CFD-Based Thermal and Productivity Analysis of Single and Double-Slope Solar Stills Integrated with Phase Change Material

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Abstract-*Solar distillation is a method that is both sustainable and eco-friendly for the production of freshwater; nevertheless, the factor of low output limits its application in a larger scale. Double-slope solar stills, among the different passive desalination systems, are the winners when it comes to vapor flow and condensation efficiency because of their symmetrical shape. The current study uses Computational Fluid Dynamics (CFD) to analyze the thermal behavior, heat and mass transfer characteristics as well as the productivity enhancement of solar stills that have either a single or double slope and are integrated with phase change material (PCM). A mathematical coupled with numerical framework is created to quantify the energy storage, evaporation–condensation mechanisms, and freshwater yield. A three-dimensional CFD simulation is performed with ANSYS Fluent using the Volume of Fluid (VOF) multiphase model to observe the interactions going on between air, liquid water, and water vapor. The governing equations for continuity, momentum, energy, and turbulence (k–ε model) are solved in the context of both natural convection and solar radiation boundary conditions. Paraffin C18 is the chosen PCM to be used with the aim to maximize thermal storage and prolong the duration of evaporation. The numerical model undergoes a validation process that involves comparing it with existing studies, which indicates that it is very close to the reality with a maximum deviation of 6% for the most important parameters. The results show that the double-slope solar still creates a higher basin temperature, vapor density, mass flow rate and condensation rate in comparison to the single-slope design. The double-slope solar still's daily productivity is calculated to have a value of 1.398 times that of the single-slope solar still, mainly because it can retain heat better and has a larger condensation area. The results of the research indicate that not only does geometric optimization make it possible to use PCM effectively in solar still performance enhancement but it also significantly improves solar still performance.*

Keywords- *Solar Still; Double-Slope Solar Still; Computational Fluid Dynamics; Phase Change Material; Freshwater Productivity.*

I. INTRODUCTION

Solar distillation is a clean method of producing freshwater but its low productivity prevents the technique from being used on a large scale as compared to the conventional ones. Despite the fact that modified solar still designs can improve the production, the extra parts usually make the system more complicated and expensive. Thus, it is necessary to optimize the design and to use accurate mathematical modeling to enhance the performance, whereby CFD has become a useful method for understanding the heat and mass transfer and assisting the solar still optimization [1].

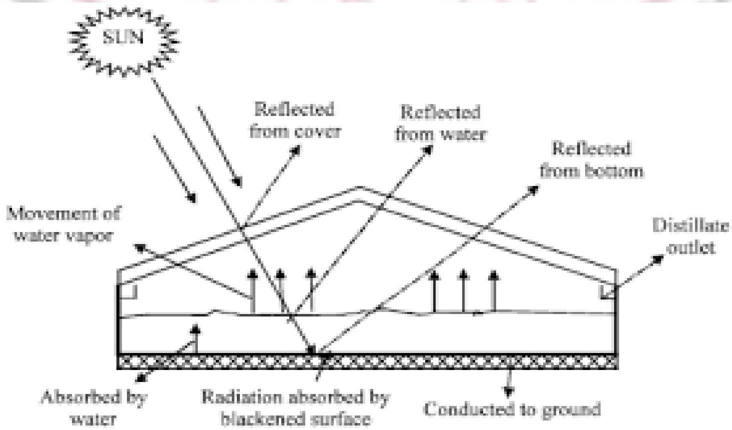

Figure 1: Block diagram of double slope solar still [2]

Water is indispensable to human existence and also plays a key role in the economic, agricultural, and industrial sectors, nonetheless, only a tiny fraction of water on our planet (less than 2.5 % of it) is freshwater, with an even smaller portion being usable, and the combination of rapid population growth, urban expansion, and climate change has made global water scarcity more acute in low-income areas [3]. The situation is made worse by the pollution of surface and groundwater due to industrial discharge, agricultural runoff, and improper waste disposal, which creates serious environmental and public health problems [4]. The use of solar energy for water desalination through evaporation-condensation processes is a sustainable solution, besides, solar stills are eco-friendly, cost-effective, and can be used in rural areas and remote places. However, since their efficiency and productivity are still lower than those of conventional desalination technologies, there is a need for more research and improvement of their performance [5].

A solar still is an uncomplicated thermal desalination instrument that takes advantage of solar energy to first evaporate the saline or polluted water and then condense it on a cooler transparent covering, thus collecting freshwater; the performance of the device is determined by the interactions of heat and mass transfer which are heavily dependent on the geometric parameters [6]. Solar stills are generally divided into passive and active systems, where passive systems depend entirely on solar power and are further divided into single-slope, double-slope, pyramid, stepped, wick, and tubular systems [7]. Among these, double-slope solar stills allow better vapor flow and more evenly distributed condensation since they have a symmetric shape, however, to achieve such performance improvement one still has to pay attention to the geometry optimization.

