The Role of Phase Change Materials in Solar Still Efficiency: A CFD-Based Review

Mayank Paswan[1], Sanjay Kumar Singh[2], Shivshankar V. Choudri[3]
[1]Research scholar,Department of Mechanical engineering, SISTECH BHOPAL(M.P.)
[2]Professor,Department of Mechanical engineering, SISTECH BHOPAL(M.P.)
[3]HOD,Department of Mechanical engineering, SISTECH BHOPAL(M.P.)
[1]Mrigankp299@gmail.com, [2]sanjaysingh@sistec.ac.in, [3]sistec.hodme@sistec.ac.in

* Corresponding Author: Mayank Paswan

Abstract: *By converting salty water into drinkable water, solar desalination uses abundant, sustainable solar energy to address the global problem of freshwater scarcity. In areas like Africa and the Middle East where freshwater resources are scarce, this technique is essential. There are two types of solar distillation: direct and indirect. Direct techniques use sun radiation to directly evaporate and condense water, while indirect methods use solar collectors to improve the distillation process. Notwithstanding the advantages of solar desalination, problems with limited output and expensive setup continue to exist. Phase change materials (PCMs) have become a viable way to improve heat storage and temperature stability in solar stills, thus increasing efficiency. Through the simulation of fluid flow and heat transfer processes, computational fluid dynamics, or CFD, is a key component in the optimization of solar still performance. This review emphasizes the use of CFD in solar stills, highlighting a number of experiments that show improvements and promise in PCM integration. The results of the research highlight the value of CFD in improving solar desalination systems and provide an overview of recent advancements and potential future research areas.*

Keywords:*Solar Desalination, Phase Change Materials (PCMs), Computational Fluid Dynamics (CFD), Solar Still*.

I. Introduction

The process of extracting freshwater from salty water by using direct sunshine is known as solar desalination. Direct sunlight is used in this method. Desalination is a process that involves evaporation, which uses solar energy directly. Solar energy is widely available and cost-free for everyone on the planet. It doesn't negatively affect the environment. further on, the evaporated water condenses and is gathered for further use. In regions of Africa and the Middle East where there is a shortage of drinkable water, this method is growing in favor. Creating an economical desalination setup is difficult since the energy-intensive process of extracting salt from saltwater raises the setup costs. Due to its low cost, desalination using sun radiation is a very appealing option. Due to water contamination and human consumption, freshwater supplies worldwide are fast disappearing, prompting significant developments and improvements in this field. Demand for and consumption of freshwater are growing steadily as the world's population continues to rise and as the amount of freshwater that is currently available is steadily decreasing due to pollution and use. 25% of our planet is made up of land, and 75% is made up of water. Merely 3% of this water is freshwater, and the remaining 97% is saltwater, which is unsuitable for direct use in our daily activities. Just 32% of the total freshwater is accessible to humans; the remaining 68% is preserved in ice caps. A little over 32% of the water in lakes, ponds, rivers, tube wells, etc. is taken out. We're losing sight of this water, which is unfortunate. There aren't enough timely rain, rivers and ponds are drying up, and the water table is declining [1].

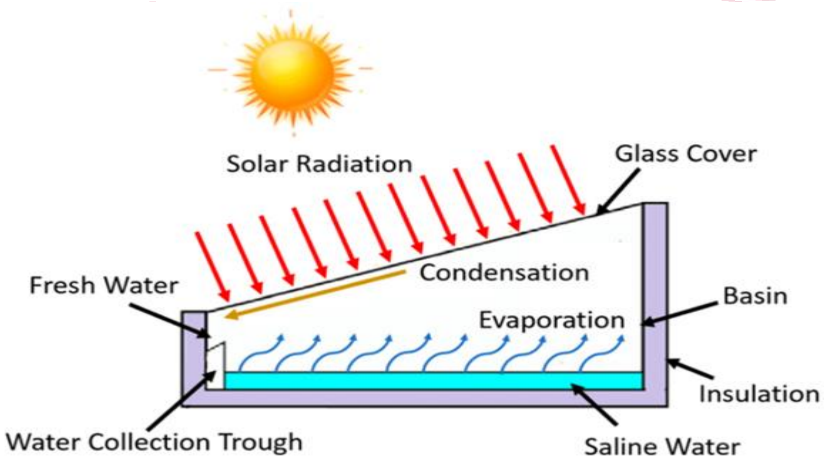

Figure 1 The working principle of a solar still [2]

