Performance Evaluation of Solar Distillation

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***Abstract*—Solar distillation is a clean and eco-friendly way to purify water, especially in areas where clean water is hard to find. However, its performance often drops due to changes in sunlight during the day. To improve this, Phase Change Materials (PCMs) like paraffin wax and sodium sulfate were used in place of regular insulation in a solar still. PCMs can absorb and store heat when the sun is strong and release it later when sunlight is weak or gone. This helps keep the water temperature steady, increases the rate of evaporation, reduces heat loss, and improves the total amount of purified water collected. In this study, using sodium sulfate as a PCM increased the system's efficiency by about 10–15% compared to a solar still without PCM. The experiment show that adding PCMs is a useful way to make solar distillation systems work better and produce more clean water throughout the day and night**

This article examines solar still desalination as well as current research on solar still system performance. Rapid industrialization and civilization have led to waste disposal and human ignorance, which has resulted in water contamination over time and throughout the world. Among the several methods available, solar distillation is one of the most effective ways to address this issue. However, it is not commercially viable in the market because of its poor efficiency. The performance of the solar still can be enhanced with a few adjustments.

***Keywords*—Solar distillation, Phase Change Material (PCM), Paraffin wax, Sodium sulfate, Latent heat storage, Water purification, Thermal energy storage, Renewable energy.**

I. INTRODUCTION

Solar distillation is eco-friendlly method of waters purification, particularly in regions with Limited is access to clear water. However, its efficiency is often limited by factors such as fluctuating solar radiation & heat loss. To overcome this problem, integrating phase change material (paraffin wax) into solar still helps store excess heat of stabilize system (Nielsen et al, 2016). Optimizing materials for the absorber such as black painted metal, improves heat absorption & evaporation (Adewale et al, 2015). Solar concentrators & hybrid system combining to extend performance (Duezine et al, 2020). Behaviour of glauber salt (sodium sulfate) for PCM as heat stosing material (Marwa Hamid et al, 2019). Model is made which will convert dirty / saline water in to pure water (Alpesh etal, 2011). Extended fins are applied to increase surface area for evaporation. (Mohammed et al, 2003). Enhancement of solas still through integration of thermoelectric module (Emre et al, 2024).

Traditional solar stills have drawbacks despite their advantages, such as a low daily output and a reliance on constant sunlight. Integrating thermal energy storage has drawn more attention as a means of overcoming these obstacles and improving the efficiency of solar distillation systems. Phase change material (PCM)-based latent heat storage devices are unique among energy storage solutions because they can store a lot of energy within a small temperature range. In order to regulate the thermal profile of the system and prolong water production into the hours of daylight, these materials absorb and release heat during phase transitions.

II. LITERATURE REVIEWS

Increasing the performance of Solar Distilation Alpesh Mehta, Arjun Vyas et al, Design of Solar Distillation System (2011). They have developed a device that uses solar energy, a renewable energy source, to transform saline or unclean water into potable, pure water. The Basic modalities of the heat transmission involved are radiation, convection and conduction. Evaporating the saline or filthy water and extracting the pure, drinking water yields the results. In six hours, the developed machine turns 14 liters of unclean water into 1.5 liters of pure water. The plant's efficiency is 64.37%. The pure water has 81 parts per million of TDS (total dissolved solids) [1].

Ugwuoke E.C, Ude M.U et at, Performance Evaluation of a Solar Still (2015). Their experiment's solar distillation equipment has a 0.68-meter collecting area. The absorber plate's absorbtivity is 0.93 while the glass cover's emissivity is 0.85. On day five, the experiment produced a maximum distillate of 2.3 liters and a maximum temperature of 54°C. It was found that the output of distillate increased with increasing sun intensity [2].

N.C. Ghuge, P.S. Desale, Performance Evaluation of Solar Still (2018) Utilized energy-storing materials: Black materials have the advantage of storing more thermal energy and raising the basin's heat capacity, which increases the quantity of solar radiation that the basin can absorb. Materials that are utilized to store energy include sponge cubes, glass, rubber, charcoal, gravel, and sawdust. According to experimental data, black gravel with a size of 20–30 mm and black rubber with a size of 10 mm boost the productivity of a shallow basin solar still by 19% and 20%, respectively.

