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NUMERICAL ANALYSIS TO IMPROVE THE EFFICIENCY OF A SOLAR STILL (SINGLE-SLOPE)

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ABSTRACT

Purpose: This study investigates enhancements to maximise the efficiency and performance of the single-slope solar still for sustainable water solutions.

Design/Methodology/Approach: This research focuses on the design of a solar still (single-slope) and integration with phase change materials (PCMs), reflective mirrors, and black dye into the solar still (single-slope) to augment its improvement in efficiency. PCMs, such as paraffin wax, are known for their latent heat storage, sustaining higher temperatures within the still to enhance evaporation.

Findings: The study found that reflective mirrors amplify solar radiation entry, increasing thermal efficiency. Black dye, added to the basin water, enhances heat absorption, accelerating water evaporation rates. Finally, all improve the efficiency of solar stills (single-slope).

Research Limitation: The research uses renewable energy (solar power); therefore, it has been limited to work in the daytime only.

Practical Implication: The results show that the insulated basin, PCMs placement at the base, reflective mirrors encircling the still, and black dye in the water significantly improve the efficiency of solar stills (single-slope). Therefore, the quest for sustainable water solutions amid global water scarcity may be achieved through solar still technology, particularly the single-slope solar still.

Social Implication: The study endorses the proposed system, which can provide sustainable and reliable water solutions through renewable solar energy as a clean energy.

Originality/Value: Comparative analysis with conventional solar still underscored significant performance gains: The enhanced configuration produced an average of 3.04 litres of distilled water daily, a 42% increase over the conventional 2.14 litres. Hourly yield data highlighted peak performance at midday, with the enhanced still yielding 260 mL/hr compared to 180 mL/hr from the conventional.

Keywords: *Reflective mirrors. solar still. sustainable. technology. water scarcity*

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INTRODUCTION

In the recent past, access to fresh water remains a critical global challenge, exacerbated by population growth, climate change, and resource depletion (Kumar et al., 2024; Mishra, 2023) (Singh, 2011). Moreover, it has been reported that billions of people worldwide suffer serious issues due to the lack of access to potable water services, and this seeks attention to the urgent need for innovative and sustainable water purification technologies (United Nations, 2019). Solar distillation has emerged as apromising method to address this challenge, particularly in drought and semi-drought regions where sunlightis abundant and conventional water sources are scarce (Varun Raja & Manokarb, 2017). Among various solar distillation technologies, the single slope solar still stands out for its simplicity, cost-effectiveness, and suitability for decentralised water treatment (Sri Gokilavani et al., 2014; Singh, 2011).

This single basin type still works on the principle of thermaldesalination, where solar energy heats saline or contaminated water in a basin, causing evaporation. The vapour then condenses on a sloped cover, typically glass or plastic, and collects aspurified water in a storage container (Diabil, 2022; Banoth et al., 2014). This process effectively separates contaminants and salts from water, producing potable water through natural evaporation and condensation.

Despite its advantages, such as minimal energy requirements and low operational costs, single-slope solar still faces several challenges that limit its widespread adoption and efficiency (Sahane et al., 2017). One of the primary limitations is its relatively low efficiency in converting solar energy into usable heat for water evaporation (Azooz & Younis, 2016). This inefficiency often results in lower water production rates, particularly during fluctuating solar intensity or suboptimal environmental conditions (Sivakumaran & Jdihesh, 2019).

Researchers and engineers have explored various strategies and technological improvements to overcome these limitations and enhance the efficiency of single-slope solar stills (Mehta et al., 2011). One promising approach involves the integration of phase change materials (PCMs) into the design of solar still (Feilizadesh et al., 2017; Alijubouri, 2017). PCMs, such as paraffin wax or salts, have a high latent heat storage capacity, allowing them to absorb and release thermal energy during phase transitions, such as melting and solidification (Faegh & Shafii, 2017; Kabeel et al., 2016; El-Sebaii et al., 2009). Researchers aim to stabilise and maintain higher temperatures within the system by incorporating PCMs into the solar still's structure, particularly at the basin or storage areas (Dashtban & Tabrizi, 2011; Hussein et al., 2008). This thermal stabilisation enhances the overall performance of the solar still by extending the daily operating hours and improving water production rates (Mohammed et al., 2021; Radomska & Mika, 2023).