Desalination, or the process of removing salt and other minerals from water, is one way to address this issue. To be more precise, desalination converts seawater into freshwater that is suitable for human use [3]. Desalination has so been emphasized as the main way to address the rising demand for freshwater. There are two types of solar desalination: direct and indirect. While indirect desalination uses assisted solar collectors built within a solar still to collect energy, direct desalination uses solar energy to directly convert salty water into distilled water [4]. While some works use distillation as a direct desalination strategy, several indirect desalination techniques are being used in practice, including multi-effect desalination, membrane distillation, humidification and dehumidification, solar pond, multi-stage flash desalination, and vapor compression desalination. An economical method that dates back centuries are distillation for desalinating saltwater. A straightforward technique for turning brackish or saltwater using solar energy into drinkable water is solar distillation [5].

Solar distillation employs solar energy stored in a device known as a solar still, which consists of a shallow bowl (basin) with a transparent glass cover, to filter water. The saline water in the basin is heated by sun radiation to aid in its evaporation. The salts, minerals, and other contaminants, including bacteria, are left behind as the moisture rises, condenses on the cover glass, and finally drips into a collection trough. Even though building a sturdy and efficient solar still can be costly, with the right design, generation, and upkeep, this equipment can generate clean water at a fair price. Unfortunately, the solar stills are rather expensive due to their low output and efficiency. Using phase change materials (PCMs) in thermal energy storage (TES) is one way to increase the freshwater yielding of these systems [6].

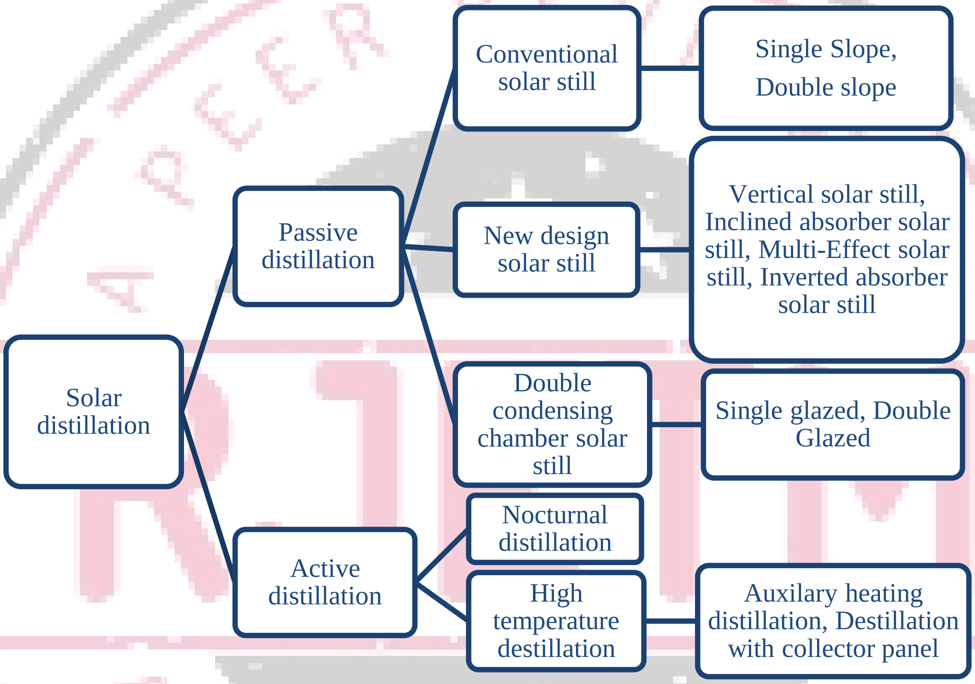

Figure 2 Classification of solar distillation [7]

This diagram shows the many kinds of solar distillation systems. They are divided into two categories: passive and active distillation techniques. Traditional sun stills (single and double slope), modern design stills (vertical, inclined absorber, multi-effect, and inverted absorber), and double condensing chamber stills (single and double glazing) are examples of passive distillation. Night distillation and high-temperature distillation methods, like auxiliary heating and distillation using collector panels, are included in the category of active distillation techniques.