Solar stills can be categorized according to their design configurations and operational modes, and this loose classification has resulted in passive systems being the most economically feasible and most appropriate for human water supply in remote areas [8]. Among the passive types, single-slope solar stills exhibit simplicity and gain much attention in studies but at the same time encounter drawbacks of small condensation area and low output. On the other hand, double-slope stills utilizing vapor flow and even condensation owing to their symmetrical design [9][10]. The productivity of double-slope solar stills varies widely depending on the pairing of cover angle, water depth, and basin dimension, which in turn affect the rates of heat and mass transfer [11]. Nevertheless, dual-slope stills have their drawbacks in terms of heat dissipation and uneven temperature distribution, so instead of upgrading the system complexity or cost, it is better to conduct systematic geometric optimization to get higher output [12]. Thus, the performance evaluation criteria of daily water yield and thermal efficiency become crucial to design evaluation in terms of sustainability and water economics of the community [13][14].

II. LITERATURE REVIEW

According to recent publications, solar stills are not only an economical alternative but also a method that is viable for freshwater production, however, their low yield is still one of the biggest barriers for massive application [15]. Changes in design such as fin inclination optimization, absorber enhancements, and mechanisms that enhance heat transfer have led to performance improvements with CFD models reflecting experimental data very closely [16][17]. Besides, the utilization of channel integration, the employment of thermoelectric modules, the implementation of evacuated tube collectors, and the incorporation of photovoltaic heaters have resulted in considerable increases in the amounts of water produced, energy efficiency, and sustainability over the entire lifetime [18]. The joint use of phase change materials and hybrid setups has also been very effective in boosting thermal storage and output, whereas cutting-edge optimization methods like genetic algorithms have made it possible to formulate a systematic approach to finding the ideal geometrical parameters for the purpose of maximizing suns energy absorption [19][20].

Recent studies have pointed solar desalination out as a great method for freshwater production, with studies proving that condenser and basin geometric optimization can increase the yield and reliability of the model remarkably [21]. State-of-the-art CFD and numerical simulations have indicated that the various operational parameters like wind speed, glass thickness, water depth, and cover angle have a considerable impact on solar still productivity, while stepped and optimized configurations are contributing to the performance gains significantly [22]. The reviews and laboratory experiments have also mentioned that the alteration of basin liner geometry, through the implementation of fins, stepped, curved, or spherical designs, is enlarging the evaporation area and the heat dissipation, thus improving the output of freshwater [23][24]. Combining peculiar basin shapes with reflectors has also led to significant yields per day and efficiencies being reached, thus the design optimization being vital for the marketability of solar stills has been established once more [25].

Table 1: Comparative Review of Performance Enhancement Techniques, Design Modifications, and Key Outcomes in Double-Slope and Advanced Solar Still Systems

Ref. No.	Objective	Methodology / Modifications	Key Results	Remarks / Novelty
[15]	Optimize DSSS performance via fin inclination	CFD simulation (ANSYS Fluent 3D), VOF for water–vapor, DO for radiation; five fin angles (18°, 34°, 45°, 75°, 90°)	Max absorber temp 62.5°C; optimal fin angle 45°; water temp ↑ 22.24% at 45° vs 9.39% at 18°	First systematic study on multiple fin angles for DSSS
[16]	Enhance DSSS performance using cylindrical fins	Experimental DSSS in Gabes, Tunisia; galvanized iron, 34° glass tilt; CFD validation; fin diameters varied	Max temperature ↑ 14.07% with 80 mm fins; energy efficiency 71.03%; water productivity 3252.55 mL/m²	Demonstrated fin diameter effect on heat transfer and productivity
[17]	Review methods for productivity enhancement in DSSS	Literature review; focus on heat addition, condensation, thermoelectric modules, ETCs, PV heaters	Thermoelectric modules ↑ 250% water production; ETC ↑ efficiency 59.42%; CSSPVH ↑ 6× water yield; water heater ↑ 370% production	Comprehensive quantitative analysis; highlights importance of advanced heat addition methods
[18]	Improve DSSS via channels of different shapes	Experimental study with Sq, Rect, Tri, Trap channels; temp measured at 2 cm water depth	DSSS+Trap ↑ yield 30.43%; water cost \$0.034/L; 5.33 tons CO_2 reduction; WHO compliant water	Shows geometric channel modifications can enhance productivity and reduce environmental impact
[19]	Enhance DSSS using binary eutectic PCM	Experimental and CFD analysis in Bhopal, India; compare conventional vs PCM-modified DSSS	Max yield 0.31 kg/m²·h (exp) vs 0.35 (sim); avg energy efficiency 30.42% vs 22.21%; simulation deviation < 11.5%	Demonstrated PCM integration improves efficiency and yield; validated CFD model
[20]	Sensitivity and optimization of DSSS design	Solar thermal modeling; GA + TOPSIS; parameters: basin length, width, tilt, azimuth, glass angles	Optimized DSSS absorbed 97.67 GJ annually; best dimensions: width 2 m, length 2 m, tilt 8°, azimuth 180°, glass inclinations 80° & 67°	Combined sensitivity analysis with GA/TOPSIS for design optimization; annual energy quantification
[21]	Investigate the effect of condenser geometry on distilled water production	ETC as basin, cubic glass condenser; studied condenser volume, surface area, wall thickness; RSM with Box–Behnken Design (BBD)	Max distilled water 7.231 $kg/m^2 \cdot day^{-1}$ at condenser volume 2940 cm³, wall thickness 4 mm, surface 3360 cm²; $R^2 = 0.9934$, $R^2_{adj} = 0.9815$	Optimized condenser geometry using RSM; high predictive accuracy for maximum water production
[22]	Study parametric effects on solar still productivity	Transient CFD model; DO radiation, species transport for water vapor, Fick's law; considered wind speed, glass thickness, water depth, water-to-cover distance, cover angle; stepped solar still configuration	Wind speed 1→6 m/s → productivity ↑ 14.4%; glass thickness 4→2 mm → ↑ 3.5%; optimal water depth 2 cm, water-to-cover 8 cm; stepped still → ↑ 17.4%	Quantified influence of multiple operational and geometric parameters; showed advantage of stepped design

