul et al. [45] investigate the effect of different solar still configurations on productivity and efficiency through experimental methods. They discovered that raising the total number of condensing surfaces in solar still led to higher levels of production and efficiency. The research by A. Al-Waeli, and colleagues [46] entailed analysing the performance of a double-basin solar still with a heat exchanger. The heat exchanger boosted solar still output and efficiency by 22% and 23.53% respectively. H. Salmi et al. [47] experimented with a pyramid shape and thermal energy storage on a solar still. Thermal energy storage increased solar still production and efficiency by 16.1% and 18%, especially during low solar radiation. Shelare et al. [48] discuss the potential benefits of geothermal desalination, including reduced energy consumption, lower carbon emissions, and more excellent reliability compared to traditional desalination methods. They suggest that government policies and funding, technological advancements, and international collaborations could help overcome these challenges and promote the broader adoption of geothermal desalination.

1.3 Findings and Research Gap

The discussed papers emphasise how important it is to evaluate the performance of various solar still setups to enhance their overall production and efficiency. They also recommend different methods that may be used to accomplish enhanced output. Also, from the above discussion, it is concluded that when a stepped absorber is used in the still, the output from the still is increased. Similarly, when the vacuum tube is coupled to the still, a significant increase in freshwater production can be obtained from the still. But the combination of a stepped absorber with an evacuated tube is not considered for study by any researcher until now.

1.4 Motivation and Objective

1.4.1 Motivation

According to a report published by the UNO in 2019, the number of persons in areas with inadequate water supplies will grow by nearly 200 crores by the end of 2025 [49]. Hence, to make raw impure water suitable for human consumption, we must purify it. The purification procedure includes eliminating dangerous bacteria in their dissolved and undissolved states. Sand filtration is a method that may be utilised to get rid of particulate matter, and chlorination or boiling water can be used to get rid of the microorganisms. A solar desalination unit employs solar energy to execute the process of desalination, which involves purifying water by eliminating salt, particulate matter, and harmful microbes. Desalination can only be accomplished using sun energy [50]. Water evaporation with a high TDS can be achieved profitably by applying sun radiation. At both the centralised and decentralised levels, efforts are being made to convert high-TDS water into potable water safe for human consumption. Hence authors have performed experimentation on modified solar still with and without evacuated tubes, and the results obtained are presented in this paper.

1.4.2 Specific Objectives

The production of an inclined solar distiller that featured a stepped absorber with corrugated fins was evaluated alongside vacuum tubes.

To conduct a commercial examination of an inclined solar distiller having stepped absorber and corrugated fins, both with and without vacuum tubes.

The solar still is constructed with a one-square-meter surface area, and the experimental setup is designed to test two modified arrangements.

2. Materials and Methods

This section of the paper delves into specifics of the experimental setup and techniques employed during the study.

2.1. Experimental setup

The investigational arrangement is developed and constructed such that it can produce 5 kg of fresh water every single day. It is assumed that there are eight hours of daylight each day. As water evaporates at 100 degrees Celsius, the latent heat of vaporisation may be calculated using the steam table at that temperature. This calculation yields a value of 2257 KJ/Kg. The heat that must be applied to the water to evaporate is 11.258 x 10^3 KJ/Kg. The average solar radiation at Nagpur City (experimentation Location) is 480 W/m^2 daily. Nagpur city is located at 21.14 degrees north latitude and 79.08 degrees east longitude; as a result, the basin area is calculated to be 0.816 m^2. Because solar radiation does not remain constant throughout the day, the base area is increased to one square meter beyond what is necessary (0.816 square meters) to soak up a greater quantity of sun irradiation and produce the predefined amount of distillate.

Figure 2 shows a single basin, single slope glass inclined solar distiller with a stepped absorber, corrugated fin, and vacuum tubes to experiment with. The solar basin still was farmed by cutting a one-millimetre-thick sheet of galvanised iron (G.I). To reduce the heat that escapes from water in the basin, the outer surface of the still is insulated with commercial wooden plywood that is 8 mm thick, and polyurethane foam is used as an insulating material between the basin wall and the outer wooden plywood. The basin's interior was painted black, allowing it to absorb vast quantities of solar energy that were striking solar still. Plain glass with a thickness of 4 mm [51] is utilised, and its position is titled at 22 degrees, which is about the equivalent latitude of Nagpur's [33]. In the current investigation, a five-step structure was employed as an absorber. The dimensions of a single step were 160 mm by 1000 mm by 30 mm in W x L X H, respectively. On each step, corrugated fins constructed of the one-mm-thick GI sheet triangular shape were installed. The trials were carried out with vacuum tubes that measured 1800 millimetres in length and had inner diameters of 47 millimetres and exterior diameters of 58 millimetres [33]. This tube is fastened to the bottom of the basin, making it 45 degrees from the horizontal. A soft bush supports the tube in its bottom part, preventing it from breaking. Twelve thermocouples are fitted in the apparatus to measure the temperature of the water, the temperature of the absorber plate, the temperature of the inner glass cover, and the temperature of the surrounding air. A measuring jar was used to take readings hourly to get an accurate picture of the pure water produced by the solar still.

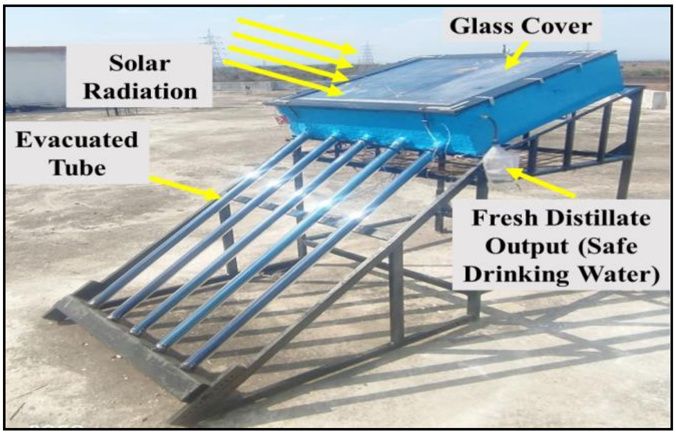

Fig. 2: Description of the equipment and arrangement used for the experiment.

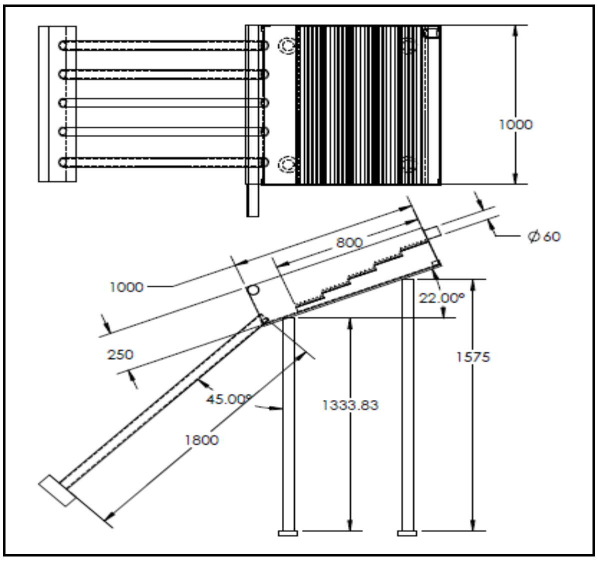

Fig. 3: Design dimension of the experimental setup.