China must deal with the problems of energy scarcity and rising environmental pollution as a nation with a fast-developing economy and high annual energy consumption. If clean energy is used in place of primary energy, it can successfully ease the strain on available resources and lower environmental pollution at the same time. Solar energy has emerged as a key concern in the realm of energy development and utilization as a clean energy source. The benefits of solar heating include safety and cleanliness; the drawbacks include instability, hourly radiation offset, and building load characteristics. In order to retain energy, an additional heat storage water tank is required; however, the standard heat storage tank has significant heat loss and takes up a lot of space. Encapsulated phase change material (PCM) can be added to heat storage water tanks to reduce tank volume while simultaneously absorbing and releasing heat continuously. This is because PCM transfers heat steadily and helps prevent the negative effects of boiling water in the tank and too-fast temperature drops at night. Nevertheless, PCMs have the drawbacks of having a poor coefficient of thermal conductivity, which results in a low heat transfer efficiency during heat charging and discharging and frequently the inability to store and release heat rapidly. Thus, increasing its heat transfer capability has emerged as a popular research topic for academics. This article provides a detailed explanation of the research methodologies, advancements in PCM research, and technologies for enhancing heat transmission. It also lists the many kinds of PCM-filled water tanks and their applications. It ultimately determines the path of future study on the water tank with PCM. Enhancing the utilisation of solar energy resources is immensely important [8].

II. CFD Modeling Techniques for PCM-Integrated Solar Stills

One way to define computational fluid dynamics (CFD) is as a collection of methods that help a computer generate a numerical simulation of fluid flows. The physical properties of every fluid can be ascertained using three fundamental principles: (i) energy conservation; (ii) Newton's second law; and (iii) mass conservation. These fundamental laws can be used to explain this flow problem. The fluid behaviour in the flow domain was represented using mathematical equations, which are often partial differential equations. These days, a variety of industries, including shipbuilding, automobile design, turbo machinery, and aircraft manufacture, frequently use CFD techniques. It also helps with oil recovery, biology, oceanography, meteorology, astrophysics, and architecture. To conduct CFD analysis, a wide range of software and numerical algorithms have been developed. PC clusters can also be used to analyse numerical simulation for physically and geometrically complicated systems, thanks to recent advancements in computer technology. Supercomputers can complete large-scale simulations in various fluid flows on grids with millions or even trillions of elements in a matter of hours [9].

The basis of CFD models is provided by fundamental equations controlling fluid flow and heat transmission, such as the mass conservation equations, the Navier-Stokes equations for fluid dynamics, and the energy equations for heat transfer. To accurately characterize the behaviour of the PCM and the working fluid (water) throughout the sun distillation process, these formulas are required in solar stills. The Finite Volume Method (FVM), which discretises these governing equations into algebraic forms that may be solved numerically, is typically used. There are special difficulties with integrating PCMs into solar stills, especially when modelling the phase transition process. In CFD simulations, the enthalpy-porosity approach is frequently used to describe the melting and solidification of PCM. By taking into consideration the PCM's latent heat storage capacity, this technique allows the simulation to forecast how the PCM collects heat during the day and releases it at night to maintain the solar still's temperature. In solar stills with PCM integration, conduction, convection, and radiation are the main modes of heat transfer. This system becomes more complex due to the phase change process, which incorporates both sensible and latent heat transmission. In order to precisely represent the convective heat transfer occurring inside the fluid, CFD models usually incorporate turbulence models, such as the k-ε or k-ω models. Another important factor that affects the effectiveness of the PCM in raising the solar still's overall efficiency is the heat transfer from the PCM to its surroundings.