[23]	Review basin liner geometry effect on freshwater output	Literature review: fins, corrugated wick, hemispherical basins, stepped still	Evaporation area increase due to basin liner shape → higher freshwater output	Demonstrated how basin geometry influences performance; provided design insights for maximizing water yield
[24]	Improve tubular solar still performance via basin geometry modification	Numerical & flow analysis of heat transfer in tubular still; curved basin implemented at D/2 and D/3	Curved basin at D/2 → 31.4% more heat dissipation than conventional still; higher freshwater production at high Rayleigh numbers	Showed that basin placement and curvature significantly affect thermal efficiency and productivity
[25]	Enhance spherical basin solar still performance with reflector	Spherical basin solar still with parabolic reflector; experimental testing with water masses 1–5 L	Daily yields: 3.54–8.26 L/m²; daily efficiencies: 19.56–39.06%; yield increased with basin water mass	Novel integration of spherical basin and parabolic reflector; established correlation between basin water mass and productivity

III. OBJECTIVES

The present research is mainly concerned with the determination of the highest possible amount of distilled water obtained from a double-slope solar still basin and the efficiency comparison of the conventional solar still design.

The specific aims of the study are:

• To improve solar still productivity by changing the important geometrical factors.

• To evaluate the proposed solar still design against the conventional design by studying temperature distribution and mass flow rate, and to improve the total efficiency of the solar still.

• To confirm the analytical performance of the solar still by drawing comparisons between all relevant parameters and those of the conventional design.

IV. METHODOLOGY

This research adopts an integrated mathematical and computational fluid dynamics (CFD) method to scrutinize the heating and mass exchange activities of solar stills with a single and double slope having phase change material (PCM) embedded. An exhaustive energy and mass balance formulation is constructed by following standard assumptions, which consist of vapor-tight operation, negligible temperature differences in both the basin water and PCM, one-dimensional heat conduction, and minor thermal resistance due to flowing condensate. The mathematical infrastructure helps in the measurement of the hourly and daily output, evaporative heat transfer coefficients, and overall effectiveness of the solar still under steady operating conditions.

This is true when the temperature of the PCM is not the same as the mean system temperature.

$$Q_{PCM} = \left[\frac{M_e}{A_p}\frac{dT_{pcm}}{dt}\right] = \left[\frac{T_l - T_{pcm}}{R_t}\right] - Q_{loss} (1)$$

When the temperature of PCM is equal to mean temperature

$$Q_{PCM} = \frac{m_{pcm} \cdot L_{pcm}}{A_p \cdot \Delta t} = \left[\frac{T_l - T_{pcm}}{R_t}\right] - Q_{loss} (2)$$

- M_e= Equivalent heat capacity of PCM
- A_p = Area of basin water (m^2)
- T_{pcm} = Temperature of PCM
- T_l = Temperature of liquid
- R_t = Total thermal resistance of PCM (m^2K/W)
- Q_{loss} = heat loss
- L_{pcm} = Latent heat of PCM (J/kg)

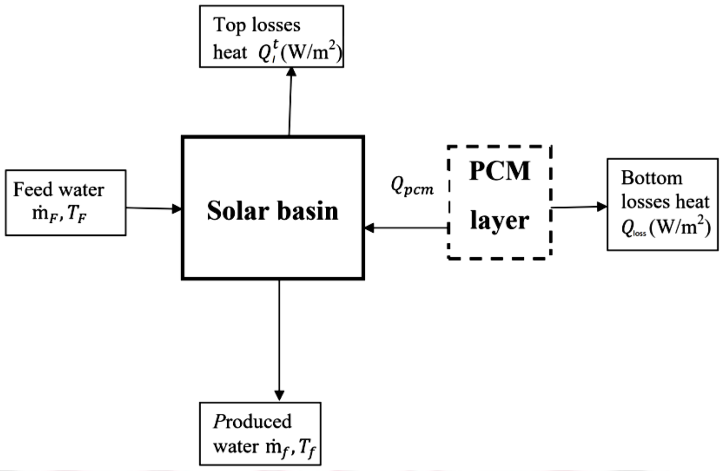

Figure 2:Schematic block diagram of the solar still in discharging mode

Figure 2 demonstrating the discharge function of a double-slope solar still particularly points out the thermal energy stored in the PCM that contributes to water evaporation at the basin. The vapor produced gets collected as distilled water after condensation on the glass cover, while heat losses happen through both the upper and lower surfaces.