2.2. Experimental Procedure

The Following procedure is followed:

1. A thermocouple is installed on an absorber plate and inner glass cover and submerged under basin water to monitor the temperature.
2. A flexible hose line is securely attached to the output path and extended to the collecting jar.
3. The TDS and pH value of raw water are measured, which is used for desalination.
4. The input valve supplies water to a basin.
5. An upper portion of a glass cover is adequately cleaned with tissue paper or cloth to avoid reflection.
6. The digital temperature indicator records the absorber plate, atmosphere, glass, and basin water temperatures hourly.
7. When sunlight strikes a glass cover, it is absorbed by black paint coated on a stepped absorber plate, and then heat energy is transmitted to the water.
8. The water absorbs the radiation, so its temperature rises and becomes vapour.
9. The vapour on the interior of the glass cover rises, collects on the glass, and condenses after some time by releasing heat into the surrounding region.
10. The condensate water is collected in the drain tube fixed at the bottom of a glass cover.
11. Fresh yield is collected in the measurement jar, which is measured hourly.
12. The TDS and pH value of fresh yield are calculated.
13. Hourly readings of the amount of solar radiation were taken using a solar meter.
14. During each hour, the temperature of the surrounding air, the temperature of an absorber plate, the temperature of the glass, and the temperature of raw water in a basin are all measured.

3. Thermodynamic Analysis

3.1. Analysis of the energy usage and efficiency of the solar still.

Analyses of energy or thermodynamics can generate yield equations, which are helpful tools for determining the temperatures of various parts of a solar distiller. The glass cover temperature, saline water temperature, and absorber plate temperature are all components. To derive an equation for overall energy balance, the following assumptions were utilised [52] - [55]:

a. The investigation is being carried out under circumstances considered to be steady-state.
b. The solar distillation system does not suffer from any leaking of vapour.
c. There is little concern over the heat lost via the still's outer walls.
d. There is no difference in temperature between the salty water and the glass cover of the condenser.
e. Radiations that are reflected from the ground's surface are not taken into account.
f. Absorber plate thickness is not significant.

The amount of solar energy that contacts the upper surface of the glass cover and is duplicated by the atmosphere contributes to a reduction in the overall quantity of radiation that is allowed to enter the solar still. The portion of the sun's rays that are not absorbed by the earth's atmosphere is allowed to pass through the condenser glass cover and into the solar still. The glass takes up a portion of this energy, while the remaining piece reaches the top of the salty water in the basin. The upper layer of water is responsible for reflecting some of the energy. However, most of it still goes down to the absorber plate, situated at the base of the container containing the salt water. The absorber can absorb the most incredible energy, whereas only a percentage can be reflected. The absorber plate is used to transmit energy to the salt water, which increases water temperature and evaporates it. The heat lost to the surrounding environment is caused by a tiny amount of conduction that occurs through the bottom and sidewalls of the casing [56]. The energy distribution throughout the solar distillation system is shown in Figure 4.

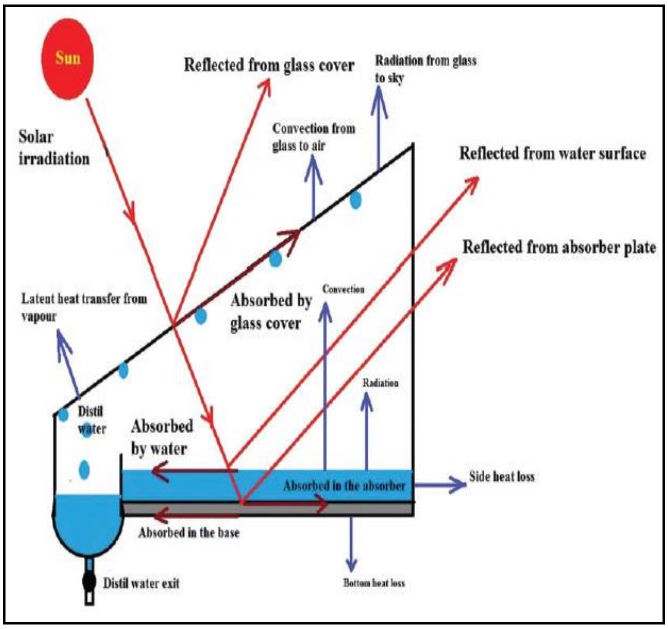

Fig. 4: Energy distribution within solar distiller [26].

The resistance to heat network utilised in the solar still may be depicted in Figure 5. When calculating the heat transfer rate between the various parts of a solar still, one commonly employed analogy involves electricity.

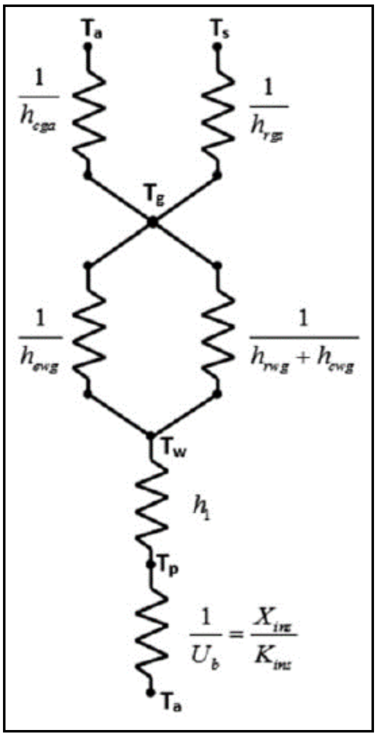

Fig. 5: An electrical analogy for solar still [23].

