Optimizing Heat Transfer in Hybrid Solar Desalination with Nano-Enhanced Phase Change Materials"

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Abstract - *Pure water is essential for human life along with agriculture, industry, and environmental sustainability, necessitating efficient purification methods. This study investigates an innovative solar distillation system incorporating a passive built-in solar water heater to enhance efficiency in regions with abundant solar energy. Solar stills augmented with phase-change materials and nanoparticles were evaluated through combined experimental and theoretical approaches.*

The integration of nano additives, particularly with paraffin wax, significantly improved system performance, yielding higher productivity, efficiency, and CO_2 reduction. The modified stills demonstrated energy efficiency improvements of 35.23%, 44.12%, and 46.81%, alongside productivity increases of 37.8%, 22.5%, and 33.5%. The results underscore the economic and environmental viability of enhanced solar desalination systems, offering a promising solution for sustainable water purification.

Key Words **Hybrid Solar stills; Exergy Approach; Yield; Phase change material; Nanoadditives**

1.INTRODUCTION

Energy is a fundamental and essential element in our daily lives. Solar energy is a particularly promising source since it's virtually inexhaustible. The available energy of abundant sunshine in India, particularly in rural and tropical regions, is a valuable natural resource for harnessing solar energy. As mentioned, the global solar radiation received in a particular location is affected by various factors, like cloud cover, amount of water vapor in the atmosphere, and other elements like dust particles, carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), and ozone (O_3). The quantity of energy from sun which comes the Earth's outer surface can be influenced by these variables [1-2]. Most of this solar resource, it's essential to analyze long-term meteorological data on solar radiation [3]. Such data can help in understanding not only the interrelationships between different components of solar radiation but also the statistical characteristics of their distributions. This analysis can be critical for designing and optimizing solar energy systems and predicting energy generation patterns [4].

One approach mentioned is the calculation of total radiation hourly values by comparing them to daily solar radiation. This approach is common in solar energy modeling and forecasting. By examining how daily solar radiation relates to hourly values, researchers and engineers can develop models and algorithms to estimate solar radiation levels at finer time intervals. These models consider factors like cloud cover, atmospheric conditions and geographical location to provide more accurate and detailed solar radiation predictions [5][6].

In India's context, where solar energy potential is high, such analyses and modeling efforts are important for the effective deployment of solar power systems. Additionally, advancements in solar technology and improvements in forecasting techniques can further enhance and improve the utilization of energy from sun in the country [4]. One of the big issues of clean drinking water availability faces the world today, particularly in coastal areas [11]. The most vital element in our daily existence is water; without it, life is impossible. The growing population increases the requisite for drinking water. A solar desalination process is used to solve this issue and produce drinking water by converting salty water into fresh water by harnessing solar energy [10].

Solar stills are indeed a simple yet effective method for distilling water using the heat of the sun. They are Specifically valuable in areas where access to clean and safe drinking water is limited or impractical [5][6]. Mainly two basic types of solar stills: the box type and the pit type, each with its own design and operational characteristics [7]. Solar stills are a reliable source of pure drinking water in villages and rural remote areas, the places where access to conventional water sources is limited [8][9]. However, it's important to remember that solar stills' efficiency can be impacted by a number of variables, like weather conditions, the angle and orientation of the still, and the quality of cover material [10]. therefore, the output of pure water from a solar still may be relatively small, and it may not be suitable for large-scale water supply. Nevertheless, they are a valuable tool for providing clean water in specific situations and can be a life-saving technology in areas with water scarcity [10][11].

