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"INVESTIGATION OF EXERGY AND ENERGY WITH TUBE BASED SOLAR STILL USING PCM MATERIAL VIA THEORETICAL AND COMPUTATIONAL APPROACH"

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ABSTRACT

A material-based solar still is an advanced design approach in solar desalination systems, where the traditional construction materials (like metal or concrete) are replaced or enhanced with FRP composites. A composite material tubular solar still is a lightweight desalination equipment with a substantial condensing area in comparison to other types of solar stills. Nonetheless, their effectiveness is often limited by fluctuating climatic circumstances. This study examines two primary research issues. The first focus is on improving the heat coefficient for evaporation (he,w-g), the heat coefficient for convection (hc,w), exergy output Ex(out), and efficiency of composite material tubular solar still without usage of phase change materials. The second involves the development of a phase change material-based system, wherein paraffin wax fills a 1-liter copper bottle. The current study uses CFD modelling to investigate how geometrical factors, operational basin temperature, and basin water temperature affect a composite tubular solar still's performance with composite material (TSS). The results indicated that the standard composite tubular solar still achieved an exergy efficiency of 43.3% and an exergy output of 76.30 W at peak temperature at 1 PM. The findings indicated that redesigned tubular solar still achieved an exergy efficiency of 49.61% and an exergy output of 113.24 W at peak temperature at 1 PM during daytime.

Key Words: *Tubular solar still, conventional solar still,CFD, efficiency*

I. INTRODUCTION

Solar energy has traditionally been used for water distillation [1]. Enhanced the productivity of an uninsulated FRP (Fibre Reinforced Plastic) solar still by approximately 29.8% by redirecting solar radiation through three sidewalls using lenses and integrating a vertical mirror." [2]. Water consumption is essential not only for humans but also for all living things on Earth[3]. There are other methods to get clean water, however solar desalination via a solar still is the most economical option[4]. Clean water is essential for human survival; nevertheless, its supply is diminishing owing to overexploitation and pollution. Solar stills lack commercial appeal owing to their diminished production [5]. Although researchers have worked to increase the distillate production of solar stills, no one has tried to commercialize this technology as of yet [6]. Solar still efficiency and output have been the subject of several research [7], [8], [9], [10]. These studies have examined a wide range of features, design circumstances, and adjustments that impact these parameters. One main aspect that affects the freshwater production of traditional solar stills is the temperature difference between the water and the glass. The temperature at which water turns into glass depends on design and operational factors [11], [12]. Increasing the temperature of the water in the basin, either actively or passively, decreasing the temperature of the glass cover, or employing a mix of the two can increase the temperature difference between the water and cover. The speeds tested included 0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0 and 4.0 rpm [6]. At a

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depth of 1 cm, the solar still absorber plate's overall yield was found to be 6.6 kg/m² when coated and 6.2 kg/m² when uncoated. The distilled production is 6.1% higher with the TiO2 nano black paint-coated pyramid solar still compared to the typical basin-type pyramid solar still [7]. With a cost of just $0.15 per unit of water produced, the system achieved a thermal efficiency of 24.61%. Suggested technology reduced water production cost by 25% and increased TSS productivity by 292.4% and efficiency by 82.3%, respectively [8]. In emergency situations, especially in dry areas, the proposed novel method could be indispensable.For the purpose of desalinating salt water, a solar still that is aided by a tubular solar collector was suggested. We looked at its environmental impact, economic aspects, and exergy performance. A rudimentary solar still with similar dimensions was used to compare the findings. The upgraded solar still produced 549.77 kg/m² per year, whereas the regular solar still produced roughly 405.04 kg/m². When compared to the active system, which attained rates of around 41% and 11%, respectively [9]. In general, multi-effect TSS results in a higher average daily water output. According to the economic studies, the overall cost of TSS-generated fresh water might vary between $0.0061 and $0.2 per kilogram. Horizontal TSS is more efficient than vertical TSS when it comes to the expenses of producing water.increase the efficiency of heat transfer between the water and the basin's surface[10]. Comparing the experimental results to the reference still, the addition of reflectors, nano-coating, a mix of the two, and phase change materials with CuO nanoparticles resulted in a total freshwater yield increase of 57%, 14%, 70.7%, and 108%, respectively, for the tray distiller. Every day, 2400 mL/m² of freshwater was collected using the conventional method, whereas 5000 mL/m² was obtained using the tray solar still. With reflectors, nano-paint coating, and PCM-CuO nanoparticles, the tray distiller achieved a thermal efficiency of 51.5%[11]. Elethylene glycol and water make up the basic fluid in a weight-for-weight ratio of 50:50. We looked at temperatures between 15 and 50 degrees Celsius and particle concentrations reaching up to 0.8%. Both nanofluids outperform the basic fluid in terms of heat conductivity[12].