In light of the presumptions mentioned above, the following are the energy balance equations for the various parts of the solar still[52]-[55]:

Glass cover

The following equation describes the condenser glass cover's role in the overall energy balance:

$$\alpha_g \, I(t)A_g + h_2 A_w \left(T_w - T_g\right) = h_{cga}A_g \left(T_g - T_a\right) + h_{rgs}A_g \left(T_g - T_{sky}\right) + (m_g c_g)\left(\frac{dT_g}{dt}\right) \quad (1)$$

The heat transfer coefficient h_2 indicates the combined impact of the convection, radiation, and evaporation heat transfer coefficients between the inside surface of the condenser glass cover and the seawater. These heat transfer coefficients arise because of the ways heat may be transferred.

$$h_2 = h_{rw} + h_{cw} + h_{ew} \quad (2)$$

Saline water

This is a depiction that is roughly accurate of the basin's saltwater energy balance:

$$\tau_g \, \alpha_w \, I(t)A_w + h_1 A_p \left(T_p - T_w\right) = h_2 A_w \left(T_w - T_g\right) + (m_w c_w)\left(\frac{dT_W}{dt}\right) \quad (3)$$

Absorber plate

The statement of the energy balance for the absorber plate that is situated at the bottom of the saltwater tank is as follows:

$$\tau_g \, \alpha_p \tau_w \, I(t)A_p = h_1 A_p \left(T_p - T_w\right) + A_p \left(\frac{k_{ins}}{x_{ins}}\right)\left(T_p - T_b\right)(m_p c_p)\left(\frac{dT_p}{dt}\right) \quad (4)$$

The following is an estimated fluctuation in the temperatures of the inner condenser glass cover, the basin saline water, and the absorber plate over a period of time, based on the calculations given above [55], [57]:

By utilising the equation for the energy balance, one can ascertain the temperature of the salty water:

$$Tw = \frac{f(\mathrm{t})}{a}(1-\mathrm{e}^{-\mathrm{at}}) + \mathrm{T}_{\mathrm{w(i)}}\mathrm{e}^{-\mathrm{at}} \quad (5)$$

Where:

$$a = \frac{U_L}{m_w \times C_{pw}} \quad (6)$$

$$f(\mathrm{t}) = \frac{\alpha_{eff} \times I(\mathrm{t}) + \mathrm{U_L} \times \mathrm{T_a}}{m_w \times C_{pw}} \quad (7)$$

The process of determining the effective absorptivity involves specific calculations:

$$\alpha_{eff} = \alpha'_b \times \frac{h_1}{h_1 + h_{tb}} + \alpha'_w + \alpha'_g \times \frac{h_2}{h_2 + h_{tga}} \quad (8)$$

It is feasible to demonstrate that absorber plate, salt water, and glass cover each absorb varying amounts of the sunlight that is incident onto them.:

$$\alpha'_p = \alpha_p \times (1-\alpha_{\mathrm{g}})(1-\tau_{\mathrm{g}})(1-\tau_{\mathrm{w}}) \times \text{attenuation factor} \quad (9)$$

$$\alpha'_w = \alpha_w \times (1-\alpha_{\mathrm{g}})(1-\tau_{\mathrm{g}})(1-\tau_{\mathrm{w}}) \times [1-\text{attenuation factor}] \quad (10)$$

$$\alpha'_g = \alpha_{\mathrm{g}}(1-\tau_{\mathrm{g}}) \quad (11)$$

In Table 1, the attenuation factor is broken out according to the various water depths [55].

Table 1. Relationship between water depth and attenuation [55]

Attenuation factor	Water depth (m)
0.6756	0.02
0.6441	0.03
0.6185	0.04
0.6124	0.05
0.5858	0.06
0.5648	0.08
0.5492	0.10

Utilising the following equations will allow one to calculate the temperature of both the absorber plate and inner glass cover:

$$T_g = \frac{\alpha'_g I(t) + h_2 \times T_w + U_L \times T_a}{h_2 + h_{tga}} \quad (12)$$

$$T_P = \frac{\alpha'_p I(t) + h_1 \times T_w + h_{tb} \times T_b}{h_1 + h_{tb}} \quad (13)$$

3.2 Energy productivity

Calculating solar still's energy and thermal efficiency is possible by comparing the evaporative heat transfer rate to the amount of solar irradiation the absorber plate receives. This will give you an estimate of the efficiency of the solar still:

$$\eta_{th} = \frac{\sum m_{ew} h_{fg}}{3600 A_p \sum I(t)} \quad (14)$$

4. Uncertainty Analysis

Uncertainty is a good indicator of the quality of measurements and the instruments used to take measures. This experimental investigation assumes that measurements are assigned consistently and solely considers systematic error uncertainty. Standard uncertainty is expressed as follows: [26],[58].

$$U = \frac{a}{\sqrt{3}} \quad (20)$$

The following equation can represent the theoretical production of distilled water:

$$m_{ew} = \frac{h_{ew} A_w (T_w - T_g) 3600}{h_{fg}} \quad (15)$$

Top loss coefficient

Calculating radiative and convective heat loss from the condenser glass cover to the atmosphere around it is a crucial step in determining the minimal thickness of glass that must be utilised. Using the formula in the following will allow you to accomplish this goal:

The term “total heat loss” refers to the amount of thermal energy that is lost as a result of condenser glass cover radiating heat into surrounding air:

$$q_{tga} = q_{rga} + q_{cga} \quad (16)$$

Side and bottom loss coefficient

Because the absorber plate and the sides and bottom of the basin are insulated, the primary modes of energy transmission from the absorber plate to the surrounding environment are conduction, convection, and radiation. The rate of heat loss on the bottom surface of the solar distiller may be calculated using the following formula:

$$q_{tba} = h_{tba} (T_b - T_a) \quad (17)$$

$$h_{sa} = h_{tba} \ (A_s / A_b) \quad (18)$$

Overall heat transfer coefficient

The contribution of each of the top, bottom, and side surfaces is included in the total heat transfer coefficient, which may be written as follows:

$$U_L = h_{tga} + h_{tba} \quad (19)$$

Where:

a = accuracy of the measurement devices

u = the standard undesirability.

The categories and parameters employed during the experiment are mentioned in Table 2, along with the measuring equipment utilised during the investigation. This demonstrates that all values are within the allowed range for their respective categories.

Table 2: The Uncertainty of measuring instrument

Equipment	Range	Accuracy	Uncertainty
TDS meter	0 PPM to 990 PPM	± 1 PPM	0.577 PPM
Solar Meter	0 W/m^2 to 2000 W/m^2	± 10 W/m^2	5.77 W/m^2
PT100 Thermocouple	-80°C to 200°C	± 0.05°C	0.028°C
PH meter	0 pH to 14 pH	± 0.1 pH	0.057 pH
Calibrated Flask	0 ml to 1000 ml	± 10 ml	5.77 ml

5. Result and Discussion

The experiment setup generated data on various cases of solar stills, each with modified basin conditions. The findings demonstrated that the adjustments influenced the productivity and efficiency of the still, particularly regarding the fresh output. This information is presented in the paper.

5.1. Variation in the quantity of distillate produced per hour for case:1 and Case:2

5.1.1 Hourly fresh distillate output for an inclined solar still having corrugated fins and stepped absorber in the summer season (Case: 1.)