The conventional solar still unit is a system designed to purify impure or saline water by using energy of sun. It operates on the principle of harnessing the sun's heat to evaporate impure water, leaving behind

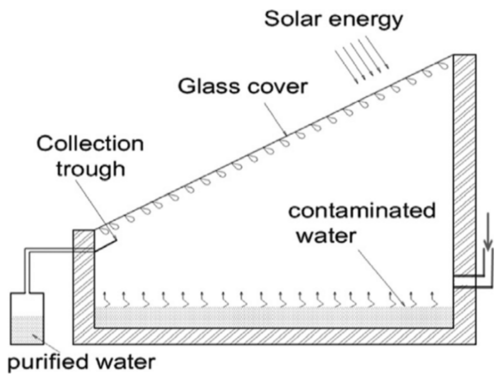

Figure 1 Distillation process on solar still

contaminants and salt, and then condensing the water vapor to obtain pure, drinkable water [12-13]. Water from different sources is either too salinized (i.e., having dissolved salts) or microbe that are harmful to drink [15-16].The process of desalination, which transforms salty water into fresh water, provides a crucial remedy for these issues [17].The capacity of desalination worldwide is currently estimated to be approx. 664 lakh m^3/d, in 2015, while it is predicted to reach roughly 1000 lakh m^3/d [18].In country like Arabian country 17.5%, UAE 14.8%, United States 16.2%, Spain 6.4%, and Kuwait 5.8% have the highest desalination capacity [19].

Solar stills are an effective choice for self-sufficient and low-capacity water supply systems, as they solely require solar radiation to generate potable water, avoiding the need for external energy sources like fuel or electricity [20]. Because of its poor productivity, solar stills are not widely used. Various researchers have conducted numerous studies in an attempt to increase output and efficiency of stills [21][22]. Important variables influencing productivity performance and efficiency of solar desalination like stills include wind speed, thickness, material of glass cover, depth of basin water, location, ambient temperature, and solar radiation intensity [23]. The solar still's maximum efficiency recorded was 5 L/m^2.day of production of fresh water under ideal operating conditions [27-29].

Parsa et al. [26] found that employing an external condenser and nanofluid, solar desalination outperformed CSS. They found that the silver nanoparticles increased productivity and had antimicrobial properties at the same time. Shoeibi et al. [32] used nanofluid to enhance the evaporation and condensation area through double slope solar desalination. A variety of nanoparticles, like TiO_2, AL_2O_3, MWCN and CuO, were mixed with water to create a nanofluid. The findings showed that concentrations of nano powders are directly impacted by CO_2 mitigation. Thermoelectric power solar desalination's environmental parameters were assessed in a numerous study conducted by Shoeibi et al. [37]. The findings showed that the system's environmental parameters are increased when a thermoelectric module and heat sink are used. D.B. Singh et al. [45] worked with medium-clustered nanoparticles in their system. Water + TiO_2 and Water + Al_2O_3 are employed as nanoparticles at varied concentrations. C. Gnanavel et al. [46] conducted an experimental analysis of productivity in Chennai and corroborated their findings using CFD studies. Karthikeyan Alagu et al. [47] used PCM's to improve solar still efficiency and performance which mixed 1% concentrated nanofluid in water. Productivity of solar desalination improves and enhances by using nano additives along with phase change material's [49-51].

2. Construction and Fabrication of Solar Still

The molecules of water vapor are contained in the area that the solar still encloses and large number of air particles. These molecules are moving randomly and could collide with the glass cover and the wall surfaces inside. When the sun rises in the early morning, solar radiation intensity enters the solar still via transparent glass material and strikes the water within. Because of kinetic energy, the still's interior temperature rises, increasing molecular motion. As a result, the molecules crash into one another quickly. Because of this, the molecules of vapor near the walls adhere to them and release condensation heat, changing their phase from vapor to liquid. As a result, yielding begins very early because of solar radiation, which only produces distillate when glass covers (caused by opaque, toughened transparent glass sheets and the walls' sides) receive enough solar radiation. As the sun moves from due south to west, the walls and the glass coverings allow the most solar radiation to enter. Because of their high absorptivity, the wall and basin liner absorb a significant portion of this radiation. The water evaporates as a result of convection, which transfers heat by the basin into the water. The condensation process begins when molecules of vapor come into contact with the glass covers and walls through collision of molecules. The condensate is directed by the troughs into the outside collection jars.