An analytical summary of experimental findings on the heat transfer properties of nanofluids is provided, using extensively dispersed material from various literature sources. Despite the abundance of publications on this problem, only a limited number of researches provide quantitative estimates over a comprehensive range of experimental settings, and many studies lack coherence[13], [14]. Finally, the issues associated with solar systems using nanofluids and their potential future applications are discussed. This paper presents concepts that will assist researchers in developing innovative applications of nanofluids to enhance solar energy across several domains[15]. Computational Fluid Dynamics was used to conduct modeling and simulations for glass-cover tilt angles of 10^0, 20^0, 30^0, and 40^0. Temperature, density, and velocity distributions of the fluid were acquired for each angle. Additionally, the convective heat transfer coefficient between the basin and the fluid was determined. Moreover, the fluid flow exhibits a laminar regime at 10° and 20° angles, but at 30° and 40° angles, the flow has turbulent behavior. Ultimately, modeling findings indicate that the heat transfer coefficient escalates with the tilt angle, varying from 2.45 W/m²-K to 3.29 W/m²-K[16].

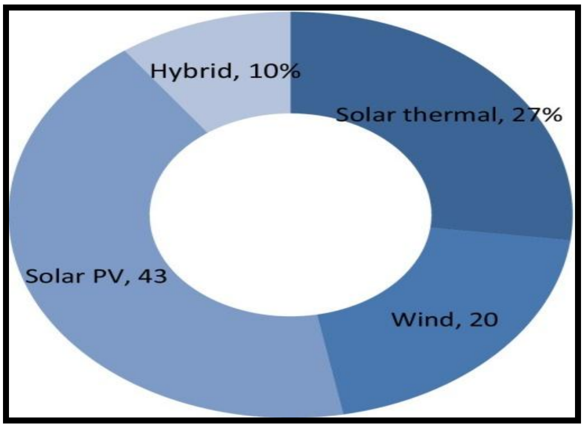

Fig.1. *Renewable energy's contribution in desalination[15].*

Using a rigorous mathematical technique, concentric tubular solar stills (CTSS) are modeled and analyzed thermodynamically. The hourly output for water and air as cooling media, though, drops to 4.575 kg/m^2 and 2.555 kg/m^2, respectively, when all losses are considered [24]. According to the aforementioned information, solar stills are basic, easy-to-use desalination equipment that is ecologically friendly. However, improving the output of fresh water is necessary since the energy efficiency of solar energy conversion in different desalination techniques is less than a few

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tens of percent. Computational fluid dynamics (CFD) study of solar stills with the developing material technique was carried out in current examination using ANSYS Fluent. This research has two aims as follows:

- Exergy output of traditional tubular solar still vs modified tubular solar still.
- Exergy efficiencies of regular tubular solar stills and modified tubular sun stills