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LITERATURE REVIEW

Hameed et al. (2023) investigates the potential for increasing the productivity of pure water in single-slope, single-basin solar stills by creating a new absorbent base design with stainless steel geometry. The results show that using stainless steel geometry increases the evaporation rate and improves still production. Cones produced the most freshwater, with an enhancement ratio of 38.2% and a water yield of 4.13 kg/m2.

A novel heat storage system based on a solar air heater (SAH) and single-slope solar still was evaluated for energy, exergy, and economic feasibility. The performance evaluation of all the various types of solar stills was compared to identify the best-performing one. At the bottom of the solar still, paraffin wax was used as a phase change material (PCM) to provide adequate thermal storage (Kumar et al., 2022).

Aftiss et al. (2024), revealed that there are three distinct solar still types: the conventional passive solar still (still-I), the solar still that uses paraffin wax as a phase change material (PCM) (still-II), and the solar still that uses PCM coupled to a storage tank (still-III). The study found that the PCM can retain some energy produced throughout the day for use at night.

In addition, the (da Silva Junior et al., 2023) investigates the possibility of treating salt water to make it suitable for human use. Numerical modelling and construction were used to forecast the performance of the inexpensive solar still without any experimental observations. The modelling findings demonstrated improved efficiency when the volume of water inside the device was smaller and the global radiation intensity was higher (Ebaid & Ammari, 2015).

Governing Equations

The equations are derived under steady-state conditions, incorporating continuity, momentum, energy, and mass transfer conservation principles. As soon as the solar energy radiation enters the water at the basin, it excites the heat transfer process, as illustrated in Figure 1. The energy balance equation is formulated underthe following assumptions:

1. No vapour escapes (leakage or losses) from the solar still.
2. The heat absorption capacity of materials, insulation and cover is negligible.
3. Uniform temperature throughout the basin and condensing surface (glass cover) of the solar still.
4. Constant level of water is preserved inside the solar still.

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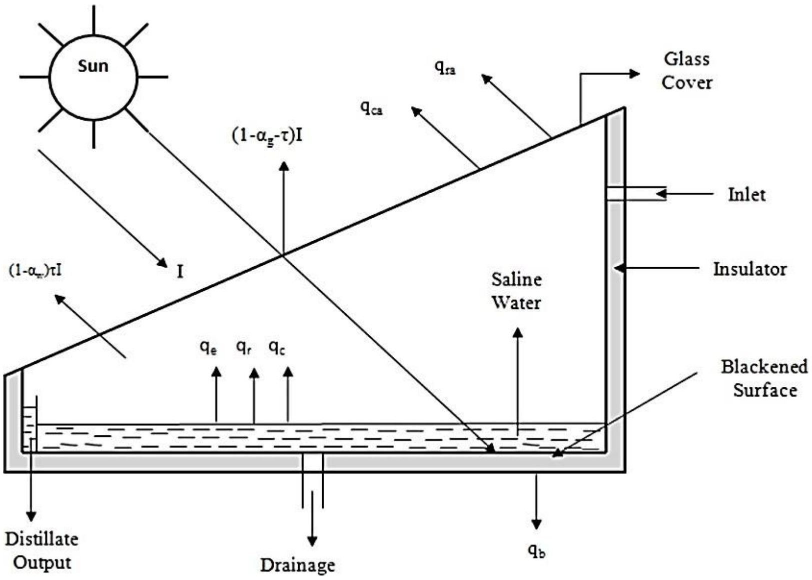

Figure 1: Flow of energy in a solar Still (single-slope) system

Equation for Energy

The equation of energy for the mixture is:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\alpha_k\rho_k E_k)+\nabla\cdot\sum_{k=1}^{n}(\alpha_k\vec{v}_k(\rho_k E_k+p_k))=\nabla\cdot(k_{\text{eff}}\nabla T)+S_E \quad (1)$$

k_{eff}: Effective thermal conductivity, combining

$$k_{\text{eff}}=\sum_{k=1}^{n}\alpha_k\left(K_k+K_t\right)$$

K_t: Turbulent thermal conductivity (from turbulence models).