In this paper two experimental setup are constructed to analyze the productivity, heat transfer and exergy. The present experimental setup made single slope type solar still using opaque and crystal-clear toughened glass having a thickness of 7 mm as cover and also another setup of a modified Single slope PCM and nano particle based solar still. In the present setup flat plate type solar collector couple with water heater is used to enhance the productivity of still.

3. Experimental methodology

To evaluate the influence of various parameters on solar still productivity, hourly measurements are conducted under controlled conditions. Key parameters recorded include sun intensity, wind speed, ambient temperature, wet and dry bulb temperatures, glass surface temperatures (inside and outside), vapor temperature, basin water temperature, plate temperature, and distilled water output. With a constant basin water mass of 3.2 kg, the water level in the solar basin is initially maintained at 15 mm, and readings are taken hourly until sunset. The same procedure is repeated by changing PCM ensuring comprehensive data collection to assess the system's performance under varying conditions.

Figure 2: Pictorial view of Experimental Setup

4.Thermal analysis of solar desalination

According to the energy balance equations at different parts of the solar still [53,54], the rate at which energy is lost to air is equal to the rate at which energy is acquired by the glass and from the water surface to the glass through radiation, convection, and evaporation.

4.1 Heat transfer outside Surface of Glass cover:

Rate of energy received from inner glass cover by conduction = Rate of energy lost to the ambient by convection and radiation

K_g/L_g□T_{gi} □T_{go} □□□ $q_{r,g}$□a □$q_{c,g}$□a. (1)

K_g/L_g (T_{gi} □□T_{go} □□□□$q_{r,g}$□a □T_{go} □T_a □ (2)

4.2 Heat transfer inside Surface of Glass cover:

Rate of energy absorbed from solar radiation + Rate of energy received from water mass by convection, evaporation and radiation = Rate of energy trans- ferred to glass outside surface

K_g/L_g□T_{gi} □T_{go} □□□□□$_g$ I□□t□$_s$ □ $q_{r,w□g}$ □ $q_{c,w□g}$ □ $q_{e,w□g}$ (3)

4.3 Heat transfer in basin liner

Rate of energy absorbed from solar radiation + Rate of energy lost to water mass by convection = Rate of energy lost to the ambient by conduction and convec- tion

□□□□□□□□□□□□□□ □□□□□□□□□□q_w□ □□q_b □□□
(4)

4.4 Energy balance for mass of water

Rate of energy absorbed from solar radiation + Rate of energy received from ba- sin liner by convection + Rate of energy received from external devices = Rate of energy stored + Rate of energy lost to the glass inner surface by convection, evaporation and radiation

□$_g$□ □□□t□$_s$□ □□q□□Q□ □□□□□□□□□w□□□t□ □□□$q_{r,w□g}$ □ $q_{c,w□g}$ □ $q_{e,w□g}$□□
(5)

4.5 Total Overall thermal efficiency

The solar still unit's overall thermal efficiency is as follows:

$$\eta_{passive} = \frac{\sum m_w \,.\, L}{A_s \int I(T)dt} \times 100 \quad (6)$$

$$\eta_{active} = \frac{\sum m_w \,.\, L}{[A_s \int I(T)dt + NA_c \int I'(t)dt]} \times 100 \quad (7)$$

5.Result and discussions

By raising the temperature differential between the water mass and condensing cover, solar radiation—which is impacted by location and climate—significantly increases the productivity of solar stills and increases distillate production.