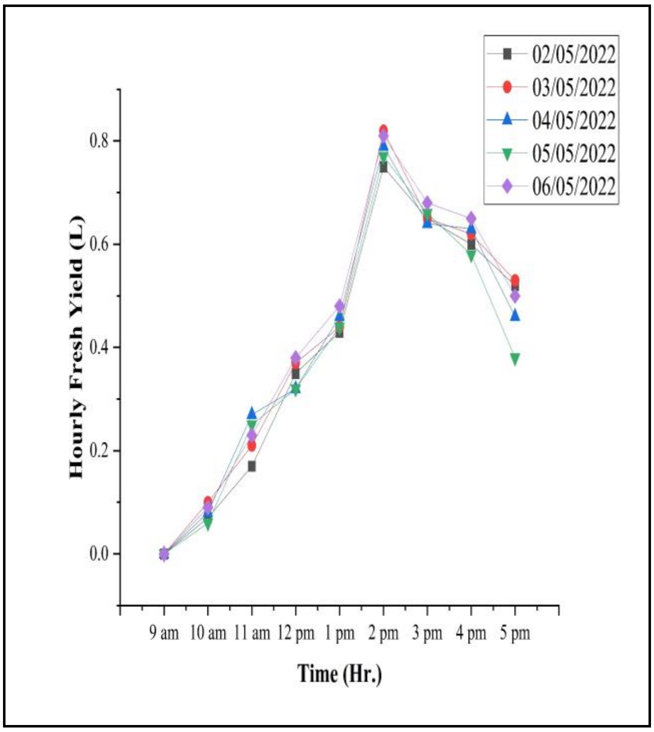

Fig. 6: Variation of Hourly Fresh Yield with Time (Case:1).

Figure 6 depicts the change in hourly fresh production achieved from the inclined solar still with a corrugated fin and stepped absorber in the summer (Case:1). This fluctuation occurred over several testing days. The experiment results show that the fresh hourly yield obtained from the still is highest from nine in the morning until two in the afternoon, after which point it starts to decline across the board for all of the different trials. Because the fresh production depends entirely on the sunlight intensity, which gradually increases from nine in the forenoon until two in the midafternoon, the fresh output is at its uppermost point at two in the afternoon. The maximum hourly yield is 0.82 kg/m^2, achieved on May 3, 2022, at 2:00 pm. Similarly, the maximum value was 0.75 kg/m^2, 0.79 kg/m^2, 0.77 kg/m^2, and 0.81 kg/m^2 of fresh products on the 02nd, 04th, 05th, and 06th of May 2022, correspondingly at 2:00pm.

5.1.2 Hourly fresh distillate output for an inclined solar still having corrugated fins and stepped absorber combined with vacuum tubes in the summer season (Case 2).

Figure 7 depicts the variance in fresh hourly output produced from the inclined solar still with a corrugated fin and stepped absorber combined with vacuum tubes in the summer season (Case:2). This variation was measured throughout several testing days. It has been discovered that the hourly fresh yield computed from the still is highest from nine in the morning until three in the afternoon, and then it begins to decrease for each trial day after that. After the peak of the solar intensity, which occurs between the hours of nine in the morning and one in the afternoon, the strength of the sun's radiation begins to decline gradually. Since the water temperature is maintained at a higher level for a more extended period when an evacuated tube is coupled to the solar still, the fresh yield is at its highest at three in the afternoon. This is why the maximum fresh output is obtained at three in the afternoon. The highest amount of 0.98 kg of hourly fresh production was achieved on the 26th of April 2022 at three o'clock in the afternoon. The same amount of the fresh output, 0.92 kg/m^2, 0.9 kg/m^2, 0.92 kg/m^2, and 0.9 kg/m^2 was collected on the 27th, 28th, 29th, and 30th of April 2022 accordingly at 3.00 pm. This was the maximum value for those trial days.

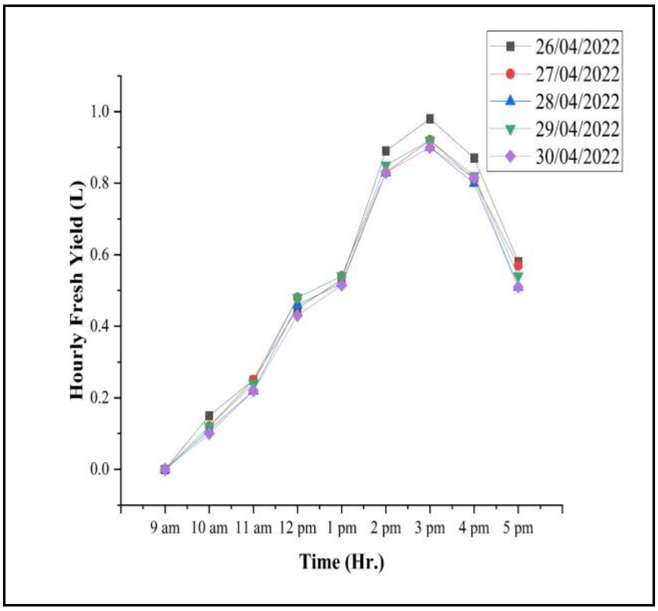

Fig. 7: Variation of Hourly Fresh Yield with Time (Case:2).

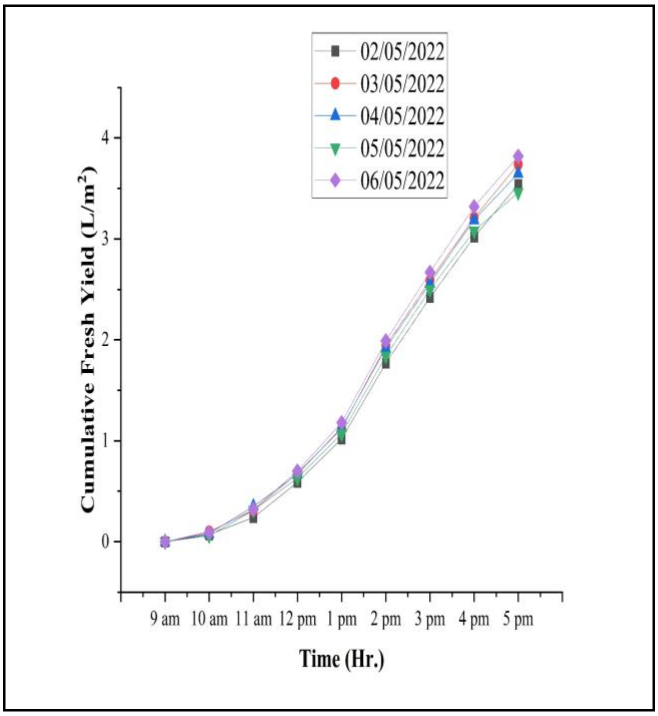

Fig. 8: Distinction of Growing Fresh Output with Time (Case:1).

5.2 Variation of Distillate Production on a Cumulative Basis

5.2.1 Cumulative fresh distillate output for an inclined solar still having corrugated fin and stepped absorber in the summer season (Case:1).