In order to delineate the intricate heat transfer and multiphase flow phenomena inside the solar still, a tri-dimensional CFD simulation is created using ANSYS Fluent. The governing equations for continuity, momentum, energy, turbulence (k–∈ model), and multiphase flow are numerically computed. The Volume of Fluid (VOF) method is used to monitor the interaction between air, water in liquid form, and water in vapor form, along with evaporation–condensation mass transfer. Solar radiation is distributed on the glass cover in accordance with geographical parameters applied for clear-sky conditions, whereas natural convection is characterized by the declaration of gravitational acceleration in the vertical direction.

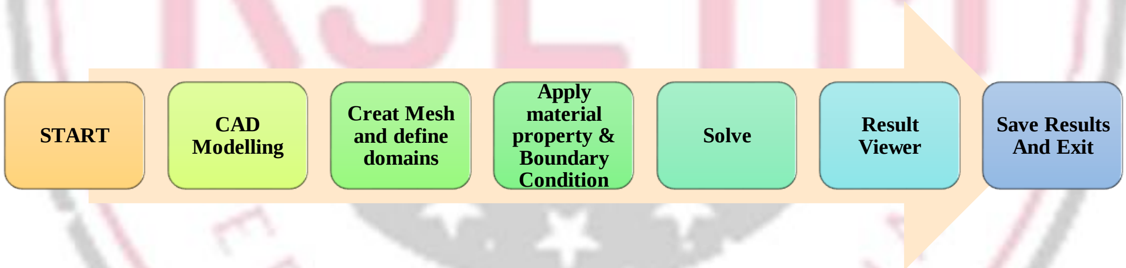

Figure 3:Algorithm used for Computational fluid dynamics analysis

The CFD workflow utilized in the present study is depicted in Figure 3 and consists of CAD modeling, meshing, specification of material properties and boundaries, numerical solution of governing equations, and post-processing of results for the purpose of analysis and documentation.

Governing Equations

The mass conservation principle (or continuity equation) is formulated in terms of the following:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\, \vec{v}) = S_m (3)$$

- S_m= mass added to the continuous phase or any user defined sources.

Conservation of momentum in an inertial reference frame is described by

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F} (4)$$

The energy equation for the mixture takes the following form:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\alpha_k\rho_k E_k) + \nabla.\sum_{k=1}^{n}\left(\alpha_k\vec{v}_k(\rho_k E_k + p)\right) = \nabla.\left(k_{eff}\nabla T\right) + S_E (5)$$

$k{-}\in$ model

The transport equations that determine turbulent kinetic energy, k, and its dissipation rate, ∈, can be expressed as:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k v_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\in-Y_M+S_k(6)$$

and

$$\frac{\partial}{\partial t}(\rho\in)+\frac{\partial}{\partial x_i}(\rho\in v_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\in}\right)\frac{\partial\in}{\partial x_j}\right]+C_{1\in}\frac{\in}{k}(G_k+C_{3\in}G_b)-C_{2\in}\rho\frac{\in^2}{k}+S_\in(7)$$

In these equations,

- G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients,
- G_b is the generation of turbulence kinetic energy due to buoyancy,
- Y_M Represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate,
- $C_{1\in}$, $C_{2\in}$, and $C_{3\in}$ are constant.
- σ_k and $\sigma_\in$ are turbulent Prandtl numbers for k and∈,
- S_k And $S_\in$ are user-defined source terms.

The conservation equations can be derived using mixture theory approach.

The phase magnitude q, V_q, is given by

$$V_q=\int_{v=1}^{n}\alpha_q dV(8)$$

Where

$$\sum_{q=1}^{n}\alpha_{q=1}(9)$$

The effective density of phase q is

$$\hat{\rho}_q=\alpha_q.\rho_q(10)$$

- ρ_q is the physical density of phase q.

Initially, three-dimensional CAD models are constructed for both single and double-slope solar stills, making use of ANSYS DesignModeler. Then, a structured hexahedral mesh is generated which is essential for the accuracy of the numerical simulation. Heat absorption, condensation and losses are coupled through the application of boundary conditions to the glass cover, absorber plate, and the walls of the enclosure. The properties of the paraffin C18 PCM are taken into account to simulate its latent heat storage and release. For the momentum and energy equations, second-order upwind discretization schemes are applied, and the ANSYS Fluent solver is used for the simulation.