II. Benefits of using FRP

In recent years, there has been growing interest in utilizing bark fibers as reinforcements for polymer composites[17].Awareness about the global sustainability among consumers had turned industries in producing eco-friendly, lightweight, and affordable materials. In line up, natural fibre–reinforced composites (NFRC) have experienced tremendous expansion in recent years. Natural plant fibers and their composites have been extensively used in various sectors for the last few decades, due to their promising potentials that compete with synthetic materials[18]. offers excellent benefits in terms of thermal resistance, durability, and weight[19]. Its low thermal conductivity minimizes heat loss, making it ideal for insulation and solar applications. It is highly durable, resisting corrosion, chemicals, UV radiation, and weathering, which ensures a long service life with minimal maintenance. Additionally. is lightweight—significantly lighter than metals—allowing for easier handling, transport, and installation. Despite its light weight, it maintains a high strength-to-weight ratio, making it suitable for structural applications. These combined properties make a preferred material in construction, renewable energy systems, and industrial components. natural rubber (NR) matrix can be of relevance for their eco-friendly and sustainable nature as the substitute for carbon-based fillers[20]. Epoxy composites reinforced with Acacia caesia bark (ACB) fibers, considering their mechanical, morphological, and thermal properties[21]. Natural fibers along with glass fibers were used as the reinforcement of an epoxy matrix for the betterment of mechanical and wear applications[22].

III. Methodology

The FRP composite material based experimental observations were place in April 2023 from 10:00 am to 5:00 pm All during the experiment, we kept track of the following temperatures: ambient (Ta), basin water (Tb), vapor (TV), and sun radiation (Ir). The basin's water temperature was recorded at a depth of 4 cm. K-type thermocouples were used to measure the temperatures, and a digital data logger was used to record the findings. An analogue Pyranometer (PYRA300) was used to measure the quantity of solar radiation (It). The aggregated, cleaned water was collected in a calibrated cup. On an hourly basis, we tracked the sun's strength, the production of freshwater, and a plethora of past temperatures reported and temperature results after the calibration technique, and the exploratory data were clearly adjusted during the review process [23].

IV. Energy and exergy aspects

The energy matrices of solar distillation are included in the thorough examination of the energy and exergy aspects. Economic balance equations, thermodynamic balance equations, and the general balance equation are all presented in a specific chapter devoted to exergy economics. Finally, a chapter on solar distillation's economic analysis wraps off the topic [24]. The

Exergy, energy, freshwater production, environmental impact, and economics were all carefully considered in the analysis of the solar still's performance. A thermoelectric cooling capacity of 36 W might potentially increase freshwater flow by 126%, according to the studies. There was a 44% improvement in energy efficiency compared to the reference solar still, but a 25% decrease in exergy efficiency. The energy matrices show that the coated glass solar still has a maximum energy production factor of 0.15 and a minimum energy payback time of 6.55 years. Over the course of its useful life, the upgraded solar still mitigated emissions of 2.97 tons of carbon dioxide. With a thermoelectric cooling power of 36 W, the lowest price per liter was calculated to be $ 0.036. Coated glass solar stills with thermoelectric cooling achieved maximum enviro-economic values of $ 83.21 and exergo-economic values of 4.64 kWh/$, respectively in

The chosen concentration (0.3 wt%) was adopted for the following circumstances since it was superior to the alternatives [26]. At this specific weight ratio, the yield of MSS1 exceeded that of CSS by 72.7%, while MSS2 showed a 57.5% higher yield compared to CSS. In the first case, a glass lid cooling system was integrated with the MSS units