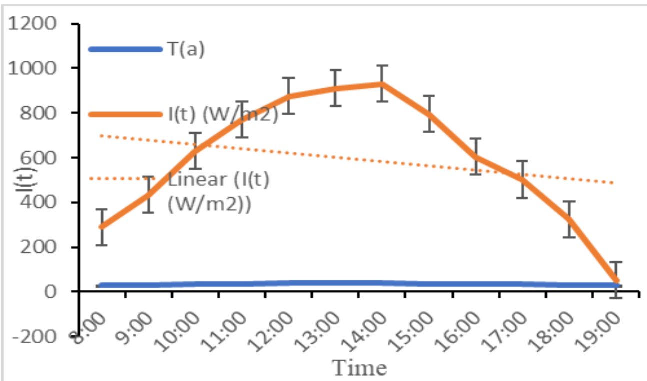

Figure 3 Variations in solar radiation on a solar still

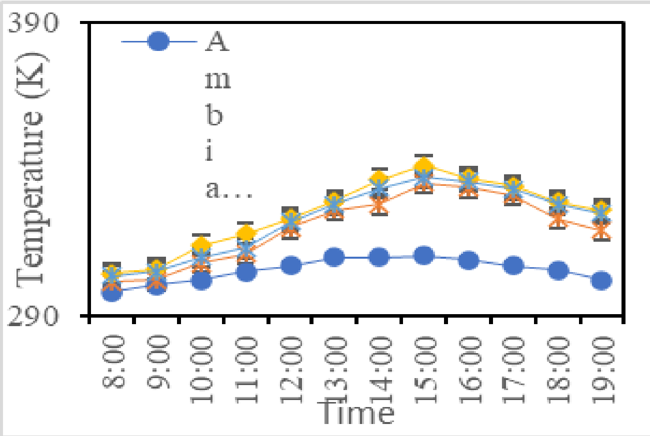

Figure 4 Variation in Basin Temperature with Various PCM in Solar Still

Figure 4 shows and explains how temperature of the basin changes with the surrounding air temperature for various PCMs.Additionally, it is discovered that the paraffin wax having basin temperature is higher than the other PCM basin temperatures. The figure 4 depicts variation of basin ambient temperature with respect to time from 8 am to 7 pm evening

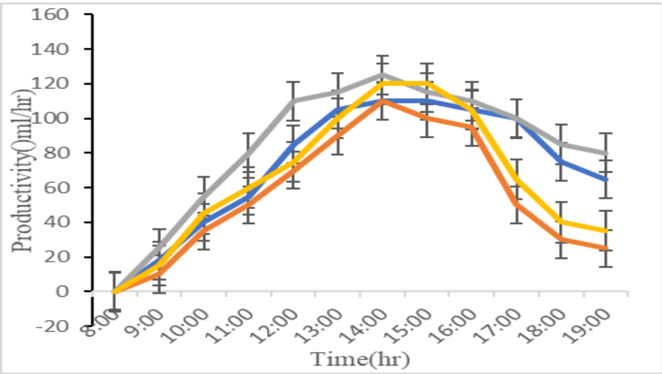

Figure 5 : Hourly Productivity of still with PCM's and without PCM's

Figure 5 illustrates the hour-based productivity variation of the solar still in all setups and compares the hour based yield production of pure ware from the solar still with PCM from morning 8:00 to evening 19:00. It is determined that PCM1 results in 36.61% higher productivity when compared to a solar still without PCM. When we use a solar water heater, the yields increase by 28.17% more.

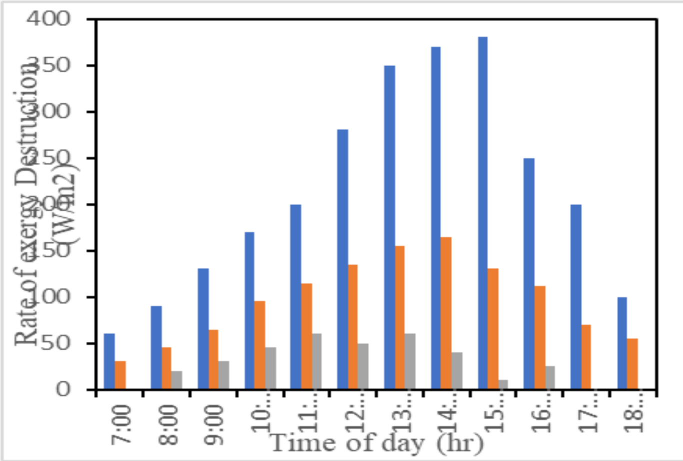

Figure 6 irreversibility rate in hourly variation

Figure 6 compares the hourly productivity variation using different constraints on a solar still and displays the hourly yield productivity from morning 8:00 hrs to evening 19:00 hrs. It compares the yield when there is no PCM, when there is a PCM . Both with and without a solar water heater attached to a flat plate collector,