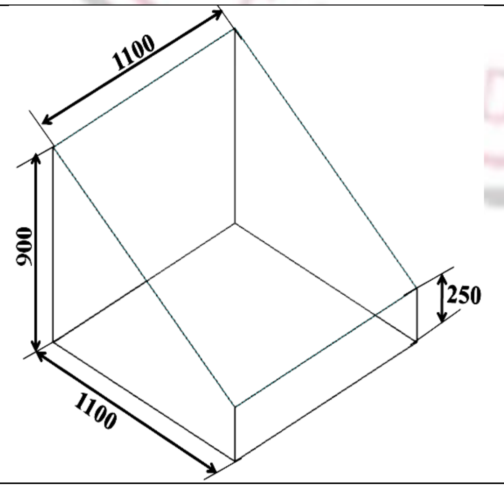

Figure 4: CAD mode of single slope solar still

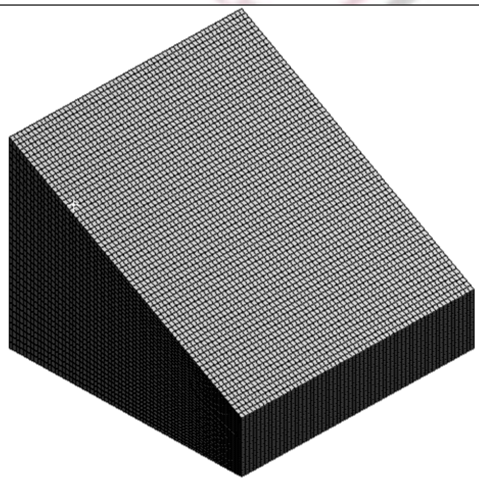

Figure 5:Meshing of single slope solar still

The single-slope solar still's three-dimensional CAD model was created through ANSYS DesignModeler based on given geometric measurements, which are depicted in Figure 4. The model received a mesh in ANSYS Workbench with hexahedral elements, leading to a total of 137,082 nodes and 128,832 elements, as indicated in Figure 5.

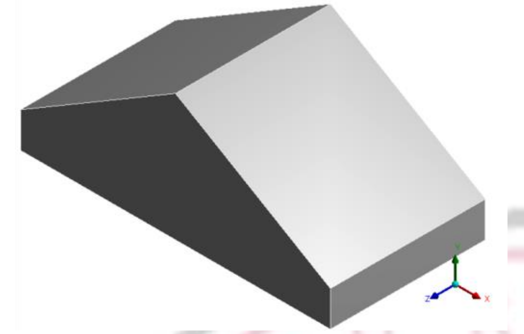

Figure 6: CAD mode of double slope solar still

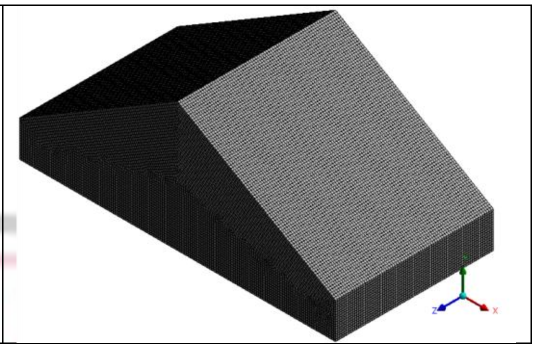

Figure 7: Meshing of double slope solar still

With specified geometric dimensions, the three-dimensional CAD model of the double-slope solar still was created with ANSYS DesignModeler, as seen in Figure 6. The model was then meshed in ANSYS Workbench employing hexahedral elements, comprising 446,550 nodes and 427,794 elements as depicted in Figure 7.

Table 2: Thermo physical property of paraffin C18 material

Property	**Values**
Melting temperature (T_m) [°C]	53.7
Specific heat (C_{ps}) [kJ/kg·K]	2.0
Specific heat (C_{pl}) [kJ/kg·K]	2.15
Thermal conductivity (k_s) [W/m·K]	0.24
Thermal conductivity (k_l) [W/m·K]	0.22
Density (ρ_s) [kg/m³]	910
Density (ρ_l) [kg/m³]	790
Latent heat of fusion [kJ/kg]	190

CFD simulations were done in ANSYS Fluent, where natural convection was considered by taking gravity in the negative y-direction and modeling multiphase flow with the VOF method involving air, water, and water vapor. The energy equation was solved for heat transfer simulation, while turbulence effects were accounted for by using the k–ε model with standard wall functions. The glass cover was subjected to solar radiation based on the site-specific geographical parameters, and evaporation–condensation mass transfer was also considered. For momentum and energy equations, second-order upwind schemes were used to enhance numerical accuracy.