Equation for Continuity

The equation of continuity for the inter-mixture is:

$$\frac{\partial\rho_m}{\partial t}+\nabla\cdot(\rho_m\vec{v}_m)=0$$

(2)

Where, v_m =mass-averaged velocity:

$$\vec{v}_m=\frac{\sum_{k=1}^{n}(\alpha_k\rho_k\vec{v}_k)}{\rho_m}$$

(3)

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Equation for Momentum

The equation of momentum for the inter-mixture (achieved through adding each momentum equation for all the phases) is:

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m^T)] + \rho_m \vec{g} + \vec{F}_m + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_k \vec{v}_k^{\text{dr}} \right)$$

(4)

Equation for Volume conservation

The constraint is that the summation of volume fraction is unity.

$$r_T + r_G = 1$$

(5)

Equation for Mass transfer

The source of energy in a cell for phase "p" and phase "q" are:

$$H_p = -\dot{m}_{piq}(h_i)$$

(6)

$$H_q = \dot{m}_{ij}(h_i + h_{f,i} - h_{f,j})$$

Where,

$h_{f,i}$: Formation enthalpy of species *i* in phase *p*.

$h_{f,j}$: Formation enthalpy of species *j* in phase *q*.

MATERIAL AND METHODS

Experimental Setup

The schematic diagram and experimental setup of the solar still (single slope) are illustrated in Figure 2. Essential solar still is constructed from a metallic (insulated) galvanised iron (GI) sheet basin with dimensions of 0.8m×1.0m. Thebasin incorporates a thermocol sheet of 1 inch thick is sandwiched between the basin walls to minimise heat loss (Varun raja & Manokarb, 2017). Internally, the basin was coated with epoxy-based black paint to enhance absorption, while externally, it was coated with white paint (metallic) to reduce thermal losses. Moreover, the side walls of the basin were equipped with mirrors to enhance the reflection of solar radiation towards the bottom surface. A 5 mm thick glass (transparent) is used to cover (condensing surface) the still; it is inclined 26° towards the south, aligning with the south to maximise solar radiation capture throughout the day (Diabil, 2022). To prevent vapour leakage and ensure efficient condensation, the solar still basin and cover of glass are sealed using the foam of 3mm, effectively containing generated vapours within the basin.

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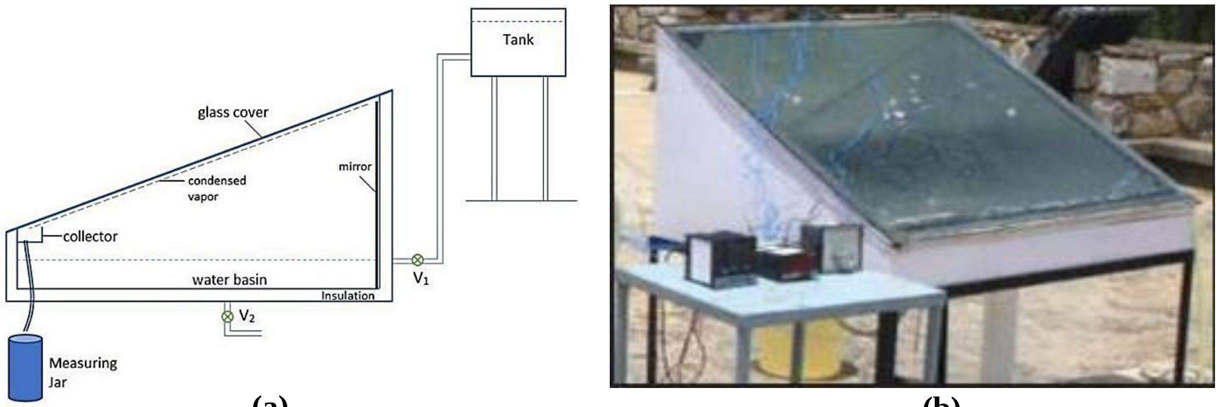

(a) (b)

Figure 2: Single Slope Solar Still; (a) Schematic Diagram, (b) Experimental Setup

Modelling

Geometry and Meshing

The 3-D model of the solar still has been replicated using ANSYS (Design Modeler) to match the exact dimensions and configurations of the experimental setup. Figure 3 depicts the 3-D model of the solar still and generates an unstructured mesh. The physical model was meshed using 3-D hexahedral meshing in ANSYS Workbench, comprising 1.5×10^{-6} elements with a growth rate 1.2. This meticulous meshing process ensures that the computational model accurately represents real-world solar still's geometric details and complexities. It facilitates precise simulation and analysis of its thermal and fluid dynamics performance.