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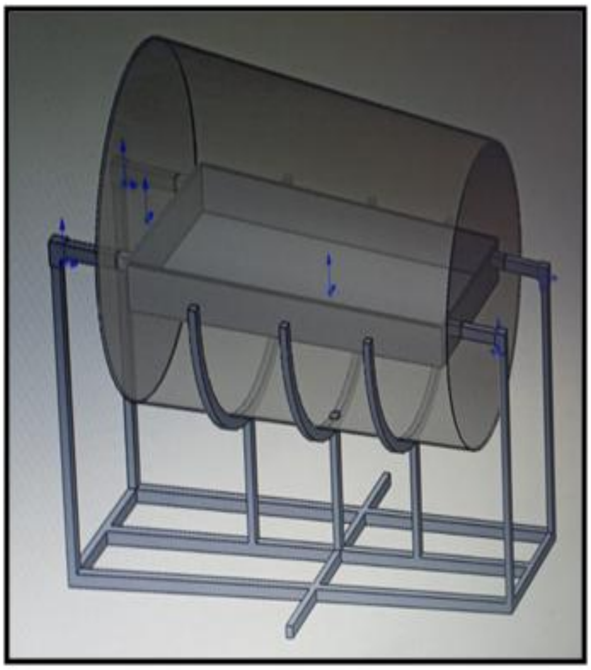
to enhance the condensation process. In the second case, reflectors were mounted on both the upper and lower surfaces of the MSS units to improve performance. In Case III, there were reflectors and cover cooling. Case IV also included the placement of ultrasonic atomizers close to the MSS basin. Concurrent comparisons between MSS1 and MSS2 and conventional SS (CSS) were conducted in each trial. In every case, the thermo-economic performance was good. With an increase of 113.72% in output, 96% in energy efficiency, and 167.62% in exergy efficiency, MSS1 in Case IV attained the optimum performance, especially with regard to yield[25]. Solar stills using energy storage materials (SSWESM) were compared to conventional solar stills (CSS) in this experiment. For the energy storage experiment, equal parts black color glass balls (BCGB), black granite (BG), and white marble stone (WMS) were utilized. Daily distillate output for CSS was 1.4 kg/m², whereas SSWESM managed 2.5 kg/m². Due to its ability to boost water evaporation during the day and disperse heat at night, ESM produces more distillate than CSS. With an exergy efficiency of 12.55 percent and 4.99%, respectively, CSS outperforms SSWESM. The SSWESM outperforms the CSS in terms of daily efficiency by a whopping 72.6% [28]. The highest output that can be achieved using a pyramid solar still in conjunction with a solar water heater is 7.99 L/m² when the water depth is 1 cm. Exergy efficiency is hourly related to still production and directly proportionate to absorber area. It is inversely correlated with the latter. Thus, at a water depth of 1 cm, APSS has a thermal efficiency of 49.36% and an exergy that is 107.59% more than CPSS. In comparison to a traditional pyramid solar still, which costs $0.0139 per liter, an active pyramid solar still provides fresh water at $ 0.00751 per liter. The research found that adding heating and decreasing the depth of water in the bottom basin increased the production of the solar still [26].

V. Exergy destruction

Exergy destruction in a solar still is accounted for by evaluating the irreversibilities in each component where energy degrades in quality. In the basin liner, exergy is destroyed due to heat losses to the surroundings and non-ideal heat transfer to the water. In the PCM zone, destruction occurs during phase change due to finite temperature differences and imperfect thermal conductivity. The glass cover contributes to exergy loss via radiative and convective heat transfer to the ambient air. Each component's exergy destruction is calculated using the second law of thermodynamics, considering environmental reference conditions and temperature gradients across the system.