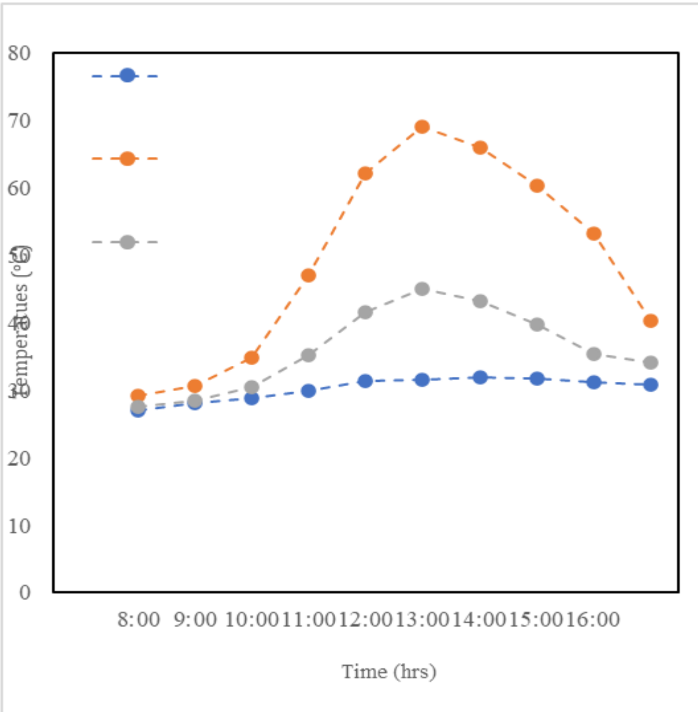

Figure 7 Temperature variation on still

these yields are found in SSSS and MSSSS. Through experimentation, it was discovered that using PCM and CuO in conjunction with a solar heater produced a higher yield, peaking at 3 p.m. Additionally, it is discovered that using PCM still results in a higher yield when compared to not using PCM.

Figure 7 illustrates temperature variations over time, from 8:00 to 16:00 hrs, for three lines represented by blue, orange, and gray dashed lines. The orange line shows the water temperature inside the still having highest temperature trend, peaking at around 70°c around noon before gradually declining in the afternoon. The glass temperature of still in gray follows a moderate trend, with temperatures reaching a maximum of approximately 60°C at midday. The ambient temperature in solar still in blue represents the lowest temperature, remaining relatively stable at around 40°C throughout the day. Overall, temperatures for all three sets rise during the morning, peak at noon, and then decline in the afternoon.

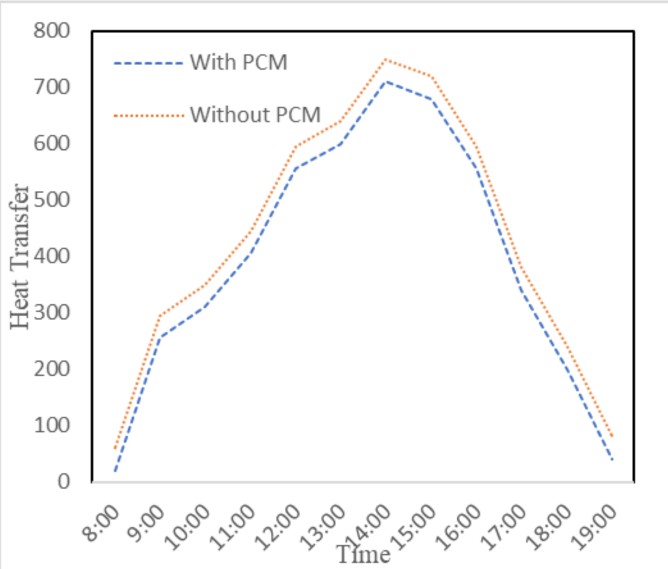

Figure 8 Hourly fluctuations of heat transfer

Figure 8 illustrates the variation of heat transfer to the working fluid by a Solar still over the experiment duration. PCM integrated Solar still was used to preheat water by directing sunlight toward the focal line of the with and without PCM. Heat transfer improvement was found to be 134.12, while using PCM