III. Critical Analysis of Existing CFD Studies on PCM in Solar Stills

Seven important research on computational fluid dynamics (CFD) and solar still performance are summarised in a comparative manner in the table. The focus, CFD approach, results, and performance measures of each study are examined. A thorough analysis of CFD applications in solar stills is given by Kabeel et al. (2019), who also include information on software improvements and computational domains. AlSaleem et al. (2022) evaluated 486 publications in a systematic review and bibliometric analysis to pinpoint important studies and potential future research areas. In their 2020 paper, Katekar and Deshmukh (partially) address phase change materials (PCMs) and emphasise the usefulness of paraffin wax in raising the productivity and efficiency of solar stills, particularly in conjunction with copper oxide nanoparticles. Edalatpour et al. (2016) examine a range of numerical simulations of solar stills, outlining several methods and proposing areas for additional study. Alqsair (2023) uses CFD to optimise a 3D solar still design, finding the best parameters for improved performance and a notable boost in efficiency. Suffer et al.'s (2020) investigation of PCMs' capacity for heat storage in solar collectors demonstrates strong agreement with experimental findings. Finally, a comparison of tubular solar stills with and without fins is presented by Sathyamurthy et al. (2022), who show that finned absorbers have higher efficiency and energy. When taken as a whole, these studies demonstrate the vital role that CFD plays in improving the performance of solar stills and draw attention to current developments and untapped research areas.

Table 1 Comparative Analysis of CFD Applications in Solar Stills: Key Studies and Findings

Study	Focus	CFD Approach	Key Findings	Materials/Techniques	Performance Metrics
Kabeel et al. (2019) [10]	CFD in solar stills	Comprehensive review	Highlights advancements in CFD for solar still performance prediction	CFD software, various operating/geometric parameters	Summary of CFD results
AlSaleem et al. (2022) [11]	CFD simulation of solar stills	Systematic review and bibliometric analysis	Reviewed 486 publications, identified significant studies and methods	CFD numerical simulation, various algorithms and still types	Efficiency assessment and future research directions
Katekar& Deshmukh (2020) [12]	Phase change materials in solar stills	Review of PCM effects	Paraffin wax found most effective; improved performance metrics	Paraffin wax, nanoparticles (copper oxide)	Productivity and efficiency improvements
Edalatpour et al. (2016) [13]	Numerical studies on solar stills	Review of various CFD simulations	Identified techniques for productivity enhancement	Nanotechnology, reflectors, storage materials	Emphasis on future CFD study opportunities
Alqsair (2023) [14]	3D solar still performance	CFD simulation and optimization	Optimal design parameters for enhanced performance	DOE, RSM, chamber height, water depth	215.6% increase in performance

Suffer et al. (2020) [15]	PCM thermal storage in solar collectors	Numerical investigation of PCM	PCM effectiveness in thermal energy storage	PCM, finite volume method, enthalpy conversion model	Temperature profiles and storage capability
Sathyamurthy et al. (2022) [16]	Tubular solar stills with/without fins	Experimental and theoretical study	Improved efficiency and exergy with finned absorber	Finned and flat absorbers	Efficiency and esxergy comparison

IV. Conclusion

One potential response to the increasing worldwide need for freshwater is the incorporation of solar energy into desalination operations. A sustainable method of turning salty water into drinking water is solar desalination, which includes both direct and indirect techniques. Although there are obvious potential advantages, there are drawbacks to the technology, especially in terms of productivity and cost-effectiveness. Although useful, using solar stills frequently has output and efficiency issues. However, developments like the incorporation of Phase Change Materials (PCMs) into designs for solar stills have demonstrated a great deal of promise in resolving these problems. PCMs improve thermal energy release and storage, which raises the efficiency of solar desalination systems as a whole.Because computational fluid dynamics (CFD) offers accurate models of fluid dynamics and heat transfer processes, it has become a crucial tool for optimising the performance of solar stills. Recent studies demonstrate how useful CFD is for assessing and enhancing designs for solar stills, especially when PCM integration is included. Through the identification of ideal configurations and operating conditions, CFD can dramatically improve the design and efficiency of solar stills, according to studies examined in this study. Despite advancements, further study is still required to address the shortcomings of the technologies in use today and look into novel alternatives. Future research should concentrate on improving PCM efficiency, improving CFD models, and creating affordable ways to increase the accessibility and sustainability of solar desalination.