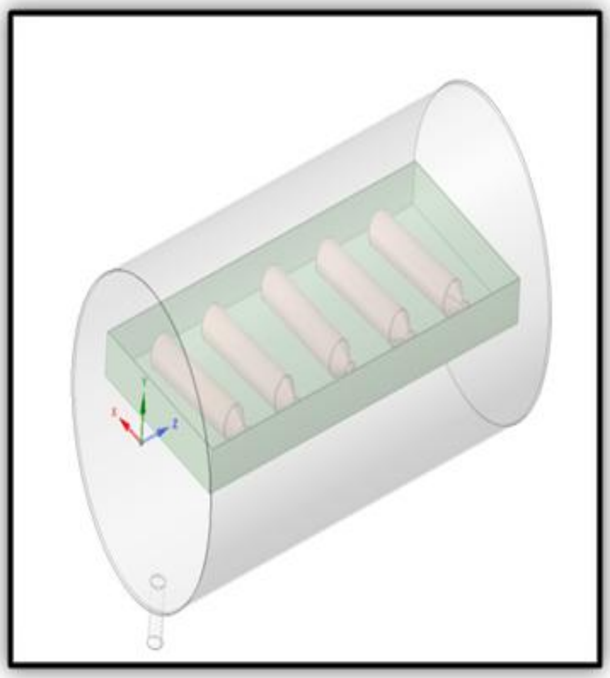


Fig.3. *CAD model CTSS and MTSS*

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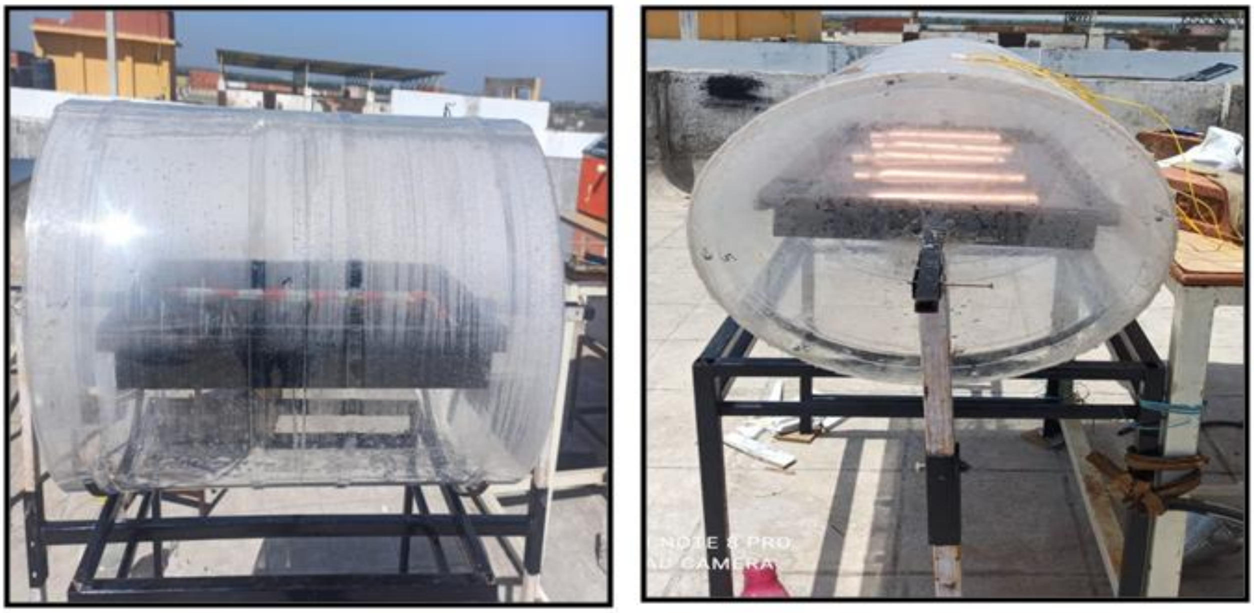

Fig.4. *(a) and (b) Photograph of experimental setup FRP composite material CTSS and MTSS solar*

VI. Result & discussion

Thermal Performance

To analyze the thermal performance of the tested composite material CTSS and composite material MTSS, the Heat coefficient for evaporation, Heat coefficient for convection as well as energy output and exergy efficiency, are evaluated under the same operating condition.