6. CONCLUSIONS

Solar stills play a vital role in providing pure potable water, especially in remote and rural coastal areas. This study evaluated the performance of solar desalination devices enhanced with phase change materials (PCMs) such as paraffin wax, stearic acid, and lauric acid, along with copper oxide nanoparticles as energy storage and efficiency-boosting elements. Two solar stills, one modified with PCMs and nanoparticles and one unmodified, were constructed and analyzed under identical conditions. A solar water heater was also integrated into the system to investigate its effect on performance. Hourly productivity of both conventional and modified solar stills was recorded and compared to assess improvements. The results revealed that the modified solar still, especially when connected to the solar water heater, demonstrated significantly higher productivity than the conventional system. The use of PCMs and nanoparticles enhanced energy storage and thermal performance, while the solar water heater amplified temperature differences, leading to increased distillation rates. These modifications highlight a promising approach to improving the efficiency of solar desalination systems for sustainable water production.

REFERENCES

[1] Akash, B.A.; Mohsen, M.S.; Osta, O.; and Elayan, Y. (1998) "Experimental evaluation of a single basin solar still using different absorbing materials "Renewable Energy, 14(1-4), 307-310.

[2] Alawee, W.H. (2015). "Improving the productivity of single effect double slope solar still by simple modification" Journal of Engineering, 21(8), 50-60.

[3] Alawee, W.H.; Dhahad, H.A.; and Mohamed, T.A. (2015) "An experimental study on improving the performance of a double slope solar still" The seventh International Conference on Sustainable Agriculture for Food, Energy and Industry in Regional and Global Context. Selangor, Malaysia, 1-10.

[4] Al-Jayyousi, O." Renewable Energy in the Arab World: Transfer of Knowledge and Prospects for Arab Cooperation" Friedrich Ebert Stintung: Bonn, Germany, 2015; ISBN 978-9957-484-54-5.

[5] Solar Still using Phase Change Material (Paraffin Wax) Meganathan. V, Sriman Saii. P. V, Sreerag. S, Santhanakrishnan. S Department of Mechanical Engineering, Meenakshi Sundararajan Engineering College, Tamil Nadu, India 2019

[6] Kantesh D.C ,'Design of solar still using Phase changing, material as a storage medium" (2012).

[7] R. Dhivagar et al.,"A case study on thermal performance analysis of a solar still basin employing ceramic magnets" Case Studies in Thermal Engineering Journal (2022).

[8] Mahmoud S. El-Sebaey et al.," Experimental study and mathematical model development for the effect of water depth on water production of a modified basin solar still" Case Studies in Thermal Engineering Journal (2022).

[9] Velmurugan V, Sritha K, Performance analysis of solar still based on various factors affecting the productivity a review. Renew. Sustain. Energy Rev; 15:1294-304 (2011).

[10] G.N. Tiwari, "Solar energy: fundamentals, design, modeling and application," New York/New Delhi Narosa Publishing House.

[11] R.H. Myers & and D. Montgomery, "Response surface methodology: process and product optimization using designed experiments," 2nd edn. Wiley, USA (in press)

[12] A.S. Nafey, M. Abdelkader, A. Abdelmotalip, and A.A. Mabrouk, Energy Convers Manage 937–946, 43 (2002).

[13] A. Sarı, Energy Convers Manage 2277–2287, 44(14) (2003).

[14] S.K. Shukla, and V.P.S. Sorayan, Fuel Energy Abstr 683–699, 30(5) (2005).

[15] D.C. Montgomery, "Design and analysis of experiments," 5th edn. Wiley, New York.

[16] P.H. Gleick "The World's Water 2008-2009 the Biennal Report on Freshwater Resources," Island Press, Chicago (in press)

[17] Global Water Intelligence (GWI/IDA Desal Data), Market profile and desalination markets, 2009–2012 yearbooks and GWI

[18] A. Khawaji, I. Kutubkhanah and J. Wie, Desalination 47–69, 221 (2008).