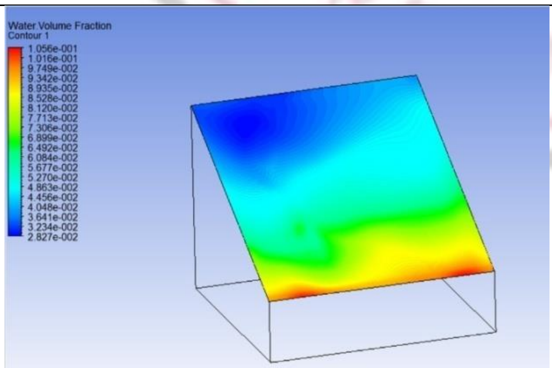

Figure 8: Volume fraction of water *[C. Gnanavel et al 2020]*

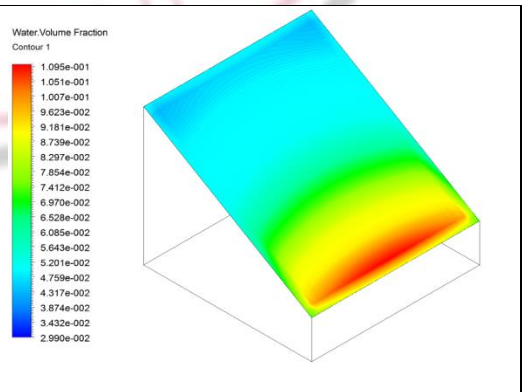

Figure 9: Volume fraction of water *[Present work]*

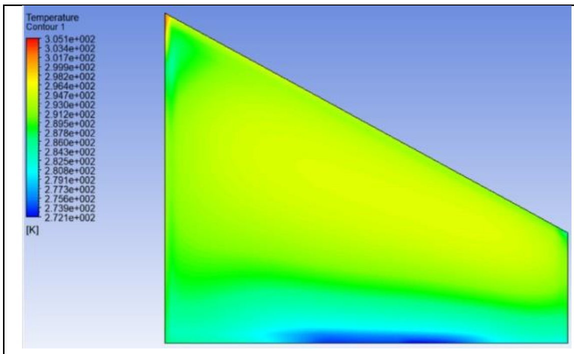

Figure 10: Temperature *[C. Gnanavel et al 2020]*

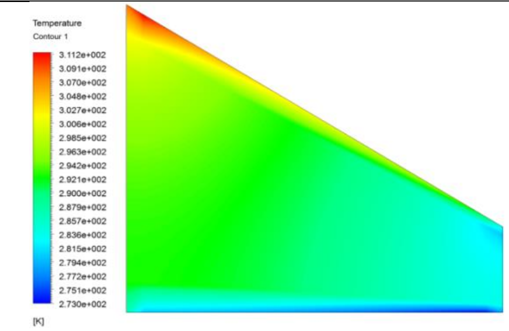

Figure 11: Temperature *[Present work]*

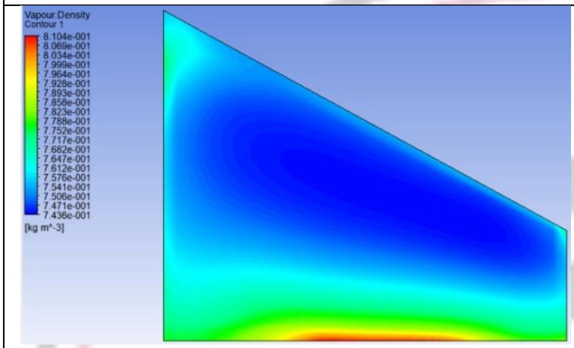

Figure 12: Vapour density *[C. Gnanavel et al 2020]*

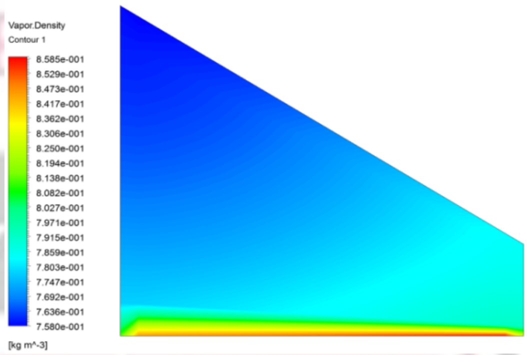

Figure 13: Vapour density *[Present work]*

The CFD model is validated through the comparison of predicted volume fractions of the water, temperature distributions, and vapor densities with those reported in the literature. The comparison reveals that there is a close agreement, with a maximum deviation of 6% for all major parameters, thus confirming the accuracy of the numerical model. This validation has led the researchers to conclude that the developed methodology is appropriate for conducting further parametric and design optimization studies of modified solar still configurations that incorporate such configurations.

V. RESULT AND DISCUSSION

The CFD analysis was performed to evaluate and compare the thermal and productivity performance of single- and double-slope solar stills which had been subjected to the same operating and boundary conditions. The three-dimensional simulations based on the VOF multiphase model showed accurately the evaporation-condensation processes that took place between air, liquid water, and water vapor. The contour plots of water volume fraction, vapor volume fraction, vapor density, temperature, and mass flow rate were examined to have an insight into the internal heat and mass transfer mechanisms that governed the production of distillate.

In the case of the single-slope solar still, the maximum water volume fraction was found to be at the glass surface, which was sloped, while the maximum temperature was 311.2 K at the glass cover. The peak values of mass flow rate and vapor volume fraction showed that evaporation and condensation were going on rather actively, and the main part of the vapor was being accumulated close to the back wall. The middle point is that heat retention and evaporation intensity were limited because of the asymmetric geometry and small effective condensing area, which was the main reason for that, the latter being the main reason for that scenario.