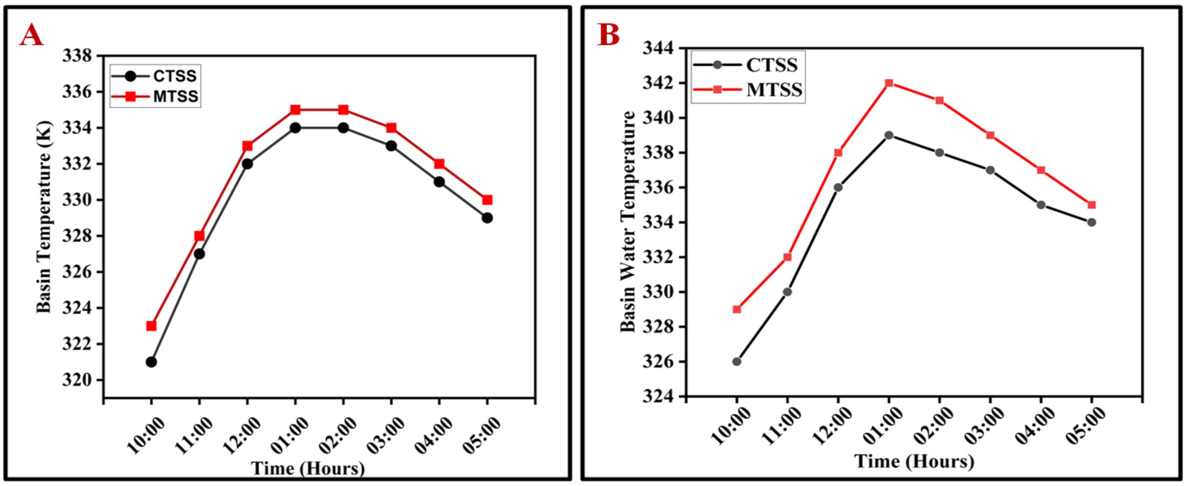

Fig.7. *(a) & (b) Basin Temperature and basin water temperature CTSS and MTSS*

This fig.7 (a) & (b) contains two-line graphs labeled A and B, comparing FRP composite material CTSS and MTSS systems over time in terms of temperature-related variables. Graph A: Basin Temperature (K) vs Time (Hours) Y-Axis: Basin Temperature (in Kelvin, K) and X-Axis: Time from 10:00 AM to 5:00 PM, FRP composite material CTSS: Circular black markers connected by a line and MTSS: Square red markers connected by a line. Here both systems show an increase in basin temperature from 10:00 AM, peaking between 1:00 PM and 2:00 PM. After the peak, temperatures gradually decrease toward 5:00 PM.MTSS consistently shows higher basin temperatures compared to

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FRP composite material CTSS throughout the time period. Graph B: Basin Water Temperature vs Time (Hours). Y-Axis: Basin Water Temperature (presumably also in Kelvin or °C) and X-Axis: Same time range, 10:00 AM to 5:00 PM FRP composite material. CTSS: Circular black markers and MTSS: Square red markers. Similar trend as in Graph A: temperature increases till early afternoon and decreases thereafter. Again, MTSS shows consistently higher water temperatures compared to composite material CTSS. composite material MTSS peaks around 1:00 PM, while FRP composite material CTSS peaks slightly earlier and at a lower temperature. composite material MTSS outperforms composite material CTSS in both basin and water temperatures, likely indicating better thermal performance. The consistent temperature advantage suggests that composite material MTSS is more efficient at heat absorption or retention.