Marwa Wasmi, Hayder Jaffa, The Behavior of Glauber's Salt as a Heat Storage Material (2019). Phase change materials (PCMs), which store heat during the day and release it at night, are thought to be a potential way to lower the energy needed for space heating. Among the materials that undergo inorganic phase change is Glauber's salt ($Na2SO4.10H2O$). It has various desirable qualities over other PCMs, such as low melting point, high thermal capacity, and high thermal conductivity. The findings showed that, in comparison to a regular one, the indoor temperature could rise by 2-4 degrees Celsius during the winter.

D. W. Meduguand L.G. Ndatuwong: Theoretical analysis of water distillation using solar still (2009). Mechanisms of mass and heat transport within the still have been theoretically analyzed. The experimental findings demonstrate that it agrees well with the theoretical analysis and that the still's productivity rises as solar radiation intensity and feed water temperature rise. Comparing the system to the theoretical analysis, the findings demonstrate a 99.64% distillation efficiency [14].

Mr. Jitendra Kumar Jangid, Mamta Meena, Jitesh Sharma: Distillation of water by Solar Energy (2021) Solar distillation is a simple and low-maintenance technology that can be used in remote or rural areas where access to fresh water is limited. The process involves using solar radiation to heat the water, causing it to evaporate and then condense on a glass cover, leaving behind the contaminants. The document covers the basic principles, types, and components of solar stills, as well as wavs to increase their efficiencv. The advantages of solar stills include no energy costs, reliability, and climate change adaptation, while the disadvantages include slow distillation rates and limited suitability for larger water needs. [5]

Naseer T. Alwan, Bashar Mahmood Ali, et al: Performance of solar still units and enhancement techniques (2024) The performance of solar stills is influenced by a number of elements, including operational and design considerations like water depth, cover thickness, and basin configuration, as well as factors like solar radiation, ambient temperature, and wind speed. Increasing sun radiation and wind speed, reducing water depth and cover thickness, employing phase transition materials, porous media, and rotating mechanisms are some methods to increase the productivity of solar stills.

Jishnu C.S, Akhil Davis et al: New Design of Tray Solar Still Using Peltier Module (2021). Solar still namely trays solar still with peltier module has been studied experimentally and theoretically. Conventional solar still modified by adding peltier modules on four edges of sloping glass plates. This modification obtained a large increase in water production. The solar still involves zero maintenance cost; the performance of tray solar still with peltier module has been studied experimentally and compared with the conventional model, peltier module technic is more effective as it is budget friendly and more efficient. [9]

Bipin Kumar Singh, C Ramji et al: Performance Analysis of Solar Still by Using Octagonal Pyramid Shape in the Solar Desalination Techniques (2023). The desalination productivity of the octagonal pyramid solar still by varying the depth of saline water in the basin and the angle of inclination of the glass cover. When compared to a traditional still, it was found that the novel still offers twice as much distillation. The optimal circumstances for high distillation are achieved when the water depth in the basin is 5 cm and the glass cover's angle of inclination is 30°.

Emre Mandev, Bayram Sahin, et al: Desalination performance evaluation of a solar still enhanced by thermoelectric modules (2024). Study explores the enhancement of solar stills through the integration of thermoelectric (TE) modules, focusing on their impact on desalination performance. The optimal saltwater levels, TE module performance, and the efficiency of the system are identified in this investigation. The results of this study reveal that the integration of TE unit into solar still systems leads to a substantial increase in water production, achieving an impressive 35% improvement in productivity compared to conventional solar stills [8].