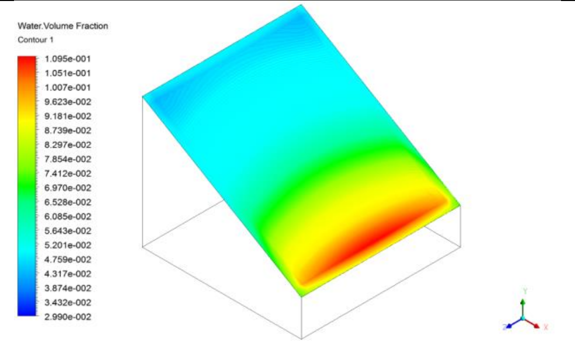

Figure 14: Water volume fraction's contour result

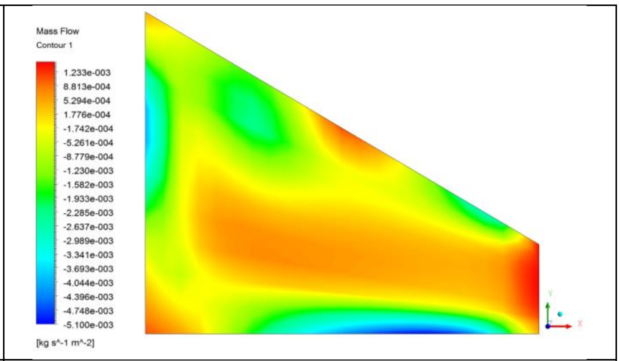

Figure 15: Result of mass flow in the solar still

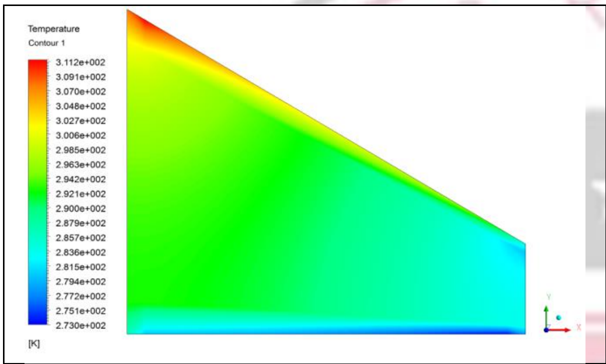

Figure 16: Contour result of temperature in the solar still

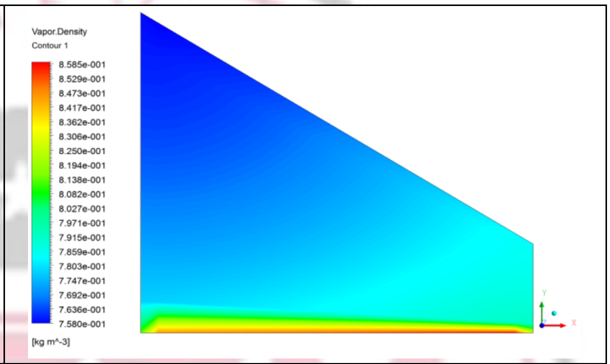

Figure 17: Contour result of vapor density in the solar still

On the other hand, the double-slope solar still achieved a notable performance boost over the single-slope in terms of all major parameters. The maximum temperature vented up to 316.7 K such that there was a marked increase in both vapor and water volume fractions which was attributed to the symmetrical glass surfaces being the main source of increased condensation area. The mass flow rate in the double-slope configuration almost reached twice that of the single-slope, which is a clear indication of the improved evaporation–condensation efficiency. Through this process, significant increases were observed in water volume fraction (≈0.0978), vapor volume fraction (≈0.077), and mass flow rate (≈0.00097 kg/s·m²).

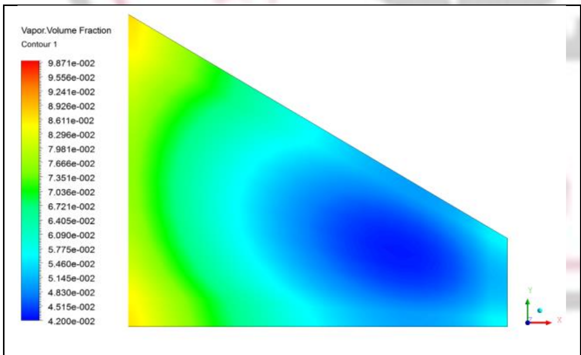

Figure 18: Contour result of vapor volume fraction

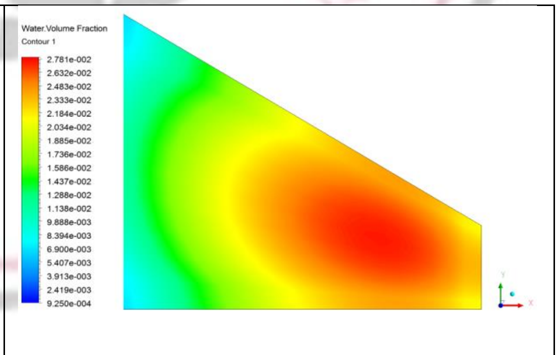

Figure 19: Contour result of water volume fraction in the solar still

A comparison of productivities further revealed that the double-slope solar still was by far superior to the others. The hourly and daily productivity of the double-slope solar still was computed to be 1.398 times greater than that of the single-slope configuration based on the CFD-derived basin water temperatures added with the corresponding latent heat values. The rise in productivity accompanies the increase in the operating temperature (≈5.5 K rise) and the vapor condensation which is a clear demonstration that the double-slope geometry greatly improves solar still performance.