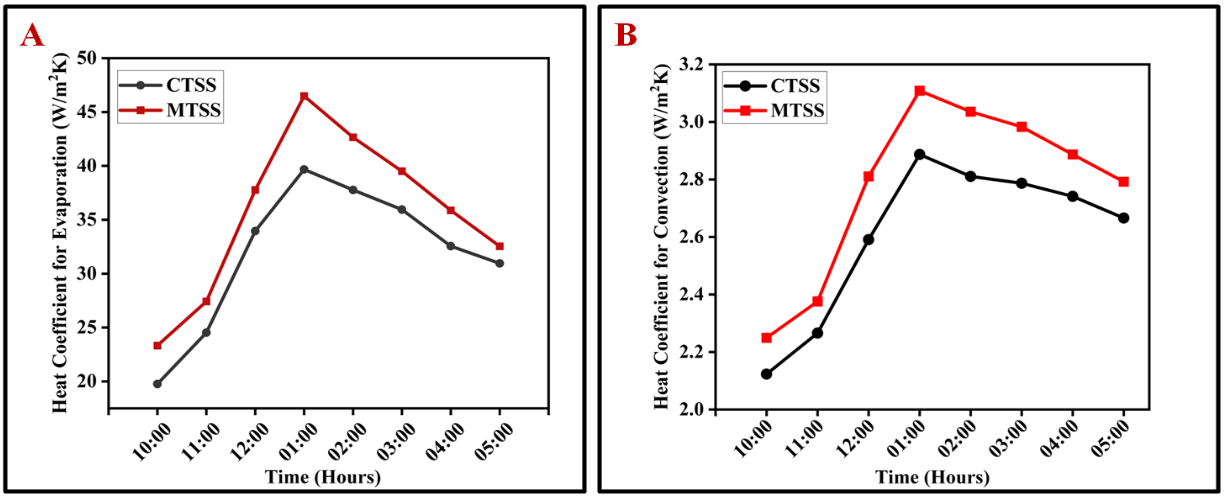

***Fig.8**. (a) & (b) Heat coefficient for evaporation and convection (W/m^2K) CTSS and MTSS*

Figure 8(a) and Figure 8(b) show the hourly changes in the convection and evaporation heat transfer coefficients for the two tested designs, respectively. Both systems showed comparable temperature behavior in the early hours, up to about 8:00 AM. Differences became increasingly noticeable, though, as sun intensity rose. With evaporation heat transfer coefficients of 39.67 W/m²K for the composite material conventional Tubular Solar Still (CTSS) and 46.48 W/m²K for the redesigned composite material Tubular Solar Still (MTSS), the redesigned system demonstrated improved evaporative performance. Similarly, composite material MTSS's convection heat transfer coefficient, which was 3.11 W/m²K as opposed to 2.89 W/m²K in the composite material CTSS, was marginally greater, indicating better heat transmission and internal air circulation. Interestingly, Fig.8 (a) also shows that, in both configurations, the basin water temperature peaked around 1:00 PM, which corresponds to the highest amount of solar insolation. This peak temperature adds credence to the finding that better heat retention and dispersion are two ways in which the composite material MTSS design enhances thermal performance.

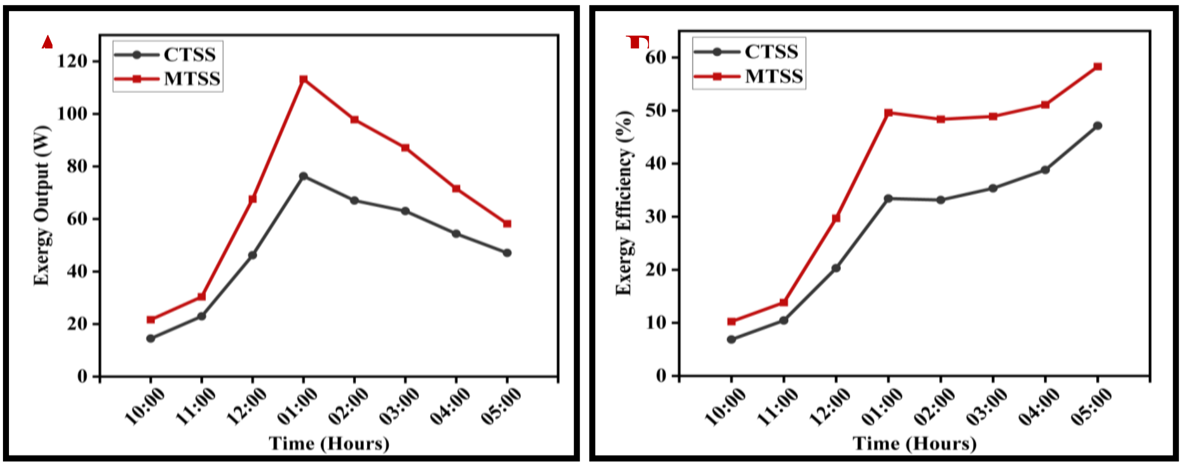

***Fig.9.** (a) & (b) Exergy Output and Exergy efficiency results CTSS and MTSS*

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Figure 9(a) and Figure 9(b) show the hourly changes in exergy output and exergy efficiency for the two tested setups, respectively. Both Instantaneous thermal and exergy efficiency of solar still observed during experiments exergy values exhibit a similar pattern throughout the day, as shown. Up until 8:00 AM, the energy production and efficiency of both systems stay quite close to one another. However, composite material Modified Tubular Solar Still (MTSS) starts to function better than FRP composite material conventional Tubular Solar Still (CTSS) when solar radiation rises.
composite material CTSS and composite material MTSS measured peak energy outputs of 76.30 W and 113.24 W, respectively. Accordingly, composite material CTSS and composite material MTSS were shown to have maximum exergy efficiencies of 33.43% and 49.61%, respectively. The enhanced thermal conductivity of the integrated Phase Change Material (PCM) is responsible for composite material MTSS's discernible improvement in exergy performance. Because of this, heat was transferred to the basin water more efficiently, raising the water's temperature and increasing the efficiency of energy conversion.