Guilong Peng, Swellam Sharshir: Progress and performance of multi-stage solar still (2023). The research progress of multi-stage solar still is reviewed, including the stacked tray solar still, the tubular solar still, as well as the vertical diffusion solar still. Both multi-stage stacked tray solar still and tubular solar still have much better performance as compared to single-stage solar still. However, the stage number of the stacked tray and tubular solar still is usually limited to less than 5. On the other hand, vertical diffusion solar stills show the best daily productivity among all three types of solar still, due to more effective stages. [14]

Ravi Gugulothu, Devendra Gatha: Solar Water Distillation Using Sensible and Latent Heat (2015) Only during the day is solar energy accessible. Therefore, effective thermal energy storage is necessary for its uses in order to store extra heat generated during the day for usage at night. The primary issue with using solar energy is its availability, which is frequently erratic, fluctuating, and intermittent. Thermal energy storage (TES) will increase solar power's output and efficiency. With a lower temperature differential between storing and releasing heat, the latent heat storage technique offers a significantly higher storage density.

Performance Evaluation of Solar Distillation:

1.Distillate Yield: The qauntity of fresh water produced by the solar still, typically measured in liters per day (L/day) or liters per hour (L/h).

2. Efficiency: The ratio of the distillate yield to the total solar radiation received by the solar still, typically expressed as a percentage (%).

3. Solar Still Productivity: The qauntity of fresh water produced per unit area of the solar still, typically measured in liters per square meter per day ($L/m^2/day$).

4.Energy Efficiency: The ratio of the energy output (in the form of fresh water) to the energy input (in the form of solar radiation), typically expressed as a percentage (%).

5.Cost-Benefit Analysis: An evaluation of the economic feasibility of the solar still, including the initial investment, operating costs, and revenue generated from the sale of fresh water.

III. METHODOLOGY

Evaporation and Condensation

Solar Steel (Passive Method): Consist of contains where a water is placed, covered by a class to allow sunlight to heat the water. Heat causes the water to evaporate and vapour then condenses on inner surface of cover. Condenser water drips into a separate collection chamber.

1.Evaporation

Evaporation of condensation, Solar still (passive method): Consists of contains where water is placed, covered by a glass. to allow sun sunlight to heat the water. Heat causes the evaporation of water & vapors then condenses on inner surface of covers. Condenser water drips into a separate collection chamber.

2.Distillation

The technique of applying and removing heat to separate a liquid or vapor mixture of two or more substances into their component fractions of desired purity. One popular method for extracting fragrant chemicals from plants, including orange blossoms and roses, is distillation. By heating the raw material and allowing the distilled vapor to condense, the aromatic chemicals are recovered. Distillation comes in two varieties for extraction. both hydro and steam distillation.

A. Solar Distillation:

Solar distillation is a water purification technique which uses energy from the sun to separate clean water from saline or polluted sources. Commonly referred to as solar water distillation, the method involves harnessing solar radiation to heat the impure water. As the temperature rises, the water evaporates, leaving behind salts and contaminants. The resulting vapor then condenses on a cooler surface often a transparent glass or plastic sheet and is subsequently collected as purified water.

B. Steam Distillation

Generated steam from boiling water is directed through the raw plant material for a period ranging from 60 to 105 minutes. This process extracts the majority of the volatile aromatic compounds. The resulting condensate, which includes both water and essential oils, is collected in a Florentine flask. This specialized container enables easy separation, as the essential oil naturally rises to the top and can be skimmed off, leaving the aromatic water beneath. This remaining water, known as hydrosol, still contains trace amounts of the plant's fragrant components and is often marketed for both commercial and personal use. This distillation method is most commonly applied to fresh botanical materials such as flowers, leaves, and stems.