Figure 8 depicts the variance in cumulative fresh output produced from the inclined solar still that had corrugated fins and stepped absorbers in the summer season (Case:1). This variation was determined for each testing day. The most significant cumulative fresh output is entirely dependent on the sun intensity, which is at its highest between the hours of nine in the morning and one in the afternoon, after which it begins to fall. Maximum cumulative fresh production of 3.82 kg/m^2/day was achieved on May 6th, 2022. Similarly, the maximum value of cumulative fresh output for the 02nd, 03rd, 04th, and 05th of May 2022, was found to be 3.54 kg/m^2/day, 3.74 kg/m^2/day, 3.65 kg/m^2/day, and 3.46 kg/m^2/day respectively.

5.2.2 Cumulative fresh distillate output for an inclined solar still having corrugated fins and stepped absorber combined with vacuum tubes in the summer season (Case 2).

Figure 9 depicts the change in cumulative fresh output achieved from the inclined solar still with a corrugated fin and stepped absorber integrated with an evacuated tube in the summer season (Case:2). This variation was seen over several testing days. The cumulative fresh output obtained from a solar still depends entirely on solar intensity, which rises from 9:00 am to 1:00 pm and then declines afterwards. Additionally, an evacuated tube is coupled to the solar still, which causes the temperature in the still to increase and remain higher for a greater period. The maximum cumulative fresh output of 4.7 kg/m^2/day was achieved on April 26th, 2022. Similarly, the cumulative fresh production for the 27th, 28th, 29th, and 30th of April 2022, was carried to be 4.52 kg/m^2/day, 4.35 kg/m^2/day, 4.51 kg/m^2/day, and 4.32 kg/m^2/day respectively.

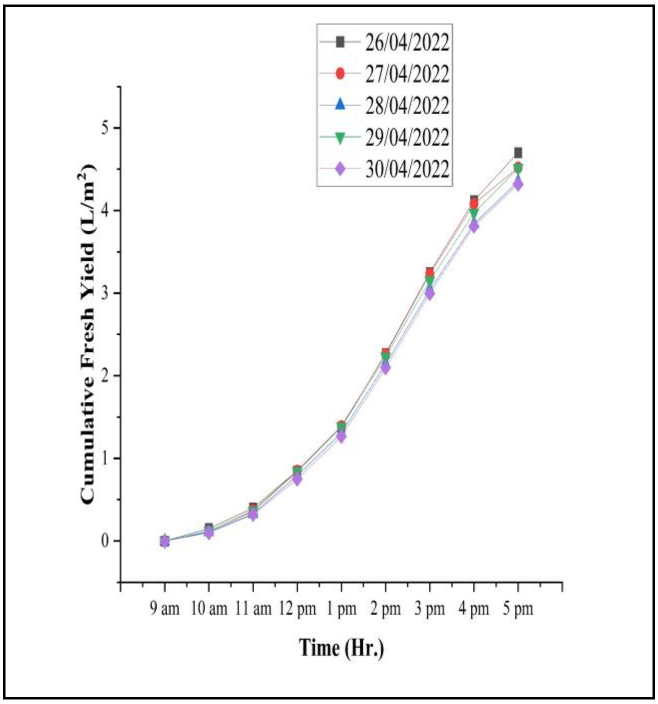

Fig. 9: Variation of Cumulative Fresh Yield with Time (Case:2).

5.*3 Comparative analysis of the cumulative output of fresh products for Cases 1 and 2.*

5.3.1 Variation of Cumulative fresh distillate output

Figure 10 depicts the distinction of cumulative fresh output for an inclined solar distiller having a corrugated fin and stepped absorber in the summer season (Case-1) and cumulative fresh yield for an inclined solar still having a corrugated fin and stepped absorber integrated with vacuum tubes in summer season (Case-2) for each day of the experiment. Compared to a solar still that does not include an evacuated tube, the cumulative amount of fresh output obtained from a solar still coupled with an evacuated tube is significantly higher. This is because the evacuated tube offers a wide variety of benefits, such as:

1. It is effective against direct as well as diffuse radiation.
2. Solar tracking is not necessary in any way.
3. In nearly every aspect, the performance of this collector surpasses that of a flat plate collector.

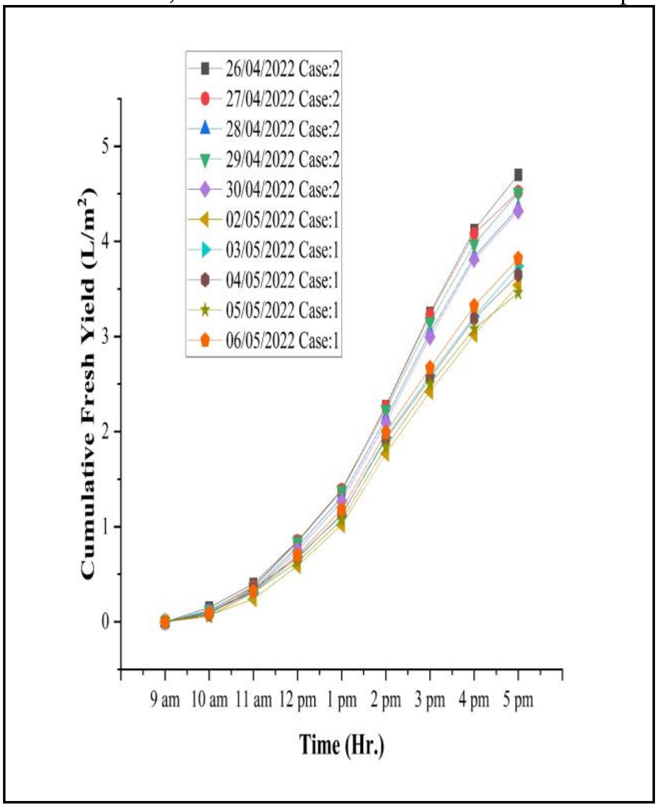

Fig. 10: Variation of Cumulative Fresh Yield with Time.

5.3.2 Variation of Daily fresh distillate output

The daily fresh yield that was achieved from inclined solar still having a corrugated fin and stepped absorber in the summer season (Case:1) and ready solar still having a corrugated fin and stepped absorber combined with evacuated tubes in the summer season (Case:2) is displayed in Figure 11 for all of the testing days. It is possible to achieve the maximum daily fresh output of 4.7 kg/m^2 from angled solar still that is equipped with an evacuated tube during the summer season (Case:2); nevertheless, it is possible to obtain a greater daily fresh yield of 3.82 kg/m^2 from a solar desalination unit that does not have an evacuated tube during the summer season (Case:1). The lowest quantity of fresh yield that a solar desalination unit can produce without an evacuated tube is 3.46 kg/m^2. In contrast, the minimal amount of freshwater obtained from solar still with vacuum tubes is 4.32 kg/m^2. The 24.85% increment in fresh output is found in modified solar still with vacuum tubes compared to still without vacuum tubes. This is because the evacuated tube performed well at low intensity and effectively in direct and diffuse radiation.