Table.1 *Simple reading at 1 pm peak temperature*

S. No.	Experimental Data				CFD Data				Percentage Error (%)			
Time	Basin Temperature (CTSS)	Basin Temperature (MTSS)	Basin water Temperature (CTSS)	Basin water Temperature (MTSS)	Basin Temperature (CTSS)	Basin Temperature (MTSS)	Basin water Temperature (CTSS)	Basin water Temperature (MTSS)	Basin Temperature (CTSS)	Basin Temperature (MTSS)	Basin water Temperature (CTSS)	Basin water Temperature (MTSS)
1 pm	334	335	339	342	335.8	334.9	339.8	341.5	0.53	0.03	0.24	0.12

EXPERIMENTAL VALIDATION

Experimental validation of solar stills with and without Phase Change Material (PCM) involves comparing their thermal performance under identical climatic conditions. In the PCM-integrated still, temperature sensors and flow meters measure heat storage and release, while productivity is recorded hourly. The still without PCM serves as a baseline. Results typically show that the PCM-based still maintains higher water temperatures during off-sunshine hours, enhancing extended evaporation and productivity. Data analysis confirms improved efficiency, reduced temperature fluctuations, and increased freshwater output in PCM-enhanced systems. These findings validate the thermal storage benefits of PCM in sustaining performance beyond peak solar hours.

DISCUSSION

Because of the higher demand for water throughout the summer, desalinated water output frequently peaks around this time. Higher temperatures and other seasonal conditions result in increased water use for cooling, irrigation, and drinking. Additionally, desalination facilities boost production in the summer to fulfil the increased demand in areas with limited natural freshwater supplies. It would be easier to understand the relationship between seasonal elements and desalination plant operating modifications if this background were explained.
A thorough analysis of recent developments in FRP composite material Modified Tubular Solar Still (MTSS) identifies a number of noteworthy technological innovations meant to raise the system's overall dependability and efficiency. The incorporation of phase change materials (PCMs), which are essential for thermal energy storage, is one of the major advancements. PCMs contribute to the system's sustained high temperatures by absorbing and releasing heat during phase transitions, which keeps the evaporation and condensation processes going long after the sun sets.
Utilizing cutting-edge building materials has also improved thermal insulation and durability, reducing heat loss and extending system longevity in a variety of climatic circumstances. In order to boost water evaporation and collection rates, creative design changes have also been made, such as better geometries for heat capture, increased surface area for condensation, and optimized inclination angles.
Future studies should investigate substitute PCM solutions with greater latent heat capacities, improved system component compatibility, and reduced costs in order to further improve performance. The design's potential for

community-level water filtration may potentially be unlocked by scaling it for bigger uses. Overall energy efficiency may be improved by combining MTSS with other renewable technologies, such as solar panels, which might supply extra electricity for heating or auxiliary systems.

Furthermore, implementing sophisticated control systems with cutting-edge sensors can provide adaptive changes and real-time monitoring, guaranteeing peak performance all day long. Finally, in order to ascertain the long-term feasibility and affordability of PCM-enhanced composite material MTSS units, thorough economic analyses are required, with an emphasis on lowering production costs to facilitate wider commercial deployment.

VII. Conclusion

In the present experimentation work, were conducted in two set. The first experimental set up was conventional tubular solar still (CTSS) and second experimental set up was modified tubular solar still (MTSS), here PCM material 'paraffin wax' used for increasing exergy output and exergy efficiency.

composite material MTSS was created for domestic use in India coastal region's rural households and communities. Because of this, the manufacturing process was kept straightforward and user-friendly and economical in terms of costs. It is evident that under various climate circumstances, composite material MTSSs' respective performances vary. The summer months are when desalinated water production is at its highest.

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