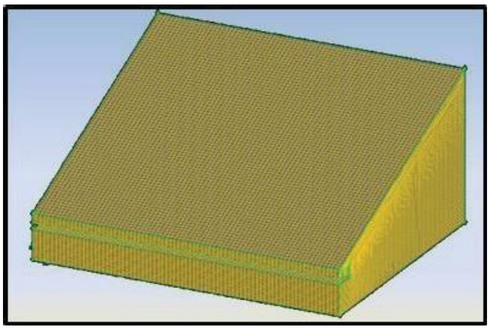

Figure 3: Meshed model of the proposed system

A grid independence test was conducted to assess the appropriate element size for the model. Criteria for convergence were established for conservation equations, such as continuity, velocity, and turbulent kinetic energy (k-ε) to 1×10^{-3}, and for the energy equation is 1×10^{-6}. The size of the grid was resolved by incrementally raising the mesh number until the criterion [p-(p+1)]/p < 1×10-3 was fulfilled (where'p' represents the measured temperature

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using the current mesh size, while 'p+1' represents the temperature for the subsequent finer size of mesh). This process ensures that the computational results stabilise and do not significantly change with further mesh refinement. Specifically, the study focused on evaluating the inside air temperature the solar still to verify grid independence and ensure the reliability of subsequent thermal and fluid dynamics simulations.

RESULTS AND DISCUSSION

ANSYS FLUENT v14.0 solver has been employed to perform numerical CFD analysis, utilising two parallel CPU processors of 3.00 GHz. The solver ensured convergence based on the previously mentioned criteria, allowing for an unsteady simulation over a specified period (Sivakumaran, 2019). Figure 4 illustrates the overall volume fraction of different phases. However, it has been observed that in the early stage, the air volume fraction was predominant because of vapour absence. With the temperature rise, there was a notable rise in the volume fraction of water-vapor, accompanied by a significant decreasein the volume fraction of air. This observation underscores the dynamic changes in phase fractions within the solar still during operation, illustrating the effectiveness of the simulation in capturing the evolving thermodynamic conditions.

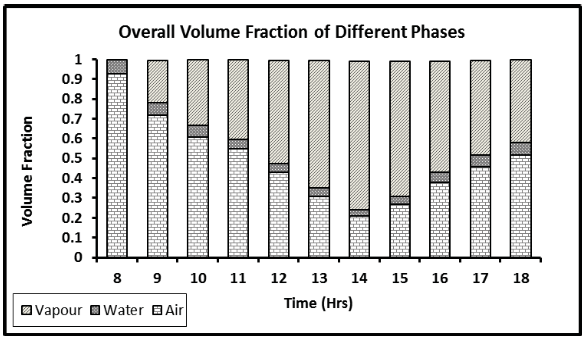

Figure 4: overall volume-fraction of different phases

Further, Figure 5 depicts the corresponding volume fraction of water over time. Red regions indicate higher water volume fractions, while those in blue regions indicate lower water volume fractions.

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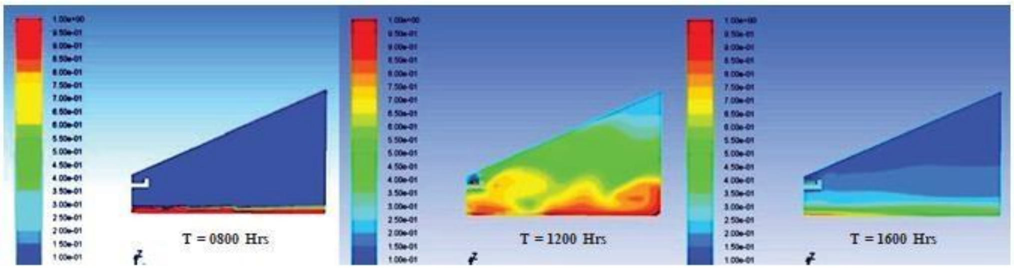

Figure 5: Volume-fraction of water at a specified hour

Figure 6(a) shows the temperature of the water-vapour mixture, while Figure 6(b) displays the water's temperature on the solar still's inner side. Both temperature plots follow the expected trend corresponding to the solar radiation intensity.