[19] E.l. Sebaii, A. A.l. Ghamdi, F. Al-Hazmi and A. Faidah, Applied Energy 1187-1195, 86 (2009).

[20] H. Mousa, and M. Abu Arabi, Desalination and Water Treatment 1296-1301, 51 (2012).

[21] S. M. Shalaby, E. El-Bialy and A. A. El-Sebaii, Desalination 247-255, 398 (2016).

[22] A. Kabeel and S. El-Agouz, Desalination 1-12, 276 (2011).

[23] R.F. Service, Desalination freshens up. Science 1088–1090, 313 (2006).

[24] Sandia, Desalination and Water Purification Roadmap – A Report of the Executive Committee. DWPR Program Report #95. U.S. Department of the Interior, Bureau of Reclamation and Sandia National Laboratories (2003).

[25] Parsa SM, Rahbar A, Koleini MH, Aberoumand S, Afrand M, Amidpour M. A renewable energy-driven thermoelectric- utilized solar still with external condenser loaded by silver/ nanofluid for simultaneously water disinfection and desalination. Desalination. 2020; 480:114354.

[26] Dhivagar R. A concise review on productivity and economic analysis of Auxiliary-component-assisted solar stills. *Energy Technol*. 2021;9(11):2100501.

[27] Dinesh Mevada et al.,"Experimental performance evaluation of solar still with zig-zag shape air cooled condenser: an energy exergy analysis approach" Energy Rep.(2023).

[28] A. Saxena et al.," A thermodynamic review on solar stills" Sol. Energy (2022)

[29] R. Sathyamurthy et al.," A review of integrating solar collectors to solar still" Renew. Sustain. Energy Rev (2017).

[30] A.K. Thakur et al.," Synergetic effect of absorber and condenser nano-coating on evaporation and thermal performance of solar distillation unit for clean water production Sol." Energy Mater. Sol. Cells (2022).

[31] Parsa SM, Rahbar A, Javadi Y D, Koleini MH, Afrand M, Amidpour M. Energy-matrices, exergy, economic, environ- mental, exergoeconomic, enviroeconomic, and heat transfer (6E/HT) analysis of two passive/active solar still water desalination nearly 4000m: altitude concept. J Clean Prod. 2020; 261:121243.

[32] Elango C, Gunasekaran N, Sampathkumar K. Thermal models of solar still—a comprehensive review. Renew Sustain Energy *Rev*. 2015; 47:856-911.

[33] Shoeibi S. Numerical analysis of optimizing a heat sink and nanofluid concentration used in a thermoelectric solar still: an economic and environmental study. *Environ Res Eng Manag*. 2021;77(2):110-122.

[34] Tiwari G.N, Solar Energy, Fundamental design, modelling and application: Naraosa Publication New Delhi; Revise Edition 2013.

[35] A.K. Thakur et al.," Augmented perfor- mance of solar desalination unit by utilization of nano-silicon coated glass cover for promoting drop-wise condensation" Desalination (2021).

[36] Shoeibi S, Rahbar N, Abedini Esfahlani A, Kargarsharifabad H.," Improving the thermoelectric solar still performance by using nanofluids– experimental study, thermodynamic modeling and energy matrices analysis" *Sustain Energy Technol Assess*, 2021; 47:101339.

[37] Shoeibi S, Kargarsharifabad H, Rahbar N, Ahmadi G, Safaei MR. Performance evaluation of a solar still using hybrid nanofluid glass cooling-CFD simulation and environmental analysis. Sustain Energy Technol Assess. 2022; 49:101728.

[38] Shoeibi S, Kargarsharifabad H, Rahbar N, Khosravi G, Sharifpur M. An integrated solar desalination with evacuated tube heat pipe solar collector and new wind ventilator external condenser. Sustain Energy Technol Assess. 2022; 50:101857.