Chemicals and Raw Materials
1.Paraffin Wax
2. Sodium Sulfate.
3.Iron Steel Plate
4.Wood
5.Glass
Apparatus Requires
1.Thermometer
2. PH Meter
3. TDS Meter.
4. Beaker
5. Measuring Cylinders
6. Distillate Collector (Container)

Comparison Between Properties

Property	Sodium Sulfate Decahydrate ($Na_2SO_4 \cdot 10H_2O$)	Paraffin Wax
Phase change temp. (°C)	32–35	45–65
Latent heat (kJ/kg)	250-270	200-220
Thermal conductivity	Higher	Lower
Cost	Low	Moderate

Table- Comparison of Properties

Experimental Setup

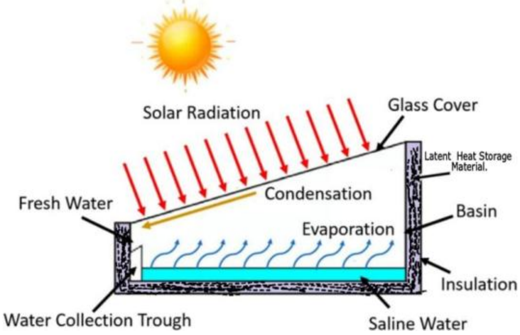

Fig. Single Effect Solar Still

Basin is made from iron steel plate with black colour coatings having a thermal conductivity of 50 W/mk. Basin is placed in wooden container which is surrounded by latent heat storage material to store energy. Energy which is release from basin gets stored in this material by going phase change. This energy is used for heating saline water for long period.

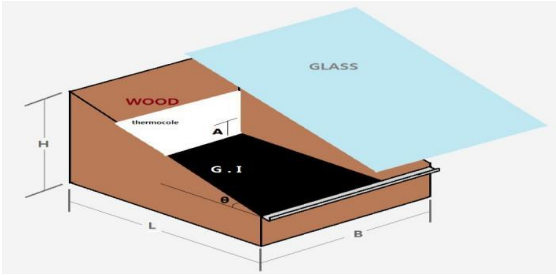

Fig. Final Experimental Setup

Still Basin: This is the section of the system that contains the water that needs to be distilled. Therefore, it must be able to absorb solar energy. Therefore, the material must either have a high absorbtivity or very low transmittivity and reflectivity. Adjacent Walls: In general, it gives the still rigidity. Technically speaking, however, it offers thermal resistance to heat flow from the system to the environment. So it must be created from the material that is having low value of thermal conductivity and should be sturdy enough to maintain its own weight and the weight of the top cover.


Fig. Proposed Model of Solar Distillation System

Top Cover
Top cover is the passageway from which radiation strikes the basin's surface. Thus, the top cover's features are: 1) Transparent to sunlight 2) Water that is not adsorbent or absorbent 3) A smooth and clean surface 4) The Materials Can Channel: This path, which extracts the pure water, is called a channel. The condensate that forms slips over the slanted top cover and falls into it.

Still Basin

The still basin is the part of the solar distillation system where the impure or saline water is stored for the distillation process. Since this part is directly used for absorbing solar energy to heat the water, the material used for the basin must have high absorptivity. In other words, it should absorb a maximum quantity of solar radiation while minimizing reflection and transmission. This ensures efficient heating and enhances the all over performance of the solar distillation system.

Side Walls

The side walls of a solar still serve a dual purpose. Structurally, they provide rigidity and support to the overall system, ensuring stability. Functionally, they act as a resistance to heat loss by offering thermal resistance, minimizing the transfer of heat from within the still to the surrounding environment. Therefore, the material chosen for the side walls should have minimum thermal conductivity to reduce energy loss. Additionally, it must be strong and durable enough to support both its own weight and that of the transparent top cover.

To function effectively, the top cover must meet several key criteria: It should be transparent to allow maximum transmission of solar energy. It must resist absorbing or adsorbing water to prevent loss of distilled water and contamination. A clean, smooth surface is essential to collect the condensed water droplets can easily slide down. The design should allow the formed condensate to flow along the inclined surface into a designated collection channel.