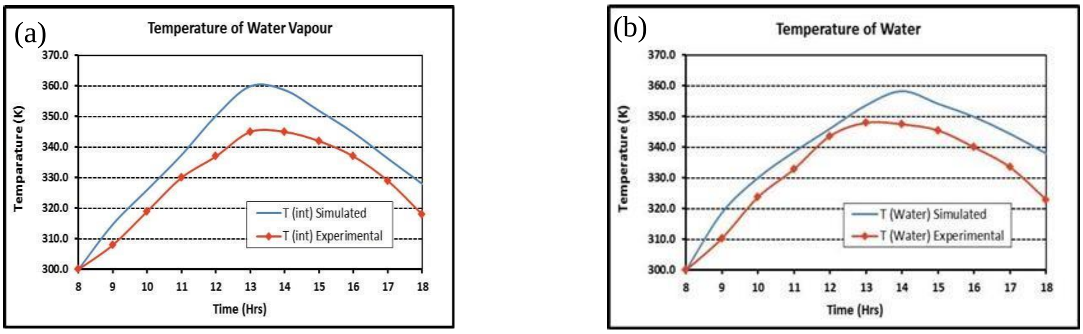

Figure 6: Numerical and Experimental results; (a) Temperature plot of gases phase (water vapour), (b) Temperature plot of liquid phase (liquid water).

The numerical and experimental results were compared, and similar patterns were found, though they were not exact matches. The discrepancy likely arises from the simulation's constant solar radiation intensity assumption without accounting for natural variation. Moreover, Figure 7 shows the solar intensity in simulated and experimental data. It has been verified that the solar intensity of the simulated is more than the experimental results for the period of 13 to 18 hrs.

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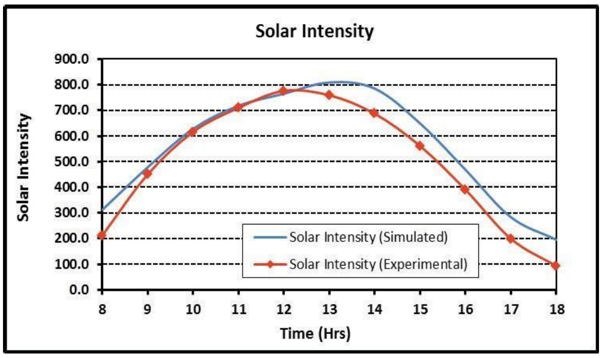

Figure 7: Numerical and Experimental results of solar intensity variations with respect to time

The solar still achieved its peak efficiency of 65% at 14:00 hrs. Higher solar radiation intensity corresponded to increased water distillation due to elevated temperatures. However, as solar radiation intensity decreased, efficiency subsequently declined. Figure 8 illustrates the efficiency trends of the solar still over time.

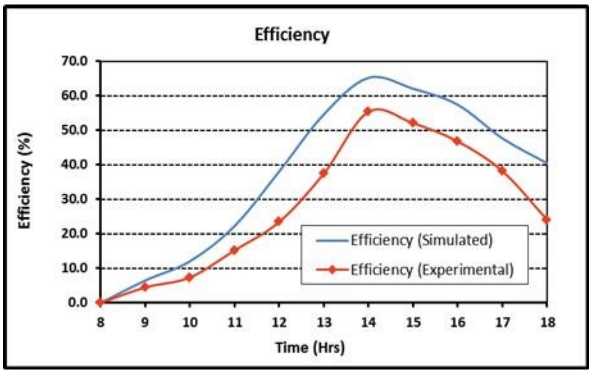

Figure 8: Efficiency of proposed system (solar still) with respect to time

The numerical analysis of the solar still yielded the expected results, showing consistency with the experimental data. The results obtained from simulation and experimentation revealed that both data sets exhibited similar patterns.

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Parametric Analysis of Solar Still

Varying the depth of water

The basin in a solar still serves several crucial functions: it collects incoming radiation from the condensing surface (glass cover) with minimal losses (reflectance and conduction) to the environment. The evaporation process still relies on the natural convection of air, driven by temperature differences between the water basin and the condensing surface (glass cover) (Diabil, 2022). Moreover, the evaporation rate is influenced by the surface area of the water in contact with the solar basin. Figure 9 indicates that the water depth of the basin significantly affects its productivity, with productivity decreasing as water depth increases. This study explores various water depths in the basin through simulations. It has been noticed that the water depth of the basin increases both the efficiency and productivity of the solar still decrease, as shown in Figure 9 and Figure 10.