[39] Hassani M, Rahbar N. Application of thermoelectric cooler as a power generator in waste heat recovery from a PEM fuel cell–an experimental study. *Int J Hydrogen Energy*. 11/16 2015; 40:15040-15051.

[40] Sharma et al., Incorporating the Social Dimension into the Assessment of Urban Water Services: with a particular focus on Greenfield development" National research flagship, water for healthy country (2009).

[41] Mohammed M Farid , Amar M Khudhair, Siddique Ali K Razack , Said Al-Hallaj, "A review on phase change energy storage: materials and applications" Energy Conversion and Management Volume 45, Issues 9–10, June 2004, Pages 1597-1615 (2004).

[42] L.F. Cabeza , A. Castell, C. Barreneche, A. de Gracia , A.I. Fernández, "Materials used as PCM in thermal energy storage in buildings: A review" Renewable and Sustainable Energy Reviews,Volume 15, Issue 3, April 2011, Pages 1675-1695 (2003).

[43] Atul Sharma [a], V.V. Tyagi [b], C.R. Chen [a], D. Buddhi [b]," Review on thermal energy storage with phase change materials and applications" Renewable and Sustainable Energy Reviews,Volume 13, Issue 2, February 2009, Pages 318-345(2009).

[44] Ashok kumar Singh, D.B.Singh , V.K.Singh, A. Guptta; "Water purification using solar still with/without nano fluid: A Review" Material Today: Proceedings.(2019).

[45] C. Gnanavel, R.Saravanam , M. Chandrasekaran; "CFD analysis of solar still with PCM" Material Today: Proceedings.(2020).

[46] Karthikeyan alagu. SivaReddy, M, Narendea kumar, Anderson Arun Gnana Dhas; "Solar desalination using solar still enhanced by PCM and nano fluid" (2020),AIP Conference Proceeedings2311,090008(2020).

[47] Shiparo and Moran , A book "A Fundamental of Thermodynamics", seventh edition, John Wiley & Sons, Ltd, New Jersey, U.S., (2014).

[48] Santosh kumar Gupta, Devesh kumar," Performance Enhancement of Solar Still Couples With Solar Water Heater by Using Different PCM's and Nanoparticle Combinations", Energy Storage, (2024),John Wiley& Sons Ltd, https://doi.org/10.1002/est2.70023

[49] Z. Ling, J. Liu, Q. Wang, W. Lin, X. Fang, Z. Zhang, $MgCl_2.6H_2O$-$Mg(NO_3)_2·6H_2O$ eutectic/SiO_2 composite phase change material with improved thermal reliability and enhanced thermal conductivity, Sol. Energy Mater Sol. Cells 172 (2017) 195-201, https://doi.org/10.1016/j.solmat.2017.07.019.

[50] Y. Zhang, X. Zhang, Thermal properties of a new type of calcium chloride hexahydrate-magnesium chloride hexahydrate/expanded graphite composite phase change material and its application in photovoltaic heat dissipation, Sol. Energy 204 (2020) 683-695, https://doi.org/10.1016/j.solener.2020.05.037

[51] V.K. Singh, D. Kumar, Sanjay, Thermal characteristics of hydrated salt blended with TiO_2 for thermal energy storage, Heat Transf. 51 (6) (2022) 5368-5385, https://doi.org/10.1002/htj.22551.

[52] V. Pethurajan, S. Sivan, Fabrication, characterisation and heat transfer study on microencapsulation of nano-enhanced phase change material, Chem. Eng. Process. 133 (2018) 12-23, https://doi.org/10.1016/j.cep.2018.09.014

[53] Omar Badran, O. (2011) Theoretical Analysis of Solar Distillation Using Active So- lar Still. *International Journal of Thermal & Environmental Engineering*, **3**, 113-120. https://doi.org/10.5383/ijtee.03.02.009

[54] Tripathi, R. and Tiwari, G.N. (2006) Thermal Modelling of Passive and Active Solar Stills for Different Depths of Water by Using the Concept of Solar Fraction. *Solar Energy*, **80**, 956-967. https://doi.org/10.1016/j.solener.2005.08.002