References

[1] Bachchan, A. A., Nakshbandi, S. M. I., Nandan, G., Shukla, A. K., Dwivedi, G., & Singh, A. K. (2021). Productivity enhancement of solar still with phase change materials and water-absorbing material. Materials Today: Proceedings, 38, 438-443.

[2] Mohiuddin, S. A., Kaviti, A. K., Rao, T. S., & Sikarwar, V. S. (2022). Historic review and recent progress in internal design modification in solar stills. Environmental Science and Pollution Research, 29(26), 38825-38878.

[3] Gnanaraj, S. J. P., Ramachandran, S., & Christopher, D. S. (2017). Enhancing the design to optimize the performance of double basin solar still. Desalination, 411, 112-123.

[4] Sathyamurthy, R., El-Agouz, S. A., Nagarajan, P. K., Subramani, J., Arunkumar, T., Mageshbabu, D., ... & Prakash, N. (2017). A review of integrating solar collectors to solar still. Renewable and Sustainable Energy Reviews, 77, 1069-1097.

[5] Panchal, H., Sathyamurthy, R., Kabeel, A. E., El-Agouz, S. A., Rufus, D., Arunkumar, T., ... & Sadasivuni, K. K. (2019). Annual performance analysis of adding different nanofluids in stepped solar still. Journal of Thermal Analysis and Calorimetry, 138, 3175-3182.

[6] Omara, A. A., Abuelnuor, A. A., Mohammed, H. A., & Khiadani, M. (2020). Phase change materials (PCMs) for improving solar still productivity: a review. Journal of Thermal Analysis and Calorimetry, 139, 1585-1617.

[7] Davim, J. P. (2014). Modern mechanical engineering. Berlin, Heidelberg: Springer Berlin Heidelberg.

[8] Xie, L., Tian, L., Yang, L., Lv, Y., & Li, Q. (2017). Review on application of phase change material in water tanks. Advances in Mechanical Engineering, 9(7), 1687814017703596.

[9] Bhatti, M. M., Marin, M., Zeeshan, A., & Abdelsalam, S. I. (2020). Recent trends in computational fluid dynamics. Frontiers in Physics, 8, 593111.

[10] Kabeel, A. E., El-Said, E. M. S., & Abdulaziz, M. (2019). Computational fluid dynamic as a tool for solar still performance analysis and design development: A review. Desalination Water Treat, 159, 200-213.

[11] AlSaleem, S. S., Al-Qadami, E., Korany, H. Z., Shafiquzzaman, M., Haider, H., Ahsan, A., ... & AlHarbi, A. (2022). Computational fluid dynamic applications for solar stills efficiency assessment: A review. Sustainability, 14(17), 10700.

[12] Katekar, V. P., & Deshmukh, S. S. (2020). A review of the use of phase change materials on performance of solar stills. Journal of Energy Storage, 30, 101398.

[13] Edalatpour, M., Aryana, K., Kianifar, A., Tiwari, G. N., Mahian, O., & Wongwises, S. (2016). Solar stills: A review of the latest developments in numerical simulations. Solar Energy, 135, 897-922.

[14] Alqsair, U. F. (2023). Numerical simulation and optimization of surface evaporation in a 3D solar still for improved performance. Results in Engineering, 20, 101554.

[15] Suffer, K. H., Jalil, J. M., & Hasan, H. A. (2020). Numerical investigation of PCM thermal storage in water solar collector. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 66(1), 164-178.

[16] Sathyamurthy, R., Kabeel, A. E., Chamkha, A., Kumar, H. A., Venkateswaran, H., Manokar, A. M., ... & Vasanthaseelan, S. (2022). Exergy and energy analysis of a tubular solar still with and without fins: a comparative theoretical and experimental approach. Environmental Science and Pollution Research, 29(5), 6612-6621.