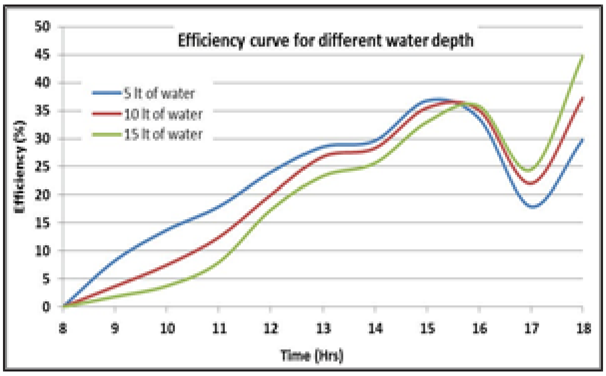

Figure 9: Efficiency of proposed system for different water depth

Moreover, the heat accumulated within the water throughout daytime hours continues to be released without sunlight, enabling continuous production through the night in a solar still. In addition, the volumetric heat capacity of water is lower in shallow basins, consequently resulting in higher water temperatures. This elevated water temperature promotes higher evaporation rates and enhances the productivity of the solar still. Therefore, shallow basins are advantageous in maintaining higher water temperatures and sustaining effective water distillation processes even during periods without direct solar radiation.

Material of basin

Various black materials possess the ability to store significant amounts of energy in the form of heat, leading to an increase in theheat capacity of the solar still basin, thereby increasing

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absorption efficiency (Diabil, 2022). Materials like glass, gravel, and rubber exhibit these beneficial properties. In simulations, it has been observed that using black rubber, characterised by its small size, can boost the still's productivity by 20%. Similarly, employing black gravel can increase productivity by 19%. In addition, Figure 10 demonstrates the productivity by comparing various materials used in the basin, highlighting the efficiency gains achieved by selecting appropriate black materials.

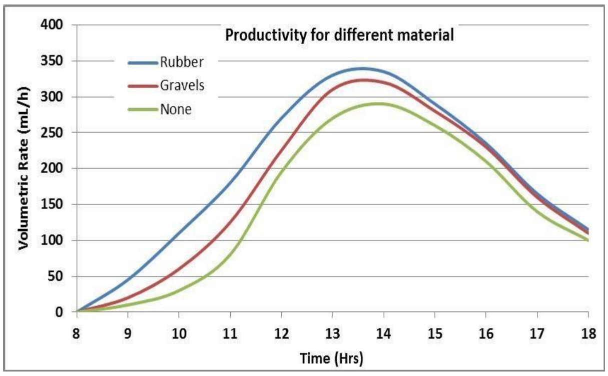

Figure 10: Potable water productivity for different basin material

Effect of maximising the solar radiation

Moreover, the inclination of the condensing surface (glass cover) is refined to receive direct sunlight, and some solar rays inevitably strike the side and back walls of the solar basin, thereby reducing the available radiation absorbed by the basin water (Diabil, 2022). However, a reflective mirror has been incorporated into the model to mitigate this loss to redirect these stray rays onto the basin. Simulation results demonstrate that solar stills equipped with reflective mirrors on their vertical walls exhibit a 22% increase in production rate compared to conventional stills. This enhancement underscores the effectiveness of reflective surfaces in maximising solar energy absorption, thereby improving overall water distillation efficiency.

CONCLUSION

In conclusion, addressing the global challenge of accessing freshwater requires innovative and sustainable purification technologies. Solar distillation, mainly through single-slope solar stills, offers a promising solution, especially in arid regions with abundant sunlight. Despite their advantages, such as simplicity and low cost, single-slope solar stills face efficiency limitations. However, integrating phase change materials (PCMs) and reflective mirrors and

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optimising basin design can enhance their performance. CFD simulations corroborate experimental findings, demonstrating the potential for improved productivity through parametric analysis and material selection. Moreover, adding reflective mirrorssignificantly boosts production rates, showcasing the importance of maximising solar radiation absorption. These advancements underscore the feasibility of single-slope solar stills as sustainable solutions for water scarcity, offering hope for meeting global water needs. Thus, the proposed system provides sustainable and reliable water solutions through renewable solar power as a clean energy.

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