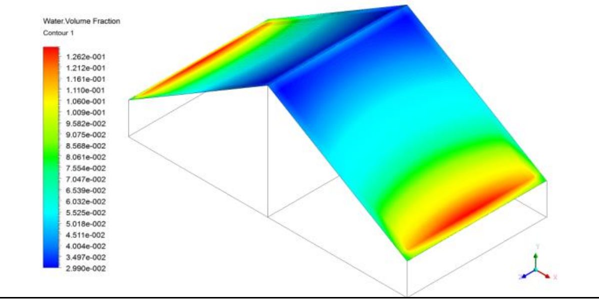

Figure20: Contour of volume fraction of water for double slop solar still

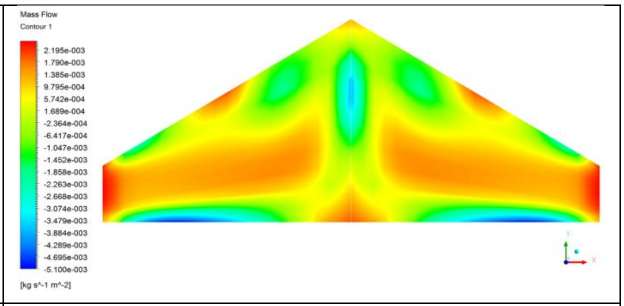

Figure 21: Mass flow contour for a double-slop solar still

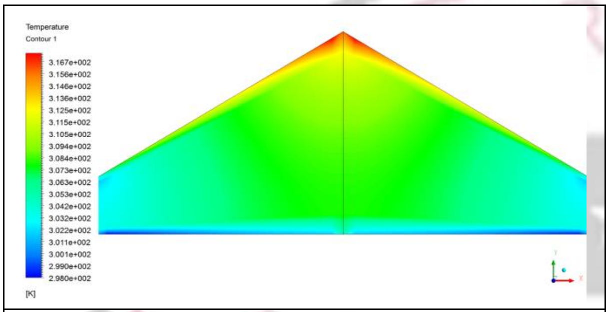

Figure 22: Temperature contour result in the double-slop solar still

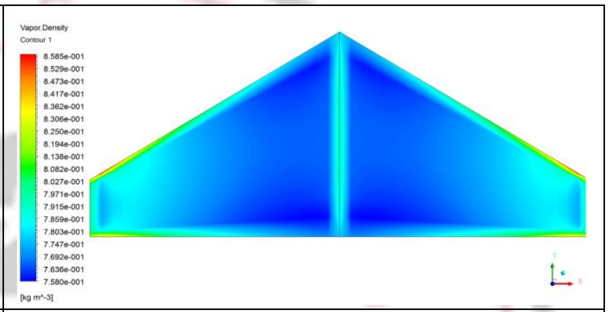

Figure 23: Vapor density contour result in the double-slop solar still

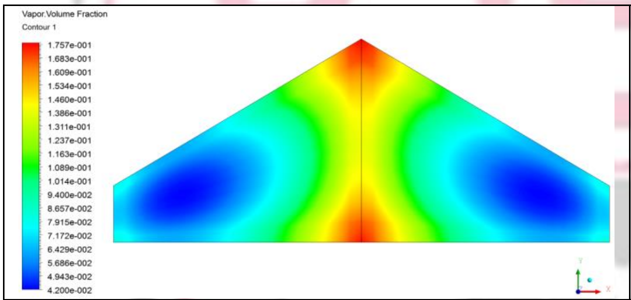

Figure 24: Result of vapor volume fraction in the double slop solar still

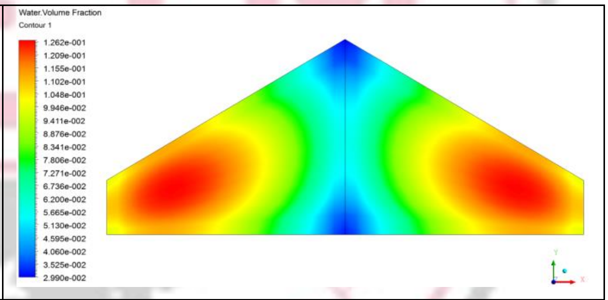

Figure 25: Contour result of water volume fraction in the double slop solar still

VI. CONCLUSION

The double-slope solar still with the phase change material showed great advantages over the single-slope configuration concerning thermal behavior and water production. The CFD simulation results correctly predicted the peak of heat retention, vapor generation, condensation, and mass flow rates owing to the even geometry and the prolonged thermal storage made possible by PCM, while the validated numerical model reliably captures the coupled heat and mass transfer processes thus establishing CFD as an efficient method for the performance assessment and design improvement. In general, the double-slope configuration appears to be a very good alternative for a passive desalination system aimed at sustainable freshwater production, and from now on, future studies might be directed towards examining the system under real climatic conditions, geometrical parameters' multi-objective optimization, hybrid PCMs or nanofluids integration, conducting transient simulations and coupling with auxiliary solar collectors to promote large-scale cold-generation throughout the year.

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