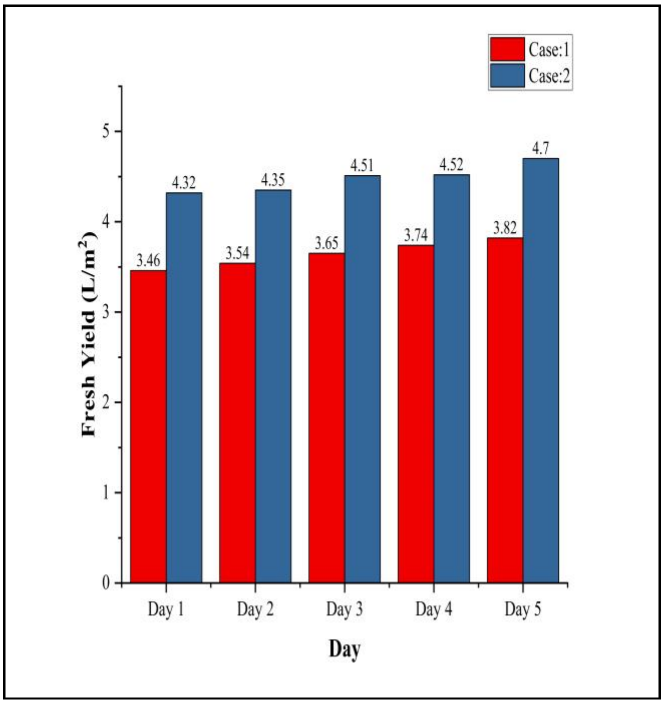

Fig. 11: Comparison of Daily Fresh Output of still

5.4 Effectiveness of the still on a daily basis

5.4.1 Daily efficiency of inclined solar still having corrugated fins and stepped absorber in the summer season (Case: 1).

The daily efficiency of inclined solar still having corrugated fins and stepped absorbers in the summer season throughout all of the trial days is depicted in Figure 12. The day of the week with the highest daily efficiency for an inclined solar still with a stepped absorber and corrugated fins is the sixth of May 2022, while the day of the week with the lowest daily efficiency is found to be the second of May 2022. The maximum daily efficiency is 39.98%, while the minimum daily efficiency is found to be 36.56%.

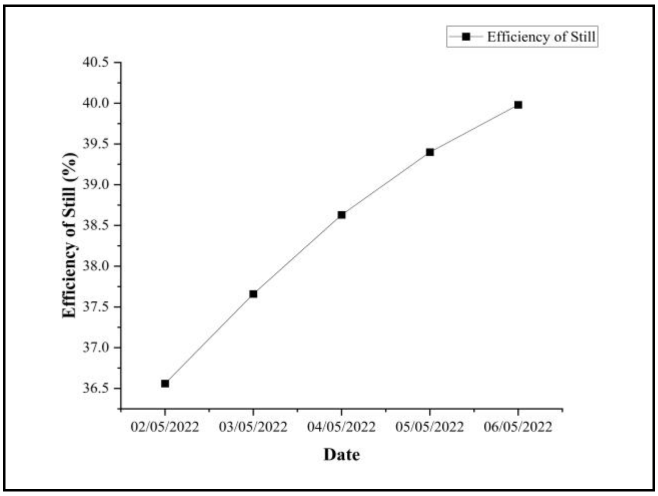

Fig. 12: Daily Efficiency of Still (Case:1)

5.4.2 Daily efficiency of an inclined solar still having corrugated fins and stepped absorber combined with an evacuated tube in the summer season (Case:2)

Figure 13 depicts the daily efficiency of inclined solar with corrugated fins, a stepped absorber, and an evacuated tube for all trial days. For an inclined solar still featuring a stepped absorber with corrugated fins combined with evacuated tubes, the maximum daily efficiency is found to be 46.72% on the 30th of April 2022, while the minimum daily efficiency is found to be 44.17% on the 26th of April 2022.

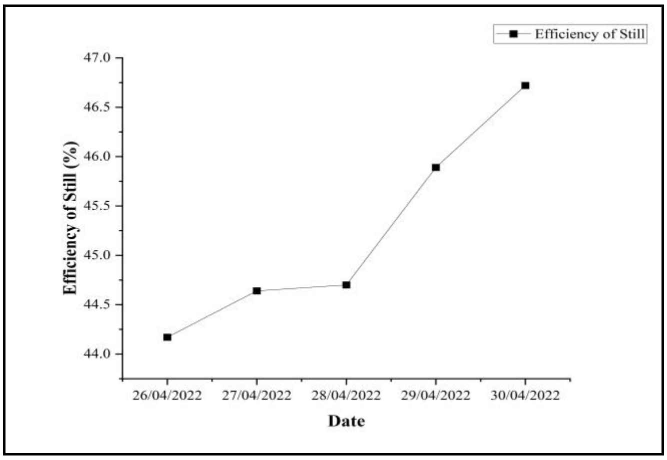

Fig. 13: Daily Efficiency of Still (Case:2).

5.5 Solar Still Efficiency Case:1 and Case:2

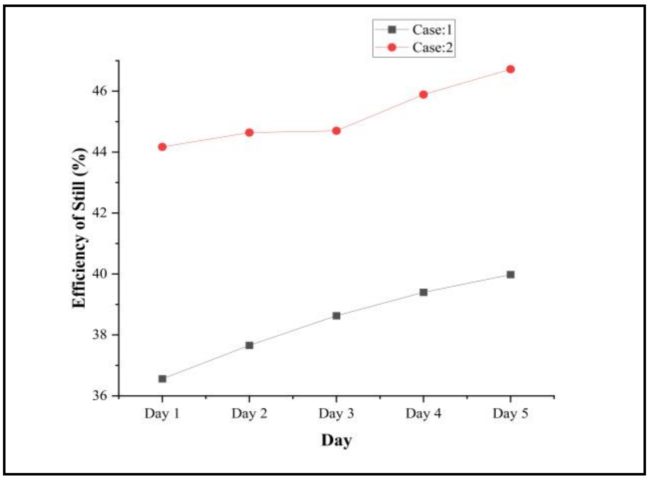

Fig. 14: Comparison of Efficiency of Still.

Figure 14 illustrates how the efficiency of the still obtained from the inclined solar still having corrugated fins and stepped absorber integrated with vacuum tubes (Case-2) is more significant when compared to the efficiency of the still obtained from inclined solar still having corrugated fins and stepped absorber (Case-1). The highest possible efficiency was found for Case 2, 46.72%, while the lowest was for Case 2, 44.17%. The highest possible efficiency for Case 1 was 39.98%, while the lowest for Case 1 was 36.56%.

5.6 Water Analysis

Laboratory tests have been conducted on water collected from the solar distillation unit before and after desalination. After going through the distillation process, it was found that the water could be consumed after being collected from the solar desalination unit. Table 3 presents a comparison of water quality both before and after the treatment.