IV. OBSERVATIONS

Time required for experiment = 9 am to 5 pm

PH of solution =8.5

TDS of solution - 350

PH of Distillate = 7.5

TDS OF Distillate = 150

OBSERVATION TABLE

Material	Temperature °C				
Time	9AM	11AM	1 PM	3PM	5PM
Thermocol	27	40	54	50	45
Paraffin Wax	27	43	57	54	50
Sodium Sulfate	27	45	59	56	52

Table: Temperature in°C of Brackish Water for Different Latent Heat Storage Material

Observation table shows the temperature in °C of Brackish Water for various Latent Heat Storage Material. Temperature in °C for Thermocol, ParaffinWax and Sodium Sulfate shows the temperature in °C resp. As per observation Sodium Sulfate is the best suitable for Latent Heat Storage Material and Thermocol Sulfate is the less suitable for Latent Heat Storage Material.

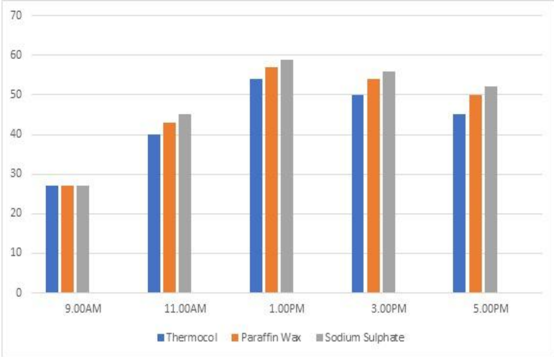

Fig: Observation Graph

V. RESULT AND DISCUSSION

1.Thermal Efficiency

η=(m.hfg) + Q_{PCM} / I.A.t

Where,

$Q_{PCM} = M_{PCM} . \Delta H_{PCM}$

M_{PCM} = mass of PCM

ΔH_{PCM}= latent heat of fusion of PCM

I= Solar radiation

A= Area in m^2

t= time

	Thermocol	Paraffin Wax	Sodium sulfate
m= distillate output(kg)	550	600	645
h_{fg}= latent heat of vaporization of water ≈ 2260 kJ/kg	2260	2260	2260
Q_{PCM} = energy released by the PCM (k	_	250	200
I= average solar radiation (kW/m²)	0.6	0.6	0.6
A= area of the solar still (m²)	0.3721	0.3721	O.3721
t= area of the solar	28800	28800	28800

still (m²)			
Thermal Efficiency(η)	22.68%	27.33%	30.47%

2. Yield
Yield=m/A
m= mass of distilled water collected (kg or L)
A= area of the solar still (m²)
For thermocol = 1.478 L/m^2/day
For Paraffin wax =1.612 L/m^2/day
For sodium sulfate = 1.733 L/m^2/day
3.Distillate (output) :
For thermocol = 550 ml
For Paraffin wax =600 ml
For sodium sulfate = 645 ml.

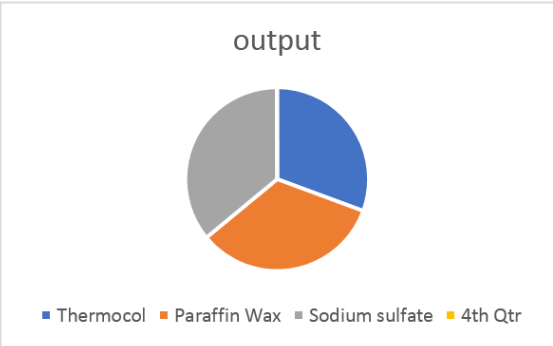

Fig: Output Graph

VI. CONCLUSION

We conclude that energy and water scarcity are pressing global challenges, intensified by high energy costs and the environmental impacts of fossil fuel usage. Renewable energy sources, particularly solar energy, offer a sustainable and eco-friendly solution to meet energy demands. Solar energy's intermittent nature, however, limits its direct application, necessitating efficient thermal energy storage (TES) systems to store excess heat collected during daylight for use at night.

By storing thermal energy for later use, TES technology significantly improves solar energy usage and energy conservation. Latent heat storage (LHS) with phase change materials (PCMs) is one of the most effective TES techniques. PCMs are useful for solar desalination and other applications because of their high storage density, low cost, and isothermal operation.

By bridging the gap between solar energy availability and desalination needs, TES and PCMs improve the feasibility and effectiveness of solar based solutions, addressing both energy and water supply challenges.

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