Table 3: pH and TDS Value comparison for fresh distillate output.

Sr. No.	Parameters	Before Distillation	After Distillation
1	pH Value	10 to 12	6 to 7.5
2	TDS (PPM)	450 to 500	60 to 100

Table 4: Comparing prior researchers' work to present work

Sr. No.	Authors	Solar still modification	Increased in productivity as compared to Conventional still (%)
1	Elshamy et al. [59]	A semi-circular corrugated absorber is still present in	26.47

		tubular solar panels.	
2	Selvendiram et al. [60]	Solar comprises a single basin and a corrugated absorber.	30
3	Shalaby et al. [61]	Solar still equipped with v-corrugated and featuring phase-changing material.	12
4	Rashidi et al. [62]	Solar still with stepped absorber and Al_2O_3 as nanoparticles	22
5	Yadav et al. [63]	Solar still with stepped weir	80
6	Abdullah [64]	Solar still has a stepped absorber, a solar air heater, and top surface glass cooling.	112
7	Present Work	Inclined solar still has corrugated fins and stepped absorber (Case:1)	96.99
8	Present work	Inclined solar still having corrugated fins and stepped absorber coupled with evacuated tube (Case:2)	172.18

5.7 Economic Analysis

To determine whether solar energy is commercially viable, an economic analysis must be performed to evaluate the still in operation. The cost of distillate water with a solar still is determined by its initial purchase and ongoing operating expenses. The following set of assumptions is utilised to conduct an economic analysis of solar stills, and the equations may be solved according to the directions in Table 5. A total cost of an inclined solar still having a stepped absorber with corrugated fins is estimated as Rs. 8800, and a total cost of an inclined solar still having a stepped absorber with corrugated fins integrated with an evacuated tube is estimated as 10300 Rs.

The following presumptions are made during economic analysis:

a. The solar still has a 10-year lifespan.
b. 15% of the annual expenditure goes toward maintenance.
c. There is a 10% interest charge.
d. A salvage value equals 10% of the initial costs of the component.
e. The number of available clear, sunny days in Nagpur City are considered to be 310.
f. The cost of selling water is set at Rs. 2.

Table 5: Different Parameters for Economic Study [65], [66].

Sr. No.	Basic Considerations	Formulations	Inferences
1	First Annual Cost (FAC)	FAC = CS x CRF	Where: CS = total cost of still
2	Capital recovery factor (CRF)	$CRF = \frac{i\,(1+i)^N}{(1+i)^N - 1}$	Where: i = interest rate N = number of years
3	Annual Operating and maintenance cost (AMC)	AMC = 15% x FAC	
4	Sinking fund factor (SFF)	$SFF = \frac{i}{((1+i)^N - 1)}$	
5	Annual salvage value (ASV)	ASV = SFF x S	Where: S = salvage value, and it is taken as 10% of capital cost
6	Annual total cost (TAC)	TAC = FAC + AMC – ASV	

7	Cost of freshwater per litre	$CPL = \frac{TAC}{L}$	Where: L= Yearly fresh water output.
8	Net payback period	$\eta_p = \frac{\ln\left(\frac{CF}{CF-(FACx\ i)}\right)}{\ln(1+i)}$	Where: CF = cash flow and calculated as below CF = yearly yield x selling price

Table 6: Cost of Different components used in solar still.

Components	Material	Cost (Rs.)
Basin	G. I Sheet	2200
Stepped Absorber	G. I Sheet	1500
Corrugated Fins	G. I Sheet	1200
Glass	Plain White Glass	1500
Plywood	Wooden	1000
PuF	-	600
Black Paint	-	300
Evacuated Tube	Borosilicate Glass	Rs. 300 per Piece 5 Nos 300 x 5 = 1500
Miscellaneous	-	500

Table 7: Comparative economic evaluation of angled solar still for different basin conditions.

Sr. No.	Equation	Inclined solar still having stepped absorber with corrugated fins	Inclined solar still having stepped absorber with corrugated fins integrated with evacuated tubes
1	Total Cost of Still (CS)	8800 Rs.	10300 Rs.
2	$CRF = \frac{i(1+i)^N}{(1+i)^N-1}$	$CRF = \frac{0.1(1+0.1)^{10}}{(1+0.1)^{10}-1}$ = 0.163	$CRF = \frac{0.1(1+0.1)^{10}}{(1+0.1)^{10}-1}$ = 0.163
3	FAC = CS x CRF	FAC = 0.163 x 8800 = 1434.4	FAC = 10300 x 0.163 = 1678.9
4	AMC = 15% x FAC	AMC = 0.15 x 1434.4 = 215.16	AMC = 0.15 x 1678.9 = 251.84
5	$SFF = \frac{i}{((1+i)^N-1)}$	$SFF = \frac{0.1}{((1+0.1)^{10}-1)}$ = 0.063	$SFF = \frac{0.1}{((1+0.1)^{10}-1)}$ = 0.063
6	ASV = SFF x S	ASV = 0.063 x 0.1 x 8800 = 55.44	ASV = 0.063 x 0.1 x 10300 = 64.89
7	TAC = FAC + AMC – ASV	TAC = 1434.4 + 215.16 – 55.44 = 1594.12	TAC = 1678.9 + 251.84 – 64.89 = 1865.85
8	$CPL = \frac{TAC}{L}$	$CPL = \frac{1594.12}{951.39}$ = 1.67 Rs/ Litre	$CPL = \frac{1865.85}{1179.24}$ = 1.58 Rs/ Litre
9	Cash flow CF = yearly yield x selling price	CF = 951.39 x 2 = 1902.78	CF = 1179.24 x 2 = 2358.48

10	$\eta_p = \dfrac{\ln\left(\dfrac{CF}{CF - (FACx\ i)}\right)}{\ln(1+i)}$	$\eta_p = \dfrac{\ln\left(\dfrac{1902.78}{1902.78 - (1434.4x\ 0.1)}\right)}{\ln(1+0.1)}$ = 0.82 Years	$\eta_p = \dfrac{\ln\left(\dfrac{2358.48}{2358.48 - (1678.9x\ 0.1)}\right)}{\ln(1+0.1)}$ = 0.77 Years

Payback time is 299 days for inclined solar stills with stepped absorbers and corrugated fins and 281 days for inclined solar stills with stepped absorbers and corrugated fins integrated with vacuum tubes.

6. Conclusions and Future Scope

6.1 Conclusions

For the aim of this study, an experimental investigation on two distinct kinds of inclined solar stills was carried out, and the findings are presented in the part that follows:

- The maximum hourly fresh output of 0.82 kg/m^2 was obtained from an inclined solar still with a stepped absorber and corrugated fins on May 3, 2022, at 2:00 pm, and 0.98 kg/m^2 was obtained from an inclined solar still with a stepped absorber and corrugated fins integrated with an evacuated tube on April 26, 2022, at 3:00 pm. The solar radiation is maximum throughout the trial periods, so it concluded that solar irradiation is a very crucial parameter in the performance of solar distiller.
- On May 6, 2022, an inclined solar still having corrugated fins and stepped absorber obtained the maximum cumulative fresh output of 3.82 kg/m^2 per day, and on April 26, 2022, an inclined solar still having corrugated fins and stepped absorber coupled with an evacuated tube obtained 4.7 kg/m^2 per day.
- An inclined solar still having corrugated fins and a stepped absorber coupled with an evacuated tube produces 23.03% more fresh distillate output than an inclined solar still having corrugated fins and a stepped absorber alone because the effectiveness of vacuum tube is more in both direct and diffuse radiation also performed well as the low intensity of sunlight.
- It has been determined that an inclined solar with corrugated fins and a stepped absorber achieves the highest possible efficiency of 39.98%.
- The inclined solar still having corrugated fins and stepped absorber combined with the evacuated tube has been determined to have a maximum efficiency of 46.72%.
- The 16.85% increment in efficiency for modified still with vacuum tubes is obtained compared to modified still without vacuum tubes because vacuum tubes have higher effectiveness than other active solar radiation absorbing devices.
- The repayment period for the angled solar still with a stepped absorber with corrugated fins is 299 days, while the angled solar still having a stepped absorber with corrugated fins integrated with vacuum tubes is 281 days. So suggested modification may reduce the payback period of solar still with significant value.
- The overall performance of an inclined solar still with corrugated fins and a stepped absorber paired with an evacuated tube is much more excellent than that of an inclined solar still that merely has corrugated fins and a stepped absorber. This is because the performance of an inclined solar still with corrugated fins and a stepped absorber linked with an evacuated tube is significantly more efficient. This is because an evacuated tube possesses numerous advantages, such as the fact that it does not need a solar tracking system and maintains a better efficiency than a flat plate collector, in addition to the fact that it functions effectively even when there is a low intensity of sunlight.

6.2 Future Scope

The following are some potential enhancements that might be made to the still to maximise its effectiveness and its output of fresh liquid.

In an inclined solar still, that features a stepped absorber with corrugated fins and evacuated tubes, it is possible to incorporate a phase change material (PCM).

It is feasible to use various nanoparticles mixed with paint in an inclined solar still that features a stepped absorber with corrugated fins and evacuated tubes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

$$h_{cw} = 0.884\left[\left(T_w - T_g\right) + \frac{\left(P_w - P_g\right)\left(T_w + 273\right)}{\left(268.9\times10^3 - P_w\right)}\right]^{1/3}$$

$$h_{ew} = \left(16.28\ x\ 10^{-3}\right) h_{cw}\left(P_w - P_g\right) / \left(T_w - T_g\right)$$

$$h_{rw} = \varepsilon_{eff}\,\sigma\left[\left(T_w + 273\right)^4 - \left(T_g + 273\right)^4\right] / \left(T_w - T_g\right)$$

$$I(t) = I_{on}\left(\tau_b\cos\theta + \tau_d\cos\theta_z\frac{\left(1+\cos\beta\right)}{2} + 0.2\left(\tau_b + \tau_d\right)\cos\theta_z\frac{\left(1-\cos\beta\right)}{2}\right)$$

$$h_1 = 0.54\left(\frac{k_w}{x_w}\right)\left(Gr\,\mathrm{Pr}_w\right)^{0.25}$$

$$Gr = \frac{\beta g d^3 \rho_w^2 \Delta T}{\mu_w^2}$$

$$\Delta T = T_p - T_w$$

$$\mathrm{Pr} = \frac{\mu_w C_w}{k_w}$$

$$m_w = \rho_w V_w A_w = \frac{\rho_w x_w A_w}{t}$$

$$T_i = \frac{T_w + T_g}{2}$$

$$C_v = 999.2 + 0.1434T_i + 1.0101\times10^{-4}T_i^2 - 6.7581\times10^{-8}T_i^3$$

$$\rho_v = \frac{353.44}{T_i + 273}$$

$$k_v = 0.0244 + 0.7673\times10^{-4}T_i$$

$$\mu_v = 1.718\times10^{-5} + 4.62\times10^{-8}T_i$$

$$P_i = \exp\left(25.317 - \frac{5144}{T_i + 273}\right)$$

$$\beta = \frac{1}{T_i + 273}$$

$$h_{fg} = 3.1615(10^6 - 761.6\ T_i), \text{When } T_i > 70$$

$$h_{fg} = 2.4935\ (10^6 - 947.79\ T_i + 0.13132\ T_i^{\ 2} - 0.0047974\ T_i^{\ 3}), \text{When } T_i < 70$$

$$q_{rga} = h_{rga}\left(T_g - T_{sky}\right)$$

$$q_{rga} = \varepsilon_g \sigma\left[\left(T_g + 273\right)^4 - \left(T_{sky} + 273\right)^4\right]$$

$$h_{rga} = \varepsilon_g \sigma\left[\left(T_g + 273\right)^4 - \left(T_{sky} + 273\right)^4\right] / \left(T_g - T_{sky}\right)$$

$$T_{sky} = 0.0552 \times T_a^{1.5}$$

$$q_{cga} = h_{cga}\left(T_g - T_a\right)$$

$$h_{cga} = 2.8 + 3.0V_w \quad if\ V_w \leq 5m/s$$

$$h_{cga} = 5.7 + 3.8V_w \quad if\ V_w > 5m/s$$

$$h_{tga} = h_{rga} + h_{cga}$$

$$h_{tba} = \left[\left(x_{ins} / K_{ins}\right) + \left(1/h_{ba}\right)\right]^{-1}$$

$$h_{tba} = h_{rba} + h_{cba}$$

$$Ex_{g\text{-}a} = h_{t,g\text{-}a} A_g (T_g - T_a)\left(1 - \frac{T_a + 273}{T_g + 273}\right)$$

$$Ex_{ew} = h_{ew} A_w\left(T_w - T_g\right)\left(1 - \frac{T_a + 273}{T_w + 273}\right)$$

$$Ex_{rw} = h_{rw} A_w\left(T_w - T_g\right)\left[1 + \frac{1}{3}\left(\frac{T_a + 273}{T_w + 273}\right)^4 - \frac{4}{3}\left(\frac{T_a + 273}{T_w + 273}\right)\right]$$

$$Ex_{sun} = A_g I(t)\left[1 + \frac{1}{3}\left(\frac{T_a + 273}{6000}\right)^4 - \frac{4}{3}\left(\frac{T_a + 273}{6000}\right)\right]$$

$$Ex_{p\text{-}w} = h_1 A_p\left(T_p - T_w\right)\left(1 - \frac{T_a + 273}{T_p + 273}\right)$$